# United Technologies Robotic Tool for Aircraft Rim Cleaning 

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## BEEM

## Robotic Tool for Aircraft Rim Cleaning

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#### Abstract

Conventional systems for cleaning aircraft split rims waste millions of dollars in water and electrical resources annually. Team B.E.E.M. was tasked by the United Technologies Research Center (UTRC) in East Hartford, CT, with developing an alternative method for cleaning aircraft rims. To suit the needs of operation facilities under United Technologies Aerospace Systems, the product must reduce annual waste, maintain the current cleaning cycle time, and avoid damaging the anodized coating on the wheel rim's surface.

These design requirements are to be met with a fully automated system that implements laser ablation. Laser ablation is a no-contact process that vaporizes targeted materials, eliminates the use of water, and significantly reduces electrical wattage. The system design consists of a 1.0 KW Yttrium-fiber laser coupled with a collimator and galvanometer on the head of a robotic arm. The galvanometer aims at a rotating wheel to ablate the entire surface. Scaled testing with a 20 -watt laser and five varying mixtures of dirt, grease, and carbon dust proved that an ablation system can clean up to $95 \%$ of the targeted dirt surface. A half-scale model of the loading system was developed to simulate the laser trajectory across the surface of the wheel rim and proved to be capable of reaching all surfaces, including the bolt and spoke holes.

This report presents design specifications for the project, as well as research on optic technology and contamination found on an aircraft wheel rim. The team proposed 120 concepts as alternative methods for cleaning aircraft split rims, which were judged by the ability to satisfy parameters in a Quality Function Deployment analysis set by the United Technologies Research Center. Engineering analysis is provided for theoretical energy requirements for vaporizing contamination, the dynamics and structural integrity of the turntable, and the trajectory algorithm for the robotic manipulator. The design and production of the half-scale model are documented, along with additional redesign features. The laser parameters were verified through scaled tests at IPG Photonics in Oxford, Massachusetts, and the half-scale model was tested for covering the entire surface of the wheel rim. A financial analysis of the project proved to significantly reduce operation costs after a high initial cost. The Laser Ablation Robotic Rim Intensive Cleaner (LARRIC) has exceeded all design specifications outlined throughout this report.

The LARRIC successfully met design considerations throughout the prototyping phase of product development. Further design considerations are provided in this report to optimize the system design and laser trajectory.


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## Nomenclature

Symbols \& Units
$\dot{A}$. Rate of surface area coverage ..... $i n^{2} / s$
$\dot{Q}$. . Rate of Heat Transfer ..... W/s
$\vec{S}$. . Poynting Vector ..... $\mathrm{W} / \mathrm{m}^{2}$
A . . Absorptance
$A_{F}$. Accommodation Factor
$A_{r}$. Area of Radiating Surface ..... $m^{2}$
$A_{s}$. Surface Area ..... $m^{2}$
$B$. . Magnetic Field Field ..... Amp/m
$C_{p}$. Specific heat of Material ..... $\mathrm{J} / \mathrm{kgC}$
$D_{m}$. Diameter of the motor head ..... in
$D_{w o}$ Contact diameter of the wheel rim ..... in
E . . Electric Field ..... V/m
$E_{w}$. Wear Energy .....  J
$F_{E}$. Electric Force ..... N
$F_{M}$. Magnetic Force ..... N
$I_{\lambda}$. . Irradiance with respect to Wavelength ..... W
$I_{i}$. . Radiant Flux Density of Incident Beam ..... $\mathrm{W} / \mathrm{m}^{2}$
$I_{r}$. . Radiant Flux Density of Reflected Beam ..... $\mathrm{W} / \mathrm{m}^{2}$
$I_{t}$. . Radiant Flux Density of Transmitted Beam ..... $\mathrm{W} / \mathrm{m}^{2}$
$I_{d}$. . Drive roller moment of inertia ..... Kg.m ${ }^{2}$
$I_{E q}$. Equivalent Moment of Inertia ..... Kg.m ${ }^{2}$
$I_{g m}$. Roller head moment of inertia ..... Kg.m $m^{2}$
$I_{r}$. . Contact roller moment of inertia ..... Kg.m ${ }^{2}$
$I_{w}$. . Wheel rim moment of inertia ..... Kg.m ${ }^{2}$
$K_{E}$. Dielectric Constant
m
$L$. . Length
$N$. . Contributing Number of Electrons
$N$. . Motor to wheel rim gear ratio
$N$. . Number of Passes of a Planarization Experiment
W
P . . Total Radiant Power
Q . . Heat Transfer ..... W
$R$. . Reflectance
$R_{a}$. Average Roughness ..... $\mu \mathrm{m}$
$R_{z}$. Root Mean Square Roughness ..... $\mu \mathrm{m}$
$R_{a}$ avg Average of the Average Roughness ..... $\mu \mathrm{m}$
$R_{a}$ clean Average Roughness of the Clean Surface ..... $\mu \mathrm{m}$
$R_{a \text { mixture }}$ Average Roughness of the Mixture Surface ..... $\mu \mathrm{m}$
$R_{\text {a referance }}$ Average Roughness of the Reference Surface ..... $\mu \mathrm{m}$
$R_{w i} \quad$ Inner radius of the 3-D printed wheel rim ..... in
$R_{z a v g}$ Average of the Root Mean Square Roughness ..... $\mu \mathrm{m}$
$R_{z \text { clean }}$ Root Mean Square Roughness of the Clean Surface ..... $\mu \mathrm{m}$
$R_{z \text { mixture }}$ Root Mean Square Roughness of the Mixture Surface ..... $\mu \mathrm{m}$
$R_{z \text { referance }}$ Root Mean Square Roughness of the Reference Surface ..... $\mu \mathrm{m}$
$S A$ Surface area of the half-scale rim ..... $i n^{2}$
$T$. . Transmittance into Material$T_{\infty}$. Ambient Temperature${ }^{\circ} \mathrm{C}$
$T_{\text {Boil }}$ Boiling/Flashpoint Temperature of Material ..... ${ }^{\circ} \mathrm{C}$
$t_{\text {cycle }}$ Cycle time ..... Sec
$T_{\text {out }}$. Transmittance out of Material
$i n / s$
$V_{\text {Tangent }}$ Average required tangential velocity along the wheel rim
$\mu \mathrm{m}$
$W$. Waviness
m
b . . Thickness of Material
$\mathrm{m} / \mathrm{s}$
c . . Speed of Light
Js
h . . Planck's Constant
$\mathrm{Nm}^{2} / \mathrm{C}^{2}$
$k$. . Coulomb's Constant
J/K
$k_{B}$. Boltzmann's Constant
N/m
$k_{E}$. Elastic Constant ..... ,
$k_{i}$. . Respective Unit Incident Propagation Vector -
$k_{r}$. . Respective Unit Reflective Propagation Vector
$k_{t}$. . Respective Unit Transmitted Propagation Vector .....
kg .....
kg
$m_{e}$. Mass of Electron
$m_{e}$. Mass of Electron
$n_{i}$. . Index of Refraction of Incident Beam
$n_{r}$. . Index of Refraction of Reflected Beam
$n_{t}$. . Index of Refraction of Transmittance Beam
$n_{t i}$. Relative Index of Refraction
$q$. . Point Charge ..... C
$r$. . Amplitude Reflection Coefficient$r$. . Radiusm
$t$. . Amplitude Transmission Coefficient ..... -
$T_{\text {Boil }}$ Time ..... s
u . . Energy Density ..... $\mathrm{kg} / \mathrm{ms}^{2}$
$u_{B}$. Energy Density of Magnetic Field ..... $\mathrm{kg} / \mathrm{ms}^{2}$
$u_{E}$. Energy Density of Electric Field ..... $\mathrm{kg} / \mathrm{ms}^{2}$
$w$. . Width of Beam .....  m
$\alpha$. . Angular acceleration ..... $\mathrm{rev} / \mathrm{s}^{2}$
$\epsilon$. . Permittivity ..... F/m
$\epsilon_{0}$. Permittivity of Free Space ..... $\mathrm{F} / \mathrm{m}$
$\gamma$. . Surface Energy ..... $\mathrm{J} / \mathrm{m}^{2}$
$\lambda$. . Wavelength ..... m
$\mu_{0}$. . Magnetic Pereability of Free Space ..... $\mathrm{N} / \mathrm{Amp}^{2}$
$\mu_{i}$. . Pereability of Incident Material ..... $\mathrm{N} / \mathrm{Amp}^{2}$
$\mu_{r}$. . Pereability of Reflected Material ..... $\mathrm{N} / \mathrm{Amp}^{2}$
$\mu_{t}$. . Pereability of Transmitted Material ..... $\mathrm{N} / \mathrm{Amp}^{2}$
$\nu$. . Speed of Electromagnetic Waves ..... m/s
$\nu_{i}$. . Velocity of Incident Beam ..... m/s
$\nu_{r}$. . Velocity of Reflected Beam ..... $\mathrm{m} / \mathrm{s}$
$\nu_{t}$. . Velocity of Transmitted Beam ..... $\mathrm{m} / \mathrm{s}$
$\omega$. . Harmonic Wave Frequency ..... Hz
$\omega_{0}$. Resonance Frequency ..... Hz
$\omega_{d}$. Rotation rate of the drive roller ..... rev/s
$\omega_{m}$. Rotation rate of the motor ..... $\mathrm{rev} / \mathrm{s}$
$\omega_{r}$. . Rotation rate of the contact roller ..... rev/s
$\omega_{w}$. Average rotation rate of the 3-D printed wheel rim ..... rev/s
$\omega_{g m}$. Rotation rate of the motor head ..... rev/s
$\phi_{E}$. Flux of an Electric Field through an Area ..... $\mathrm{V}^{*} \mathrm{~m}$
$\rho$. . Density of Material ..... $\mathrm{kg} / \mathrm{m}^{3}$
$\tau_{m}$. Torque experienced by the drive motor ..... N.m
$\tau_{w}$. . Torque experienced by the wheel rim ..... N.m
$\theta$. . Divergence of Beam .....  ${ }^{\circ}$
$\theta_{i}$. . Angle of Incidence ..... 。
$\theta_{r}$. . Angle of Reflectance .....  ${ }^{\circ}$
$\theta_{t}$. . Angle of Transmittance ..... 。
Acronyms
LARRICLaser Ablation Robotic Rim Intensive Cleaner
NISOH National Institute of Occupational Safety and Health
OSHA Occupational Safety and Health Administration
QFD Quality Function Deployment
UTC United Technologies
UTRC United Technologies Research Center

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## 1 Introduction

During an aircraft's landing, carbon brake pads reach extreme temperatures and experience significant wear. The dust produced during landing, in addition to the axle-bearing grease and dirt collected from the run way, contaminates the interior of the wheel. Operation facilities under United Technologies Aerospace Systems (UTAS) provide routine maintenance after a specified number of landings per overhaul have been reached. The wheels are disassembled and are currently being cleaned in a Mart 60 water-jet system. Although a biodegradable solvent is used, the water is not allowed to be drained to the environment and must be either recycled or shipped to a water treatment facility. A current recycling system allows the water to be recycled for up to a month; however, the United Technologies Corporation (UTC) still pays out millions of dollars every year for the remaining waste. The United Technologies Research Center (UTRC) in East Hartford, CT, has tasked the design team with finding an alternative cleaning method for aircraft wheel rims with the goal of reducing water waste and cycle time.

The selected method for this project must have a universal interface for aircraft rims of all classes and brake systems. In order to meet the demand of wheels that need to be cleaned, the time cycle of the system must surpass a ratio of two full aircraft rims in 15 minutes including loading and unloading time. Based on the STINGRAY 6036 Aircraft Wheel Washer, which is similar the Mart 60, a reduction of resources will be met if the alternative cleaning method uses less than 397 gallons of water per cycle and 105 kW of electricity for heating elements and pumps. The volume of the system is constrained to $6^{\prime} \times 66^{\prime} \times 7.5$ ' to avoid heavy rearrangement of the operation facilities. Finally, an absolute requirement is that the system may not damage any coatings that can be found on aircraft rims.

Prior to this team assignment, the United Technologies Research Center performed initial investigations in cleaning systems involving plasma electrolysis, ultrasonic cleaning, and laser ablation. Each of these processes are common methods used for cleaning smaller aircraft components with simpler geometries and show potential for cleaning the split rims of an aircraft. This team is the first to work with UTRC to find an affective cleaning solution.

This project is aimed toward researching and identifying a resourceful method for cleaning aircraft rims, as well as designing a mechanical system that may be implemented in UTAS operation facilities. Patent and literature searches concluded that laser ablation, a no-contact process for vaporizing contamination, was the most suitable method for cleaning aircraft rims. An engineering analysis was performed to numerically determine the viability of the designed system, named the Laser Ablation Robotic Rim Intensive Cleaner (LARRIC). A proof of concept was necessary to ensure that laser-energy pulses could be controlled to vaporize varying mixtures of dirt, grease, and carbon dust without damaging the anodized coating of a sheet of aluminum 6061. A half-scale prototype was then constructed to simulate the laser trajectory along the surface of the wheel rim and ensure all complex geometries can be ablated using the proposed system.

## 2 Project Plan

The project presented in this design report began Thursday, September 21, 2017. The overall project was divided into two terms in accordance to the University of Rhode Island's academic schedule. The objective throughout the Fall of 2017 was to establish a design approach that specified expectations from the United Technologies Research Center, investigate concepts for meeting the design specifications, and attaining a tangible proof of concept for the select cleaning method: laser ablation. The Spring of 2018 aimed to develop, test, and optimize a half-scale prototype which could simulate the trajectory path of a laser across the surface of a Boeing 747 split rim.

Using Microsoft Project Office, a Gantt chart was created as a project planning tool. On the left-hand side, task details are listed with their respective duration time, start dates, deadlines, and team members involved. The right side consists of a horizontal chart that uses bars to visually illustrate task deadlines. Next to each bar, the team members involved with each task are displayed. A Gantt chart was developed for the Fall of 2017 and Spring of 2018 to coordinate tasks and remain on schedule.

### 2.1 Fall of 2017

A summary view of the project plan for the Fall of 2017 is shown in the figure below. A detailed view of the design team's project plan can be seen in Appendix ??.


Figure 2.1: Fall of 2017 Project plan in summary view

The Gantt chart is split into four separate groups: Capstone Project milestones, Problem Definition, System Design, and Proof of Concept. Team meetings occurred at least twice a
week and used the Gantt Chart to stay on top of tasks.
Once students were assigned to a project, the team met to share their initial ideas about the project as well as strengths and weaknesses. Given everyone's skills, each team member accepted a role in the project. Brian's interests and courses for the semester differentiated his skill with a focus on control systems engineering. Erik had previous internship experience working with modeling software and developing part and assembly drawings; therefore, Erik accepted the title of design engineer. Mkrtich had expressed interest in thoroughly learning the fundamentals of advanced cleaning systems and had taken the role of research engineer. Ibrahim's previous experience in an innovation challenge and a product development internship had given him the qualifications to work as project leader.

With these roles, the team had begun initial research on various types of alternative cleaning methods. With guidance from the United Technologies Research Center contact, Dr. Thomas Filburn, the design team had found three alternative methods for cleaning an aircraft split rim. The three concepts that were of interest to the group were plasma electrolysis, ultrasonic cleaning, and laser ablation. With these narrowed topics, a patent and literature search was conducted to prevent overlap with any already-existing designs and gain creative inspiration for developing an innovative design concept. Most of the systems available for aircraft wheel cleaning are water-jet based and no patents were found that directly use the aforementioned cleaning concepts for cleaning aircraft wheel rims.

While continuing to search for patents and literature pertaining to the previously listed concepts, the team began to generate thirty unique design concepts addressing all aspects of the system. All three potential cleaning alternatives were used as inspiration for the design concepts. The open concept generation was then narrowed by the development of design requirement specifications. Using these design requirements as a reference, Brian lead the design team through a Quality Function Deployment (QFD) analysis to determine the critical design parameters for meeting the requirements of this system. The design specifications and QFD will be further presented later in this report.

Once the design specifications and QFD analysis were complete, each team member completed their creative concept generation. The team then regrouped to select one of the three major cleaning concepts. After thorough consideration, a laser ablation system was deemed suitable for cleaning aircraft rims. After determining that laser ablation the most appropriate design system for this project, a brief presentation was prepared to serve as a Critical Design Review. This presentation was given to the Mechanical Engineering Capstone class to receive feedback and concerns about the feasibility of the project.

Having received reassurance from the audience that the selected concept would be feasible to develop, the team used the class's feedback and constructive criticism to improve the design approach for the product. The project leader had then divide the tasks into two objectives, system design and attaining a proof of concept. Brian and Erik were delegated as the primary engineers for developing a full-scale system design. Ibrahim and Mkrtich were responsible for attaining a proof of concept.

The team begun to search for on-campus labs with available lasers for testing. Unfortunately, the necessary laser for this project (Neodymium doped: Yttrium Aluminum Garnet) was not available. Erik had then contacted IPG Photonics, a laser company specialized in manufacturing and cleaning applications. An initial appointment was made to discuss optical technology that should be considered for the system design. It was then agreed to
organize a second appointment for the team to return to IPG Photonics to perform tests and attain a tangible proof of concept.

Mkrtich had then met with Dr. Donna Meyer at the University of Rhode Island for technical guidance on how to affectively perform engineering analysis on a laser ablation system. Mkrtich and Ibrahim then proceeded to develop an energy and optic analysis to numerically determine the limitations of laser ablation in this application. Ibrahim had then mapped out a testing procedure for the proof of concept at IPG Photonics. A Proof of Concept presentation was prepared for Capstone classmates to receive feedback on the testing procedure and numerical analysis. The team then developed a bill of materials for the tests and then proceeded to prepare test samples of dirt covered aluminum 6061 sheets, which were then tested on December 8th.

In parallel, Brian and Erik had researched various optical devices that may be applied and used in the laser ablation system. Both members proceeded to construct three-dimensional Computer Aided Drawings of the system assembly and individual components. Brian had then performed a financial analysis to determine the overall return on investment the LARRIC will offer.

### 2.2 Spring of 2018

The project schedule for the Spring of 2018 is shown in a summary view in the figure below. Further details of the project plan can be found in Appendix A.2.


Figure 2.2: Spring of 2017 Project plan in summary view

The objective throughout the spring semester was to investigate laser trajectories for ablating all surfaces of a Boeing 747 split rim, including the bolt and spoke holes. The design team split into two groups to develop a half-scale prototype of the LARRIC. Ibrahim and Erik previously worked in development and manufacturing environments. This qualification resulted in the design of the system's mechanical hardware being delegated to Ibrahim and Erik. The courses which Brian and Mkrtich participated in throughout the spring semester focused on the programming and manipulation of robotic systems. As a result, Brian and

Mkrtich were assigned responsibility for developing a robotic manipulator and automating the entire ablation system.

The month of January was delegated to modeling and drafting a half-scale prototype of the LARRIC. Mkrtich and Brian investigated design requirements for a robotic manipulator to be included in the system and compared the specifications with available options found on the internet. With the selected manipulator parameters, Ibrahim and Erik proceeded to generate system concepts for cleaning various aircraft wheel rims. Once a final concept was selected, the system was modeled with incorporated space for the robotic manipulator and a turntable. Each component, sub-assembly, and system assembly was then drawn with appropriate geometric dimensions and tolerances. An online order form and purchasing list for all necessary material and equipment was developed and submitted on February 7.

As raw materials and electronic equipment arrived at the Schneider Electric facility, the geometric dimensions and tolerances were documented for manufacturing and application consideration. Throughout February, Ibrahim and Erik manufactured individual parts and components of the LARRIC prototype at the Capstone Mechanical Engineering Machine Shop. Finished parts were documented and compared with drawing tolerances to ensure the quality of the components would satisfy the needs of the system. Once the robotic arm arrived at the Schneider Electric facility, Mkrtich and Brian assembled the frame and servomotors for the robotic manipulator. The manipulator models were then updated to incorporate the physical link dimensions to ensure the manipulator could reach the top and bottom of the rim.

Throughout late February and early March, the individual components of the LARRIC system were assembled to develop a loading drawer and turntable. In order to replicate the aircraft split rim, the larger half of the Boeing 747 wheel rim was modeled and printed with ABS plastic. A clear coat was applied to the print to smooth the surface of the rim. In addition, a florescent powder mixed with clear glue covered the wheel rim to indicate areas that have been lased by ultra-violet light. The head of the robotic manipulator was coupled with an ultra-violet flashlight. Prior to mounting the base of the arm to the halfscale prototype, a trajectory algorithm was developed for controlling the angular position of each joint in the robotic arm. On March 21st, the team submitted a Test Engineering Plan Report which outlined all testing procedures for the subassemblies and complete integrated system. Throughout the first week of April, initial tests of the turntable were executed to ensure the loaded wheel rim properly rotates at the desired speed. Testing procedures were temporarily halted as subassembly results showed issues the rim's ability to rotate with the turntable. As the turntable was redesigned to reduce the number of contacts to three-points of contact, Mkrtich integrated all electrical components and wiring throughout the system. An initial trajectory was tested to reach the top and bottom portions of the split rim but had failed due to the length of the links. Mkrtich and Brian proceed to research linear actuators to incorporate in the system to allow accessibility for the top and bottom of the split rim.

Half way through April, the redesign features for the linear actuator and the turntable were successfully implements and passed subsection testing. Mkrtich and Brian continued to program the LARRIC prototype to develop a full-cycle cleaning program with light indications and safety interlocks. Erik and Ibrahim began investigating the structural integrity of the mechanical loading system to determine if the static safety factor meets UTRC design standards. An additional FEA study was performed to determine the loading response of a
wheel rim being dropped overhead onto one of the contact points.
A full-cycle program successfully implemented on Tuesday, April 24th. All remaining test procedures were conducted to determine the cycle time and system's ability to ablate all surfaces of the rim. The data was then summarized and presented at the University of Rhode Island Mechanical Engineering Design Showcase on Friday, April 27, 2018.

## 3 Financial Analysis

The following section is an entire financial analysis of the capstone project with United Technology Research Center. The first section focuses on comparing the cost of the current system using the Mart 60 water jet system to the proposed system of laser ablation. The points are based on purchasing, installing and operational costs. The second section is a breakdown of would-be cost if each member of the team was employed to UTRC. An additional analysis is included to illustrate what each team member spent their time on and why it was financially important to the team. The last section analyzes the would-be cost of consultations to individuals to gain information or equipment necessary to the team for the project.

### 3.1 Cost of System Implementation

Table 3.1: Approximate calculations for system implementation

| Product | Amount | Price |
| :---: | :---: | :---: |
| Hydraulic Lift | 1 | $\$ 400$ |
| DC Motor | 3 | $\$ 2,831$ |
| IPG Photonics 5 Kilowatt Laser w/ Galvo Head | 1 | $\$ 250,000$ |
| Robotic Arm with Application Specific Programming | 1 | $\$ 150,000$ |
| Conveyor Bearings | 3 | $\$ 108$ |
| Steel Rotary Shaft | 3 | $\$ 537$ |
| Housing Building and Installation with Safety Features | 1 | $\$ 100,000$ |
| Laser Programming and Software | 1 | $\$ 50,000$ |
| Installation Price and Worker Hours to Install | 1 | $\$ 100,000$ |
| Total |  | $\$ 653,876$ |

Table 3.1 represents the cost to purchase and install each system. The values for laser ablation were determined by numbers given to the team during the initial visit to IPG Photonics. The values for the current process are on the right side and are an approximate cost to purchase and install the system. These numbers were determined by researching availability of the current system and the complexity of installation. As shown in the table, the cost to install a laser system with a robotic arm exceeds the cost of the current system used by UTRC.

Table 3.2: Annual Breakdown of Laser Ablation System

| Parameter | Operating Power (W) | Cycle Cost | Yearly Cost |
| :---: | :---: | :---: | :---: |
| Laser | $5,000.00$ | $\$ 0.27$ | $\$ 7,904.00$ |
| Cooling System | 2000 | $\$ 0.11$ | $\$ 3,161.60$ |
| Robotic Arm | 250 | $\$ 0.01$ | $\$ 395.20$ |
| Rim Motor | 2237 | $\$ 0.12$ | $\$ 3,536.25$ |
| Total | $9,487.00$ | $\$ 0.52$ | $\$ 14,997.05$ |

Table 3.2 illustrates the power consumption of the components necessary for laser cleaning with laser ablation. The primary power consumption is due to the laser. The other elements which drew noticeable power were the cooling system and the motor required to rotate the rim. The robotic arm drew significantly less power but the power rating was included for completeness. A cooling system is necessary for the laser that is operating continuously to meet specifications. Power rating for the motor was determined by browsing motors and selecting a motor with enough power to rotate a rim of weight three times the standard weight of the rim. This was necessary as the system needed to be versatile to clean rims of sizes larger than the model given.

Table 3.3: Cost of system currently implemented by UTRC

|  | Power (kW) | Cycle Cost | Yearly Cost |
| :---: | :---: | :---: | :---: |
| Cost to run pumps | 30 | $\$ 0.18$ | $\$ 8,299.20$ |
| Cost to run heaters | 40 | $\$ 0.24$ | $\$ 11,065.60$ |
| Cost of soap | N/A | $\$ 0.05$ | $\$ 1,560.00$ |
| Cost of water disposal | N/A | $\$ 30.05$ | $\$ 1,000,000.00$ |
| Total | 70 | $\$ 30.51$ | $\$ 1,020,924.80$ |

Table 3.3 is representative of the current process used by UTRC to clean aircraft rims. The values calculated were based on the Mart 60 specifications of standard aircraft rim cleaning devices. Neglecting the cost to dispose of the contaminated water, the annual cost to run the system is higher than the proposed method of laser ablation. Compounding with the cost of water disposal costs, the current system has a significant cost of water disposal and makes up the majority of the cost to operate the system. The only indication the team received for the cost of water disposal was quoted as "Millions annually". Thus no exact value was given for the cost of water disposal and a baseline of $\$ 1,000,000$ was determined to be an acceptable approximation.

Table 3.4: Basis for laser ablation costs

| Cycle Time / Half Rim | $2.5(\mathrm{~min})$ |
| :---: | :---: |
| Hours/Work Day | 8 Hr |
| kW-Hr (KY) | $\$ 0.095$ |

All calculations were based on the standards set between the team and UTRC's current process. Table 3.4 defines the amount of time it takes to clean one rim half. Next the standard work day of eight hours was used as the basis for the amount of time each system
would be operational. The most important value from the table is the cost of electricity at the nearest facility that uses the systems, which is in Kentucky, USA. This value was derived from a data base of electrical costs in the united states. Rates differ for certain companies and house hold consumption, therefore an average between companies was determined to be $\$ 0.095$ each kilo-watt hour.


Figure 3.1: Cost to implement lasers Opposed to current process

The previous figure is a comparison of the cost of each system if they were both implemented simultaneously. These include the cost of purchasing, and installation as well as the operational costs given by Tables 3.2 and Table 3.3. As previously mentioned, the initial cost of the laser system would be greater but as shown in Figure 3.1, the current process exceeds the cost of laser ablation in just under one year. This is significant because UTRC will be saving money throughout the rest of the life cycle of the laser ablation system. Figure 3.2 shows the net value saved throughout the course of three years. Just after two years the company will have saved $\$ 1,000,000$ and over $\$ 2,200,000$ after three.


Figure 3.2: Difference between the cost of implementing both systems

### 3.2 Team Member Financial Report

Table 3.5: Fall semester weekly hours spent on capstone project per team MEMBER

|  | Hours |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Week Ending | Brian | Ibrahim | Mkrtich | Erik | Total | Over Time | Payout |
| $9 / 24 / 2017$ | 12 | 12 | 12 | 12 | 48 | 0 | $\$ 1,070.88$ |
| $10 / 1 / 2017$ | 18 | 20 | 18 | 18 | 74 | 0 | $\$ 1,650.94$ |
| $10 / 8 / 2017$ | 21.5 | 23 | 21.5 | 21.5 | 87.5 | 0 | $\$ 1,952.13$ |
| $10 / 15 / 2017$ | 23 | 25 | 23 | 23 | 94 | 0 | $\$ 2,097.14$ |
| $10 / 22 / 2017$ | 31 | 31 | 31 | 31 | 124 | 0 | $\$ 2,766.44$ |
| $10 / 29 / 2017$ | 26 | 31.5 | 27.5 | 24 | 109 | 0 | $\$ 2,431.79$ |
| $11 / 5 / 2017$ | 24 | 29.5 | 31 | 18.5 | 103 | 0 | $\$ 2,297.93$ |
| $11 / 12 / 2017$ | 22 | 39 | 50.5 | 18 | 129.5 | 10.5 | $\$ 3,006.27$ |
| $11 / 19 / 2017$ | 27 | 35 | 64 | 24.5 | 150.5 | 24 | $\$ 3,625.38$ |
| $11 / 26 / 2017$ | 26 | 27 | 52 | 17.5 | 122.5 | 12 | $\$ 2,866.84$ |
| $12 / 3 / 2017$ | 25 | 33 | 48 | 22.5 | 128.5 | 8 | $\$ 2,956.08$ |
| $12 / 10 / 2017$ | 25.8 | 30 | 48 | 13.5 | 117.3 | 8 | $\$ 2,706.20$ |
| $12 / 17 / 2017$ | 31.5 | 34 | 31.5 | 31.5 | 128.5 | 0 | $\$ 2,866.84$ |
| Term Total | 312.8 | 370 | 458 | 275.5 | 1416.3 | 62.5 | $\$ 32,294.84$ |

Tables 3.5 and 3.6 represent Fall and Spring hourly contributions by each team member spent working on the capstone project. The hourly wage is based on an average entry

Table 3.6: Spring semester weekly hours spent on capstone project per TEAM MEMBER

|  | Hours |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Week Ending | Brian | EB | Mike | Erik | Total | Over Time | Payout |  |
| $1 / 29 / 2018$ | 8 | 9 | 33 | 6 | 56 | 0 | $\$ 1,750.00$ |  |
| $2 / 5 / 2018$ | 15 | 14 | 24 | 12 | 65 | 0 | $\$ 2,031.25$ |  |
| $2 / 12 / 2018$ | 10 | 38.5 | 47 | 15 | 110.5 | 7 | $\$ 3,781.25$ |  |
| $2 / 19 / 2018$ | 17 | 21.5 | 25 | 12 | 75.5 | 0 | $\$ 2,359.38$ |  |
| $2 / 26 / 2018$ | 18.5 | 27 | 26.5 | 15 | 87 | 0 | $\$ 2,718.75$ |  |
| $3 / 5 / 2018$ | 26 | 21 | 36 | 12 | 95 | 0 | $\$ 2,968.75$ |  |
| $3 / 12 / 2018$ | 15 | 38.5 | 24 | 10 | 87.5 | 0 | $\$ 2,734.38$ |  |
| $3 / 19 / 2018$ | 24 | 0 | 2 | 3 | 29 | 0 | $\$ 906.25$ |  |
| $3 / 26 / 2018$ | 20.5 | 14 | 17 | 17 | 68.5 | 0 | $\$ 2,140.63$ |  |
| $4 / 2 / 2018$ | 17 | 19.5 | 73 | 12 | 121.5 | 33 | $\$ 5,343.75$ |  |
| $4 / 9 / 2018$ | 12 | 19 | 64 | 10 | 105 | 24 | $\$ 4,406.25$ |  |
| $4 / 16 / 2018$ | 13 | 21.5 | 36 | 13 | 83.5 | 0 | $\$ 2,609.38$ |  |
| $4 / 23 / 2018$ | 22 | 15 | 63 | 12 | 112 | 23 | $\$ 4,578.13$ |  |
| $4 / 30 / 2018$ | 2 | 4 | 85 | 12 | 103 | 45 | $\$ 5,328.13$ |  |
| $5 / 7 / 2018$ | 12 | 25 | 55 | 25 | 117 | 15 | $\$ 4,359.38$ |  |
| Term Total | 232 | 287.5 | 610.5 | 186 | 1316 | 147 | $\$ 48,015.63$ |  |

level engineering salary of $\$ 65,000$. This was determined by factoring in to account the magnitude of the project and the cost for entry level individuals who are competent and capable of handling a project of similar caliber. Each members hours were tracked based on what tasks they performed. Overtime was also considered and was based on time-and-a-half rate of hourly wage from the aforementioned salary of $\$ 65,000$.

### 3.2.1 Breakdown of hours spent for each team member

The following Figures 3.3-3.6 illustrate the percent of time spent on each category of task listed in the chart. Research was evident in each chart due to the complexity of the capstone project. Early during the Fall semester each member conducted research because there were multiple different solutions to the problem. This lead to each member doing research on specific methods for rim cleaning which included laser ablation, ultrasonic, electrolytic, and other unique methods.

During the Spring semester, tasks were split into two categories and divided between the team. Mkrtich and Brian were tasked with research, development, theory and control of robotic manipulators. Ibrahim and Erik were tasked with designing, building and ensuring the apparatus housing the manipulator and laser met design specifications. Writing was a primary element in each chart due to the number of reports required for the spring semester. Research became more evident in Mkrtich and Brian's chart as they were required to learn the theory of manipulators and control. On the contrary, research became less evident in Ibrahim and Erik's charts as they spent majority of their time designing and building the apparatus utilizing skills they previously developed.


Figure 3.3: Breakdown of Brian's hours spent per task

Designated as the System Control Engineer, Brian was primarily tasked with developing methods to control the robotic manipulator and create a trajectory. Brian's chart shown in Figure 3.3 indicates that the majority of his time was spent between research and building. A considerable amount of research was conducted pertaining to control methods of robotic manipulators. After determining the optimal method was training the manipulator, Brian built four Matlab programs to calibrate, test repeatability and generate a trajectory. In addition to robotics research, Brian also conducted research on the fundamentals of lasers and their applications during the Fall semester.

During the testing phase, Brian was in charge of testing the robotic arm and performing maintenance to optimize the motion of the arm. Lastly, Brian was also in charge of financial research and analysis. This included keeping track of each members hours spent contributing to the capstone project and also what the time was spent on. In addition to tracking team member financial, he was also in charge of analyzing the cost of current system at UTRC and developing a cost comparison to the proposed method of laser ablation.


Figure 3.4: Breakdown of Ibrahim's hours spent per task

Ibrahim's chart shown in Figure 3.4 indicates a coarse balance between each task.This distribution is due in-part to Ibrahim's role as team leader. He was required to be up to date with everyones progress in addition to working with all members to ensure the team was working towards a common goal. Design is largest section in the chart as Ibrahim spent considerable amount of time building and rebuilding the system in Solidworks. Further design work was done by Ibrahim while developing a PID algorithm to rotate the rim at the desired rate.

During the Fall semester a large portion of Ibrahim's time was spent doing design which involved creative manipulation of laser beams. As the team leader, Ibrahim spent updating the progress plan, progress reports and seeking avenues for testing. Additional time was spent creating PowerPoints and determining optimal presentation flow which further contributed to his hours spent on managerial tasks. The final element is the analysis which was spent determining variables, equations and methods for quantifying experimental procedures and also conducting the analysis of said experiments.


Figure 3.5: Breakdown of Erik's hours spent per task

The prominent element of Erik's chart shown in in Figure 3.5 is the amount of design work he conducted as he is the lead design engineer. During the Fall semester his designs ranged from initial concepts using lasers and ultrasonic, to drafting a Solidworks model of the rim needed to clean. In addition to design work, he also contributed valuable input to designs created by other team members. This included feasibility, performance, ease of manufacturing, maintenance and cost of parts.

Early during the spring semester, Erik gathered the materials and built the housing apparatus for the system as well as affixing the sliding drawer for the rim. Also evident from the chart is the amount of time spent writing. Erik always began writing reports early as he wanted to be able to edit and make suggestions to improve reports. The last noteworthy segment of the chart is the time spent analyzing the prototype as well as the final design. This time was spent analyzing the choice of materials for the prototype and conducting simulations to choose materials for the final system design.


Figure 3.6: Breakdown of Mkrtich's hours spent per task

The breakdown of Mkrtich's hours is shown in Figure 3.6. Mkrtich is the Research Engineer and when analyzing his pie chart it is obvious where his time was spent. The largest portion of the pie chart is building, which was due to the amount of time he spent wiring the prototype. The system was complex with multiple power supplies, motors, drivers, relays, transistors and actuators. In order to wire the system properly circuit diagrams were created and each wire was labeled individually such that if a problem were to arise it would be easier to determine the source. Furthermore, Mkrtich also formulated and built the Matlab code which allowed the robotic arm to complete a full ablation cycle while the rim was in motion. This code also implemented all the interlocks and safety features dictated by the design specifications.

The next two sections dominating Mkrtich's chart were research and writing. In addition to Brian, Mkritch was also tasked with researching robotic manipulators. The research conducted by Mkrtich focused on theory and simulation in order to purchase a robotic arm with maneuverability that allowed ablation of the entire rim. Lastly, Mkrtich spent a majority of his time creating templates for the reports and spent time throughout the semester recording his work to prepare for the final report.

### 3.3 Financial Evaluation of Time Spent With Consultants



Figure 3.7: Financial breakdown of consulting costs

Figure 3.7 provides an approximate break down of the consulting costs of each consultant. The values shown on the chart are based on estimated consulting fees determined by each consultants education, position held and the amount of time spent per consultation throughout the semester. The largest element on the chart is from Dr. Meyer, who was extremely helpful and answered many questions which related to composition of grease and oils. The second largest element was from Johanna Ylanen, who was a member of the IPG team who helped the team conduct the experiments in their lab. Charles Bridge and Vijayy Kancharla were other key consultant as they were also members of IPG and gave the team a tour of the facility, provided insight to laser functions in addition to further opportunities with IPG Photonics.

Dr.Jouaneh is a robotics and control systems professor and was consulted during the spring semester to better understand robotic manipulators in addition to methods for trajectory generation. Dr. Brown is a material engineer at the University of Rhode Island who provided information on material properties of the rim, the coating as well as the paint. Dr. Zheng is another professor at the University of Rhode Island who specializes in heat transfer, he guided the team to resources that could be used to determine optical constants needed for the equations dictating laser ablation. Dr. Shukla was minor consultant who helped the team with avenues for laser labs on the University of Rhode Island. Mark Daughenbaugh was invaluable as he was a member of UTRC, very involved and knowledgeable about the
current process used to clean rims. The last two members of the charts Dr. Wei and Tahany Wardany are laser experts that provided insight on lasers and acknowledged when the group was on the right track or needed additional information.

### 3.4 Budget Report

| Quantity | Description | Subtotal |
| :---: | :---: | :---: |
| 1 | Skydrol - LD4 Low Density Hydraulic Fuild, Quart | \$43.22 |
| 1 | Granular Activated Carbon - 5 lb bag | \$25.65 |
| 1 | Anodized 6061 Aluminum 3ft x 4in x 1/4in Clear Finish | \$84.31 |
| 1 | Anodized 6061 Aluminum 1ft x 4in x 1/4in Clear Finish | \$37.94 |
| 1 | Abb Industrial Robot 798 Mechanical Arm | \$208.25 |
| 1 | ARDUINO A000067 DEV BRD, ATMEGA2560, ARDUINO MEGA 2560 R3 | \$44.95 |
| 1 | Paxcoo 4 Pieces Breadboards Kit with 120 Pieces Jumper Wires for Arduino | \$11.99 |
| 2 | Electronix Express- Hook up Wire Kit (Solid Wire Kit) 22 Gage (25 Feet) | \$41.90 |
| 1 | CHP-170 Micro Cutter | \$4.97 |
| 1 | Hakko CHP CSP-30-1 Wire Stripper, 30-20 Gauge Maximum Cutting Capacity | \$11.07 |
| 1 | 3M Scotch \#35 Electrical Tape Value 2 Packs of 5 | \$16.97 |
| 1 | Black Electrical Tape (GIANT 3 PACK) | \$5.99 |
| 1 | 50Pcs IRFZ44N Transistor IRFZ44 N-Channel International Rectifier Power Mosfet 49A 55V | \$13.88 |
| 1 | CHANZON H\&PC-59042 100pcs (10 colors x 10pcs) 5mm Light Emitting Diode LED | \$7.95 |
| 1 | Elegoo 17 Values 1\% Resistor Kit Assortment, 0 Ohm-1M Ohm (Pack of 525) | \$10.86 |
| 1 | 10 Pieces 12mm Waterproof Push Button Momentary On Off Switch ANKG-01 (5 Colors) | \$8.99 |
| 1 | Durham LP24-CLEAR Clear Polypropylene 24 Compartment Large Box | \$9.07 |
| 1 | Plano 23780-00 Deep Stowaway Box with Adjustable Dividers | \$10.49 |
| 1 | DC 12V 300RPM Gear Motor High Torque Electric Micro Speed Reduction Geared Motor | \$9.51 |
| 2 | 5V Power Supply, VCZHS DC 5V 5A Universal Regulated Switching Power Supply | \$19.98 |
| 2 | GALYGG AC 110V-220V to DC 12V 5A (60W) Universal Regulated Switching Power Supply | \$27.98 |
| 3 | Elegoo 6PCS 170 tie-points Mini Breadboard kit for Arduino | \$20.58 |
| 2 | TR Industrial TR88302 Multi-Purpose Cable Tie (100 Piece), 8", Black | \$11.62 |
| 1 | Loctite 40140 Clear 40140401 Prism Surface Insensitive Instant Adhesive | \$18.17 |
| 1 | Elmer's Liquid School Glue | \$19.99 |
| 1 | Elegoo HC-SR04 Ultrasonic Module Distance Sensor for Arduino | \$11.49 |
| 3 | Laser Ranging Sensor Distance Measurement Module I2C Interface for Arduino | \$41.97 |
| 1 | Royal Brush RART-140 Multi-Purpose Golden Taklon Paint Brush Set | \$6.36 |
| 1 | Outlet Surge Protector Power Strip, 6ft Cord, 790 Joules, Black, 20K Insurance (TLP606B) | \$9.71 |
| 1 | 10 Sealed Bearing 1616-2RS $1 / 2 \times 11 / 8 \times 3 / 8$ inch Ball Bearings | \$36.45 |
| 6 | 600p/r Incremental Rotary Encoder Dc5-24v Wide Voltage Power Supply 6mm Shaft | \$107.94 |
| 4 | 12 ft 18 AWG Universal Power Cord (NEMA 5-15P to IEC320C13) - Length $=12 \mathrm{ft}$ | \$23.80 |
| 2 | AmazonBasics USB 2.0 Cable - A-Male to B-Male - 6 Feet (1.8 Meters) | \$9.98 |
| 2 | Bulbrite 105425 25W Transparent Green A19 Bulb - GREEN COLOR | \$6.70 |
| 2 | Bulbrite 105725 25W Transparent Red A19 Bulb - RED COLOR | \$10.32 |
| 2 | Bulbrite 105825 25W Transparent Yellow A19 Bulb - YELLOW COLOR | \$11.04 |
| 1 | 4 Pieces 3/4" ALUMINUM 6061 ROUND ROD 12" long Solid T6511 New Lathe Bar Stock | \$14.39 |
| 2 | GLOW DUST! - INVISIBLE BLUE - 50 grams | \$20.00 |
| 1 | 5MW UV LASER PEN FOR SOLAR AND GLOW DRAWING! | \$20.00 |
| 1 | Soft-Closing Drawer Slides - 22" Closed Length | \$21.39 |
| 4 | Sleeve Bearing for Conveyor Rollers for 1-1/2 Pipe | \$32.00 |
| 1 | Abrasion-Resistant Urethane Drive Roller with Aluminum Hub | \$29.84 |
| 1 | Shaft-Mount Conveyor Roller Polyurethane, for 1/2" Shaft, 1-1/2" OD, 3/4" Wide | \$6.82 |
| 1 | 6061 Aluminum Round Tube 0.058" Wall Thickness, $5 / 8$ " OD - Length $=0.5 \mathrm{ft}$ | \$6.60 |
| 1 | POWERTEC 71008 110/220V Single Phase On/Off Switch | \$11.99 |
| 2 | Baomain Red Sign Emergency Stop Push Button | \$21.38 |
| 1 | Kuman Arduino UNO R3 3.5 inch TFT Touch Screen with SD Card Socket | \$17.80 |
| 2 | uxcell Emergency Push Button Switch Red Clear Protector Cover 22mm | \$16.78 |
| 1 | Laqiya 100Pcs 2N3904 TO-92 NPN General Purpose Transistor | \$5.90 |
| 2 | F Sharp Infrared Proximity Sensor Long Range GP2Y0A21 for Arduino | \$23.80 |
| 1 | SN754410 - Quad Half Bridge Driver (36V 1.1A) | \$4.20 |
| 1 | PG36 Waterproof Cable Gland Joints Adjustable Lock Nut Connector | \$8.00 |
| 1 | uxcell 1-1/4" Flexible Wire Loom Tubing Electrical Cord Covers | \$23.21 |
| 2 | Indoor Enclosure with Hinged Cover and Knockouts, 12" x 12" x 4" | \$82.44 |


| 1 | Gorilla Epoxy, . 85 oz., Clear 1-Pack | \$5.47 |
| :---: | :---: | :---: |
| 1 | 12 Piece Value Pack of Economical Paint Brushes, Assorted Sizes | \$8.94 |
| 1 | Uxcell a14092200ux0209 50 Piece 10K Ohm 0.05W 3435B NTC Thermistors Resistor | \$10.54 |
| 2 | Dorman Hardware 29993 Pegboard, 16-Inch X 16-Inch | \$28.26 |
| 1 | RioRand $4 \times$ MG90S Metal Geared Micro Servo For Plane Helicopter Boat Car New | \$17.80 |
| 1 | 12V / 366rpm / 12kg.cm Metal DC Geared Motor w/Encoder | \$35.87 |
| 1 | Black Light | \$9.19 |
| 1 | Sharpie Art Pens, Fine Point, Assorted Colors, Hard Case, 12 Pack (1982057) | \$10.79 |
| 1 | Chanzon 10 pcs High Power Led Chip 3W Purple Ultraviolet | \$8.50 |
| 2 | 4PCS MG996R Metal Torque Gear Digital Servo RC Truck Car Boat Helicopte | \$35.80 |
|  | Wood froom Arnold Lumber | \$125.00 |
| 1 | A ARDUINO MEGA 2560 R3 | \$43.48 |
| 1 | DROK L298 Dual H Bridge Motor Driver DC 6.5V-27V 7A | \$15.99 |
| 1 | 12V / 366rpm / 12kg.cm Metal DC Geared Motor w/Encoder | \$35.87 |
| 1 | MG996R 55g Metal Gear Torque Digital Servo | \$27.39 |
| 1 | UV Flashlight | \$10.99 |
|  |  | \$1,798.46 |
|  |  | \$3,000.00 |
|  |  | 59.95\% |

Table 3.7: LIST OF ALL MATERIALS PURCHASED FOR THE PROJECT
Table 3.7 is a list of all materials purchased throughout the semester in order to complete the project. Funds were first utilized at the end of the first semester to purchase materials to testing laser ablation at IPG Photonics. These materials needed for the tests accumulated to only $6 \%$ of the total budget. The rest of the $54 \%$ of the budget was spent during the spring semester building the prototype and rebuilding it during the redesign. Primary contributing factors to the funds used on the project were the robotic manipulator, electrical panels, motors, wood and a variety of electrical equipment for sensors and system control.

The manipulator contributed $7 \%$ of the funds spent and was a necessity as the prototype and final system were designed around manipulation of a laser. Wood was also necessary as it was a cheap and easy to machine as opposed to to industrial materials that would be implemented in the final product. The motors were purchased to rotate the rim, move the actuator and control the robotic arm. Multiple servos were purchased throughout the semester due to malfunctions. The initial brand used to replace the broken servos were low quality and eventually malfunctioned as well. Higher quality servos were purchased in order to guarantee a working product for the design showcase. The largest contributing factor to the funds used was due to the abundance of electrical components. Each component purchased was necessary for the system to run as indicated by the design specifications. Above all, the team was successful in developing a working prototype well within the budget funded by UTRC.

## 4 Literature and Patent Searches

The purpose of a patent search is to check for legally existing documents that uses technology similar to a developing product. In addition to checking the legal status of technology, patent searches help stimulate creative ideas and can ultimately help with the production of an innovative system design. A literature search also assists with the creative process by exposing technical problems or statistics that have come to light from previous
research. The patent search and literature search are included in the following section. Both tasks address the three original concepts propose by the United Technologies Research Center: ultrasonic cleaning, plasma electrolysis, and laser ablation.

### 4.1 Patent Search

### 4.1.1 Ultrasonic Cleaning

US5095925A/Aseptic cleaning apparatus
Publication Date: March 13, 1989
Rights owned by: David M. Elledge, Dwain W. Smith
Abstract: This invention discloses a fluid sterile system for use in the medical and dental industries for the removal and cleaning of gross tissue forms from biological articles and a method of preparing the biological articles for transplant and corrective surgeries and in the electronic and aerospace industries, the present invention discloses a portable, fluid cleaning system that clean articles such as fixtures, aerospace electronic and other equipment, microelectronic chips and electronic printed circuit boards for reducing the contamination level of such articles measured in parts per million (ppm). The aseptic system includes an enclosed high pressure sterile jet cleaning apparatus member for use in a first stage cleaning of particulates from an article used in a particular industry and a sterile ultrasonic bath apparatus member for use in a second stage cleaning of particulates from the same article.

Relevance: This patent introduces a dual cleaning system that incorporates multiple stages of water jets and an ultrasonic cleaning baths. This system introduces the fundamentals and concepts behind ultrasonic cleaning and demonstrated the use of multiple cleaning cycle cycles for the desired clean part. For this small system, the quality of cleanliness was met after a 10 -hour cycle for medical devices.
US5218980A/Ultrasonic dishwasher system
Publication Date: October 10, 1991
Rights owned by: David H. Evans
Abstract: An improved dishwasher system utilizes ultrasonic signals to clean a wide range of kitchen and/or dining ware items. The system includes one or more ultrasonic signal generators submerged within a water bath and regulated by a controller to generate an ultrasonic signal, resulting in the production of a large quantity of cavitation bubbles which implode with a vigorous cleaning action against submerged kitchen ware items. The controller rapidly varies the specific frequency of the generated ultrasonic signal, preferably in conjunction with a rapid on-off pulse cycling of the signal, to prevent damage to or breakage of fragile ware items.

Relevance: This patent provided a summary for the fundamentals of the ultrasonic cleaning. The use of an ultrasonic bath could be implemented for cleaning aircraft wheel rims. The concepts generated throughout this report used this patent as a model for ultrasonic system designs.

### 4.1.2 Plasma Electrolysis

## US0157964A1/System and Method for Electrolytic Cleaning

Publication Date: October 31, 2002
Rights owned by: John E. Hoffman JR., Richard A. Hoffman SR.
Abstract: A method and apparatus for cleaning conductive bodies using an electrolytic cleaning solution. An inverter power source is used to supply a high voltage, low current output for the electrolytic cleaning. The outside surfaces of a metallic body are cleaned by spraying the cleaning solution on to the body and passing a current through the cleaning solution on the conductive body, thereby causing the cleaning solution to electrolytically clean the body. The body is connected to the negative terminal of the power supply. The positive terminal of the power supply is connected to a spray nozzle and causes a current to pass through the spray to the cleaning solution on the body for electrolytic cleaning. Alternatively, a current can be induced in the cleaning solution on the body by placing a grid near the body and connecting the grid to the positive terminal, thereby generating an electric field.

Relevance: The patent mentioned above provides a unique method of cleaning using electrolysis. Typical electrolytic cleaning has an anode placed arbitrarily into an alkaline solution in which the body was submerged. This provided a creative alternative to filling an entire tank with the alkaline solution. Filling an entire tank with the cleaning solution would be time consuming. By supplying a current to the solution flowing from the nozzles, the time spent filling the tank could be eliminated.

## US005700366A/Electrolytic Process For Cleaning And Coating Electrically Conducting Surfaces <br> Publication Date: December 23, 1997 <br> Rights owned by: Metal Technology, Inc. Mandeville, LA.

Abstract: An electrolytic process for simultaneously cleaning and metal-coating the surface of a workpiece of an electrically conducting material, which process comprises: i) providing an electrolytic cell with a cathode comprising the surface of the workpiece and an anode comprising the metal for metal-coating of the surface of the workpiece; ii) introducing an electrolyte into the zone created between the anode and the cathode by causing it to flow under pressure through at least one opening in the anode and thereby impinge on the cathode; and iii) applying a voltage between the anode and cathode and operating in a regime in which the electrical current decreases or remains substantially constant with increase in the voltage applied between the anode and the cathode, and in the regime in which discrete gas bubbles are present on the surface of the workpiece during treatment.

Relevance: The project of cleaning aircraft rims had two necessary conditions; first, the wheel rim must reach a clean finish and second, the process must not remove the anodized coating from the wheel. Aluminum is typically anodized in a similar manner to electrolysis cleaning. Sinse the material of aircraft wheel rims is anodized aluminum 2024, this patent was significant because it could potentially clean the rim and apply a new coating to it. Unfortunately, there was little information on how the process affected anodized aluminum, meaning it could potentially remove the coating or lock certain particulates into a fresh coating which would be undesirable.

### 4.1.3 Laser Ablation

US 6693255 B2/Laser ablation cleaning
Publication Date: February 17, 2004
Rights owned by: David A. Freiwald, Michael Youngman, Kevin Youngman
Abstract: Laser ablation cleaning apparatus. An optical box containing mirrors for specially directing laser light, such as repeated pulsed CO2 laser, is mounted in a handheld cleaning head or in a custom work head. The hand-held cleaning head can be used to safely direct laser energy to a surface to be cleaned; the laser beam ablates from the surface coatings, corrosion, and the like without harming the substrate. The custom work head is removably mountable upon the iron core stack of a conventional commercial electric generator, and features an optics box carriage that is selectively movable along the axis of the stack to direct a laser beam into the slots of the stack for cleaning.

Relevance: The patent presented above shows that a CO2 laser is capable of cleaning and removing any corroded portions of the ablated surface. This may not be an appropriate laser for the design project because the anodized layer cannot be removed from the wheel rim's surface. The patent also summarizes the optical techniques that were used to deliver the beam to the surface of the target. If this project were to automate the process for cleaning the wheel rim, a similar mirror box may be necessary to move the beam across the surface of the wheel. In addition, the hand-held portion of the system may be attached to a robotic arm and programed from ablating various surfaces of a rim.

US20040231682A1/Scanned small spot ablation with a high-rep-rate
Publication Date: March 20, 2003
Rights owned by: Richard Stoltz, Jeff Bullington
Abstract: The present invention is a system and method of ablation laser-machining, that includes the steps of generating pulses at 1 to 50 MHz by one or more semiconductorchip laser diodes, each pulse having a pulse-duration less than three picoseconds, directing a less than 1 square mm beam of the pulses to a work-piece with an ablating pulse-energydensity; and scanning the beam with a power-driven scanner to ablate a scanned area at least 25 times larger than the beam area.

Relevance: This patent complements the previous laser ablation patent by introducing the energy pulse requirements for a laser ablation system. In addition to the energy pulse requirements, this patent provides an overview of the hardware used to control the energy pulses and scan the surface of a target to determine which areas are critical for ablation. These concepts are critical for control in this project to prevent damaging the anodized layer through energy control. In addition, the surface scanning mechanism may be useful for optimizing energy usage across the surface that is to be ablated.

### 4.2 Literature Search

### 4.2.1 Ultrasonic Cleaning

Ultrasonic cleaning methods have been developed for industrial applications since 1950. Today aerospace companies use ultrasonic machines for production and the maintenance
of small and simple-geometric parts. This project used the following two resources to gain thorough insight on the fundamentals and control parameters of ultrasonic cleaning. These sources also provided information on the use of transducers and the primary characteristics that must be considered when being applied to ultrasonic baths. The references are listed below:

### 4.2.2 Plasma Electrolysis

An emerging cleaning method for industrial applications is plasma electrolysis. This method typically submerges metallic parts in an alkaline bath and implements an electric current by positively charging an aircraft rim and submerging an anode rod in the solution. This recently developed procedure is typically used for the removal of corroded materials. The following resources provide a thorough introduction to the fundamentals of electrolysis and some of the challenges that innovators face while developing this technology. Due to the typical application of this procedure, most articles and pieces of literature that were available on plasma electrolysis were focused on the coating of the material. These results are outside the scope of the project but do reflect on the parameters that are crucial for damaging the coating of the aircraft rims.

### 4.2.3 Laser Ablation

In the medical field, there are many applications for the use of laser ablation systems. To this day, research is being performed on ablation applications for tattoo removal, cancer treatment, and neurosurgery. Such sensitive applications immediately indicated that laser ablation could be well controlled for aerospace applications and are currently being investigated by the United States military and Air Force. The fundamentals of laser systems were covered in an optics textbook, which had also covered fundamental equations used for this report's engineering analysis. A power point presented by the University of California Berkeley studied the impacts of laser ablation on a materials surface at the micron scale with respect to varying pulse rates. Finally, a range of optical technology was found on the RP Photonics webpage. Here fundamental equations for each device were presented and explained in thorough detail. Below is the list of relevant literature associated with laser ablation cleaning systems.

## 5 Evaluation of the Competition

The aerospace industry is required by the Federal Aviation Administration to perform routine crack checks after a specified number of overhauls [7]. In order to thoroughly inspect a wheel for cracks, the aircraft split rim must be entirely cleaned of dirt and grease so that dye penetrant can be applied for ultraviolet inspection. The requirement of cleanliness calls for a base demanding in cleaning machines that will remove all dirt from the surface of the wheel rim. Modern machines use water-jet systems and rely on shear pressure to remove dirt
from the surface of the rim. Although affective in attaining a clean rim surface, the excess waste produced by the cleaning system leaves opportunity for system improvement that will reduce the amount of waste produced. The suppliers of these systems are cleaning focused companies that provide water and solvent machines for various industrial applications.

In operation facilities under the United Technologies Aerospace Systems, the current machine being used is the Mart 60. This system is comparable with the Stingray 6036 Aircraft Wheel Washer. This system can be loaded with up to four rim halves per cycle and uses 10 minutes of run time. With a closed loop, recyclable water system, a total of 397 gallons of water are used per cycle along with 105 kW of energy for pumps and heating elements [8]. Although the Stingray 6036 Aircraft Wheel Washer is quite resourceful with a recyclable system, the United States Air force had provided a poor review of the system with issues associated with the poor performance of the washing equipment. Stingray engineering determined that the lack of heating elements and washer power density led to poor cleaning results.

Another cleaning system the design team used as a standard of efficiency is the Aqua Clean Super Brush ${ }^{\text {TM }}$. This system consists of a single-rim loaded turn table [9]. In addition to the water jet system, rotating brush rods are used to make contact with the surface of the rim. The cycle time is extended to five full wheels per hour but successfully provides a better quality of cleanliness. The resources used throughout the system are 160 gallons and approximately 40 kW of electrical energy per cycle.

## 6 Design Specifications

The team was assigned the task by the United Technologies Research Center to develop an alternative cleaning method for aircraft rims that will be used by the operation facilities under the United Technologies Aerospace Systems. The design specifications for this specific task define a set of requirements as identified by the project sponsor, Dr. Thomas Filburn. The specifications relate to the current UTRC process and the performance standards of it. Consideration must be taken to the facility in which the device will be used as well as the reliability of the product.

In order to quantify the design specifications for the proposed design, the performance of the current UTRC cleaning process, the Mart 60, was analyzed. The current process cleans four rims in under fifteen minutes, meaning that each individual rim must be cleaned in under five minutes. UTRC has specified that it will not be acceptable if this process is slower than the current Mart 60 because of the high demand and number of rims that are cleaned on a daily basis. The current system also uses a volume of six feet by six feet by 7 feet and is used in an industrial building. The proposed design must not be any larger than this size because of the limited space available in these locations.

As well as meeting the size and cycle time of the current Mart 60 system, UTRC would like to reduce the energy as well as the amount of waste water that needs to be disposed. The Mart 60 system contains a seven hundred fifty liter water tank that must be recycled and disposed of monthly. The removal and recycling of this water costs UTRC upwards of
one million dollars per year. In order to heat the water in the tank, a forty Kilowatt heating supply is used to maintain its running temperature of one hundred thirty degrees Fahrenheit. The forty Kilowatt heater requires a substantial amount of energy to keep the water in the tank at the required temperature. UTRC has specified that they would like to reduce the amount of water and waste that is accrued when cleaning the aircraft rims, as well as reduce the amount of energy necessary to clean the rims.

Based on these requirements from the United Technologies Research Center, the design specifications of this project were quantified. This design should require very low maintenance in order to effectively run the cleaning process in an industrial application and last for upwards of five years. Table 6.1 quantifies the specific design requirements that are imperative to the success of this project. A full analysis of the design specifications including Training Requirements, Market Identification and Social, Political and Legal Requirements is included in the Appendix in Table A.1.

Table 6.1: Design Specifications

| Category | Requested | Proposed |
| :---: | :---: | :---: |
| Size | 6'x6'x3.5' per Rim | $4^{\prime} \times 4{ }^{\prime} \times 3.5$ ' per Rim Half |
| Loading Direction | Loading from Above | Horizontal Slide Rack |
| Interface Size | Varying Sizes | $10^{\prime}-30^{\prime}$ Diameter |
| Cycle Time | Less than 5 min per Rim | 2.5 min per Rim Half |
| Water usage per Cycle | Less than 750 L per Rim | No Water |
| Wattage per Cycle | Less than 25 kW per Rim | 5 kW per Rim Half |
| Maintenance | Less than $1 / 2$ Hours per Work Day | $1 / 2$ hours Every 2 Weeks |
| Life Cycle | 5 years | Minimum 5 years |

## 7 Concept Generation

Before a final concept for the design problem was drafted, the team members were instructed to conduct a conceptual design assignment in which all members of the team must create thirty or more designs to inspire feasible options for the final solution. The concepts of each of the four team members are shown here.

### 7.1 Mkrtich Arslanyan Concept List



Figure 7.1: Mkrtich Arslanyan Design Concept 1

1. Figure 7.1 uses a water jet based system to clean the overall surface area of the rim. The rim is held in place by a fixture mechanism that is then cleaned using two water jets that will clean the entire surface of the rim. The system uses very high flow rates which in return will guarantee that all the material will be removed. The system is supplied with a filtration system to be able to reuse the water used for cleaning and reduce material usage. This design was given a rating of five out of ten because even though resources will be saved, the system will still use a significant amount of water and materials to clean the rims.


Figure 7.2: Mkrtich Arslanyan Design Concept 2
2. Figure 7.2 uses a water jet based system in which the rim is placed horizontally on top of a rotating fixture that will control the speed and direction of the rotation of the rim. Only one water jet is used in this system which reduces material and parts costs, however much of the surface would not be able to be cleaned using this design. This concept was given a rating of two out of ten because one water jet in the entire system would be very difficult and time consuming to clean the entire surface area of the rim.


Figure 7.3: Mkrtich Arslanyan Design Concept 3
3. Figure 7.3 uses a water jet based system in which the rim is being held by a fixture mechanism. Two water jets would be used in this design, one placed vertically to clean the outside diameter of the rim and another facing downwards to clean the main face of the rim. The system is attached to a water filtration system so that the water can be reused for multiple cleaning cycles. This design was given a three out of ten rating because the system would still use a lot of water as well as require a lot of money to recycle the water materials, as well as that the entire rim would not be cleaned in one cycle, as it would need to be flipped over to clean the back face of the rim.


Figure 7.4: Mkrtich Arslanyan Design Concept 4
4. Figure 7.4 utilizes a water jet based cleaning system that is attached with a conveyorbelt system that will allow for easy loading and unloading. The only human interaction needed in this process would be for the worker to place the rim on the conveyor belt. Two water jets are used to clean the rim, which is secured by a fixturing inside the mechanism. The system is supplied by a water filtration system so that the materials can be reused for multiple cycles, reducing material costs. This concept was given a rating of five out of ten because the water jet based system would still require a lot of raw materials and costly filtering to clean the rims.


Figure 7.5: Mkrtich Arslanyan Design Concept 5
5. Figure 7.5 utilizes a water jet based system including two conveyor belt systems for easy loading and unloading. The rim is secured by a fixture inside the mechanism and cleaned by two high pressure water jets. The rim will be loaded using one conveyor belt and unloaded using another, ensuring that the clean rim does not need to travel the dirty surface of the initial conveyor belt. The system is attached with a filtration system to reuse water for multiple cycles. This system was rated a seven out of ten because of the ability to have two people working on the system to load and unload rims, decreasing the down time as well as ensuring that clean rims do not need to travel over a dirty surface.


Figure 7.6: Mkrtich Arslanyan Design Concept 6
6. Figure 7.6 uses a water jet based system with an autonomous crane that will be used for loading and unloading of the rims. The rim is secured in the system with a fixture mechanism and two high pressure water jets are used to clean the entire rim. The system is accompanied with a filtration system so that the water and materials can be reused for multiple cycles. This system was given a rating of three out of ten because of the difficulty of automating a crane arm for loading and unloading and the large amount of raw material used in water jet based cleaning systems.


Figure 7.7: Mkrtich Arslanyan Design Concept 7
7. Figure 7.7 utilizes ultrasonic cleaning methods to clean the entire surface of the rim. The rim is submerged in an alkaline tub that is then activated by a wave generator to create small molecular explosions in the alkaline solution, in return cleaning the surface of the rim. This system is paired with a filtration system so that the alkaline based system can be used for multiple cycles without replacing the raw material. This concept was given a rating of four out of ten because of the difficulty of the loading and unloading process of the rim. Alkaline solutions can also be very costly, especially in industrial applications.


Figure 7.8: Mkrtich Arslanyan Design Concept 8
8. Figure 7.8 uses an ultrasonic cleaning system to clean the entire rim. Te rim is submerged in an alkaline solution and secured by a fixturing in the tub that is allowed to rotate. The wave generator activates the hydrogen in the alkaline solution, creating small explosions which then cleans the surface of the rim. The system is attached with a filtration system so that the alkaline solution can be reused through multiple cycles. This concept was given a rating of six out of ten because the rotating fixture allows for all parts of the rim to be directly affected by the wave propagator. Alkaline cleaning systems are costly and use a lot of raw materials and solution for the cleaning process.


Figure 7.9: Mkrtich Arslanyan Design Concept 9
9. Figure 7.9 utilizes an ultrasonic cleaning system with two wave propagators to ensure that all sides of the rim are being cleaned. The rim is secured inside the alkaline tub by a fixture that is able to rotate so that all parts of the rim will be directly afected by the wave propagation and the ultrasonic cleaning process, ensuring an even clean over the entire rim. The system is paired with a filtration system so that the alkaline solution can be used for multiple cycles. This concept was given a rating of eight out of ten because all surfaces of the rim will be cleaned evenly across the entire surface.


Figure 7.10: Mkrtich Arslanyan Design Concept 10
10. Figure 7.10 utilizes an ultrasonic cleaning system in which two wave propagators clean the entire surface area of the rim. A hydraulic plate raises and lowers the plate for easy loading and unloading of the rim into the tub. Having two wave propagators reduces the time needed to clean the rim because each generator is now responsible for less surface area of the rim. The system is equipped with a filtration system so that the alkaline solution can be reused for multiple cycles. This concept was given a rating of five out of ten because the alkaline system may not clean the entire rim evenly, as some walls of the rim may block the waves generated and decrease the energy, in return not cleaning the rim evenly.


Figure 7.11: Mkrtich Arslanyan Design Concept 11
11. Figure 7.11 uses a vibrational cleaning system to clean the surface of the rim. The rim is fixed to a mechanism that vibrates horizontally and vertically at very high rates. The vibrations of the mechanism will shake the particulates off the rim. This mechanism uses no water and a very small amount of resources. This concept was given a rating of four out of ten because of the many moving parts of the system. The vibrations of the system may not be able to shake off all of the dirt and grease coated on the material.


Figure 7.12: Mkrtich Arslanyan Design Concept 12
12. Figure 7.12 utilizes vibrational cleaning to clean the surface of the rim. The rim is held by a vibrating fixture mechanism which vibrates clockwise and counter-clockwise. The high rates of rotation will cause the material to be cleaned off of the surface of the rim. This design was given a rating of ix out of tn because the high amounts of shear stress created by the vibration of the system would cause high failure rates of the system and also uses a lot of moving parts.


Figure 7.13: Mkrtich Arslanyan Design Concept 13
13. Figure 7.13 utilizes vibrational and dry ice methods to clean the rim surface. The rim is secured with a fixture mechanism and the surface is frozen with dry ice before being vibrated in the system. The vibrational system pulses horizontally and verically at very high rates. The dry ice spraying before the vibration process will cause the dirt and grease on the surface to become brittle and will be removed easier. This system was given a rating of two out of ten because of the many complex moving parts as well as the high cost of using a $\mathrm{CO}_{2}$ system.


Figure 7.14: Mkrtich Arslanyan Design Concept 14
14. Figure 7.14 utilizes a vibrational cleaning system in which a dry ice application freezes the surface of the rim before the vibration begins. The rim is fixed to the vibrational mechanism which rotates clockwise and counter-clockwise at very high rates. A ventilation system is used to remove the $C O_{2}$ from the air. This concept was given a rating of a two out of ten because of the complexity of the design and the many moving parts of the system.


Figure 7.15: Mkrtich Arslanyan Design Concept 15
15. Figure 7.15 uses an ultrasonic cleaning system to clean two rims simultaneously. Two rims are submerged in the ultrasonic tank by a hinged fixture that will raise and lower the rims out of the tank. Two wave propagators are used to reduce cleaning time of the cycle and a filtration system is used to recycle the alkaline solution. This concept was given a rating of six out of ten because of the efficiency of cleaning multiple rims at once, however the rims may not be cleaned uniformly because of interference of the rim surfaces on the wave propagation.


Figure 7.16: Mkrtich Arslanyan Design Concept 16
16. Figure 7.16 is a system to ensure that the rim has been placed evenly on the fixture. The pressure sensors are placed in between the rim and the fixture in a cross pattern to ensure that the pressure is distributed evenly across the fixture. This design was given a rating of four out of ten because it does not directly consider the cleaning process, however ensuring that the rim has been secured evenly across the fixture is imperative to the effectiveness of the entire cleaning process.


Figure 7.17: Mkrtich Arslanyan Design Concept 17
17. Figure 7.17 uses infrared proximity lasers to ensure that the entirety of the rim is being submerged in the alkaline solution. Sensors for this application are imperative because if the entire rim is not submerged in the alkaline solution than those surfaces will not be cleaned. This design concept was given a rating of seven out of ten because the sensors will ensure that the rim is fully submerged and increase the quality and effectiveness of the ultrasonic cleaning process.


Figure 7.18: Mkrtich Arslanyan Design Concept 18
18. Figure 7.18 utilizes sensors in an ultrasonic cleaning solution to ensure that the volume of the solution in the tank is sufficient to submerge the entire rim and clean it. The sensors confirm whether or not there is enough solution in the tank and if not will engage an error message saying that more solution needs to be added. This concept was give a rating of five out of ten because it is imperative that there is enough solution in an ultrasonic tank, however it does not fully define the cleaning process of the rim.


Figure 7.19: Mkrtich Arslanyan Design Concept 19
19. Figure 7.19 uses an ultrasonic cleaning system and a dryer to clean and dry the aircraft rim. Two wave generators produce small molecular explosions that will remove the dirt and grease of the rim that is secured by a fixture. Once cleaning has finished a dryer system dries the rim so that it does not need to be done at another time. A filtration system is paired with the system so that the alkaline solution can be reused through multiple cycles. This concept was given a rating of eight out of ten because it encompasses both the cleaning and drying process for the rim, however uneven cleaning is probable.


Figure 7.20: Mkrtich Arslanyan Design Concept 20
20. Figure 7.20 utilizes the technologies of laser ablation to clean the surface of the rim. The rim is secured to a fixture mechanism that rotates so all angles of the rim can be ablated. A ventilation system is integrated to remove the vapors from the air. This concept was given a rating of eight out of ten because it significantly reduces the amount of materials used to clean the rim, however the entire surface of the rim will not be ablated.


Figure 7.21: Mkrtich Arslanyan Design Concept 21
21. Figure 7.21 uses a two laser ablation system to clean the entire surface of the rim. The rim is secured to a rotating fixture which is then cleaned by one laser faced horizontal to the rim and another one placed above the rim. A ventilation system is in place to remove the vapors generated from the ablation process. This concept was given a rating of nine out of ten because the system will run much quicker using two lasers and clean much more surface area.


Figure 7.22: Mkrtich Arslanyan Design Concept 22
22. Figure 7.22 utilizes a water jet based system and scrubbers to clean the surface of the rim. The rim is secured by a rotating fixture. Two high pressure water jets spray the rim and the dirt and grease particles will be removed with the aid of two scrubbers. A filtration system is attached to this system to reuse the water for multiple cycles. This design was given a rating of three out of ten because this system would use a considerable amount of water which is already the main issue of the current design at UTRC.


Figure 7.23: Mkrtich Arslanyan Design Concept 23
23. Figure 7.23 uses a laser ablation system to clean the rim surface. The rim is secured by a rotating fixture that will then be ablated by a large laser than can clean the entire width of the rim in one pass. This concept was given a rating of two out of ten because of the expense of a laser this size as well as that the concept would only clean the outside diameter of the rim and not the entirety of it.


Figure 7.24: Mkrtich Arslanyan Design Concept 24
24. Figure 7.24 uses an alkaline cleaning system along with scrubbers to clean the rim. Two wave generators will propagate waves through the alkakline solution, creating small molecular explosions that will remove the material from the rim. With the help of two scrubbers, it will help remove larger materials from the rim surface. A filtration system is used to recycle the alkaline solution. This concept was given a rating of six out of ten because of the large amount of raw materials it will take to clean the rim surface.


Figure 7.25: Mkrtich Arslanyan Design Concept 25
25. Figure 7.25 uses plasma electrolysis technologies to clean the rim. A voltage source electrically charges an a zinc coating on the rim to evaporate the zinc coating and clean the dirt materials off of the rim. This is a relatively inexpensive process and uses a small amount of raw materials, which is helped by the addition of a filtration system to be able to reuse the alkaline solution for multiple cycles. This concept was given a rating of nine out of ten for its low cost, low material usage and cycle time.


Figure 7.26: Mkrtich Arslanyan Design Concept 26
26. Figure 7.26 uses the technology of plasma electrolysis to clean the surface of the rim. A Nickel coating is added to the surface of the rim to act as a cathode when applied a high voltage from the power supply. The rim is secured by a fixture and a filtration system is used to recycle the materials for further uses. This design was given a rating of ten out of ten because of its quick cycle time, low material usage and filtration method.


Figure 7.27: Mkrtich Arslanyan Design Concept 27
27. Figure 7.27 uses the technologies of plasma electrolysis to clean the surface of the rim. The rim is coated with a copper cathode that vaporizes the materials on the surface of the rim when a high voltage is supplied. The rim is secured to a fixture and a filtration system is in place to reuse the materials for further cycles. This design was given a rating of seven out of ten because although a copper cathode has the shortest cycle time, it is also the most expensive.


Figure 7.28: Mkrtich Arslanyan Design Concept 28
28. Figure 7.28 uses a laser ablation system that includes two conveyor belts to clean the rim. The dirty rim is loaded on one side of the system and while moving through the system is cleaned using two lasers. The clean rim is then removed from the other side, ensuring that the rim does not move across any dirty surfaces. A ventilation system is used to remove the vapors that are produced from the ablation process. This design was given a rating of six out of ten because of its reduction of materials and cost, however not all surfaces of the rim would be cleaned.


Figure 7.29: Mkrtich Arslanyan Design Concept 29
29. Figure 7.29 uses a laser ablation system that loads and unloads the rim using a crane system. The rim is secured to a fixture and rotated. Two large lasers are used to ablate the surfaces of the rim in a timely manner. A ventilation system is in place to remove vapors from the air that were generated during the ablation process. This concept was given a rating of three out of ten because of the cost of high powered lasers and the entire surface of the laser would not be cleaned.


Figure 7.30: Mkrtich Arslanyan Design Concept 30
30. Figure 7.30 uses a heated cleaning system to remove the materials off of the rim. The rim is held in place by a fixture that rotates. Two heaters will be placed on the vertical walls to heat the rim up to three hundred degrees Fahrenheit to burn off the dirt and grease from the system. A ventilation system is used to remove particles that have been burned off of the rim. This system was given a rating of one out of ten because of the large amount of power needed to use the heaters as well as possible damage to the rim from heating it to this temperature.

### 7.2 Brian Bestoso Concept List



Figure 7.31: Brian Bestoso Design Concept 1

1. Figure 7.31 Shows an extremely simple cleaning apparatus. It utilizes a clamp to hold the rim then three jets that are allowed to move left and right, or up and down to clean the entirety of the rim using pressurized water. This concept was given a rating of eight out of ten because the system cleans the entirety of the rim in a short cycle time and is able to reuse the water for multiple cycles.


Figure 7.32: Brian Bestoso Design Concept 2
2. Figure 7.32 is a laser ablation technique currently used in industry. It is a feasible concept, with difficulty arising in the choice of settings in order to clean the rim without removing the paint. This concept was rated eight out of ten because laser ablation will be able to quickly and effectively clean the surface of the rim, although this concept is not an autonomous design.

Concept \# 3: Robotic Arm coupled with Laser for Dirt Ablation


Figure 7.33: Brian Bestoso Design Concept 3
3. Figure 7.33 is an addition to concept 2 which utilizes a fully robotic arm and a laser to ablate the dirt. This concept is rated six out of ten because laser ablation is a viable solution to the design task, however the cycle time would be lengthy with this orientation and difficult to program.


Figure 7.34: Brian Bestoso Design Concept 4
4. Figure 7.34 is another laser ablation technique that instead uses a track to ablate up, then down and repeats until the entire area of the rim is ablated. This is simpler than the previous, but along the same idea. This concept was given a rating of six out of ten because the track system using laser ablation would be a quick and effective cleaning method, however this design would not clean the entire surface area of the rim.

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concepts #5: ROTARY CLEANHNG
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Figure 7.35: Brian Bestoso Design Concept 5
5. Figure 7.35 shows a rotary wheel that has a clamp attached to the rim. The rim spins
and is misted by steam. Scrubbers are activated and make contact to the rim while it rotates and scrubs the dirt off. This concept was given a rating of eight out of ten because the two scrubbers would ensure that all surfaces and complex geometries were cleaned. The filtration system would allow for the water to be reused for multiple cycles.


Figure 7.36: Brian Bestoso Design Concept 6
6. Figure 7.36 is another rotary stand but this utilizes laser ablation to clean the surface. The laser is actuated and is allowed to move from position 1 to position 2. In order to clean the entire wheel, the rotary stand must stop and the rim flipped. Thus the addition of the flipping arm. This concept was rated seven out of ten because laser ablation is a viable solution to the design application and the track system of the laser and rotating stand ensure that the total surface area is ablated. The flipping arm completes this concept as a fully autonomous process where the only human interaction is loading and unloading the rim.

## Concept \#7



Figure 7.37: Brian Bestoso Design Concept 7
7. Figure 7.37 utilizes ultrasonic waves to relieve dirt. This is done by adding solvents and soap to react with the ultrasonic waves and absorb the oil and grease. There are commercially available ultrasonic baths. In this design there are racks, similar to a dishwasher that slide in and out, which allows multiple rims to be washed simultaneously. This concept was rated ten out of ten because the system would allow eight rims to be cleaned in one cycle and the water and alkaline solution would be able to be used for multiple cycles.

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CONCEPT #8: HANDHELD WET
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                        SODA BLASTER
    

Figure 7.38: Brian Bestoso Design Concept 8
8. Figure 7.38 was considered because of the usefulness of soda blasting in industry. It can clean machines used for industrial applications without damaging them because
the sodium bicarbonate shatters on impact. There is a concern that the blasting will remove the paint. This concept was rated two out of ten because the soda blasting system would require a large amount of water and sodium bicarbonate materials to clean. This concept also has no means of recycling the soda water that was previously used, incurring a large amount of wasted materials.


Figure 7.39: Brian Bestoso Design Concept 9
9. Figure 7.39 is another rotary wheel set up combined with wet soda blasting. This is water mixed with sodium bicarbonate which is more delicate than dry sodium bicarbonate. The ground of the housing is sloped in order to better drain the wet material and waste. This concept was given a rating of six out of ten because the process would be fully autonomous and would be able to recycle the soda water previously used, however the sod blasting cleaning method is expensive to maintain.

CONCEPT \# 10: ULTRASONIC CLEANER WITH WATER RECYCLER


Figure 7.40: Brian Bestoso Design Concept 10
10. Figure 7.40 is another ultrasonic bath, however, this iteration uses a centripetal filtration system to separate the solvent, dirt and grease from the water so that it may be recycled. This esign was given a rating of ten out of ten because of its ability to clean many rims at once as well as filtering the alkaline solution to be able to be used for multiple cycles.


Figure 7.41: Brian Bestoso Design Concept 11
11. Figure 7.41 is a smaller apparatus without any rotating parts. The Nozzles for the water jets may be angles to reach all parts of the rims. Not pictured are the jets firing at the rims parallel to the plane of the page. This concept was rated six out of ten because of its ability to clean multiple rims in one cycle, however a water jet based system is very costly with regards to filtering and waste removal.

CONCEPT \# 12: CENTRIFUGAL CCEANER


Figure 7.42: Brian Bestoso Design Concept 12
12. Figure 7.42 is a centripetal machine washer which utilizes the surface tension on the
dirt on the rim to peel off the dirt and grease. In addition, micro solids are added into the mix in order to add some abrasive cleaning to the hard-to-remove dirt. This design was given a rating of four out of ten because of the material costs of the water filtration and removal as well of the cost of adding and filtering micro solids in this process.


Figure 7.43: Brian Bestoso Design Concept 13
13. Figure 7.43 builds on a previous idea of using ultrasonic cleaners. Once the fluid is drained out, then hot air is forced over the rims to heat up and dry the rim halves on the racks they are being held on. This design was given a rating of one oout of ten because the fluid must be drained out of the system every cycle in order to be dried, as well as the process being expensive to heat the fans to dry the rims.


Figure 7.44: Brian Bestoso Design Concept 14
14. Figure 7.44 takes a new approach by using a conveyor belt to clean the rim halves in a similar fashion to an automated car wash. In this only soap is applied then water jets attack the rims from both sides removing dirt and grease as they progress. The water and waste is then sent to a water recycling system. This design was given a rating of six out of ten because it would not fit the design specification requirements given by UTRC and would require a large amount of water to clean the rims.


Figure 7.45: Brian Bestoso Design Concept 15
15. Figure 7.45 builds off the previous concept by utilizing a series of lasers on both sides of the housing. The housing is made of anti-reflective and laser absorbent material to avoid damaging the apparatus. This concept was given a rating of six out of ten because of the feasibility of using lasers to clean the surfaces of aircraft rims, however the entire surface area of the rim would not be able to be cleaned using this concept.


Figure 7.46: Brian Bestoso Design Concept 16
16. Figure 7.46 is an idea inspired by a device built by iRobot company. It is a clamping device with rollers that spins around the rim. This utilizes a water jet to wet the rim and then dual scrubbers to clean while it rotates around the rim. This concept was given a rating of five out of ten because although it is a fully autonomous process, the water jet based system uses a lot of resources and is expensive to filter and recycle the material.


Figure 7.47: Brian Bestoso Design Concept 17
17. Figure 7.47 is a cleaning bath similar to the ultrasonic idea. The tank is full of water and semi-buoyant abrasive particles are dumped into the water. An industrial vibrator then vibrates the tank and cleans the rims using the vibrations and abrasives. This concept was given a rating of two out of ten because of the high material costs of filtering and recycling the water as well as the uncertainty of even cleaning across the entire rim.


Figure 7.48: Brian Bestoso Design Concept 18
18. Figure 7.48 is another rotary style device. This time it utilizes jets that spray carbonated water at the rim. The bubbles pop on the rim causing a force to remove the dirt and grease. The set up for each is shown on the right and is fed to the jets utilizing pumps. The water is drained and recycled to be sent back to water source. This concept was given a rating of two out of ten because the system does not fall within the size constraints specified by UTRC. The process is fully automated and would clean the entire rim surface, however the water jet based system would use a lot of materials and be costly to recycle and filter.


Figure 7.49: Brian Bestoso Design Concept 19
19. Figure 7.49 is another rotary style cleaner. This time it uses hot soap water jets to spray the rim. Then high pressured hot air is fired at the rim to melt and peel off dirt and grease. There would be low waste with this concept. This concept was rated five out of ten because of the short cycle time and automated process, however the cost of the soap mix and filtering the water would increase the cost of operating.


Figure 7.50: Brian Bestoso Design Concept 20
20. Figure 7.50 builds on the simple scrubbing water rotary cleaner. This time there are vibrators attached to each scrubber. The rim rotates while it is sprayed with water. The scrubbers actuate to touch the rim then remove dirt by scrubbing with the additional help of the vibrators. This concept was given a rating of six out of ten because of the fully automated process and assurance from the scrubbers that the materials will be removed. This design,however, uses a great deal of water and the cost of filtering and recycling the material is costly.


Figure 7.51: Brian Bestoso Design Concept 21
21. Figure 7.51 takes a different approach by utilizing electrolytic cleaning methods. The racks that are attached to the rims are considered to be the anode. The cathode is a metal bar submerged in water. A voltage is applied across both while submerged in a Ph solution. This causing oxygen bubbles to form under the dirt and on the surface. This is very effective but may remove the paint. This concept was given a rating of nine out of ten because of the short cycle time necessary for plasma electrolysis as well as the ability to clean multiple rims at a time.


Figure 7.52: Brian Bestoso Design Concept 22
22. Figure 7.52 is another conveyor belt style design this time with a scrubbing cycle and a convection drying cycle. The rims are clamped to the conveyor and are initially sprayed with hot water and soap. Then rotating scrubbers are applied to each surface of the rim to remove the dirt. Then hot air is blown at the rims to dry the rims quickly. This can be a very efficient method for cleaning rims. This design concept was given
a rating of nine out of ten because of its ability to clean the rim in a short period of time using less resources. Using this concept, the spatial requirements as specified by UTRC would not be met.


Figure 7.53: Brian Bestoso Design Concept 23
23. Figure 7.53 is another clamp on cleaning device. It attaches right to the rim and is rotated using a motor. Bearing on the edge allow this motion without damaging the rims. The length of the clamps is adjustable. The most difficulty this would be to have a variable size beam sheet to cover larger rims. This concept was given a rating of one out of ten because of its inability to work with various sizes of rims. Multiple clamps would be necessary for different sizes of aircraft rims.

CONCEPT \# 24: WARM LATHER \& LASER AblATION


Figure 7.54: Brian Bestoso Design Concept 24
24. Figure 7.54 is a further addition to the rotary system by using soap and water and a laser. The soap and water absorbs grease. The laser then ablates the surface removing any additional dirt or grease and in the process, the heat also dries the rim. This design was rated six out of ten because the soap and water mixture makes it easier for the grease and dirt to be ablated, however the cost of soap and water mixture that would be necessary for every cycle would become costly.


Figure 7.55: Brian Bestoso Design Concept 25
25. Figure 7.55 is a wave maker shown in green, and a tank with the rims. The oscillating nature brushes against the rims cleaning them periodically. In this design the water is constant and eventually must be removed and replaced. This design was given a rating of seven out of ten because of its ability to clean multiple rims at a time. This design does not incorporate a filtration system for the water, therefore creating a significant amount of down time when replacement of the water is necessary.


Figure 7.56: Brian Bestoso Design Concept 26
26. Figure 7.56 builds on the previous concept by adding soap and micro-abrasive materials to the solution. The soap helps to remove to grease and oil The abrasives allow each period to remove more dirt. The Rims would be placed in rows with the circular face towards the oscillator. The rows would then be staggered so that each wave can hit the following row without much loss of friction force. This design was rated nine out of ten because the addition of the soap and micro-abrasive material would increase the quality of the cleaning process and decrease the cycle time to clean.

## CONCEPT \# 27: AIR JETS FOR RMS SUBMERGGD IN LIQUID



Figure 7.57: Brian Bestoso Design Concept 27
27. Figure 7.57 utilizes jets in a whole different setting. This time the water is in the tank where the rims are placed. Then air jets are faced towards both the top and bottom of the rims. Air surges through the water causing bubbles. Upon impacting and popping the dirt and grease is removed. This design was given a rating of seven out of ten because of the ability to clean multiple rims at a time, however the cost to filter and replace the water in the tank would be substantial.


Figure 7.58: Brian Bestoso Design Concept 28
28. Figure 7.58 further builds on the previous design by making the air jets a second phase in a two phase operation. Water enters the tank by jets facing the top and bottom of the rim half. Once sufficient water is in the tank, water is blown across the rims to continue cleaning it while they are submerged. Water is then drained, recycled and returned to the source. This concept wis rated nine out of ten because of its quick cycle time, filtration system and ability to clean multiple rims at a time in an effective way.


Figure 7.59: Brian Bestoso Design Concept 29
29. Figure 7.59 is a further addition to the initial submerged air jet design. Water enters the tank, then the air jets are activated. The jets have a rotating scrubbing head attached to them. This allows the bristles to remove dirt more effectively also, the air jets would be closer and give more force to remove the dirt and grease. The rim would be safe from contact with the nozzle because the scrubber would also act as a barrier. This concept was rated six out of ten because of the lack of a filtration system which would increase the cost of water materials and material removal of the dirty water.


$$
\begin{aligned}
& \text { 1. SETS CLEAN RIMS } \\
& \text { 2. TANK FILLS } \\
& \text { 3. SOLVENT ENTERS } \\
& \text { 7. ULTRA SONIC DHIEE } \\
& \text { 5. WATER EXITS } \\
& \text { 6. WATER IS TREATED } \\
& \text { 7. WATER RETURNS TO SOVRCE }
\end{aligned}
$$

Figure 7.60: Brian Bestoso Design Concept 30
30. Figure 7.60 is another combination design which uses both water jets and ultrasonic cleaning. The jets remove a surface layer of dirt in addition to filling the tank with water. While the water is filling the tank, solvent is allowed to pour in which is necessary for the ultrasonic phase. The ultrasound uses the solvent and waves to remove dirt from the rims. Once completed, the waste water is drained from the tank and center to a recycling system and back to the water jet source. This concept was given a rating of eight out of ten because of its ability to clean multiple rims in an effective way while still conforming to the spatial requirements of UTRC.

### 7.3 Ibrahim Brown Concept List



Figure 7.61: Ibrahim Brown Design Concept 1

1. Figure 7.61 uses an extend-able arm from the upper wall to move vertically and a rotatable head for the laser to change its orientation direction. The wheel is clamped onto a turn table with the flange facing downward. This application is suitable for loading the machine on a sliding rack. This concept was given a ranking of three out of ten because it evaluates how loading and unloading can be done for the cleaning system, however does not define the actual cleaning system.


Figure 7.62: Ibrahim Brown Design Concept 2
2. Figure 7.62 uses an extend-able arm from the lower wall to move vertically and a rotatable head for the laser to change its orientation direction. The wheel is clamped onto a turn table with the flange facing toward the upper wall. This application is
suitable for loading the machine with a door on the upper wall. This concept was given a rating of two out of ten because of the difficulty to clamp and move the rim autonomously using this arm.


Figure 7.63: Ibrahim Brown Design Concept 3
3. Figure 7.63 uses plasma electrolysis to fill a tub with an alkaline solution, an interface that positively charges the wheel (coated with zinc, copper, or aluminum powder), and an extendable cathode. A motor is attached to the wheel to rotate and create convection within the tub. An inlet and outlet for the alkaline solution are illustrated on the side and bottom of the tub, respectively. This concept was given a rating of three out of ten because of the inability to reuse the resources that are required to clean the rim using plasma electrolysis.


Figure 7.64: Ibrahim Brown Design Concept 4
4. Figure 7.64 utilizes a wheel that is loaded onto an adjustable to axel interface and slid into an insulated pod. the cap of the pod has a ground for the system and the wheel is positively charge. A motor is used to rotate the wheel and produces convection in the pod. The inlet and outlet of resources are placed on the top and bottom of the system, respectively. This concept was given a rating of four out of ten because the design would be fully autonomous, however damage to the rim could occur when heating it.


Figure 7.65: Ibrahim Brown Design Concept 5
5. Figure 7.65 uses the same concept as Design 7.64 but in a vertical position. This allows partial fill of the tub with respect to the size of the rim half. The motor is placed on the bottom to shake and vibrate the wheel. Inlet and outlets are included for both fluids and air for drying. This concept was given a rating of three out of ten because of
the amount of water resources that would need to be used and recycled for this process to work.


Figure 7.66: Ibrahim Brown Design Concept 6
6. Figure 7.66 is a horizontal version of Concept 7.61, allowing horizontal loading of the rim half. This design was given a ranking of three because it defines the issue of unloading and loading the rim, however the full design and cleaning system is not defined.


Figure 7.67: Ibrahim Brown Design Concept 7
7. Figure 7.67 is similar to Concept 7.66 but uses two lasers to optimize the laser head for cleaning the internal and external circumferences of the wheel.


Figure 7.68: Ibrahim Brown Design Concept 8
8. Figure 7.68 uses plasma electrolysis to clean the wheel. The cathode is submerged from the pod cap and is attached to a dynamic positioning device to control current gradients. This may potentially allow lower voltage usage with equal cleaning effectiveness. The motor driving the turn table allows for an additional degree of freedom for the positioning system. This system was rated five out because the strategy of plasma electrolysis is effective for this application, however there is no filtration system to recycle the resources previously used, increasing cost to run.


Figure 7.69: Ibrahim Brown Design Concept 9
9. Figure 7.69 would mount the wheel in the horizontal position like that shown in Concept 7.66 but uses elongated laser head to cover more surface area per revolution. This concept was given a rating of one out of ten because of the high cost of a laser powerful enough to have such a wide area of surface coverage.


Figure 7.70: Ibrahim Brown Design Concept 10
10. Figure 7.70 uses the plasma electrolysis method using a pod cap with a rotatable anode which uses fins to drive convection in the system. This avoids the need for a turntable under the rim half. This concept was rated eight out of ten because of the quick cleaning cycle and the reduction of the amount of moving parts necessary.


Figure 7.71: Ibrahim Brown Design Concept 11
11. Figure 7.71 illustrates a potential slide system that includes an inlet and outlet for alkaline solutions. This would reduce the necessary amount of room. This design was given a rating of four out of ten as it reduces the amount of space needed to maintain the system, however the concept does not fully define the system.


Figure 7.72: Ibrahim Brown Design Concept 12
12. Figure 7.72 refines Concept 7.71 in the case that the design is not possible. A lower pipe system could detach and re-snap into connection with the electrolysis pod. This design was given a rating of seven out of ten because of the ease of use to replace the materials needed for the plasma electrolysis method.


Figure 7.73: Ibrahim Brown Design Concept 13
13. Figure 7.73 shows another mechanism for generating convection in the system. A chain system fixed and wrapped around the tub is driven by a pinion. The chain is additionally connected to fins within the pod, which rotate with along the circumference of the pod. This concept was given a rating of four out of ten because of the power required from the motor to create enough convection in the system to clean the rim.


Figure 7.74: Ibrahim Brown Design Concept 14
14. Figure 7.74 shows a vibration method that uses a single turn of a double threaded spindle to generate oscillation of the pod. The vibration operates at an optimal frequency
that shakes off the dirt. This concept was given a rating of four out of ten because of the uncertainty of a uniform clean throughout the entire rim when vibrating the particles off.


Figure 7.75: Ibrahim Brown Design Concept 15
15. Figure 7.75 is a buffering wheel that moves vertically and along the circumference of the wheel to absorb and remove grease and lubricants. This concept was given a rating of one out of ten because although the buffering wheel will absorb grease and lubricants on the rim, it will need to be replaced very often in order to remain clean.


Figure 7.76: Ibrahim Brown Design Concept 16
16. Figure 7.76 shows a clamp design that will be able to hold the rim. The part on the right is a cross section of the smaller rim half. The clamp is adjustable with respect to the radius of the rim. A screw is used to push against the wheel and secures the wheel
with respect to the turntable. This concept was rated three out of ten because the clamp does not fully show how the design would be applicable to the entire cleaning apparatus.


Figure 7.77: Ibrahim Brown Design Concept 17
17. Figure 7.77 is another mechanism that uses a combination of helical gears and spindle axles to automatically adjust the clamping system to the size of the inserted wheel. This concept was rated seven out of ten because it is able to clamp multiple types of rims with varying diameters and fully defines how the clamp would be incorporated into the full apparatus.


Figure 7.78: Ibrahim Brown Design Concept 18
18. Figure 7.78 shows a model of the general components of the laser head for any of the applicable designs above. A hole with a key slot is drive for fixed positioning about the axis of rotation. Lasers are aligned on the flat end of the device and a thermal sensor is attached to the top to monitor the heat stresses on the wheel. A motor system is attached to flaps that are extend-able and can reduce random emission of light that
can be harmful to users. This concept was given a rating of eight out of ten because the design is able to control the direction and action of the laser, allowing for a controlled, even cleaning process.


Figure 7.79: Ibrahim Brown Design Concept 19
19. Figure 7.79 is a hand-held laser ablation device that has a program screen on the user end to monitor the system performance and adjust frequency properties of the laser with respect rim material. The far-left trigger activates the laser system and the trigger to the right adjusts blinds that cover the laser. This concept was rated four out of ten because although the laser functions as wished, it is not an automated process and may cause uneven clean across the rim based on the worker that is using the hand-held laser.


Figure 7.80: Ibrahim Brown Design Concept 20
20. Figure 7.80 shows a mechanism within the laser that could be used for bending light from the laser and to clean corners of the wheel. When activated, a spring system releases two optic prisms in the path of the lasers at the end the laser line. This design was given a rating of six out of ten because light bending will be a very critical part of the success of a laser ablation apparatus so that all geometries and faces of the rim will be cleaned sufficiently.


Figure 7.81: Ibrahim Brown Design Concept 21
21. Figure 7.81 shows an alternative light bending method. An optic film placed at the end of the laser is bent into or out of the laser head to clean internal and external corners of the wheel. This concept was given a rating a rating of six out of ten because it allows for a laser to be used to clean the complex geometries of the rim.


Figure 7.82: Ibrahim Brown Design Concept 22
22. Figure 7.82 is a potential latching system for Concept 7.72. A spring system clicks into place with significant tolerances that align the pipe with the drain port of the pod. Hub magnets would pull the clips away and allows the pod to slide out of the system like in Figure 12. This design was rated seven out of ten because it allows for easy maintenance and use of the entire system.


Figure 7.83: Ibrahim Brown Design Concept 23
23. Figure 7.83 combines the clamping device of Concept 7.77 with the oscillator from Concept 7.74. A pin shifting between the two drives allows either oscillation of the pod or movement of the clamps. The figure to the right shows how the bottom plate would be assembled to allow movement of the clamps. This design was rated six out of ten because of the clamp's ability to fit multiple sized rims as well as not interfere with a large surface area of the rim, as these are still places on the rim that need to be cleaned.


Figure 7.84: Ibrahim Brown Design Concept 24
24. Figure 7.84 is a plasma electrolysis method that positively charges the larger wheel half and uses the small rim half as a cathode to clean both rims with 1 circuit. The wheels are held horizontally by a non-conductive axle. This design was given a rating of seven out of ten because of its ability to clean multiple rims at once in a short amount of time. This process would use a substantial amount of resources, however, increasing the cost to run the apparatus.


Figure 7.85: Ibrahim Brown Design Concept 25
25. Figure 7.85 uses a honeycomb mesh to break apart air or CO2 jets. The bubbles produce shear that would remove the dirt and grease from the rims. a smaller rim rests on the honeycomb structure while the larger rim rests on a stand over the first wheel to simultaneously clean both wheels. The chain mechanism of Concept 7.74 is further used to produce convection in the pod. This concept was given a rating of five out of ten because it has the ability to clean multiple rims at a time. This system may have difficulty, however, cleaning the rim half at the top of the apparatus because there will be interference from the larger rim underneath.


Figure 7.86: Ibrahim Brown Design Concept 26
26. Figure 7.86 is a system that uses a similar air jet method as Concept 7.85 but utilizes a rotating fin head to drive convection throughout the system. This concept was rated six out of ten because of the minimal amount of moving parts which reduces the amount of maintenance and energy needed to run the system.


Figure 7.87: Ibrahim Brown Design Concept 27
27. Figure 7.87 implements the design from Concept 7.61 on a conveyor system. This would allow a continuous process. This concept was rated four out of ten because although the process would be autonomous, it would not fit the spatial requirements set by UTRC as well as using a considerable amount of water which would increase running costs.


Figure 7.88: Ibrahim Brown Design Concept 28
28. Figure 7.88 uses an overhanging conveyor belt to clean a rim half. The hanger is used to positively charge the wheel and a cathode fin rotates in the tub to generate convection in the system. The wheel is then brought through a heated drying process. This design was given a rating of six out of ten because it is afully autonomous process that requires very little resources to clean, however it would not meet the spatial requirements set by UTRC.


Figure 7.89: Ibrahim Brown Design Concept 29
29. Figure 7.89 uses an oscillating disk to produce waves throughout the pod. The frequency of this wave be manipulated to clean the surface of the rim halves. This concept was given a rating of two out of ten because of the possibility of uneven cleanliness throughout the rim. This process would use a considerable amount of resources and would be costly to filter these materials for multiple cycles.


Figure 7.90: Ibrahim Brown Design Concept 30
30. Figure 7.90 shows a door latching mechanism for the pods. This is optimal for a system that keeps a smooth geometry along the cap. The latching pin is met on the opposite
side of the axis of rotation. This concept was given a rating of two out of ten as it does not define the entire cleaning apparatus, however it does provide a safe design to ensure that the entire apparatus is securely closed and ready to begin the cleaning process.


Figure 7.91: Ibrahim Brown Design Concept 31
31. Figure 7.91 shows a cap that flips vertically to allow complex cap geometries for electrolysis. The latch is located on the opposite side of the axis of rotation. This design was rated six out of ten because it allows for complex geometries to easily be loaded and removed from a system, while ensuring that the moving components of the apparatus are safe from incident and possible breaking.


Figure 7.92: Ibrahim Brown Design Concept 32
32. Figure 7.92 is a mechanism that uses two prongs to clamp and hold the rim half still. These prongs are driven by a spindle system on the left-hand side of the prongs. this
design was given a rating of one out of ten because of the difficulty to program and calibrate this clamp system to effectively clamp and hold the various sized rims.

### 7.4 Erik Pelletier Concept List



Figure 7.93: Erik Pelletier Design Concept 1

1. Figure 7.93 features the technology of ultrasonic cleaning in which high frequency sound waves are resonated through a fluid to clean. This design features a tank for the rim to sit in, a tank for the debris to settle in and a filter that removes small waste materials from the alkaline solution. This design is appropriate for the project because it is a simple, cost-effective solution that uses very little water and can save a lot of money on waste removal. This concept was given a rating of five out of ten because the design would be difficult to insert and retrieve the rim once submerged because there is no lifting mechanism


Figure 7.94: Erik Pelletier Design Concept 2
2. Figure 7.94 utilizes alkaline cleaning in a tank as well using a lifting porous grate that will remove the rim from the tank in a safe effective manner. Two pistons raise and lower the grate so that a worker can easily insert and remove the rim. This design is more appropriate than Concept 7.93 because it is easier for an employee to maneuver the rim. This concept was given a rating of six out of ten because the worker would have to lean over the tank of alkaline solution which could lead to dangerous accidents.


Figure 7.95: Erik Pelletier Design Concept 3
3. Figure 7.95 incorporates the ideas from the first two designs but adds a sensor and a reservoir of solution that when the sensor is triggered that the fluid level in the tank is low, the reservoir will autonomously fill the tank. This design is a good option for the overall design of the project and was rated seven out of ten because it allows for many parts of the cleaning to be autonomous and does not require a worker to manually add more solution to the tank.


Figure 7.96: Erik Pelletier Design Concept 4
4. Figure 7.96 involves the tire rim sitting on a rotating porous grate and consists of two halves inside the tank. The first have is the cleaning stage where a water-based cleaning solution would spray and clean the rim. The second half would be a clean water spray to remove any particulates and remaining cleaning solution from the rim. Both stages would filter and cycle to its respective tanks. This design is not very relevant to the design problem and was rated three out of ten because UTCRC is looking to reduce their water usage and waste and this system would use a considerable amount of water.


Figure 7.97: Erik Pelletier Design Concept 5
5. Figure 7.97 involves a rim sitting on a stationary grate and two pumps rotating and cleaning the rim. The pumps would use a water-based cleaning solution and be filtered before being re-used. This concept was given a rating of thre out of ten and is not very relevant to the design problem because it would use a significant amount of water and it would be very difficult to program and design multiple pumps to rotate and function properly inside of the housing.


Figure 7.98: Erik Pelletier Design Concept 6
6. Figure 7.98 uses a water-based cleaning solution with two jets, one facing the face of the rim and the other spraying the outside diameter of the rim. The design also consists of a raising and lowering door and a system that allows the rim to be slid out of the housing before and/or after the cleaning process. The cleaning process using water based cleaning uses too much water resources and is not a viable solution for the design problem, however the concept of a raising door with a sliding base to handle the rim easier should be considered in the final design. For these reasons, the design was given a rating of four out of ten.


Figure 7.99: Erik Pelletier Design Concept 7
7. Figure 7.99 places the rim on a shaft that is attached to the main door of the housing. The door hinges downwards so that the rim can easily be placed on and secured before the cleaning cycle. Two water cleaning solution jets would clean the rim and the rim would rotate so that all parts are being cleaned. This design was rated four out of ten and is not very relevant to the design problem because it still would use a considerable amount of water. It would also be very difficult and improbable to design a door that consists of a motor and can hold the rim.


Figure 7.100: Erik Pelletier Design Concept 8
8. Figure 7.100 utilizes a two-stage process. The first process is the ultrasonic cleaning process, where the grate with the rim sitting on it would be lowered into the alkaline solution and cleaned. After the ultrasonic stage, the alkaline solution is drained and filtered and the rim is raised and rinsed with a water mist to remove and remaining particulates. The main door, locating above the alkaline solution level, will hinge down and the rim can slide out to be easily transported and manipulated within the housing. This is a very viable solution for the final design problem and was rated eight out of ten because it reduces the amount of water being used and is safe and easy for a worker to use.


Figure 7.101: Erik Pelletier Design Concept 9
9. Figure 7.101 uses a technology called plasma electrolysis cleaning. A battery of a certain voltage is connected to a switch and using an aqueous solution, hydrogen bubbles are formed on the surface of the rim and the waste is removed from the rim. This design contains a lifting grate in which the rim will be held on and an additional water tank so that water can be autonomously added to the aqueous solution for the correct requirements. This is a viable solution for the design problem and was rated seven out of ten because it would be difficult for a worker to control the process and maneuver the rim because they would need to work over the aqueous solution


Figure 7.102: Erik Pelletier Design Concept 10
10. Figure 7.102 utilizes plasma electrolysis as well as a lifting table in which the rim will sit on. This design also uses a two-stage process in which after the initial plasma electrolysis cleaning stage it would be rinsed with a mist of water. The main door of the housing will hinge downwards so the worker can easily maneuver the rim. This concept was given a rating of eight out of 10 because of the ease of maneuverability from the rim and the low amount of resources it would use. The water mist would not have to be filtered from the aqueous solution because the water would fit well with the solution that will be in the main tank.


Figure 7.103: Erik Pelletier Design Concept 11
11. Figure 7.103 utilizes plasma electrolysis and has the capacity to hold two rims per cycle. The rims are held by latches on the table that will raise and lower the rims out of the aqueous solution. This is a viable design for the design problem because it allows for multiple rims to be cleaned at a time while also keeping raw material usage down thanks to the filter and the technology of plasma electrolysis. The hinges would hinder the ability to clean the rims in the area that they are being held at during cleaning. For these reasons, this concept was given a rating of eight out of ten.


Figure 7.104: Erik Pelletier Design Concept 12
12. Figure 7.104 uses plasma electrolysis but includes a rotating shaft in which the wheel will be attached to. The rim is only semi-submerged so that the areas of the rim that have already been cleaned can drip the solution back into the tank while the other part of the rim is cleaned. This will reduce cleaning time as well as down time. This is a feasible design for the design problem and was given a rating of seven out of ten because of its efficiency, however the rim would be difficult to load on and off of the shaft inside of the housing.


Figure 7.105: Erik Pelletier Design Concept 13
13. Figure 7.105 utilizes plasma electrolysis; however a vibrator is now attached to the table that is being raised or lowered in or out of the tank of aqueous solution. The addition of a vibrator will help the dirt and other waste particles fall off the rim and settle at the bottom of the tank. This design solution was rated six out of ten because it will allow the residue on the rim to be removed easier. Adding a vibrating part to the design may however cause consequences into the energy used during cleaning as well as the life-cycle of the design.


Figure 7.106: Erik Pelletier Design Concept 14
14. Figure 7.106 utilizes ultrasonic cleaning as well as vibrating device to clean the rim. The vibrating device will be attached to the raising/lowering table and aid in removing the residue on the rim. This design also incorporates a secondary tank of solution that will autonomously add more solution when the tank is running low. This design is a feasible design to the possible solution of the design problem and was rated seven out of ten, however the introduction of a vibrating part could cause more complexity to the design of the part and possibly cause more breakdowns and down time.


Figure 7.107: ERik Pelletier Design Concept 15
15. Figure 7.107 uses ultrasonic cleaning to clean a tire that is attached to a rotating shaft that is partially submerged. While one half of the rim is being cleaned the other half will be above the solution, where the remaining debris and alkaline solution will drop off of the rim. This design contains a secondary tank of alkaline solution where when the level in the main tank gets low, can autonomously raise the level of the fluid. This is a viable design for the design problem, however loading and unloading of the rim may be difficult and possibly dangerous. For these reasons, this concept was given a rating of seven out of ten.


Figure 7.108: Erik Pelletier Design Concept 16
16. Figure 7.108 utilizes laser ablation in two different directions, one on the face of the rim and one on the diameter. After the lasers have been applied a water mist will rinse the rim off of particulates and help to remove any vapors from the air. The rim rotates on a shaft so that all sides can be cleaned. This design is a viable concept for the final design problem and was rated eight out of ten because it reduces the resources used and ensures the same quality of clean every cycle.


Figure 7.109: Erik Pelletier Design Concept 17
17. Figure 7.109 is a hand-held laser ablation device to clean the entire rim. The power of the laser will be able to be manually adjusted based on the initial cleanliness state of the rim. The worker has the ability to clean every part of the rim and can be used for many applications. The idea of laser ablation is a viable concept for the solution but the hand-held device design is not suitable for the final design, resulting in a rating of five out of ten. The overall quality of the final product will vary based on who is using it at that time. UTRC would also like a fairly automated process, independent of the worker cleaning the rim.


Figure 7.110: Erik Pelletier Design Concept 18
18. Figure 7.110 utilizes a laser ablation technology with two lasers applied to clean the entirety of the rim. This design involves an air filter that will remove the dangerous vapors and gases that are produced using this process. The rim will rotate about a shaft so that all parts of the rim can be cleaned. This design is a viable solution to the design solution, because the filter removes contaminants that may be harmful to workers. The design would, however, be difficult to load and maneuver because of the location of the shaft and rim. For these reasons, this design was given a rating of six out of ten.


Figure 7.111: Erik Pelletier Design Concept 19
19. Figure 7.111 utilizes two rollers and a vertically placed rim to clean the rim. The jets spray an alkaline cleaning solution while the rollers turn to provide full coverage of cleaning for the rim. The alkaline solution would be recycled and re-used continuously to reduce waste disposal. This is a feasible design for the design solution, however this concept would still use a considerable amount of water and other material resources. For these reasons, this concept was given a rating of six out of ten.


Figure 7.112: Erik Pelletier Design Concept 20
20. Figure 7.112 provides a design to clean four rims in one cycle. Utilizing ultrasonic cleaning processes, the four arms along the faces of the housing would be lowered into the alkaline tank and cleaned. Because the rims are positioned vertically, the solution and waste particles will have the tendency to drip off the rim. This is a very viable design concept for the final solution and was rated nine out of ten because it allows a large number of rims to be cleaned at once. This design has the ability to exceed the cycle time of the current UTCRC rim cleaning process.


Figure 7.113: Erik Pelletier Design Concept 21
21. Figure 7.113 allows for four rims to be cleaned in one cycle, using just one arm attached to the top surface of the housing to clean the rims. This design uses ultrasonic cleaning technologies which uses very little water and reduces waste needed to be disposed. The rims are positioned vertically, so the leftover alkaline solution will drop off of the rim when removed from the solution. This process may be difficult for an employee to load and unload the rims based on the positioning of the arm in the housing. For these reasons, this concept was given a rating of nine out of ten.


Figure 7.114: Erik Pelletier Design Concept 22
22. Figure 7.114 uses plasma electrolysis technologies to clean four rims in one cycle. This design is equipped with a filter and a main tank for the aqueous solution so that the resources can be re-used and autonomously filled into the tank of the aqueous solution. This design has the capability to compete with the current technologies on the market for aircraft rim cleaning designs and was given a score of nine out of ten. Based on the geometry of the rims located inside the tank it may be difficult for a worker to load and remove the rims.


Figure 7.115: Erik Pelletier Design Concept 23
23. Figure 7.115 uses plasma electrolysis technologies to clean four rims in one cleaning cycle. The four rims are attached to an arm on the top of the housing and dropped into the aqueous solution. After the cleaning process the main door hinges downwards and the arm can be pulled out for easy removal and loading of the rims. This is a very viable design to the final solution of the design problem because it offers a semiautonomous process that is easy to handle and significantly reduces water and material waste. For these reasons, this design was rated ten out of ten.


Figure 7.116: Erik Pelletier Design Concept 24
24. Figure 7.116 utilizes fine sand jets to clean the rims. Mixed with a small amount of a water based cleaning the solution the sand blasting process will remove the debris on the rim. The help of the water mix will drag away certain oils and greases left on the rim. The rim is attached to a rotating shaft so that all sides of the rim can be cleaned. This concept is not a relevant design for the final solution and was rated two out of ten because the sand blasting process can be potentially expensive and dangerous, removing paint and coatings from the rim.


Figure 7.117: Erik Pelletier Design Concept 25
25. Figure 7.117 utilizes one robotic arm and a rotating shaft connected to the rim that will clean the entire rim. The robotic arm would use laser ablation technologies to clean the rim. The design is equipped with an air filter to remove vapors that have been released into the air from the ablation process. This design was rated five out of ten but is not applicable to the design solution because of the immense difficulty of completely coding a robotic arm to clean the rim.


Figure 7.118: Erik Pelletier Design Concept 26
26. Figure 7.118 utilizes a conveyor belt and a three-stage cleaning technique to clean the rims. The rim would be cleaned with an aqueous cleaning mixture, a clean water spray and a rinsing solution. This design has the capacity to clean many rims at once and shorten the process immensely. This concept is not a relevant design and was rated four out of ten because of the size of the design and the large amount of water and resources it uses.


Figure 7.119: Erik Pelletier Design Concept 27
27. Figure 7.119 uses brushes and a water based cleaning solution to clean the rims. Three brushes would be sprayed with the cleaning solution so that the wet brush can clean off the debris on the rim. The rim would rotate on the shaft so that all parts of the rim
are cleaned. This is not a very relevant design to the design solution because of the number of moving parts that would be needed to solve the problem and the amount of water resources that would be used. For these reasons, this concept was given a rating of three out of ten.


Figure 7.120: Erik Pelletier Design Concept 28
28. Figure 7.120 utilizes sand cleaning technology to clean the rim. A rotating table that the rim sits on would be cleaned by three jets spraying a fine sand and water based cleaning solution mix. The door of the housing hinges down and the table can be moved in and out for easy removal and loading of the rim. This design is not applicable to the final solution and was rated two out of ten because the sand blasting concept can cause issues to the integrity of the rim.


Figure 7.121: Erik Pelletier Design Concept 29
29. Figure 7.121 has the capability to hold four rims in one cycle. The rims and the arm holding the rims will rotate while two jets clean the entirety of the rim. The water based cleaning solution will be filtered and re-used for multiple cleanings. This concept is not relevant because of the amount of water and solution that would be necessary to clean the rim. This design concept was given a rating of five out of ten.


Figure 7.122: Erik Pelletier Design Concept 30
30. Figure 7.122 utilizes two lasers and rollers to clean the entire rim. The rollers rotate the rim so that the two lasers can clean the entire rim. An air filter is equipped so that the vapors that are created when using laser ablation do not escape into open air. This is a feasible design concept, given a rating of six out of ten, however it would be difficult for a worker to maneuver and load a rim into this concept.

### 7.5 Concept Evaluation

After analyzing all of the one hundred twenty-two concepts that were generated, the designs were categorized into four different sections of Water jet Based systems, Ultrasonic cleaning systems, Plasma Electrolysis systems and Laser Ablation systems. Each category was individually evaluated based on the positives and negatives of the designs and the processes themselves. Evaluations of each four categories are presented below.

### 7.5.1 Waterjet Based System

The United Technologies Research Center currently uses a water jet based system to clean the aircraft rims of dirt, grease, carbon brake dust and other particulates that may accrue during taxiing, take-off and landing. The process of water jet cleaning has proved itself to be a successful cleaning concept of aircraft rims, as the high pressure water jets are able to remove the dirt and grease from the anodized aluminum rims to an acceptable quality of clean.

Water jet systems are especially successful in the application of cleaning aircraft rims because the water jet system is able to clean all surfaces of the rim, especially the complex geometries. The current UTRC method cleans four rim halves in just under fifteen minutes and is able to recycle the water that is used for up to a month.

Although the water jet based cleaning system has shown great success in the past for aircraft rim cleaning applications, there are many aspects to the water jet based cleaning systems that create problems. The largest issue that has been identified is the cost to recycle and dispose of the dirty water once it is considered unusable. UTRC spends upwards of one million dollars each year to safely dispose of the waste water that contains the grease, dirt and carbon particulates from cleaning the aircraft rims. UTRC has specified that they are interested in alternative cleaning methods that will reduce the cost of removing the waste materials that are left after cleaning the rims.

Another aspect of the water jet based cleaning system that is of concern is the high price of running the water jet based system for multiple work shifts throughout the course of a week. The UTRC system currently uses upwards forty Kilowatts to heat its seven hundred fifty liter water tank. The energy cost to heat the water in this system alone is substantial and increases the amount of money required to run this system considerably. Although this technology has been proven in industry to successfully clean aircraft rim in a timely manner, based on the material disposal as well as the cost to run this system, the water jet based system was not considered the best possible cleaning solution method for this design task and optional methods will be investigated to find a suitable solution to the design problem.

### 7.5.2 Ultrasonic Cleaning Systems

The team also generated many designs in the concept generation based on Ultrasonic Cleaning Systems. Ultrasonic systems use an alkaline solution in a tank that is excited by a high frequency wave generator. These frequencies can range anywhere from fifty to eighty Kilohertz in cleaning applications. The wave generator excites the molecules in the alkaline solution, creating microscopic explosions of hydrogen bubbles which in return removes dirt, grease and other particulates from the surface of an object. Ultrasonic systems have been used in many industrial applications, from degreasing and cleaning applications to rust removal and more.

Ultrasonic cleaning systems were highly considered as an alternative method to clean aircraft rims. These systems requires less water than a water jet based system because the fluid is stagnant and only acted upon by the wave generator, instead of being sprayed out of a high pressure nozzle. Ultrasonic applications also have a wide range of intensity levels based on the frequency of the wave generator and the selection of the alkaline solution. This would ensure that the ultrasonic cleaning application does not remove the anodized coating from the aircraft rim. The ultrasonic system would be able to be filtered and recycled for multiple uses and due to the smaller tank size necessary to clean the aircraft rim, the cost to recycle and dispose of the dirty solution would be reduced.

There are many attributes to ultrasonic cleaning applications that cause it to have setbacks. The main issue of ultrasonic cleaning would be the cycle time to remove the dirt and grease from the rim. Based on the design specifications of the task as specified in Section ?? one split rim must be able to be cleaned in under four and one half minutes. Ultrasonic systems have a very slow cycle time and because of the large size of the aircraft rim, the cycle time would not meet the requirements specified by UTRC.

The second issue that arises with ultrasonic cleaning is complex geometry of the actual aircraft rim. Based on the location of the wave generator in reference to the ultrasonic tank and the rim within it, the walls of the rim would create interference of the wave generator to be propagated to the entire surface area of the rim. This would cause an uneven cleaning around the surface area of the rim, where some sections of the rim would be considered acceptable cleanliness and others would not. As required by UTRC, the rims must have an even quality of cleanliness throughout the rim in order to pass inspection before reconstructing the entire aircraft wheel.

### 7.5.3 Plasma Electrolysis Cleaning Systems

Plasma Electrolysis is a concept of cleaning that has a large amount of potential. Plasma electrolysis utilizes a system similar to ultrasonic cleaning, however it uses an aqueous solution and a sacrificial cathode to electrically excite the atoms in the solution and cleaning the surface that the cathode has been coated to. The technology behind plasma electrolysis is still very young and has not been used in many industrial applications.

Because of the very low amount of applications that currently use plasma electrolysis, there would be a lot of freedom when designing the process for aircraft rim cleaning applications. There are very little patents on this technology which means that the team would not have to worry about the issue of potentially illegally using a patent on this type of method.

Plasma electrolysis is a more powerful method of cleaning than ultrasonic cleaning, resulting in a shorter cycle time and meeting the requirements specified by UTRC. A plasma electrolysis system would require much less energy than the energy required to heat and power a water jet system and would reduce the amount of water and materials needed to be recycled and removed, as the tank would be much smaller compared to the four hundred gallon water tank of the current UTRC system.

Plasma electrolysis is a very novel technology, meaning that there is not a great deal of information known yet about this type of system for cleaning applications. This type of system creates a great deal of uncertainty with regards to safety, material selection and product quality. This process can become very volatile in certain applications, with a high risk of removing the paint and anodized coating from the surface of the aircraft rim which is not acceptable by UTRC. Because plasma electrolysis is a higher powered system, it has the possibility to easily create larger bubbles within the aqueous solution which would cause for the removal of the paint and anodized coating.

Because plasma electrolysis uses a sacrificial cathode coating on the surface looking to be cleaned, there is a lot of material lost during this process. Zinc, Nickel and Copper coatings are common coatings for this process and the price to purchase these materials to be used constantly in an industrial application will become very costly. Although the cost of recycling and removing dirty solution from the tank, the price of the coatings would raise the price to run this process significantly. Plasma electrolysis also has a tendency to coat materials based on the cathode that has been applied, an aspect that cannot happen for this cleaning application. If the process were to incidentally coat a rim instead of cleaning it based on incorrect running conditions, it would notably increase the cost of UTRC to remove and replace the rims.

### 7.5.4 Laser Ablation Cleaning Systems

The last system that was investigated in the concept generated is that of laser ablation. Laser ablation uses lasers to vaporize dirt, grease and other unwanted materials from surfaces requiring zero water or alkaline solutions to clean the object. Laser ablation can and has been used in many various applications from brain surgery for killing cancer cells and tumors to refurbishing ancient hieroglyphics and removing rust from metallic surfaces. Lasers have the capability to be calibrated to ablate certain materials without damaging the object underneath.

Laser ablation technologies provide a lot of positive qualities to the application of cleaning aircraft rims. Based on the power and the pulse energy of the laser, it can remove particulate such as dirt, grease and carbon break dust while causing no harm to the paint and anodized coating that lay on the surface of the rim. Laser applications can be altered very easily based on the application and the requirements of the process. Adding parts to the laser assembly such as the use of a Galvo Head, which uses micro-controllers to move and position the laser beam, gives the laser a wider range of area that can be ablated before having to move and readjust the laser.

Another aspect of laser ablation that is very appropriate for the use of this design problem is the removal of any water or aqueous based solutions in order to clean. Because the material is being vaporized, the ablation process requires no water or solution to remove
the dirt, grease and other particles from the surface of the object. Instead of using a filter to recycle the solution to be able to be reused in further cleaning cycles, laser ablation only requires a vacuum pump to and an air filter to remove the vapors from the work surroundings. By doing this instead of filtering water and alkaline solutions, the amount of materials that need to be recycled and disposed decreases to almost nothing.

Laser ablation has been proven to be a very productive cleaning method for applications where the surface in question is parallel to the laser beam. For the task of cleaning an aircraft rim, however, there are many complex geometries that will retain dirt and grease particles that will be difficult for a laser to reach. With this concern in mind, the laser head would need to be attached to a robotic arm or a type of moving device so that the laser can orient itself better to the faces of the complex geometries of the aircraft rim. This solution must deal with the programming and path definition of a laser arm or other moving device to autonomously clean the entirety of the rim.

### 7.6 Concept Generation Conclusions

After analyzing all of the good and bad aspects from each of the four cleaning systems, it was determined that the best solution for this design problem would be to use laser ablation technologies. The main concern of the United Technologies Research Center in this design task was the amount of waste water that must be disposed using a water jet based system. Laser ablation cleaning systems requires no water or alkaline solutions to clean the surface of the rim, reducing the cost of material disposal to zero. A laser ablation system also validates a uniform quality of clean throughout the rim surface, because the pulse energy of the laser will never change regardless of where it is cleaning the rim surface. Lastly, a laser ablation system allows the cycle time requirement of four and one half minutes to be feasible, because based on the power and intensity of the laser the system can clean one entire rim in this amount of time.

## 8 Quality Function Deployment (QFD)

Given the design requirements provided by the United Technology Research Center, each engineering parameter of the system was prioritized throughout a called Quality Function Deployment analysis (QFD). QFD organizes customer requirements and needs in a house of quality. The specific needs of the customer are organized by rows and the design approach that addresses how each need will be controlled is listed in columns. Within the grid, what (customer requirements) and how (engineering solutions) are related on a scale of 1,3 , and 9; where 9 signifies a strong relationship or dependence between the two parameters. The "roof" on the house of quality correlates the technical aspects of the project by indicating if the improvement has a positive or negative affect on another. The resulting QFD analysis of this project is shown in the Figure 8.1.


Figure 8.1: Quality Function Deployment analysis for the LARRIC system

The first section filled in this chart was the customer requirements. UTRC had started this project with the interest of reducing waste and resource expenses. In addition, the cycle time was critical reduce due to meet the high demand of wheels that need to be clean during the work day. The system must also be reliable to properly prepare the aircraft rims for crack checking and other forms of routine maintenance. Along with reliability, the air craft rim cannot experience any damage on its surface. The last critical request was to limit the volume of the system to avoid readjusting the organization of the facility. The demanded quality parameters are shown in Figure 8.2 .


Figure 8.2: The Demanded Quality of the LARRIC

Along the columns on the top of the chart, the quality characteristics were listed. These characteristics address how the design team plans to meet the quality of demand from the customer. The quality characteristics are marked with units when needed and states whether the characteristic should be maximized, minimized, or meet a requested value. Some of the key characteristics that were listed on the chart are the volume constraints, waste reduction, semi-autonomous, and the materials used to build the device. Figure 8.3 .

| Column ${ }^{\text {a }}$ |  | 2 | 3 | 4 | 5 | ． | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Direction of Improvement Minimize（ $\mathbf{F})$ Marimize $(\mathbf{4})$ or Tarpet（s） | V | V | V | 4 | V | V | V | A | A | V | V | V | V |
| Quality Characteristic： Ta．ka．＂Functiona Roquirements or |  | $\begin{aligned} & E \\ & \text { E } \\ & \text { 言 } \\ & \vdots \end{aligned}$ |  |  | （Degrees |  | \％ |  | $\stackrel{\varrho}{\underline{E}}$ |  |  |  |  |
|  |  |  |  |  |  | $\begin{aligned} & \text { zan } \\ & \text { zo } \\ & \text { zo } \\ & 0 \end{aligned}$ |  | 등 |  | $\begin{aligned} & \text { 은 } \\ & \text { N } \\ & \text { 世゙ } \\ & 3 \end{aligned}$ | $\begin{aligned} & \text { ㅇo } \\ & \frac{I}{n} \\ & \text { O} \end{aligned}$ |  |  |

Figure 8．3：The Quality Characteristics of the LARRIC

Correlations were drawn between two coinciding parameters within the grid area．Each correlation was ranked with either a 1,3 ，or 9 to signify the dependency each parameter has on one another．Along the base of the grid，the importance of achieving each characteristic was calculated based on how many customer demands the characteristic fulfills．The chart shown in Figure 8.4 shows that the top three priorities for this design project consist of material selection，power usage，and cycle time reduction，respectively．


Figure 8.4: The relationships between the Quality Characteristic and the Demanded Quality of the LaRRIC

The "roof" of the house of quality relates each of the quality characteristics together with either a positive or negative correlation. The flowing two Figures present the legend and the chart of relations between each quality characteristic.

| Legend |  |  |
| :---: | :---: | :---: |
| O | Strong Relationship | 9 |
| O | Moderate Relationship | 3 |
| Weak Relationship | 1 |  |
| + | Strong Positive Correlation |  |
| X | Positive Correlation |  |
| X | Obgative Correlation |  |
| Objective is To Megative Correlation |  |  |
| Objective is To Hit Target |  |  |

Figure 8.5: The legend for the symbols used in the QFD analysis


Figure 8.6: The Relations Between Each Quality Characteristic
The final visual result from the Quality Function Deployment analysis is a comparison chart of the market competition's ability to satisfy the customer requirements. This analysis is shown in the figure below. Each represented company failed to completely satisfy the needs of the United Technology Research Center. Although the Stingray6036 Aircraft Wheel Washer proved to be reliable and maintains the spatial volume as the Mart 60 currently being used in the UTRC operation facilities, the cycle time and quality of cleanliness were sacrificed. The Aqua Clean Super Brush ${ }^{\mathrm{TM}}$ provides a quality clean of the air craft rims but sacrifices cycle time due to its single loading system.


Figure 8.7: The QFD competition analysis of the Mart 60, Stingray, and Aqua Clean systems

## 9 Design for X

The project was given a budget of $\$ 3,000$. To remain underbudget, the team decided to 3-D print the rim with PLS plastic as a normal rim would have cost $\$ 1,299.95$ [10]. Not only did 3 -D printing the rim reduce its cost, it also reduced its weight from 601 bs to 5 lbs. The reduction of weight allowed for cheaper material to be selected for the manufacturing of the turntable and frame. The required tensile and yield strength of the materials was greatly reduced allowing the team to build the turntable and frame from wood instead of aluminum or steel. Furthermore, the team decided to build a half-scale model to cut the cost in half. This allowed for the system to be manufactured for only $\$ 357$. An unassembled robotic manipulator was purchased from China along with the servo motors. With the team assembling the manipulator, the cost for it reduced. Table 9.1 provides a breakdown of the cost of the half-scale model.

Table 9.1: Cost for the system

| Item | Cost (\$) |
| :---: | :---: |
| Arduino Mega2560 | 44.95 |
| Electrical Equipment | 753.94 |
| Turntable | 357.00 |
| Rim | 84.04 |
| Robotic Manipulator | 180.13 |
| Miscellaneous | 200.00 |
| Total | $\mathbf{1 7 9 8 . 4 4 6}$ |

### 9.1 Design for Safety

Numerous precautions were taken to ensure the safety of the device. Each power supply was activated through a relay that was controlled by the Arduino, making it easy to disconnect certain sections of the system from power by turning the relay off. Furthermore, emergency stop buttons were implemented for the the robotic manipulator and the overall system. When the emergency stop for the manipulator was pressed, its motion was stopped at its current position to ensure that it was not damaged any further. When the emergency stop for the overall system was pressed, the turntable for the motor was stopped and power to the sensors was be cut off. Furthermore, the relays connected to the power supplies were switched to an off position. Each electrical component was also connected to a fuse rated to its maximum operating current and a voltage regulator rated to its maximum operating voltage to protect the system form power overloads and unexpected power surges.

### 9.2 Design for Ease of Use and Repeatability

The operator had minimum influence on the cleaning process. The operator was responsible for the loading and unloading of the rim. After the rim was loaded, there were numerous tests conducted by proximity sensors to ensure that that rim was loaded properly. If the loading was incorrect than the system would reject the rim and inform the user that it must be loaded again. The cleaning process was controlled by a computer and the Arduino. Since the whole process was automated the results were the same for every trial. A crucial design specification was the repeatability of the process across numerous rims. The automation of the system allowed for the consistency of the clean to remain the same regardless of the trial.

### 9.3 Design for Ergonomics

Extensive consideration was taken into account to the ergonomics of how the aircraft rim would be loaded into the LARRIC system. Based on information provided from the United Technologies Research Center, a majority of the workers that will use this product utilize an overhead rolling hydraulic crane to load the rim from overhead. For this reason, the design of the LARRIC prototype must allow for the aircraft rims to be loaded overhead without reaching over any obstacles. For this reason the sliding tray design was incorporated. The tray slides out of the working area of the system so that the operator does not have to reach
over potentially dangerous moving parts while loading the rim from overhead. The sliding Tray also allows for no overhead interference so that the whatever the dimensions of the hydraulic crane, the rim will still be able to be loaded with ease.

### 9.4 Design for Environment

The entire purpose of the design task was centered around environmental considerations. The United Technologies Research Center was searching for a method to reduce their environmental footprint and the energy consumption of the current water-jet based system that is in use. To recycle the amount of water waste that is accrued from daily functioning of the water-jet system costs UTRC over one million dollars each year per facility to either filter the waste from the water or dispose of all of the material. The system also consumes over one hundred kilowatts to run the system as well as heat the four hundred gallon tank that holds the water. Designing the system using laser ablation technologies significantly reduces the energy as well as waste produced. A full-scale design proposes a five kilowatt laser to clean the aircraft rims which will require five times less power consumption during a cycle. The overall running costs and maintenance costs are drastically reduced using laser ablation and if implemented in UTRC facilities, could save the company millions of dollars over time (Fig. 3.1). Using Laser ablation over a traditional water-jet based system will also reduce the environmental footprint of United Technologies Research Center.

## 10 Project Specific Details \& Analysis

### 10.1 Market Analysis

The information found in this section is derived from the aerospace industry as a whole, based on the amount of companies that require aircraft rim cleaning and the amount of companies that offer rim cleaning. The companies that supply rim cleaning services often have multiple facilities which provide the service. Due to the global size of the aerospace industry, much of the analysis is restricted to the U.S. and companies associated with U.S. aerospace industry. This information stems from, but is not limited to organizations such as UTC, Honeywell, Goodyear, Boeing, Lockheed Martin, U.S. Military and NASA.

### 10.2 Market Trends and Demand Forecast



Figure 10.1: Air traffic annual percent growth 11

As shown in Figure 10.1, the aerospace industry is growing between six and seven percent annually. The article states that the projected growth in 2018 will be six percent. As technology, and the methods to manufacture aircraft improves, the ease and availability of air travel increases. Economically, this means traveling by air will be more affordable which will in turn cause traveling by aircraft to increase in demand. Aircraft passengers will increase by an average of $2.8 \%$ annually in North America alone 12 . Other regions are also projected to see more passengers such as the Asia-Pacific region with a growth average of $4.7 \%$ annually [12]. Consequently more aircraft will need to be put in service to meet the market demand which indicates a market increase for aircraft rims.

In addition to commercial airlines, military aircraft also require rim cleaning and inspection. The military comprises of the Army, Navy and Airforce. There is a total of 13,762 active military aircraft in 2017 [13]. Furthermore, many aircraft are still in production. Lockheed Martin has been slowly releasing the F-35 and by 2020 there will be an estimated total of 600 U.S. owned F-35's. Also, in 2020 Lockheed Martin also anticipates completing their rapid assembly of $\mathrm{F}-35 \mathrm{~s}$ which will be produced at a rate of seventeen jets every month [14]. These numbers show that demand for aircraft rim cleaning will increase significantly over the course of three years.
cents per kilowatthour
percent change from prior year


Figure 10.2: RECORDED AND PROJECTED PRICE OF ELECTRICAL ENERGY [15]

### 10.3 Market Opportunity

Currently the market for aircraft rim cleaning is limited to water jet systems. There are many brands with various features but the general system remains the same. The current system has been optimized repeatedly since it was first implemented. Opportunity arises in the market because the current system has reached an optimization plateau and now requires innovation. Furthermore, as shown in Figure 10.2 the price of electricity has been steadily increasing for ten years and is projected to continue increasing. Economically the laser ablation system is attractive because it requires less energy to operate especially when factoring in cost for energy consumption.

### 10.4 Market Profitability

As mentioned during the financial analysis, this system is meant entirely for use by United Technologies to improve the process currently in use at their facilities. The laser ablation system was not originally intended to be sold as a product to other companies. A short analysis of market profitability was conducted to provide a hypothetical profit if it was on the market for other companies.

Based on the increasing demand in the aerospace industry, the laser ablation system would see profits from manufacturing and selling the system. The initial factor of the price versus cost is the cost of the laser which is approximately $\$ 150,000$. The next major cost is the robotic arm and installation which all together comes to $\$ 1,000,000$. A laser with installation is a necessary cost to the company. Robotic arm and cleaning apparatus could be manufactured elsewhere and made compatible with the laser. This would drive the cost down for the company and enable a more profitable product that could be sold to other companies. Assuming the cost of manufacturing and installing the system comes to $\$ 800,000$. If the price to other companies remains the previously mentioned $\$ 1,000,000$ then there is a
net profit of $\$ 200,000$.

### 10.5 Survey of Potential Users

Due to the quantity of aircraft in the aerospace industry there are many potential users of the product. There are hundreds of aircraft companies in the United States alone. Due to the strict rules set by the FAA, the rims used on their aircraft must be cleaned and inspected to ensure the safety of the passengers. The largest aircraft companies would be the first to use the technology as they have the money to invest compared to smaller companies. Initial users of the product would be logically United Technologies, Boeing, and the Military. Other potential users are companies overseas that have regulations for rim inspection similar to the ones set by the FAA. The first overseas company to implement the technology would theoretically be in the Asia-Pacific region. This foresight is due to the previously mentioned average annual increase of passenger flight in that region.

## 11 Detailed Product Design

### 11.1 Half-Scale Model

### 11.1.1 Boeing 737 Split Rim Model

This design task focused trajectory and cleaning efforts toward a sample split rim from a Boeing 737 NG. The wheel rim is separable into two components with one rim half being thicker than the other. The prototype presented throughout section 11.1 is designed to support the larger half of the split rim as specified by the Honeywell data sheet for Boeing 737 NG wheels [16]. The geometric specifications shown in Figure 11.1 were used to develop a 3-D model in Solidworks.


Figure 11.1: Commercially available geometric dimensions of a Boeing 737
NG wheel rim 16]

Throughout the Spring of 2018, the rim was replicated using 3-D printers available at the University of Rhode Island. Printing challenges arose when developing a half-scale model of the rim due to the limited bed size of the 3-D printers. The model was adjusted for printing by dividing the wheel rim into four prints. Future assembly was further assisted by incorporating press fit keys on the top and bottom of the wheel to secure assembly. Two separate STL files were made to account for hole placement and can be seen in Figure 11.2 a and Figure 11.2 b .

After printing two copies of each wheel rim section, the parts were assembled using adhesive. First the mating faces were covered with clear and water-soluble Elmer's glue. The interlocks were fitted together to keep the surfaces flush while drying the glue. Along the contacting edges, ABS filament from the 3-D printers were soldered on to melt and bond

(a) First Solidworks MODEL FOR PRINTING A HALF-SCALE WHEEL RIM MODEL

(b) Second Solidworks MODEL FOR PRINTING A HALF-SCALE WHEEL RIM MODEL
the creases of the wheels. The rim was left to sit for two days to ensure the glue had solidified and resulted in a complete 3 -D printed wheel rim model.

The wheel rim was then sanded to smoothen and remove any uneven surfaces. The dust was then cleared and XTC-3D High Performance 3D Print Coating was used to create a chic aesthetic and further protect the rim from fall damage. A white coating of primer was then applied to give practical coloration that simulates the reflectivity of an aircraft wheel rim. A final coating was applied using a mixture of Solar Colored Dust and Elmer's glue. The dried coating successfully resulted in a florescent coating that responded to incidence from an Ultraviolet wavelength. The final wheel rim replica is shown in Figure 11.3.


Figure 11.3: The 3-D Printed wheel rim assembly with a florescent coating Which responds to an ultraviolet wavelength.

### 11.1.2 Turntable

The LARRIC system incorporates a turntable to rotate the targeted wheel rim along the axel axis. In the half-scale prototype, the geometric dimensions and configurations were built to interface with the Boeing 737 NG replica presented in Section 11.1.1. The design of the turntable has a direct impact on two of the product specifications: the system must be capable of overhead loading and the cycle time is limited to three minutes per rim half. In addition, the geometric dimensions of the frame are constrained in order to conserve room for a robotic manipulator and to allow the arm to have an undisturbed view of the wheel rim's cross section.

The design parameters are to be met with the inclusion of four subassemblies. The first subassembly is a frame which supports the turntable and slides horizontally into the system housing. The second subassembly is a motor which drives the wheel rim to rotate. The third subassembly is the drive roller which supports a quarter of the weight and interfaces with the turntable motor to transmit rotational energy into the wheel. The final subassembly is a contact roller which serves as a cantilever beam and supports a quarter of the weight of the wheel rim.

### 11.1.2.1 Frame

In the half-scale prototype, material selection was simplified for the sake of manufacturability and production cost. The hardware for the frame was design to be manufacturable
using 2 " by 4" pressure-treated plywood. Each joint was fastened using a minimum of two 3 " screws through the base of each beam and one L-bracket along the sides of the connection. The resulting model of the frame assembly is shown in Figure 11.4 Detailed drawings for each component and subassembly can be found in Appendix ?? - ??.


Figure 11.4: A Solidworks model of the frame assembly and sliders.
The primary design consideration for the frame of the turntable was to allow enough spacing for various aircraft rim classes to be interfaced in the system. The range of aircraft wheel rim diameters this system is meant to incorporate ranges from 10 inches 32 inches in diameter. Given the maximum wheel rim size, a half-scale model would need to accommodate a 16 in . diameter rim. By including one-inch minimum clearance between the rim diameter and the frame wall, an 18 "x18" clearance was reserved for loading a wheel.

In addition to the wheel clearance, the right side of the frame was expanded to incorporate space for a robotic manipulator. An estimated 20 inches of clearance was reserved between the center axis of the wheel resting position and the back-right wall of the system's housing. As a result, the right-hand wall was expanded 10.5 inches as illustrated in Figure 11.4 In addition, the resulting clearance specified that the back wall must be space 33 inches from the center axis of the wheel to further provide space and to install the robotic manipulator at a 45-degree angle with from the center axis of the turntable.

Once the external frame spacing was established, four points of contact were implemented into the frame. The four points of contact were selected to assist with the translation of rotational energy from the motor to the wheel rim. Figure 11.5 illustrates the reactant forces from a turntable with four points of contact. As the drive roller on the left beam of the frame rotates positively in the X-axis, the torque of the drive roller applies a tangential force on the wheel toward the front end of the frame. The contact support on the front beam provides an axial force in line with the center axis of the rim. The resulting parallel forces create an efficient mechanical advantage which translates into a torque on the wheel rim.


Figure 11.5: The rotational dynamics of a turntable with four points of CONTACT.

The four points of contact are mounted at the mid-point of the 18 -inch clearance toward the inner portion of the frame. In order to allow clearance for the robotic manipulator to reach the entire cross section of the wheel rim, beams were not implemented toward the back-right corner of the frame (see Figure 11.4). In addition, the beam on the left side of the frame was cut along its length to form a gap for a driver wheel and motor head to mesh between the frame and side wall. At the base of the beams along the left and right-side walls are two drawer slides. The combined spacing from the beam cutout and slider on the left side of the frame forms a 1.25 " gap between the upper frame and the left side wall. These sliders are mounted on the bottom two inches of the beams and allow the frame to be pulled out horizontally from the system. This feature resembles a dishwasher and allows the user to load the aircraft rim onto the four contacts from an overhead cart. Once loaded, the user can push the frame back into the system and the drive roller would slide into contact with the driver motor.

### 11.1.2.2 Motor Implementation

Once an aircraft wheel rim is loaded onto the tray, the frame of the turntable will slide back into position and lock in contact with a driver motor. Section 12.8 .2 demonstrated the motor requirements for the application of a half-scale prototype. In summary, the selected motor must be capable of producing a peak torque of $1.7 \mathrm{~kg} . \mathrm{cm}$ and maintain a steady speed of 512 rpm . The resulting power requirement of the motor is 0.17 Watts.

A 12 Volt DC motor was selected for this application with peak speed of 366 rpm and torque of $13 \mathrm{~kg} . \mathrm{cm}$. The motor's dimensions followed ISO standards and consisted of a 6 mm , D-profile shaft with a length of 14.9 mm . This shaft required a diameter adapter to couple the motor with a roller head which has a half-inch inner diameter. The adapter shown in

(a) Motor and roller HEAD SHAFT ADAPTER
(b) Motor driver head

Figure 11.6 a includes a size 8 set screw to fasten the adapter on the D-profile shaft. The outer diameter of the shaft adapter is coupled with a 1.5 -inch-long neoprene roller head shown in Figure 11.6b


Figure 11.7: The interface for mounting the motor on the outer housing WALL.

The motor was mounted on the outer wall of the system's housing to allow sufficient space for the roller head in the 1.25 in gap between the upper frame and the left wall. The interface is shown in Figure 11.7. The thickness of the interface matches the height of the shaft base on the motor to optimize clearance between the frame and the end of the motor head. The interface was mounted flush onto the wall and 16 inches high off the base of the system. The completed assembly is shown in Figure 11.8. The detailed drawings for all components and motor assemblies can be found in Appendix ?? - ??.


Figure 11.8: The motor assembly on the prototype.

### 11.1.2.3 Drive roller

On the left side of the turntable frame, a drive roller assembly is used to translate the rotational energy from the motor to the loaded aircraft wheel rim. The diameter at each end of the main shaft is a half inch to provide a clearance fit through a set of ball bearings and a plastic roller head as seen in the exploded assembly view of Figure 11.9). The plastic roller head shown consists of a 1.5 -inch contact diameter and has a 0.2 -inch lip around the base to prevent the wheel from sliding off track. The resulting cantilever beam has an arm length of 3.2 inches from the wall of the frame to the front side of the roller head lip.


Figure 11.9: Exploded assembly view of the drive roller.

The opposite end of from the roller head has 1.75 inches of extended shaft length. In the assembly, a ball bearing is first added onto the shaft. A spacer of approximately 0.125 inches is used to separate a second ball bearing and distribute the reactant load from the cantilever shaft. The remaining 0.875 inches is reserved for a washer and is couple with a neoprene roller. The overall assembly can be seen in Figure 11.10. Only one driver contact assembly is used in the system and remains constant throughout the entire prototyping process.


Figure 11.10: A Solidworks model of the drive roller.

### 11.1.2.4 Contact Rollers

Three of the contact points serve to only support the rotation of the aircraft wheel rim. The contact rollers consist of a half-inch diameter cantilever beam with a roller head adhered to the end of the shaft. An exploded view of the contact roller can be seen in Figure 11.11 , On the opposite end of the shaft are two ball bearings which maintain separation due to a 0.8 inch spacer. The outer end of the shaft has a $0.5 \times 13$ ANSI external thread and closed with a complementing nut to hold the assembly together. Throughout the initial turntable design, three of the roller assembly shown in Figure 11.12 were included along the front, back, and right support beam.


Figure 11.11: Exploded assembly view of the contact roller.


Figure 11.12: A Solidworks model of the contact roller.

### 11.1.2.5 Turntable Assembly

Throughout late February and early March, the individual components of the turntable were assembled together. All components and the final assembly fell into proper tolerance as specified by the drawings presented in the Appendix. The Table 11.1 below summarizes the parts included in each subassembly and Table 11.2 summarizes the part list for the entire assembly of the turntable.

Table 11.1: Component listing for the LARRIC subassemblies

| Sub Assembly | Part Name | Drawing ID | Quantity |
| :--- | :--- | :--- | :--- |
| Frame | Back Beam | Prt_Beam1 | 1 |
|  | Middle Beam | Prt_Beam2 | 1 |
|  | Middle Support Beam | Prt_Beam3 | 1 |
|  | Right Wall Beam | Prt_Beam4 | 1 |
|  | Left Wall Beam | Prt_Beam5 | 1 |
|  | Front Beam | Prt_Beam6 | 1 |
|  | Drawer Slider | N/A | 2 |
|  | Corner Bracket | N/A | 6 |
| Motor | Motor Interface | Prt_TTM1 | 1 |
|  | Turntable Motor Shaft Adaptor | Prt_TTM2 | 1 |
|  | Motor Head | N/A | 1 |
|  | Drive Roller Shaft | Prt_Roll1 | 1 |
|  | Small Spacer | Prt_Roll3 | 2 |
|  | Contact Roller Head | N/A | 1 |
|  | 1616-2RS-NR Ball Bearing | N/A | 2 |
|  | Drive Roller Contact | N/A | 1 |
| Housing | Contact Roller Shaft | Prt_Roll2 | 1 |
|  | Small Spacer | Prt_Roll3 | 1 |
|  | Large Spacer | Prt_Roll4 | 1 |
|  | Contact Roller Head | N/A | 1 |
|  | $1616-2 R S-N R ~ B a l l ~ B e a r i n g ~$ | N/A | 2 |
|  | $0.5 x 13$ Nut | N/A | 1 |
|  | Left Wall | Prt_Base1 | 1 |
|  | Right Wall | Pack Wall_Base2 | 1 |
|  | Base Wall | Prt_Base3 | 1 |
|  | Prt_Base4 | 1 |  |

Table 11.2: Assembly list for the LARRIC system

| Assembly | Sub Assembly | Drawing ID | Quantity |
| :--- | :--- | :--- | :--- |
| Turntable | Frame | Asm_Frame | 1 |
|  | Motor | Asm_TTM3 | 1 |
|  | Driver Roller | Asb_Roll1 | 1 |
|  | Contact Roller | Asb_Roll2 | 3 |
| Base | Housing | Asm_Base1 | 1 |
|  | Electrical Pannels | N/A | 2 |
|  | Ultra Sonic Sensor | N/A | 2 |
|  | Infrared Sensor | N/A | 1 |
| Robotic Arm | Arm Support | Prt_Arm1 | 1 |
|  | Robotic Arm | N/A | 1 |

The resulting turntable was checked along all critical dimensions to ensure sufficient room was saved for the motor interaction and clearance for the robotic manipulator was
provided. A level verified the tray was flat and would be able to slide into and out of the system horizontally. A 3-D model of the turntable design is presented in Figure 11.13 and is in juxtaposition with the physical prototype in Figure 11.14 .


Figure 11.13: A Solidworks model of the complete turntable assembly.


Figure 11.14: The developed prototype of the turntable.
$"$

### 11.1.3 Housing

The design of the system housing has a direct impact on the prototype's ability to comply with the product specifications identified in Section 6. At a full-scale, the system is allotted to be 6'x6'x7' to avoid heavy rearrangements at UTAS operations facilities. The system housing of the prototype is designed to be $2.8^{\prime} \times 2.75^{\prime} \times 1.875$ '. The set dimensions do not include an enclosure for electrical wiring, a closing door at the front of the system, or a top for the system. In order to complete the enclosure, it is estimated to require an extra foot
of over head clearance for the robotic arm, 3 inches along the width of system for coverage on the driver motor, and three inches toward the front of the system to account for a door. The resulting dimensions of the corrected half scale model would be 3 ' $x 2.25$ ' $\times 2.875$ '. If the proposed model were brought to full scale, the overall dimensions for the system would be $6^{\prime} \times 4.5^{\prime} \times 5.75$ ', which satisfies the design requirements proposed from UTRC. Figure 11.15 shows a 3-D model of the prototype housing.


Figure 11.15: A Solidworks model of the system housing design for the HALF-SCALE PROTOTYPE.

The interior space of the system is $2^{\prime} 8.7^{\prime \prime}$ wide and $2^{\prime} 8.7^{\prime \prime}$ deep to allow sufficient storage space for the robotic arm in the back right corner. The drawer slides are mounted 12.5 " from the base of the system to provide clearance underneath the wheel rim for the robotic arm to ablate the wheel. On the left wall, a $1.5 "$ hole is drilled approximately $15.5 "$ above the base of the system to align the roller head of the turntable motor horizontally with the drive roller.

Additional planks of plywood are position in the system to mount sensors for the system interlocks. Approximately 1 " above the slide drawer, a shelf has been mounted to position an ultrasonic sensor facing the center axis of the turntable. This sensor is used to verify the wheel rim is properly center on the system. A second ultrasonic sensor is place directly underneath the from beam of the frame and centered along the width of the system. This sensor is used to verify the frame is properly pushed into position and the system is properly closed. Underneath the turntable, approximately 3.125 " away from the center axis of rotation, is an inferred laser sensor. This sensor is elevated 10.5 " from the floor base to improve the sensor's accuracy when scanning for hole positions as the wheel rotates. The interior positioning of all electrical sensors and motors are shown in Figure 11.16. Figure 11.17 shows the entire housing assembly for the prototype.


Figure 11.16: The positioning of electrical equipment along the internal SYSTEM HOUSING.


Figure 11.17: The system housing for the half-scale prototype.

### 11.1.4 Robotic Manipulator

The complex geometry of the rim required an intricate solution so that the entirety of the rim would be ablated. After intensive research, the team concluded that a six degree of freedom robotic manipulator would be the best option. The high number of degrees of freedom will allow for the manipulator to reach every corner of the rim. Furthermore, they provide flexibility in the programming because now there will be at least two positions to reach the same spot.

Figure 11.18 provides a label schematic Fig. 11.19 provides a side view and Fig. 11.20 provides a front view of the robotic manipulator. At point $\mathrm{A}, \mathrm{B}$, and C , the manipulator can rotate in the X-Y plane and the Y-Z plane. $\overline{A B}$ and $\overline{B C}$ represent link one and two respectively. Link one, the shoulder, has a length of 13.125 cm and link two, the elbow, has a length of 17.6 cm . Point $\mathrm{C}, \mathrm{D}$, and E , are fixed to each other, therefore $\overline{C E}$ is treated as one link (link three), the wrist. Link three has a length of 7 cm . The manipulator is fastened to a linear actuator to increase its range of motion. The actuator has has a stroke of twelve inches, allowing for point A to be 3.5 inches above and below the rim.


Figure 11.18: Labeled schematic of the Robotic manipulator


Figure 11.19: Robotic manipulator: Side View


Figure 11.20: Robotic manipulator: Front View
The manipulator is manufactured out of stainless steel and each joint is fastened to the next. Ball bearings are attached to the links allow for the smooth rotation created by the servo motors. Overall, there are seven servos motors attached to the manipulator, 5 MG996R and 2 MG90S. Three MG996R servo motors are attached to the shoulder (point A), one to control rotation in the Y-Z plane and two to control rotation in the X-Y plane. Two MG996R servo motors are attached to the elbow (point B), one to control rotation in the X-Y plane and the other to control rotation in the Y-Z plane. The two MG90s servo motors are attached to the wrist, one controls rotation in the X-Y Plane and the other in the Y-Z plane. The MG996R motors are rated for $5 \mathrm{~V}, 1 \mathrm{Amp}, 12 \mathrm{~kg}^{*} \mathrm{~cm}$ of torque, and can operate up-to $40^{\circ} \mathrm{C}$. The MG90s motors are rated for $5 \mathrm{~V}, 1 \mathrm{Amp}, 8 \mathrm{~kg}^{*} \mathrm{~cm}$ of torque, and can operate up-to $40^{\circ} \mathrm{C}$. All of the servos have metal gears to ensure they do not wear quickly and to increase the strength of them. Furthermore, all of the motors have a range of motion of $180^{\circ}$.

### 11.1.5 Linear Actuator

The robotic manipulator was not big enough the reach the top and bottom of the rim. Therefore, a linear actuator, Fig. 11.21 was implemented into the system. It was mounted using the fixture seen in Fig. 11.22 through the use of fasteners. The robotic manipulator was attached to the linear actuator with the fixture seen in Fig. 11.23. The actuator has two positions, 3.5 inches above the top of the rim and 3.5 inches below the bottom of the rim. This allowed the manipulator to reach the entirety of the rim with ease. The two fixtures were modeled in SolidWorks and then 3-D printed.


Figure 11.21: Linear Actuator


Figure 11.22: Stand fixture for the Linear Actuator


Figure 11.23: FIXTURE FOR THE LINEAR ACTUATOR TO ATTACH THE ROBOTIC MANIPULATOR

### 11.1.6 Electrical Components

To ensure the automation of the system the Arduino Mega 2560 Rev3 micro-controller, fig. 11.28 was used. The Arduino provided control over the components however, all of the programming was done using MATLAB. The processor of the Arduino was not capable of handling the complex calculations required therefore, MATLAB completed all of the calculations while the Arduino controlled the physical components. By splitting up the tasks, the overall system was able to run smoother and faster. Furthermore, the reduced strain on the Arduino made it possible to add more components to the system. Table 11.3 provides a bill of materials for all of the components used in the system. Table 11.4 provides the meaning of each wire color. Figure 11.24 and Fig. 11.25 provide the physical wiring of the system. Two separate electrical cabinets were used. Figure 11.26 provides the breadboard schematic for the wiring of the overall system. Figure 11.27 provides a normal schematic view of the wiring of the overall system.

Table 11.3: Bill of materials for the electrical components

| Component | Quantity | Role |
| :---: | :---: | :---: |
| 5V 5A Power Supply 22 | 2 | Power the robotic manipulator and the sensors |
| 12V 5A Power Supply [23] | 1 | Power the DC Motors |
| 12V DC Motor 24] | 1 | Motor for the turntable |
| 5 V Relay 25 | 2 | Controls on/off of the power supplies |
| Arduino Mega2560 Rev3 26 | 1 | Micro-controller of the system |
| Emergency Stop Button 27 ] | 2 | Emergency stop for robotic manipulator; overall system |
| Encoder 24 | 1 | Velocity and position control for the turntable motor |
| L298N Motor Controller [28] | 1 | Direction control of the linear actuator |
| Laser Proximity Sensor [29] | 1 | Detect the holes of the aircraft rim |
| Lightbulb - Red 30 | 1 | Signals an error |
| Lightbulb - Yellow 30 | 1 | Signals loading/down time |
| Lightbulb - Green 30 | 1 | Signals ablation is occurring |
| Linear Actuator 31] | 1 | Control of vertical position of the robotic manipulator |
| MG996R Servo Motor 32 | 5 | Control of shoulder \& elbow of manipulator |
| MG90S Servo Motor 33] | 2 | Control of the wrist of the robotic manipulator |
| Resistor 34] | 4 | Used in the thermistor circuit |
| SN754410 H-Bridge 35] | 1 | Direction control of the turntable motor |
| Start/Stop Push Button 36] | 1 | Starts and stops the ablation process |
| Thermistor 37] | 4 | Monitors the temperature of the serov motors |
| TIP 120 Transistor 38] | 5 | controls switching of on/off of components |
| Ultraviolet Flashlight 39] | 1 | Used to simulate the laser |
| Ultrasonic Proximity Sensor 40. | 3 | Detect the rim, the alignment of the turntable, and position control of linear actuator |

Table 11.4: Color code for wiring

| Wire Color | Representation |
| :---: | :---: |
| Red | Voltage |
| Green | Ground |
| Black | Component connections |
| Yellow | Output |
| White | Communication with sensor |
| Blue | Input |



Figure 11.24: Wiring of the system:1st electrical cabinet


Figure 11.25: Wiring of the system:2nd electrical cabinet


Figure 11.26: OvERALL SYSTEM WIRING:BREADBOARD VIEW


Figure 11.27: Overall system wiring:Schematic view

### 11.1.6.1 Arduino Mega2560 and MATLAB

The Arduino Mega2560 was selected because of its ease of use. It is a open-source program therefore, there was a lot of support for when problems arose. Furthermore, MATLAB had specific packages for download that made it compatible with the Arduino. These packages allowed for all of the code to be written in MATLAB. Furthermore, the Arduino was not capable of handling all of the computations needed for the trajectory of the arm. Therefore, MATLAB completed all of the computations and then wrote to the Arduino. This reduced the strain on the Arduino allowing it to function faster. Furthermore, with MATLAB handling the bulk of the work, more components could now be controlled with the Arduino. All of the programs were written in MATLAB then with a serial connection MATLAB wrote to the Arduino. Also, MATLAB provided flexibility in the programming because multiple functions could be written and called during the cycle instead of only one overall program. This allowed the operator to change specific sections of the code with ease, without affecting the other sections. Figure 11.28 provides a visual of the micro-controller. Table 11.5 provides technical information about the Arduino Mega2560.


Figure 11.28: Arduino Mega2560 Rev3

Table 11.5: Technical specifications of the Arduino Mega2560 Rev3 |26|

| Component | $\underline{\text { Value }}$ |
| :---: | :---: |
| Microcontroller | ATmega2560 |
| Operating Voltage | 5 V |
| Input Voltage (recommended) | $7-12 \mathrm{~V}$ |
| Input Voltage (limit) | $6-20 \mathrm{~V}$ |
| Digital I/O Pins | 54 (of which 15 provide PWM output) |
| Analog Input Pins | 16 |
| DC Current per I/O Pin | 20 mA |
| DC Current for 3.3V Pin | 50 mA |
| Flash Memory | 256 KB of which 8 KB used by bootloader |
| SRAM | 8 KB |
| EEPROM | 4 KB |
| Clock Speed | 16 MHz |
| LED_BUILTIN | 13 |
| Length | 101.52 mm |
| Width | 53.3 mm |
| Weight | 37 g |

### 11.1.6.2 Motor Control

Speed and direction control were needed for the turntable. By controlling the speed, the cycle time for the ablation was easily modified. A H-bridge was used with the DC motor to easily modify the speed and direction of rotation. The speed was modified with the use of one of the pulse-width modulation pins. The direction was modified with the H -bridge. By setting one side of the motor "high" (five volts) and the other side "low" (zero volts) the motor would spin in a certain direction. By switching the high and low pins, the motor would spin in the other direction.


Figure 11.29: Turntable Motor 24


Figure 11.30: Control of a DC motor with a H-bridge

## Sample Code

\% connects to the arduino
a = arduino()
\% assigns pins to these variables
DIR_A = 'D23';
DIR_B = 'D25';
PWM = 'D10';
\% time to wait before changing diections
Wait_Time = 3;
\% tells the motor to spin clockwise
writeDigitalPin(a, DIR_A, 1)
writeDigitalPin(a, DIR_B, 0)
$\%$ controls the speed of the motor. Range of 0 to 5.5 being max speed writePWMVoltage(a, PWM, 5)
\% waits for the pre-determined time. the motor spins for tis duration

```
pause(Wait_Time)
% the motor is stopped
writePWMVoltage(a, PWM, 0)
% waits for 1 second
pause(1)
% motor spins in the counter-clockwise direction
writeDigitalPin(a, DIR_A, 0)
writeDigitalPin(a, DIR_B, 1)
writePWMVoltage(a, PWM, 3)
% waits for the pre-determined time. the motor spins for tis duration
pause(Wait_Time)
% motor is stopped. all pins are made low.
writeDigitalPin(a, DIR_A, 0)
writeDigitalPin(a, DIR_B, 0)
writePWMVoltage(a, PWM, 0)
```


### 11.1.6.3 Ultrasonic Proximity sensor

Three ultrasonic proximity sensors are used in the system. One to detect the presence of the rim, the second to ensure that the turntable has been slid in or out (depending on need), and the third to determine the position of the linear actuator. The HC-SR04 ultrasonic proximity sensor functions by sending out an ultrasonic wave through the trigger. The wave reaches an object and bounces off the object back to the sensor. The echo then records the returning wave and the time it took for the wave to return. By knowing the time it took for the wave to be sent and to return and by using the speed of sound for the velocity of the wave, the distance traveled is calculated.


Figure 11.31: HC-SR04:Ultrasonic Proximity sensor

(b) Schematic View

Figure 11.32: Wiring of the HC-SR04; Ultrasonic Proximity Sensor

## Sample code

\% connects to the arduino
a = arduino()
\% adds the ultrasonic package to the pins
\% defines pin D41 as the trigger

```
% defines pin D43 as the echo
sensor = addon(a, 'JRodrigoTech/HCSR04', 'D41', 'D43')
% while to to continuously read the distance
while 1
% distance read by the sensor
val = readDistance(sensor);
% displays the distance ot the command window
disp(['Current distance is ', num2str(val), ' meters'])
% waits for 0.1 seconds between each measurement
pause(0.1)
% end of the while loop
end
```


### 11.1.6.4 Laser Proximity Sensor

The laser proximity sensor (VL53L0X) behaves similarly to the ultrasonic sensor. Instead of using ultrasonic waves, it transmits as laser beam. The beam travels to and reflects off the object and comes back to the sensor. On the sensor there is a receiver that detects the reflected beam. The flight time is recorded and using the speed of light, the distance from the sensor to the object is calculated. The benefit of the laser sensor over the ultrasonic sensor is its precision. It can detect much smaller objects at further distance than the ultrasonic sensor. This made it the ideal sensor for detecting the holes of the aircraft rim.

The sensor is an I2C (Inter-Integrated Circuit) device. It uses the data line (SDA) and the clock line (SCL) to complete its measurements. This means that the Arduino and the laser sensor have a master-slave relationship, with the Arduino as the master. The Arduino has full control over the laser sensor and what it does. As there can only be one master-slave relationship per Arduino, only one laser proximity sensor can be used at a time.


Figure 11.33: VL53L0X: LaSER PRoximity SEnsor

## LASER PROXIMITY SENSOR


fritzing
(a) Breadboard View

fritzing
(b) Schematic View

Figure 11.34: Wiring of the VL53L0X; Laser Proximity Sensor

## Sample Code

\% connects to the arduino and adds the package for using the VL53LOX
a = arduino('COM8','Uno','Libraries','Adafruit/VL53L0X')
\% connects the laser sensor to the arduino
LASER_Sensor = addon(a,'Adafruit/VL53LOX')
\% turns the laser sensor on begin(LASER_Sensor)
\% reads a measurement from the sensor, in millimeters
mm = rangeMilliMeter(LASER_Sensor);

```
% outputs the measurement in millimeters to the command window
sprintf('Current distance is %.4f inches\n', mm)
```


### 11.1.6.5 Servo Motor

The robotic manipulator is controlled by seven servo motors; five MG996R and two MG90S. These servos are different from the DC motors because they do not continuously rotate. They have a range of zero to one-hundred eighty degrees. The user writes a position to the servo and the servo will move to that position and remain there until a new position is written or the power is turned off. Servo motors were ideal for the robotic manipulator because a certain position could be easily written and be held for as long as necessary. The user writes a position from 0 to 1 ( 0 is 0 degrees and 1 is 180 degrees). A simple line slope equation relates the 0 to 1 scale to 0 to 180 degrees.


Figure 11.35: SERVO MOTORS

fritzing $\qquad$
(a) Breadboard View
(b) Schematic View

Figure 11.36: Wiring of a servo motor

## Sample Code

\% connects to the arduino
a = arduino()
\% adds the servo library to the arduino
a = arduino('COM4', 'Uno', 'Libraries', 'Servo');
\% assigns the servo to pin D2
$\%$ The min and max pulse determine the range of the servo
$\mathrm{s}=$ servo (a, 'D4', 'MinPulseDuration', 700*10^-6, 'MaxPulseDuration', 2300*10^-6)
\% for loop to write the servo from 0 to 180 degrees by increments of 36 degrees.

```
for angle = 0:0.2:1
    % writes position to the servo
    writePosition(s, angle);
    % reads the current position of the servo
    current_pos = readPosition(s);
    % converts the position to degrees
    current_pos = current_pos*180;
    % displays the position in degrees in the command window
    fprintf('Current motor position is %d degrees\n', current_pos);
    % waits for 2 seconds between loops
    pause(2);
% ends the for loop
end
```


### 11.1.6.6 Thermistor

Thermistors are types of resistors whose resistance is dependent on temperature. Four of the servos had thermistors attached to them to monitor their temperature; the three controlling the shoulder and one for the elbow. The servos are rated for a maximum temperature of fifty-five degrees Celsius. Since, that is the insider temperature of the servo and the thermistor were placed on the outside, it was determined that the maximum temperature for the outside was thirty-five degrees Celsius. If the temperature of one of the servos reached or was higher than thirty-five degrees, the program warned the operator and initiated a system shut down. The system shut down was a quick as possible to try to ensure that the servo would not be damaged. The temperatures were read for every iteration of the trajectory.


Figure 11.37: Wiring of a Thermistor circuit

## Sample Code

\% connects to the arduino
a = arduino()
\% Resistor value in Ohms.
Resistor = 10000;
\% Room temperature in celcius
Room_Temp = 21;
\% Resistance at room temperature
Room_Res = 9900;

```
% B coefficient of the thermistor
B_coeff = 3435;
% number of readings to make
Num_Samples = 5;
% take Num_Samples amount of readings
samples = zeros(1, Num_Samples);
for i = 1:Num_Samples
    samples(i) = readVoltage(a, 'A8');
    pause(0.01)
end % ends the for loop for taking readings
average = sum(samples)/Num_Samples;
average = (average/5) * 1023;
disp(['Number of bits read is ', num2str(average)])
% Converts bits to resistance
average = (1023/average) - 1;
average = Resistor/average;
disp(['The resistance is ', num2str(average), ' ohms'])
steinhart = average/Room_Res;
steinhart = log(steinhart);
steinhart = 1/B_coeff * steinhart;
steinhart = steinhart + 1/(Room_Temp + 273.15);
steinhart = 1/steinhart;
steinhart = steinhart - 273.15;
% displays the temperature in the command window
disp(['The temperature is ', num2str(steinhart), ' degrees celuis'])
```


### 11.1.6.7 Lights

Three light-bulbs were used in the design, a red, a yellow, and a green, as seen in Fig. 11.38. The red light bulb represented an emergency or an error. It would turn on if the emergency stop were pressed or if there was a problem with the system, i.e. the servos overheating. The yellow light-bulb signified the loading and down time of the system. If the ablation was not occurring, then the yellow bulb would be on. The green light-bulb represented the run time. Whenever the rim was being ablated, the green bulb would be on. The wiring diagram of a light-bulb/LED is provided in Fig. 11.39 .


Figure 11.38: The lights used in the system


Figure 11.39: Wiring of a Light-bulb/LED

## Sample Code

\% connects to the arduino
a = arduino()
\% turns the light off
writeDigitalPin(a, 'D11', 0);
\% waits for 2 seconds
pause(2);
\%t turns the light on
writeDigitalPin(a, 'D11', 1);

### 11.1.6.8 Emergency stops

Two emergency stops were implemented in the system, Fig. 11.40. The first only affected the robotic manipulator. Before being implemented into the overall system, the manipulator was tested extensively by itself. To ensure the safety of the operator and the manipulator the emergency stop would halt the motion of the manipulator in its current position. This would allow the operator to quickly resolve the issue and insured that the manipulator from damaging itself or the items around it. Furthermore, by halting it in its current position, it reduced the probability of the servos overheating.

The second emergency stop was for the overall system. Not only would this stop the motion of the manipulator, but also the rotation of the turntable. It would first turn the turntable motor off and then cut off the power to the motor. Furthermore, power would be cut off from all of the sensors as-well. This protected the motor and sensors from and voltage or current overloads that would cause them to short-circuit. Whenever, the button was pressed, the program would execute the shut-down protocol. At the end of the protocol an error would be created that would halt the program. This ensured that MATLAB and the Arduino were no longer communicating and the components could no longer be controlled.


Figure 11.40: Emergency stops. Top: Robotic Manipulator. Bottom: Overall system


Figure 11.41: Wiring of a Light-bulb/LED

## Sample Code

\% connects to the arduino
a=arduino()
\% reads the value of the pin
$\%$ will be a 1 or a 0.
$\% 1=$ high $=5 \mathrm{~V}=$ button HAS NOT been pressed
$\% ~ 0=$ low $=0 V=$ button HAS been pressed
readDigitalPin(a, 'D46')
\% if statement to see if the button has been pressed
if readDigitalPin(a, 'D46') == 0

```
    % button has been pressed
    % creates an error message that is displayed to the command window
    msg = 'The emergency stop has been pressed';
    error(msg)
%ends the if statement
end
```


## 12 Engineering analysis

The engineering analysis section is broken up into multiple sections. The first section is the Theory, Pg. ??, that was used to complete the numerical simulations. The second section is the numerical analysis, Pg. ??, and the results of the numerical analysis. The third section, Pg. ??, provides the results of the computer simulations that were completed with COMSOL Multiphysics. The fourth section, the Experimental Analysis [Pg. ??] provides the analysis of the experimentation completed at IPG Photonics.

### 12.1 Theory:Laser Ablation

### 12.1.1 Electromagnetic Theory

### 12.1.1.1 Basic Laws of Electromagnetic Theory

To determine the equations necessary for the mathematical computation of laser ablation an understanding of the Electromagnetic Theory was necessary. The first equation used was the point charge equation;

$$
\begin{equation*}
q=\vec{F}_{E} \cdot \vec{E} \tag{1}
\end{equation*}
$$

The point charge equation can be altered so that the magnetic forces are taken into consideration.

$$
\begin{equation*}
\vec{F}_{M}=q \cdot \vec{v} \times \vec{B} \tag{2}
\end{equation*}
$$

Equation 1 and the Equation 2 can be combined to derive a vector equation for the general force;

$$
\begin{equation*}
\vec{F}=q \cdot \vec{E}+q \cdot \vec{v} \times \vec{B} \tag{3}
\end{equation*}
$$

In 1822, Michael Faraday discovered that changing a magnetic field generated a current. By thrusting a magnet into a coil, Faraday showed that there is a voltage, also known as the induced electromotive force of emf, across the terminals of the coils. The amplitude of the emf depends on how rapidly the magnet is moved. The induced emf depends on how readily the magnet is moved. When the $\vec{B}$-field is changing, the induced emf is proportional to the area, A, of the loop penetrated perpendicularly by the field. When the $\vec{B}$-field is constant, the induced emf is proportional to the rate-of-change of the perpendicular area penetrated. This all sugests that the emf depends on the rate-of-change of both the perpendicular area nd the magnetic field. Therefore, the flux od the magnetic field is defined as;

$$
\begin{equation*}
\phi_{M}=B_{\perp} A=B A_{\perp}=B A \cos \theta \tag{4}
\end{equation*}
$$

If the magnetic field, $B$, varies in space the flux of the magnetic field through an open area, A , bounded by the conducting loop is;

$$
\begin{equation*}
\phi_{M}=\iint_{A} \vec{B} \cdot d \vec{S} \tag{5}
\end{equation*}
$$

The induced electromagnetic field, emf Eq. 6, exists only as a result of the presence of an electric field taken around the closed curve C.

$$
\begin{equation*}
e m f=\oint_{C} \vec{E} \cdot d \vec{l} \tag{6}
\end{equation*}
$$

By equating Eq. 6 to Eq. 15 , the Induction Law, Eq. 7 is derived

$$
\begin{equation*}
\oint_{C} \vec{E} \cdot d \vec{l}=-\frac{d}{d t} \iint_{A} \vec{B} \cdot d \vec{S} \tag{7}
\end{equation*}
$$

A partial derivative with respect to $t$ is then taken of Eq. 7 because $\vec{B}$ is usually a function of the space variables. This expression, Eq. 8 indicates that a time-varying magnetic field will have an electric field associated with it.

$$
\begin{equation*}
\oint_{C} \vec{E} \cdot d \vec{l}=-\iint_{A} \frac{\partial \vec{B}}{\partial t} \cdot d \vec{S} \tag{8}
\end{equation*}
$$

For electromagnetic waves, Gauss's Electric Law must be taken into consideration. Gauss's Electric Law relates the flux of the electric field and the sources of the flux, which
is the charge. When there are no sources or sinks in the electric field within the region encompassed by the closed surface, the net flux through the surface equals zero.

$$
\begin{gather*}
\Phi_{E}=\oiint_{A} \vec{E} \cdot d \vec{S}  \tag{9}\\
\Phi_{E}=E 4 \pi r^{2}  \tag{10}\\
\Phi_{E}=\frac{q .}{\epsilon_{0}} \tag{11}
\end{gather*}
$$

Equation 11 represents the electric flux associated with a single point charge, q.

$$
\begin{equation*}
\Phi_{E}=\frac{1}{\epsilon_{0}} \sum_{i=1}^{\infty} q . \tag{12}
\end{equation*}
$$

Equation 12 represents the electric flux associated with all point charges, q. $\epsilon_{0}$ represents the electric permittivity of free space, which is $8.8542 \times 10^{-12} \mathrm{C}^{2} / \mathrm{Nm}^{2}$. The permittivity of material can be found with Eq. 13.

$$
\begin{equation*}
\epsilon=K_{E} \epsilon_{0} \tag{13}
\end{equation*}
$$

$\mathrm{K}_{E}$ is the dielectric constant.
The charge distribution is appoximated as being continiuous. then if the volume enclosed by A is V and the charge distribution has a density $\rho$, Gauss's Law, Eq. 9 becomes;

$$
\begin{equation*}
\oiint_{A} \vec{E} \cdot d \vec{S}=\frac{1}{\epsilon_{0}} \iiint_{V} \rho d V \tag{14}
\end{equation*}
$$

While Gauss's Magnetic Law must be taken into consideration, there is no known magnetic counterpart to the electric charge. No isolated magnetic pole have been found. The magnetic field, $\vec{B}$, does not diverge or converge toward some kind of magnetic charge. The magnetic fields can be described in terms of current distributions. Any closed surfaces in a region of magnetic fields would accordingly have an equal number of line $\vec{B}$ entering and emerging from it. Therefore, the flux of the magnetic field, $\Phi_{M}$ through a such a field is zero. This provides the magnetic equivalent of Gauss's Law.

$$
\begin{equation*}
\Phi_{M}=\oiint_{A} \vec{B} \cdot d \vec{S}=0 \tag{15}
\end{equation*}
$$

Another important law to take into consideration is Ampere's Law,. it relates a line integral of $\vec{B}$ tangent to a closed curve C. When the current has a nonuniform cross section, Ampere's Law is written in terms of the current density or current per unit area J;

$$
\begin{equation*}
\oint_{C} \vec{B} \cdot d \vec{l}=\mu_{0} \iint_{A} \vec{J} \cdot d \vec{S} \tag{16}
\end{equation*}
$$



Figure 12.1: Current density through an open area A 41

The open surface A is bounded by C Fig. 12.1. The variable $\mu_{0}$ is defined as the permeability of free space and it has a value of $4 \pi \times 10^{-7} \mathrm{~N} . \mathrm{s}^{2} / \mathrm{C}^{2}$. When the current is imbedded in a material medium, its permeability, Eq. 17 will areas in Eq. 16

$$
\begin{equation*}
\mu=K_{M} \mu_{0} \tag{17}
\end{equation*}
$$

However, Ampere's Law is not particular about the area used, provided it is bounded by the curve C. When a magnetic field is applied, Eq. 16 changes. For a magnetic field between two plates, the electric charge can be found by using the area, A, of each plate and the charge, Q, on it;

$$
\begin{equation*}
E=\frac{Q}{\epsilon A} \tag{18}
\end{equation*}
$$

As the charges varies, the electric field will change. By taking the derivative of Eq. 18 the rate of the change can be found;

$$
\begin{equation*}
\epsilon \frac{\partial E}{\partial t}=\frac{i}{A} \tag{19}
\end{equation*}
$$

Equation 19 as effectively a $\vec{E}$ current density. James Clark Maxwell hypothesized the existence of just such a relationship, which he called the displacement current density, as defined by;

$$
\begin{equation*}
\vec{J}_{D}=\epsilon \frac{\partial \vec{E}}{\partial t} \tag{20}
\end{equation*}
$$

Equation 20 is then applied to Eq. 16 to create a restatement of Ampere's Law, Eq. 21 was one of Maxwell's greatest contributions. it points out that even when $\vec{J}=0$, a timevarying $\vec{E}$-field will be accompanied by a $\vec{B}$-field.

$$
\begin{equation*}
\oint_{C} \vec{B} \cdot d \vec{l}=\mu \iint_{A}\left(\vec{J}+\epsilon \frac{\partial \vec{E}}{\partial t}\right) \cdot \vec{S} \tag{21}
\end{equation*}
$$

## Maxwell's Equations

The set of integral expressions given by Eq. 14, Eq. 8, Eq 15, and Eq. 21 have come to be known as Maxwell's Equations. Maxwell's Equations can be written in vector form. The vector form equations, in Cartesian coordinates are as follows;

$$
\begin{align*}
& \frac{\partial \vec{E}_{z}}{\partial y}-\frac{\partial \vec{E}_{y}}{\partial z}=-\frac{\partial \vec{B}_{x}}{\partial t}  \tag{22}\\
& \frac{\partial \vec{E}_{x}}{\partial z}-\frac{\partial \vec{E}_{z}}{\partial x}=-\frac{\partial \vec{B}_{y}}{\partial t}  \tag{23}\\
& \frac{\partial \vec{E}_{y}}{\partial x}-\frac{\partial \vec{E}_{x}}{\partial y}=-\frac{\partial \vec{B}_{z}}{\partial t}  \tag{24}\\
& \frac{\partial \vec{B}_{z}}{\partial y}-\frac{\partial \vec{B}_{y}}{\partial z}=\mu_{0} \epsilon_{0} \frac{\partial \vec{E}_{x}}{\partial t}  \tag{25}\\
& \frac{\partial \vec{B}_{x}}{\partial z}-\frac{\partial \vec{B}_{z}}{\partial x}=\mu_{0} \epsilon_{0} \frac{\partial \vec{E}_{y}}{\partial t} \tag{26}
\end{align*}
$$

$$
\begin{equation*}
\frac{\partial \vec{B}_{y}}{\partial x}-\frac{\partial \vec{B}_{x}}{\partial y}=\mu_{0} \epsilon_{0} \frac{\partial \vec{E}_{z}}{\partial t} \tag{27}
\end{equation*}
$$

These six equations can be combines to form two equations. One equation is for the magnetic field and the other for the electric field.

$$
\begin{align*}
& \frac{\partial \vec{B}_{x}}{\partial x}+\frac{\partial \vec{B}_{y}}{\partial y}+\frac{\partial \vec{B}_{z}}{\partial z}=0  \tag{28}\\
& \frac{\partial \vec{E}_{x}}{\partial x}+\frac{\partial \vec{E}_{y}}{\partial y}+\frac{\partial \vec{E}_{z}}{\partial z}=0 \tag{29}
\end{align*}
$$

### 12.1.1.2 Electromagnetic Waves

Maxwell's Equation for free space can be manipulated in the form of two extremely concise vector expressions;

$$
\begin{align*}
& \nabla^{2} E=\epsilon_{0} \mu_{0} \frac{\delta^{2} E}{\delta^{2} t^{2}}  \tag{30}\\
& \nabla^{2} B=\epsilon_{0} \mu_{0} \frac{\delta^{2} B}{\delta^{2} t^{2}} \tag{31}
\end{align*}
$$

In these equations, $\mu_{0}$ is the permeability of free space, $\mu_{0}=4 \pi \times 106-7 \mathrm{Ns}^{2} / \mathrm{C}^{2}$, and $\nabla$ represent the laplacian. The laplacian operates on each of the components of the vectors $\vec{E}$ and $\vec{B}$, so that the two vector equations actually represent the six scaler equations, in Cartesian coordinates below;

$$
\begin{align*}
& \frac{\partial^{2} E_{x}}{\partial x^{2}}+\frac{\partial^{2} E_{x}}{\partial y^{2}}+\frac{\partial^{2} E_{x}}{\partial z^{2}}=\epsilon_{0} \mu_{0} \frac{\partial^{2} E_{x}}{\partial t^{2}}  \tag{32}\\
& \frac{\partial^{2} E_{y}}{\partial x^{2}}+\frac{\partial^{2} E_{y}}{\partial y^{2}}+\frac{\partial^{2} E_{y}}{\partial z^{2}}=\epsilon_{0} \mu_{0} \frac{\partial^{2} E_{y}}{\partial t^{2}}  \tag{33}\\
& \frac{\partial^{2} E_{z}}{\partial x^{2}}+\frac{\partial^{2} E_{z}}{\partial y^{2}}+\frac{\partial^{2} E_{z}}{\partial z^{2}}=\epsilon_{0} \mu_{0} \frac{\partial^{2} E_{z}}{\partial t^{2}}  \tag{34}\\
& \frac{\partial^{2} B_{x}}{\partial x^{2}}+\frac{\partial^{2} B_{x}}{\partial y^{2}}+\frac{\partial^{2} B_{x}}{\partial z^{2}}=\epsilon_{0} \mu_{0} \frac{\partial^{2} B_{x}}{\partial t^{2}}  \tag{35}\\
& \frac{\partial^{2} B_{y}}{\partial x^{2}}+\frac{\partial^{2} B_{y}}{\partial y^{2}}+\frac{\partial^{2} B_{y}}{\partial z^{2}}=\epsilon_{0} \mu_{0} \frac{\partial^{2} B_{y}}{\partial t^{2}} \tag{36}
\end{align*}
$$

$$
\begin{equation*}
\frac{\partial^{2} B_{z}}{\partial x^{2}}+\frac{\partial^{2} B_{z}}{\partial y^{2}}+\frac{\partial^{2} B_{z}}{\partial z^{2}}=\epsilon_{0} \mu_{0} \frac{\partial^{2} B_{z}}{\partial t^{2}} \tag{37}
\end{equation*}
$$

## Transverse Waves

The electric field intensity in a solution of the Maxwell vector equations, where $\vec{E}$ is constant over an infinite set of planes perpendicular to the x-axis. Therefore, it is only a function of $x$ and $t$;

$$
\begin{equation*}
\vec{E}=E(x, t) \tag{38}
\end{equation*}
$$

Since $\vec{E}$ is not a function of y or z, Eq. 29 can be reduced to;

$$
\begin{equation*}
\frac{\partial \vec{E}_{x}}{\partial x}=0 \tag{39}
\end{equation*}
$$

If $\vec{E}_{x}$ is not zero, Eq. 39 does not vary with x. Furthermore, at any given time $\vec{E}_{x}$ is constant for all values of x. For a wave with $\vec{E}_{x}=0$, the electromagnetic wave has no electric field component in the direction of propagation. Also, the $\vec{E}_{x}$-Field associated with the plane wave is then exclusively transverse. The fact that the Electric field is transverse means that in order to completely specify the wave, the moment-by-moment direction of $\vec{E}$ must be specified. Without any loss of generality, the plane or linearly polarized waves for which the direction of the vibrating $\vec{E}$ is fixed. Therefore, the coordinate axis is oriented so that the electric field is parallel to the y-axis, whereupon;

$$
\begin{equation*}
\vec{E}=\hat{j} \vec{E}_{y}(x, t) \tag{40}
\end{equation*}
$$

Therefore;

$$
\begin{equation*}
\frac{\partial E_{y}}{\partial x}=-\frac{\partial B_{z}}{\partial t} \tag{41}
\end{equation*}
$$

$B_{x}$ and $B_{y}$ are constant therefore, the time dependent B-field can only have a component in the z -direction.

In space, the plane electromagnetic wave is transverse. It is needed to specify the form of disturbance other than calling it a plane wave. Harmonic functions are of particular interest because any waveform can be expressed in terms of sinusoidal waves Fourier techniques. Eq. 40 as;

$$
\begin{equation*}
E_{y}(x, t)=E_{0} y \cos [\omega(t-x / c)+\epsilon] \tag{42}
\end{equation*}
$$

Where c is the speed of propagation

The associated magnetic flux density can be found by;

$$
\begin{equation*}
B_{z}=-\int \frac{\partial E_{y}}{\partial x} d t \tag{43}
\end{equation*}
$$

Equation 42 and Equation 43 can be combined to obtain;

$$
\begin{gather*}
B_{z}=-\frac{E_{0 y} \omega}{c} \int \sin [\omega(t-x / c+\epsilon)] d t  \tag{44}\\
B_{z}=\frac{1}{c} E_{0 y} \cos [\omega(t-x / c+\epsilon)] \tag{45}
\end{gather*}
$$

The comparison of Eq. 42 and Eq. 45 shows that;

$$
\begin{equation*}
E_{y}=c B_{z} \tag{46}
\end{equation*}
$$

### 12.1.1.3 Energy and Momentum

## The Poynting Vector

Any electromagnetic wave exists within some region of space and it is therefore natural to consider the radiant energy per unit volume or energy density, $u$. It is assumed that the electric field itself can store energy. The classical field is continuous therefore, its energy is continuous.

The energy density of the $\vec{E}$-Field can be computed with;

$$
\begin{equation*}
u_{E}=\frac{\epsilon_{0}}{2} E^{2} \tag{47}
\end{equation*}
$$

The energy density of the $\vec{B}$-Field can be computed with;

$$
\begin{equation*}
u_{B}=\frac{1}{2 \mu_{0}} B^{2} \tag{48}
\end{equation*}
$$

The relationship $\mathrm{E}=\mathrm{cB}$ was derived specifically for plane waves; nonetheless, it is general in its applicability. Using;

$$
\begin{equation*}
c=\frac{1}{\sqrt{\epsilon_{0} \mu_{0}}} \tag{49}
\end{equation*}
$$

> It follows that;

$$
\begin{equation*}
u_{E}=u_{B} \tag{50}
\end{equation*}
$$

The energy is shared equally between the constituent electric and magnetic fields as it streams through space in the form of an electromagnetic wave. Therefore;

$$
\begin{gather*}
u=u_{E}+u_{B}  \tag{51}\\
u=\epsilon_{0} E^{2}=\frac{1}{u_{0}} B^{2} \tag{52}
\end{gather*}
$$

To represent the flow of electromagnetic energy associated with a traveling wave, let S $\left(\mathrm{W} / m^{2}\right)$ symbolize the transport of energy per unit time (the power) across a unit area.During a very small interval of time, $\Delta \mathrm{t}$, only the energy contained in the cylindrical volume $\mathrm{u}(\mathrm{c} \Delta \mathrm{t}$ A), will cross A, thus;

$$
\begin{gather*}
S=\frac{u c \Delta t A}{\delta t A}=u c  \tag{53}\\
S=\frac{1}{\mu_{0}} E B \tag{54}
\end{gather*}
$$



Figure 12.2: The Flow of Electromagnetic Energy 41

For isotropic media, the energy flows in the direction of the propagation of the wave. Therefore, the corresponding $\vec{S}$ is then;

$$
\begin{align*}
& \vec{S}=\frac{1}{\mu_{0}} \vec{E} \times \vec{B}  \tag{55}\\
& \vec{S}=c^{2} \epsilon_{0} \vec{E} \times \vec{B} \tag{56}
\end{align*}
$$

The magnitude of the $\vec{S}$ is the power per unit area crossing a surface whose normal is parallel to the $\vec{S}$. This is called the Poynting vector. These considerations can be appied to the case of a harmonic, linearly polarized plane wave traveling through free in the direction of $\vec{k}$

$$
\begin{align*}
\vec{E} & =\vec{E}_{0} \cos (\vec{k} \cdot \vec{r}-\omega t)  \tag{57}\\
\vec{B} & =\vec{B}_{0} \cos (\vec{k} \cdot \vec{r}-\omega t) \tag{58}
\end{align*}
$$

Applying Eq. 56 to Eq. 57 and Eq. 58 , the instantaneous flow of energy per unit area per unit time can be calculated, Eq. refS instantaneous

$$
\begin{equation*}
\vec{S}=c^{2} \epsilon_{0} \vec{E}_{0} \times \vec{B}_{0} \cos ^{2}(\vec{k} \cdot \vec{r}-\omega t) \tag{59}
\end{equation*}
$$

The $\vec{E} \times \vec{B}$ cycles from maxima to minima. At optical frequencies $\left(=10^{1} 5 \mathrm{~Hz}\right), \vec{S}$ is an extremely rapidly varying function of time. It is twice as rapid as the fields since the $\cos ^{2}$ has the double the frequency of cosine. Therefore, its instantaneous value would be an impractical quantity to measure directly. Therefore, an averaging procedure is employed. The radiant energy is absorbed during a finite interval of time. ADD Eq.3.42..... The average cosine is itself a cosine, oscillating with the frequency but having a sine-function amplitude that drops off from its initial value of 1.0 very rapidly. Since the sine at $u=0$ and $\mathrm{u}=\omega \mathrm{T} / 2=\pi$, it follows that the cosine of $\omega \mathrm{t}$ averages to zero over any whole number of periods, as does $\sin (\omega t)$.

## Irradiance

Irradiance is defined as the amount of light illuminating a surface. Irradiance is denoted by I and it is the average energy per unit area per time. Any kind of light-level detector has an entrance window that admits radiant energy through some fixed area, A. The dependence on the size of that particular window is removed by dividing the total energy received by A. Since the power arriving cannot be measured instantaneously, the detector must integrate the energy flux of some period of time, T. The time-averaged value ( $\mathrm{T}>\tau$ ) of the magnitude of the Poynting vector, symbolized by $\vec{S}_{T}$, is a measure of I.

In this specific case of harmonic fields and Eq. 59

$$
\begin{equation*}
S_{T}=I=\frac{c^{2} \epsilon_{0}}{2} E_{0}^{2} \tag{60}
\end{equation*}
$$

The irradiance is proportional to the square of the amplitude of the electric field.
The $\vec{E}$ is considerably more effective at exerting forces and doing work on charges than the $\vec{B}$. Therefore, the $\vec{E}$ is referred to as the optical field. EQ. 4.46. The time rate of flow of radiant energy is the optical power, P , or radiant flux, usually in units of Watts, W. If the radiant flux is incident on or exiting form a surface by the area of the surface, the radiant flux density $\left(\mathrm{W} / \mathrm{m}^{2}\right)$ is obtained. The irradiance is a measure of the concentration of power.

## Dispersion

Dispersion corresponds to the phenomenon whereby the index of refraction of a medium is frequency dependent. All material media is dispersive, only a vacuum is non-dispersive. Maxwell's Theory treats substantial matter as continuous, representing its electric and magnetic responses to the applied $\vec{E}$ and $\vec{B}$ fields in terms of the constant, $\epsilon$ and $\mu$.

When a dielectric is subjected to an applied electric field, the interval charge distribution is distorted. This corresponds to the generation of electric dipole moments, which in turn
contribute to the total internal field. The external field separates positive and negative charges in the medium, and these charges then contribute an additional field component. The resultant dipole moment per unit volume is called the electric polarization, $\vec{P}$. For most materials, the $\vec{P}$ and $\vec{E}$ are proportional and can be related by;

$$
\begin{equation*}
\left(\epsilon-\epsilon_{0}\right) \vec{E}=\vec{P} \tag{61}
\end{equation*}
$$

The dipole moment is equal to the charge $\mathrm{q}_{e}$ multiplied by its displacement and if there are N contributing electrons per unit volume, the electric polarization, or density of the dipole moments is;

$$
\begin{equation*}
P=q_{e} x N \tag{62}
\end{equation*}
$$

Hence;

$$
\begin{equation*}
P=\frac{q^{2}{ }_{e} N E / m_{e}}{\left(\omega^{2}{ }_{0}-\omega^{2}\right)} \tag{63}
\end{equation*}
$$

and;

$$
\begin{equation*}
\epsilon=\epsilon_{0}+\frac{P(t)}{E(t)}=\epsilon_{0}+\frac{q^{2}{ }_{e} N E / m_{e}}{\left(\omega^{2}{ }_{0}-\omega^{2}\right)} \tag{64}
\end{equation*}
$$

Since $\mathrm{n}^{2}=\mathrm{K}_{E}=\epsilon / \epsilon_{0}$, an expression for n as a function of $\omega$ can be derived. This expression is known as a dispersion equation;

$$
\begin{equation*}
n^{2}(\omega)=1+\frac{N q_{e}^{2}}{\epsilon_{0} m_{e}} \frac{1}{\left(\omega^{2}{ }_{0}-\omega^{2}\right)} \tag{65}
\end{equation*}
$$

### 12.1.2 The Propagation of Light

### 12.1.2.1 Rayleigh Scattering

When light comes into contact with molecules, the molecules cannot be raised into a higher state of energy by absorbing a quantum of light. Instead each molecule behaves as a little oscillator whose electron cloud can be driven into a ground-state vibration by an incoming photon. Immediately upon being set vibrating, the molecule initiates the re-emission of light. A Photon is absorbed and without delay another photon of the same frequency is emitted. The light is elastically scattered and these molecules are randomly oriented and the photons scatter out every direction. Even when the light is dim, the number of photons is immense. It looks like as if the molecules are scattering little classical spherical wavelets. The energy streams out in every which way. The process is still weak and the gas is tenuous therefore, the beam is very little attenuated unless it passes through a tremendous volume
of air.

The amplitudes of these ground-state vibrations, and therefore the amplitudes of scattered light increase with frequency because all the molecules have electronic resonances in the UV. The closer he driving frequency is to a resonance, the more vigorously the oscillator responds. For example, violet light is strongly scattered laterally out of the beam. The beam that traverses the gas will thus be richer in the red end of the spectrum while, the light scattered out will be richer in blue.

## Scattering and Interference

The denser the substance through which light advances, the less the lateral scattering. Interference is the superposition of two or more waves producing a resultant disturbance that is the sum of the overlapping wave contributions. As can be seen in Fig. 12.3, two harmonic wves of the same frequency traveling in the same direction are precisely in-phase, the resultant is the sum of the two wave-height values. This is defined as constructive interference. When the wave phase reaches 180deg, the waves cancel each other out. This is defined as destructive interference.


Figure 12.3: Superposition of two sinusoids 41]

The theory of Rayleigh Scattering has independent molecules randomly arrayed in space
so that the phases of the secondary wavelets scattered off to the side have no particular relationship to one another and there is no sustained pattern of interference. This situation occurs when the separation between the molecular scatterers is roughly a wavelength or more, as it is in a tenuous gas. In Fig. 12.4, a parallel beam of light is incident from the left. This primary light field illuminates a group of widely spaced molecules. A continuing progression of primary wavefronts sweep over and successively energize and re-energize each molecule, which, in turn, scatters light in all direction and in particular out to some lateral point $p$. Random, widely spaced scatterers driven by an incident primary wave emit wavelets that are essentially independent of one another in all directions except forward; Laterally scattered light, impeded by interference, streams out of the beam.


Figure 12.4: The Scattering of Light 41
a.) The scattering of light from a widely spaced distribution of molecules: b.) The wavelets arriving at a lateral Point have a jumble of different phases and tend not to interfere in a sustained constructive fashion: c.) That can probably be appreciated most easily using phasors. As they arrive at P the phasors have large phase angle differences with re-
spect to each other. When added tip-to-tail they therefore tend to spiral around keeping the resultant phasor quite small.

In Fig. 12.5 the the forward point, P , for all of the different paths taken by the light are approximately the same length. This is because scattering alters the various path lengths by very little. The scattered wavelets arrive at P more or less in-phase and essentially interfere constructively Because of the scattered wavelengths introduced by the beam itself, all the scattered wavelengths add constructively with each other in the forward direction.


Figure 12.5: Scattering in the Forward Direction 41

## Transmission and the Index of Refraction

The transmission of light through a homogeneous medium is an ongoing repetitive process of scattering and re-scattering.Each such event introduces a phase shift into the light field which ultimately shows up as a shift in the apparent phase velocity of the transmitted beam from it nominal value of $c$. The corresponds to an index of refraction for the medium $(\mathrm{n}=\mathrm{c} / \mathrm{v})$ which is other than one, even though photons exist only at a speed c .

In Fig. 12.6 the scattered wavelets all combine in-phase in the forward direction to form what is best called as the secondary wave. It is anticipated that the secondary wave will combine with what is left of the primary wave to yield the only observed disturbance within the medium. This will namely be the transmitted wave. Both the primary and secondary electromagnetic waves propagate through the inter-atomic void with the speed of c. Yet the medium can certainly possess an index of refraction other than 1 . The refracted wave may appear to have a phase velocity than, equal to, or even greater than c. The key to this apparent contradiction resides in the phase relationship between the secondary and primary waves. The index of refraction arises when the absorption and emission process advances or retards the phases of the scattered photons, even as they travel at speed c.


Figure 12.6: Scattered wavelets 41

### 12.1.2.2 Reflection

When a beam of light impinges on the surface of a transparent material, such as a sheet of glass, the wave "sees" a vast array of closely spaced atoms that will scatter it. This is because the wave could be 500 nm in length, whereas, the atoms and their separations ( 0.2 nm ) are thousands of times smaller. In the case of transmission through a dense medium, the
scattered wavelets cancel each other in all but the forward direction, and just the ongoing beam is sustained. This can only occur if there are no discontinuities. This is not the case at an interface between two different transparent media (such as air and glass), which is jolting discontinuity. When a beam strikes such an interface, some light is always scattered backward. This phenomenon is called reflection. If the transition between the two media is gradual (the index of refraction changes from one medium to another over a distance of a wavelength or more) there will be very little reflection. On the other hand, a transition from one medium to another over a distance of $1 / 4$ wavelength or less behaves very much like a totally discontinuous change.

## Internal and External Reflection

Imagine that light is traveling across a large homogeneous block of glass.Now suppose that the block is sheared in half, perpendicular to the beam. The segments are then separated, exposing the smooth flat surface. Just before the cut was made, there was no lightwave traveling to the left inside the glass (the beam only advances). Now there must be a wave moving to the left, reflected from the surface off the surface of the right-hand block. For an air-glass interface, about 4 percent of the energy of an incident beam falling perpendicular IN air TO glass will be reflected straight back out by this layer of unpaired scatterers. This is true whether the glass is 1.0 mm or 1.0 m thick.


Figure 12.7: A Light-beam propagating though a dense homogeneous MEDIUM 41]

As can be seen in part b of Fig. 12.7, when the block of glass is cut and separated, the light is reflected backward at the two new interfaces. Beam-I is externally reflected and Beam-II is internally reflected. Beam-I reflects off the right-hand block because light was initially traveling from a less to a more optically dense medium, this is called external reflection. In other words, the index of the incident medium $\left(\mathrm{n}_{i}\right)$ is less than the index of the transmitting medium $\left(\mathrm{n}_{t}\right)$. Since the same thing happens to the unpaired layer on the section that was moved to the left, it too reflects backwards. With the beam perpendicularly in glass to air, 4 percent must again be reflected. This process is called internal reflection because $\mathrm{n}_{i}$ is greater than $\mathrm{n}_{t}$.

## The Law of Reflection

Figure 12.8 shows a beam composed of plane wavefronts impinging $t$ some angle on the smooth, flat surface of an optically dense medium. It is assumed that the surrounding environment is a vacuum. As the wavefront descends, it energizes and re-energizes one
scatterer after another, each of which radiates a stream of photons that can be regarded as a hemispherical wavelet in the incident medium. This is because the wavelength is so much greater than the separation between the molecules, the wavelets emitted back into the incident medium advance together and add constructively in only one direction, and there is one well-defined reflected beam. That would not be the true if the incident radiation was a short-wavelength. And it would not be true if the scatterers were far apart compared to $\lambda$, as they are for diffraction grating, in which case there would be several reflected beams. The direction of the reflected beam is determined by the constant phase difference between the atomic scatterers. That in turn is determined by the angle made by the incident wave and the surface of the so-called angle-of-incidence.


Figure 12.8: A Beam of Plane Waves 41]


Figure 12.9: A plane wave sweeps in stimulating atoms across the INTERFACE 41]

As seen in Fig. 12.9, when the plane sweeps across the interface, the atoms radiate and re-radiate, thereby giving rise to both the reflected and transmitted waves.


Figure 12.10: The reflection of a wave as the result of scattering 41]

In Fig. 12.11, the line AB lies along an incoming wavefront, while CD lies on an outgoing wavefront. In effect, AB transforms on reflection into CD. From what Fig. 12.10 shows, the wavelets jsut being emiited from A will arrive at $C$ in-phase with the wavelet just being emitted from D . This will be the case as long as $\overline{A C}$ and $\overline{B D}$ are equal. In other words, if all the wavelets emitted from all the surface scatterers are to overlap in-phase and form a single reflected plane wave, it must be that $\overline{A C}=\overline{B D}$. Then since the two triangles have a common hypotenuse;

$$
\begin{equation*}
\frac{\sin \left(\theta_{i}\right)}{\overline{B D}}=\frac{\sin \left(\theta_{r}\right)}{\overline{A C}} \tag{66}
\end{equation*}
$$



Figure 12.11: The plane waves enter form the left and are reflected off TO THE RIGHT 41]

All waves travel in the incident medium with the same speed $\mathrm{v}_{i}$. It follows that in the time ( $\Delta \mathrm{t})$ it takes for point B on the wavefront to reach point D on the surface, the wavelet emitted from A reaches point C. In other words;

$$
\begin{equation*}
\overline{B D}=\delta t=\overline{A C} \tag{67}
\end{equation*}
$$

Therefore, Eq. 66 can be reduced to;

$$
\begin{equation*}
\sin \left(\theta_{i}\right)=\sin \left(\theta_{r}\right) \tag{68}
\end{equation*}
$$

Which means that;

$$
\begin{equation*}
\theta_{i}=\theta_{r} \tag{69}
\end{equation*}
$$

From Eq. 69 it is now known that the angle-of-incidence is equal to the angle-of-reflection. Equation 69 is the first part of the Law of Reflection.

## Rays

A ray is a line drawn in space corresponding to the direction of flow of radiant energy. It is a mathematical construct and not a physical entity. In a medium that is uniform (homogeneous), rays are straight. If the medium behaves in the same manner in every direction (isotropic), the rays are perpendicular to the wave-fronts. Thus a point source emitting spherical waves, the rays, which are perpendicular to them, point radially outward from the source. The second part of the Law of Reflection, maintains that the incident rays, the perpendicular to the surface, and the reflected rays all lie in a plane called the plane-of-incidence, as can be seen in Fig. 12.12.


Figure 12.12: The Plane plane of incidence 41

Figure 12.13a shows a beam of light incident upon a reflecting surface that is smooth. In that case, the light re-emitted by millions upon millions of atoms will combine to form a single well-defined beam in a process called specular reflection. Provided that the ridges and valleys are small compared to $\lambda$, the scattered wavelets will still arrive more or less in-phase when $\theta_{i}=\theta_{r}$. Figure 12.13 b shows a beam of light incident upon a reflecting surface that is rough therefore, a lot more absorption occurs.


Figure 12.13: A.) Specular Reflection b.) Diffuse Reflection 41

### 12.1.2.3 Refraction

Figure 12.8 shows a beam of light impinging o an interface at some angle $\theta_{i}=/ \theta_{o}$. The interface corresponds to a major inhomogeneity, and the atoms that compose it scatter light both backward, as the reflected beam, and forward, as the transmitted beam. The fact that the incident rays are bent, is called refraction. The transmitted wave usually propagates with an effective speed $\mathrm{v}_{t}<\mathrm{c}$. It is essentially as if the atoms at the interface scattered "slow wavelets" into the glass that combine back to this imagery when we talk about Huygens's Principle. Since the cooperative phenomenon the incident electromagnetic wave, the transmitted wavefronts are refracted, displaced (turn with respect to the incident wavefronts), and the beam bends.

## The Law of Refraction

Figure 12.14 depicts several wavefronts, all shown at a single instant in time. Each wavefront is a surface of constant phase, and, to the degree that the phase of the net field is retarded by the transmitting medium, each wavefront is held back, as it were. The wavefronts "bend" as they cross the boundary because of the speed change. Alternatively, we can envision Fig. 12.14 as a multiple-exposure picture of a single wavefront showing it after successive equal intervals of time. Notice that in the time $\delta \mathrm{t}$, which it takes for point B on a wavefront (traveling at speed $\mathrm{v}_{i}$ ) to reach point D , the transmitted portion of that same wavefront (traveling at speed $\mathrm{v}_{t}$ ) has reached point E. If the glass ( $\mathrm{n}_{t}=1.5$ ) is immersed in an incident medium that is vacuum ( $\mathrm{n}_{i}=1$ ) or air ( $\mathrm{n}_{i}=1.0003$ ) or anything else where $n_{t}>n_{i}, v_{t}<v_{i}$ and $\mathrm{AE}<\mathrm{BD}$, the wavefront bends.


Figure 12.14: The refraction of waves 41

The refracted wavefront extends from E to D , making an angle with the interface $\theta_{t}$. As before, the two triangles $\overline{A B D}$ and $\overline{A E D}$ in Fig. 12.14 share a common hypotenuse $(\overline{A D})$ and so;

$$
\begin{equation*}
\frac{\sin \left(\theta_{i}\right)}{\overline{B D}}=\frac{\theta_{r}}{\overline{A E}} \tag{70}
\end{equation*}
$$

Where $\overline{B D}=v_{i} \Delta \operatorname{tand} \overline{A E}=v_{t} \Delta t$. Hence,

$$
\begin{equation*}
\frac{\sin \left(\theta_{i}\right)}{v_{i}}=\frac{\theta_{r}}{v_{t}} \tag{71}
\end{equation*}
$$

Multiply both sides by c , and since $n_{i}=c / v_{i}$ and $n_{t}=c / v_{t}$;

$$
\begin{equation*}
n_{i} \sin \left(\theta_{i}\right)=n_{t} \sin \left(\theta_{t}\right) \tag{72}
\end{equation*}
$$

Equation 72 is the first portion of the Law of Refraction and is known as Snell's Law.


Figure 12.15: Descartes's arrangement for deriving the Law of Refraction 41]

What was found through observation was that the bending of the rays could be quantified via the ratio of $x_{i}$ to x , which is constant for all $\theta_{i}$. This constant is called the index of refraction, Eq. 73

$$
\begin{equation*}
\frac{x_{i}}{x_{t}}=n_{t} \tag{73}
\end{equation*}
$$

Along with Eq. 72, there goes an understanding that the incident, reflected, and refracted rays all lie in the plane-of-incidence. In other words, the respective unit propagation vectors $\overrightarrow{k_{i}}, \overrightarrow{k_{r}}$, and $\overrightarrow{k_{t}}$ are coplanar. When $n_{i}<n_{t}$ ( when the light is initially traveling within the lower-index medium), it follows from Snell's Law that $\sin \left(\theta_{i}\right)>\sin \left(\theta_{t}\right)$ and since the same function is everywhere positive between 0 degrees and 90 degrees, then $\theta_{i}>\theta_{t}$. Rather than going straight through, the ray entering a higher-index medium bends toward the normal, Fig. 12.16a. The reverse is also true for Fig. 12.16b. On entering a medium having a lower index, the ray, rather than going straight through, will bend away from the normal. This implies that the rays will transverse the same path going either way, into or out of either medium. The arrows can be reserved and the resulting picture is still true.


Figure 12.16: The bending of rays at an interface 41]
Figure 12.16a shows that when a beam of light enters a more optically dense medium, one with a greater index of refraction $\left(n_{i}<n_{t}\right)$, it bends towards the perpendicular. Figure 12.16 shows that when a beam goes from a more dense to a less dense medium $\left(n_{i}>n_{t}\right)$, it bends away form the perpendicular.

Snell's Law, Eq. 72, can be re-written in the form;

$$
\begin{equation*}
\frac{\sin \left(\theta_{i}\right)}{\sin \left(\theta_{t}\right)}=n_{t i} \tag{74}
\end{equation*}
$$

Where;

$$
\begin{equation*}
n_{t i}=\frac{n_{t}}{n_{i}} \tag{75}
\end{equation*}
$$

Equation 75 is known as the relative index of refraction of the two media.
Let $\hat{u}_{n}$ be a unit vector normal to the interface pointing in the direction from the incident to the transmitting medium. The complete statement of the Law of Refraction can be written vectorially as;

$$
\begin{equation*}
n_{i}\left(\hat{k}_{i} \times \hat{u}_{n}\right)=n_{t}\left(\hat{k}_{t} \times \hat{u}_{n}\right) \tag{76}
\end{equation*}
$$

or alternatively as;

$$
\begin{equation*}
n_{i} \hat{k}_{t}-n_{i} \hat{k}_{i}=\left(n_{t} \cos \left(\theta_{t}\right)-n_{i} \cos \left(\theta_{i}\right)\right) \hat{u}_{n} \tag{77}
\end{equation*}
$$

Figure 12.14 illustrates the three important changes that occur in the beam transversing the interface. First, it changes direction because the leading portion of the wavefront in the glass slows down, the part still in the air advances more rapidly, sweeping past and bending the wave toward the normal. Second, the beam in the glass has a broader cross section than the beam in the air therefore, the transmitted energy is spread thinner. Third, the wavelength decreases because the frequency is unchanged while the speed decreases;

$$
\begin{gather*}
\lambda=\frac{\nu}{v}=\frac{c}{n v}  \tag{78}\\
\lambda=\frac{\lambda_{0}}{n} \tag{79}
\end{gather*}
$$

This latter notion suggests that the color aspect of light is better thought as associated with its frequency (or energy, $\xi=\mathrm{h} \nu$ ) than its wavelength, since the wavelength changes with the medium through which the light moves.

### 12.1.2.4 The Electromagnetic Approach

Electromagnetic Theory speaks about the incident, reflected, and transmitted radiant flux densities ( $\mathrm{I}_{i}, \mathrm{I}_{r} \mathrm{I}_{t}$, respectively). Suppose that the incident monochromatic light-wave is planar, so that it has the form;

$$
\begin{gather*}
\vec{E}_{i}=\vec{E}_{0 i} \exp \left[i\left(\vec{k}_{i} \cdot \vec{r}-\omega_{i} t\right)\right]  \tag{80}\\
\text { or, more simply; } \\
\left.\vec{E}_{i}=\vec{E}_{0 i} \cos \left(\vec{k}_{i} \cdot \vec{r}-\omega_{i} t\right)\right] \tag{81}
\end{gather*}
$$

It is assumed that $\vec{E}_{0 i}$ is constant in time. Therefore, the wave is linearly or plane polarized. Note that just at the origin in time, $\mathrm{t}=0$, is arbitrary, so too is the origin O in space, where $\vec{r}=0$. Thus, making no assumptions about their directions, wavelengths, phases, or amplitudes, we can write the reflected and transmitted waves as;

$$
\begin{equation*}
\left.\vec{E}_{r}=\vec{E}_{0 r} \cos \left(\vec{k}_{r} \cdot \vec{r}-\omega_{r} t+\epsilon_{r}\right)\right] \tag{82}
\end{equation*}
$$

and

$$
\begin{equation*}
\left.\vec{E}_{t}=\vec{E}_{0 t} \cos \left(\vec{k}_{t} \cdot \vec{t}-\omega_{t} t+\epsilon_{t}\right)\right] \tag{83}
\end{equation*}
$$

For Eq. 82 and Eq. 83, $\epsilon_{r}$ and $\epsilon_{t}$ are phase constant that are relative to $\vec{E}_{i}$ and are introduce because the position of the origin is not complete. Figure 12.17 depicts the waves in the vicinity of the planar interface between two homogeneous lossless dielectric media of indices $\mathrm{n}_{i}$ and $\mathrm{n}_{t}$.


Figure 12.17: Plane waves incident on the boundary between two homogeneous, ISOTROPIC, LOSSLESS DIELECTRIC MEDIA 41

The laws of Electromagnetic Theory lead to certain requirements that must be met by the fields, and they are referred to as the boundary conditions. Specifically, one of these is component of the electric field $\vec{E}$ that is tangent to the interface must be continuous across it (the same is true for $\vec{H}$ ). In other words, the total tangential component of $\vec{E}$ on one side of the surface must equal that on the other. Thus since $\hat{u}_{n}$ is the unit control vector normal to the interface, regardless of the direction of the electric field within the wavefront, the cross-product of it with $\hat{u}_{n}$ will be perpendicular to $\hat{u}_{n}$ and therefore tangent to the interface;

$$
\begin{equation*}
\hat{u}_{n} \times \vec{E}_{i}+\hat{u}_{n} \times \vec{E}_{r}=\hat{u}_{n} \times \vec{E}_{t} \tag{84}
\end{equation*}
$$

or

$$
\begin{equation*}
\hat{u}_{n} \times \vec{E}_{0 i} \cos \left(\vec{k}_{i} \cdot \vec{r} \omega_{i} t\right)+\hat{u}_{n} \times \vec{E}_{0 r} \cos \left(\vec{k}_{r} \cdot \vec{r} \omega_{r} t+\epsilon_{r}\right)=\hat{u}_{n} \times \vec{E}_{0 t} \cos \left(\vec{k}_{t} \cdot \vec{r} \omega_{t} t+\epsilon_{t}\right) \tag{85}
\end{equation*}
$$

This relationship must obtain at any instant in time and at any point on the interface $(\mathrm{y}=\mathrm{b})$. Consequently, $\vec{E}_{i}, \vec{E}_{r}$, and $\vec{E}_{t}$ must have precisely the same functional dependence on the variables $t$ and $r$, which means;

$$
\begin{equation*}
\left.\left(\vec{k}_{i} \cdot \vec{r}-\omega_{t} t\right)\right|_{y=b}=\left.\left(\vec{k}_{r} \cdot \vec{r}-\omega_{r} t+\epsilon_{r}\right)\right|_{y=b}=\left.\left(\vec{k}_{t} \cdot \vec{r}-\omega_{t} t+\epsilon_{t}\right)\right|_{y=b} \tag{86}
\end{equation*}
$$

with Eq. 86, the cosines in Eq. 85 cancel, leaving an expression independent of t and r . This has to be true for all values in time, the coefficients of $t$ must be equal, therefore;

$$
\begin{equation*}
\omega_{i}=\omega_{r}=\omega_{t} \tag{87}
\end{equation*}
$$

Recall that the electrons within the media are undergoing (linear) forced vibrations at the frequency of the incident wave. Whatever light is scattered has that same frequency, therefore;

$$
\begin{equation*}
\left.\left(\vec{k}_{i} \cdot \vec{r}\right)\right|_{y=b}=\left.\left(\vec{k}_{r} \cdot \vec{r}+\epsilon_{r}\right)\right|_{y=b}=\left.\left(\vec{k}_{t} \cdot \vec{r}+\epsilon_{t}\right)\right|_{y=b} \tag{88}
\end{equation*}
$$

In Eq. 88 the $\vec{R}$ terminates on the interface. The values of $\epsilon_{r}$ and $\epsilon_{t}$ correspond to a given position O. Thus, they allow the relation to be valid regardless of the location. From the first two terms in Eq. 88, it is obtained that;

$$
\begin{equation*}
\left.\left[\left(\vec{k}_{i}-\vec{k}_{r}\right) \cdot \vec{r}\right]\right|_{y=b}=\epsilon_{r} \tag{89}
\end{equation*}
$$

Equation 89 states that the endpoint of $\vec{r}$ sweeps out a plane perpendicular to the vector $\left(\vec{k}_{i}-\vec{k}_{r}\right)$. To phrase it differently, $\left(\vec{k}_{i}-\vec{k}_{r}\right)$ is parallel to $\hat{u}_{n}$. However, since the incident and reflected waves are in the same medium, $\mathrm{k}_{i}=\mathrm{k}_{r}$. Since $\left(\vec{k}_{i}-\vec{k}_{r}\right)$ has no component in the plane of the interface $\left(\hat{u}_{n} \times\left(\vec{k}_{i}-\vec{k}_{r}\right)=0\right)$, it can be concluded that;

$$
\begin{equation*}
k_{i} \sin \left(\theta_{i}\right)=k_{r} \sin \left(\theta_{r}\right) \tag{90}
\end{equation*}
$$

Therefore, the Law of Refraction is derived; that is,

$$
\begin{equation*}
\theta_{i}=\theta_{r} \tag{91}
\end{equation*}
$$

Furthermore, since $\vec{k}_{i}-\vec{k}_{r}$ ) is parallel to $\hat{u}_{n}$, all three vectors, $\vec{k}_{i}, \vec{k}_{r}$, and $\hat{u}_{n}$ are in the same plane, the plane-of-incidence. Therefore, from Eq. 86;

$$
\begin{equation*}
\left.\left[\left(\vec{k}_{i}-\vec{k}_{t}\right) \cdot \vec{r}\right]\right|_{y=b}=\epsilon_{t} \tag{92}
\end{equation*}
$$

Therefore, $\left(\vec{k}_{i}-\vec{k}_{t}\right)$ is also normal to the interface. Thus, $\vec{k}_{i}, \vec{k}_{r}, \vec{k}_{t}$, and $\hat{u}_{n}$ are all coplanar. As before, the tangential components of $\vec{k}_{i}$ and $\vec{k}_{t}$ must be equal, therefore;

$$
\begin{equation*}
k_{i} \sin \left(\theta_{i}\right)=k_{t} \sin \left(\theta_{t}\right) \tag{93}
\end{equation*}
$$

Since it is known from Eq. 87 that $\omega_{i}=\omega_{t}$, both sides of Eq. 93 can be multiplied by c/ $\omega_{i}$ to get,

$$
\begin{equation*}
n_{i} \sin \left(\theta_{i}\right)=n_{t} \sin \left(\theta_{t}\right) \tag{94}
\end{equation*}
$$

## The Frensel Equations

In the previous section, it was determined that a relationship exists among the phases of $\vec{E}_{i}(\vec{r}, t), \vec{E}_{r}(\vec{r}, t)$, and $\vec{E}_{t}(\vec{r}, t)$ at the boundary. However, there is still an interdependence shared among the amplitudes of $\vec{E}_{0 i}, \vec{E}_{0 r}$, and $\vec{E}_{0 t}$, which can now be evaluated. It is assumed that $\vec{E}$ is perpendicular to the plane-of-incidence, and that the $\vec{B}$ is parallel to it. Also, recall that $\vec{E}=\nu B$, so that;

$$
\begin{gather*}
\hat{k} \times \vec{E}=\nu \vec{B}  \tag{95}\\
\text { and } \\
\hat{k} \cdot \vec{E}=0 \tag{96}
\end{gather*}
$$

Making use of the continuity of the tangential components of the $\vec{E}$ field, we have at the boundary at any time and any point where the cosines cancel;

$$
\begin{equation*}
\vec{E}_{0 i}+\vec{E}_{0 r}=\vec{E}_{0 t} \tag{97}
\end{equation*}
$$



Figure 12.18: An incoming wave whose $\vec{E}$-field is normal to the PLANE-OF-INCIDENCE 41

One more boundary condition needs to be invoked in order to get one more equation. The presence of material substances that become electrically polarized by the wave has a definite effect on the field configuration. Thus, although the tangential component of $\vec{E}$ is continuous across the boundary, its normal component is not. instead the normal component of the product $\epsilon \vec{E}$ is the same on either side of the interface. Similarly, the normal component of $\vec{B}$ is continuous, as is the tangential component of $\mu^{-1} \vec{B}$. The magnetic effect of the two media now appears via their permeabilities $\mu_{i}$ and $\mu_{t}$. This boundary condition will be the
simplest to use, particularly as applied to reflection from the surface of a conductor. Thus the continuity of the tangential component of $\vec{B} / \mu$ requires that;

$$
\begin{equation*}
\frac{B_{i}}{\mu_{i}} \cos \left(\theta_{i}\right)+\frac{B_{r}}{\mu_{i}} \cos \left(\theta_{r}\right)=-\frac{B_{t}}{\mu_{t}} \cos \left(\theta_{t}\right) \tag{98}
\end{equation*}
$$

In Eq. 98 the left and right sides are the total magnitude of $\vec{B} / \mu$ parallel to the interface in the incident and transmitting media, respectively. The positive direction is that of increasing x, so that the scalar components of $\vec{B}_{i}, \vec{B}_{r}$, and $\vec{B}_{t}$, appear with minus signs. Therefore, from Eq. 95, it is derived that;

$$
\begin{gather*}
B_{i}=\frac{E_{i}}{\nu_{i}}  \tag{99}\\
B_{r}=\frac{E_{r}}{\nu_{r}}  \tag{100}\\
\text { and } \\
B_{t}=\frac{E_{t}}{\nu_{t}} \tag{101}
\end{gather*}
$$

Since $\nu_{i}=\nu_{r}$ and $\theta_{i}=\theta_{r}$, Eq. 98 can be re-written as;

$$
\begin{equation*}
\frac{1}{\mu_{i} \nu_{i}}\left(E_{i}-E_{r}\right) \cos \left(\theta_{i}\right)=\frac{1}{\mu_{t} \nu_{t}} E_{t} \cos \left(\theta_{t}\right) \tag{102}
\end{equation*}
$$

Through the use of Eq. 81, Eq. 82, and Eq. 83 and remembering that the cosines are equal to one another at $\mathrm{y}=0$, it is obtained that;

$$
\begin{equation*}
\frac{n_{i}}{\mu_{i}}\left(E_{0 i}-E_{0 r}\right) \cos \left(\theta_{i}\right)=\frac{n_{t}}{\mu_{t}} E_{0 t} \cos \left(\theta_{t}\right) \tag{103}
\end{equation*}
$$

By combining Eq. 103 with Eq. 97, it is obtained that;

$$
\begin{gather*}
\left(\frac{E_{0 r}}{E_{0 i}}\right)_{\perp}=\frac{\frac{n_{i}}{\mu_{i}} \cos \left(\theta_{i}\right)-\frac{n_{t}}{\mu_{t}} \cos \left(\theta_{t}\right)}{\frac{n_{i}}{\mu_{i}} \cos \left(\theta_{i}\right)+\frac{n_{t}}{\mu_{t}} \cos \left(\theta_{t}\right)}  \tag{104}\\
\text { and } \\
\left(\frac{E_{0 t}}{E_{0 i}}\right)_{\perp}=\frac{2 \frac{n_{i}}{\mu_{i}} \cos \left(\theta_{i}\right)}{\frac{n_{i}}{\mu_{i}} \cos \left(\theta_{i}\right)+\frac{n_{t}}{\mu_{t}} \cos \left(\theta_{t}\right)} \tag{105}
\end{gather*}
$$

The purpose of the $\perp$ subscript is to serve as a reminder that $\vec{E}$ is perpendicular to the plane-of-incidence. Equation 104 and Eq. 105 are completely general statements applying to any linear, isotropic, homogeneous media and are two ff the Fresnel Equations. Most often one deals with dielectrics for which;

$$
\begin{equation*}
\mu_{i}=\mu_{t}=\mu_{0} \tag{106}
\end{equation*}
$$

Therefore, Eq. 104 and Eq. 105 are simplified to

$$
\begin{gather*}
r_{\perp}=\left(\frac{E_{0 r}}{E_{0 i}}\right)_{\perp}=\frac{n_{i} \cos \left(\theta_{i}\right)-n_{t} \cos \left(\theta_{t}\right.}{n_{i} \cos \left(\theta_{i}\right)+n_{t} \cos \left(\theta_{t}\right)}  \tag{107}\\
\text { and } \\
t_{\perp}=\left(\frac{E_{0 t}}{E_{0 i}}\right)_{\perp}=\frac{2 n_{i} \cos \left(\theta_{i}\right)}{n_{i} \cos \left(\theta_{i}\right)+n_{t} \cos \left(\theta_{t}\right)} \tag{108}
\end{gather*}
$$

### 12.1.2.5 Reflectance and Transmittance



Figure 12.19: Reflectance and transmission of an incident beam 41]

Consider a circular beam of light incident on a surface, as shown in Fig. 12.19, such that there is an illuminated spot of area A. recall, that the power per unit area crossing a surface in vacuum whose normal is parallel to $\vec{S}$, the Poynting vector, is given by Eq. 56;

$$
\begin{equation*}
\vec{S}=c^{2} \epsilon_{0} \vec{E} \times \vec{B} \tag{??}
\end{equation*}
$$

Furthermore, the radiant flux density $\left(\mathrm{W} / \mathrm{m}^{2}\right)$ or irradiance is

$$
\begin{equation*}
S_{T}=I=\frac{c^{2} \epsilon_{0}}{2} E_{0}^{2} \tag{??}
\end{equation*}
$$

Equation 60 is the average energy per unit time crossing a unit area that is normal to $\vec{S}$. In Fig. 12.19, let $\mathrm{I}_{i}, \mathrm{I}_{r}$, and $\mathrm{I}_{t}$ be the incident, reflected, and transmitted flux densities respectively.The cross-sectional areas of the incident power of the incident, reflected, and transmitted beams respectively, are $A \cos \left(\theta_{i}\right), A \cos \left(\theta_{r}\right)$, and $A \cos \left(\theta_{t}\right)$. Accordingly, the incident power is;

$$
\begin{equation*}
P_{i}=I_{i} A \cos \left(\theta_{i}\right) \tag{109}
\end{equation*}
$$

Equation 109 is the energy per unit time flowing in the incident beam, and it is therefore the power arriving on the surface over A. Similarly, Eq. 110 is the power of the reflected beam and Eq. 111 is the power of the transmitted beam.

$$
\begin{equation*}
P_{r}=I_{r} A \cos \left(\theta_{r}\right) \tag{110}
\end{equation*}
$$

and

$$
\begin{equation*}
P_{t}=I_{t} A \cos \left(\theta_{t}\right) \tag{111}
\end{equation*}
$$



Figure 12.20: The reflected $\vec{E}$-field at different angles 41

The reflectance, $R$, is defined as the ratio of the reflected power (or flux) to the incident power;

$$
\begin{equation*}
R=\frac{I_{r} A \cos \left(\theta_{r}\right)}{I_{i} A \cos \left(\theta_{i}\right)}=\frac{I_{r}}{I_{i}} \tag{112}
\end{equation*}
$$

The transmittance, $T$, is defined as the ratio of the transmitted flux to the incident flux;

$$
\begin{equation*}
R=\frac{I_{r} A \cos \left(\theta_{r}\right)}{I_{t} A \cos \left(\theta_{t}\right)} \tag{113}
\end{equation*}
$$

The quotient $\mathrm{I}_{r} / \mathrm{I}_{i}$ equals;

$$
\begin{equation*}
\frac{I_{r}}{I_{i}}=\frac{\nu_{r} \epsilon_{r} E_{0 r}^{2}}{\nu_{i} \epsilon_{i} E_{0 i}^{2}} \tag{114}
\end{equation*}
$$

Since the incident and reflected waves are in the same medium;

$$
\begin{gather*}
\nu_{r}=\nu_{i} \\
\text { and } \\
\epsilon_{r}=\epsilon_{i} \tag{116}
\end{gather*}
$$

Equation 112 becomes;

$$
\begin{equation*}
R=\left(\frac{E_{0 r}}{E_{0 i}}\right)^{2}=r^{2} \tag{117}
\end{equation*}
$$

Assuming that $\mu_{i}=\mu_{t}=\mu_{0}$, Eq. 113 becomes;

$$
\begin{equation*}
T=\frac{n_{t} \cos \left(\theta_{t}\right)}{n_{i} \cos \left(\theta_{i}\right)}\left(\frac{E_{0 t}}{E_{0 i}}\right)^{2}=\frac{n_{t} \cos \left(\theta_{t}\right)}{n_{i} \cos \left(\theta_{i}\right)} t^{2} \tag{118}
\end{equation*}
$$

In Eq. 118, T is not equal to $\mathrm{t}^{2}$ for two reasons. First, the ratio of the indices of refraction must be there, since the speeds at which energy is transported into and out of the interface are different. Second, the cross-sectional areas of the incident and refracted beams are different. The energy flow per unit area is affected accordingly and that manifests itself in the presence of the ratio of the cosine terms.

An expression for the conservation of energy can now be written for the configuration depicted in Fig. 12.19. The total energy flowing into area A per unit time must be equal to the amount of energy flowing outward from it per unit time;

$$
\begin{equation*}
I_{i} A \cos \left(\theta_{i}\right)=I_{r} A \cos \left(\theta_{r}\right)+I_{t} A \cos \left(\theta_{t}\right) \tag{119}
\end{equation*}
$$

When both sides of Eq. 119 are multiplied by c, the expression becomes;

$$
\begin{equation*}
n_{i} E_{0 i}^{2} \cos \left(\theta_{i}\right)=n_{i} E_{0 r}^{2} I_{r} A \cos \left(\theta_{r}\right)+n_{i} E_{0 t}^{2} I_{t} A \cos \left(\theta_{t}\right) \tag{120}
\end{equation*}
$$

$$
1=\left(\frac{E_{0 r}}{E_{0 i}}\right)^{2}+\frac{n_{t} \cos \left(\theta_{t}\right)}{n_{i} \cos \left(\theta_{i}\right)}\left(\frac{E_{0 t}}{E_{0 i}}\right)^{2}
$$

But this is simply

$$
\begin{equation*}
R+T=1 \tag{122}
\end{equation*}
$$

Figure 12.21 shows the relationship between the transmittance, reflectance, and the incident angle. It is easily noticed that as the incident angle increases, the reflectance decreases while the transmittance increases.


Figure 12.21: Reflectance and transmittance versus incident angle 41]

As the beam is transmitted through the beam, a portion of the transmittance, T , is absorbed by the media. The absorptance, A, is defined as;

$$
\begin{equation*}
A=2-\log (100 T) \tag{123}
\end{equation*}
$$

Furthermore, the energy of the beam that is transmitted out of the media is defined as;

$$
\begin{equation*}
T_{\text {out }}=(1-A) T \tag{124}
\end{equation*}
$$

### 12.1.3 Lasers

### 12.1.3.1 Radiant Energy and Matter in Equilibrium

Gustav Robert Kirchhoff was involved in analyzing the way bodies in thermal equilibrium behave in the process of radiant energy. This thermal radiation is electromagnetic energy that is emitted by all objects. The source of the thermal radiation is the random motion of their constituent atoms. Kirchhoff characterized the abilities of a body to emit and absorb electromagnetic energy by an emission coefficient, $\epsilon_{\lambda}$, and an absorption coefficient, $\alpha_{\lambda}$. Epsilon is the energy per unit are per unit time emitted in a tiny wavelength range around $\lambda$ (in units of $\mathrm{W} / \mathrm{m}^{2} / \mathrm{m}$ ). Thermal radiation is comprised of a wide range of frequencies and an energy-measuring device by necessity admits a band of wavelengths. $\alpha$ is the fraction of the incident radiant energy absorbed per unit area per unit time in that wavelength range. The emission and absorption coefficients depend on both the nature of the surface of that body and the wavelength.

Consider an isolated chamber that is in thermal equilibrium that is fixed at temperature T. The chamber would be filled with radiant energy at a bunch of different wavelengths. Kirchhoff assumed that there was some formula or expression $I_{\lambda}(\lambda)$, which is dependent on T and provides the values of the energy per unit area per unit time at each wavelength. It is called the spectral flux density within the cavity. Kirchhoff concluded that the total amount of energy at all wavelengths being absorbed by the walls versus the amount emitted by them must be the same or else the temperature would change, and it does not. Therefore, the energy absorbed at $\lambda$, namely $\alpha_{\lambda} I_{\lambda}$, must be equal the energy radiated, $\epsilon_{\lambda}$, and this is true for all materials no matter how different they are. Kirchhoff's Radiation Law is therefore;

$$
\begin{equation*}
\frac{\epsilon_{\lambda}}{\alpha_{\lambda}}=I_{\lambda} \tag{125}
\end{equation*}
$$

$I_{\lambda}$ is the distribution, in units of $\mathrm{J} / \mathrm{m}^{3} \mathrm{~s}$ or $\mathrm{W} / \mathrm{m}^{3}$, and it is a universal function that is the same for every type of cavity wall regardless of material, color, size, and shape and it is only dependent on T and $\lambda$.

## Stefan-Boltzmann Law

Josef Stefan noticed that the rate at which energy is radiated is proportional to $\mathrm{T}^{4}$ when he was looking over the experimental results published by John Tyndall in 1865. In his observation Stefan was correct that the results from Tyndall were actually far more from those of a blackbody.Stefan's conclusion led ay for L. Boltzmann to derive what is known today as the Stefan-Boltzmann Law for blackbodies;

$$
\begin{equation*}
P=\sigma A T^{4} \tag{126}
\end{equation*}
$$

In E 126 P is the total radiant power at all wavelengths, A is the area of the radiating surface, T is the absolute temperature in Kelvin, and $\alpha$ is a universal constant given as;

$$
\begin{equation*}
\sigma=5.67033 \times 10^{-8} W / m^{2} K^{4} \tag{127}
\end{equation*}
$$

However, real objects are not perfect blackbodies. Therefore, an expression is need for ordinary objects. This expression can be written by altering Eq. 126 to include a multiplicative factor called the total emissivity $(\epsilon)$, which relates the radiated power to that of a blackbody for which $\epsilon=1$, at the same temperature, thus;

$$
\begin{equation*}
P=\epsilon \sigma A T^{4} \tag{128}
\end{equation*}
$$

However, Eq. 128 does not taken into consideration the temperature of the environment, $\mathrm{T}_{e}$. Therefore, Eq. 128 must be altered to Eq. 129, which s the complete Stefan-Boltzmann Law.

$$
\begin{equation*}
P=\epsilon \sigma A\left(T^{4}-T_{e}^{4}\right) \tag{129}
\end{equation*}
$$

## Planck Radiation Law

In October 1900, Max Karl Ernst Ludwig Planck produced a distribution formula that was based on all of the latest experimental results from Stefan, Boltzmann, and Kirchhoff. His formula contained two fundamental constants, one of which (h) is known as Planck's Constant.

$$
\begin{equation*}
h=6.626075 \times 10^{-34} J \cdot \text { sor } 4.1356692 \times 10^{-15} \mathrm{eV} \cdot \mathrm{~s} \tag{130}
\end{equation*}
$$

While deriving Planck's Constant, Planck stumbled upon a hidden mystery f nature: energy is quantized. Planck derived the following formula for the spectral existence (or spectral irradiance), known as Planck's Radiation Law;

$$
\begin{equation*}
I_{\lambda}=\frac{2 \pi h c^{2}}{\lambda^{5}} \frac{1}{e^{\frac{h c}{\lambda k_{B}{ }^{T}}}-1} \tag{131}
\end{equation*}
$$

### 12.1.3.2 The Laser

Consider an ordinary medium in which a few atoms are in some excited state, it will be called $\mid j>$ to conform with quantum mechanical notation. If a photon in an incident beam is to trigger one of these excited atoms into stimulated emission then it must have the frequency $\nu_{j i}$. A remarkable feature of this process is that the emitted photon is inphase with, has the polarization of, and propagates in the same direction as the stimulating radiation. Population inversion occurs when High percentage of atoms are excited into an
upper state, leaving the lower state empty. An incident photon of the proper frequency then triggers an avalanche of stimulated photons that are all in phase. The initial wave would continue to build, so long as there was no dominant competitive processes (such as scattering) and provided the population inversion could be maintained. In effect, energy would be pumped in to sustain the inversion. A beam of light would be extracted after sweeping across the active medium.

## Transverse Modes

Beams are very normal to the z-direction. This is known as $\mathrm{TEM}_{m n}$, where m is the integer number of transverse nodal lines in the x -direction across the merging beam and n is the integer number of transverse nodal lines in the $y$-direction across the emerging beam. The lowest order, $\mathrm{TEM}_{00}$ is the most used mode for several reasons. First, the flux density is ideally Gaussian over the beam's cross section. Second, there are no phase shifts in the electric field across the beam, as there are in other mode/ Third, it is completely coherent. Forth, the amplitude in this mode is not constant over the wavefront, it is an inhomogeneous wave.


Figure 12.22: TEM mode patterns 41


Figure 12.23: TEM mode configurations 41]

## Gaussian laser-beams

The $\mathrm{TEM}_{00}$ mode that develops within a resonator has a Gaussian profile. The strength of the beam-like wave falls off transversely following a bell-shaped curve that is symmetrical around the central axis. A Gaussian is a negative exponential that is a function of the square of the variable. In this case, the distance ( r ) measured in a transverse plane from the central axis of propagation ( z ) because the beam trails off radially it is useful to put an arbitrary boundary to its width. Let $\mathrm{r}=\mathrm{w}$ be the beam half-width The distance at which the electric field of the beam drops from its maximum axial value of $\mathrm{E}_{0}$ to $\mathrm{E}_{0} / \mathrm{e}$ or $37 \% \mathrm{E}_{0}$. At $\mathrm{r}=\mathrm{w}$ the beam's irradiance is $\mathrm{I}_{0} / \mathrm{e}^{2}$ which is only $14 \% \mathrm{I}_{0}$. The irradiance depends on the square of the amplitude Most of the energy of the beam resides within this imaginary cylinder of radius w , therefore;

$$
\begin{gather*}
I=I_{0} e^{\frac{-2 r^{2}}{w^{2}}} \\
I=I_{0} e^{-2} \quad \text { at } \quad r=w \tag{133}
\end{gather*}
$$



Figure 12.24: Gaussian irradiance distribution 41

When curved mirrors form the laser cavity there is a tendency to "focus" the beam, giving it a minimum cross section or waist or radius $\mathrm{w}_{0}$, the minimum cross-section. Under such circumstances, the external divergence of the laser-beam is essentially a continuation of the divergence out from this waist, $\mathrm{w}_{0}$. In general, there will be a beam waist somewhere between the mirrors of a laser resonator. Its exact location depends on the specific design. For example, a confocal resonator has a waist halfway between the mirrors. A more complete analysis of EM-waves in the cavity, setting $\mathrm{z}=0$ at the beam waist yields the expression for the half-width at any location z;

$$
\begin{equation*}
w(z)=w_{0}\left[1+\left(\frac{\lambda z}{\pi w_{0}^{2}}\right)^{2}\right]^{1 / 2} \tag{134}
\end{equation*}
$$

The shape of the beam as specified by this expression for $\mathrm{w}(\mathrm{z})$ is a hyperbola of revolution about the z -axis A practical measure of the divergence of the beam is the distance over which its cross-sectional area doubles, the value of z for which $\mathrm{w}(\mathrm{z})=\sqrt{2 w_{0}}$. This special distance $\mathrm{z}_{R}$ is known as the Rayleigh range and it follows from Eq. 134 that;

$$
\begin{equation*}
z_{R}=\frac{\pi w_{0}^{2}}{\lambda} \tag{135}
\end{equation*}
$$

The smaller the waist, the smaller the Rayleigh range and the faster the beam diverges At large distances from the waist ( $\mathrm{z} \gg \mathrm{zR}$ ) the full-angular width of the beam, $\theta$ (in radians) approaches $2 \mathrm{w}(\mathrm{z}) / \mathrm{z}$. In other words, as the line length z , rotates through the angle $\theta$, its endpoint sweeps out a distance of approximately $2 \mathrm{w}(\mathrm{z})$. When z is large and $\mathrm{w}_{0}$ is small, the second term in the expression for $\mathrm{w}(\mathrm{z})$, Eq. 134 is much greater than 1 and therefore;

$$
\begin{equation*}
w(z)=w_{0}\left[\left(\frac{\lambda z}{\pi w_{0}^{2}}\right)^{2}\right]^{1 / 2}=\frac{\lambda z}{\pi w_{0}} \tag{136}
\end{equation*}
$$

The smaller $\mathrm{w}_{0}$ is, the larger $\theta$, the beam divergence, will be;

$$
\begin{equation*}
\theta=\frac{2 \lambda}{\pi w_{0}}=0.637 \frac{\lambda}{w_{0}} \tag{137}
\end{equation*}
$$



Figure 12.25: Gaussian beam 3-D 41


Figure 12.26: GAUSSIAN BEAM 2-D $\sqrt{41}$


Figure 12.27: Gaussian beam waist 41

### 12.1.4 Heat Transfer

Heat, which is a measure of thermal energy, can be transferred from one point to another. Through the laws of equilibrium, heat transfers form the point of higher temperature to one of lower temperature. The heat content, Q , of an object depends upon its specific heat, $c_{p}$, and its mass, m . The heat transfer is the measurement of the thermal energy transferred when an object having a defined specific heat and mass undergoes a defined temperature change.

$$
\begin{equation*}
Q=m c_{p} \Delta T \tag{138}
\end{equation*}
$$

It is known that;

$$
\begin{equation*}
m=\rho V \tag{139}
\end{equation*}
$$

Therefore, Eq. 139 can be applied to Eq. 138 to create the modified Heat Transfer equation below;

$$
\begin{equation*}
Q=\rho V c_{p} \Delta T \tag{140}
\end{equation*}
$$

Furthermore, it is known that the volume of an object can be written as its area, A, multiplied by its thickness, b;

$$
\begin{equation*}
V=A b \tag{141}
\end{equation*}
$$

When Eq. 141 is applied to E. 140 , the equation below is derived;

$$
\begin{equation*}
Q=\rho A b c_{p} \Delta T \tag{142}
\end{equation*}
$$

Also, $\Delta T$ can be described with Eq. 143 below, with $\mathrm{T} \infty$ representing the ambient
Temperature and $\mathrm{T}_{\text {Boil }}$ representing the flash point temperature of the material.

$$
\begin{equation*}
\Delta T=\left(T_{\text {Boil }}-T_{\infty}\right) \tag{143}
\end{equation*}
$$

When Eq. 143 is applied to Eq. 142 , the full Heat Transfer Equation is derived, as seen below in Eq. 144

$$
\begin{equation*}
Q=\rho A b c_{p}\left(T_{\text {Boil }}-T_{\infty}\right) \tag{144}
\end{equation*}
$$

Equation 144 expresses all of the variables need to calculate the heat transfer in a material. However, Eq. 144 is not a time-dependent equation. To derive a time-dependent Heat Transfer equation, the first derivative of Eq. 144 is taken with respect to time, t, to determine the rate at which the Heat Transfer occurs;

$$
\begin{equation*}
\frac{\partial Q}{\partial t}=\frac{\rho A b c_{p}\left(T_{\text {Boil }}-T_{\infty}\right)}{t} \tag{145}
\end{equation*}
$$

The mathematical relationship between the variables in Eq. 145 is provided in the following six Pi Groups below;

$$
\begin{gather*}
\frac{\frac{\partial Q}{\partial t}}{C_{p}^{2.5} \rho t T_{\text {Boil }}^{2.5}}  \tag{146}\\
\frac{A}{C_{p} t^{2} T_{\text {Boil }}}  \tag{147}\\
\frac{b}{C_{p}^{0.5} t T_{\text {Boil }}^{0.5}}  \tag{148}\\
\frac{T_{\text {Boil }}}{T_{\infty}} \tag{149}
\end{gather*}
$$

$$
\begin{gather*}
\frac{A}{b^{2}}  \tag{150}\\
\frac{\partial Q}{\partial t} t^{2}  \tag{151}\\
A b^{3} \rho
\end{gather*}
$$

### 12.2 Theory:Surface Roughness Measurement

When determining the surface roughness of a material, two values are critical. These values are the average roughness, $\mathrm{R}_{a}$, and the root mean square roughness, $\mathrm{R}_{z}$. They can be computed through the asperity peaks of the material. There are precise metrology devices, like the MarSurf XR 20 [Fig. 12.106 that can compute these values automatically. The mathematical equations used by these machines is shown below;

$$
\begin{gather*}
R_{a}=\frac{1}{L} \int_{x=0}^{L}|z| d x  \tag{152}\\
R_{z}=\left[\frac{1}{L} \int_{x=0}^{L} z^{2} d x\right]^{1 / 2} \tag{153}
\end{gather*}
$$

If multiple measurements are made on the same specimen, the average values for $\mathrm{R}_{a}$ and $\mathrm{R}_{z}$ can be calculated with the equation below;

$$
\begin{align*}
& R_{\text {a avg }}=\sum_{n=1}^{\infty} R_{a}  \tag{154}\\
& R_{z ~ a v g}=\sum_{n=1}^{\infty} R_{z} \tag{155}
\end{align*}
$$

For the post-processing of the experimental analysis the equations below were used;

$$
\begin{gather*}
R_{a \text { clean }}=R_{a \text { mixture }}-R_{a} \text { reference }  \tag{156}\\
R_{z \text { clean }}=R_{z \text { mixture }}-R_{z \text { reference }}  \tag{157}\\
\text { Efficiency } y_{a} \text { clean } \%=100 \frac{R_{a \text { mixture }}-R_{a} \text { reference }}{R_{a} \text { reference }} \tag{158}
\end{gather*}
$$

$$
\begin{align*}
& \quad \text { Efficiency } y_{z \text { clean }} \%=100 \frac{R_{z \text { mixture }}-R_{z \text { reference }}}{R_{z \text { reference }}}  \tag{159}\\
& \text { Efficiency }_{a} \text { dirty } \%=100 \frac{R_{a \text { mixture }}-R_{a \text { mixture reference }}}{R_{a \text { mixture reference }}}  \tag{160}\\
& \text { Efficiency } y_{z \text { dirty }} \%=100 \frac{R_{z \text { mixture }}-R_{z \text { mixture reference }}}{R_{z \text { mixture reference }}} \tag{161}
\end{align*}
$$

### 12.3 Theory of Robotics

### 12.3.1 Spatial descriptions and transformations

### 12.3.1.1 Descriptions: Positions, Orientations, and Frames

## 1. Description of an Orientation

(a). In order to describe the orientation of a body,a coordinate system is attached to the body and then is given a description of this coordinate system relative to the reference system.


Figure 12.28: LOCATING AN OBJECt I POSition and ORIENTATION 42]
(b). In Fig. 12.28, coordinate system B has been attached to the body in a known way. A description of $B$ relative to $A$ now suffices to give the orientation of the body.
(c). Thus, positions of points are described as vectors and orientations of bodies are described with an attached coordinate system.
i. One way to describe the body-attached coordinate system, B , is to write the unite vectors of its three principal axes in terms of the coordinate system A.
(d). The unit vectors are denoted by giving the principal directions of coordinate system B as $\hat{X}_{B}, \hat{Y}_{B}$, and $\hat{Z_{B}}$.
i. When written in terms of coordinate system A , they are called ${ }^{A} \hat{X}_{B},{ }^{A} \hat{Y}_{B}$, and ${ }^{A} \hat{Z}_{B}$.
A. I is convenient is these three unit vectors are stacked together as the columns of a 3 by 3 matrix, in the order ${ }^{A} \hat{X}_{B},{ }^{A} \hat{Y}_{B},{ }^{A} \hat{Z}_{B}$.
(I). This matrix will be called a rotation matrix.
(a). Since this particular rotation matrix describes B relative to A, it is named with the notation ${ }_{B}^{A} R$

$$
{ }_{B}^{A} R=\left[\begin{array}{lll}
{ }^{A} \hat{X}_{B} & { }^{A} \hat{Y}_{B} & { }^{A} \hat{Z}_{B}
\end{array}\right]=\left[\begin{array}{lll}
r_{11} & r_{12} & r_{13}  \tag{162}\\
r_{12} & r_{22} & r_{23} \\
r_{13} & r_{32} & r_{33}
\end{array}\right]
$$

(e). In summary, a set of three vectors maybe used to specify an orientation. A $3 x 3$ matrix is constructed below that has these three vectors as its columns.
i. Whereas the position of a point is represented with a vector, the orientation of a body is represented with a matrix.
(f). An expression can be written for the scalars $r_{i j}$ in Eq. 162 by noting the components of any vector are simply the projections of that vector onto the unit directions of its reference frame.
i. Hence, each component of ${ }_{B}^{a} R$ can be written as the dot product of a pair of unit vectors.
i. The dot product of two unit vectors yields the cosine of the angle between them, therefore the components of rotation matrices are referred to as direction cosines.
A. For solving Eq. 163 , the product for the first column of the first row is, the cosine of the angle of $\hat{X}_{B}$ - the angle of $\hat{X}_{A}$

$$
{ }_{B}^{A} R=\left[\begin{array}{lll}
{ }^{A} \hat{X}_{B} & { }^{A} \hat{Y}_{B} & { }^{A} \hat{Z}_{B}
\end{array}\right]=\left[\begin{array}{ccc}
\hat{X}_{B} \cdot \hat{X}_{A} & \hat{Y}_{B} \cdot \hat{X}_{A} & \hat{Z}_{B} \cdot \hat{X}_{A}  \tag{163}\\
\hat{X}_{B} \cdot \hat{Y}_{A} & \hat{Y}_{B} \cdot \hat{Y}_{A} & \hat{Z}_{B} \cdot \hat{Y}_{A} \\
\hat{X}_{B} \cdot \hat{Z}_{A} & \hat{Y}_{B} \cdot \hat{Z}_{A} & \hat{Z}_{B} \cdot \hat{Z}_{A}
\end{array}\right]
$$

(g). Further inspection of Eq. 163 shows that the rows of the matrix are the unit vectors of $A$ expressed in B; that is

$$
{ }_{B}^{A} R=\left[\begin{array}{lll}
{ }^{A} \hat{X}_{B} & { }^{A} \hat{Y}_{B} & { }^{A} \hat{Z}_{B}
\end{array}\right]=\left[\begin{array}{c}
{ }^{B} \hat{X}_{B}^{T}  \tag{164}\\
{ }^{B} \hat{Y}_{A}^{T} \\
{ }^{B} \hat{Z}_{A}^{T}
\end{array}\right]
$$

Hence;

$$
\begin{equation*}
{ }_{A}^{B} R={ }_{B}^{A} R^{T} \tag{165}
\end{equation*}
$$

## 2. Description of a Frame

(a). The information needed to completely specify the whereabouts of the manipulator hand in Fig. 12.28 is a position and an orientation.
i. The point on the body whose position is described can be chosen arbitrarily. For convenience, the point whose position we will describe is chosen as the origin of the body-attached frame.
A. The situation of a position and an orientation pair arises so often i robotics that the entity is called a frame, which is a set of four vectors giving position and orientation information.
(I). For example, in Fig. 12.28 one vector locates the fingertip position and three more describe its orientation. Equivalently, the description of a frame can be though of as a position vector and a rotation matrix.
(b). Frame B is described by ${ }_{B}^{A} R$ and ${ }^{A} P_{B O R G}$, where ${ }^{A} P_{B O R G}$ is the vector that locates the origin of frame B;

$$
\begin{equation*}
\{B\}=\left\{{ }_{B}^{A} R,{ }^{A} P_{B O R G}\right\} \tag{166}
\end{equation*}
$$

(c). In Fig. 12.29, there are three frames that are shown along with the universe coordinate system. Frames A and B are known relative to the universe coordinate system, and frame C is known relative to frame A
i. A frame is depicted by three arrows representing unit vectors defining the principal axes of the frame. An arrow representing a vector is drawn from one origin to the another. This vector represents the position of the origin at the head in terms of the frame at the tail of the arrow.


Figure 12.29: Examples of Several frames 42

### 12.3.1.2 Mappings: Changing descriptions from frame to frame

## 1. Mappings involving translated frames

(a). Mapping is used in order to change descriptions from frame to frame
(b). In Fig. 12.30, a position is defined by the vector ${ }^{B} P$. This point in space now needs to be expressed in terms of frame A, when A has the same orientation as B.
i. In this case, B differs from A only by a translation, which is given by ${ }^{A} P_{B O R G}$, a vector that locates the origin of B relative to A .
A. Since both vectors are defined relative to frames of the same orientation, the description of point P relative to $\mathrm{A},{ }^{A} P$, can be calculated by vector addition.

$$
\begin{equation*}
{ }^{A} P={ }^{B} P+{ }^{A} P_{B O R G} \tag{167}
\end{equation*}
$$



Figure 12.30: Translational Mapping 42]

## 2. Mappings involving rotated frames

(a). As seen in Fig. 12.31, the situation can arise where the definition of a vector with respect to some frame, B , is known and it is necessary to know its definition with respect to another frame, A, where the origins of the two frames are coincident.
$[B] \quad|A|$


Figure 12.31: Rotating the description of a vector 42
(b). This computation is possible when a description of the orientation of of B is known relative to A . This orientation is given by the rotation matrix ${ }_{B}^{A} R$, whose columns are the unit vectors of B written in A .
(c). In order to calculate ${ }^{A} P$, it is noted that the components of any vector are simply the projections of that vector onto the unit directions of its frame. The projection is calculated as the vector dot product. Thus, the components of ${ }^{A} P$ may be calculated as;

$$
\begin{align*}
{ }^{A} p_{x} & ={ }^{B} \hat{X}_{A} \cdot{ }^{B} P \\
{ }^{A} p_{y} & ={ }^{B} \hat{Y}_{A} \cdot{ }^{B} P  \tag{168}\\
{ }^{A} p_{z} & ={ }^{B} \hat{Z}_{A} \cdot{ }^{B} P
\end{align*}
$$

Hence;

$$
\begin{equation*}
{ }^{A} P={ }_{B}^{A} R{ }^{B} P \tag{169}
\end{equation*}
$$

(d). Equation 169 implements a mapping (it changes the description of a vector) from ${ }^{B} P$, which describes a point in space relative to B , into ${ }^{A} P$, which is a description of the same point, but expessed relative to A .

## 3. Mappings involving general frames

(a). Very often, the description of a vector with respect to some frame B is known, and its description with respect to another frame A is needed.
i. Here, the origin of frame B is not coincident with that of frame A but has a general vector offset. The vector that locates B 's origin is called ${ }^{A} P_{B O R G}$.
A. Also, B is rotated with respect to A, as described by ${ }_{B}^{A} R$.


Figure 12.32: General transform of a vector 42
(b). Given ${ }^{B} P$, the desire is to compute ${ }^{A} P$, as seen in Fig. 12.32.
i. First, the description of ${ }^{B} P$ id changed relative to an intermediate frame that has the same orientation as A, but whose origin is coincident with the origin of B.
A. This is done by premultiplying by ${ }_{B}^{A} R$. The account for the translation between origins by simple vector addition, and obtain;

$$
\begin{equation*}
{ }^{A} P={ }_{B}^{A} R^{B} P+{ }^{A} P_{B} O R G \tag{170}
\end{equation*}
$$

ii. Equation 170 describes a general transformation mapping of a vector from its description in one frame to a description in a second frame.
A. Note the following interpretation of the notation in Eq. 170; the B's cancel, leaving all quantities as vectors written in terms of A, which may then be added.
iii. The form of Eq. 170 is not as appealing as the conceptual form below;

$$
\begin{equation*}
{ }^{A} P={ }_{B}^{A} T^{B} P \tag{171}
\end{equation*}
$$

iv. Think of mapping from one frame to another as an operator in matrix form. This aids in writing compact equations and is conceptually cleaner than Eq. 170.
A. In order to write the mathematics given in Eq. 170 in the matrix operator form suggested by Eq. 171, a 4 x 4 matrix operator is defined and 4 x 1 position vectors are used, so that Eq. 171 has the form shown below;

$$
\left[\begin{array}{c}
{ }^{A} P  \tag{172}\\
1
\end{array}\right]=\left[\begin{array}{c|c}
{ }_{B}^{A} R & { }^{A} P_{B O R G} \\
\hline 000 & 1
\end{array}\right]\left[\begin{array}{c}
{ }^{B} P \\
1
\end{array}\right]
$$

v. The $4 x 4$ matrix in Eq. 172 is called a homogeneous transform. It can be regarded as a construction used to cast the rotation and translation of the general transform into a single matrix form.
A. Note that, although homogeneous transforms are useful in writing compact equations, a computer program to transform vectors would generally not use them, because of time wasted multiplying ones and zeros. Thus, this representation is mainly for convenience when thinking and writing equations down on paper.
vi. Similar to how rotation matrices are used to specify an orientation, transforms are used to specify a frame.
A. Although, transforms were introduced in the context of mappings, they also serve as descriptions of frames.
(I). The description of frame B relative to A is ${ }_{B}^{A} T$.

### 12.3.1.3 Operators: Translations, Rotations, and Transformations

## 1. Translational Operators

(a). A translation moves a point in space a finite distance along a given vector direction.
i. With this interpretation of actually translating the point in space, only one coordinate system needs to be involved. Translating the point in space is accomplished with the same mathematics as mapping the point to a second frame.
A. Almost always, it is very important to understand which interpretation of the mathematics is being used. The distinction is as simple as this:
(I). When a vector is moved "forward" relative to a frame, it is considered that the vector moved "forward" or the frame moved "backward".
(a). The mathematics involved in the two cases is identical: only the view of the situation is different.
(b). Figure 12.33 indicates pictorially how a vector ${ }^{A} P_{1}$ is translated by a vector ${ }^{A} Q$. Here, the vector ${ }^{A} Q$ gives the information needed to perform the translation.
i. The result of the operation is a new vector ${ }^{A} P_{2}$, calculated as

$$
\begin{equation*}
{ }^{A} P_{2}={ }^{A} P_{1}+{ }^{A} Q \tag{173}
\end{equation*}
$$

To write this translation operation as a matrix operator, the notation below is used;

$$
\begin{equation*}
{ }^{A} P_{2}=D_{Q}(q)^{A} P_{1} \tag{174}
\end{equation*}
$$

Where q is the signed magnitude of the translation along the vector direction $\hat{Q}$. the $D_{Q}$ operator may be thought of as a homogeneous transform of a special simple form

$$
D_{Q}(q)=\left[\begin{array}{cccc}
1 & 0 & 0 & q_{x}  \tag{175}\\
0 & 1 & 0 & q_{y} \\
0 & 0 & 1 & q_{z} \\
0 & 0 & 0 & 1
\end{array}\right]
$$

where $q_{x}, q_{y}$, and $q_{z}$ are the components of the translation vector Q and

$$
\begin{equation*}
q=\sqrt{q_{x}^{2}+q_{y}^{2}+q_{z}^{2}} \tag{176}
\end{equation*}
$$



Figure 12.33: Translation operator 42 |

## 2. Rotational operators

(a). Another interpretation of a rotation matrix is as a rotational operator that operates on a vector ${ }^{A} P_{1}$ and changes to a new vector, ${ }^{A} P_{2}$, by means of a rotation, R. Usually, when a rotation matrix is shown as an operator, no sub- or superscripts appear, because it is not viewed as relating two frames. Therefore,

$$
\begin{equation*}
{ }^{A} P_{2}=R^{A} P_{1} \tag{177}
\end{equation*}
$$

i. Again, as in the case of translations, the mathematics described in Eq. 169 and Eq. 177 is the same. This fact allows the possibility to see how to obtain rotational matrices that are to be used as operators
A. The rotation matrix that rotates vectors through some rotation, $R$, is the same as the rotation matrix that describes a frame rotated by R relative to the reference frame.
(b). Although a rotation matrix is easily views as an operator, another notation can be defined for a rotational operator that clearly indicates which axis is being rotated about:

$$
\begin{equation*}
{ }^{A} P_{2}=R_{K}(\theta){ }^{A} P_{1} \tag{178}
\end{equation*}
$$

(c). In this notation, " $R_{K}(\theta)$ ", is a rotational operator that performs a rotation about the axis direction $\hat{K}$ by $\theta$ degrees. This operator can be written as a homogeneous transform whose position-vector part is zero. For example, substitution into Eq. 164 yields the operator that rotates about the $\hat{Z}$ axis by $\theta$ as

$$
R_{z}(\theta)=\left[\begin{array}{cccc}
\cos \theta & -\sin \theta & 0 & 0  \tag{179}\\
\sin \theta & \cos \theta & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{array}\right]
$$

## 3. Transformation operators

(a). As with vectors and rotation matrices, a frame has another interpretation as a transformation operator. In this interpretation, only one coordinate system is involved, and so the T is used without sub- or superscripts. The operator T rotates and translates a vector ${ }^{A} P_{1}$ to compute a new vector;

$$
\begin{equation*}
{ }^{A} P_{2}=T^{A} P_{1} \tag{180}
\end{equation*}
$$

(b). Again, as in the case of rotations, the mathematics described in Eq. 171 and Eq. 180 is the same, only the interpretation is different. This shows how to obtain homogeneous transforms that are to be used as operators.
i. The transform that rotates by R and translates by Q is the same as the transform that describes a frame rotated by R and translated by Q relative to the reference frame.
A. transform is usually thought of as being in the form of a homogeneous transform with general rotation-matrix and position-vector parts.

### 12.3.1.4 Transformation Arithmetic

## 1. Compound Transformations

(a). In Fig. $12.34{ }^{C} P$ is known and the desire is to find ${ }^{A} P$.


Figure 12.34: Compound frames: Each is known relative to the previous ONE. 42
(b). Frame C is known relative to frame B , and frame B is known relative to frame A . Therefore, ${ }^{C} P$ can be transformed into ${ }^{B} P$ as

$$
\begin{equation*}
{ }^{B} P={ }_{C}^{B} T^{C} P \tag{181}
\end{equation*}
$$

Then ${ }^{B} P$ can be transformed into ${ }^{A} P$ as

$$
\begin{equation*}
{ }^{A} P={ }_{B}^{A} T^{B} P \tag{182}
\end{equation*}
$$

Combining Eq. 181 and Eq. 182, the result is

$$
\begin{equation*}
{ }^{A} P={ }_{B}^{A} T_{C}^{B} T^{C} P \tag{183}
\end{equation*}
$$

From Eq. 183, it can be defined that

$$
\begin{equation*}
{ }_{C}^{A} T={ }_{B}^{A} T{ }_{C}^{B} T \tag{184}
\end{equation*}
$$

In terms of the known descriptions of B and C , the expression for ${ }_{C}^{A} T$ can be written as

$$
{ }_{C}^{A} T=\left[\begin{array}{c|c}
{ }_{B}^{A} R{ }_{C}^{B} R & { }_{B}^{A} R^{B} P_{C O R G}+{ }^{A} P_{B O R G}  \tag{185}\\
\hline 000 & 1
\end{array}\right]
$$

## 2. Inverting a Transform

(a). Consider a frame B that is known with respct to a frame A (the value of ${ }_{B}^{A} T$ is known). Sometimes it is necessary to invert this transform, in order to get a description of A relative to B, (that is ${ }_{A}^{B} T$ ).
i. A straightforward way of calculating the inverse is to compute the inverse of the $4 \times 4$ homogeneous transform. However, this method does not take full advantage of the structure inherent in the transform.
(b). To find ${ }_{A}^{B} T,{ }_{A}^{B} R$ and ${ }^{B} P_{A O R G}$ must be computed from ${ }_{B}^{A} R$ and ${ }^{A} P_{B O R G}$. First, recall that;

$$
\begin{equation*}
{ }_{A}^{B} R={ }_{B}^{A} R^{T} \tag{186}
\end{equation*}
$$

Next, the description of ${ }^{A} P_{B O R G}$ is changed into B by using Eq. 168

$$
\begin{equation*}
{ }^{B}\left({ }^{A} P_{B O R G}\right)={ }_{A}^{B} R{ }^{A} P_{B O R G}+{ }^{B} P_{A O R G} \tag{187}
\end{equation*}
$$

The left-hand side of Eq. 187 must be zero, therefore,

$$
\begin{equation*}
{ }^{B} P_{A O R G}={ }_{A}^{B} R^{A} P_{B O R G}=-{ }_{B}^{A} R^{T A} P_{B O R G} \tag{188}
\end{equation*}
$$

Using Eq. 186 and Eq. 188 , the form of ${ }_{A}^{B} T$ can be written as;

$$
{ }_{A}^{B} T=\left[\begin{array}{c|c}
{ }_{B}^{A} R^{T} & -{ }_{B}^{A} R^{T A} P_{B O R G}  \tag{189}\\
\hline 000 & 1
\end{array}\right]
$$

Therefore, from this notation,

$$
\begin{equation*}
{ }_{A}^{B} T={ }_{B}^{A} T^{-1} \tag{190}
\end{equation*}
$$

### 12.3.1.5 Transform Equations

1. Figure 12.35 indicates a situation in which frame D can be expressed as products of transformations in two different ways. First,

$$
\begin{equation*}
{ }_{D}^{U} T={ }_{A}^{U} T{ }_{D}^{A} T \tag{191}
\end{equation*}
$$

Second:

$$
\begin{equation*}
{ }_{D}^{U} T={ }_{B}^{U} T_{C}^{B} T_{D}^{C} T \tag{192}
\end{equation*}
$$

Equation 191 and Eq. 192 can be set equal to each other to construct a transform equation:

$$
\begin{equation*}
{ }_{A}^{U} T_{D}^{A} T={ }_{B}^{U} T_{C}^{B} T_{D}^{C} T \tag{193}
\end{equation*}
$$



Figure 12.35: SET OF TRANSFORMS FORMING A LOOP 42
2. Transform equations can be used to solve for transforms in the case of $n$ unknown transforms and $n$ transform equations.
(a). Consider Eq. 193 in the case that all transforms are known expect for ${ }_{C}^{B} T$. Here, there is one transform equation and one unknown transform, the solution can be easily found by;

$$
\begin{equation*}
{ }_{C}^{B} T={ }_{B}^{U} T^{-1 U} T_{D}^{A} T_{D}^{C} T^{-1} \tag{194}
\end{equation*}
$$

3. Assume the transform ${ }_{T}^{B} T$ in Fig. 12.36 is known, which describes the frame at the manipulator's fingertips $T$ relative to the base of the manipulator $B$, that the location of the tabletop is known relative to the manipulator's base (because, there is a description of the frame $S$ that is attached to the table as shown, ${ }_{S}^{B} T$ ), and that the location of the frame attached to the bolt lying on the table relative to the table frame is known, ${ }_{G}^{S} T$.
(a). The position and orientation of the bolt relative to the manipulator's hand, ${ }_{G}^{T} T$, can be calculated as shown below;

$$
\begin{equation*}
{ }_{G}^{T} T={ }_{T}^{B} T{ }_{S}^{-1 B} T_{G}^{S} T \tag{195}
\end{equation*}
$$



Figure 12.36: Manipulator Reaching for a bolt |42

### 12.3.1.6 More on Representation of Orientation

1. Rotation matrices are special in that all columns are mutually orthogonal and have unit magnitude. Further, the determinant of a rotation matrix is always equal to +1 .
(a). Rotation matrices may also be called proper orthonormal matrices.
i. proper refers to the fact that the determinant is +1 . Non-proper orthonormal matrices have the determinant -1 .
2. It is natural to ask whether it is possible to describe an orientation with fewer than nine numbers. A result from linear algebra (known as Cayley's formula for orthonormal matrices), states that, for any proper orthonormal matrix R, there exists a skewsymmetric $S$ such that;

$$
\begin{equation*}
R=\left(I_{3}-S\right)^{-1}\left(I_{3}+S\right) \tag{196}
\end{equation*}
$$

Where $I_{3}$ is a $3 \times 3$ unit matrix. A skew-symmetric matrix ( $\mathrm{S}=-S^{-1}$ ) of dimension 3 is specified by three parameters, $\left(s_{x}, s_{y}, s_{z}\right)$ as

$$
S=\left[\begin{array}{ccc}
0 & -s_{x} & s_{y}  \tag{197}\\
s_{x} & 0 & -s_{x} \\
-s_{y} & s_{x} & 0
\end{array}\right]
$$

Therefore, an immediate consequence of Eq. 196 is that any $3 \times 3$ rotation matrix can be specified by just three parameters
3. The nine elements of a rotation matrix are not all independent. In fact, given a rotation matrix, $R$, it is easy to write down six dependencies between the elements. Imagine $R$ as three columns, as originally introduced;

$$
R=\left[\begin{array}{lll}
\hat{X} & \hat{Y} & \hat{Z} \tag{198}
\end{array}\right]
$$

These three vectors are the unit axes of some frame written in terms of the reference frame. Each is a unit vector, and all three must be mutually perpendicular therefore, there are six constraints on the nine matrix elements;

$$
\begin{array}{r}
|\hat{X}|=1, \\
|\hat{Y}|=1, \\
|\hat{Z}|=1, \\
\hat{X} \cdot \hat{Y}=0,  \tag{199}\\
\hat{X} \cdot \hat{Z}=0, \\
\hat{Y} \cdot \hat{Z}=0
\end{array}
$$

4. Since rotation can be thought of either as operators or as descriptions of orientation, it is not surprising that different representations are favored for each of these uses.

Rotation matrices are useful as operators. Their matrix form is such that, when multiplied by a vector, they perform the rotation operation.

However, rotation matrices are somewhat unwieldy when used to specify an orientation.

A human operator at a computer terminal who wishes to type in the specification of the desired orientation of a robot's hand would have a hard time inputting a nine-element matrix with orthonormal columns. A representation that requires only three numbers would be simpler. The following sections introduce several such representations.

## X-Y-Z Fixed Angles

One method of describing the orientation of a frame $B$ is as follows

Start with the frame coincident with a known reference frame A. Rotate B first about $\hat{X}_{A}$ by an angle $\gamma$, then about $\hat{Y}_{A}$ by an angle $\beta$, and finally about $\hat{Z}_{A}$ by an angle $\alpha$

Each of the three rotations take place about an axis in the fixed reference frame A. This convection for specifying an orientation will be called X-Y-Z Fixed Angles
"Fixed" refers to the fact that the rotations are specified about the fixed reference frame, Fig. 12.37.

Sometimes this convection is refereed to as roll, pitch, yaw angles, but care must be used, as this name is often given to other related but different convections.


Figure 12.37: X-Y-Z fixed angles 42]

### 12.3.1.7 Computational Considerations

1. The availability of inexpensive computing power is largely responsible for the growth of the robotics industry; yet, for some time to come, efficient computation will remain an important issue in the design of a manipulation system.
2. The homogeneous representation is useful as a conceptual entity, but transformation software typically used in industrial manipulation systems does not make use of it directly, because the time spent multiplying zeros and ones is wasteful.
(a). Usually, the computations shown in Eq. 188 and Eq. 189 are performed, rather than the direct multiplication or inversion of $4 \times 4$ matrices.


Figure 12.38: Transforming velocities 42]

1. The order in which transformations are applied can make a large difference in the amount of computation required to compute the same quantity. Consider performing multiple rotations of a vector, as in;

$$
\begin{equation*}
{ }^{A} P={ }_{B}^{A} R_{C}^{B} R_{D}^{C} R^{D} P \tag{200}
\end{equation*}
$$

One choice is to first multiply the three rotation matrices together to form ${ }_{D}^{A} R$ in the expression;

$$
\begin{equation*}
{ }^{A} P={ }_{D}^{A} R^{D} P \tag{201}
\end{equation*}
$$

Forming ${ }_{D}^{A} R$ from its three constituents requires 54 multiplication and 36 additions.
Performing the final matrix-vector multiplication of Eq. 201 requires an additional 9 multiplications and 6 additions, bringing the total to 63 multiplications and 42 additions If, Instead, the vector is transformed though the matrices one at a time, that is;

$$
\begin{align*}
{ }^{A} P & ={ }_{B}^{A} R{ }_{C}^{B} R{ }_{D}^{C} R{ }^{D} P, \\
{ }^{A} P & ={ }_{B}^{A} R{ }_{C}^{B} R^{C} P, \\
{ }^{A} P & ={ }_{B}^{A} R{ }^{B} P,  \tag{202}\\
{ }^{A} P & ={ }^{A} P
\end{align*}
$$

Then the total computation requires only 27 multiplications and 18 additions, fewer than half the computations required by the other method.

### 12.3.2 Manipulator Kinematics

1. Kinematics is the science of motion that treats the subject without regard to the forces that cause it.
(a). Within the science of kinematics, one studies the position, the velocity, the acceleration, and all higher order derivatives of the position variables.
i. Hence, the study of the kinematics of manipulators refers to all the geometrical and time-based properties of the motion.

### 12.3.2.1 Link Description

1. A manipulator may be thought of as a set of bodies connected in a chain of joints. These bodies are called links. Joints form a connection between a neighboring pair of links. The term lower pair is used to describe the connection between a pair of bodies when the relative motion is characterized by two surfaces sliding over one another. Figure 12.39 shows the six possible lower pair joints


Figure 12.39: The six possible lower-Pair joints 42
2. Mechanical-design considerations favor manipulators' generally being constructed from joints that exhibit just one degree of freedom.
(a). Most manipulators have revolute joints or have sliding joints called prismatic joints.
i. In the rare case that a mechanism is built with a joint having having $n$ degrees of freedom, it can be modeled as $n$ joints of one degree of freedom connected to $n-1$ links of zero length.
3. The links are numbered starting from the immobile base of the arm, which might be called link 0 . The first moving body is link 1 , and so on, out to the free end of the arm, which is link $n$.
(a). In order to position an end-effector generally in 3-space, a minimum of six joints is required. Typically manipulators have five or six joints. Some robots are actually not as simple as a single kinematic chain - these have parallelogram linkages or other closed kinematic structures.
4. A single link of a typical robot has many attributes that a mechanical designer had to consider during its design: the type of material used, the strength and stiffness of the link, the location and type of joint bearings, the external shape, the weight and inertia, and more.
(a). However, for the purposes of obtaining the kinematic equations of the mechanism, a link is considered only a a rigid body that defines the relationship between two neighboring joint axes of a manipulator.
i. Joint axes are defined by lines in space. Joint axis $i$ is defined by a line in space, or a vector direction, about which link $i$ rotates relative to link $i-1$.
A. It turns out that, for kinematic purposes, a link can be specified with two numbers, which define the relative location of the two axes in space.


Figure 12.40: Example of a link 42
5. For any axes in 3 -space, there exists a well-defined measure of distance between them. This distance is measured along a line that is mutually perpendicular to both axes.
(a). This mutual perpendicular always exists; it is unique expect when both axes are parallel, in which case, there are many mutually perpendiculars of equal length
(b). Figure 12.40 shows a link $i-1$ and the mutually perpendicular line along which the link length, $a_{i-1}$, is measured.
i. Another way to visualize the link parameter $a_{i-1}$ is to imagine an expanding cylinder whose axis is the joint $i-1$ axis -when it just touches axis $i$, the radius of the cylinder is equal to $a_{i-1}$.
6. The second parameter needed to define the relative location of the two axes is called the link twist. Imagine a plane whose normal is the mutually perpendicular line just constructed, project the axes $i-1$ and $i$ onto this plane and measure the angle between them.
(a). This angle is measured from $i-1$ to axis $i$ in the right-hand sense about $a_{i-1}{ }^{2}$.
i. The definition to be used for the twist of a link is $i-1, \alpha_{i-1}$.
A. In Fig. 12.40, $\alpha_{i-1}$ is indicated as the angle between $i-1$ and axis $i$.
B. In the case of intersecting axes, twist is measured in the plane containing both axes, but the sense of $\alpha_{i-1}$ is lost. In this special case, one is free to assign the sign of $\alpha_{i-1}$ arbitrarily.


Figure 12.41: A simple link that supports two revolute axes 42

### 12.3.2.2 Link-Connection Description

1. The problem of connecting the links of a robot together is once again filled with many questions for the mechanical designer to resolve. These include the strength of the joint, its lubrication, and the bearing and gearing of mounting.
(a). However, for the investigation of kinematics, only two quantities are need to completely specify the way in which links are connected together.


Figure 12.42: The link offset, D, And the joint angle, $\theta$, are two PARAMETERS THAT MAY BE USED TO DESCRIBE THE NATURE OF THE CONNECTION BETWEEN NEIGHBORING LINKS. 42

## Intermediate links in the chain

1. Neighboring links have a common joint axis between them. One parameter of interconnection has to do with the distance along the common axis from one link to the next. This parameter is called the link offset.
(a). The offset at joint axis $i$ is called $d_{i}$.
(b). The second parameter describes the amount of rotation about this common axis between one link and its neighbor. This is called the joint angle, $\theta_{i}$.
2. Figure 12.42 shows the interconnection of link $i-1$ and link $i$. Recall that, $a_{i-1}$ is the mutual perpendicular between the two axes of link $i-1$. Likewise $a_{i}$ is the mutual perpendicular defined for link $i$.
(a). The first parameter of interconnection is the link offset, $d_{i}$, which is the signed distance measured along the axis of joint $i$ from the point where $a_{i}$ intersects the axis to the point where $a_{i}$ intersects the axis.
i. The offset $d_{i}$ is indicated in Fig. 12.42. The link offset $d_{i}$ is variable if joint $i$ is prismatic.
(b). The second parameter of interconnection is the angle made between an extension of $a_{i-1}$ and $a_{i}$ measured about the axis of joint $i$.
i. This is indicated in Fig. 12.42, where the lines with the double has marks are parallel. This parameter is named $\theta_{i}$ and is variable for a revolute joint.

## First and last links in the chain

1. Link length, $a_{i}$, and link twist, $\alpha_{i}$, depend on joint axes $i$ and $i+1$.
(a). Hence, $a_{1}$ through $a_{n-1}$ and $\alpha_{1}$ through $\alpha_{n-1}$ are defined.
i. At the ends of the chain, zero will be assigned to these quantities.
A. That is, $a_{0}=a_{n}=0.0$ and $\alpha_{0}=\alpha_{n}=0.0$
ii. Link offset, $d_{i}$, and joint angle, $\theta_{i}$, are well defined for joints 2 through $n-1$ according to the conventions previously used.
A. If joint 1 is revolute, the zero position for $\theta_{i}$ may be chosen arbitrarily; $d_{1}=0.0$ will be the convention.
B. If joint 1 is prismatic, the zero position of of $d_{1}$ may be chosen arbitrarily; $\theta_{1}=0.0$ will be the convention.
C. The exact same statements apply to joint $n$.
D. These conventions have been chosen so that, in a case where a quantity could be assigned arbitrarily, a zero value is assigned so that later calculations will be as simple as possible.

## Link Parameters

1. Any robot can be described kinematically by giving the values of four quantities for each link.
(a). Two describe the link itself and two describe the link's connection to a neighboring link.
(b). In the usual case of a revolute joint, $\theta_{i}$, is called the joint variable, and the other three quantities would be fixed link parameters.
(c). For prismatic joints, $d_{i}$ is the joint variable, and the other three quantities are fixed link parameters.
(d). The definition of mechanisms by means of these quantities is a convection called the Denavit-Hartenberg notation.
2. For a six-jointed robot, 18 numbers would be required to describe the fixed portion of its kinematics completely.
(a). In the case of a six-jointed robot with all revolute joints, the numbers are in the form of six sets of ( $\alpha_{i}, \alpha_{i}, d_{i}$ ).

### 12.3.2.3 Convection for Affixing Frames to Links

1. In order to describe the location of each link relative to its neighbors, define a frame attached to each link.
(a). The link frames are named by number according to the link to which they are attached.
i. That is, $\{i\}$ is attached to link $i$.

## Intermediate links in the chain

1. The convection used to locate frames on the links is as follows;
(a). The $\hat{Z}$-axis of frame $\{i\}$, called $\hat{Z}_{i}$, is coincident with the joint axis $i$.
(b). the origin of frame $\{i\}$ is located where the $a_{i}$ perpendicular intersects the joint $i$ axis.
(c). $\hat{X}_{i}$ points along $a_{i}$ in the direction from joint $i$ to $i+1$.
2. In the case of $a_{i}=0, \hat{X}$ is normal to the plane $\hat{Z}_{i}$ and $\hat{Z_{i+1}}$.
(a). $\alpha_{i}$ is defined as being measured in the right-hand sense about $\hat{X}_{i}$, and so the freedom of choosing the sign $\alpha_{i}$ in this case corresponds to two choices for the direction of $X^{\wedge}-i$.
(b). $\hat{Y}_{i}$ is formed by the right-hand rule to complete the $i$ th frame.
(c). Figure 12.43 shows the location of $\{i-1\}$ for a general manipulator


Figure 12.43: Link frames are attached so that frame $\{i\}$ is attached RIGIDLY TO LINK $i$. 42]

## First and last links in the chain

1. Attach a frame to the base of a robot, or link 0 , called $\{0\}$.
(a). This frame does not move; for the problem of arm kinematics; it can be considered the reference frame.
i. The position of all other link frames can be described in terms of this frame.
2. Frame $\{0\}$ is arbitrary so it always simplifies matter to choose $\hat{Z}_{0}$ along xis 1 and to locate frame $\{0\}$ so that it coincides with frame $\{1\}$ when joint variable 1 is zero.
(a). Using this convention, $a_{0}=0.0, \alpha_{0}=0.0$ will always be true.
i. Additionally, it ensures that $d_{i}=0.0$ if joint 1 is revolute, or $\theta_{1}=0.0$ if joint 1 is prismatic.
3. For joint $n$ revolute, the direction of $\hat{X_{N}}$ is chosen so that it aligns with $\hat{X_{N-1}}$ when $\theta_{n}=0.0$, and the origin of frame $\{N\}$ is chosen so that $d_{n}=0.0$
4. For joint $n$ prismatic, the direction of $\hat{X}_{N}$ is chosen so that $\theta_{n}=0.0$, and the origin of frame $\{N\}$ is chosen at the intersection of $X_{N-1}$ and joint axis $n$ when $d_{n}=0.0$

## Summary of the link parameters in terms of the link frames

1. If the link frames have been attached to the links according to the used convention, the following definitions of the link parameters are valid:
(a). $a_{i}=$ the distance from $\hat{Z}_{i}$ to $\hat{Z_{i+1}}$ measured along $\hat{X}_{i}$
(b). $\alpha_{i}=$ the angle from from $\hat{Z}_{i}$ to $\hat{Z_{i+1}}$ measured about $\hat{X}_{i}$
(c). $d_{i}=$ the distance from $\hat{X_{i-1}}$ to $\hat{X}_{i}$ measured along $\hat{Z}_{i}$
(d). $\theta_{i}=$ the angle from $\widehat{X_{i-1}}$ to $\hat{X}_{i}$ measured about $\hat{Z}_{i}$
2. Usually it is chosen that $a_{i}>0$, because it corresponds to a distance.
(a). However, $\alpha_{i}, d_{i}, \theta_{i}$ are signed quantities.
3. The convection outlined above does not result in a unique attachment of frames to links.
(a). First of all, when when the $\hat{Z}_{i}$ axis is aligned with joint axis $i$, there are two choices of direction in which to point $\hat{Z}_{i}$.
(b). Furthermore, in the case of intersecting joint axes (i.e. $a_{i}=0$ ), there are two choices for the direction of $\hat{X}_{i}$, corresponding to the choice of signs for thenormal to the plane containing $\hat{Z}_{i}$ and $\hat{Z_{i+1}}$.
(c). When axes $i$ and $i+1$ are parallel, the choice of origin location of $\{i\}$ is arbitrary.
i. Though generally chosen in order to cause $d_{i}$ to be zero
(d). Also, when prismatic joints are present, there is quite a bit of freedom in frame assignment

## Summary of link-frame attachment procedure

1. The following is a summary of the procedure too follow when faced with a new mechanism, in order to properly attach the link frames:
(a). Identify the joint axes and imagine (or draw) infinite lines along them.
i. For steps B through E below, consider two of these neighboring lines (at axes $i$ and $i+1$
(b). Identify the common perpendicular between them, or point of intersection.
i. At the point of intersection, or at the point where the common perpendicular meets the $i$ th axis, assign the link-frame origin
(c). Assign the $\hat{Z}_{i}$ axis pointing along the $i$ th joint axis.
(d). Assign the $\hat{X}_{i}$ axis pointing along the common perpendicular, or, if the axes intersect, assign $\hat{X}_{i}$ to be normal to the plane containing the two axes
(e). Assign the $\hat{Y}_{i}$ axis to complete a right-hand coordinate system.
(f). Assign $\{0\}$ to match $\{1\}$ when the first joint variable is zero. For $\{N\}$, choose an origin location and $\hat{X}_{N}$ direction freely, but generally so as to cause as many linkage parameters as possible to become zero.

## Example 1 of link-frame attachment

1. Figure 12.44 (a) shows a three-link planar arm. Since all the joints are revolute, this manipulator is sometimes called an RRR (or 3R) mechanism.
2. Figure 12.44 (b) is a schematic representation of the same manipulator.
(a). Note, the double hash marks indicated on each of the three axes, which indicate that these axes are parallel.
3. Assign link frames to the mechanism and give the Denavit-Hartenberg parameters


Figure 12.44: A three-Link planar arm. On the right, the same
manipulator is Shown by means of a simple schematic notation. Hash marks ON THE AXES INDICATE THAT THEY ARE MUTUALLY PARALLEL. [42

1. Start by defining the reference frame $\{0\}$.
(a). It is fixed to the base and aligns with frame $\{1\}$ when the joint variable $\left(\theta_{1}\right)$ is zero.
i. Therefore, frame $\{0\}$ is positioned as shown in Fig. 12.45 with $\hat{Z}_{0}$ aligned with the joint- 1 axis.
2. For this arm, all joint axes are oriented perpendicular to the plane of the arm.
3. Since, the arm lies in a plane with all $\hat{Z}$ axes parallel, there are no link offsets.
(a). All $d_{i}$ are zero.
4. All joints are rotational, so when they are at zero degrees all $\hat{X}$ axes must align.


Figure 12.45: Link-Frame assignments 42]

| $i$ | $\alpha_{i-1}$ | $a_{i-1}$ | $d_{i}$ | $\theta_{i}$ |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 0 | 0 | 0 | $\theta_{1}$ |
| 2 | 0 | $L_{1}$ | 0 | $\theta_{2}$ |
| 3 | 0 | $L_{2}$ | 0 | $\theta_{3}$ |

Figure 12.46: LINK Parameters of the three-Link Planar manipulator. \|42

1. With all previous comments in mind, it is easy to find the frame assignments shown in Fig. 12.46
2. Note that, because the joint axes are all parallel and the $\hat{Z}$ axes are taken as pointing out of the paper, all $\alpha_{i}$ are zero.
3. Note also that the kinematic analysis always ends at a frame whose origin lies on the last joint.
(a). Therefore, link 3 does not appear in the link parameters

## Example 2 of link-frame attachments

1. Figure 12.47(a) shows a robot having three degrees of freedom and one prismatic joint. This manipulator can be called a RPR mechanism, in a notation that specifies the type and order of the joints.
2. It is a "cylindrical" robot whose first two joints are analogous to polar coordinates when viewed from above.
3. The last joint provides "roll" for the hand.
4. Figure 12.47 (b) shows the same manipulator in schematic form.
(a). Note the symbol used to represent prismatic joints
(b). Note that a "dot" is used to indicate at which joint two adjacent axes intersect.
(c). Also note, that axes 1 and 2 are orthogonal has been indicated

(a)

(b)

Figure 12.47: Manipulator having three degrees of freedom and one PRISMATIC JOINT. 42

1. Figure 12.48 (a) shows the manipulator with the prismatic joint at minimum extension.
2. The assignment of link frames is shown in Fig. 12.48(b)
3. Note that frame $\{0\}$ and frame $\{1\}$ are shown as exactly coincident in this figure, because the robot is drawn from position $\theta_{1}=0$.
4. Note that frame $\{0\}$, although not at the bottom of the flanged base of the robot, is nonetheless rigidly affixed to link 0 , the non-moving part of the robot.
(a). just as the link frames are not used to describe the kinematics all the way out to the hand, they need not be attached all the way back to the lowest part of the robot.
i. It is sufficient that frame $\{0\}$ be attached anywhere to the non-moving link 0 , and that frame $\{N\}$, the final frame, be attached anywhere to the last link of the manipulator.
5. Note that rotational joints rotate about the $\hat{Z}$ axis of the associated frame, but prismatic joints slide along $\hat{Z}$.
6. In the case that joint $i$ is prismatic, $\theta_{i}$ is a fixed constant, and $d_{i}$ is the variable.


Figure 12.48: LINK-FRAME ASSIGNMENTS OF MANIPULATOR HAVING THREE DEGREES of FREEDOM AND ONE PRISMATIC JOINT. 42

## Example 3 of link-frame assignments

1. Figure 12.49(a) shows a three-link, 3R manipulator for which axes 1 and 2 intersect and axes 2 and 3 are parallel.
2. Figure 12.49 (b) shows the kinematic schematic of the manipulator.
(a). Note that the schematic includes annotations indicating that the first two axes are orthogonal and that the last two are parallel.
3. Demonstrate the non-uniqueness of frame assignments and of the Denavit-Hartenberg parameters by showing several possible correct assignments of frames $\{1\}$ and $\{2\}$.


Figure 12.49: Three-Link, non-Planar manipulator. 42

1. Figure 12.50 shows two possible frame assignments and corresponding parameters for the two possible choices of direction of $\hat{Z}_{2}$.
2. In general, when $\hat{Z}_{i}$ and $\hat{Z_{i+1}}$ intersect, there are two choice for $\hat{X}_{i}$.
(a). In this example, joint axes 1 and 2 intersect, so there are two choices for the direction of $\hat{X}_{1}$.


Figure 12.50: Two possible frame assignments for a three-link, non-PLANAR MANIPULATOR. 42

### 12.3.2.4 Manipulator Kinematics

## Derivation of link transformations

1. The wish is to construct the transform that defines frame $\{i\}$ relative to frame $\{i-1\}$.
(a). In general, this transformation will be a function of the four link parameters. For any given robot, this transformation will be a function of only one variable, the other three parameters being fixed by mechanical design.
i. By defining a frame for each link, the kinematics problem is broken down into $n$ subproblems.
A. In order to solve each of these subproblems, namely ${ }_{i}^{i-1} T$, each subproblem will be broken down into four sub-subproblems.
(I). Each of these four transformations will be a function of one link parameter only and will be simple enough that one can write down its form by inspection
(a). Three intermediate frames will be defined for each link $-\{P\}$, $\{Q\}$, ad $\{R\}$.
2. Figure 12.51 shows the same pair of joints as before with frames $\{P\},\{Q\}$, ad $\{R\}$ defined.
(a). Note that only the $\hat{X}$ and $\hat{Z}$ axes are shown for each from, to make the drawing clearer.
(b). Frame $\{R\}$ differs from $\{i-1\}$ only by a rotation of $\alpha_{i-1}$.
(c). Frame $\{Q\}$ differs from $\{R\}$ by a translation of $a_{i-1}$
(d). Frame $\{P\}$ differs from $\{Q\}$ by a rotation $\theta_{i}$
(e). Frame $\{i\}$ differs from $\{P\}$ by a translation $d_{i}$.


Figure 12.51: Location of intermediate frames $\{P\},\{Q\}$, ad $\{R\}$
3. TO write the transformation that transforms vectors defined in $\{i\}$ to the description $\{i-1\}$, write;

$$
\begin{gather*}
{ }^{i-1} P={ }_{R}^{i-1} T{ }_{Q}^{R} T{ }_{P}^{Q} T{ }_{i}^{P} T^{i} P  \tag{203}\\
\text { or, } \\
{ }^{i-1} P={ }_{i}^{i-1} T^{i} P \tag{204}
\end{gather*}
$$

where;

$$
\begin{equation*}
{ }_{i}^{i-1} T={ }_{R}^{i-1} T{ }_{Q}^{R} T{ }_{P}^{Q} T{ }_{i}^{P} T \tag{205}
\end{equation*}
$$

Considering each of these transformations, Eq. 205 may be written as;

$$
\begin{equation*}
{ }_{i}^{i-1} T=R_{x}\left(\alpha_{i-1}\right) D_{x}\left(a_{i-1}\right) R_{z}\left(\theta_{i}\right) D_{z}\left(D_{i}\right) \tag{206}
\end{equation*}
$$

$$
\begin{equation*}
{ }_{i}^{i-1} T=\operatorname{Screw}_{X}\left(a_{i-1}, \alpha_{i-1}\right) \operatorname{Screw}_{Z}\left(d_{i}, \theta_{i}\right) \tag{207}
\end{equation*}
$$

where the notation $\operatorname{Screw}_{Q}(r, \phi)$ stands for the combination of a translation along an axis $\hat{Q}$ by a distance $r$ and a rotation about the same axis by angle $\phi$.

Multiple out Eq. 206 to obtain the general form of $i_{i}^{i-1} T$

$$
{ }_{i}^{i-1} T=\left[\begin{array}{cccc}
c \theta_{i} & -s \theta_{i} & 0 & a_{i-1}  \tag{208}\\
s \theta_{i} c \alpha_{i-1} & c \theta_{i} c \alpha_{i-1} & -s \alpha_{i-1} & -s \alpha_{i-1} d_{i} \\
s \theta_{i} s \alpha_{i-1} & c \theta_{i} s \alpha_{i-1} & c \alpha_{i-1} & c \alpha_{i-1} d_{i} \\
0 & 0 & 0 & 1
\end{array}\right]
$$

## Actuator Space, Joint Space, and Cartesian Space

1. The position of all links of a manipulator of $n$ degrees of freedom can be specified with a set of $n$ joint variables.
(a). This set or variables is often referred to as the $n \times 1$ joint vector
i. The space of all such joint vectors is referred to as joint space
2. SO far, the concern has been with computing the Cartesian space description from knowledge of the joint-space description.
(a). The term Cartesian space is use when position is measured along orthogonal axes and orientation is measured according to any of the conventions mentioned previously.
i. Sometimes, the terms task-oriented space and operational space are used for the Cartesian space.
3. So far, the assumption has been that each kinematic joint is actuated directly by some sort of actuator.
(a). However, in the case of many industrial robots, this is not so.
i. For example, sometimes two actuators work together in a differential pair to move a single joint, or sometimes a linear actuator is used to rotate a revolute joint, through the use of four-bar linkage.
A. In these cases, it is helpful to consider the notion of actuator positions (I). The sensors that measure the position of the manipulator are often located at the actuators, so some computations must be performed to realize the joint vector as a function of a set of actuator aloes, or actuator vector.
4. As indicated in Fig. 12.52, there are three representations of a manipulator's position and orientation.
(a). Descriptions in actuator space, in joint space, and in Cartesian space
i. Until now the concern has been with mappings between representations, as indicated by the solid arrows.


Figure 12.52: Mappings between kinematic descriptions 42

### 12.3.2.5 Frames with Standard Names

1. As a matter of convention, it will be helpful to assign specific names and locations to certain "standard" frames associated with a robot and its workspace.
(a). Figure 12.53 shows a typical situation in which a robot has grasped some sort of tool and is to position the tool tip to a user-defined location.
i. The five frames indicated in Fig. 12.53 are so often referred to that they have defined names.
A. The naming and subsequent use of these five frames in a robot programming and control system facilitates providing general capabilities in an easily understandable way.
(I). All robot motions will be described in terms of these frames.


Figure 12.53: The standard frames 42]

The base frame $\{B\}$

1. $\{B\}$ is located at the base of the manipulator.
2. It is merely another name for frame $\{0\}$.
3. It is affixed to a non-moving pat of the robot, sometimes called link 0 .

The station frame $\{S\}$

1. $\{S\}$ is located in a task-relevant location.
2. In Fig. 12.54, it is at the corner of a table upon which the robot is to work.
3. As far as the user of this robot system is concerned, $\{S\}$ is the universe frame, and all actions of the robot are performed relative to it.
4. It is sometimes called the task frame, the world frame, or the universe frame.
5. The station frame is always specified with respect to the base frame ${ }_{S}^{B} T$.

The wrist frame $\{W\}$

1. $\{W\}$ is affixed to the last link of the manipulator.
2. It is another name for frame $\{N\}$, the link frame attached to the last link of the robot.
3. Very often, $\{W\}$ has its origin fixed at a point called the wrist of the manipulator, and $\{W\}$ moves with the last link of the manipulator.
4. It is defined relative to the base frame.
(a). that is, $\{W\}={ }_{W}^{B} T={ }_{N}^{0} T$

## The tool frame $\{T\}$

1. $\{T\}$ is affixed to the end of any toll the robot happens to be holding.
2. When the hand is empty, $\{T\}$ s usually located with its origin between the fingertips of the robot
3. The tool frame is always specified with respect to the wrist frame.
4. In Fig. 12.54, the tool frame is defined with its origin at the tip of a pin that the robot is holding.

## The goal frame $\{G\}$

1. $\{G\}$ is a description of the location to which the robot is to move the tool.
(a). Specifically, this means that, at the end of the motion, the tool frame should be brought to coincidence with the goal frame.
2. $\{G\}$ is always specified relative to the station frame.
3. In Fig. 12.54 , the goal is located at a hole in which the pin is to be inserted.

### 12.3.2.6 Where is the tool?

1. One of the first capabilities a robot must have is to be able to calculate the position and orientation of the tool it is holding (or of its empty hand) with respect to a convenient coordinate system.
(a). That is, the wish is to calculate he value of the tool frame, $\{T\}$, relative to the station frame, $\{S\}$.
i. Solving a simple transform leads to;

$$
\begin{equation*}
{ }_{T}^{S} T={ }_{S}^{B} T^{-1}{ }_{W}^{B} T{ }_{T}^{W} T \tag{209}
\end{equation*}
$$

2. Equation 209 implements whats is called the WHERE function in some robot systems.
(a). It computes "where" the arm is.
i. For Fig. 12.54 , the output of the WHERE function would be the position and orientation of the pin relative to the table top.
3. Equation 209 can be thought of as generalizing the kinematics.
(a). ${ }_{T}^{S} T$ computes the kinematics due to geometry of the linkages, along with a general transform (which might be considered a fixed link) at the base $\left({ }_{S}^{B} T\right)$ and another at the end-effector $\left({ }_{T}^{W} T\right)$.
i. These extra transforms allow for the inclusion of tools with offsets and twist to operate with respect ti an arbitrary station frame.


Figure 12.54: Assignment of the standard frames 42

### 12.3.3 Inverse manipulator kinematics

### 12.3.3.1 Solvability

## Existence of Solutions

1. The problem of solving the kinematic equations of a manipulator is a nonlinear one.
2. The question for whether any solution exists at all raises the question of the manipulator's workspace.
(a). Workspace is that volume of space that the end-effector of the manipulator can reach.
(b). For a solution to exist, the specified goal point must lie within th workspace.
(c). It is useful to consider two definitions of workspace:
i. Dextrous workspace is that volume of space that the robot end-effector cna reach with all its orientations.
ii. Reachable workspace is the volume of space that the robot can reach in at least one orientation.
3. Consider the workspace of the two-link manipulator in Fig. 12.55.
(a). If $l_{1}=l_{2}$, the the reachable workspace consists of a disc of radius $2 l_{1}$.
i. The dextrous workspace consists of only a single point, the origin.
(b). If $l_{1}$ does not equal $l_{2}$, then there is no dextrous workspace, and the reachable workspace becomes a ring of outer radius $l_{1}+l_{2}$ and inner radius - $l_{1}-l_{2}-$.
(c). Inside the reachable workspace there are four possible orientations of the endeffector. On the boundaries of the workspace there is only one possible orientation.


Figure 12.55: Two-Link manipulator with Link Lengths $l_{1}$ and $l_{2}$ 42
4. These considerations of workspace for the two-link manipulator have assumed that all the joints can rotate 360 degrees. This is rarely true for actual mechanisms.
(a). When joint limits are a subset of the full 360 degrees, then the workspace is obviously correspondingly reduced, with in extent, or in the number of possible orientations attainable.
i. For example, if the arm in Fig. 12.55 has 360 -degree motion for $\theta_{1}$, but only $0 \leq \theta_{2} \leq 180^{\circ}$, the the reachable workspace has the same extent, but only one orientation is attainable at each point.
5. When a manipulator has fewer than six degrees of freedom, it cannot attain general goal positions and orientations in 3-space.
(a). Clearly, the planar manipulator in Fig. 12.55 cannot reach out of the plane, so any goal point with a non-zero Z coordinate value can be quickly rejected as unreachable.
6. Workspace also depends on the tool-frame transformation, because it is usually the tool-tip that is discussed when speaking of reachable points in space.
(a). Generally, the tool transformations is performed independetly of the manipulator kinematics and inverse kinematics therefore, one must consider the workspace of the wrist frame $\{W\}$.
i. FOr a given end-effector, a tool frame, $\{T\}$, is defined.
A. Given a goal frame, $\{G\}$, the corresponding $\{W\}$ frame is calculated therefore, the question must be asked; Does this desired position and orientation of $\{W\}$ lie in the workspace?
(I). If the desired position and orientation of the wrist frame is in the workspace, then at least one solution exists.

## Multiple solutions

1. Another possible problem encounter in solving kinematic equations is hat of multiple solutions.
(a). A planar arm with three revolute joints has a large dextrous workspace in the plane, because any position in the interior of its workspace can be reached with any orientation.
2. Figure ?? shows a three-link planar arm with its end-effector at a certain position and orientation.
(a). The dashed lines indicate a second possible configuration in which the same endeffector position and orientation are achieved.


Figure 12.56: Two-LINK manipulator with Link lengths $l_{1}$ and $l_{2}$ 42]


Figure 12.57: Two-LINK MANIPULATOR WITH LINK LENGTHS $l_{1}$ AND $l_{2}$ 42]
3. The fact that a manipulator has multiple solutions can cause problems, because the system has to be able to chose one.
(a). The criteria upon which to base a decision vary, but a reasonable choice would be the closest solution.
i. For example, if the manipulator at point $\mathrm{A}_{i}$ as seen in FIg. 12.57, and the wish is to move it to point B , a good choice would be the solution that minimizes the amount that each joint is required to move.
A. Hence, in the absence of the obstacle, the upper dashed configuration in Fig. 12.57 would be chosen.
B. Furthermore, the size and weight of each joint must be considered. It is easier to move smaller and lighter joints that bigger joints
C. Another problem is obstacles in the way of the path. Therefore, in Fig. 12.57 the lower dotted line is the best option because of the obstacle.
4. The number of solutions depends upon the number of joints in the manipulator BUT is also a function of the link parameters and the allowable ranges of motion of the joints.
(a). For example, the robot in Fig. ?? can reach certain goals with eight different solutions.
i. Figure ?? shows four solutions. For each solution pictured, there is another solution in which the last three joint "flip" to an alternate configuration according to the following formulas;

$$
\begin{array}{r}
\theta_{4}^{\prime}=\theta_{4}+180^{\circ} \\
\theta_{5}^{\prime}=-\theta_{5}  \tag{210}\\
\theta_{6}^{\prime}=\theta_{6}+180^{\circ}
\end{array}
$$



Figure 12.58: Four solutions for a 6 DEGREES OF FREEDOM 42
5. In general, the more nonzero link parameters there are, the more ways there will be to reach a certain goal.
(a). For example, consider a manipulator with six rotational joints. Figure 12.59 shows how the maximum number of solutions is related to how many of the link length parameters (the $a_{i}$ are zero.
i. The more that are nonzero, the bigger is the maximum number of solutions.


Figure 12.59: Number of solutions vs nonzero $a_{i} \sqrt{42}$

## Method of Solution

1. Unlike linear equations, there are no general algorithms that may be employed to solve a set of nonlinear equations.
(a). In considering methods of solutions, it will be wise to define what constitutes the "solution" of a given manipulator.
2. A manipulator will be considered solvable if the joint variable can be determined by an algorithm that allow one to determine all sets of joint variables associated with a given position and orientation.
3. The main point of definition is that it requires, in the case of multiple solutions, that it be possible to calculate all solutions.
(a). Hence, one does not consider some numerical iterative procedure as solving the manipulator - namely, those methods not guaranteed to find all solutions.
4. All proposed manipulator strategies are split into two broad classes: closed-form solutions and numerical solutions
(a). Because of their iterative nature, numerical solutions generally are much slower than the corresponding closed-form solution
i. So much so that for most uses, the numerical approach is not considered for the solution of kinematics.
5. Because of the problems with numeric solution, the focus will be on closed-form solution methods.
(a). In this context, "closed form" means a solution method based on analytic expressions or on the solution of a polynomial of degree 4 or less, such that non-iterative calculations suffice to arrive at a solution.
i. Within the class of closed-form solutions, there are two methods of obtaining the solution: algebraic and geometric.
A. Any geometric methods brought to bear are applied by means of algebraic expressions, so the two methods are similar. The methods differ in approach only.
6. A major recent result in kinematics is that, according to the definition of solvability, all systems with revolute and prismatic joints have a total of six degrees of freedom in a single series chain are solvable.
(a). However, this general solution is a numerical one. Only in special cases can robots of six degrees of freedom be solved analytically.
i. These robots for which an analytic (or closed-form) solution exists are characterized either by having several intersecting joint axes or by having many $\alpha_{i}$ equal to 0 or $+-90^{\circ}$.
A. Calculating numerical solutions is generally time consuming relative to evaluating analytic expressions;
(I). Hence, it is considered very important to design a manipulator so that a closed-formed solution exists.
ii. A sufficient condition that a manipulator with six revolute joints have a closed-form solution is that three neighboring joint axes intersect at a point.

### 12.3.3.2 Algebraic vs. Geometric

## Algebraic solution

1. Consider the three-link planar manipulator shown in Fig. 12.60
(a). Following the method introduced earlier, the link parameters can be used to find the kinematic equations of this arm.

$$
{ }_{W}^{B} T={ }_{3}^{0} T=\left[\begin{array}{cccc}
c_{123} & -s_{123} & 0.0 & l_{1} c_{1}+l_{2} c_{12}  \tag{211}\\
s_{123} & c_{123} & 0.0 & l_{1} c_{1}+l_{2} s_{12} \\
0.0 & 0.0 & 1.0 & 0.0 \\
0 & 0 & 0 & 1
\end{array}\right]
$$



Figure 12.60: Three-Link planar manipulator and its link parameters. 42

1. To focus the discussion on inverse kinematics, it is assumed that the necessary transformations have been performed so that the goal point is a specification of the wrist frame relative to the base frame, ${ }_{W}^{B} T$.
(a). Because the focus is on a planar manipulator, specification of these goal points can be accomplished most easily by specifying three numbers: $\mathrm{x}, \mathrm{y}$, and $\phi$, where $\phi$ is the orientation of link 3 in the plane (relative to the $+\hat{X}$ axis).
i. Hence, rather than giving a general ${ }_{W}^{B} T$ as a goal specification, a transformation with the structure below will be assumed.

$$
{ }_{W}^{B} T=\left[\begin{array}{cccc}
c_{\phi} & -s_{\phi} & 0.0 & x  \tag{212}\\
s_{\phi} & c_{\phi} & 0.0 & y \\
0.0 & 0.0 & 1.0 & 0.0 \\
0 & 0 & 0 & 1
\end{array}\right]
$$

All attainable goals must lie in the subspace implied by the structure of Eq. 212. By equating Eq. 210 and Eq. 212, a set of four nonlinear equations are derived and must be solved for $\theta_{1}, \theta_{2}$, and $\theta_{3}$ :

$$
\begin{align*}
c_{\phi} & =c_{123} \\
s_{\phi} & =s_{123}  \tag{213}\\
x & =l_{1} c_{1}+l_{2} c_{12} \\
y & =l_{1} s_{1}+l_{2} s_{12}
\end{align*}
$$

Now the equations must be solved algebraically. First the third and fourth equations are squared and then added together to obtain;

$$
\begin{equation*}
x^{2}+y^{2}=l_{1}^{2}+l_{2}^{2}+2 l_{1} l_{2} c_{2} \tag{214}
\end{equation*}
$$

where one makes use of,

$$
\begin{align*}
& c_{12}=c_{1} c_{2}-s_{1} s_{2}  \tag{215}\\
& s_{12}=c_{1} s_{2}+s_{1} c_{2}
\end{align*}
$$

Solve Eq. 214 for $c_{2}$ to obtain;

$$
\begin{equation*}
c_{2}=\frac{x^{2}+y^{2}-l_{1}^{2}-l_{2}^{2}}{2 L-1 l_{2}} \tag{216}
\end{equation*}
$$

In order for a solution to exist, the right-hand side of Eq. 216 must have a value between -1 and 1. In the solution algorithm, this constraint would be becked at this time to find out whether a solution exists. Physically, if this constraint is not satisfied, then the goal point is too far away for the manipulator to reach.

Assuming the goal is in the workspace, $s_{2}$ can be written as;

$$
\begin{equation*}
s_{2}= \pm \sqrt{1-c_{2}^{2}} \tag{217}
\end{equation*}
$$

Finally, $\theta_{2}$ can be computed with;

$$
\begin{equation*}
\theta_{2}=\operatorname{Atan} 2\left(s_{2}, c_{2}\right) \tag{218}
\end{equation*}
$$

The choice of signs in Eq. 217 corresponds to the multiple solution in which the choice of "elbow-up" or "elbow-down" can be made. Having found $\theta_{2}$, the third and fourth equations in Eq. 213 can be solved for $\theta_{2}$.

$$
\begin{align*}
& x=k_{1} c_{1}-k_{2} s_{1}  \tag{219}\\
& y=k_{1} s_{1}+k_{2} c_{1}  \tag{220}\\
& \text { where; } \\
& k_{1}=l_{1}+l_{2} c_{2} \\
& k_{2}=l_{2} s_{2} \tag{221}
\end{align*}
$$

In order to solve an equation of this form, a change is performed on the variables.

$$
\begin{gather*}
\text { If, } \\
r=+\sqrt{k_{1}^{2}+k_{2}^{2}}  \tag{222}\\
\text { and } \\
\gamma=\operatorname{Atan} 2\left(k_{2}, k_{1}\right),  \tag{223}\\
\text { then } \\
k_{1}=r \cos (\gamma) k_{2}=r \sin (\gamma) \tag{224}
\end{gather*}
$$

Equation 219 and Eq. 220 can now be written as;

$$
\begin{gather*}
\frac{x}{r}=\cos (\gamma) \cos \left(\theta_{1}\right)-\sin (\gamma) \sin \left(\theta_{1}\right)  \tag{225}\\
\frac{y}{r}=\cos (\gamma) \sin \left(\theta_{1}\right)-\sin (\gamma) \cos \left(\theta_{1}\right)  \tag{226}\\
\text { so, } \\
\cos \left(\gamma+\theta_{1}\right)=\frac{x}{r}  \tag{227}\\
\sin \left(\gamma+\theta_{1}\right)=\frac{y}{r} \tag{228}
\end{gather*}
$$

Use the two-argument arctangent to get;

$$
\begin{gather*}
\gamma+\theta_{1}=\operatorname{Atan} 2\left(\frac{y}{r}, \frac{x}{r}\right)=\operatorname{Atan} 2(y, x)  \tag{229}\\
\text { and so } \\
\theta_{1}=\operatorname{Atan} 2(y, x)-\operatorname{Atan} 2\left(k_{2}, k_{1}\right) \tag{230}
\end{gather*}
$$

Note that, when a choice of sign is made in the solution for $\theta_{2}$ above, it will cause a sign change in $k_{2}$, thus affecting $\theta_{1}$.

Finally, the sum of $\theta_{1}$ through $\theta_{3}$ :

$$
\begin{equation*}
\theta_{1}+\theta_{2}+\theta_{3}=\operatorname{Atan} 2\left(s_{\phi}, c_{\phi}\right)=\phi \tag{231}
\end{equation*}
$$

From Eq. $231 \theta_{3}$ can be solved for.

## Geometric solution

1. In a geometric approach to finding a manipulator's solution, one tries to decompose the spatial geometry of the arm into several plane-geometry problems.
(a). For many manipulators (particularly when $\alpha_{i}=0$ or $\pm 90$ ) this can be done quite easily.
i. For the joint Joint angles can then be solved for by using the tools of plane geometry.
A. For, the arm with three degrees of freedom shown in Fig. 12.60 because the arm is planar, plane geometry directly to find a solution.
2. Figure 12.61 shows the triangle formed by $l_{1}, l_{2}$, and the line joining the origin of frame $\{0\}$ with the origin of frame $\{3\}$.
(a). The dashed lines represent the other possible configuration of the triangle, which would lead to the same position of the frame $\{3\}$.
i. Considering the solid triangle, the "law of cosines" to solve for $\theta_{2}$. Now $\cos \left(180+\theta_{2}\right)=-\cos \left(\theta_{2}\right)$, to get;

$$
\begin{equation*}
c_{2}=\frac{x^{2}+y^{2}-l_{l}^{2}-l_{2}^{2}}{2 l_{1} l_{2}} \tag{232}
\end{equation*}
$$

1. In order for this triangle to exist, the distance to the goal point $\sqrt{x^{2}+y^{2}}$ must be less than or equal to the sum of the link lengths, $l_{1}+l_{2}$.
(a). This condition would be checked at this point in a computational algorithm to verify existence of solutions.
i. This condition is not satisfied when the goal point is out of reach of the manipulator.
A. Assuming a solution exists, this equation is solved for that value of $\theta_{2}$ that lies between 0 and 180 degrees, because only for these values does the triangle in Fig. 12.61 exist.
(I). The other possible solution (the one indicated by the dashed-line triangle) is found by symmetry to be $\theta_{2}^{\prime}=-\theta_{2}$.


Figure 12.61: Plane geometry associated with a three-Link planar Rовот 42]

1. To solve for $\theta_{1}$, expressions must be found for angles $\psi$ and $\beta$ as indicated in Fig. 12.61. (a). First, $\beta$ may be in any quadrant, depending on the signs of x and y . Therefore, a two-argument arctangent must be used:

$$
\begin{equation*}
\beta=\operatorname{Atan} 2(y, x) \tag{233}
\end{equation*}
$$

The law of cosines is again applied to find $\psi$;

$$
\begin{equation*}
\cos (\psi)=\frac{x^{2}+y^{2}+l_{1}^{2}-l_{2}^{2}}{2 l_{1} \sqrt{x^{2}+y^{2}}} \tag{234}
\end{equation*}
$$

Here, the arc-cosine must be solved so that $0 \leq \psi \leq 180^{\circ}$, in order that the geometry which leads to Eq. 234 will be preserved. These considerations are typical when using a geometric approach - one must apply the formulas derived over only a range of variables such that the geometry is preserved. Then one has;

$$
\begin{equation*}
\theta_{1}=\beta \pm \psi \tag{235}
\end{equation*}
$$

where the plus sign is used if $\theta_{2}<0$ and the minus sign if $\theta_{2}>0$.

The sum of the three joint angles must be the orientation of the last link;

$$
\begin{equation*}
\theta_{1}+\theta_{2}+\theta_{3}=\phi \tag{236}
\end{equation*}
$$

Equation 236 is solved for $\theta_{3}$ to complete the solution.

### 12.3.3.3 Algebraic solution by reduction to polynomial

1. Transcendental equations are often difficult to solve because, even when there is only one variable (say $\theta) \mathrm{m}$ it generally appears as $\sin \theta$ and $\cos \theta$.
(a). Making the following substitutions, however, yields an expression in terms of a single variable, $u$

$$
\begin{align*}
u & =\tan \frac{\theta}{2} \\
\cos \theta & =\frac{1-u^{2}}{1+u^{2}}  \tag{237}\\
\sin \theta & =\frac{2 u}{1+u^{2}}
\end{align*}
$$

(b). This is a very important geometric substitution used often in solving kinematic equations.
i. These substitutions convert transcendental equations into polynomial equations in $u$.

### 12.3.3.4 Pieper's solution when three axes intersect

1. As mentioned earlier, although a completely general robot woth six degrees of freedom does not have a closed-form solution, certain important special cases can be solved.
2. When the last three axes intersect, the origins of link frames $\{4\},\{5\}$, and $\{6\}$ are all located at this point in the intersection. This point is given in base coordinates as;

$$
{ }^{0} P_{4 O R G}={ }_{1}^{0} T{ }_{2}^{1} T{ }_{3}^{2} T^{3} P_{4 O R G}=\left[\begin{array}{c}
x  \tag{238}\\
y \\
z \\
1
\end{array}\right]
$$

or, using the fourth column of Eq. 208 for $i=4$, as

$$
\begin{gathered}
{ }^{0} P_{4 O R G}={ }_{1}^{0} T{ }_{2}^{1} T{ }_{3}^{2} T\left[\begin{array}{c}
a_{3} \\
-d_{4} s \alpha_{3} \\
d_{4} c \alpha_{3} \\
1
\end{array}\right] \\
\text { or as, }
\end{gathered}
$$

$$
{ }^{0} P_{4 O R G}={ }_{1}^{0} T{ }_{2}^{1} T\left[\begin{array}{c}
f_{1}\left(\theta_{3}\right)  \tag{240}\\
f_{2}\left(\theta_{3}\right) \\
f_{3}\left(\theta_{3}\right) \\
1
\end{array}\right]
$$

where

$$
\left[\begin{array}{c}
f_{1}  \tag{241}\\
f_{2} \\
f_{3} \\
1
\end{array}\right]={ }_{3}^{2} T\left[\begin{array}{c}
a_{3} \\
-d_{4} s \alpha_{3} \\
d_{4} c \alpha_{3} \\
1
\end{array}\right]
$$

Using Eq. 208 in Eq. 242 yields the following expressions for $f_{1}$ :

$$
\begin{aligned}
& f_{1}=a_{3} c_{3}+d_{4} \alpha_{3} S_{3}+a_{2} \\
& f_{2}=a_{3} c \alpha_{2} s_{3}-d_{4} s \alpha_{3} c \alpha_{2} c_{3}-d_{4} s \alpha_{2} c \alpha_{3}-d_{3} s \alpha_{2} \\
& f_{3}=a_{3} s \alpha_{2} s_{3}-d_{4} s \alpha_{3} s \alpha_{2} c_{3}-d_{4} c \alpha_{2} c \alpha_{3}-d_{3} s \alpha_{2}
\end{aligned}
$$

Using Eq. 208 for ${ }_{1}^{0} T$ and ${ }_{2}^{1} T$ in Eq. 241, to obtain;

$$
{ }^{0} P_{4 O R G}=\left[\begin{array}{c}
c_{1} g_{1}-s_{1} g_{2}  \tag{243}\\
s_{1} g_{1}+c_{1} g_{2} \\
g_{3} \\
1
\end{array}\right]
$$

where;

$$
\begin{align*}
g_{1} & =c_{2} f_{1}-s_{2} f_{2}+a_{1} \\
g_{2} & =s_{2} c \alpha_{1} f_{1}+c_{2} c \alpha_{1} f_{2}-s \alpha_{1} f_{3}-d_{2} s \alpha_{1}  \tag{244}\\
g_{3} & =s_{2} s \alpha_{1} f_{1}+c_{2} s \alpha_{1} f_{2}+c \alpha_{1} f_{3}-d_{2} c \alpha_{1}
\end{align*}
$$

Now an expression for the squared magnitude of ${ }^{0} P_{4 O R G}$ can be written, which will be denoted as $r=x^{2}+y^{2}+z^{2}$ and which is seen from Eq. 243 to be;

$$
\begin{equation*}
r=g_{1}^{2}+g_{2}^{2}+g_{3}^{2} \tag{245}
\end{equation*}
$$

So, using Eq. 244, along with the Z-component equation from Eq. 244, as a system of two equations in the form;

$$
\begin{align*}
& r=\left(k_{1} c_{1}+k_{2} s_{2}\right) 2 a_{1}+k_{4}  \tag{246}\\
& z=\left(k_{1} s_{1}+k_{2} c_{2}\right) s \alpha_{1}+k_{4}
\end{align*}
$$

where;

$$
\begin{align*}
k_{1} & =f_{1} \\
k_{2} & =-f_{2} \\
k_{3} & =f_{1}^{2}+f_{2}^{2}+f_{3}^{2}+a_{1}^{2}+d_{2}^{2}+2 d_{2} f_{3}  \tag{247}\\
k_{4} & =f_{3} c \alpha_{1}+d_{2} c \alpha_{1}
\end{align*}
$$

### 12.3.4 Trajectory generation

### 12.3.4.1 General considerations in path description and generation

1. For the most part, the motions of the manipulator will be considered as motions of the tool frame, $\{T\}$, relative to the station frame, $\{S\}$.
(a). This is the same manner in which an eventual user of the system would think, and designing a path description and generation system in these terms will result in a few important advantages.
2. When the paths are specified as motions of the tool frame relative to the station frame, one decouples the motion description from any particular robot, end-effector, or workpieces.
(a). This results in a certain modularity and would allow the same path description to be used with a different manipulator - or with the same manipulator but a different tool size.
i. Further, one can specify and plan motions relative to a moving workstation (i.e. a conveyor belt) by planning motions relative to the station frame as always and, the run time, causing the definition of $\{S\}$ to be changing with time.
3. As shown in Fig. 12.62, the basic problem is to move the manipulator from an initial position to some desired final position.
(a). that is, the wish is to move the tool frame from its current value, $\left\{T_{\text {initial }}\right\}$, to its desired final value, $\left\{T_{\text {final }}\right\}$.
(b). Note that, in general, this motion involves both a change in orientation and a change in the position of the tool relative to the station.
4. Sometimes it is necessary to specify the motion in much more detail than by simply stating the desired final configuration.
(a). One way to include more detail in a path description is to give a sequence of desired via points (intermediate points between the initial an final positions).
i. Thus, in completing the motion, the tool frame must pass through a set of intermediate position and orientation as described by the via points.
A. Each of these via points od actually a frame that specifies both the position and orientation of the tool relative to the station.
(I). The name path points includes all the via points plus the initial and final points
(b). Along with the spatial constraints on the motion, the user could also wish to specify temporal attributes of the motion.
(c). For example, the time elapsed between via points might be specified in the description of the path.


Figure 12.62: In EXECUTING A TRAJECTORY, A MANIPULATOR MOVES FROM ITS initial position to a desired goal position in a smooth manner. 42

1. Usually, it is desirable for the motion of the manipulator to be smooth.
(a). A smooth function is defined as a function that is continuous and has a continuous first derivative.
i. Sometimes a continuous second derivative is also desirable.
ii. Rough, jerky motions tend to cause increased wear on the mechanism and cause vibrations by exciting resonances in the manipulator.
A. In order to guarantee smooth paths, some sort of constraints must be put on the spatial and temporal qualities of the path between the via points.

### 12.3.4.2 Joint-space schemes

1. Each point is usually specified in terms of a desired position and orientation of the tool frame, $\{T\}$, relative to the station frame, $\{S\}$.
(a). Each of these via points is "converted" into a set of desired joint angles by application of the inverse kinematics.
i. Then a smooth function is found for each on the $n$ joints that pass through the via points and end at the goal point.
A. The time required for each segment is the same for each joint so that all joints will reach the via point at the same time, thus resulting in the desired Cartesian position of $\{T\}$ at each via point.
(I). Other than specifying the same duration for each joint, the determination of the desired joint angle function for a particular joint does not depend on the functions for the other joints.
2. Hence, joint-space schemes achieve the desired position and orientation at the via points.
(a). In between via points, the shape of the path, although rather simple in joint space, is complex if desired in Cartesian space.
i. Joint-space schemes are usually the easiest to compute, and, because there are no continuous correspondence between joint space and Cartesian space, there is essentially no problem with singularities of the mechanism.

## Cubic polynomials

1. Consider the problem of moving the tool form its initial position to a goal position in a certain amount of time,
(a). Inverse kinematics allow he set of joint angles hat correspond to the goal position and orientation to be calculated.
i. The initial position of the manipulator is also known in the form of a set of joint angles.
ii. What is required is a function for each joint whose value at $t_{0}$ is the initial position of the joint and whose value at $t_{f}$ is the desired goal position of the joint.
A. As seen in Fig. 12.63 , there are many smooth functions, $\theta(t)$, that might be used to interpolate the joint value.


Figure 12.63: Several possible path shapes for a single joint. 42

1. In making a single smooth motion, at least four constraints on $\theta(t)$ are evident.
(a). Two constraints on the function's value come from the selection of initial and final values:

$$
\begin{align*}
\theta(0) & =\theta_{0} \\
\theta\left(t_{f}\right) & =\theta_{f} \tag{248}
\end{align*}
$$

2. An additional two constraints are that the function be continuous in velocity, which in this case means that the initial and final velocity are zero.

$$
\begin{align*}
\dot{\theta}(0) & =0 \\
\dot{\theta}\left(t_{f}\right) & =0 \tag{249}
\end{align*}
$$

3. These four constraints can be satisfied by a polynomial of at least third degree. These constraints uniquely specify a particular cubic. A cubic has the form;

$$
\begin{equation*}
\theta(t)=a_{0}+a_{1} t+a_{2} t^{2}+a_{3} t^{3} \tag{250}
\end{equation*}
$$

so the joint velocity and acceleration along this path are;

$$
\begin{align*}
& \dot{\theta}(t)=a_{1}+2 a_{2} t+3 a_{3} t^{3} \\
& \ddot{\theta}(t)=2 a_{2}+6 a_{e} t \tag{251}
\end{align*}
$$

Combining Eq. 250 and Eq. 251 with the four desired constraints yields four equations in four unknowns:

$$
\begin{align*}
\theta_{0} & =a_{0} \\
\theta_{f} & =a_{0}+a_{1} t_{f}+a_{2} t_{f}^{2}+a_{3} t_{f}^{3}  \tag{252}\\
0 & =a_{1} \\
0 & =a_{1}+2 a_{2} t_{f}+3 a_{3} t_{f}^{2}
\end{align*}
$$

Solving these equations for $a_{i}$,

$$
\begin{align*}
& a_{0}=\theta_{0} \\
& a_{1}=0 \\
& a_{2}=\frac{3}{t_{f}^{3}}\left(\theta_{f}-\theta_{0}\right)  \tag{253}\\
& a_{3}=-\frac{2}{t_{f}^{3}}\left(\theta_{f}-\theta_{0}\right)
\end{align*}
$$

4. Using Eq. 253, one can calculate the cubic polynomial that connects any initial jointangle position with any desired final position.
(a). This solution is for the cases when the joint starts and finished at zero velocity.


Figure 12.64: Position, Velocity, and acceleration profiles for a single cubic segment that starts and ends at rest. 42]

## Cubic polynomials for a path with via points

1. SO far the paths with a initial and final point have bee discussed. In general, the wish is to allow paths to be specified that include intermediate via points
(a). If the manipulator comes to rest at each via point, then the cubic solution previously shown can be used.
i. However, usually the wish is to pass through a via point without stopping, and so a way is needed to generalize the way in which cubics are fit to the path constraints.
2. As is the case of a single goal point, each via point is usually specified in terms of a desired position and orientation of the tool frame relative to the station frame.
(a). Each of these via points is "converted" into a set of desired joint angles by application of the inverse kinematics.
i. Then the cubics must be computed to connect the via-point values for each joint together in a smooth way.
3. If desired velocities of the joints at the via points are known, the one can construct cubic polynomials as before; however, the velocity constraints at each end are not zero, but rather, some known velocity.
(a). The constraints of Eq. 250 now become;

$$
\begin{align*}
\dot{\theta}(0) & =\dot{\theta_{0}} \\
\dot{\theta}\left(t_{f}\right) & =\dot{\theta_{f}} \tag{254}
\end{align*}
$$

The four equations describing this general cubic are;

$$
\begin{align*}
& \theta_{0}=a_{0} \\
& \theta_{f}=a_{0}+a_{1} t_{f}+a_{2} t_{f}^{2}+a_{3} t_{f}^{3} \\
& \dot{\theta_{0}}=a_{1}  \tag{255}\\
& \dot{\theta_{f}}=a_{1}+2 a_{2} t_{f}+3 a_{3} t_{f}^{2}
\end{align*}
$$

Solving these equation for $a_{i}$, obtains;

$$
\begin{align*}
a_{0} & =\theta_{0} \\
a_{1} & =\dot{\theta}_{0} \\
a_{2} & =\frac{3}{t_{f}^{2}}\left(\theta_{f}-\theta_{0}\right)-\frac{2}{t_{f}} \dot{\theta_{0}}-\frac{1}{t_{f}} \dot{\theta_{f}}  \tag{256}\\
a_{3} & =-\frac{2}{t_{f}^{3}}\left(\theta_{f}-\theta_{0}\right)+\frac{1}{t_{f}^{2}}\left(\dot{\theta_{f}}+\dot{\theta_{0}}\right.
\end{align*}
$$

4. Using Eq. 256, one can calculate the cubic polynomial that connects any initial and final position with any initial and final velocities.
(a). If the desired joint velocities are known at each via point, then Eq 256 is applied to each segment to find the required cubics.
i. There are several ways in which the desired velocity at the via points might be specified;
A. The user specifies the desired velocity at each via point in terms of a Cartesian linear and angular velocity of the tool frame at that instant.
B. The system automatically chooses the velocities at the via points by applying a suitable heuristic either in Cartesian space or joint space.
C. The system automatically chooses the velocities at the via points in such a away as to cause the acceleration at the via points to be continuous.
(I). In the first option, Cartesian desired velocities at the via points are "mapped" to desired joint rates by using the inverse Jacobian of the manipulator evaluated at the via point.
(a). If the manipulator is at a singular point at a particular via point, then the user is not free to assign an arbitrary velocity at this point.
(1). It is a useful capability of a path-generation scheme to be able to meet a desired velocity that the user specifies, but it would be a burden to require that the user always make these specifications.
(i). Therefore, a convenient system should include either option 2 or 3 (or both).
(II). In option 2 , the system automatically chooses reasonable intermediate velocities, using some kind of heuristic. Consider the path specified by the via points shown for some joint, $\theta$, in Fig. 12.65
(a). In Fig. 12.65, a reasonable choice has been made for the joint velocities at the via points, as indicated with small line segments representing tangents to the curve at each via point.
(1). This choice is a result of applying a conceptually and computationally simple heuristic.
(i). Imagine the via points connected with straight line segments.
(A). if the slope of these lines changes sign at the via point, choose zero velocity
(B). If the slope of these lines foes not change sign, choose the average of the two slopes as the via velocity. In this way, from specification of the desired via points alone, the system can choose the velocity at each point.
(III). In option 3, the system chooses velocities in such a way that acceleration is continuous at the via point.
(a). To do this, a new approach is needed. In this kind of spline, set of data one replaces the two velocity constraints at the connection of two cubics with two constraints that velocity be continuous and acceleration be continuous.


Figure 12.65: Via points with desired velocities at the points indicated by TANGENTS. 42

## Higher-order polynomials

1. Higher-order polynomials are sometimes used for path segments.
(a). For example, if one wishes to be able to specify the position, velocity, and acceleration at the beginning and end of a path segment, a quintic polynomial is required, namely;

$$
\begin{equation*}
\theta(t)=a_{o}+a_{1} t+a_{2} t^{2}+a_{3} t^{3}+a_{4} t^{4}+a_{5} t^{5} \tag{257}
\end{equation*}
$$

where the constraints are given as

$$
\begin{align*}
& \theta_{0}=a_{0} \\
& \theta_{f}=a_{o}+a_{1} t_{f}+a_{2} t_{f}^{2}+a_{3} t_{f}^{3}+a_{4} t_{f}^{4}+a_{5} t_{f}^{5} \\
& \dot{\theta_{0}}=a_{1} \\
& \dot{\theta_{f}}=a_{1}+2 a_{2} t_{f}+3 a_{3} t_{f}^{2}+4 a_{4} t_{f}^{3}+5 a_{5} t_{f}^{4}  \tag{258}\\
& \ddot{\theta_{0}}=2 a_{2} \\
& \ddot{\theta_{f}}=2 a_{2}+6 a_{3} t_{f}+12 a_{4} t_{f}^{2}+20 a_{5} t_{f}^{3}
\end{align*}
$$

These constraints specify a linear set of equations with six unknowns, whose solution is;

$$
\begin{align*}
& a_{0}=\theta_{0} \\
& a_{1}=\dot{\theta}_{0} \\
& a_{2}=\frac{\ddot{\theta}_{0}}{2} \\
& a_{3}=\frac{20 \theta_{f}-20 \theta_{0}-\left(8 \theta_{f}+12 \dot{\theta}_{0} t_{f}-\left(3 \ddot{\theta}_{0}-\ddot{\theta}_{f}\right) t_{f}^{2}\right.}{2 t_{f}^{3}}  \tag{259}\\
& a_{4}=\frac{30 \theta_{0}-30 \theta_{f}-\left(14 \theta_{f}+16 \dot{\theta}_{0} t_{f}-\left(3 \ddot{\theta}_{0}-2 \ddot{\theta}_{f}\right) t_{f}^{2}\right.}{2 t_{f}^{4}} \\
& a_{5}=\frac{12 \theta_{f}-12 \theta_{0}-\left(6 \theta_{f}+6 \dot{\theta}_{0} t_{f}-\left(\ddot{\theta}_{0}-\ddot{\theta}_{f}\right) t_{f}^{2}\right.}{2 t_{f}^{5}}
\end{align*}
$$

## Linear function with parabolic blends

1. Another choice of path shape is linear. That is, one simply interpolates linearly to move form the present joint position to the final position, as seen in Fig. 12.66.
(a). Although the motion of each joint in this scheme is linear, the end-effector in general does not move in a straight line in space.


Figure 12.66: LINEAR INTERPOLATION REQUIRING INFINITE ACCELERATION. \|42
2. However, straightforward linear interpolation would cause the velocity to be discontinuous at the beginning and end of the motion.
(a). To create a smooth path with continuous position and velocity, one starts with the linear function but add a parabolic blend region at each point.
3. During the blend portion of the trajectory, constant acceleration is used to change velocity smoothly.
(a). Figure 12.67 shows a simple path constructed in this way.
i. The linear function and the two parabolic functions are "splined" together so that the entire path is continuous in position and velocity.


Figure 12.67: Linear segment with parabolic blends 42


Figure 12.68: Linear segment with parabolic blends 42
4. In order to construct this single segment, it is assumed that the parabolic blends both have the same duration
(a). Therefore, the same constant acceleration is used during both blends.
i. As indicated in Fig. 12.68, there are many solutions to this problem.
A. But note, that the solution is always symmetric about the halfway point in time $t_{h}$, and about the halfway point in position $\theta_{h}$.
ii. The velocity at th end of the blend region must equal the velocity of the linear section so that;

$$
\begin{equation*}
\ddot{\theta} t_{b}=\frac{\theta_{h}=\theta_{b}}{t_{h}=t_{b}} \tag{260}
\end{equation*}
$$

where $\theta_{b}$ is the value of $\theta$ at the end of the blend region, and $\ddot{\theta}$ is the acceleration acting during the blend region. The value of $\theta_{b}$ is given by;

$$
\begin{equation*}
\theta_{b}=\theta_{0}+\frac{1}{2} \ddot{\theta} t_{b}^{2} \tag{261}
\end{equation*}
$$

Combining Eq. 260 and Eq. 261 and $t=2 t_{h}$, to get;

$$
\begin{equation*}
\ddot{\theta} t_{b}^{2}-\ddot{\theta} t t_{b}+\left(\theta_{f}-\theta_{0}\right)=0 \tag{262}
\end{equation*}
$$

where $t$ is the desired duration of the motion
5. Given any $\theta_{f}, \theta_{0}$, and t , one can follow any of the paths given by choices of $\ddot{\theta}$ and $t_{b}$ that satisfy Eq. 262.
(a). Usually, an acceleration, $\ddot{\theta}$, is chosen and Eq. 262 is solved for the corresponding $t_{b}$.
i. The acceleration chosen must be sufficiently high, or a solution will not exist.
(b). Solving Eq. 262 for $t_{b}$ in terms of the acceleration and other known parameters, obtains;

$$
\begin{equation*}
t_{b}=\frac{t}{2}-\frac{\sqrt{\ddot{\theta}^{2} t^{2}-4 \ddot{\theta}\left(\theta_{f}-\theta_{0}\right)}}{2 \ddot{\theta}} \tag{263}
\end{equation*}
$$

The constraint on the acceleration used in the blend is;

$$
\begin{equation*}
\ddot{\theta} \geq \frac{4\left(\theta_{f}-\theta_{0}\right)}{t^{2}} \tag{264}
\end{equation*}
$$

6. When equality occurs in Eq. 264 , the linear portion has shrunk to zero length and the path is composed of two blends that connect with equivalent slope.
(a). As the acceleration used becomes larger and larger, the length of the blend region becomes shorter and shorter.
i. In the limit, with infinite acceleration, the path becomes a linear-interpolation case.

## Linear function with parabolic blends for a path with via points

1. Now consider linear paths with parabolic blends for the case in which they are an arbitrary number of via points specified.
(a). Figure 12.69 shows a set of joint-space via points for some joint $\theta$. Linear functions connect the via points, and parabolic blend regions are added around each via point.
2. Use the following notation: Consider three neighboring path points, which will be called $j, k$, and $l$.
(a). The duration of the linear portion between points $j$ and $k$ is $t_{j k}$.
i. The overall duration of the segment connecting points $j$ and $k$ is $t_{d j k}$.
(b). The velocity during the linear portion is $\dot{\theta_{j k}}$.
(c). The acceleration during the blend at point $j$ is $\ddot{\theta}_{j}$
i. Figure 12.70 provides an example.


Figure 12.69: Position, VElocity, and acceleration profiles for linear interpolation with parabolic blends. The set of curves on the left is based on a higher acceleration during the blends than is that on the right. [42


Figure 12.70: Multi-SEGMEnt Linear path with parabolic blends. 42
3. As with the single-segment case, there are many possible solutions, depending on the value of acceleration used at each blend.
(a). Given all the path points $\theta_{k}$, the desired durations $t_{d j k}$, and the magnitude of acceleration to use at each path point $\left|\ddot{\theta_{k}}\right|$. one can compute the blend time $t_{k}$.
i. For interior path points, this follows simply from the equations;

$$
\begin{align*}
\dot{\theta_{j k}} & =\frac{\theta_{k}-\theta_{j}}{t_{d j k}} \\
\ddot{\theta_{k}} & =S G N\left(\dot{\theta_{k l}}-\dot{\theta_{j k}}\right)\left|\ddot{\theta_{k}}\right| \\
t_{k} & =\frac{\dot{\theta_{k l}}-\dot{\theta_{j k}}}{\ddot{\theta_{k}}}  \tag{265}\\
t_{j k} & =t_{d j k}-\frac{1}{2} t_{j}-\frac{1}{2} t_{k}
\end{align*}
$$

4. The first and last segments must be handled slightly differently, because an entire blend region at one end of the segment must be counted in the total segment's time duration.
(a). For the first segment, solve for $t_{1}$ by equating two expressions for the velocity during the linear phase of the segment;

$$
\begin{equation*}
\frac{\theta_{2}-\theta_{1}}{t_{12}-\frac{1}{2} t_{1}}=\ddot{\theta_{1}} t_{1} \tag{266}
\end{equation*}
$$

This can be solved for $t_{1}$, the blend time at the initial point; then $\dot{\theta_{12}}$ and $t_{12}$ are easily computed;

$$
\begin{align*}
\ddot{\theta_{1}} & =S G N\left(\theta_{2}-\theta_{1}\right)\left|\ddot{\theta_{1}}\right| \\
t_{1} & =t_{d 12}-\sqrt{t_{d 12}^{2}-\frac{2\left(\theta_{2}-\theta_{1}\right)}{\ddot{\theta}_{1}}} \\
\dot{\theta_{12}} & =\frac{\theta_{2}-\theta 1}{t_{d 12}-\frac{1}{2} t_{1}}  \tag{267}\\
t_{12} & =t_{d 12}-t_{1}-\frac{1}{2} t_{2}
\end{align*}
$$

Likewise, for the last segment (the one connecting point $n-1$ and $n$ );

$$
\begin{equation*}
\frac{\theta_{n-1}-\theta_{n}}{t_{d(n-1) n}-\frac{1}{2} t_{n}}=\ddot{\theta_{n}} t_{n} \tag{268}
\end{equation*}
$$

which leads to the solution

$$
\begin{align*}
\ddot{\theta}_{n} & =\operatorname{SGN}\left(\theta_{n-1}-\theta_{n}\right)\left|\ddot{\theta}_{n}\right| \\
t_{n} & =t_{d(n-1) n}-\sqrt{t_{d(n-1) n}+\frac{2\left(\theta_{n}-\theta_{n-1}\right.}{\ddot{\theta}_{n}}} \\
\theta_{(n-1) n} & =\frac{\theta_{n}-\theta_{n-1}}{t_{d(n-1) n}-\frac{1}{2} t_{n}}  \tag{269}\\
t_{(n-1) n} & =t_{d(n-1) n}-t_{n}-\frac{1}{2} t_{n-1}
\end{align*}
$$

5. Using Eq. 266 and Eq. 269, one can solve for the blend times and velocities for a multi-segment path.
(a). Usually, the user specifies only the via points and the desired duration of the segments.
i. In this case, the system uses default values for acceleration for each joint.
A. Sometimes, to make things even simpler for the user, the system will calculate durations based on default velocities.
(I). At all blends, sufficiently large acceleration must be used so that there is sufficient time to get into the linear portion of the segment before the next blend region starts.
6. In these linear-parabolic-blend splines, note that the via points are not actually reached unless the manipulator comes to a stop.
(a). Often, when acceleration capability is sufficiently high, the paths will come quite close to the desired via point.
i. If the wish is to actually pass through a point, by coming to a stop, the via point is simply repeated in the path specification.
7. If the user wishes to specify that the manipulator pass exactly through a via point without stopping, this specification can be accommodated by using the same formulation as before, but with the following addition;
(a). The system automatically replaces the via point through which the manipulator to pass with two pseudo via points, one on each side of the original (as seen in Fig. 12.71 .
i. Then the path generation takes place as before. The original via point will now lie in the linear region of the path connecting the two pseudo via points.
A. In addition to requesting that the manipulator pass exactly through a via point, the user can specify this velocity, the system chooses it by means of suitable heuristic.
(I). The term through point might be used (rather than via point) to specify a path through which the manipulator passes exactly through.


FIGURE 7.10: Use of pseudo via points to create a "through" point.

Figure 12.71: Use of pSEudo via points to create a "through" point. 42

### 12.3.4.3 Path generation at run time

1. At run time, the path-generator routine constructs the trajectory, usually in terms of $\theta, \dot{\theta}$, and $\ddot{\theta}$ and feeds this information to the manipulator's control system.
(a). This path generator computes the trajectory at the path-update rate

## Generation of joint-space paths

1. The result of having planned a path by using any of the splining methods mentioned earlier is a set of data for each segment of the trajectory.
(a). These data are used by the path generator at run time to calculate $\theta, \dot{\theta}$, and $\ddot{\theta}$.
2. In the case of cubic splines, the path generator simply computes Eq. 250 as $t$ is advanced,
(a). When the end of one segment is reached, a new set of cubic coefficients is recalled, $t$ is set back to zero, and the generation continues.
3. In the case of linear splines with parablic blends, the value of time, $t$ is checked on each update to determine whether the path is currently in the linear or the blend portion of the segment.
(a). In the linear portion, the trajectory for each joint is calculated as;

$$
\begin{align*}
& \theta=\theta_{j}+\dot{\theta_{j k} t} \\
& \dot{\theta}=\dot{\theta_{j k}}  \tag{270}\\
& \ddot{\theta}=0
\end{align*}
$$

where $t$ is the time since the $j$ th via point and $\dot{\theta_{j k}}$ was calculated at path-planning time from Eq. 265 .
(b). In the blend region, the trajectory for each joint is calculated as;

$$
\begin{align*}
t_{i n b} & =t-\left(\frac{1}{2} t_{j}+t_{j k}\right) \\
\theta & =\theta_{j}+\dot{\theta_{j k}}\left(t-t_{i n b}\right)+\frac{1}{2} \ddot{\theta}_{k} t_{i n b}^{2}  \tag{271}\\
t h e t_{a} a & =\dot{\theta_{j k}}+\ddot{\theta}_{k} t_{i n b} \\
\ddot{\theta} & =\ddot{\theta_{k}}
\end{align*}
$$

where $\dot{\theta_{j k}}, \ddot{\theta_{k}}, t_{j}$, and $t_{j k}$ were calculated at the path-planning time by equations Eq. 265 through Eq. 269 . This continues, with $t$ being reset to $\frac{1}{2} t_{k}$ when a new linear segment is entered, until the program has worked itself through all data sets representing the path segments.

### 12.4 Numerical Analysis

### 12.4.1 Refraction from the Ambient to the Dirt Layer

To calculate accurate numerical results, a wide range of information was needed. The the composition of the dirt layer is unpredictable because the percentage of dirt, grease, and carbon varies across the rim. Therefore, it was concluded that the index of refraction of the dirt layer would vary. Equation 117, Eq. 118, Eq. 123 , and Eq. 124 were used to calculate the reflectance, transmittance into the dirt layer, absorption by the dirt layer, and transmittance out of the dirt layer and into the coating layer respectively. As the angle-of-incidence would change when the laser moves, the change in $\theta_{i}$ was taken into consideration. Furthermore, from the analysis of of the change in the angle-of-incidence a critical angle of approximately 45 deg was calculated. Table 12.1 shows the values for a relative index of refraction between the ambient air and the dirt layer of 2.5 . The values for the reflectance, transmittance, absorptance, and transmittance out of the dirt layer can be found in the Appendices in Tables REFERNCE TABLES NUMBERS.

Table 12.1: Dirt layer Results for $\mathrm{N}_{t i}=2.5$

| Relative index of refraction of 2.5 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.7429 | 0.0887 | 0.8152 | 0.1848 | 5 | 1.9979 |
| 0.7383 | 0.0906 | 0.8118 | 0.1882 | 10 | 3.9829 |
| 0.7305 | 0.0937 | 0.8060 | 0.1940 | 15 | 5.9423 |
| 0.7193 | 0.0982 | 0.7976 | 0.2024 | 20 | 7.8632 |
| 0.7043 | 0.1044 | 0.7864 | 0.2136 | 25 | 9.7324 |
| 0.6851 | 0.1124 | 0.7719 | 0.2281 | 30 | 11.5370 |
| 0.6611 | 0.1228 | 0.7537 | 0.2463 | 35 | 13.2635 |
| 0.6317 | 0.1360 | 0.7311 | 0.2689 | 40 | 14.8989 |
| 0.5960 | 0.1528 | 0.7035 | 0.2965 | 45 | 16.4299 |
| 0.5532 | 0.1741 | 0.6698 | 0.3302 | 50 | 17.8435 |
| 0.5022 | 0.2015 | 0.6288 | 0.3712 | 55 | 19.1269 |
| 0.4421 | 0.2370 | 0.5794 | 0.4206 | 60 | 20.2679 |
| 0.3722 | 0.2841 | 0.5199 | 0.4801 | 65 | 21.2552 |
| 0.2922 | 0.3484 | 0.4484 | 0.5516 | 70 | 22.0785 |
| 0.2032 | 0.4402 | 0.3629 | 0.6371 | 75 | 22.7288 |
| 0.1090 | 0.5829 | 0.2613 | 0.7387 | 80 | 23.1988 |
| 0.0211 | 0.8504 | 0.1411 | 0.8589 | 85 | 23.4831 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 23.5782 |



## Figure 12.72: Reflectance of the dirt layer

As can be seen in Fig. 12.72 the reflectance of the dirt layer is relatively constant until the angle-of-incidence reaches approximately $45^{\circ}$. After the $45^{\circ}$ mark, the reflectance of the dirt exponentially increases. At $90^{\circ} 100 \%$ of the energy from the laser-beam is reflected. As the relative index of refraction of the dirt layer increases, so does the reflectance of the dirt layer. Therefore, the relative index of refraction, the angle-of-incidence and the reflectance are proportional to one another. To ablate the dirt layer off of the rim, a high value for the reflectance is undesirable. Therefore, it is crucial that the angle-of-incidence of the laserbeam is never greater than $45^{\circ}$. As more of the energy is reflected, less is used to ablate the dirt layer therefore, if an angle-of-incidence grater than $45^{\circ}$ is needed, a more powerful laser will be required.


Figure 12.73: Transmittance into the Dirt Layer from the Ambient

As can be seen in Fig. 12.73 the critical angle for which the transmittance starts to decease is approximately $45^{\circ}$. From $0^{\circ}$ to $45^{\circ}$ the transmittance into the dirt layer is relatively constant. From $45^{\circ}$ to $90^{\circ}$ the percentage of the transmittance into the dirt layer decreases exponentially to the point where at $90^{\circ}$ there is no transmittance. therefore, the relative index of refraction, the angle-of-incidence and the reflectance are inversely proportional to one another. Since the value of the transmittance remains relatively constant from $0^{\circ}$ to $45^{\circ}$, the angle-of-incidence can be slightly changed. However, it needs to remain below $45^{\circ}$ so that the efficiency of the laser does not change. A less efficient laser would require a powerful laser. Furthermore, with inefficient laser ablating, the cycle time per rim would increase, which is undesirable.


## Figure 12.74: Absorptance of the dirt

As can be seen in Fig. 12.74 the critical angle for the absorptance is approximately $45^{\circ}$. Once the angle-of-incidence passes the critical angle, the percentage of energy that is absorbed by the dirt increases exponentially. Before the critical angle the percentage that is absorbed by the dirt is relatively constant. However, since the transmittance starts to exponentially decrease after the critical angle, the increase in absorptance truly has no effect. This is because the absorptance is is a function of the transmittance. Therefore, when the transmittance decrease the value of the absorptance will decrease regardless of the angle. The absorptance of the dirt layer is the critical parameter in the laser ablation of it. The value of the absorptance is the governing variable for how powerful of a laser is required. Therefore, to keep the value of the absorptance as high as possible, the angle-of-incidence cannot be higher than $45^{\circ}$.


Figure 12.75: Transmittance out of the Dirt Layer and into the Anodized Coating Layer

As can be seen in Fig. 12.75 after a certain angle the percent of the transmittance of energy leaving the dirt layer decreases to 0 . The critical angle for the exponential relative to the relative index of refraction. As the relative index of refraction increase, the critical angle decreases. Therefore, it can be concluded that a material with a high index of refraction will not allow a lot of energy to be transmitted out of it, the energy will either be absorbed or reflected. A low value for the transmittance out of the dirt layer is desirable because the less energy entering the anodized coating layer, the lower the probability of damaging the coating. Therefore, a high index of refraction for the dirt layer would be ideal.


Figure 12.76: $\theta_{i}$ vs $\theta_{t}$ FOR The Dirt Layer

As can be seen in Fig. 12.76, as the relative index of refraction increases, the angle-oftransmittance, $\theta_{t}$, decreases. The energy of the beam will bend more when it encounters a material with a high index of refraction relative to the incident material.

### 12.4.2 Refraction from the Dirt Layer into the Anodized Coating Layer

Now that the reflectance, transmittance into, absorptance, the angle-of-transmittance, and the transmittance out with regards to the dirt layer, an analysis of the anodized coating layer can be made. the $\theta_{t}$ of the dirt layer now becomes the angle-of-incidence of the anodized coating layer. The index of refraction of the anodized coating is 1.75 . Equation 117, Eq. 118 , Eq. 123 , and Eq. 124 were again used to calculate the reflectance, transmittance into the coating layer, absorption by the coating layer, and transmittance out of the coating layer and into the rim respectively. The index of refraction of the anodized coating is 1.75 . The table below, Tbl. 12.2 shows the results for a dirt layer with an index of refraction of 2.5. The results for the remainder of the index of refractions can be found in the Numerical Analysis section of the Appendices.

Table 12.2: Anodized Coating Layer Results for $\mathrm{N}_{t i}=0.7$

| Relative index of refraction of 0.7 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{o} u t$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.9556 | 0.0137 | 0.9689 | 0.0311 | 1.9979 | 1.3984 |
| 0.9558 | 0.0136 | 0.9691 | 0.0309 | 3.9829 | 2.7869 |
| 0.9562 | 0.0135 | 0.9693 | 0.0307 | 5.9423 | 4.1558 |
| 0.9567 | 0.0134 | 0.9697 | 0.0303 | 7.8632 | 5.4954 |
| 0.9573 | 0.0132 | 0.9701 | 0.0299 | 9.7324 | 6.7959 |
| 0.9581 | 0.0129 | 0.9706 | 0.0294 | 11.5370 | 8.0478 |
| 0.9589 | 0.0127 | 0.9712 | 0.0288 | 13.2635 | 9.2418 |
| 0.9598 | 0.0124 | 0.9718 | 0.0282 | 14.8989 | 10.3686 |
| 0.9607 | 0.0121 | 0.9725 | 0.0275 | 16.4299 | 11.4194 |
| 0.9616 | 0.0118 | 0.9731 | 0.0269 | 17.8435 | 12.3858 |
| 0.9625 | 0.0116 | 0.9738 | 0.0262 | 19.1269 | 13.2595 |
| 0.9634 | 0.0113 | 0.9744 | 0.0256 | 20.2679 | 14.0334 |
| 0.9641 | 0.0110 | 0.9749 | 0.0251 | 21.2552 | 14.7005 |
| 0.9648 | 0.0108 | 0.9754 | 0.0246 | 22.0785 | 15.2549 |
| 0.9654 | 0.0106 | 0.9758 | 0.0242 | 22.7288 | 15.6916 |
| 0.9658 | 0.0105 | 0.9761 | 0.0239 | 23.1988 | 16.0065 |
| 0.9661 | 0.0104 | 0.9762 | 0.0238 | 23.4831 | 16.1966 |
| 0.9661 | 0.0104 | 0.9763 | 0.0237 | 23.5782 | 16.2602 |



Figure 12.77: Reflectance of the Anodized Coating Layer

As can be seen in Fig. 12.77, the value of the reflectance remains constant with respect to the angle-of-incidence. Furthermore, the higher the relative index of refraction, the higher the value of the reflectance. For the anodized coating layer, a high reflectance value is desirable because the more energy is reflected off the coating, the less energy is being transmitted through it. This will lead to a higher probability that the coating layer will not be damaged. What is not ideal is that the maximum value of the reflectance is below $25 \%$ therefore, at the very least over $75 \%$ of the energy that is experienced by the coating layer will be transmitted through it.


Figure 12.78: Transmittance into the Anodized Coating Layer

As can be seen in Fig. 12.78, the value of the transmittance into the anodized coating layer remains constant with respect to the angle-of-incidence. While the values of the transmittance are high, it does not mean that the coating will be damaged. They key factor on determining the probability of the coating becoming damaged or removed is the absorptance.


Figure 12.79: Absorptance of the Anodized Coating Layer

As can be seen in Fig. 12.79, the value for the absorptance remains constant for all values of the angle-of-incidence. Figure 12.79 is they key factor in determining whether the coating will be damaged or not. The highest value for the absorptance is approximately 0.12 , which occurs with a relative index of refraction of 0.35 . Therefore, only a maximum value of $12 \%$ of the energy that is transmitted thorough the coating will be absorbed by it. This means that there is a very low probability that the coating will be damaged because it cannot absorb enough energy to overcome its flash point temperature. Therefore, laser ablation will succeed in removing the dirt layer without damaging or removing the anodized coating layer.


Figure 12.80: Transmittance out of the Anodized Coating Layer

As can be seen in Fig. 12.80, most of the energy of the laser-beam is transmitted out of the coating layer. The lower the relative index of refraction is, the more energy is transmitted out of the coating. The value of the transmittance out of the coating remains relatively constant with respect of the angle-of-incidence. Since most of the energy is being transmitted out of the coating, it is very unlikely that the coating layer will be removed through the laser ablation process.


Figure 12.81: $\theta_{i}$ vs $\theta_{t}$ of the Anodized Coating Layer

As can be seen in Fig.??, the angle-of-transmittance is proportional to the relative index of refraction. As the relative index of refraction decreases, the angle-of-transmittance also decreases.

### 12.4.3 Refraction from the Anodized Coating Layer into the Rim

The angle-of-transmittance that was calculated for the anodized coating layer is now the angle-of-incidence for the rim. The index of refraction for the rim is 2 and the index of refraction for the anodized coating layer is 1.75 . Therefore, the relative index of refraction is 1.143 . The rim itself cannot be damaged by the laser. Therefore, it is crucial that the rim does not absorb any of the energy form the laser-beam. Below, Tbl. 12.3 of the results of the calculations of the reflectance, transmittance into the rim, absorptance of the rim, transmittance out of the rim, and the angle-of-transmittance with respect to the angle-ofincidence.

Table 12.3: Rim Results for $\mathrm{N}_{t i}=1.143$

| Relative index of refraction of 1.143 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{o}$ ut | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.9937 | 0.0019 | 0.9956 | 0.0044 | 3.8075 | 4.3524 |
| 0.9939 | 0.0019 | 0.9957 | 0.0043 | 7.6027 | 8.6967 |
| 0.9942 | 0.0018 | 0.9960 | 0.0040 | 11.3730 | 13.0244 |
| 0.9947 | 0.0016 | 0.9963 | 0.0037 | 15.1049 | 17.3263 |
| 0.9952 | 0.0014 | 0.9967 | 0.0033 | 18.7836 | 21.5920 |
| 0.9959 | 0.0012 | 0.9972 | 0.0028 | 22.3927 | 25.8091 |
| 0.9967 | 0.0010 | 0.9977 | 0.0023 | 25.9133 | 29.9630 |
| 0.9975 | 0.0007 | 0.9983 | 0.0017 | 29.3237 | 34.0355 |
| 0.9984 | 0.0005 | 0.9989 | 0.0011 | 32.5985 | 38.0037 |
| 0.9992 | 0.0002 | 0.9994 | 0.0006 | 35.7079 | 41.8384 |
| 0.9998 | 0.0001 | 0.9998 | 0.0002 | 38.6173 | 45.5020 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 41.2868 | 48.9459 |
| 0.9997 | 0.0001 | 0.9998 | 0.0002 | 43.6713 | 52.1076 |
| 0.9987 | 0.0004 | 0.9991 | 0.0009 | 45.7216 | 54.9086 |
| 0.9970 | 0.0009 | 0.9979 | 0.0021 | 47.3870 | 57.2542 |
| 0.9951 | 0.0015 | 0.9966 | 0.0034 | 48.6189 | 59.0392 |
| 0.9934 | 0.0020 | 0.9954 | 0.0046 | 49.3766 | 60.1619 |
| 0.9928 | 0.0022 | 0.9950 | 0.0050 | 49.6324 | 60.5457 |



Figure 12.82: Reflectance of the Rim

As seen in Fig. 12.82, very little of the energy from the laser-beam is being reflected by the rim. This is due to the relationship between the index of refraction of the coating and the rim and the fact that the energy has already transfered through three layers (the ambient, the dirt layer, and the anodized coating layer).


Figure 12.83: Transmittance into the Rim

As seen in Fig. 12.83, almost $100 \%$ of the energy seen by the rim is transmitted through it. While this is not ideal, it is not necessarily problematic because the amount absorbed by the rim is very low.


Figure 12.84: Absorptance of the Rim

As seen in fig. 12.84 , the rim absorbs very little energy. this means that there is a very low to non-existent chance that the rim will be damaged. Since a design specification is that the rim cannot be damaged, the results form Fig. 12.84 show that this specific design specification will be met.


Figure 12.85: Transmittance out of the Rim

As seen in Fig. 12.85, the majority of the energy seen by the rim will be transmitted out of it. Therefore, the rim will experience very low change in temperature.


Figure 12.86: $\theta_{i}$ vs $\theta_{t}$ OF The Rim

As seen in Fig. 12.86, the relationship between the angle-of-incidence and the angle-oftransmittance is linear. They are proportional to each other.

### 12.4.4 Laser Intensity Requirements

In the previous section, an analysis of the transfer of energy between the layers was completed. From the analysis, a maximum power for the required laser can now be calculated. The limit of the power of the laser was determined by the energy required to remove the anodized coating layer. Equation 144 was used to determine the intensity of the laser required to remove material from the rim. The material properties of the anodized coating layer and the energy required to remove the coating layer can be found below in Tbl. 12.4. The area of the coating was calculated from the dimensions of the rim given to the Team by UTRC and the time was determined from the design specifications.

Table 12.4: Material Properties of the Anodized Coating Layer

| Maximum Power That Can Be Applied Before the Anodized Coating is Removed |  |  |  |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Material | $\mathbf{Q}(\mathbf{W} / \mathbf{s})$ | $\mathbf{b}(\mathbf{m})$ | $\rho\left(\mathrm{kg} / \mathbf{m}^{3}\right)$ | $\mathbf{C}_{p}\left(\mathbf{J} / \mathbf{k g}{ }^{\circ} \mathbf{C}\right)$ | $\mathbf{T}_{-}\{$boil $\}\left({ }^{\circ} \mathbf{C}\right)$ | $\mathbf{A}\left(\mathbf{m}^{2}\right)$ | $\mathbf{T}_{\infty}\left({ }^{\circ} \mathbf{C}\right)$ | $\mathbf{t}(\mathbf{s})$ |
| Anodized <br> Aluminum | 957.6650164 | 0.00001 | 3987 | 1830 | 2073 | 1.918 | 20 | 300 |

The exact composition of the dirt layer was unknown therefore, the intensity required to ablate multiple types of materials was determined. The material properties of these materials can be found below in Tbl. 12.5.

Table 12.5: Materials Found in the Dirt Layer

| $\underline{\text { Material }}$ | $\underline{\rho\left(\mathbf{k g} / \mathbf{m}^{3}\right)}$ | $\underline{\mathbf{C}_{p}\left(\mathbf{J} / \mathbf{k g}^{\circ} \mathbf{C}\right)}$ | $\underline{\mathbf{T}_{\text {Boil }}\left({ }^{\circ} \mathbf{C}\right)}$ |
| :---: | :---: | :---: | :---: |
| Mineral Oils | 860 | 1632.54 | 105 |
| Diesters | 900 | 1925.56 | 230 |
| Phosphate Esters | 1090 | 1758.12 | 180 |
| Phenyl Methyl | 1030 | 1423.24 | 260 |
| Silicate Esters | 890 | 1600 | 180 |
| Group II Oils | 851 | 2000 | 220 |

Furthermore, the thickness of the dirt layer is not constant across the rim. Therefore, the change in thickness of the dirt layer must be taken into consideration. The table below Tbl. 12.6 shows the laser intensity to remove the materials found in Tbl. 12.5 with varying thicknesses.

Table 12.6: Laser Intensity Required to Remove the Dirt Layer

| Thickness (m) | Mineral <br> Oils | Phosphate <br> Esters | Silicate <br> Esters | Group II <br> Oils | Diesters | Phenyl <br> Methyl |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 0.0001 | 76.2972 | 196.0299 | 150.2178 | 217.6291 | 232.6731 | 224.9334 |
| 0.0003 | 190.7130 | 490.0748 | 375.5444 | 544.0727 | 581.6828 | 562.3335 |
| 0.0005 | 381.4860 | 980.1496 | 751.0888 | 1088.1453 | 1163.3656 | 1124.6670 |
| 0.0008 | 572.2289 | 1470.2243 | 1126.6332 | 1632.2180 | 1745.0484 | 1687.0005 |
| 0.0010 | 762.9719 | 1960.2991 | 1502.1776 | 2176.2907 | 2326.7312 | 2249.3340 |
| 0.0020 | 1525.9438 | 3920.5982 | 3004.3552 | 4352.5813 | 4653.4623 | 4498.6681 |

Now that the laser intensity to remove the dirt layer is known. A comparison between the different types of materials found on the dirt layer can be made.


Figure 12.87: Maximum Laser Power

Figure 12.87 provides a visual representation of the maximum power that the laser can have. As seen by the dotted red line, the laser can have a maximum power of $1500 \mathrm{~W} / \mathrm{s}$ before the anodized coating layer is removed or damaged. Furthermore, a dirt layer thickness of greater than 1 mm is not expected. Therefore, for best possible results the intensity of the laser and the thickness of the dirt layer should remain in the bottom left corner of the graph.

### 12.4.5 Conclusions from Numerical Analysis

The factor that determines whether or not the dirt laser will be ablated by the laser is the absorptance of the layer. As Fig. 12.74 shows, the dirt layer has a high value of absorptance. Therefore, the dirt layer will absorb a high amount of the energy transmitted into it by the laser-beam. Furthermore, from the high value of absorptance it, it can be concluded that the dirt layer will be easier to ablate than the anodized coating layer. As, can be seen in Fig. 12.79, the anodized coating layer absorbs very little of the energy transmitted through it. Carbon, the main component of the dirt layer, has a index of refraction of 2.4 and the anodized coating has an index of refraction of 1.75. Therefore, the relative index of refraction of the dirt layer and the anodized coating layer is 0.723 . In Fig. 12.79, the closest relative index of refraction is 0.7 , the red line. Therefore, it can be concluded that the coating layer will experience a level of absorptance similar to the red line. Only approximately $2 \%$ of the energy transmitted through the anodized coating layer is absorbed by it. However, the
anodized coating layer is extremely thin, approximately $10 \mu \mathrm{~m}$, and it is possible that even $2 \%$ of the energy from the laser-beam could damage it.

As Fig 12.87 shows, the maximum power that the laser can have before the anodized coating layer is damaged is $1500 \mathrm{~W} / \mathrm{s}$. This value was calculated from the material properties of the anodized layer, the surface area of the rim, and a time of 300 seconds, the maximum amount of time allowed per cycle. After a consultation with a engineer at IPG Phonetics, a quote of $1000 \mathrm{~W} / \mathrm{s}$ to $1500 \mathrm{~W} / \mathrm{s}$ for the power of the required laser was received. Therefore, the numerical calculations are in agreement with the quote received. From the numerical analysis, it can be concluded that laser ablation is a viable option to remove the dirt layer without removing the anodized coating. However, more testing needs to be completed before a definitive conclusion can be made.

### 12.5 Simulation Results

The numerical analysis provided confidence that laser ablation could be used to remove the dirt layer off of the rim without removing the anodized coating layer. However, before any physical experimentation could be completed, it was necessary to complete computer simulations on the process. It is possible that the physical experimentation could fail. If the experimentation failed, then it would have been a waste of time and money. The computer simulation would be able to accurately simulate how the laser would affect all the layers. Furthermore, there was no cost for the simulations. Therefore, it was financially beneficial to complete computer simulations. Furthermore, the numerical analysis was through the use of optics and light bending. The computer simulations were with only heat transfer. Therefore, whether or not laser ablation is a viable method to remove the dirt layer will be decided by two independent methods of analysis. COMSOL Multiphysics was used to complete the simulations, as it is the most accurate program to simulate laser ablation and heat transfer with. The simulation were completed. The first was to simulate how the laser would move across the material and how the material would react to the laser.

### 12.5.1 First Simulation: Motion of Laser Across Material

To simplify the simulation, the model was scaled down. The material had a radius of 2.54 cm and a thickness of 1 mm . When the full scale design is completed, the rim itself would rotate on its axis. Therefore, the model rotated with an angular velocity of 6.283 Hz . The laser moved across the x -axis with a period of 10 seconds, This means that it took the laser 10 seconds to travel from one end of the model to the other end and back. The material of the model had an emissivity of 0.8 , which is the emissivity of carbon, the main component of the dirt layer The laser had a spot size radius of 2.5 mm , similar to the spot size of the laser at IPG Photonics. The laser had a power of 18W, scaled down to make the simulation run-time shorter. The laser itself had a Gaussian Pulse.

The Heat Transfer in Solids Module was used for the simulation. A heat flux boundary condition was created at the surface of the material. This would simulate the heating of the material through the use of the laser. A surface to ambient radiation boundary condition was also added to the top surface of the material to simulate the dissipation of energy from the material. A fine mesh, Fig. 12.89 was created for the material so that the results of the
simulation were more accurate. Since the power of the laser was scaled down, the time of the simulation must be scaled up. Therefore, the simulation ran from a time of 0 seconds to 60 seconds. In the figures below, the results of the first simulation are provided.


Figure 12.88: The power of the simulated laser-beam [ $\mathrm{W} / \mathrm{M}^{2}$ ]

As can be seen in Fig. 12.88, the simulated laser is still fairly powerful. It has a maximum irradiance of $4.1215 \times 10^{6} \mathrm{~W} / \mathrm{m}^{2}$. The laser-beam itself is very concentrated and therefore will be able to ablate the dirt fairly easily.


Figure 12.89: The mesh created for the simulation


Figure 12.90: Temperature of the dirt layer at 0s [Temperature in ${ }^{\circ} \mathrm{C}$ ]

As can be seen in Fig. 12.90, The temperature of the surface layer is equal to the ambient temperature of $20^{\circ} \mathrm{C}$. The laser begins at the right side of the material and will move linearly
left and right. The material rotates in a counter-clockwise fashion as shown by the black arrows. The legend on the right the range of the surface temperature of the dirt layer in Celsius.


Figure 12.91: Temperature of the dirt layer at 28s [Temperature in ${ }^{\circ} \mathrm{C}$ ]

As can be seen in Fig. 12.91, after a time of twenty-eight seconds, the temperature of the surface has increased to a minimum of $130^{\circ} \mathrm{C}$ and maximum of $160^{\circ} \mathrm{C}$. The laser is in motion and is currently near the center of the surface. While the spot size of the laser is small, the energy dissipated from it is fairly large, as seen by the high temperatures near the laser spot.


Figure 12.92: Temperature of the dirt layer at 60s [Temperature in ${ }^{\circ} \mathrm{C}$ ]

As can be seen in Fig. 12.92, after a time of 60 seconds the temperature of the surface has risen to a minimum of $234^{\circ} \mathrm{C}$ and a maximum of $248^{\circ} \mathrm{C}$. The critical temperature for the dirt layer is $180^{\circ} \mathrm{C}$. After the critical temperature has been reached, the dirt is ablated off of the rim. Therefore, the simulation proves that a laser can raise the temperature of the dirt layer to this critical temperature.


Figure 12.93: The isothermal contours of the material at 0s [Temperature IN $\left.{ }^{\circ} \mathrm{C}\right]$

The isothermal contours provide a better analysis of the temperature of the dirt layer. The contour lines represent the temperature at that specific position in the dirt layer. The provide a more accurate analysis of how the laser-beam is actually affecting the material. As can be seen in Fig. 12.93, at the start of the simulation there are barely any isothermal contours in the material because the laser has not yet started to heat the surface.


Figure 12.94: The isothermal contours of the material at 26 s
[TEmperature in ${ }^{\circ} \mathrm{C}$ ]

As can be seen in Fig. 12.94, once the laser beings to heat up the temperature of the surface, the isothermal contours form more consciously. The origin of each contour is the laser spot and from the laser pot they either go to the edge of the material or form a circle/ellipse. The contours are helpful in showing what part of the surface experiences the greatest change in temperature with respect to the the location of the laser.


Figure 12.95: The isothermal contours of the material at 48 s
[Temperature in ${ }^{\circ} \mathrm{C}$ ]

As can be seen in Fig. 12.95, when the laser is near the center of the material the isothermal contours are circular and more symmetrically. None of the contours reach the edge of the material. Furthermore, all of the contours are over the critical temperature of $180^{\circ} \mathrm{C}$ therefore, at a time of forty-eight seconds, all of the dirt on the surface of the rim has been ablated off.


Figure 12.96: The isothermal contours of the material at 60 S [Temperature in ${ }^{\circ} \mathrm{C}$ ]

As can be seen in Fig. 12.96, when the laser-beam is at the edge of the material the contours are more condensed. Furthermore, they lose the symmetrical shape that they have near the middle of the material. Therefore, the laser is better at evenly heating the material when it is near its center. Again, the concentration of the contours occurs right next to the location of the laser.

The first simulation proves that the laser can ablate the dirt off of the rim. Even with a scaled down model, the laser had no problems in raising the temperature of the surface to above the critical value for the dirt. While the simulation is successful in confirming that the laser ablation method will succeed in removing the dirt layer, it did not confirm whether or not the anodized coating layer was removed or damaged. Therefore, another simulation must be completed to analyze the effect that the laser has on the anodized coating layer.

### 12.5.2 Second Simulation: Transfer of Energy Between Layers

As previously stated, the first simulation was successful in proving that laser ablation could be used in removing the dirt from a material. However, it could not confirm whether or not the anodized coating layer was damaged. Therefore, another simulation was completed. In this simulation, three layers were modeled, the dirt layer, the anodized coating layer and the rim itself. The model was again scale down so that the simulation time would be lower. All the layers had the same radius of 20 mm . The dirt layer had a thickness of 0.5 mm , the anodized coating layer had a thickness of $1 \mu \mathrm{~m}$ and the rim had a thickness of 1 cm . The emissivity of the materials was selected to be $0.85,0.4$, and 0.2 for the dirt layer, the anodized coating layer, and the rim respectively. For the this simulation the model was fixed, there
was no rotation. Also, since it was already known how the laser would effect the material, a constant heat flux was used instead to see how the energy transfered from layer to layer. While it would have been optimal to simulate a laser acting on the three layer, the run-time for the simulation was too long (over a week). Therefore, the simulation was simplified to a constant heat flux so that more iterations could be ran.

The Heat Transfer in Solids Module was used once more for this simulation. A heat flux boundary condition was added to the top surface of the dirt layer. The heat flux had a fixed value of $2000 \mathrm{~W} / \mathrm{m}^{2}$. An initial temperature boundary condition of $20^{\circ} \mathrm{C}$ was set for the model. A surface to ambient boundary condition was set for the top surface of the dirt layer to simulate the dissipation of energy into the ambient. A surface to surface radiation boundary condition was set for the connection between the bottom of the dirt layer and the top of the anodized coating layer. A surface to surface radiation boundary condition was also set for the connection between the bottom of the anodized coating layer and the rim. A fine mesh, 12.97 was created for the model so that accurate results were produced. The simulation ran for a time of zero seconds to sixty seconds.


Figure 12.97: The mesh created for the simulation


Figure 12.98: Temperature of the dirt layer at 60s [Temperature in ${ }^{\circ} \mathrm{C}$ ]

As can be seen in Fig. 12.98, the temperature of the dirt layer reaches approximately $200^{\circ} \mathrm{C}$. This is once again above the critical temperature needed to ablate the dirt form the rim. Therefore, it can be concluded that the simulation was able to remove the dirt from the rim


Figure 12.99: Radiosity of surface of the dirt layer

As can be seen in Fig. 12.99, the top surface of the dirt layer experiences a radiosity of approximately $2500 \mathrm{~W} / \mathrm{m}^{2}$. The initial heat flux on the top surface was $2000 \mathrm{~W} / \mathrm{m}^{2}$. this figure shows that of the $2000 \mathrm{~W} / \mathrm{m}^{2}$ that enters the dirt layer, approximately $500 \mathrm{~W} / \mathrm{m}^{2}$ is reflected off of the surface and into the ambient. The red arrows on the surface show the direction of the radiosity. Since the arrows are pointed away form the model, it can be concluded that the energy is being radiated from the model into the ambient.


Figure 12.100: Radiosity of the bottom surface of the dirt layer

As can be seen in Fig. 12.100, the bottom surface of the dirt layer experiences a radiosity of approximately $1500 \mathrm{~W} / \mathrm{m}^{2}$. This means that of the $2000 \mathrm{~W} / \mathrm{m}^{2}$ experienced by the dirt layer, $1500 \mathrm{~W} / \mathrm{m}^{2}$ is transmitted through the dirt layer. A percentage of the $1500 \mathrm{~W} / \mathrm{m}^{2}$ is absorbed by the dirt, raising the temperature of the dirt layer. Once enough of the energy is absorbed, the dirt layer will be ablated.


Figure 12.101: Temperature of the Dirt Layer at 60s

As can be seen in Fig. 12.101, the temperature of the dirt layer increases rapidly. Before a time of five seconds has passed, the temperature of the dirt layer has risen to approximately $200^{\circ} \mathrm{C}$. It can be concluded form the graph that the temperature of the dirt has risen above the critical temperature of $180^{\circ} \mathrm{C}$ therefore, the dirt layer has been successfully ablated.


Figure 12.102: Temperature of the Anodized Coating Layer at 60s

As can be seen in Fig. 12.102, the temperature of the anodized coating layer also increases. However, it does not increase as fast as the dirt layer. The temperature of the anodized coating layer never reaches its critical value of $300^{\circ} \mathrm{C}$. Therefore, it can be concluded that the anodized coating layer was not damaged or removed by the laser ablation process.


Figure 12.103: Temperature of the Rim at 60s

As can be seen in Fig. 12.103, the temperature of the rim does not increase. This is due to the magnitude of the rim when compared to the dirt layer and the coating layer. Not enough energy is absorbed by the rim for its temperature to increase. Therefore, it can be concluded that laser ablation will not be able to damage the aluminum material underneath the anodized coating layer.

### 12.5.3 Conclusions from Simulations

Both the first and second simulation were able to accurately simulate the laser ablation process. After a detailed and through analysis of the simulation it can be concluded that the laser ablation process will be able to remove the dirt layer without damaging the anodized coating layer. This is because the laser will be able to increase the temperature of the dirt layer to above $180^{\circ} \mathrm{C}$, its critical value (flash point) without increasing the temperature of the anodized coating layer to its critical value of $300^{\circ} \mathrm{C}$. The analysis of the second simulation provides substantial evidence that the temperature of the dirt layer will reach approximately $200^{\circ} \mathrm{C}$, while the temperature of the anodized coating layer never rises above $130^{\circ} \mathrm{C}$. Also, there is minimal risk of damaging the rim itself because the temperature of the rim did not increase.

### 12.6 Experimental Analysis

### 12.6.1 Description of Experimentation

The numerical analysis and the computer simulations provided confidence that the laserablation process was plausible. While they could not confirm that the process would be successful, they were instrumentally in determining a range of plausible laser intensities for the proof of concept. The range allowed for the time and cost of the physical experimentation to be reduced. A range of $75 \mu \mathrm{~J}$ to $150 \mu \mathrm{~J}$ was used for samples with a dirt laser. For the reference samples a laser intensity range of $1 \mu \mathrm{~J}$ to 1 mJ was used. After the physical experimentations were completed, the surface roughness of every affected area was measured and compared to determine how the material reacted to the laser. The Physical experimentation was completed at IPG Photonics, with help from Johanna Ylenen and the post-processing of the data was completed in the metrology laboratory at the University of Rhode Island, with help from Dr. Donna Meyer. The purpose of the experimentation was to determine whether or not the laser would damage/remove the anodized coating, determine what effect the different compositions of the dirt layer had on the cleanliness of the rim, and to determine how changing the angle of incidence effected the cleanliness of the specimen.

### 12.6.2 Experimental Procedure

### 12.6.2.1 Preparation of Samples

Before the experimentation could be completed, the samples needed to be prepared. Table 12.7 provides the molar composition of the five different mixtures used. The grease was held constant for all mixtures while the dirt and carbon dust had an inversely proportional relationship. The materials used to simulate the carbon dust can be found in Fig. 12.104 , The grains of the carbon that was purchased were too large. Therefore, a grinder was used to reduce the grain size to the order of magnitude of "dust". The material in Fig. 12.105 was used as the grease. Skydrol is an aviation hydraulic fluid used throughout the aerospace industry. It provided the closest representation of what would be commonly found on aircraft rims. To keep the thickness of the dirt layer consistent, the volume of the mixture was measured before being applied. A constant volume insured that the thickness of the dirt layer would be the same across all samples. After the mixtures were applied, the samples were heated treated for an hour at $180^{\circ} \mathrm{F}$ to simulate the heating of the brake pads and the rim that is experienced during the braking process. The different compositions of the dirt mixture were applied to five different samples. Two samples remained clean so that a base measurement could be made. Furthermore, one plate was to be measured for the angle measurement position of the experimentation, with one side clean and the other had Mixture D applied to it.

The aircraft rim to be cleaned is manufactured from anodized Aluminum 2024. However, anodized Aluminum 6061 was used for the experimentation because of the cost and the difficulty of access of anodized Aluminum 2024. The materials share many common material properties but have a couple of major differences. The biggest difference is in the thermal conductivity of the two materials. Anodized Aluminum 2024 has a thermal conductivity of $120 \mathrm{~W} / \mathrm{mK}$ while anodized Aluminum 6061 has a thermal conductivity of $170 \mathrm{~W} / \mathrm{mK}$. The
higher the thermal conductivity of a material, the more susceptible to heat the material is. Therefore, it is easier to damage the anodized Aluminum 6061 through heat treatment, for example laser ablation. Therefore, if the experimentation proves that the anodized coating of the Aluminum 6061 was not removed, it can be concluded that the anodized coating of the Aluminum 2024 would also not be removed.

Table 12.7: the molar compositions of each sample mixture

| Mixture | Dirt [\%] | Grease [\%] | Carbon Dust [\%] |
| :---: | :---: | :---: | :---: |
| A | 80 | 20 | 0 |
| B | 60 | 20 | 20 |
| C | 40 | 20 | 40 |
| D | 20 | 20 | 60 |
| E | 0 | 20 | 80 |



Figure 12.104: The carbon material used to simulate carbon brake dust


Figure 12.105: The lubricant material used to simulate grease and LUBRICANTS ON AIRCRAFT RIMS

### 12.6.2.2 IPG Photonics

The experimental apparatus is shown in REFEREMCE.Each sample was placed under the Galvo head one by one. The laser had a rating of 50 W . The focal length of the laser was 254 mm . The affected area of the material was a $20 \mathrm{~mm} \times 20 \mathrm{~mm}$ area. The spot size of the laser-beam was 40 mm . The distance in-between each pulse was 35 mm , therefore there was a small overlap of the pulses. The path of the laser was horizontal at first from $\mathrm{x}=$ 0 mm to $\mathrm{x}=20 \mathrm{~mm}$, then the path shifted down in the y -direction to create the next row of ablation. These were the base values used and they were held constant throughout all of the experimentation. After each trial a photo was taken of each sample.

First the reference samples were ablated.The first trial started a low energy of $1 \mu \mathrm{~J}$ to a high laser energy of 1 mJ . The purpose was to determine a range of laser energy where the anodized coating layer was not being removed to slightly being damaged. The determined range was from $5 \mu \mathrm{~J}$ to $150 \mu \mathrm{~J}$. Both sides of the plates were covered with the mixture. The front side of the plate was only ablated once, one pass, while the back sid eof the plate was ablated twice, two passes. Therefore, for the samples with mixture A-E applied to them, the range of the laser energy was from $75 \mu \mathrm{~J}$ to $150 \mu \mathrm{~J}$, increasing in increments of $10 \mu \mathrm{~J}$. After the mixture samples were testing was completed, the angle testing began. The angle of the plate to the horizontal was change from $0^{\circ}$ to $60^{\circ}$ in increments of $15^{\circ}$. A laser energy of
$75 \mu \mathrm{~J}$ to $175 \mu \mathrm{~J}$, increasing in increments of $25 \mu \mathrm{~J}$ was used. One side of the plate was kept clena so that a base reference could be determined. The other side of the plate was covered in Mixture D to see how effectively the ablation occurred at different angles of incidence.

### 12.6.2.3 Post-Processing

The post-processing of the experimentation was completed in the metrology laboratory at the University of Rhode Island. The MarSurf XR 20 Perthometer was used, Fig. 12.106. The average roughness, $\mathrm{R}_{a}$, and the mean roughness, $\mathrm{R}_{z}$. For each sample, three measurements were made parallel to the path of the laser-beam (x-direction) and three measurements were made perpendicular to the path of the laser-beam (y-direction).


Figure 12.106: Mahr XR 20 Perthometer

### 12.6.3 Presentation of Results

### 12.6.3.1 Reference Sample One

As can be seen below in Fig. 12.121 and Fig. 12.122 , the first experiment was over a wide range of laser energies. From $10 \mu \mathrm{~m}$ to $100 \mu \mathrm{~m}$, there was no apparent damage to the coating. From a laser energy of $150 \mu \mathrm{~m}$ to $1000 \mu \mathrm{~m}$, there is obvious damage to the anodized coating. As the laser energy increases, the damage to the coating also increases. From the results of this trial, it was determined that a focus on the laser energy between $75 \mu \mathrm{~J}$ and $150 \mu \mathrm{~J}$ was necessary. Therefore, this range was used for all of the different mixture trials.


Figure 12.107: Reference Sample One: Single Pass


Figure 12.108: Reference Sample One: Single Pass: Individual Energies

### 12.6.3.2 Reference Sample Two

## One Pass

To determine the base measurements that the mixture samples would be compared to, the remaining clean plate was ablated with a laser energy of $75 \mu \mathrm{~J}$ to $150 \mu \mathrm{~J}$ in increasing increments of $10 \mu \mathrm{~J}$. Figure 12.107 and Fig. 12.108 provide the results of this trial. As the energy of the laser increased, so did the change in the material. From the naked eye, it seems that there is no to slight damage from $75 \mu \mathrm{~J}$ to $115 \mu \mathrm{~J}$. The $125 \mu \mathrm{~J}$ sample is questionable, it is possible that it is not damaged or that it is. The $150 \mu \mathrm{~J}$ seems clearly damaged to the naked eye.


Figure 12.109: Reference Sample Two: One Pass


Figure 12.110: Reference Sample Two: One Pass: Individual Energies

## Two Passes

For the second experiment on the clean reference plate, the material was ablated twice. The purpose behind this experimentation was to determine whether a second passing of the laser over the same area affected the previously ablated area. It does seem like the ablated areas are more defined that the ones with only one pass. Therefore, it is possible that the more passes over the same area will result in more damage to the material.


Figure 12.111: Reference Sample Two: Two Passes


Figure 12.112: Reference Sample Two: Two Passes: Individual Energies

### 12.6.3.3 Mixture A

## One Pass

Figure 12.113 provides the before (right) and after (left) of the Mixture A sample. It is clearly seen that the laser succeeded in removing the mixture from the material. However, when examining Fig. 12.114 , it is noticed that some of the mixture remains in the ablated area. While there is not a lot, the tiny specks could possibly affect the crack checking that the rims will go through after the cleaning process. As the energy of the laser-beam increases so does the cleanliness of the ablated area. The area ablated by $150 \mu \mathrm{~J}$ is very clean while the area ablated by $75 \mu \mathrm{~J}$ is still dirty.


Figure 12.113: Mixture A: One Pass


Figure 12.114: Mixture A: One Pass: Individual Energies

## Two Passes

Figure 12.115 provides the before (right) and after (left) of the sample with two passes in the ablated area. As can be seen in the magnified photos in Fig. 12.116, the effect of the second pass is not noticeable. When comparing the area ablated with $75 \mu \mathrm{~J}$ one pass and two passes there is not a noticeable difference. This may be because of the density of the dirt that must be ablated. Furthermore, all ablated areas still have some of the dirt mixture inside of them. Therefore, the ablation was not that successful at removing Mixture A.


Figure 12.115: Mixture A: Two Passes


Figure 12.116: Mixture A: Two Passes: Individual Energies

### 12.6.3.4 Mixture B

## One Pass

The laser was much more successful in removing Mixture B than Mixture A. When examining Fig. 12.118 it is visible to the naked eye that almost all of Mixture B was ablated. It is noticeable in Fig. 12.117 that the plate is not very dirty however, the dirt that was on the sample was removed. The increase in laser energy does have an affect on the ablated area however, the affect is too minimal to notice with the naked eye. Accurate measurements will be needed to determine how exactly the areas were affected.


Figure 12.117: Mixture B: One Pass


Figure 12.118: Mixture B: One Pass: Individual Energies

## Two Passes

Through the examination of Fig. 12.120, it is noticeable that the second pass did remove more of Mixture B. However, it is unknown at this moment whether or not the second pass did more damage to the material. Figure 12.119. The amount of dirt in the Mixture B was less than Mixture A. Since the laser ablated Mixture B easier than Mixture A, it is possible that there is a direct correlation between the amount of dirt in the mixture and the cleanliness of the material.


Figure 12.119: Mixture B: Two Passes


Figure 12.120: Mixture B: Two Passes: Individual Energies

### 12.6.3.5 Mixture C

## One Pass

Figure 12.121 provides the comparison of Mixture C before (right) and after (left) the ablation process.The left side of the figure shows how well the laser was able to ablate Mixture C. Figure 12.122 provides to magnified photo of each test. There is no visible difference between the cleanliness of the low energy levels and the high energy levels.


Figure 12.121: Mixture C: One Pass


Figure 12.122: Mixture C: One Pass: Individual Energies

## Two Passes

Figure 12.123 provides the comparison between the before (right) and after (left) of the laser ablation process. This experienced two passes of the laser. It is noticeable from the left image that there is a significant difference in the effect of the $75 \mu \mathrm{~J}$ laser-beam and the $150 \mu \mathrm{~J}$ laser-beam. The $75 \mu \mathrm{~J}$ had almost no effect on the material, while it is clear that the $150 \mu \mathrm{~J}$ laser-beam damaged the material.Figure 12.124 shows that all energy levels were successful in removing Mixture C from the material.


Figure 12.123: Mixture C: Two Passes


Figure 12.124: Mixture C: Two Passes: Individual Energies

### 12.6.3.6 Mixture D

## One Pass

Figure 12.125 provides the comparison of the before (right) and after (left) of the laser ablation process. The laser-beam passed over the ablated area only once. As can be seen in the right image, there was a high amount of Mixture D on the sample. Furthermore, the left image shows that the laser was bale to easily remove Mixture D from the plate. Figure 12.126 shows that every energy level was able to successfully remove Mixture D from the aluminum plate. The affected area of the $150 \mu \mathrm{~J}$ laser is cleaner than the other energy levels. However, it appears that the most damage t the material also occurs with the $150 \mu \mathrm{~J}$ energy level.


Figure 12.125: Mixture D: One Pass


Figure 12.126: Mixture D: One Pass: Individual Energies

## Two Passes

Figure 12.127 provides the comparison of the before (right) and after (left) of the laser ablation process. The laser-beam passed over the ablated area twice. As can be seen in the right image, there was a high amount of Mixture D on the sample. Furthermore, the left image shows that the laser was bale to easily remove Mixture D from the plate. Figure 12.128 shows that every energy level was able to successfully remove Mixture D from the aluminum plate. While the laser was able to efficiently remove Mixture D from the material, there are still some specs left in the affected area. Therefore, the laser was not able to successfully remove $100 \%$ of Mixture D.


Figure 12.127: Mixture D: Two Passes


Figure 12.128: Mixture D: Two Passes: Individual Energies

### 12.6.3.7 Mixture $\mathbf{E}$

## One Pass

Figure 12.129 provides the comparison of the sample before (right) and after (left) of the laser ablation process. The laser was able to remove Mixture E from the ablated area. From the naked eye it seems that the anodized aluminum coating was not removed. However, it is possible that it was damaged at the higher energy levels. Figure 12.130 provides a comparison of the magnified ablated areas. All eight of the areas are very clean. There are no noticeable specks of dirt inside of the ablated areas.


Figure 12.129: Mixture E: One Pass


Figure 12.130: Mixture E: One Pass: Individual Energies

## Two Passes

Figure 12.131 provides the comparison of the sample before (right) and after (left) the laser ablation process for Mixture E. The affected area was ablated twice by the laser. As can
be sen in the left image, the laser was able to remove Mixture E from the anodized aluminum with ease. Figure 12.132 provides the comparison of the eight ablated areas on the sample. All areas area clear of Mixture E. It appears as if the anodized aluminum coating was not removed by the laser.


Figure 12.131: Mixture E: Two Passes


Figure 12.132: Mixture E: Two Passes: Individual Energies

### 12.6.3.8 Sample at an Angle of $15^{\circ}$

## With Dirt Layer

To determine the effect of a change in the angle of incidence, $\theta_{i}$, Mixture D was applied to the last test sample. The test sample was set at different angles so that the effect of the angles could be easily compared. As can be seen in Fig. 12.133 and Fig. 12.134, an angle of incidence of $15^{\circ}$ did not have any major effects on the cleanliness of the sample. The ablated area remained the same as the previous samples. Comparing the results in Fig. 12.134 to Fig. 12.126 shows that the cleanliness of the affected areas are relatively the same. Therefore, an angle of incidence of $15^{\circ}$ will not have any noticeable effects on the cleanliness of the rim.


Figure 12.133: Mixture D: 15 Degrees Incline: One Pass


Figure 12.134: Mixture D: 15 Degrees Incline: One Pass: Individual Energies

### 12.6.3.9 Sample at an Angle of $30^{\circ}$

Figure 12.135 and Fig. 12.136 provide the base reference values for an angle of incidence of $30^{\circ}$. The analysis of the ablated areas in Fig. 12.137 and Fig. 12.138 will be compared to the base reference values. As can be seen in Fig. 12.138, an angle of incidence of $30^{\circ}$ has a large effect on the ablated area. Only the middle of the specified area is cleaned well. The $20 \mathrm{~mm} \times 20 \mathrm{~mm}$ work area was kept the same. However, it is noticeable that the length of the work area has increased to 25.4 mm . However, the affected area has deceased to only 12.5 mm . Not only did the cleanliness of the sample decrease, so did the area ablated.

## Clean



Figure 12.135: Mixture D: 30 Degrees Incline: One Pass


Figure 12.136: Mixture D: 30 Degrees Incline: One Pass: Individual Energies

## With Dirt Layer



Figure 12.137: Mixture D: 30 Degrees Incline: One Pass


Figure 12.138: Mixture D: 30 Degrees Incline: One Pass: Individual Energies

### 12.6.3.10 Sample at an Angle of $45^{\circ}$

When the angle of incidence was increased to $45^{\circ}$, the cleanliness of the ablated area decreased even more. While some parts of the projected area was cleaned, most of it was not. As can be seen in Fig. 12.139, Fig. 12.140, Fig 12.141, ad Fig. 12.142, the top part of the projected area was not cleaned. Only a small section 10 mm long was ablated. However, the ablation across the reduced area was not constant as the height of the top of the area and the bottom were different. Therefore, the focal length of the laser was different throughout the projected area.

## Clean



Figure 12.139: Mixture D: 45 Degrees Incline: One Pass


Figure 12.140: Mixture D: 45 Degrees Incline: One Pass: Individual Energies

## With Dirt Layer



Figure 12.141: Mixture D: 45 Degrees Incline: One Pass


Figure 12.142: Mixture D: 45 Degrees Incline: One Pass: Individual Energies

### 12.6.3.11 Sample at an Angle of $60^{\circ}$

As can be seen in Fig. 12.143, Fig. 12.144, Fig 12.145, ad Fig. 12.146, the projected area was barely cleaned when the angle of incidence was equal to $60^{\circ}$. The quality of the ablation is very low and the actual area cleaned is less than 5 mm in length. There was a drastic
change in the focal length of the laser throughout the projected area because if the steepness of the sample with respect to the horizontal axis.

## Clean



Figure 12.143: Mixture D: 60 Degrees Incline: One Pass


Figure 12.144: Mixture D: 60 Degrees Incline: One Pass: Individual Energies

## With Dirt Layer



Figure 12.145: Mixture D: 60 Degrees Incline: One Pass


Figure 12.146: Mixture D: 60 Degrees Incline: One Pass: Individual Energies
12.6.3.12 Base Roughness of Each Sample

Table 12.8: Parallel to the Path of the laser-beam

| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ |  |  |
| :---: | :---: | :---: |
| Sample |  | Ra $(\mu \mathbf{m})$ |
| $\mathbf{R z}(\mu \mathbf{m})$ |  |  |
| Clean: Reference One | 1.784 | 9.907 |
| Clean: Reference Two | 1.85 | 11.153 |
| Mixture A: One Pass | 1.443 | 8.84 |
| Mixture B: One Pass | 1.627 | 9.563 |
| Mixture C: One Pass | 1.64 | 9.29 |
| Mixture D: One Pass | 1.617 | 9.397 |
| Mixture E: One Pass | 1.34 | 8.347 |
| Mixture A: Two Passes | 1.68 | 9.15 |
| Mixture B: Two Passes | 1.627 | 9.563 |
| Mixture C: Two Passes | 1.64 | 9.29 |
| Mixture D: Two Passes | 1.367 | 7.583 |
| Mixture E: Two Passes | 1.57 | 9.547 |

Table 12.9: Perpendicular to the Path of the laser-beam

| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ |  |  |
| :---: | :---: | :---: |
| Sample |  |  |
| Ra $(\mu \mathbf{m})$ | Rz $(\mu \mathbf{m})$ |  |
| Clean: Reference One | 0.5 | 2.946 |
| Clean: Reference Two | 0.293 | 1.813 |
| Mixture A: One Pass | 0.443 | 3.193 |
| Mixture B: One Pass | 0.493 | 3.243 |
| Mixture C: One Pass | 0.46 | 2.977 |
| Mixture D: One Pass | 0.91 | 5.213 |
| Mixture E: One Pass | 0.457 | 3.13 |
| Mixture A: Two Passes | 0.487 | 3.22 |
| Mixture B: Two Passes | 0.493 | 3.243 |
| Mixture C: Two Passes | 0.46 | 2.96 |
| Mixture D: Two Passes | 0.49 | 3.423 |
| Mixture E: Two Passes | 0.713 | 4.24 |

Table 12.10: Average of Parallel and Perpendicular Roughnesses

| Average of Parallel and Perpendicular |  |  |
| :---: | :---: | :---: |
| Sample | Ra $(\mu \mathbf{m})$ | $\mathbf{R z}(\mu \mathbf{m})$ |
| Clean: Reference One | 1.142 | 6.427 |
| Clean: Reference Two | 1.072 | 6.483 |
| Mixture A: One Pass | 0.943 | 6.017 |
| Mixture B: One Pass | 1.06 | 6.403 |
| Mixture C: One Pass | 1.05 | 6.133 |
| Mixture D: One Pass | 1.263 | 7.305 |
| Mixture E: One Pass | 0.898 | 5.738 |
| Mixture A: Two Passes | 1.083 | 6.185 |
| Mixture B: Two Passes | 1.06 | 6.403 |
| Mixture C: Two Passes | 1.05 | 6.125 |
| Mixture D: Two Passes | 0.928 | 5.503 |
| Mixture E: Two Passes | 1.142 | 6.893 |
|  |  |  |

### 12.6.3.13 Laser Energy of $75 \mu \mathrm{~J}$ with One Pass over Sample

Table 12.11: Comparison of Mixtures with a Laser Energy of $75 \mu \mathrm{~J}$

| One Pass |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $75 \mu \mathrm{~J}$ |  |  |  |  |  |  |
| Parameter (Average) | Clean Reference | Mixture A | Mixture B | Mixture C | Mixture D | Mixture E |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.578 | 0.988 | 1.105 | 1.233 | 1.205 | 1.048 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 10.618 | 6.472 | 7.625 | 8.39 | 8.115 | 7.075 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.508 | -0.049 | -0.045 | -0.185 | 0.058 | -0.147 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -4.135 | -0.455 | -1.222 | -2.257 | -0.81 | -1.337 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.436 | 0.044 | 0.162 | 0.289 | 0.262 | 0.104 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 4.135 | 0.455 | 1.608 | 2.373 | 2.098 | 1.058 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 0 | -13.443 | -3.226 | 7.867 | 5.532 | -8.335 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 0 | 0.7 | 18.646 | 30.55 | 26.271 | 10.088 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | 0 | -104.77 | -104.245 | -117.302 | -95.383 | -116.512 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | 0 | -107.562 | -119.079 | -136.793 | -111.088 | -123.294 |



Figure 12.147: Average $\mathrm{R}_{a}$ for $75 \mu \mathrm{~J}$ with One Pass


Figure 12.148: Average $\mathrm{R}_{z}$ for $75 \mu \mathrm{~J}$ with One Pass


Figure 12.149: $\mathrm{R}_{a}$ : Unablated Reference - Ablated Mixture: $75 \mu \mathrm{~J}$ : One Pass


Figure 12.150: $\mathrm{R}_{z}$ : Unablated Reference - Ablated Mixture: $75 \mu \mathrm{~J}$ : One Pass


Figure 12.151: Average $\mathrm{R}_{a}$ clean For $75 \mu \mathrm{~J}$ with One Pass


Figure 12.152: Average $\mathrm{R}_{z \text { clean }}$ For $75 \mu \mathrm{~J}$ with One Pass


Figure 12.153: $\mathrm{R}_{a}$ Effectiveness: Unablated Reference - Ablated Mixture: $75 \mu \mathrm{~J}$ : One Pass


Figure 12.154: $\mathrm{R}_{z}$ Effectiveness: Unablated Reference - Ablated Mixture: $75 \mu \mathrm{~J}$ : One Pass


Figure 12.155: Effectiveness of $\mathrm{R}_{a}$ for $75 \mu \mathrm{~J}$ with Respect to the clean reference with One Pass


Figure 12.156: Effectiveness of $\mathrm{R}_{z}$ for $75 \mu \mathrm{~J}$ with Respect to the clean reference with One Pass


Figure 12.157: Effectiveness of $\mathrm{R}_{a}$ FOR $75 \mu \mathrm{~J}$ with Respect to the dirt layer with One Pass


Figure 12.158: Effectiveness of $\mathrm{R}_{z}$ For $75 \mu \mathrm{~J}$ with Respect to the dirt layer with One Pass

### 12.6.3.14 Laser Energy of $115 \mu \mathrm{~J}$ with One Pass over Sample

Table 12.12: Comparison of Mixtures with a Laser Energy of $115 \mu \mathrm{~J}$

| One Pass |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $115 \mu \mathrm{~J}$ |  |  |  |  |  |  |
| Parameter (Average) | Clean Reference | Mixture A | Mixture B | Mixture C | Mixture D | Mixture E |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 2.103 | 1.07 | 1.738 | 1.578 | 1.733 | 1.645 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 12.442 | 6.31 | 11.207 | 10.412 | 10.678 | 9.967 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.041 | -0.119 | -0.68 | -0.53 | -0.484 | -0.764 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -5.958 | -0.293 | -4.803 | -9.362 | -3.373 | -4.228 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.961 | 0.127 | 0.794 | 0.634 | 0.789 | 0.702 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 5.958 | 0.293 | 5.19 | 4.395 | 4.662 | 3.95 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 0 | -6.583 | 51.803 | 37.936 | 52.095 | 44.358 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 0 | -1.815 | 74.378 | 62.007 | 66.157 | 55.083 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | 0 | -113.074 | -163.522 | -150 | -137.467 | -183.488 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | 0 | -104.875 | -175.013 | -252.636 | -146.178 | -173.686 |



Figure 12.159: Average $\mathrm{R}_{a}$ for $115 \mu \mathrm{~J}$ with One Pass


Figure 12.160: Average $\mathrm{R}_{z}$ For $115 \mu \mathrm{~J}$ with One Pass


Figure 12.161: $\mathrm{R}_{a}$ : Unablated Reference - Ablated Mixture: $115 \mu \mathrm{~J}$ : One PASS


Figure 12.162: $\mathrm{R}_{z}$ : Unablated Reference - Ablated Mixture: $115 \mu \mathrm{~J}$ : One Pass


Figure 12.163: Average $\mathrm{R}_{\text {a clean }}$ For $115 \mu \mathrm{~J}$ with One Pass


Figure 12.164: Average $\mathrm{R}_{z \text { clean }}$ For $115 \mu \mathrm{~J}$ with One Pass


Figure 12.165: $\mathrm{R}_{a}$ Effectiveness: Unablated Reference - Ablated Mixture: $115 \mu \mathrm{~J}:$ One Pass


Figure 12.166: $\mathrm{R}_{z}$ Effectiveness: Unablated Reference - Ablated Mixture: $115 \mu \mathrm{~J}:$ One Pass


Figure 12.167: Effectiveness of $\mathrm{R}_{a}$ For $115 \mu \mathrm{~J}$ with Respect to the clean reference with One Pass


Figure 12.168: Effectiveness of $\mathrm{R}_{z}$ for $115 \mu \mathrm{~J}$ with respect to the clean reference with One Pass


Figure 12.169: Effectiveness of $\mathrm{R}_{a}$ For $115 \mu \mathrm{~J}$ with Respect to the dirt layer with One Pass


Figure 12.170: Effectiveness of $\mathrm{R}_{z}$ FOR $115 \mu \mathrm{~J}$ with Respect to the dirt layer with One Pass
12.6.3.15 Laser Energy of $150 \mu \mathrm{~J}$ with One Pass over Sample

Table 12.13: Comparison of Mixtures with a Laser Energy of $150 \mu \mathrm{~J}$

| One Pass |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $150 \mu \mathrm{~J}$ |  |  |  |  |  |  |
| Parameter (Average) | Clean Reference | Mixture A | Mixture B | Mixture C | Mixture D | Mixture E |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.617 | 1.845 | 1.89 | 1.82 | 1.843 | 1.86 |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ | 10.153 | 9.58 | 10.427 | 11.958 | 10.68 | 10.795 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.023 | -0.914 | -0.815 | -0.768 | -0.589 | -1.009 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -10.153 | -3.563 | -4.023 | -5.833 | -3.375 | -5.057 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.475 | 0.902 | 0.947 | 0.877 | 0.899 | 0.917 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 3.727 | 3.563 | 4.41 | 5.942 | 4.663 | 4.778 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 0 | 61.728 | 64.356 | 59.539 | 61.436 | 64.064 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 0 | 49.066 | 62.241 | 86.074 | 66.183 | 67.972 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | 0 | -195.76 | -177.044 | -171.855 | -145.91 | -208.534 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | 0 | -159.224 | -162.832 | -195.238 | -146.201 | -188.121 |



Figure 12.171: Average $\mathrm{R}_{a}$ for $150 \mu \mathrm{~J}$ with One Pass


Figure 12.172: Average $\mathrm{R}_{z}$ For $150 \mu \mathrm{~J}$ with One Pass


Figure 12.173: $\mathrm{R}_{a}$ : Unablated Reference - Ablated Mixture: $150 \mu \mathrm{~J}$ : One Pass


Figure 12.174: $\mathrm{R}_{z}$ : Unablated Reference - Ablated Mixture: $150 \mu \mathrm{~J}$ : One Pass


Figure 12.175: Average $\mathrm{R}_{a}$ clean For $150 \mu \mathrm{~J}$ with One Pass


Figure 12.176: Average $\mathrm{R}_{z \text { clean }}$ For $150 \mu \mathrm{~J}$ with One Pass


Figure 12.177: $\mathrm{R}_{a}$ Effectiveness: Unablated Reference - Ablated Mixture: $150 \mu \mathrm{~J}:$ One Pass


Figure 12.178: $\mathrm{R}_{z}$ Effectiveness: Unablated Reference - Ablated Mixture: $150 \mu \mathrm{~J}$ : One Pass


Figure 12.179: Effectiveness of $\mathrm{R}_{a}$ FOR $150 \mu \mathrm{~J}$ with Respect to the clean reference with One Pass


Figure 12.180: Effectiveness of $\mathrm{R}_{z}$ for $150 \mu \mathrm{~J}$ with respect to the clean reference with One Pass


Figure 12.181: Effectiveness of $\mathrm{R}_{a}$ For $150 \mu \mathrm{~J}$ with Respect to the dirt layer with One Pass


Figure 12.182: Effectiveness of $\mathrm{R}_{z}$ FOR $150 \mu \mathrm{~J}$ with Respect to the dirt layer with One Pass

### 12.6.3.16 Laser Energy of $75 \mu \mathrm{~J}$ with Two Passes over Sample

Table 12.14: Comparison of Mixtures with a Laser Energy of $75 \mu \mathrm{~J}$ : Two Passes

| Two Passes |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $75 \mu \mathrm{~J}$ |  |  |  |  |  |  |
| Parameter (Average) | Clean Reference | Mixture A | Mixture B | Mixture C | Mixture D | Mixture E |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.04 | 1.14 | 1.293 | 1.333 | 1.285 | 1.36 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 8.628 | 7.818 | 9.015 | 8.835 | 9.503 | 9.575 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | 0.029 | -0.062 | -0.235 | -0.293 | -0.362 | -0.213 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -2.145 | -1.633 | -2.612 | -2.71 | -4 | -2.682 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | -0.032 | 0.197 | 0.349 | 0.389 | 0.342 | 0.417 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 2.145 | 1.802 | 2.998 | 2.818 | 3.487 | 3.558 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 0 | -0.015 | 13.268 | 16.917 | 12.684 | 18.815 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 0 | 21.655 | 40.275 | 37.474 | 47.873 | 48.989 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | 0 | -105.385 | -122.013 | -127.143 | -138.6 | -118.832 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | 0 | -126.408 | -140.786 | -144.245 | -172.683 | -138.902 |

Ra: $75 \mu \mathrm{~J}$ : Two Passes


Figure 12.183: Average $\mathrm{R}_{a}$ for $75 \mu \mathrm{~J}$ with Two Passes


Figure 12.184: Average $\mathrm{R}_{z}$ for $75 \mu \mathrm{~J}$ with Two Passes


Figure 12.185: $\mathrm{R}_{a}$ : Unablated Reference - Ablated Mixture: $75 \mu \mathrm{~J}$ : Two PASSES


Figure 12.186: $\mathrm{R}_{z}$ : Unablated Reference - Ablated Mixture: $75 \mu \mathrm{~J}$ : Two Passes


Figure 12.187: Average $\mathrm{R}_{a}$ clean $\mathrm{FOR} 75 \mu \mathrm{~J}$ with Two Passes


Figure 12.188: Average $\mathrm{R}_{z}$ clean for $75 \mu \mathrm{~J}$ with Two Passes


Figure 12.189: $\mathrm{R}_{a}$ Effectiveness: Unablated Reference - Ablated Mixture: $75 \mu \mathrm{~J}$ : Two Passes


Figure 12.190: $\mathrm{R}_{z}$ Effectiveness: Unablated Reference - Ablated Mixture: $75 \mu \mathrm{~J}$ : Two Passes


Figure 12.191: Effectiveness of $\mathrm{R}_{a}$ for $75 \mu \mathrm{~J}$ with Respect to the clean reference with Two Passes


Figure 12.192: Effectiveness of $\mathrm{R}_{z}$ for $75 \mu \mathrm{~J}$ with Respect to the clean reference with Two Passes


Figure 12.193: Effectiveness of $\mathrm{R}_{a}$ For $75 \mu \mathrm{~J}$ with Respect to the dirt layer with Two Passes


Figure 12.194: Effectiveness of $\mathrm{R}_{z}$ for $75 \mu \mathrm{~J}$ with Respect to the dirt layer with Two Passes
12.6.3.17 Laser Energy of $115 \mu \mathrm{~J}$ with Two Passes over Sample

Table 12.15: Comparison of Mixtures with a Laser Energy of $115 \mu \mathrm{~J}$ : Two Passes

| Two Passes |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $115 \mu \mathrm{~J}$ |  |  |  |  |  |  |
| Parameter <br> (Average) | Clean Reference | Mixture A | Mixture B | Mixture C | Mixture D | Mixture E |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 2.148 | 1.883 | 1.768 | 1.82 | 1.663 | 1.77 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 12.098 | 11.495 | 11.308 | 11.958 | 11.092 | 11.487 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.098 | -0.812 | -0.718 | -0.768 | -0.613 | -0.636 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -5.615 | -5.31 | -4.905 | -5.833 | -5.588 | -4.593 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 1.076 | 0.939 | 0.824 | 0.877 | 0.719 | 0.827 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 5.615 | 5.478 | 5.292 | 5.942 | 5.075 | 5.47 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 0 | 65.085 | 55.16 | 59.539 | 45.964 | 55.16 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 0 | 78.864 | 75.96 | 86.074 | 72.588 | 78.734 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | 0 | -174 | -167.138 | -171.855 | -165.35 | -155.182 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | 0 | -185.853 | -176.601 | -195.238 | -201.545 | -166.634 |



Figure 12.195: Average $\mathrm{R}_{a}$ for 115 mJ with Two Passes


Figure 12.196: Average $\mathrm{R}_{z}$ For $115 \mu \mathrm{~J}$ with Two Passes


Figure 12.197: $\mathrm{R}_{a}$ : Unablated Reference - Ablated Mixture: $115 \mu \mathrm{~J}$ : Two PASSES


Figure 12.198: $\mathrm{R}_{z}$ : Unablated Reference - Ablated Mixture: $115 \mu \mathrm{~J}$ : Two PASSES


Figure 12.199: Average $\mathrm{R}_{a}$ clean $\operatorname{For} 115 \mu \mathrm{~J}$ with Two Passes


Figure 12.200: Average $\mathrm{R}_{z \text { clean }}$ For $115 \mu \mathrm{~J}$ with Two Passes


Figure 12.201: $\mathrm{R}_{a}$ Effectiveness: Unablated Reference - Ablated Mixture: $115 \mu \mathrm{~J}$ : Two Passes


Figure 12.202: $\mathrm{R}_{z}$ Effectiveness: Unablated Reference - Ablated Mixture: $115 \mu \mathrm{~J}:$ Two Passes


Figure 12.203: Effectiveness of $\mathrm{R}_{a}$ For $115 \mu \mathrm{~J}$ with Respect to the clean reference with Two Passes


Figure 12.204: Effectiveness of $\mathrm{R}_{z}$ For $115 \mu \mathrm{~J}$ with Respect to the clean reference with Two Passes

Ra Efficiency: Unablated Mixture minus Ablated Mixture: $115 \mu \mathrm{~J}$ : Two Passes


Figure 12.205: Effectiveness of $\mathrm{R}_{a}$ FOR $115 \mu \mathrm{~J}$ with Respect to the dirt layer with Two Passes


Figure 12.206: Effectiveness of $\mathrm{R}_{z}$ FOR $115 \mu \mathrm{~J}$ with Respect to the dirt layer with Two Passes

### 12.6.3.18 Laser Energy of $150 \mu \mathrm{~J}$ with Two Passes over Sample

Table 12.16: Comparison of Mixtures with a Laser Energy of $150 \mu \mathrm{~J}$ : Two Passes

| Two Passes |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $150 \mu \mathrm{~J}$ |  |  |  |  |  |  |
| Parameter <br> (Average) | Clean Reference | Mixture A | Mixture B | Mixture C | Mixture D | Mixture E |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.617 | 1.918 | 1.89 | 1.988 | 1.813 | 2.008 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 10.153 | 11.792 | 10.427 | 11.82 | 11.42 | 12.887 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.023 | -0.847 | -0.815 | -0.94 | -0.763 | -0.871 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -10.153 | -5.607 | -4.023 | -5.695 | -5.917 | -5.993 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.475 | 0.974 | 0.947 | 1.044 | 0.869 | 1.064 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 3.727 | 5.775 | 4.41 | 5.803 | 5.403 | 6.87 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 0 | 68.151 | 64.356 | 74.135 | 58.809 | 75.741 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 0 | 83.48 | 62.241 | 83.921 | 77.697 | 100.519 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | 0 | -177.231 | -177.044 | -187.579 | -181.149 | -175.766 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | 0 | -190.649 | -162.832 | -192.98 | -207.511 | -186.944 |

Ra: $150 \mu \mathrm{~J}$ : Two Passes


Figure 12.207: Average $\mathrm{R}_{a}$ for $150 \mu \mathrm{~J}$ with Two Passes


Figure 12.208: Average $\mathrm{R}_{z}$ for $150 \mu \mathrm{~J}$ with Two Passes


Figure 12.209: $\mathrm{R}_{a}$ : Unablated Reference - Ablated Mixture: $150 \mu \mathrm{~J}$ : Two PasSes


Figure 12.210: $\mathrm{R}_{z}$ : Unablated Reference - Ablated Mixture: $150 \mu \mathrm{~J}$ : Two Passes


Figure 12.211: Average $\mathrm{R}_{a}$ clean $\operatorname{For} 150 \mu \mathrm{~J}$ with Two Passes


Figure 12.212: Average $\mathrm{R}_{z \text { clean }}$ For $150 \mu \mathrm{~J}$ with Two Passes


Figure 12.213: $\mathrm{R}_{a}$ Effectiveness: Unablated Reference - Ablated Mixture: $150 \mu \mathrm{~J}$ : Two Passes


Figure 12.214: $\mathrm{R}_{z}$ Effectiveness: Unablated Reference - Ablated Mixture: $150 \mu \mathrm{~J}$ : Two Passes


Figure 12.215: Effectiveness of $\mathrm{R}_{a}$ For $150 \mu \mathrm{~J}$ with Respect to the clean reference with Two Passes


Figure 12.216: Effectiveness of $\mathrm{R}_{z}$ for $150 \mu \mathrm{~J}$ with Respect to the clean reference with Two Passes

Ra Efficiency: Unablated Mixture minus Ablated Mixture: $\mathbf{1 5 0} \mu \mathrm{J}$ : Two Passes


Figure 12.217: Effectiveness of $\mathrm{R}_{a}$ For $150 \mu \mathrm{~J}$ with Respect to the dirt layer with Two Passes


Figure 12.218: Effectiveness of $\mathrm{R}_{z}$ FOR $150 \mu \mathrm{~J}$ with ReSpect to the dirt layer with Two Passes

### 12.7 Robotic Manipulator

To determine the placement of the manipulator with respect to the rim and the optimum trajectory, the range of motion of the arm was needed. MATLAB was used to create a script that would map all possible points that the arm could theoretically reached. The map is provided in Fig. 12.219 . The blue figure, is an outline of the half-scale rim implemented in the system. The red dots represents all of the points that the arm can reach. however, the points do not take into consideration the physical object that is the rim. Therefore, the actual range of motion is reduced.


Figure 12.219: Range of motion of the robotic manipulator

Furthermore, the torques applied to the motors can now be calculated. Since the maximum torque that can be applied to the motors was known, the safety of the motors was determined. If a torque greater than what the motor can handle is applied, the gears begin to skip and the motor overheats. If the motor overheats for long enough the motor will break. The free body diagram of the manipulator is provided in Fig. 12.220 . The equilibrium and the summation of moments was used to determine the torques applied to the motors.


Figure 12.220: Free-body diagram of the robotic manipulator

$$
\begin{align*}
\cos \left(\theta_{A}\right) & =c_{A} ; \cos \left(\theta_{B}\right)=c_{B} ; \cos \left(\theta_{C}\right)=c_{C}  \tag{272}\\
\sum M_{A} & =-W_{(C+L)} L_{1} c_{A}+L_{2} c_{B}+\frac{L_{D E}}{2} c_{C} \\
& -W_{M 90 S} L_{1} c_{A}+L_{2} c_{B}-W_{B}\left(L_{1} c_{A}\right. \\
& \left.+\frac{L_{2}}{2}\right)-W_{M 90 S}\left(L_{1} c_{A}+L_{2} c_{B}\right)  \tag{273}\\
& -\left(W_{M 996} L_{1}+W_{A}\left(\frac{L_{1}}{2}\right) c_{A}+M_{B}=0\right. \\
\sum M_{B}= & -\frac{W_{B} L_{2}}{2} c_{B}-W_{(C+L)}\left(L_{2} c_{B}+\frac{L_{D E}}{2} c_{C}\right)  \tag{274}\\
- & W_{M 90 S}\left(L_{2}\right) c_{B}+M_{C}=0 \\
& \sum M_{C}=-W_{(C+L)} \frac{L_{2}}{2} c_{C}=0 \tag{275}
\end{align*}
$$

MATLAB was once again used to calculate and plot the range of torques. Figure 12.221 , Fig. 12.222 , and Fig. 12.223 provide the range of torques applied to the motors at point $\mathrm{A}, \mathrm{B}$, and C respectively. As can be seen in Fig. 12.221 and Fig. 12.224 the highest torque was applied at the motors positioned at the shoulder. It was $17 \mathrm{~kg}^{*} \mathrm{~cm}$ across both of the servos, therefore it was $8.5 \mathrm{~kg}^{*} \mathrm{~cm}$ per servo. The maximum torque allowed on the MG 996R motors was
$12 \mathrm{~kg}^{*} \mathrm{~cm}$. Therefore, there is a safety safety of 1.4 . The MG90s servo is rated for a maximum torque of $1.8 \mathrm{~kg}^{*} \mathrm{~cm}$ and as can be seen in Fig. 12.223 and Fig. 12.226 the maximum torque applied to one was $0.8 \mathrm{~kg}^{*} \mathrm{~cm}$. Therefore, the MG90s servos have a safety factor of 2.25 .


Figure 12.221: Range of torques at point A


Figure 12.222: Range of torques at point B


Figure 12.223: Range of torques at point C


Figure 12.224: Sum of the torques at point A with respect to the position of the servo


Figure 12.225: Sum of the torques at point B with respect to the position of the servo

Sumation of the torques at the WRIST (kg*cm)


Figure 12.226: Sum of the torques at point C with Respect to the position OF THE SERVO

### 12.7.1 Trajectory Generation

In order to generate the trajectory for the robotic manipulator, the joints of the robot were trained. This meant each joint was control individually until the tool point reached a via point. Once reached the position of each joint was recorded and given a time required to reach the current point from the previous. The tool point was then moved to the next via point by controlling each individual joint. Upon arriving at the next point, the positions were again saved and given a time to reach that point from the previous point. These steps were done numerous times to generate the full trajectory for the top of the rim, position it for ablating the side, the bottom and then a final trajectory was generated for the holes.

Simply having the positions and times was not sufficient to generate a trajectory. The program had to know where to send each joint for every iteration of the loop controlling the manipulator. Thus, the position of each joint was interpolated between via points using a linear function of time. This was accomplished by knowing the start $\left(\theta_{o}\right)$ and end point $\left(\theta_{f}\right)$ given any time interval $(\Delta t)$.

$$
\begin{equation*}
\theta=\frac{\theta_{f}-\theta_{o}}{\Delta t} t+\theta_{o} \tag{276}
\end{equation*}
$$

Equation 276 only represents the function for a single joint. Position for each joint had to be calculated using the same function but with variables in their own space. Thus the position of each joint was put into a column vector for each via point, then concatenated to
form a matrix. The rows of the matrix were the positions of each individual joint. Columns represented a vector of positions for each joint at any given via point. Since time was also recorded between via points, it was also constructed into its own column vector. Equation 277 shows the format of the matrix developed while saving the positions. Row one is the collection of positions of joint 1 at the $V$ th via point, row two is the collection of positions of joint 2 at the $V t h$ via point and so forth.

$$
\left[\begin{array}{c}
\Theta_{1}  \tag{277}\\
\Theta_{2} \\
\Theta_{3} \\
\Theta_{4} \\
\Theta_{5} \\
\Theta_{6}
\end{array}\right]=\left[\begin{array}{lllll}
\theta_{1,1} & \theta_{1,2} & \theta_{1,3} & \ldots & \theta_{1, V} \\
\theta_{2,1} & \theta_{2,2} & \theta_{2,3} & \ldots & \theta_{2, V} \\
\theta_{3,1} & \theta_{3,2} & \theta_{3,3} & \ldots & \theta_{3, V} \\
\theta_{4,1} & \theta_{4,2} & \theta_{4,3} & \ldots & \theta_{4, V} \\
\theta_{5,1} & \theta_{5,2} & \theta_{5,3} & \ldots & \theta_{5, V} \\
\theta_{6,1} & \theta_{6,2} & \theta_{6,3} & \ldots & \theta_{6, V}
\end{array}\right]
$$

The time vector was set up in the form of equation 278 , such that there was a time between each via point including the starting and final points.

$$
\Delta t=\left[\begin{array}{c}
\Delta t_{1}  \tag{278}\\
\Delta t_{2} \\
\Delta t_{3} \\
\vdots \\
\Delta t_{V}
\end{array}\right]
$$

The initial point before the trajectory began had to be recorded to give it an initial position. The initial position was store in the first column for each joint such that the initial point of the first joint was $\theta_{1, o}=\theta_{11}$. If this had not been done then the code would error out as the time vector would one length too long. Furthermore this allowed the manipulator to locate itself. This collection of vectors transformed the singular equation 276 into a collection of similar equations for each joint.

$$
\left[\begin{array}{c}
\Theta_{1}(t)  \tag{279}\\
\Theta_{2}(t) \\
\Theta_{3}(t) \\
\Theta_{4}(t) \\
\Theta_{5}(t) \\
\Theta_{6}(t)
\end{array}\right]=\left[\begin{array}{l}
\theta_{1, V}-\theta_{1, V-1} \\
\theta_{2, V}-\theta_{2, V-1} \\
\theta_{3, V}-\theta_{3, V-1} \\
\theta_{4, V}-\theta_{4, V-1} \\
\theta_{5, V}-\theta_{5, V-1} \\
\theta_{6, V}-\theta_{6, V-1}
\end{array}\right] \frac{t}{\Delta t_{V}}+\left[\begin{array}{l}
\theta_{1, V-1} \\
\theta_{2, V-1} \\
\theta_{3, V-1} \\
\theta_{4, V-1} \\
\theta_{5, V-1} \\
\theta_{6, V-1}
\end{array}\right]
$$

Once the trajectory was mapped using the trajectory making program, equation 279 was used to iteratively command the position of each joint of the manipulator. Time $t$ is scalar and was derived from the clock within the computer. Finally, the trajectory was accomplished by placing the matrix into a loop. Once $t=\Delta t$, the timer was reset $(t=0)$ and the via point was updated $(V \rightarrow V+1)$. This continued until there were no more via points in the matrix.

### 12.7.2 Trajectory Cycle

To create the trajectory, the positions necessary were written to the servos in a while loop. The loop would continue until all positions were written. Figure 12.227 provides the
total number of loops required for the trajectory (black bar). It also provides the number of loops in each sub-section of the trajectory. Using this data the trajectory can be optimized as required, either by increasing the number of loops thereby decreasing the distance between each position or decreasing the number of loops, thereby increasing the distance between each position. The cycle time can reduced with a reduction in loops however, the trajectory will not be as smooth.

Figures $12.228-12.231$ provide a breakdown of a loop in the top, side, bottom, and holes section of the trajectory respectively. Each loop was broken down into two sub-sections; trajectory and thermistor. In the trajectory sub-section, the positions are written to the servos. In the thermistor sub-section, the temperatures of the servos are checked. If the temperature is above $35^{\circ} \mathrm{C}$, then the system will activate the emergency shutdown protocol.


Figure 12.227: Number of loops for the trajectory

Comparison of the time to complete the trajectory and thermistor loops: Top section of the rim


Figure 12.228: Top Section:Breakdown of the trajectory

Comparison of the time to complete the trajectory and thermistor loops: Side section of the rim


Figure 12.229: Side Section:Breakdown of the trajectory

Comparison of the time to complete the trajectory and thermistor loops:

Bottom section of the rim


Figure 12.230: Bottom Section:Breakdown of the trajectory


Figure 12.231: Holes Section:Breakdown of the trajectory

### 12.8 Turntable

### 12.8.1 Motor Selection

### 12.8.1.1 Required Rotation Rate

The performance of the turntable system directly impacts the LARRIC's ability to comply with the product specifications. The United Technologies Research Center has specified a cycle time limit to ensure the daily operation of the system will be sufficient to meet the quantity of wheel rims required for cleaning. The Stingray 6036 Aircraft Wheel Washer presented in Section 5 is comparable to the Mart 60 which is currently implemented in UTAS operation facilities. The current cycle time allows four rim halves to be cleaned through a 10 -minute runtime cycle. This project targets trajectory effort toward the larger half of a Boeing 737 NG split rim, which is estimated to need a 3 -minute cycle for cleaning.

The Solidworks rendering of the half-scale wheel rim determined that the total surface area for laser ablation is $703 \mathrm{in}^{2}$. The required rate of surface area coverage uses the total surface area over the desired cycle time as shown in Equation 280.

$$
\begin{equation*}
\dot{A}=\frac{S A}{t_{\text {cycle }}} \tag{280}
\end{equation*}
$$

where,

$$
\begin{equation*}
\dot{A}=\frac{703 \mathrm{in}^{2}}{180 \mathrm{sec}}=3.9 \mathrm{in}^{2} / \mathrm{s} \tag{281}
\end{equation*}
$$

The required rate of surface area coverage is $3.9 \mathrm{in}^{2} / \mathrm{s}$. The half-scale prototype assumes the galvanometer is capable of outputting a 0.5 -inch wide laser beam, $w$. The average tangential velocity can be determined through the following equation:

$$
\begin{equation*}
V_{\text {Tangent }}=\frac{\dot{A}}{w} \tag{282}
\end{equation*}
$$

where,

$$
\begin{equation*}
V_{\text {Tangent }}=\frac{3.9 \mathrm{in}^{2} / \mathrm{s}}{0.5 \mathrm{in}}=7.8 \mathrm{in} / \mathrm{s} \tag{283}
\end{equation*}
$$

An average tangential velocity of $7.8 \mathrm{in} / \mathrm{s}$ across the surface of the wheel rim is necessary to clean the entire surface of the rim. As the wheel rotates on the turntable, the slowest surface of tangential velocity is found along the smallest diameter of the wheel rim. On the half-scale replica of the Boeing 737 NG , the smallest diameter is 3 inches which results in a 1.5 radius, $R_{w i}$. The average rotation rate of the wheel rim, $\omega_{w}$, is determine using Equation 284 .

$$
\begin{equation*}
\omega_{w}=\frac{V_{\text {Tangent }}}{2 \pi R_{w i}} \tag{284}
\end{equation*}
$$

The resulting rate of rotation for the wheel rim is 49.7 rpm . The output rotation rate of the wheel rim is related to the motor input by a gear ratio, $N$, specified in Equation 285 .

$$
\begin{equation*}
N=\frac{\omega_{w}}{\omega_{m}}=\frac{D_{m}}{D_{w o}} \tag{285}
\end{equation*}
$$

$\omega_{m}$ is the rotation rate of the input motor head, $D_{m}$ is the diameter of the motor head, and $D_{w o}$ is the contact diameter of the wheel rim. Given a motor head diameter of 1.5 in and a wheel rim contact diameter of 10.5 in , the resulting gear ratio for the turntable is 1:7. The required input speed of the drive motor with respect to the desired rotation rate of the wheel rim is determine in the equation below:

$$
\begin{equation*}
\omega_{m}=\frac{\omega_{w}}{N} \tag{286}
\end{equation*}
$$

where,

$$
\begin{equation*}
\omega_{m}=49.7 \mathrm{rpm} \times 7=348 \mathrm{rpm} \tag{287}
\end{equation*}
$$

When further considering the application for this motor, higher speed may be required depending on the surface area of the loaded wheel rim. To accommodate for these universal rim sizes, the motor selection should incorporate a 1.2 accommodation factor, $A_{F}$, to ensure the motor can reach high enough velocities. Equation 288 shows the application of the accommodation factor.

$$
\begin{equation*}
\omega_{m}=\omega_{m} \times A_{F} \tag{288}
\end{equation*}
$$

where,

$$
\begin{equation*}
\omega_{m}=348 \mathrm{rpm} \times 1.2=417.6 \mathrm{rpm} \tag{289}
\end{equation*}
$$

The motor required for the half-scale prototype is required to be rated for 417.6 rpm .

### 12.8.1.2 Torque Requirement

The cycle time for cleaning the loaded aircraft wheel rim can be further reduced by limiting the response time for the turntable to reach steady state. The torque rating of the selected motor determines the response time for the wheel rim. Throughout the LARRIC prototype, a maximum desired response time was set to 3 seconds, $t_{\text {response }}$. The maximum acceleration experience by the wheel can be determined with a starting rotation rate of 0 $\mathrm{rpm}, \omega_{i}$, and a maximum desired rotation rate of $\omega_{m}=417.6 \mathrm{rpm}$. Equation 290 determines the maximum potential angular acceleration experienced by the model wheel rim.

$$
\begin{equation*}
\alpha=\frac{\omega_{m}-\omega_{i}}{t_{\text {response }}} \tag{290}
\end{equation*}
$$

where,

$$
\begin{equation*}
\alpha=\frac{417.6 \mathrm{rpm}-0}{3 \mathrm{sec}}=2.32 \mathrm{rev} / \mathrm{s}^{2} \tag{291}
\end{equation*}
$$

Given an angular acceleration of $2.32 \mathrm{rev} / \mathrm{s}^{2}$, the output torque from the turntable can be determined using the equivalent moment of inertia throughout the rotating system, $I_{E q}$. The rotating members in the system design consists of three contact rollers, one drive roller, one motor head, and the loaded wheel rim. The Equation below shows the summation of kinetic energy from all rotating components in the turntable.

$$
\begin{equation*}
\frac{1}{2} I_{r} \omega_{r}^{2} \times 3+\frac{1}{2} I_{d} \omega_{d}^{2}+\frac{1}{2} I_{g m} \omega_{g m}^{2}+\frac{1}{2} I_{w} \omega_{w}^{2} \tag{292}
\end{equation*}
$$

$\omega_{r}$ is the rotation rate of the contact rollers, $\omega_{d}$ is the rotation rate of the drive roller, and $\omega_{g m}$ is the rotation rate of the motor head. $I_{r}, I_{d}, I_{g m}$, and $I_{w}$ are the moment areas of inertia for the contact rollers, drive roller, motor head, and wheel rim - respectively. The rotation rates associated with the contact rollers, drive roller, and motor head are constant, whereas the wheel rim experiences a rotation reduction of $N=1 / 7$ with respect to the input velocity. The equivalent moment of inertia is extracted from the summation of kinematic energy by relating the rotation rates to the rate of the wheel rotation as shown in Equation 293 Equation 295.

$$
\begin{gather*}
\frac{1}{2} I_{r}\left(7 \omega_{w}\right)^{2} \times 3+\frac{1}{2} I_{d}\left(7 \omega_{w}\right)^{2}+\frac{1}{2} I_{g m}\left(7 \omega_{w}\right)^{2}+\frac{1}{2} I_{w} \omega_{w}^{2}  \tag{293}\\
\frac{1}{2} \times\left[49 \times\left(3 I_{r}+I_{d}+I_{g m}\right)+I_{w}\right] \times \omega_{w}^{2}  \tag{294}\\
I_{E q}=49 \times\left(3 I_{r}+I_{d}+I_{g m}\right)+I_{w} \tag{295}
\end{gather*}
$$

The values for $I_{r}, I_{d}, I_{g m}$, and $I_{w}$ were extracted from the Solidworks models. Table 12.17 summarizes the Mass moment of inertias for each subassembly and the quantity of members rotating with the turntable.

Table 12.17: Mass Moment of Inertia of each subassemblies in the Turntable

| Subassembly | Mass Moment <br> of Inertia <br> Kg.m | Quantity |
| :--- | :---: | :---: |
| Motor Head | $I_{g m}=3.39 \times 10^{-4}$ | 1 |
| Drive Roller | $I_{d}=2.43 \times 10^{-3}$ | 1 |
| Wheel rim | $I_{w}=0.0717$ | 1 |
| Contact Roller | $I_{r}=5.08 \times 10^{-4}$ | 3 |

Inputting the values from Table 12.17 into Equation 295 results in an equivalent mass moment of inertia of $I_{E q}=0.282 \mathrm{Kg} . \mathrm{m}^{2}$. The product of the equivalent mass moment of inertia and the angular acceleration determines the torque experienced by the rotating wheel rim. Equation 296 shows the resulting calculation of torque experienced from the loaded wheel rim.

$$
\begin{equation*}
\tau_{w}=I_{E q} \times \alpha=0.282 \mathrm{Kg} . \mathrm{m}^{2} \times 2.32 \mathrm{rev} / \mathrm{s}^{2}=0.65 \mathrm{~N} . \mathrm{m} \tag{296}
\end{equation*}
$$

The gear ratio, $N$, relates the input torque to the output torque as shown in Equation 297

$$
\begin{equation*}
\tau_{m}=\tau_{w} \times N=\frac{0.65 \mathrm{~N} . \mathrm{m}}{7}=0.093 \mathrm{~N} . \mathrm{m} \tag{297}
\end{equation*}
$$

To accommodate for the universal weights of various aircraft wheel classes, the motor selection should incorporate a 1.2 accommodation factor, $A_{F}$, to ensure the motor has the desired time response for heavier rims. Equation 298 Shows the resulting torque requirement for the motor.

$$
\begin{equation*}
\tau_{m}=\tau_{m} \times A_{F}=0.093 \text { N.m1.2 }=0.108 \text { N.m } \tag{298}
\end{equation*}
$$

### 12.8.2 Structural Analysis

The Turntable design studies the basic theories of cantilever beams. Each of the arms in its most general form can be identified as a cantilever beam. The issue with cantilevered beams is the amount of stress that is concentrated at the wall. Each arm also has a large tendency to displace when under a load. To ensure that the full-scale LARRIC prototype will not fail under normal working conditions, Finite Element Simulations were conducted to identify where the stresses concentrate the most in the Turntable assembly. Figure 12.232 shows the concentration of stresses in the full Turntable assemblies.


Figure 12.232: Stress Concentrations of Turntable Design

As seen in the figure, the maximum stress in the assembly is $2,410 \mathrm{psi}$. When comparing this stress to the yield strength of 1020 Cold Rolled Steel, the full-scale model maintains a factor of safety of twenty-one. These values can be confirmed and also compared to an Abaqus CAE simulation done of one single cantilever beam in Section 15.5. Figure 12.233 shows the maximum displacement in the turntable assembly.


Figure 12.233: Displacement of Turntable Design

The maximum displacement in the turntable design is also in the cantilevered arms and reaches a maximum of 0.004 inch. This simulation can also be confirmed and compared to an Abaqus CAE simulation done in Section 15.5 .

Due to the large amount of stress concentrated in the cantilevered arms, the simulation was also analyzed ignoring the stresses in these parts. When doing so, the stress distribution in the frame of the turntable can be seen more clearly. The frame of the turntable was fixed as if the turntable was in the loading position. This way, the stresses in the assembly are identified when the full system is at its weakest. Figure 12.234 shows the stress concentrations in the frame of the turntable.


Figure 12.234: Stress Concentration of Turntable Frame

This simulation shows how the stress is concentrated around the bearings of the system. This information is critical for the reliability of the system by choosing bearings that are rated for this amount of stress. The benefits of this frame design is the minimal amount of stress that is distributed throughout. The team was also interested in identifying the displacement in the frame of the turntable to identify which areas would need to be reinforced for a possible redesign. Figure 12.235 shows the displacement of the frame when under loading conditions.


Figure 12.235: Displacement of Turntable Frame

As seen, the end of the frame displaces the most because of the loading conditions and where the turntable is fixed. The maximum displacement can be seen in the bottom right corner of the frame and displaces at a maximum of 0.003 inches. This is a very minuscule amount of displacement, however this area should be reinforced to ensure uniformity throughout the entire frame. Based on these two simulations, the turntable design has been validated and offers a factor of safety of 21 . This factor of safety was under the conditions that the frame was machined out of 1020 Cold Rolled Steel. The United Technologies Research Center could investigate alternative, cheaper materials for the frame design because of the strength of this prospective model.

### 12.8.3 Discussion of Results

From the results of the experimentation on different compositions of the dirt layer, it can be concluded that the percentage of dirt will have the greatest affect on the cleanliness of the material. Mixture A, the mixture with the highest percentage of dirt was cleaned the least while Mixture E, no dirt, had the best clean. The percentage of dirt in the composition of the dirt layer and the cleanliness of the ablated area are inversely proportional to each other. Furthermore, from the analysis of the different energy levels of the laser-beam, it can be concluded the higher the energy of the laser-beam, the cleanliness of the ablated area will ave a higher quality. However, too high of an energy level and the material will be damaged and the anodized coating will be removed, both of which are unacceptable. The last aspect of the experimentation with different mixtures was to determine the effect of a second pass
in the ablated area. By comparing the results from samples with only one pass to samples with two passes it can be concluded that, the second pass is unnecessary. The cleanliness of the sample does not increase enough for it to be worth the risk of further damage to the rim.

Changing the angle of incidence of the laser-beam greatly effected the quality of the ablation. The higher the angle of incidence, the worse the quality becomes. Furthermore, the greater the value of the angle of incidence, the less of the projected area will be ablated. At an angle of incidence of $15^{\circ}$ the whole length of the project area ( 20 mm ) was still ablated, however at an angle of incidence of $60^{\circ}$, only 5 mm of the 20 mm was ablated, a drop of $75 \%$. It can also be concluded that there is a critical angle of incidence of $45^{\circ}$. After the $45^{\circ}$ mark, the quality of the ablation drastically decreases whereas at when the angle of incidence was $15^{\circ}$ or $30^{\circ}$, the difference was not as noticeable. Ideally the laser would always be perpendicular to the area it is ablating, so that the focal length is consistent throughout the projected area.

Figures 12.147 through Fig. 12.155 provide the analysis of the surface roughness for the $75 \mu \mathrm{~J}$ Laser-beam with one pass over the ablated area. When examining the effectiveness of the ablation process with the clean surface as the reference, it can be concluded that the surface roughness decreased for Mixture A, Mixture B, and Mixture E, and increased for Mixture C and Mixture D. Therefore, it can be concluded that the material was not damaged for Mixture A, Mixture B, and Mixture E but was damaged for Mixture C and Mixture D. When comparing the effectiveness of the laser ablation with the dirt layer as the reference, it is concluded that the ablation process was effective in reducing the surface roughness of the ablated area by a minimum of $100 \%$.

Figures 12.163 through Fig. 12.168 provide the analysis of the surface roughness for the $115 \mu \mathrm{~J}$ laser-beam with one pass over the ablated area. As can be sen in Fig. 12.159 and Fig. 12.160 the average and mean roughnesses for the mixtures are lower than the reference roughness. However, when comparing the effectiveness of the ablation process to the roughness of the unablated area (Fig. 12.167 and Fig. 12.168), it is concluded that only the ablated area under Mixture A was not damaged. Therefore, the experimentation was successful for Mixture A. When the surface roughness is compared tot he dirt layer of each mixture, there is over a $1050 \%$ decrease in the surface roughness. Therefore, the laser is very successful in removing the dirt from the aluminum plate.

Figures 12.171 through Fig. 12.208 provide the analysis of the surface roughness for the different mixtures for the $150 \mu \mathrm{~J}$ laser-beam with one pass over the ablated area. Figure 12.171 ad Fig. 12.172 show that the surface roughness increases for every mixture when compared to the clean reference. Therefore, $150 \mu \mathrm{~J}$ is too powerful of an energy level for the laser-beam. There is obvious damage to the surface of the aluminum, which is unacceptable. The mean roughness remains relative constant and similar to the clean surface however, the average roughness is significantly higher. The effectiveness of the ablation shows an increase in the average surface roughness and the mean surface roughness by approximately $50 \%$. Even though the laser energy was too high and the material was damaged, the laser was very effective in removing the dirt layer from the surface of the aluminum plate. There was close to a $200 \%$ decrease in the surface roughness when compared to the unablated dirt layer for each mixture.

Figures 12.183 through Fig. 12.194 provide the analysis of the effect of the $75 \mu \mathrm{~J}$ laserbeam with two passes over the ablated area. The purpose of this experimentation was to
determine whether the second pass over the ablated material affected the surface roughness of it. Comparing the average and mean roughness of two passes to only one pass shows that the surface roughness is rougher for the trials wit two passes. Therefore, the second pass does affect the material. The increase in surface roughness is not large but it is enough to be taken into consideration. The effective of the two pass was similar to only one pass. Therefore, it can be concluded that for $75 \mu \mathrm{~J}$, the second pass is unnecessary and will only add to the cycle time.

Figures 12.195 through Fig. 12.206 provides the analysis of the effect of the $115 \mu \mathrm{~J}$ laserbeam with two passes over the ablated area. The surface roughness of the mixtures after ablation was smoother than the clean reference, as can be seen in Fig. 12.195 and Fig. 12.196 . When compared to the average and mean roughness of the same energy level but with only one pass, it is concluded that the values remain similar. Furthermore, the effectiveness of the ablation compared to the unablated dirt layer is also similar. Therefore, it can be concluded that the second pass is unnecessary and does not provide anything positive to the process.

Figures 12.207 through Fig. 12.218 provides the analysis of the effect of the $115 \mu \mathrm{~J}$ laserbeam with two passes over the ablated area. When comparing the results to the trials with a laser energy of $150 \mu \mathrm{~J}$ but only one pass over the ablated area, it can be concluded that the second pass increased the roughness of the surface. Therefore, it the second pass is unnecessary and provides more harm to the material. he effectiveness of the removal of the dirt layer does increase with the second pass but the benefit is not great enough to deem the second pass as necessary.

## 13 Proof of concept

The objective of the project was to prove that laser ablation could be used to remove the dirt layer from the anodized coating layer and that the coating layer itself would not be removed during the process. The complexity of the problem definition required multiple methods to prove the concept. Three different and independent method were used, numerical analysis, computer simulations, and physical experimentation. All three of the methods provided similar conclusions that it is possible to ablate the dirt layer from the aircraft rim and not remove the anodized coating off of the rim.

The numerical analysis provided the theoretical calculations of what is to be expected from the laser ablation process. Figure $12.73[\mathrm{Pg} 290$, Fig. $12.74[\mathrm{Pg} 291$, Fig. $12.78[\mathrm{Pg} 295$, and Fig. 12.79 [Pg. 296] are instrumental in proving that it is possible to remove the dirt layer without removing the anodized coating layer. Figure 12.73 [Pg. 290 and Fig. 12.74 [Pg. 291] show that the majority of the energy form the laser will be transmitted into the dirt layer and absorbed by it. Therefore, the remaining energy that is transmitted into the coating layer is small in comparison. The less energy that enters the coating layer, the lower the probability that it will be damaged. Furthermore, Fig. 12.78 [Pg. 295 and Fig. 12.79 [Pg. 296 increase the confidence of claiming that the anodized coating will not be removed. Although the majority of the remain energy is transmitted through the coating layer, very little is absorbed by it. The energy is only transmitted in and then out of the coating. Less
than ten percent of the total energy of the laser will be absorbed by the coating layer.
The second computer simulation [Pg. 314, shows how the heat transfer between the layers will occur. Furthermore, it provide the increase in temperature in all three layers. It was determined that the critical flash point temperature, when the dirt is ablated, was $180^{\circ} \mathrm{C}$. Figure 12.101 [Pg 319 provides the increase in temperature throughout the dirt layer. The temperature almost immediately rises to approximately $200^{\circ} \mathrm{C}$, proving that the dirt layer would be removed. Whereas, Fig. 12.102 [Pg. 319 shows that the temperature of the coating layer only reaches a maximum temperature of $120^{\circ} \mathrm{C}$, well below the critical value. Furthermore, the rise in the temperature of the coating layer is very slow compared to the rise in the temperature of the dirt layer. It takes a full sixty seconds for the coating temperature to reach $120^{\circ} \mathrm{C}$ and it takes the dirt layer approximately five seconds. to reach $200^{\circ} \mathrm{C}$. At the point in time when the temperature of the dirt layer reaches $200^{\circ} \mathrm{C}$, the temperature in the coating layer is only approximately $35^{\circ} \mathrm{C}$. The computer simulation proves that it is very unlikely for the coating layer to be removed through the process of laser ablation because the temperature of the coating layer never approaches its critical value.

The purpose of the physical experimentation was to confirm the conclusions made in the numerical analysis [Pg.288] section and the Computer Simulations [Pg 306] section. Furthermore, once the conclusions were confirmed, the boundary limits of the laser were pushed to determine when the material would become damage. The purpose of reaching failure was to determine the absolute maximum limit of the energy of the laser. Knowing the failure point would allow for easier optimization and designing of the full scale system. Figure 12.108 [Pg. 326 provides the base testing done to determine whether or not the laser would remove the anodized coating. It can be seen clearly that from an energy level of $10 \mu \mathrm{~J}$ to $75 \mu \mathrm{~J}$, there is no damage to the coating. Therefore, the experimentation was successful is confirming that laser ablation would not damage the coating. Furthermore, test trials were ran with different dirt layer compositions to determine if laser ablation would be able to remove the dirt layer. As can be seen in the Presentation of results subsection in the Engineering Analysis Section [Pg. 324], the laser was able to easily remove the dirt from every sample. There was never a failed trial. Furthermore, the boundary limit of the laser were pushed in the roughness analysis subsection, starting on Pg . 354, to determine the failure of the system. By knowing the failure, the design will be optimized to make sure that the proof of concept will never fail during the May model or the full scale model.

## 14 Build/Manufacture

### 14.1 Full Scale Model

The prototype presented throughout this report has provided significant insight and design considerations for a full-scale system to be implemented into UTAS operations facilities. Design suggestions are presented throughout this section toward the final product pertaining to laser selection, robotic manipulator selection, turntable motor selection, and the design of a loading tray assembly. Vendors for each system application are provided as options
that can supply mechanical components to the final product. The specific derivations of modifications and suggestions to the system design are outlined in section ??.
"

### 14.1.1 Laser Selection

The selection of an appropriate laser is a critical aspect for this project that sets the constraints for all other engineering parameters in this system design. The laser's ability to clean any aircraft rim under a short cycle time without damaging metallic coatings affects the required rotation rate of the rim and the overall feasibility of the process. According to [17, most laser ablation applications for metal cleaning use a Neodymium doped: Yttrium Aluminum Garnet laser (Nd:YAG). The electrical excitation of neodymium ions encased in a Yttrium Aluminum Garnet produces light with a wavelength of 1064 nm , an inferred wavelength. This wavelength falls under the absorption spectrum for most dirt mixtures and conveniently falls under the reflection spectrum for aluminum alloys [?]. In sensitive ablation applications, a pulsing technique is used to excite the neodymium ions at a frequency that resonates the emitting light. Once a specified level of energy is produced, a Q-switch is activated and allows the light beams to emit through an open cavity in the system. This technique is commonly known as Q-Switching.

Representatives of the IPG Photonics facility in Oxford, Massachusetts, provided further design assistance for selecting an appropriate laser system. Given the time constraint and energy requirements for ablating the wheel rim, a one-Kilowatt laser was recommended for attaining a quality clean. The optic products at IPG Photonics reach efficiencies greater than $30 \%$ through their fiber lasers as opposed to other solid state or gas lasers [18]. The vertically loaded laser system can connect to a string composite of optical fibers attached to a laser head. For the purpose of aiming the laser beam over a wide spread surface area, a collimator and galvanometer should be coupled to the head of the laser to concentrate and direct the laser beam across the rim. A collimator is used to focus dispersed light emittance from the laser, producing a straight and organized beam of light. A galvanometer is an electromechanical lens that focuses collimated energy to a point and uses mirrors attached to servomotors to adjust the position of the laser beam. Figure 14.1 illustrates the assembly of the laser system coupled with a collimator and galvanometer.


Figure 14.1: A model assembly of a fiber laser coupled with a collimator and galvanometer 18.

The combined photon generation properties and optical bending components are adjustable to attain a thorough dry clean across any wheel rim surface without damaging anodized coatings on the aluminum alloy material. Section 15.2 presents a detailed analysis pertaining to a proof of concept for the laser ablation process.

### 14.1.2 Robotic Manipulator Selection

Selecting a robotic manipulator for the application of an automated laser system direct impacts the quality, repeatability, and flexibility for the system design. An industrial robotic manipulator will be necessary to comply with each of the previously specified parameters. One of the greatest challenges faced throughout the prototyping process was the inconsistence and reliability of the servomotors on the robotic arm. The laser assembly described in Section 14.1.1 can produce significant torque loads at each of the joints. An additional parameter to consider with selecting a robotic manipulator is the length of the second member between the shoulder and elbow joints (See member AB in Figure 11.18). The robotic manipulator used in the prototype had a short range and was not able to properly reach the top and bottom of the wheel rim. By increasing the length of member AB , the manipulator will be better able to reach the entire surface of the wheel rim while also being able to home itself into a compact position for rotating to the top and bottom of the wheel rim. In the New England region, there are several vendors that provide robotic solutions for manufacturing applications. FANUC North America located in Holliston, Massachusetts, is a world leader in robotics, CNC systems, and factory automation [19]. The six-axis robotic arms are customizable and can be tailored to suit the exact needs of the user's applications. Another company offering robotic solutions is ABB in Bloomfield, CT. The company develops
general control solutions for aerospace and manufacturing applications. The robotic solutions are also customizable and software solutions can be provided as well 20.

### 14.1.3 Motor Selection

An electric motor is required to drive the turntable for the loaded wheel rim. The turntable is designed to incorporate aircraft wheel rims that range in weight from 15 lbs to 60 lbs . By following the calculation procedure presented in Section 12.8.1, the torque requirement for the final LARRIC model will need to reach 4.8 Nm . With the assumption that the gear reduction ratio between the roller contacts and wheel diameter remain constant at $1: 7$, the required speed of the motor must be rate for 230 rpm . The safety factor for this application is 1.2 for both the torque and speed of the motor. The resulting power output for the required motor is 18.5 Watts. In addition, it is advised to incorporate an encoder at the end of the motor to implement PID control for attaining a steady rotation rate while rotating the wheel rim.

An 18.5-Watt driver can be achieved through the use of a DC motor. A suggested vendor for purchasing a specific motor with customizable gear and head attachments is Maxon Precision Motors. In 2019, the Swiss company will open a production facility for standardized products in Taunton, Massachusetts [21]. The standardized products reach a peak wattage of 500 Watts and can be customizable for any position sensitive or power-driven application.

### 14.1.4 Frame Design

The primary concept illustrated in Section 11.1 .2 .1 will continue to be used in the fullscale assembly. A few of the key parameters should be modified to improve the contact grip on the rotating wheel rim and improve the structural support throughout the frame. The material proposed for the final frame design uses Aluminum 2024 to improve the structural stability of the frame. The light weight material will allow the frame to easily be pulled out of the system for loading and unloading as well.

The prototype utilized four points of contact to efficiently translate rotational energy from the driver motor into the wheel rim. After production, an issue developed where assembly tolerances were not precise enough and the wheel rim would occasionally loose contact with the drive motor, which stopped the wheel rim from rotating. The final design of the frame should incorporate three points of contact to allow constant support and distribution of weight throughout the turntable. The points of contact should be evenly distributed at 120 degrees around the loaded wheel rim radially and the drive roller should remain perpendicular to left wall of the system housing. Figure 14.2 shows a 3-D Solidworks model of the proposed frame design.


Figure 14.2: A Solidworks model of the final tray assembly design.

The excess space on the right side of the frame has been removed primarily to reduce the moment arm for supporting the back side of the wheel rim. In addition, the tray reduction conserves space inside of the system housing for implementing a robotic arm. Unlike the prototype, the right wall should be extended out to support the tray slider and ultimately reduce the width of the door.

Another update for the final frame design is to incorporate an interchangeable roller sets for various rim classes. The contact rollers can be easily removed by unscrewing the nut on the outer side of the tray. The rollers can then be replaced with longer or shorter roller shafts to accommodate for the wheel rim diameter. The roller head and shaft assembly from the prototype can be simplified by manufacturing the shaft to include the roller head on the end of the shaft. A Solidworks model of the roller shaft can be seen in Figure 14.3. In addition to merging the roller head and the shaft to one component, the containment lip along the roller head is extended to one inch to ensure the wheel rim does not fall off the turntable. A final assembly of the turntable tray is shown in Figure 14.4. Detailed drawing of the components and subassemblies for the turntable tray are available in Appendix ?? ??


Figure 14.3: A Solidworks model of the roller shaft.


Figure 14.4: A Solidworks model of the final tray assembly.

## 15 Testing

In order to ensure proper and thorough testing of the LARRIC system, test protocols were split into five subsections that would confirm the functionality of each part before conducted full system tests. The test tasks were separated into items involving laser ablation, The robotic arm, Turntable, Safety Systems and Electrical Equipment. Table 15.1 identifies all of the individual test tasks necessary to validate the quality of the LARRIC prototype.

Table 15.1: Test Matrix
$\left.\begin{array}{|c|c|c|c|c|}\hline \begin{array}{c}\text { Test } \\ \text { Case }\end{array} & \begin{array}{c}\text { Person } \\ \text { Responsible }\end{array} & \text { Feature } & \text { What to Test? } & \begin{array}{c}\text { Test } \\ \text { Parameters }\end{array} \\ \hline 1.1 & \text { Mkrtich } & \text { Electrical Equipment } & \text { Laser Proximity Sensor } & \begin{array}{c}\text { Accuracy } \\ \text { Precision }\end{array} \\ \hline 1.2 & \text { Mkrtich } & \text { Electrical Equipment } & \text { Ultrasonic Proximity Sensor } & \begin{array}{c}\text { Accuracy } \\ \text { Precision }\end{array} \\ \hline 1.3 & \text { Mkrtich } & \text { Electrical Equipment } & \text { Connection with Arduino } & \begin{array}{c}\text { Communication with Turntable, } \\ \text { Robotic Manipulator, } \\ \text { Emergency Stop Buttons, } \\ \text { Ultrasonic Proximity Sensor, } \\ \text { Laser Proximity Sensor, }\end{array} \\ \text { Thermistors }\end{array}\right\}$

### 15.1 Electrical Equipment

### 15.1.1 Ultrasonic Proximity Sensor

To ensure the quality of the ultrasonic proximity sensor, the accuracy and precision were tested. A block was held away from the sensor and the measurement was taken. The distance from the block to the sensor was increased by one inch after every measurement. The testing was repeated three times and the values were averaged together to form valid data. The results of the individual trials are located in the Appendix (A.5.1). Table 15.2 provides the average distance measurement and error in the measurement. Figure 15.1 provides a visualization of the measured distance versus the actual distance. Figure 15.2 provides the graph of the error at each distance.

Table 15.2: Average Measurements:Ultrasonic Proximity Sensor

| Average |  |  |
| :---: | :---: | :---: |
| Actual Distance (in) | Measured Distance (in) | Percent Error (\%) |
| 1 | 1.1811 | 18.110 |
| 2 | 1.9685 | 1.575 |
| 3 | 3.1496 | 4.987 |
| 4 | 3.937 | 1.575 |
| 5 | 5.1181 | 2.362 |
| 6 | 6.2992 | 4.987 |
| 7 | 7.0866 | 1.237 |
| 8 | 8.2677 | 3.346 |
| 9 | 9.0551 | 0.612 |
| 10 | 10.2362 | 2.362 |
| 11 | 11.0236 | 0.215 |
| 12 | 11.811 | 1.575 |



Figure 15.1: Theoretical distance vs measured distance: Ultrasonic PROXIMITY SENSOR


Figure 15.2: Error in the measurement:Ultrasonic Proximity sensor

It can be concluded that the sensor was accurate from a range of 2 inches to 12 inches because the error for all measurements in this range was below $5 \%$. When the block was only 1 inch away, there was a $18 \%$ error in the measurement meaning that the sensor was not accurate at detecting objects in a very close vicinity. When including the error at the 1 inch mark, the average error for all measurements was $3.58 \%$. When excluding the error at the 1 inch mark, because it is an outlier, the average error for all measurements was $2.25 \%$. The Test Form for the ultrasonic proximity sensor can be found in the Appendix( A.5.1).

### 15.1.2 Laser Proximity Sensor

To ensure the quality of the laser proximity sensor, the accuracy and precision were tested. A block was held away from the sensor and the measurement was taken. The distance from the block to the sensor was increased by one inch after every measurement. The testing was repeated three times and the values were averaged together to form valid data. The results of the individual trials are located in the Appendix (A.5.2). Table 15.3 provides the average distance measurement and error in the measurement. Figure 15.3 provides a visualization of the measured distance versus the actual distance. Figure 15.4 provides the graph of the error at each distance.

Table 15.3: Average measurements and error:Laser Proximity Sensor

| Average |  |  |
| :---: | :---: | :---: |
| Actual Distance (in) | Measured Distance (in) | Percent Error (\%) |
| 1 | 1.1548 | 15.483 |
| 2 | 2.0341 | 2.755 |
| 3 | 3.0446 | 2.537 |
| 4 | 4.0026 | 1.115 |
| 5 | 5.0656 | 1.312 |
| 6 | 6.0236 | 1.006 |
| 7 | 7.1654 | 2.362 |
| 8 | 8.3071 | 3.838 |
| 9 | 9.3701 | 4.112 |
| 10 | 10.6037 | 6.037 |
| 11 | 11.5879 | 5.345 |
| 12 | 12.7690 | 6.409 |



Figure 15.3: Theoretical distance vs measured distance: Laser proximity SENSOR


Figure 15.4: Error in the measurement:Laser Proximity sensor

It can be concluded that the laser proximity sensor was very accurate from a range of 2 inches to 9 inches. There was an average error of $2.3796 \%$. From 10 to 12 inches there was an average error of $5.93 \%$ and at 1 inch there was an error of $15.483 \%$. Therefore, as long as the laser proximity sensor is 2 to 9 inches away from the rim, it will read very accurately. Furthermore, the sensor was able to detect all of the holes in the rim. The test form can be found in the Appendix (A.5.2 In conclusion, the laser proximity sensor will perform as required when implemented into the overall system.

### 15.1.3 Connection with Arduino

To ensure that the Arduino would be able to communicate with each component, initialization tests were completed. The Arduino was connected to the each component individually and would attempt to connect with it. If successful, MATLAB would output a response informing the operator that the connection was a success. If unsuccessful, MATLAB would pout a response informing the operator that the connection was a failure. The test form below summaries the results of the test.

### 15.1.3.1 Test Form 1.3

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 1.3) Connection with Arduino |
| Test Date: | $4-23-2018$ |
| Test Iteration: | 1 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: |  |
| Test Parameter | Y |
| Response from Turntable (Y/N) | Y |
| Response from Robotic Manipulator (Y/N) | Y |
| Response from Emergency Stop Buttons (Y/N) |  |
| Response from Ultrasonic Proximity Sensor (Y/N) | Y |
| Response from Laser Proximity Sensor (Y/N) | Y |
| Response from Thermistors (Y/N) | Y |
| Observation Notes: | All responses were correct and within the <br> acceptable time frame |
| Resolutions if Needed: |  |
| Test End Time (hh:mm) |  |
| Further Attachments? (file location) | Migrtich Arslanyan |
| Primary Test Executor Signature: |  |

### 15.1.4 Proper Electrical Connections

ALl of the wiring was inspected to ensure there were no problems. The color coding of the wire, the fastening of the wire, and the solder joints were inspected. The wire must have been fastened to either a wall or to the electrical cabinet. All wire outside of the electrical cabinet must have passed through the insulated tubing. All solder joints must have been taped to ensure they would not contact each other and short-circuit. The Test form below provides the results of the test.

### 15.1.4.1 Test Form 1.4

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 1.4) Proper Electrical Connections |
| Test Date: | $4-17-2018$ |
| Test Iteration: | 1 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: | Test Parameter |
| Test Result |  |
| Proper Selection of Wires (Y/N) | Y |
| Properly Fastened Wires (Y/N) | Y |
| Proper Soldered Connections (Y/N) | Y |
| Observation Notes: | All wires are properly fastened. No wires will become <br> entangled. All solder joints are covered. Color coding of <br> wires is correct |
| Resolutions if Needed: |  |
|  |  |
| Primary Test Executor Signature: | Mkrtich Arslanyan |
| Second in Command Signature: |  |
| Test End Time (hh:mm) | 09:46 PM |
| Further Attachments? (file location) |  |

### 15.1.5 Sufficient Power to the System

Tests were completed to ensure that all components were receiving the correct amount voltage and current. If the voltage or current was too low then the component would not turn on or function properly. If the voltage or current was too high then the component would short-circuit and would have to be replaced. The test form below provides the results of the test.

| MCE 402 Team \#14 Team B.E.E.M. | Record of Individual Test |
| :---: | :---: |
| Test Description (refer to Test Matrix): | 1.5) Sufficient Power to the System |
| Test Date: | 4-17-2018 |
| Test Iteration: | 1 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: |  |
| Test Parameter | Test Result |
| Delivered Volts, Amps, and Watts: Turntable | 12V; 1 Amp; 12W |
| Delivered Volts, Amps, and Watts: Robotic Manipulator | 5V; 1Amp; 5W |
| Delivered Volts, Amps, and Watts: Ultrasonic Proximity Sensor | 5V; 50mA; 0.25W |
| Delivered Volts, Amps, and Watts: Laser Proximity Sensor | $3.3 \mathrm{~V} ; 50 \mathrm{~mA} ; 0.165 \mathrm{~W}$ |
| Observation Notes: | Power to all components is correct. No voltage or current was too high. |
| Resolutions if Needed: |  |
| Primary Test Executor Signature: | Mkrtich Arslanyan |
| Second in Command Signature: |  |
| Test End Time (hh:mm) | 10:06 PM |
| Further Attachments? (file location) |  |

### 15.2 Laser Ablation

Testing to prove the validity of Laser Ablation was conducted on December 9, 2018 at IPG Photonics in Oxford, Massachusetts. The testing consisted of testing five different samples of anodized aluminum materials. Each sample had a different mixture of carboncarbon brake dust, dirt, and grease. A variety of pulse energies were used when ablating the samples to see what the optimal pulse energy was to most effectively clean the samples, as well as at what energy would cause damage to the anodized aluminum samples. Figure 15.5 shows the various mixtures that were coated onto the anodized aluminum pieces.


Figure 15.5: Laser Ablation Test Samples
The five samples were labeled A-E (Samples A and B featured left to right on the bottom and samples C,D, and E on the top). Table 15.4 characterizes the different mixtures between the five samples.

Table 15.4: Mixtures Tested

| Mixture | $\underline{\text { Dirt (\%) }}$ | $\underline{\text { Grease (\%) }}$ | $\underline{\text { Carbon Dust (\%) }}$ |
| :---: | :---: | :---: | :---: |
| $\mathbf{A}$ | 80 | 20 | 0 |
| $\mathbf{B}$ | 60 | 20 | 20 |
| $\mathbf{C}$ | 40 | 20 | 40 |
| $\mathbf{D}$ | 20 | 20 | 60 |
| $\mathbf{E}$ | 0 | 20 | 80 |

Incorporating multiple samples of various mixtures helps to identify if laser ablation can effectively clean all of the samples, regardless of their makeup. Before testing each of the five samples, a base-line measurement was taken on a sample piece of aluminum that had no mixture coated on it. The purpose of this base-line test was to identify how laser ablation functioned on the anodized aluminum samples without any interference from other materials. Figure 15.6 shows the bare aluminum sample after being ablated by ten different pulse energies.


Figure 15.6: Base-Line Laser Ablation Test

As shown, the pulse energy varies from 10 Microjoule to 1 millijoule and creates a different surface finish roughness between each square. The team then identified an acceptable range of pulse energy to test between so that the anodized coating would not be removed and that the aluminum sample was not damaged. Once the acceptable pulse energy range was found testing on the five mixtures began. The team was looking for various qualities of the test from overall cleanliness to surface finish and leftover residue in the test area. Figure 15.7 shows the results of the testing on sample A which had a mixture of $80 \%$ Dirt, 20\% Grease and 0\% Carbon Brake Dust.


Figure 15.7: Laser Ablation Sample A Results

The results provided from the laser ablation testing prove that this technology is a viable substitute for a water-jet based system to clean aircraft rims. This technology is highly customizable for the customer's requirements and produces a significantly lower amount of waste. For further information about the results of the testing done at IPG Photonics and the measurements taken to validate this process, please refer to the Appendix.

### 15.2.1 Cycle Time

Figure 15.8 process the total time for one cycle along with a breakdown of how long each section of the process lasts. The time for one cycle was 306 seconds or 5.1 minutes. As Fig. 15.9 shows, the ablation process lasts for almost $75 \%$ of the entire cycle time. $25 \%$ for the cycle time being the down time is not ideal. However, in the full scale model, this can be reduced by having two or more sections running at he same time. For example, the safety checks for proper loading can run at the same time. The limitations of the Arduino Mega2560 did not allow for the half scale model to have this feature.


Figure 15.8: Cycle time for each section of the ablation process


Figure 15.9: Percentage of the cycle time for each section of the ablation PROCESS


Figure 15.10: Comparison of the run time and down time


Figure 15.11: Percentage of the run time and down time

Figure 15.12 provides a breaks the ablation time into the four sections. As can be seen in Fig. 15.13 the ablation of the holes is almost $50 \%$ of the total ablation time. The side section of the rim took the shortest amount of time because it has the least complex geometry. Each section immediately entered the next section once complete therefore, there was no down time between sections. The limitations of he robotic manipulator and th turntable did not allow for a faster cycle time. The professional equipment in the full scale model will allow for much faster times. The rotation of the rim was limited to 15 rpm .Furthermore, the faster the manipulator moved, the smoothness of the trajectory decreased. Therefore, the combination of turntable speed and manipulator speed was selected to provide the smoothest and fastest cycle time possible. The test form for the cycle time can be found in the Appendix (A.5.3.1)


Figure 15.12: Cycle time for each section of the trajectory


Figure 15.13: Percentage of cycle time for each section of the trajectory

### 15.3 Robotic Manipulator

### 15.3.1 Repeatability

Repeatability testing of the robotic manipulator was conducted in order to validate point to point accuracy and time based accuracy of the manipulator. Two separate tests were conducted to test single point trajectory, and a continuous repeated trajectory. Testing was performed by mounting a marking tool to the end effector. Once attached, a trajectory was planned using the trajectory planning GUI developed by the team. The controller instructed the manipulator to move to a location and mark a piece of paper. This initial mark was labeled as the origin of a new coordinate system. The manipulator was repeatedly instructed to move back to the location based on the trajectory planned by the controller and a mark was placed each iteration. For single point trajectory, the trajectory was performed at the command of the user for each new mark. Continuous tests commanded the manipulator to repeatedly mark the same location every 5.45 seconds for three minutes.

Table 15.5: Repeatability Test Results

|  | Single point | Continuous Test |
| :--- | :--- | :--- |
| Number Data Points | 25 | 33 |
| Maximum Drift $(\mathrm{cm})$ | 0.55 | 0.55 |
| Test Time (seconds) | N/A | 180 |
| Average | 0.0064 | 0.0097 |
| Standard Deviation $(\mathrm{cm})$ | 0.229 | 0.307 |

Results from the tests shown in Table 15.5 indicated the absolute maximum drift was 0.55 cm . Average drift and standard deviation was higher for the continuous test than the single point trajectory test. Although the time varying test indicated higher deviation, the results from both tests were within the desired range to adequately simulate laser ablation. Figures 15.14 and 15.15 provide the data acquired throughout the testing. Figure 15.14 is a graph of all of the recorded points for the single point test plotted against the iteration number. Figure 15.15 illustrates the results from the continuous test. The Y-axis represents the drift from the starting point and the x -axis is the time at which the position was recorded.


Figure 15.14: Single Repeated Test


Figure 15.15: Displacement over Time

### 15.3.2 Linear Actuator

The linear actuator was tested to ensure its velocity and position readings were correct. Furthermore, the limit switches were tested to ensure they functioned properly. The results of the testing are summarized in the test form below.

### 15.3.2.1 Test Form 3.2

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 3.2 ) Linear Actuator |
| Test Date: | $40-23-2018$ |
| Test Iteration: | 3 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: |  |
| Test Parameter | 3 |
| Number of Trials | $95 \%$ |
| Velocity Accuracy | $100 \%$ |
| Coordinate Accuracy | Y |
| Limit Switch Top (Y/N) | Y Result |
| Limit Switch Bottom (Y/N) | Smooth movement. Constant velocity. |
| Observation Notes: |  |
|  |  |
| Resolutions if Needed: |  |
|  |  |
| Primary Test Executor Signature: | Mkrtich Arslanyan |
| Second in Command Signature: |  |
| Test End Time (hh:mm) | $5: 54$ PM |
| Further Attachments? (file location) |  |

### 15.4 Safety Systems

### 15.4.1 Emergency Stops

Two emergency stops were implemented into the system. The first controlled the emergency protocol for the robotic manipulator. This stop was used only when the manipulator was being tested by itself. When pressed, it would halt the motion of the manipulator in its last position. This ensured that it would be become more damaged. It also gave he operator the opportunity to free the arm is stuck or remove the object interfering with the manipulator. The second emergency stop was for the overall system. When pressed it did the same as the stop for the manipulator and more. It would stop the rotation of the turntable, cut off power to all DC motors and sensors. Then it would switch off the relays connected to the power supplies to ensure no active voltage or current was flowing through the system. The test form below provides the results of the testing to determine if the protocol works and measure how long it takes.

### 15.4.1.1 Test Form 4.1

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 4.1) Emergency Stop Buttons |
| Test Date: | $4-22$-2018 |
| Test Iteration: | Mkrtich Arslanyan |
| Name of Primary Test Executor: |  |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: | Test Parameter |
| Yest Result |  |
| Arm: Shut Down Procedure Works | 7.2 seconds |
| Arm: Shut Down Time | 11.8 seconds |
| Overall: Shut Down Procedure Works | Yes |
| Overall: Shut Down Time |  |
| Observation Notes: |  |
| Resolutions if Needed: |  |
|  |  |
| Primary Test Executor Signature: | Mkrtich Arslanyan |
| Second in Command Signature: |  |
| Test End Time (hh:mm) | $11: 42$ PM |
| Further Attachments? (file location) |  |

### 15.4.2 Interlocks

Interlocks are a process of steps that occur when an error arises. The interlocks tested were for the sliding of the turntable and the improper loading of the rim. If the requirements for an error were met, then the program would go into its shutdown protocol. The operator would be made aware of the error and then the system would be shut down. All motion would be stopped and power to all devices would be cut off. The test form below provides the results of the testing.

### 15.4.2.1 Test Form 4.2

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 4.2 ) Interlocks |
| Test Date: | 4 -25-2018 |
| Test Iteration: | 1 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: |  |
| Test Parameter | Success |
| Unscheduled Door Opening | Success |
| Improper Loading | Success |
| Shut Down Procedure Works | $00: 12$ |
| Shut Down Times (mm:ss) |  |
| Observation Notes: |  |
|  |  |
| Resolutions if Needed: |  |
| Primary Test Executor Signature: | Mkrtich Arslanyan |
| Second in Command Signature: |  |
| Test End Time (hh:mm) | $08: 42$ PM |
| Further Attachments? (file location) |  |

### 15.4.3 Over-Heating Protection

It was determined that four out of the seven servo motors were in danger of over-heating. These four were the three controlling the shoulder of the manipulator and one controlling the elbow of the manipulator in the XY-plane. Thermistors were attached to each servo to measure the temperature during operation. The servos were rated for a maximum internal temperature of $55^{\circ} \mathrm{C}$. The thermistors were not capable of measuring the internal temperature therefore, it was determined that the maximum external temperature would be $35^{\circ} \mathrm{C}$. If the temperature of one of the servos was equal to or greater than $35^{\circ} \mathrm{C}$ then the shut-down protocol was activated. The operator was told which servo was overheating and the motion of the manipulator was stopped to prevent further damage to the servos.

Figure 15.16 provides the temperatures of the servos for one full cycle. As can be seen, the highest temperatures are experienced by the servo controlling the elbow. However, the highest temperature was only $28^{\circ} \mathrm{C}$. The other three servos remain in a range of $22-24^{\circ} \mathrm{C}$. As time increases the temperatures decrease. This can be attributed to that complexity of the trajectory. The most complex portion was for the top section of the rim. Therefore, the
logical assumption was that this portion would experience the highest temperatures. The trajectory was split into four sections. Figures 15.1715 .20 provide the temperatures for the top section, side section, bottom section, and the holes respectively.


Figure 15.16: Temperature readings throughout the entire ablation PROCESS


Figure 15.17: Temperature readings for the ablation process of the top SECTION OF THE RIM


Figure 15.18: Temperature readings for the ablation process of the side SECTION OF THE RIM


Figure 15.19: Temperature readings for the ablation process of the BOTTOM OF THE RIM


Figure 15.20: Temperature readings for the ablation process of a hole of THE RIM

To better understand the temperatures, the frequency of occurrence of a temperature was graphed. This provided a simple visualization of the temperature range for each servo. Figure 15.21 provides the number of times a certain temperature occurred for the servo on the left-side of the shoulder. As can be seen, the most common temperatures were between $22.0^{\circ} \mathrm{C}$ and $22.5^{\circ} \mathrm{C}$. Figure 15.22 provides the temperature occurrences for the servo on the right-side of the shoulder. The most common temperatures were from $21^{\circ} \mathrm{C}$ to $22.5^{\circ} \mathrm{C}$. Figure 15.23 provides the temperature occurrences for the servo that controls the rotation in the YZ plane of the shoulder. The most common temperatures were from $23^{\circ} \mathrm{C}$ to $24^{\circ} \mathrm{C}$. Figure 15.22 provides the temperature occurrences for the servo mounted on the elbow. The most common temperatures were from $25^{\circ} \mathrm{C}$ to $26^{\circ} \mathrm{C}$. These four figures provide enough evidence that the servos are not in danger of over=heating. A temperature of $28^{\circ} \mathrm{C}$ or higher was only recorded twice. The test form for can be found in the Appendix (A.5.4


Figure 15.21: Temperature occurrence:Servo mounted on the left-side of THE SHOULDER


Figure 15.22: Temperature occurrence:Servo mounted on the right-side of THE SHOULDER


Figure 15.23: Temperature occurrence:Servo controlling rotation of the SHOULDER


Figure 15.24: Number of times a temperature occurred for the servo MOUNTED ON THE ELBOW

### 15.5 Turntable

Testing for the turntable design was conducted using Finite Element Analysis simulations with the Abaqus CAE software. These simulations were used to test if the design of the turntable would be able to withstand the weight of a full-sized aircraft rim, as well as if the design would be able to withstand a drop from the aircraft rim from a set height. As it would be too dangerous and inefficient to test the LARRIC prototype design to failure, the Abaqus CAE software provides accurate results for this application.

Two separate tests were conducted for the turntable design and focused on the three cantilever beams that extrude from the walls of the turntable design. Based on the weight and and necessary length of the cantilever beams, the required diameter can be calculated to ensure a factor of safety for the system. This information will be crucial for a prospective full-scale design built by the United Technologies Research Center to ensure that the limits of the assembly are never exceeded.

The first test of the turntable assembly focused on the static loading of a rim onto the cantilever beams. Due the uniformity of the system design, analysis of only one of the three cantilever beams will provide information for all of the arms in the assembly. Assuming a sixty pound rim is loaded uniformly on the the three arms, each arm carries twenty pounds of the load. Under this assumption, the first test analyzed a static loading of twenty pounds on a cantilevered beam that is 12 inches long and has a diameter of one inch. An Axi-symmetric model was used for the cantilevered beam calculations, which allows for more accurate results
because of the smaller amount of nodes that must be analyzed. Shown below in Figure 15.25 is the Von Mises stress in the arm in units of psi.


Figure 15.25: Von Mises Stress of a Statically Loaded Beam

The maximum Von Mises stress is shown in the upper left table of Figure 15.25 and reads a value of $2.38 \times 10^{3} \mathrm{psi}$. When related this maximum Von Mises stress to the 50,800 psi yield stress of 1020 Cold Rolled Steel (Anticipated material of Turntable arms), the cantilever beam falls well under the threshold of yielding and provides a factor of safety of 21. In the interest of deflection of the arm when loaded, the arm will only deflect a maximum vertical distance of 0.008 ", as seen in Figure 15.26 .


Figure 15.26: Displacement of a Statically Loaded Beam

The team was also interested in determining whether the Turntable assembly would become damaged in the unlikely accident of a rim falling onto the turntable from a certain height. To analyze exactly how the beam would act in a dynamic situation, the beam was modeled in 3-D. This helps identify where exactly the maximum stresses occur and under what circumstances would the assembly fail. A dynamic model was created in Abaqus by relating the potential energy of the rim before being dropped to the velocity of the rim directly before impact. For these tests a length of twelve inches was used for the beam, with a two inch diameter and a sixty pound rim being dropped from a height of three inches. The following figures show the maximum Von Mises stresses of the dynamic test (Figure 15.27) and the maximum deflection of the arm (Figure 15.28)


Figure 15.27: Von Mises Stress of a Dynamically Loaded Beam


Figure 15.28: Displacement of a Dynamically Loaded Beam

As seen, the maximum Von Mises stress is much higher than the yield stress of titanium and therefore further considerations must be taken into account to ensure that the system does not fail.

## 16 Redesign

### 16.1 Completed Redesign

Upon review of the test data, there were various considerations for redesign that would allow for the system to become fully integrated into an industrial system in the United Technologies Facilities. These redesign considerations improved the performance, safety, and efficiency of the entire system. Aspects of the redesign to be considered can be broken into multiple sections including Housing, Turntable and Robotic Arm.

Redesign of the LARRIC prototype reduced the number of arms of the turntable from four to three. The benefit of incorporating only three, evenly spaced arms is the stability of the aircraft rim when placed on the turntable. In the first design, slight discrepancies between the four arms caused the rotation of the rim to stall because the rim would lose contact with the rollers. Mathematically, any three points must always lie in the same plane however, the fourth point can lie anywhere. Therefore, a turntable with three arms guaranteed that the rim will always be in contact with all of the rollers. Furthermore, the reduction in arms decreased the friction in the system. With less friction there was less loss in the system allowing the rim to rotate faster. However, the weight of the rim was distributed as $33 \%$ on each of arm instead of the previous $25 \%$. While the critical stress was not reached because no live impact test was completed, the material selection for the full scale model was modified. The larger applied weight required for materials with higher tensile and yield strengths.


Figure 16.1: Original design of the Turntable


Figure 16.2: Redesign of the Turntable
After reviewing the capabilities of the robotic manipulator and its geometric limitations, a linear actuator was added to increase the range of motion of the robotic manipulator because it was not able to ablate the entirety of the rim. With the addition of the actuator, the manipulator was able to move a maximum distance of 12 inches in the y -axis. The actuator had two fixed positions, 3.5 inches above and 3.5 inches below the rim. When the location of the manipulator was above the rim, the manipulator was able to easily reach the top half of the center walls. When the location of the manipulator was below the rim, the manipulator was able to easily reach the holes and the bottom half of the center walls. Furthermore, the trajectory for the side of the rim was simplified. Instead of moving the manipulator, the position of it was kept constant and the actuator was lowered from its top position to its bottom.

The device used to simulate the laser was also redesigned. Originally, ten ultraviolet LEDs were connected together, in parallel and placed inside of a collimator, the gray box in Fig. 16.3 . However, the collimator was 3-D printed and the plastic used was not very
reflective which caused a lot of the light to be absorbed by the material and reduced the strength of the beam. Furthermore, since there was no lens at the end of the collimator, the beam was not focused and immediately diverged once it exited. This caused multiple beams to be seen on the rim and reduced the effectiveness $f$ the "laser". Lastly, the collimator was too large and could not fit into the tight space of the rim without hitting it. An ultraviolet flashlight, the black cylinder at the end of the manipulator in Fig. 16.4, was modified as the replacement to the collimator. It already had the ultraviolet LEDs wired into it and more importantly there was a lens to focus the beam. The battery pack was removed, and the LEDs were wired to one of the 5 volt power supplies. Furthermore, the flashlight was approximately half the size of the collimator, allowing it to easily access the tight spaces of the rim.


Figure 16.3: Original design of the Robotic Manipulator


Figure 16.4: Redesign of the robotic manipulator

### 16.2 Further considerations

The full-scale model will require the system to be completely enclosed. Therefore, a roof and front door must be added to the system. When using an actual laser, there are numerous safety concerns of the light enter the eyes of the operator. The simplest solution is to ensure that the light will not be able to escape the system. Also, a ventilation system will be required for the vapors caused by the ablation process. A vacuum must be added to the floor and the side walls to eliminate the vapors. Not only are the vapors dangerous to the operator, they can also affect the ablation process by interfering with the laser. If there
is too much debris built up on the lens of the laser, its efficiency will decrease.
Per OSHA standards [43], a person is not allowed to lift more than 50 pounds and the rim weighs an average of 60 pounds. Therefore, a device is needed to load and unload the rim. This device must be able to load rims of different size and shape. Furthermore, it must be possible for only one person to operate the device.

## 17 Operation

The operation of the system was broken down into multiple sub-sections. The purpose was to make the process as simple as possible to follow and modify for the future. A statetransition diagram of the overall process is provided in Fig. 17.1. It provides in detail all of the possible outcomes that can occur during a cycle. The blocks are the states of the program and the arrows are the cause for a transition from one state to another. The blocks represent the sections of the program. The yellow colored ones represent the down time of the system (i.e. loading, unloading, safety checks), the green colored ones represent the run time of the system (laser ablation is occurring), and the red ones represent the errors that can occur throughout a cycle. The arrows entering and exiting the blocks represent the path that the program can follow. If the statement above an arrow occurs, then the program will follow that path. Statements in red represent errors that can occur during the cycle.


Figure 17.1: State Transition Diagram

### 17.1 Breakdown of a Cycle

The first state is the "Initialize All Components" block where, the Arduino Mega2560, electrical components used, and needed variables are setup. First, MATLAB connects to the Arduino and then connects to the linear actuator, the encoder, the turntable motor, the three ultrasonic proximity sensors, and the robotic manipulator. Next all of the Arduino pins used are assigned to a variable. This allows for the user to change the variable and have the pin number change in all of the programs. Finally, all of the other necessary variables (i.e. room temperature, distance limits) are created. After all of the components are successfully initialized, the program transitions to the "Homing" state.

In the "Homing" state, the linear actuator and robotic manipulator are homed. First, the distance from the linear actuator and its reference point is checked. If the distance is greater than the reference point, the linear actuator is lowered until the two distance are the same. If the distance is less than the reference point, it is raised until the two distances are the same. Once the homing of the linear actuator is completed, the robotic manipulator is homed. The home location for the manipulator is an up-right position looking down onto the rim. This position was selected to make it easier to transition to ablating the top section of the rim. Once both are successfully homed, the program transitions to the "Loading" state.

At the beginning of the "Loading" state, the operator is instructed (by audio) to load the rim onto the turntable. Once is the rim loaded, the operator is instructed to close the turntable door by sliding it in. There is an ultrasonic proximity sensor that determines if the turntable has been slid in. If the distance read by the sensor is less than 0.27 meters then the loading process has been successfully completed and the program transitions to the "Rim Check" state.

The presence and location of the rim is checked for in the "Rim Check" state. An ultrasonic sensor mounted on on the side wall measures the distance to the rim. If the distance read is between 0.07 meters and 0.09 meters then, the rim is correctly positioned on the rollers. If the distance read is out of this range, it means that either no rim is present or the rim has been improperly loaded. Both cases cause an error in the system and the program transition to the "Error:System Shutdown" state, the operator is notified of the error and the rim is unloaded, and then the process starts over. If the rim is correctly positioned, the program transitions to the "Hole Check" state.

The connection between the rim, the rollers, and the turntable motor is tested in the "Hole Check" state. The turntable motor is turned on at fifty percent of its maximum speed, slowly rotating the rim. The laser proximity sensor is located below the rim, perpendicular to the holes. Since, the speed of the rim is known, the time for one revolution can be calculated. To ensure a good connection between the three components, all of the hole must be detected in the time it takes for one revolution to occur. If it takes longer than one revolution, then the connection is not good and the program transition to the "Error:System Shutdown" state, the operator is notified of the error and the rim is unloaded, and then the process starts over. If the connection is good then the program transitions to the "Ablation: Top Section" state.

In the "Ablation: Top Section" state the ablation process starts. The manipulator moves from its initial position to the edge of the rim. It ablates from the outside to the inside.

FIrst it ablates the outer edge, then moves to the inner side wall, next to the flat bottom on the rim, and then back up the center wall. Next it ablates the inner edge of the rim and then moves into the center hole where i ablates the inner wall. Figure 17.2 provides the position of each of the servos throughout the trajectory. After the inner wall has been ablated the manipulator returns to its initial position and then transition to the "Ablation: Side Section" state.


Figure 17.2: Trajectory:Top section of the Rim

The outer side of the rim is ablated in the "Ablation: Side Section". The manipulator only has one position in this state, where the ultraviolet flashlight is perpendicular to the side of the rim. The linear actuator then moves down to its secondary position, 3.5 inches below th bottom of the rim. Figure 17.3 provides the position of the servos for the trajectory of the side. Once the actuator has reached its position, the program transitions to the "Ablation: Bottom Section" state.


Figure 17.3: Trajectory:Side section of the Rim

In the "Ablation: Bottom Section" state, the bottom of the rim and the lower half of the center walls are ablated. The manipulator moves from the position used to ablate the side of the rim to its initial position for the bottom of the rim. Then it ablates from the outside to the inside and then ablates the bottom half of the center walls. Once the entire section has been ablated, the manipulator returns to its initial position for the bottom and the program transitions to the "Locating Holes" state.


Figure 17.4: Trajectory:Bottom section of the Rim

There are ten holes that need to be ablated. In the "Locating Holes" state the rim is slowly rotated until the laser proximity sensor detects a hole. Once the hole has been detected, the rotation of the rim is stopped and the program transitions to the "Ablation: A Hole" state. In this state the hole is ablated on all four sides. Once the hole is ablated, the manipulator returns to its initial position for the bottom of the rim and the program transitions back into the "Locating Holes" state. This cycle is repeated until all ten of the holes have been completed. Figure 17.5 provides the comparison of the time it takes to detect a hole and the time it takes to ablate a hole. Figure 17.6 provides the trajectory of the manipulator for ablating a hole. Once all of the holes have been ablated, the ablation process is complete. Figure 17.7 provides the trajectory of the manipulator for the entire ablation process. The program now transitions to the "Unloading" state.


Figure 17.5: Detecting and ablating the holes


Figure 17.6: Trajectory: A hole of the Rim


Figure 17.7: Trajectory:Entire Rim
In the "Unloading" state, the operator is informed that the rim has been successfully cleaned. Then the operator is informed that he/she must press the red stop button, slide the turntable out and unload the rim. The program checks for the pressing of the button, once pressed the ultrasonic proximity sensor checks the distance to the turntable. Once it reads a distance greater than 0.3 meters, the program recognizes that the turntable has been slid out and the rim has been unloaded. It then transitions to the "Post-Processing" state.

Throughout the cycle, MATLAB has been recording data that it will now output to the operator. MATLAB graphs the time it takes to complete each state, the trajectory of the manipulator, the breakdown of the trajectory loop, and the temperatures of the servos. From this data the operator can determine if the process needs to be modified and what section is the best option to modify. All of the figures are automatically saved to a folder with the trial number, the name of the operator, the date of operation, and the time of operation. Once the post-processing is complete, the program transitions back into the "Homing" state and a new cycle is started.

### 17.2 Standard Operating Procedure

The following is a set of standard operating procedures that would be issued with the LARRIC system. Human factors play a considerable role in destructive events which may cause harm to the operator or damage the device. Standard operating procedures improve the safety of the operator and adds longevity to the device by minimizing uncertainty.

1. The sliding drawer containing the rim rollers is pulled out until it is fully extended.
2. Matlab is opened and the initializing function is ran distribute power to the system.
3. The rim is then placed onto the rollers such that the inside portion of the split rim makes contact with the rollers.
4. Next the drawer containing the rollers and rim is pushed into place until the neoprene driver on the roller connects to the neoprene driver on the motor.

The drawer makes an audible click once it is in the correct position. If the click is not heard, the drawer must be pulled back and reinserted.
5. Once the drawer is in place and the click is heard, the system will vocalize the current phase and also dictate commands to the operator.
6. The operator must stand by while all parameters are checked.

If a error is indicated by the system, the operator must pull out the drawer and recenter the rim. Once completed, the drawer is pushed back into place and the positioning is checked again.
7. After the checks have been completed such that the rim and drawer are in place, the operator is instructed to press the GREEN button labeled START. This button is pressed upon the command of the system.
8. Ablation of the rim will begin to cycle. The operator is to stand by during cycle time.

If a malfunction is identified during system operation then the operator must hit the SYSTEM EMERGENCY STOP button located in front of the drawer and to the right of the start button.
9. A green light will indicate that the system has completed the cycle. Once this occurs, the operator pushes the red STOP button located beneath the start button.
10. After pressing the stop button the operator then must pull out the drawer and then remove the rim.
11. This ends the full procedure for ablating a single rim and can then be repeated to further clean other rims.

## 18 Maintenance

### 18.1 Carbon Dust Inspection

As with any industrial system, maintenance is inevitable for the LARRIC. There will be periods of down time to ensure the device maintains an effective cleaning and promotes the
life of the system. The primary concern for the LARRIC is the accumulation of carbon dust from cleaning the rim. As discovered by testing done at IPG Photonics, a certain portion of the carbon dust is ablated while the other portion is simply pushed around. Dust that accumulates on the ground of the apparatus is fine but the rollers cannot be covered in the dust as this will cause slipping. A visual inspection of the surface of the rollers must be conducted before each cycle to ensure there is no build up where the roller contacts the rim. When build up does occur, short maintenance must be conducted to wipe the rollers of the carbon dust.

Carbon dust can also affect the air filter in the device as well as the lens used for the laser. An air filter will be present in the full scale system in order to remove particles and vapor from the facility. In addition the air filter provides protection to other assets in the system by reducing build up and friction of the motors and bearings. Thus a weekly check of the air filter must be conducted to eliminate the possibility of a clog. Air filters can be disposable or reusable and are easily replaced. Once a build up in the filter has been noted, the operator must remove the current filter and replace it with a clean one. Proper air filtration is also necessary to prevent accumulation of particles on the lens of the laser. These particles can obstruct the laser and reduce the efficiency. There is no significant concern regarding damage to the lens from the laser. This is because the energy of the laser is significantly lower at the lens than at the focus point. Typical laser lenses such as those found in DVD players can be cleaned with rubbing alcohol and cotton swabs. Since the system is industrial a more specialized formula must be used along with a clean microfiber cloth.

### 18.2 Motor Inspection

Maintenance must also be conducted on the motors present in the apparatus and the robotic arm. These checks will be spaced further apart than maintenance due to carbon dust. This is because the motors present are more durable than the lenses and filters. Checks would occur on a monthly basis and would last no longer three hours. If a motor has visual build up of carbon or wearing of gears then the motors would fail inspection. The course of action would depend on what caused the failed inspection. If carbon dust has accumulated in the motor then the motor can be reconstructed and the carbon dust can be wiped out. A secondary motor can be put into service in place of the first such that the LARRIC can operate and the first motor can be cleaned. If wear is noted within the motor then the motor must be replaced and the worn motor would be serviced at the supplier. Since the arm and rim driver would need to be opened to access the motors, the replacement would take no longer than two hours per motor that failed inspection. This is under the assumption of a single technician working on any single motor. The motor that rotates the rim would require less time as it is more easily accessible than the motors present in the robotic arm.

### 18.3 Laser Inspection

Lastly, the laser used to ablate the rims must be checked annually by the producers of the laser or by an expert laser technician. Annual checks may seem sparse, but when comparing the ablation system to other laser based systems annual inspection is typical.

Moreover, similar systems run at higher power and more regularly when used in cutting and welding applications. Laser inspection is still necessary as it is the sole component cleaning the rims. Thus it is imperative for tests to be run to check actual fluence against the desired fluence so that the operators can ensure the correct energy is being delivered to the surface containments. Maintenance for the laser varies as many other components must be checked such as the power source, fiber cables, lenses, collimator and galvanometer. Furthermore, the course of action also varies depending whether a component has entirely failed or a subcomponent must be replaced. Therefore it is up to the technician to determine the best course of action when maintaining the laser.

## 19 Additional Considerations

### 19.1 Economic impact

Through the implementation of the LARRIC system, UTC will be able to save millions of dollars per year. It costs UTC over one million dollars per year per facility to run their current water jet system. Three of UTC's facilities are used to clean their rims, therefore over three million dollars per year are used for the cleaning of aircraft rims. The LARRIC will cost only 14,997.05 dollars per year (Tbl. ??) to run for a total of 44,991.15 dollars. UTC can re-invest the money they save by switching to the LARRIC. With the reduction in cost of operation, UTC will be able to offer their rim cleaning services for a much lower price than the competition. Hopefully, this will increase the number of customers that switch to UTC from their competitors. Furthermore, the increase in profit will allow UTC to further develop the system and/or to input more money into the local economy through new partnerships.

UTC will endure a net loss when the system is first implemented. Currently, the price for a LARRIC is approximately $\$ 653,876$ (Tbl. ?? whereas, the Mart 60 is approximetly $\$ 250,000$. However, after one ear of operation the LARRIC will re-coup its initial price. While the Mart is a better short-term solution, the LARRIC is much better in the longterm. Over a three-year period, the LARRIC will save UTC $\$ 2,000,000$ (Fig. 3.1).

The reduction of water use will also affect the people who live near the facility. With millions of gallons of water now not being used, the demand for water will decrease. With less demand, the price of the water per person will decrease. This will reduce the utility bill of the neighborhood, providing more money to the locals.

### 19.2 Environmental impact

The largest environmental impact will occur from the removal of water from the system. UTC will go from using millions of gallons per year to to zero for cleaning the aircraft rims. The local water reverses near the facilities will now be preserved. The preservation of water will lead to an increase of wild-life and vegetation in the nearby area.

Furthermore, with no water being heated, there is no carbon dioxide production form the system. By implementing the LARRIC into their facilities, UTC has the opportunity to
lead the aviation industry in reducing their carbon footprint. With less of a carbon footprint, UTC can help lead the fight against global warming. Along with the reduction in carbon consumption, there will also be a reduction in fossil fuels. The water temperature in the Mart 60, Sting Ray [8], and the Aqua Clean [9] must be approximately $200^{\circ}$ F. Furthermore, each of these systems used up to 400 gallons of water for a ten minute cycle(Sec. 5 ) therefore, a large volume of fossils fuels must be burned to raise the temperature of the water. By burning fossil fuels, UTC is reducing the limited supply remaining on Earth however, with the implementation of the LARRIC and the removal of water from the system, fossil fuels will no longer be used. Instead the entire system will be powered with electricity.

However, the vapors created by the laser ablation process will harm the environment. To help mitigate the damage, the LARRIC will have a state-of-the-art ventilation system. It will absorb all of the harmful vapors and filter out the harmful chemicals. The filtered and clean air will then be inputted back into the environment.

### 19.3 Societal impact

As stated in the design specifications as well as section 19.2, the LARRIC sought to eliminate the usage of water to clean rims. This has a a societal impact in addition to environmental. Natural resources and how they are consumed are fundamental to societal beliefs. Similar to the way solar panels changed the beliefs about how energy should be produced, the LARRIC reconstructs the way people think about cleaning industrial materials. The LARRIC is a symbol of the progressive mindset of developing creative and technical solutions to processes that are detrimental to the environment.

United Technologies could lead an industrial revolution in the aviation field and lead the charge in going green. If the implementation of the LARRIC into the facilities of UTC is successful, other aviation companies like Boeing, Lockheed Martin, Airbus, and MTU Aero Engines could also implement a LARRIC or a similar system.

### 19.4 Political impact

Depending how the product is utilized and sold, the political effect can be small to unnoticeable within politics. The LARRIC is for a specialized industry of aerospace systems that require a specific service. During the design showcase, the most common question to the team was "Why do the rims have to be cleaned?". This indicated that the general population is unaware such systems actually exist and for what purpose they serve. If there is any political impact, then it will be for setting new industrial standards. When marketed correctly, the societal impact could push industrial systems to set new standards that utilize green technology.

### 19.5 Ethical considerations

With the automation of the system, it is possible that some of the employees could lose their jobs. Currently, a team of four operate the cleaning system. However, the LARRIC will only need a one employee. If UTC has an employee union, there could be problems with implementing the LARRIC into the facility. The union will not take kindly to the lose of jobs,
especially if there is more than one machine at a facility. Furthermore, the purpose of the project was not to reduce the workforce. This would e an unfortunate by-product. However, the majority of industries today are increasing the automation of facilities. Therefore, it might be a matter of time until UTC fully automates the repair and maintenance process for their brake and wheel assemblies.

### 19.6 Health, ergonomics, and safety considerations

The Occupational Safety and Health Administration (OSHA) and the National Institute of Occupational Safety and Health (NISOH) are two organizations where Team 14 and the LARRIC must conform too. With the high level of danger that comes with operating a laser, safety is the number one concern of the LARRIC. With the LARRIC being a fully enclosed system, the light from the laser cannot exit and harm the operator. Furthermore, safety interlocks will be implemented into the system in case of an emergency situation in which the seal is broken. Once the system recognizes that it is not sealed, the laser will be immediately shut off to ensure the safety of the operator.Furthermore, every operator will be wearing safety goggles rated for the specific wavelength of the laser to ensure no one's eyesight is damaged.

Furthermore, the health of the operators is crucial. Per OSHA standards 43] an employee cannot lift more than fifty pounds and the average aircraft rim weighs sixty pounds. Therefore, a crane-like device will be added onto the LARRIC for the operator to use in the loading and unloading process. Another health concern would be the vapors created by the laser ablation process. These vapors could be very harmful to an individual if ingested. Therefore, a state-of-the-art ventilation system will be implemented to ensure all of the dangerous particles are filtered out and only clean air exits the system.

### 19.7 Sustainability considerations

The aerospace industry is continuously growing with little to no saturation point in sight. With that in mind the LARRIC will have a growing use in that industry. Furthermore, continuing with the trend of progressive green technology, the LARRIC utilizes no water which is a rising cost factor in the aerospace maintenance. By eliminating the water disposal, the LARRIC maintains a cost that is only a function of the cost of energy needed to power the laser. Since the cost is significantly lower than the current system, more funds can be allocated to other sectors of the industry. Additionally, since operating costs are low it would allow more laser and mechanical technicians to be hired for maintenance which would foster a long life for each system. In the long run, the device is projected to develop and grow with the industry as it is cost effective and efficient for the job it was designed for.

## 20 Conclusions

The project, sponsored by the United Technology Research Center in East Hartford, CT, was an investigation of alternative methods for cleaning aircraft wheel rims. The conventional water-jet system at operation facilities under United Technology Aerospace Systems costs the corporation millions of dollars from annual water waste. As specified by the team sponsor, the alternative solution must reduce annual resource costs and must match the cycle time of the current Mart 60 cleaning system. After extensive research and analysis, laser ablation was found to be the most suitable approach to address all needs of UTRC.

The constraints of the project were set forth by the Federal Aviation Administration and performance of the current system. The wheel rim's anodized coating cannot be damaged during the cleaning process or else the structural integrity of the wheels will be compromised and removed from service. The system must also be able to clean rims as fast or faster than the current process due to high demand and potential bottlenecking of wheel maintenance. The system must be more cost effective than the current system which spent millions of dollars a year on water disposal alone. The system must fit within a 6 ' $\times 6$ ' $x 7.5$ area due to limited floor space. A laser ablation system is the most attractive cleaning concept because of its ability to satisfy each of these design specifications.

The project spanned over the course of two academic semester between 2017 and 2018. Throughout the fall of 2017, the design team focused on gathering information and generating concepts for alternative solutions. The latter half of the semester was aimed toward achieving a proof of concept to validate that the proposed solution can clean the aircraft rims. In the spring of 2018, a half-scale prototype was built to simulate the loading system and various laser trajectory paths. The second half of the spring of 2018 tested the system design and include a brief phase of redesign. The results were summarized and presented to at the University of Rhode Island Mechanical Engineering Design Showcase.

Previous research has been conducted from the United Technologies Research Center pertaining to ultrasonic cleaning, plasma electrolysis cleaning, and laser ablation. Team B.E.E.M. furthered investigations pertaining to the three suggested concepts. Ultrasonic cleaning is commonly practiced in the aerospace industry from small components with a range of geometries. The typical cycle time for such systems can be upwards of 10 to 20 minutes which conflicts with demand of wheels to be cleaned. Plasma electrolysis is a relatively new procedure that is primarily used to modify coating properties on selected materials. The lack of literature pertaining to the controllability with respect to cleaning raised an extreme challenge and placed a great amount of risk on damaging the wheel rim's anodized coating. Laser ablation is a developing process with applications ranging from tattoo removal to the removal of rust. The dry-cleaning method is extremely controllable and offers the greatest potential for satisfying the product specifications.

After deciding that laser ablation was an optimal concept for cleaning aircraft wheel rims, the design team pursued a proof of concept by means of physical testing with a laser. The IPG Photonics facility in Oxford, Massachusetts, provided design guidance with selecting optical equipment. For the time constraint of a 3-minute cycle, a 1-kilowatt fiber crystal laser was recommended. Another laser option to consider is a Neodymium-doped: Yttrium Aluminum

Garnet (Nd:YAG).The power supply should be attached to a string of optic fibers that are coupled with a collimator and galvanometer. The team was permitted to return to the facility to perform preliminary testing with a 20 -watt fiber crystal laser. Energy parameters were tested against 5 dirt mixtures of carbon dust, street dirt, and hydraulic fluid coated over anodized aluminum 6061. One plate was tested at various angles to determine how angles affect the energy requirements. Under all circumstances, the laser parameters can be controlled to affectively clean off $95 \%$ of the dirt coating. This confirmed that laser ablation is an appropriate method for cleaning aircraft wheel rims.

Throughout the spring of 2018, a half-scale prototype was developed to simulate trajectories across the surface of a Boeing 737 NG model. The system incorporates a turntable that resembles a slide drawer and can be pullout of the system for over head loading. Once the turntable slides back into the closed position, a side support slides into contact with a DC motor and causes the wheel to rotate. While on the initial four points of contact, a robotic manipulator was used to incident an ultraviolet laser across the surface of the rim. A florescent coating indicated the laser path and surface area that was covered. Initial tests indicated the turntable often slipped and would not continue to rotate smoothly. On the other hand, the robotic arm could not reach both the top and bottom of the rim from a fixed base position. Throughout a brief redesign phase, the turntable frame was modified to three supporting beams to allow continuous contact throughout operation. In addition, the robotic arm was mounted to a linear actuator to affectively reposition the arm to the top and bottom of the rim. Final system testing resulted in $100 \%$ of the surface area to be ablated.

There are substantial benefits that pertain to implementing the system in UTAS operation facilities. The initial purchasing cost for the system would be approximately $\$ 653,000$; however, the savings would be made within the first year as annual costs would fall in the range of $\$ 10,000$ per year due to electrical costs. In addition, the maintenance requirements for the system are minimized to a half-hour every week to check on optical alignment. The ease of operation from a voice guided loading system will reduce user error. Health risks are further reduced with the implementation of system interlocks to ensure the system is closed and the laser does not fire prematurely.

Alternative methods for aircraft rim cleaning has proven to be a challenging and informative senior capstone project. New obstacles were introduced routinely in which the team had to work together to overcome. The culmination of the hard work and research resulted in a feasible solution using laser ablation to clean the rims. Numerical analysis indicated that lasers and the mechanical system were feasible cleaning applications. Experiments further demonstrated the capabilities and limitations of lasers. The previous results coupled with low operating costs leaves no speculation that lasers are the optimal solution to the problem presented by United Technologies.

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A Appendix

## A. 1 Detailed Project Plan



Figure A.1: Fall of 2017 project plan in detailed view


Figure A.2: Spring of 20118 project plan in detailed view

## A. 2 Appendix:Design Specifications

Table A.1: In-depth Design Specification

| Design Specifications |  |
| :--- | :--- |
| Special Features | This device will be a semi-autonomous/robotic tool that will re- <br> move all dirt, grease, and lubricants from both halves of a split <br> rim. After the cleaning procedure, the wheel will be visually <br> clean of all forms of contaminants. The overall waste produced <br> from the process will be lower than any current procedure on the <br> market, resulting in an eco-friendlier system. The device will be <br> safe, quick, and reliable. |
| Training requirements | Employees working with this device will need to be familiar with <br> the following: |
|  | The potential health hazards related to the device |
|  | The proper Personal Protective Equipment (PPE) for operation |
|  | Loading and unloading procedure of the split rims going into the <br> device |
|  | Activation of the device and various programs/cycles the device <br> is capable of |
|  | Troubleshooting issues or problems with the machine <br> Refilling necessary resources (ie: soap, alkaline solvents if appli- <br> cable) |
| Remice Environment | General machine maintenance |
| Physical Description | This product will operate in various aircraft maintenance or op- <br> erations facilities |
|  | Constraints: |
| The total volume of the system must fit within a 6'x6'x7' space |  |
|  | The design of the system must allow loading from an over- <br> hanging trolley |
|  | The cleaning process cannot damage or remove paint/coating on <br> the rim |
|  | Variables: |
| The system must be compatible with Airbus-350 wheels |  |
| Beneficial if the interface of the device is compatible with all |  |
| aircraft classes |  |

Table A. 1 continued from previous page

| Table A.1 continued from previous page |  |
| :--- | :--- |
| Design Specifications | Market IdentificationThis device is intended to be produced for United Technologies <br> plied to the United Technologies Operation facilities as a replace- <br> ment for current products. Market competition consists of cur- <br> rent water cycle system produced by StingRay Parts Washer, <br> Aqua Clean Aviation, Mart Corporation, and Aerowash. A high <br> demand exists for an alternative cleaning process that reduces <br> resource cost and operates at a quicker wash time |
| Social, Political and Le- <br> gal Requirements | The final device must comply with the standards from the fol- <br> lowing agencies: |
|  | Federal Aviation Administration |
|  | Occupational Safety and Health Administration |
|  | American Society of Mechanical Engineers |
| internal standards that apply at United Technologies Operation |  |
| Centers |  |
|  | Hazards associated with this device must be addressed and la- <br> beled on the machine where applicable. The intended use of the <br> device is for aircraft vehicles and can increase risk of danger or <br> malfunction if improper parts and material classes are used in <br> the machine. Instructions for proper loading must be specified <br> in the user manual |
| Key Deadlines | Cocember 18, 2017: Final Report and all Electronic Files |
| Fixempleted Project: Deadlines: | October 26, 2017: Critical Design Review Presentation |
|  | November 30, 2017: Proof of Concept Presentation |

## A. 3 Appendix:Detailed Product Design

## A.3.1 Turntable

## A.3.1.1 Frame



Figure A.3: Back Beam


Figure A.4: Middle Beam


Figure A.5: Middle Support Beam


Figure A.6: Right Wall Beam


Figure A.7: Left Wall Beam


Figure A.8: Front Beam


Figure A.9: Wood Frame Assembly

## A.3.1.2 Motor



Figure A.10: Motor Interface


Figure A.11: Turntable Motor Shaft Interface


Figure A.12: Turntable motor assembly

## A.3.1.3 Drive Roller



Figure A.13: Drive Roller Shaft


Figure A.14: Small Spacer


Figure A.15: Drive Roller Assembly

## A.3.1.4 Contact Roller



Figure A.16: Contact Roller Shaft


Figure A.17: Large Spacer


Figure A.18: Contact Roller Assembly

## A.3.1.5 Turntable and Slider Assembly



Figure A.19: Turntable and Slider assembly

## A.3.2 Base

## A.3.2.1 Housing



Figure A.20: Left Wall


Figure A.21: Right Wall


Figure A.22: Back Wall


Figure A.23: Base Wall


Figure A.24: Housing Assembly

## A.3.3 Robotic Manipulator



Figure A.25: Arm Support Beam

## A.3.4 Full Assemblies



Figure A.26: Arm Support and Housing Assembly


Figure A.27: Slider to housing Assembly


Figure A.28: Turntable motor and housing assembly

## A. 4 Appendix:Engineering Analysis

## A.4.1 Appendix: Numerical Calculations

Table A.2: Dirt Layer Results for $\mathrm{N}_{t i}=1$

| Relative index of refraction of 1.0 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left(^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 5 | 5 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 10 | 10 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 15 | 15 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 20 | 20 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 25 | 25 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 30 | 30 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 35 | 35 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 40 | 40 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 45 | 45 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 50 | 50 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 55 | 55 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 60 | 60 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 65 | 65 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 70 | 70 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 75 | 75 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 80 | 80 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 85 | 85 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 90 | 90 |

Table A.3: Dirt Layer Results for $\mathrm{N}_{t i}=1.5$

| Relative index of refraction of 1.5 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.9424 | 0.0179 | 0.9596 | 0.0404 | 5 | 3.3310 |
| 0.9406 | 0.0185 | 0.9583 | 0.0417 | 10 | 6.6478 |
| 0.9376 | 0.0195 | 0.9562 | 0.0438 | 15 | 9.9359 |
| 0.9330 | 0.0209 | 0.9529 | 0.0471 | 20 | 13.1801 |
| 0.9265 | 0.0230 | 0.9484 | 0.0516 | 25 | 16.3644 |
| 0.9178 | 0.0259 | 0.9422 | 0.0578 | 30 | 19.4712 |
| 0.9062 | 0.0297 | 0.9339 | 0.0661 | 35 | 22.4814 |
| 0.8907 | 0.0349 | 0.9228 | 0.0772 | 40 | 25.3740 |
| 0.8699 | 0.0419 | 0.9080 | 0.0920 | 45 | 28.1255 |
| 0.8421 | 0.0516 | 0.8880 | 0.1120 | 50 | 30.7102 |
| 0.8047 | 0.0651 | 0.8607 | 0.1393 | 55 | 33.1000 |
| 0.7540 | 0.0844 | 0.8234 | 0.1766 | 60 | 35.2644 |
| 0.6852 | 0.1124 | 0.7719 | 0.2281 | 65 | 37.1717 |
| 0.5921 | 0.1547 | 0.7004 | 0.2996 | 70 | 38.7896 |
| 0.4677 | 0.2214 | 0.6006 | 0.3994 | 75 | 40.0870 |
| 0.3064 | 0.3359 | 0.4614 | 0.5386 | 80 | 41.0364 |
| 0.1144 | 0.5724 | 0.2677 | 0.7323 | 85 | 41.6156 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 41.8103 |

Table A.4: Dirt Layer Results for $\mathrm{N}_{t i}=2.0$

| Relative index of refraction of 2.0 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.8422 | 0.0516 | 0.8880 | 0.1120 | 5 | 2.4976 |
| 0.8387 | 0.0528 | 0.8855 | 0.1145 | 10 | 4.9809 |
| 0.8325 | 0.0550 | 0.8810 | 0.1190 | 15 | 7.4355 |
| 0.8236 | 0.0582 | 0.8745 | 0.1255 | 20 | 9.8466 |
| 0.8115 | 0.0626 | 0.8657 | 0.1343 | 25 | 12.1991 |
| 0.7956 | 0.0685 | 0.8541 | 0.1459 | 30 | 14.4775 |
| 0.7753 | 0.0761 | 0.8392 | 0.1608 | 35 | 16.6658 |
| 0.7496 | 0.0861 | 0.8202 | 0.1798 | 40 | 18.7472 |
| 0.7174 | 0.0990 | 0.7962 | 0.2038 | 45 | 20.7048 |
| 0.6773 | 0.1158 | 0.7660 | 0.2340 | 50 | 22.5210 |
| 0.6275 | 0.1379 | 0.7279 | 0.2721 | 55 | 24.1782 |
| 0.5660 | 0.1675 | 0.6799 | 0.3201 | 60 | 25.6589 |
| 0.4908 | 0.2079 | 0.6196 | 0.3804 | 65 | 26.9462 |
| 0.3999 | 0.2646 | 0.5438 | 0.4562 | 70 | 28.0243 |
| 0.2926 | 0.3480 | 0.4487 | 0.5513 | 75 | 28.8791 |
| 0.1710 | 0.4816 | 0.3299 | 0.6701 | 80 | 29.4987 |
| 0.0475 | 0.7393 | 0.1822 | 0.8178 | 85 | 29.8742 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 30.0000 |

Table A.5: Dirt Layer Results for $\mathrm{N}_{t i}=2.5$

| Relative index of refraction of 2.5 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.7429 | 0.0887 | 0.8152 | 0.1848 | 5 | 1.9979 |
| 0.7383 | 0.0906 | 0.8118 | 0.1882 | 10 | 3.9829 |
| 0.7305 | 0.0937 | 0.8060 | 0.1940 | 15 | 5.9423 |
| 0.7193 | 0.0982 | 0.7976 | 0.2024 | 20 | 7.8632 |
| 0.7043 | 0.1044 | 0.7864 | 0.2136 | 25 | 9.7324 |
| 0.6851 | 0.1124 | 0.7719 | 0.2281 | 30 | 11.5370 |
| 0.6611 | 0.1228 | 0.7537 | 0.2463 | 35 | 13.2635 |
| 0.6317 | 0.1360 | 0.7311 | 0.2689 | 40 | 14.8989 |
| 0.5960 | 0.1528 | 0.7035 | 0.2965 | 45 | 16.4299 |
| 0.5532 | 0.1741 | 0.6698 | 0.3302 | 50 | 17.8435 |
| 0.5022 | 0.2015 | 0.6288 | 0.3712 | 55 | 19.1269 |
| 0.4421 | 0.2370 | 0.5794 | 0.4206 | 60 | 20.2679 |
| 0.3722 | 0.2841 | 0.5199 | 0.4801 | 65 | 21.2552 |
| 0.2922 | 0.3484 | 0.4484 | 0.5516 | 70 | 22.0785 |
| 0.2032 | 0.4402 | 0.3629 | 0.6371 | 75 | 22.7288 |
| 0.1090 | 0.5829 | 0.2613 | 0.7387 | 80 | 23.1988 |
| 0.0211 | 0.8504 | 0.1411 | 0.8589 | 85 | 23.4831 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 23.5782 |

Table A.6: Dirt Layer Results for $\mathrm{N}_{t i}=3.0$

| Relative index of refraction of 3.0 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.6546 | 0.1257 | 0.7487 | 0.2513 | 5 | 1.6648 |
| 0.6496 | 0.1279 | 0.7449 | 0.2551 | 10 | 3.3183 |
| 0.6411 | 0.1317 | 0.7384 | 0.2616 | 15 | 4.9492 |
| 0.6289 | 0.1373 | 0.7290 | 0.2710 | 20 | 6.5463 |
| 0.6128 | 0.1448 | 0.7166 | 0.2834 | 25 | 8.0984 |
| 0.5925 | 0.1545 | 0.7007 | 0.2993 | 30 | 9.5941 |
| 0.5675 | 0.1668 | 0.6811 | 0.3189 | 35 | 11.0224 |
| 0.5374 | 0.1823 | 0.6572 | 0.3428 | 40 | 12.3723 |
| 0.5016 | 0.2018 | 0.6284 | 0.3716 | 45 | 13.6330 |
| 0.4596 | 0.2262 | 0.5940 | 0.4060 | 50 | 14.7942 |
| 0.4110 | 0.2571 | 0.5532 | 0.4468 | 55 | 15.8459 |
| 0.3553 | 0.2966 | 0.5051 | 0.4949 | 60 | 16.7787 |
| 0.2925 | 0.3480 | 0.4487 | 0.5513 | 65 | 17.5839 |
| 0.2231 | 0.4171 | 0.3828 | 0.6172 | 70 | 18.2540 |
| 0.1488 | 0.5140 | 0.3062 | 0.6938 | 75 | 18.7824 |
| 0.0735 | 0.6623 | 0.2176 | 0.7824 | 80 | 19.1638 |
| 0.0075 | 0.9357 | 0.1159 | 0.8841 | 85 | 19.3942 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 19.4712 |

Table A.7: Dirt Layer Results for $\mathrm{N}_{t i}=3.5$

| Relative index of refraction of 3.5 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.5788 | 0.1611 | 0.6900 | 0.3100 | 5 | 1.4269 |
| 0.5737 | 0.1637 | 0.6859 | 0.3141 | 10 | 2.8438 |
| 0.5649 | 0.1681 | 0.6791 | 0.3209 | 15 | 4.2408 |
| 0.5526 | 0.1744 | 0.6693 | 0.3307 | 20 | 5.6079 |
| 0.5363 | 0.1829 | 0.6563 | 0.3437 | 25 | 6.9353 |
| 0.5160 | 0.1938 | 0.6400 | 0.3600 | 30 | 8.2132 |
| 0.4912 | 0.2076 | 0.6199 | 0.3801 | 35 | 9.4321 |
| 0.4618 | 0.2249 | 0.5958 | 0.4042 | 40 | 10.5826 |
| 0.4273 | 0.2464 | 0.5671 | 0.4329 | 45 | 11.6557 |
| 0.3876 | 0.2731 | 0.5332 | 0.4668 | 50 | 12.6427 |
| 0.3424 | 0.3065 | 0.4938 | 0.5062 | 55 | 13.5352 |
| 0.2917 | 0.3488 | 0.4479 | 0.5521 | 60 | 14.3258 |
| 0.2357 | 0.4033 | 0.3951 | 0.6049 | 65 | 15.0075 |
| 0.1754 | 0.4756 | 0.3345 | 0.6655 | 70 | 15.5741 |
| 0.1125 | 0.5762 | 0.2653 | 0.7347 | 75 | 16.0204 |
| 0.0508 | 0.7282 | 0.1870 | 0.8130 | 80 | 16.3422 |
| 0.0022 | 0.9788 | 0.1050 | 0.9013 | 85 | 16.5366 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 16.6015 |

Table A.8: Dirt Layer Results for $\mathrm{N}_{t i}=4.0$

| Relative index of refraction of 4.0 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.5143 | 0.1948 | 0.6386 | 0.3614 | 5 | 1.2485 |
| 0.5091 | 0.1976 | 0.6345 | 0.3655 | 10 | 2.4881 |
| 0.5005 | 0.2024 | 0.6275 | 0.3725 | 15 | 3.7099 |
| 0.4883 | 0.2093 | 0.6176 | 0.3824 | 20 | 4.9051 |
| 0.4724 | 0.2186 | 0.6045 | 0.3955 | 25 | 6.0649 |
| 0.4526 | 0.2305 | 0.5882 | 0.4118 | 30 | 7.1808 |
| 0.4287 | 0.2455 | 0.5682 | 0.4318 | 35 | 8.2443 |
| 0.4006 | 0.2641 | 0.5444 | 0.4556 | 40 | 9.2473 |
| 0.3681 | 0.2871 | 0.5163 | 0.4837 | 45 | 10.1821 |
| 0.3310 | 0.3155 | 0.4836 | 0.5164 | 50 | 11.0410 |
| 0.2894 | 0.3509 | 0.4458 | 0.5542 | 55 | 11.8171 |
| 0.2434 | 0.3953 | 0.4025 | 0.5975 | 60 | 12.5039 |
| 0.1935 | 0.4521 | 0.3531 | 0.6469 | 65 | 13.0956 |
| 0.1407 | 0.5269 | 0.2973 | 0.7027 | 70 | 13.5871 |
| 0.0867 | 0.6300 | 0.2344 | 0.7656 | 75 | 13.9740 |
| 0.0353 | 0.7848 | 0.1641 | 0.8359 | 80 | 14.2529 |
| 0.0031 | 0.9706 | 0.1070 | 0.9139 | 85 | 14.4212 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 14.4775 |

Table A.9: Dirt Layer Results for $\mathrm{N}_{t i}=4.5$

| Relative index of refraction of 4.5 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.4592 | 0.2265 | 0.5937 | 0.4063 | 5 | 1.1098 |
| 0.4542 | 0.2295 | 0.5895 | 0.4105 | 10 | 2.2115 |
| 0.4459 | 0.2346 | 0.5826 | 0.4174 | 15 | 3.2972 |
| 0.4341 | 0.2421 | 0.5727 | 0.4273 | 20 | 4.3589 |
| 0.4187 | 0.2520 | 0.5598 | 0.4402 | 25 | 5.3889 |
| 0.3998 | 0.2647 | 0.5437 | 0.4563 | 30 | 6.3794 |
| 0.3770 | 0.2806 | 0.5241 | 0.4759 | 35 | 7.3229 |
| 0.3505 | 0.3003 | 0.5009 | 0.4991 | 40 | 8.2123 |
| 0.3200 | 0.3245 | 0.4737 | 0.5263 | 45 | 9.0406 |
| 0.2856 | 0.3543 | 0.4423 | 0.5577 | 50 | 9.8013 |
| 0.2474 | 0.3911 | 0.4063 | 0.5937 | 55 | 10.4882 |
| 0.2057 | 0.4372 | 0.3655 | 0.6345 | 60 | 11.0958 |
| 0.1610 | 0.4957 | 0.3193 | 0.6807 | 65 | 11.6189 |
| 0.1144 | 0.5724 | 0.2677 | 0.7323 | 70 | 12.0532 |
| 0.0677 | 0.6776 | 0.2101 | 0.7899 | 75 | 12.3950 |
| 0.0242 | 0.8345 | 0.1464 | 0.8536 | 80 | 12.6413 |
| 0.0095 | 0.9208 | 0.1200 | 0.9236 | 85 | 12.7899 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 12.8396 |

Table A.10: Dirt Layer Results for $\mathrm{N}_{t i}=5.0$

| Relative index of refraction of 5.0 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.4121 | 0.2563 | 0.5542 | 0.4458 | 5 | 0.998781827 |
| 0.4073 | 0.2595 | 0.5501 | 0.4499 | 10 | 1.990261768 |
| 0.3993 | 0.2650 | 0.5433 | 0.4567 | 15 | 2.967173882 |
| 0.3880 | 0.2728 | 0.5336 | 0.4664 | 20 | 3.922325042 |
| 0.3734 | 0.2832 | 0.5209 | 0.4791 | 25 | 4.848633585 |
| 0.3553 | 0.2966 | 0.5051 | 0.4949 | 30 | 5.739170477 |
| 0.3338 | 0.3133 | 0.4861 | 0.5139 | 35 | 6.587203533 |
| 0.3089 | 0.3338 | 0.4636 | 0.5364 | 40 | 7.386244977 |
| 0.2804 | 0.3590 | 0.4375 | 0.5625 | 45 | 8.130102354 |
| 0.2486 | 0.3899 | 0.4075 | 0.5925 | 50 | 8.812932417 |
| 0.2135 | 0.4280 | 0.3733 | 0.6267 | 55 | 9.429297286 |
| 0.1756 | 0.4753 | 0.3347 | 0.6653 | 60 | 9.974221794 |
| 0.1355 | 0.5353 | 0.2915 | 0.7085 | 65 | 10.44325058 |
| 0.0941 | 0.6135 | 0.2435 | 0.7565 | 70 | 10.83250321 |
| 0.0533 | 0.7203 | 0.1904 | 0.8096 | 75 | 11.13872546 |
| 0.0160 | 0.8789 | 0.1322 | 0.8678 | 80 | 11.35933475 |
| 0.0046 | 0.9586 | 0.1100 | 0.9313 | 85 | 11.49245783 |
| 0.0000 | 1.0000 | 0.1000 | 1.0000 | 90 | 11.53695903 |

Table A.11: Anodized Coating Layer Results for $\mathrm{N}_{t i}=1.167$

| Relative index of refraction of 1.167 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.9916 | 0.0026 | 0.9941 | 0.0059 | 3.3310 | 3.8869 |
| 0.9918 | 0.0025 | 0.9943 | 0.0057 | 6.6478 | 7.7621 |
| 0.9921 | 0.0024 | 0.9945 | 0.0055 | 9.9359 | 11.6132 |
| 0.9926 | 0.0023 | 0.9948 | 0.0052 | 13.1801 | 15.4273 |
| 0.9932 | 0.0021 | 0.9952 | 0.0048 | 16.3644 | 19.1901 |
| 0.9939 | 0.0019 | 0.9957 | 0.0043 | 19.4712 | 22.8854 |
| 0.9947 | 0.0016 | 0.9963 | 0.0037 | 22.4814 | 26.4947 |
| 0.9955 | 0.0014 | 0.9969 | 0.0031 | 25.3740 | 29.9964 |
| 0.9964 | 0.0011 | 0.9975 | 0.0025 | 28.1255 | 33.3651 |
| 0.9974 | 0.0008 | 0.9982 | 0.0018 | 30.7102 | 36.5706 |
| 0.9982 | 0.0005 | 0.9987 | 0.0013 | 33.1000 | 39.5773 |
| 0.9989 | 0.0003 | 0.9993 | 0.0007 | 35.2644 | 42.3436 |
| 0.9995 | 0.0002 | 0.9996 | 0.0004 | 37.1717 | 44.8220 |
| 0.9998 | 0.0000 | 0.9999 | 0.0001 | 38.7896 | 46.9596 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 40.0870 | 48.7010 |
| 1.0000 | 0.0000 | 1.0000 | 0.0000 | 41.0364 | 49.9926 |
| 0.9999 | 0.0000 | 1.0000 | 0.0000 | 41.6156 | 50.7885 |
| 0.9999 | 0.0000 | 0.9999 | 0.0001 | 41.8103 | 51.0576 |

Table A.12: Anodized Coating Layer Results for $\mathrm{N}_{t i}=0.875$

| Relative index of refraction of 0.875 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.9937 | 0.0019 | 0.9956 | 0.0044 | 2.4976 | 2.1853 |
| 0.9937 | 0.0019 | 0.9956 | 0.0044 | 4.9809 | 4.3570 |
| 0.9938 | 0.0019 | 0.9957 | 0.0043 | 7.4355 | 6.5017 |
| 0.9940 | 0.0018 | 0.9958 | 0.0042 | 9.8466 | 8.6057 |
| 0.9941 | 0.0018 | 0.9959 | 0.0041 | 12.1991 | 10.6550 |
| 0.9943 | 0.0017 | 0.9961 | 0.0039 | 14.4775 | 12.6356 |
| 0.9946 | 0.0016 | 0.9962 | 0.0038 | 16.6658 | 14.5331 |
| 0.9948 | 0.0016 | 0.9964 | 0.0036 | 18.7472 | 16.3330 |
| 0.9951 | 0.0015 | 0.9966 | 0.0034 | 20.7048 | 18.0206 |
| 0.9954 | 0.0014 | 0.9968 | 0.0032 | 22.5210 | 19.5813 |
| 0.9956 | 0.0013 | 0.9970 | 0.0030 | 24.1782 | 21.0007 |
| 0.9959 | 0.0012 | 0.9971 | 0.0029 | 25.6589 | 22.2647 |
| 0.9961 | 0.0012 | 0.9973 | 0.0027 | 26.9462 | 23.3602 |
| 0.9963 | 0.0011 | 0.9974 | 0.0026 | 28.0243 | 24.2749 |
| 0.9965 | 0.0011 | 0.9975 | 0.0025 | 28.8791 | 24.9984 |
| 0.9966 | 0.0010 | 0.9976 | 0.0024 | 29.4987 | 25.5217 |
| 0.9967 | 0.0010 | 0.9977 | 0.0023 | 29.8742 | 25.8384 |
| 0.9967 | 0.0010 | 0.9977 | 0.0023 | 30.0000 | 25.9445 |

Table A.13: Anodized Coating Layer Results for $\mathrm{N}_{t i}=0.7$

| Relative index of refraction of 0.7 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.9556 | 0.0137 | 0.9689 | 0.0311 | 1.9979 | 1.3984 |
| 0.9558 | 0.0136 | 0.9691 | 0.0309 | 3.9829 | 2.7869 |
| 0.9562 | 0.0135 | 0.9693 | 0.0307 | 5.9423 | 4.1558 |
| 0.9567 | 0.0134 | 0.9697 | 0.0303 | 7.8632 | 5.4954 |
| 0.9573 | 0.0132 | 0.9701 | 0.0299 | 9.7324 | 6.7959 |
| 0.9581 | 0.0129 | 0.9706 | 0.0294 | 11.5370 | 8.0478 |
| 0.9589 | 0.0127 | 0.9712 | 0.0288 | 13.2635 | 9.2418 |
| 0.9598 | 0.0124 | 0.9718 | 0.0282 | 14.8989 | 10.3686 |
| 0.9607 | 0.0121 | 0.9725 | 0.0275 | 16.4299 | 11.4194 |
| 0.9616 | 0.0118 | 0.9731 | 0.0269 | 17.8435 | 12.3858 |
| 0.9625 | 0.0116 | 0.9738 | 0.0262 | 19.1269 | 13.2595 |
| 0.9634 | 0.0113 | 0.9744 | 0.0256 | 20.2679 | 14.0334 |
| 0.9641 | 0.0110 | 0.9749 | 0.0251 | 21.2552 | 14.7005 |
| 0.9648 | 0.0108 | 0.9754 | 0.0246 | 22.0785 | 15.2549 |
| 0.9654 | 0.0106 | 0.9758 | 0.0242 | 22.7288 | 15.6916 |
| 0.9658 | 0.0105 | 0.9761 | 0.0239 | 23.1988 | 16.0065 |
| 0.9661 | 0.0104 | 0.9762 | 0.0238 | 23.4831 | 16.1966 |
| 0.9661 | 0.0104 | 0.9763 | 0.0237 | 23.5782 | 16.2602 |

Table A.14: Anodized Coating Layer Results for $\mathrm{N}_{t i}=0.583$

| Relative index of refraction of 0.583 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.9018 | 0.0311 | 0.9308 | 0.0692 | 1.6648 | 0.9710 |
| 0.9021 | 0.0310 | 0.9310 | 0.0690 | 3.3183 | 1.9350 |
| 0.9026 | 0.0309 | 0.9314 | 0.0686 | 4.9492 | 2.8847 |
| 0.9032 | 0.0307 | 0.9318 | 0.0682 | 6.5463 | 3.8132 |
| 0.9040 | 0.0304 | 0.9324 | 0.0676 | 8.0984 | 4.7136 |
| 0.9049 | 0.0301 | 0.9330 | 0.0670 | 9.5941 | 5.5792 |
| 0.9059 | 0.0298 | 0.9337 | 0.0663 | 11.0224 | 6.4034 |
| 0.9070 | 0.0294 | 0.9345 | 0.0655 | 12.3723 | 7.1800 |
| 0.9082 | 0.0290 | 0.9353 | 0.0647 | 13.6330 | 7.9028 |
| 0.9093 | 0.0286 | 0.9362 | 0.0638 | 14.7942 | 8.5663 |
| 0.9105 | 0.0283 | 0.9370 | 0.0630 | 15.8459 | 9.1651 |
| 0.9115 | 0.0279 | 0.9377 | 0.0623 | 16.7787 | 9.6944 |
| 0.9125 | 0.0276 | 0.9384 | 0.0616 | 17.5839 | 10.1500 |
| 0.9133 | 0.0273 | 0.9390 | 0.0610 | 18.2540 | 10.5281 |
| 0.9140 | 0.0271 | 0.9395 | 0.0605 | 18.7824 | 10.8255 |
| 0.9145 | 0.0269 | 0.9399 | 0.0601 | 19.1638 | 11.0398 |
| 0.9149 | 0.0268 | 0.9401 | 0.0599 | 19.3942 | 11.1691 |
| 0.9150 | 0.0268 | 0.9402 | 0.0598 | 19.4712 | 11.2123 |

Table A.15: Anodized Coating Layer Results for $\mathrm{N}_{t i}=0.5$

| Relative index of refraction of 0.5 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.8435 | 0.0511 | 0.8890 | 0.1110 | 1.4269 | 0.7134 |
| 0.8438 | 0.0510 | 0.8892 | 0.1108 | 2.8438 | 1.4215 |
| 0.8443 | 0.0509 | 0.8895 | 0.1105 | 4.2408 | 2.1189 |
| 0.8449 | 0.0506 | 0.8900 | 0.1100 | 5.6079 | 2.8006 |
| 0.8457 | 0.0504 | 0.8905 | 0.1095 | 6.9353 | 3.4613 |
| 0.8466 | 0.0500 | 0.8912 | 0.1088 | 8.2132 | 4.0960 |
| 0.8476 | 0.0497 | 0.8919 | 0.1081 | 9.4321 | 4.7001 |
| 0.8487 | 0.0493 | 0.8927 | 0.1073 | 10.5826 | 5.2687 |
| 0.8498 | 0.0489 | 0.8935 | 0.1065 | 11.6557 | 5.7976 |
| 0.8509 | 0.0485 | 0.8943 | 0.1057 | 12.6427 | 6.2827 |
| 0.8521 | 0.0481 | 0.8951 | 0.1049 | 13.5352 | 6.7202 |
| 0.8531 | 0.0478 | 0.8959 | 0.1041 | 14.3258 | 7.1067 |
| 0.8540 | 0.0474 | 0.8966 | 0.1034 | 15.0075 | 7.4391 |
| 0.8549 | 0.0471 | 0.8972 | 0.1028 | 15.5741 | 7.7148 |
| 0.8555 | 0.0469 | 0.8976 | 0.1024 | 16.0204 | 7.9315 |
| 0.8560 | 0.0467 | 0.8980 | 0.1020 | 16.3422 | 8.0876 |
| 0.8563 | 0.0466 | 0.8982 | 0.1018 | 16.5366 | 8.1817 |
| 0.8564 | 0.0466 | 0.8983 | 0.1017 | 16.6015 | 8.2132 |

Table A.16: Anodized Coating Layer Results for $\mathrm{N}_{t i}=0.4375$

| Relative index of refraction of 0.4375 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.7858 | 0.0721 | 0.8469 | 0.1531 | 1.2485 | 0.5462 |
| 0.7861 | 0.0720 | 0.8471 | 0.1529 | 2.4881 | 1.0883 |
| 0.7865 | 0.0719 | 0.8474 | 0.1526 | 3.7099 | 1.6222 |
| 0.7871 | 0.0717 | 0.8479 | 0.1521 | 4.9051 | 2.1438 |
| 0.7878 | 0.0714 | 0.8484 | 0.1516 | 6.0649 | 2.6494 |
| 0.7886 | 0.0711 | 0.8490 | 0.1510 | 7.1808 | 3.1349 |
| 0.7895 | 0.0708 | 0.8497 | 0.1503 | 8.2443 | 3.5968 |
| 0.7905 | 0.0704 | 0.8504 | 0.1496 | 9.2473 | 4.0315 |
| 0.7915 | 0.0700 | 0.8511 | 0.1489 | 10.1821 | 4.4357 |
| 0.7926 | 0.0696 | 0.8519 | 0.1481 | 11.0410 | 4.8062 |
| 0.7936 | 0.0692 | 0.8526 | 0.1474 | 11.8171 | 5.1403 |
| 0.7945 | 0.0689 | 0.8533 | 0.1467 | 12.5039 | 5.4353 |
| 0.7954 | 0.0686 | 0.8539 | 0.1461 | 13.0956 | 5.6889 |
| 0.7961 | 0.0683 | 0.8545 | 0.1455 | 13.5871 | 5.8992 |
| 0.7967 | 0.0681 | 0.8549 | 0.1451 | 13.9740 | 6.0645 |
| 0.7971 | 0.0679 | 0.8552 | 0.1448 | 14.2529 | 6.1835 |
| 0.7974 | 0.0678 | 0.8554 | 0.1446 | 14.4212 | 6.2553 |
| 0.7975 | 0.0678 | 0.8555 | 0.1445 | 14.4775 | 6.2793 |

Table A.17: Anodized Coating Layer Results for $\mathrm{N}_{t i}=0.389$

| Relative index of refraction of 0.389 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.7311 | 0.0934 | 0.8065 | 0.1935 | 1.1098 | 0.4316 |
| 0.7313 | 0.0933 | 0.8066 | 0.1934 | 2.2115 | 0.8598 |
| 0.7317 | 0.0932 | 0.8069 | 0.1931 | 3.2972 | 1.2816 |
| 0.7322 | 0.0930 | 0.8073 | 0.1927 | 4.3589 | 1.6938 |
| 0.7328 | 0.0927 | 0.8077 | 0.1923 | 5.3889 | 2.0931 |
| 0.7336 | 0.0924 | 0.8083 | 0.1917 | 6.3794 | 2.4765 |
| 0.7343 | 0.0921 | 0.8089 | 0.1911 | 7.3229 | 2.8412 |
| 0.7352 | 0.0918 | 0.8095 | 0.1905 | 8.2123 | 3.1844 |
| 0.7361 | 0.0914 | 0.8102 | 0.1898 | 9.0406 | 3.5034 |
| 0.7370 | 0.0911 | 0.8108 | 0.1892 | 9.8013 | 3.7958 |
| 0.7378 | 0.0907 | 0.8115 | 0.1885 | 10.4882 | 4.0594 |
| 0.7387 | 0.0904 | 0.8121 | 0.1879 | 11.0958 | 4.2921 |
| 0.7394 | 0.0901 | 0.8126 | 0.1874 | 11.6189 | 4.4922 |
| 0.7400 | 0.0899 | 0.8131 | 0.1869 | 12.0532 | 4.6580 |
| 0.7406 | 0.0896 | 0.8135 | 0.1865 | 12.3950 | 4.7883 |
| 0.7410 | 0.0895 | 0.8138 | 0.1862 | 12.6413 | 4.8822 |
| 0.7412 | 0.0894 | 0.8140 | 0.1860 | 12.7899 | 4.9388 |
| 0.7413 | 0.0894 | 0.8140 | 0.1860 | 12.8396 | 4.9577 |

Table A.18: Anodized Coating Layer Results for $\mathrm{N}_{t i}=0.35$

| Relative index of refraction of 0.35 |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\mathbf{T}_{\text {out }}$ | $\mathbf{A}$ | $\mathbf{T}$ | $\mathbf{R}$ | $\theta_{i}\left({ }^{\circ}\right)$ | $\theta_{t}\left({ }^{\circ}\right)$ |
| 0.6803 | 0.1145 | 0.7682 | 0.2318 | 0.9988 | 0.3496 |
| 0.6804 | 0.1144 | 0.7684 | 0.2316 | 1.9903 | 0.6965 |
| 0.6808 | 0.1143 | 0.7686 | 0.2314 | 2.9672 | 1.0381 |
| 0.6812 | 0.1141 | 0.7689 | 0.2311 | 3.9223 | 1.3719 |
| 0.6817 | 0.1139 | 0.7693 | 0.2307 | 4.8486 | 1.6952 |
| 0.6823 | 0.1136 | 0.7698 | 0.2302 | 5.7392 | 2.0058 |
| 0.6830 | 0.1133 | 0.7703 | 0.2297 | 6.5872 | 2.3011 |
| 0.6838 | 0.1130 | 0.7709 | 0.2291 | 7.3862 | 2.5789 |
| 0.6845 | 0.1127 | 0.7715 | 0.2285 | 8.1301 | 2.8372 |
| 0.6853 | 0.1124 | 0.7720 | 0.2280 | 8.8129 | 3.0739 |
| 0.6860 | 0.1121 | 0.7726 | 0.2274 | 9.4293 | 3.2872 |
| 0.6867 | 0.1118 | 0.7731 | 0.2269 | 9.9742 | 3.4755 |
| 0.6873 | 0.1115 | 0.7736 | 0.2264 | 10.4433 | 3.6374 |
| 0.6879 | 0.1113 | 0.7740 | 0.2260 | 10.8325 | 3.7716 |
| 0.6883 | 0.1111 | 0.7743 | 0.2257 | 11.1387 | 3.8770 |
| 0.6887 | 0.1109 | 0.7746 | 0.2254 | 11.3593 | 3.9529 |
| 0.6889 | 0.1108 | 0.7747 | 0.2253 | 11.4925 | 3.9987 |
| 0.6889 | 0.1108 | 0.7748 | 0.2252 | 11.5370 | 4.0140 |

Table A.19: Laser Intensity Required to Remove Dirt Layer for Varying Thicknesses

| Material | Q (W/s) | b (m) | $\underline{\rho\left(\mathrm{kg} / \mathrm{m}^{3}\right)}$ | $\underline{\mathbf{C}_{p}\left(\mathbf{J} / \mathrm{kg}^{\circ} \mathrm{C}\right)}$ | $\mathbf{T}_{\text {Boil }}\left({ }^{\circ} \mathrm{C}\right)$ | A ( $\mathrm{m}^{2}$ ) | $\mathrm{T}_{\infty}\left({ }^{\circ} \mathrm{C}\right)$ | t (s) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Mineral Oils | 76.29719224 | 0.0001 | 860 | 1632.54 | 105 | 1.918 | 20 | 300 |
| Phosphate Esters | 196.0299112 | 0.0001 | 1090 | 1758.12 | 180 | 1.918 | 20 | 300 |
| Silicate Esters | 150.21776 | 0.0001 | 890 | 1600 | 185 | 1.918 | 20 | 300 |
| Group II Oils | 217.6290667 | 0.0001 | 851 | 2000 | 220 | 1.918 | 20 | 300 |
| Diesters | 232.673117 | 0.0001 | 900 | 1925.56 | 230 | 1.918 | 20 | 300 |
| Phenyl Methyl | 224.933404 | 0.0001 | 1030 | 1423.24 | 260 | 1.918 | 20 | 300 |
| Mineral Oils | 190.7429806 | 0.00025 | 860 | 1632.54 | 105 | 1.918 | 20 | 300 |
| Phosphate Esters | 490.0747779 | 0.00025 | 1090 | 1758.12 | 180 | 1.918 | 20 | 300 |
| Silicate Esters | 375.5444 | 0.00025 | 890 | 1600 | 185 | 1.918 | 20 | 300 |
| Group II Oils | 544.0726667 | 0.00025 | 851 | 2000 | 220 | 1.918 | 20 | 300 |
| Diesters | 581.6827926 | 0.00025 | 900 | 1925.56 | 230 | 1.918 | 20 | 300 |
| Phenyl Methyl | 562.3335099 | 0.00025 | 1030 | 1423.24 | 260 | 1.918 | 20 | 300 |
| Mineral Oils | 381.4859612 | 0.0005 | 860 | 1632.54 | 105 | 1.918 | 20 | 300 |
| Phosphate Esters | 980.1495558 | 0.0005 | 1090 | 1758.12 | 180 | 1.918 | 20 | 300 |
| Silicate Esters | 751.0888 | 0.0005 | 890 | 1600 | 185 | 1.918 | 20 | 300 |
| Group II Oils | 1088.145333 | 0.0005 | 851 | 2000 | 220 | 1.918 | 20 | 300 |
| Diesters | 1163.365585 | 0.0005 | 900 | 1925.56 | 230 | 1.918 | 20 | 300 |
| Phenyl Methyl | 1124.66702 | 0.0005 | 1030 | 1423.24 | 260 | 1.918 | 20 | 300 |
| Mineral Oils | 572.2289418 | 0.00075 | 860 | 1632.54 | 105 | 1.918 | 20 | 300 |
| Phosphate Esters | 1470.224334 | 0.00075 | 1090 | 1758.12 | 180 | 1.918 | 20 | 300 |
| Silicate Esters | 1126.6332 | 0.00075 | 890 | 1600 | 185 | 1.918 | 20 | 300 |
| Group II Oils | 1632.218 | 0.00075 | 851 | 2000 | 220 | 1.918 | 20 | 300 |
| Diesters | 1745.048378 | 0.00075 | 900 | 1925.56 | 230 | 1.918 | 20 | 300 |
| Phenyl Methyl | 1687.00053 | 0.00075 | 1030 | 1423.24 | 260 | 1.918 | 20 | 300 |
| Mineral Oils | 762.9719224 | 0.001 | 860 | 1632.54 | 105 | 1.918 | 20 | 300 |
| Phosphate Esters | 1960.299112 | 0.001 | 1090 | 1758.12 | 180 | 1.918 | 20 | 300 |
| Silicate Esters | 1502.1776 | 0.001 | 890 | 1600 | 185 | 1.918 | 20 | 300 |
| Group II Oils | 2176.290667 | 0.001 | 851 | 2000 | 220 | 1.918 | 20 | 300 |
| Diesters | 2326.73117 | 0.001 | 900 | 1925.56 | 230 | 1.918 | 20 | 300 |
| Phenyl Methyl | 2249.33404 | 0.001 | 1030 | 1423.24 | 260 | 1.918 | 20 | 300 |
| Mineral Oils | 1525.943845 | 0.002 | 860 | 1632.54 | 105 | 1.918 | 20 | 300 |
| Phosphate Esters | 3920.598223 | 0.002 | 1090 | 1758.12 | 180 | 1.918 | 20 | 300 |
| Silicate Esters | 3004.3552 | 0.002 | 890 | 1600 | 185 | 1.918 | 20 | 300 |
| Group II Oils | 4352.581333 | 0.002 | 851 | 2000 | 220 | 1.918 | 20 | 300 |
| Diesters | 4653.462341 | 0.002 | 900 | 1925.56 | 230 | 1.918 | 20 | 300 |
| Phenyl Methyl | 4498.668079 | 0.002 | 1030 | 1423.24 | 260 | 1.918 | 20 | 300 |

## A.4.2 Appendix:Experimental Results

## A.4.3 Tables of the Average Values of the Trials

Table A.20: Clean Reference One: Average: One Pass

| Average |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference One |  |  |  |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |  |  |  |
| $\begin{gathered} \hline \text { Energy } \\ (\mu \mathbf{J}) \end{gathered}$ | 10 | 50 | 100 | 150 | 200 | 300 | 400 | 500 | 750 | 1000 |
| $\begin{gathered} \mathbf{R}_{a} \\ (\mu \mathrm{~m}) \end{gathered}$ | 1.025 | 1.068 | 1.38 | 1.617 | 1.885 | 2.05 | 2.345 | 2.628 | 2.408 | 2.305 |
| $\begin{gathered} \mathbf{R}_{z} \\ (\mu \mathrm{~m}) \end{gathered}$ | 6.148 | 6.827 | 9.408 | 10.153 | 10.73 | 10.825 | 14.223 | 15.998 | 15.482 | 14.283 |
| $\begin{gathered} \mathbf{R}_{a e, w, c} \\ (\mu \mathrm{~m}) \end{gathered}$ | -0.43 | -0.474 | -0.786 | -1.023 | -1.291 | -1.456 | -1.751 | -2.034 | -1.814 | -1.711 |
| $\begin{gathered} \mathbf{R}_{z e, w, c} \\ (\mu \mathrm{~m}) \end{gathered}$ | -6.148 | -6.827 | -9.408 | -10.153 | -10.73 | -10.825 | -14.223 | -15.998 | -15.482 | -14.283 |
| $\begin{gathered} \mathbf{R}_{\text {a clean }} \\ (\mu \mathrm{m}) \end{gathered}$ | -0.117 | -0.074 | 0.238 | 0.475 | 0.743 | 0.908 | 1.203 | 1.487 | 1.267 | 1.163 |
| $\begin{gathered} \mathbf{R}_{z \text { clean }} \\ (\mu \mathrm{m}) \end{gathered}$ | -0.278 | 0.4 | 2.982 | 3.727 | 4.303 | 4.398 | 7.797 | 9.572 | 9.055 | 7.857 |
| Effectiveness of $\mathbf{R}_{a}$ (\%) | -137.688 | -141.541 | -168.837 | -189.564 | -213.064 | -227.514 | -253.35 | -278.164 | -258.897 | -249.847 |
| Effectiveness of $\mathbf{R}_{z}$ (\%) | -195.669 | -206.224 | -246.395 | -257.988 | -266.961 | -268.439 | -321.317 | -348.937 | -340.897 | -322.251 |

Table A.21: Clean Reference Two: Average: One Pass

| Average |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference 2 |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\begin{gathered} \hline \text { Energy } \\ (\mu \mathbf{J}) \\ \hline \end{gathered}$ | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| $\begin{gathered} \mathbf{R}_{a} \\ (\mu \mathrm{~m}) \end{gathered}$ | 1.578 | 2.085 | 2.09 | 1.875 | 2.103 | 2.728 | 1.617 |
| $\begin{gathered} \mathbf{R}_{z} \\ (\mu \mathbf{m}) \\ \hline \end{gathered}$ | 10.618 | 13.22 | 13.442 | 12.668 | 12.442 | 14.73 | 10.153 |
| $\begin{gathered} \mathbf{R}_{a e, w, c} \\ (\mu \mathrm{~m}) \end{gathered}$ | -0.508 | -1.016 | -1.023 | -0.816 | -1.041 | -1.668 | -1.023 |
| $\begin{gathered} \mathbf{R}_{z e, w, c} \\ (\mu \mathbf{m}) \end{gathered}$ | -4.135 | -6.737 | -6.958 | -6.185 | -5.958 | -8.247 | -10.153 |
| $\begin{gathered} \mathbf{R}_{\text {a clean }} \\ (\mu \mathbf{m}) \end{gathered}$ | 0.436 | 0.943 | 0.948 | 0.733 | 0.961 | 1.586 | 0.475 |
| $\begin{gathered} \mathbf{R}_{z \text { clean }} \\ (\mu \mathrm{m}) \end{gathered}$ | 4.135 | 6.737 | 6.958 | 6.185 | 5.958 | 8.247 | 3.727 |
| Effectiveness of $\mathbf{R}_{a}$ (\%) | -147.278 | -194.712 | -195.334 | -175.428 | -196.423 | -254.743 | -189.564 |
| Effectiveness of $\mathbf{R}_{z}$ (\%) | -163.779 | -203.907 | -207.326 | -195.398 | -191.902 | -227.198 | -257.988 |

Table A.22: Clean Reference Two: Two Passes

| Average |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference 2 |  |  |  |  |  |  |  |
| Eno Passes <br> $(\mu \mathbf{J})$ |  | $\mathbf{7 5}$ | $\mathbf{8 5}$ | $\mathbf{9 5}$ | $\mathbf{1 0 5}$ | $\mathbf{1 1 5}$ | $\mathbf{1 2 5}$ |
| $\mathbf{R}_{a}$ <br> $(\mu \mathbf{m})$ | 1.04 | 0.658 | 1.913 | 1.668 | 2.148 | 2.01 | 1.617 |
| $\mathbf{R}_{z}$ <br> $(\mu \mathbf{m})$ | 8.628 | 7.23 | 11.718 | 9.385 | 12.098 | 11.1 | 10.153 |
| $\mathbf{R}_{a}$ e,w,c <br> $(\mu \mathbf{m})$ | 0.029 | 0.412 | -0.856 | -0.613 | -1.098 | -0.953 | -1.023 |
| $\mathbf{R}_{z \text { e ew,c }}$ <br> $(\mu \mathbf{m})$ | -2.145 | -0.747 | -5.235 | -2.902 | -5.615 | -4.617 | -10.153 |
| $\mathbf{R}_{a}$ clean <br> $(\mu \mathbf{m})$ | -0.032 | -0.414 | 0.841 | 0.596 | 1.076 | 0.938 | 0.475 |
| $\mathbf{R}_{z}$ clean <br> $(\mu \mathbf{m})$ | 2.145 | 0.747 | 5.235 | 2.902 | 5.615 | 4.617 | 3.727 |
| Effectiveness <br> of <br> $\mathbf{R}_{a}$ <br> $(\%)$ | -97.045 | -61.431 | -178.849 | -155.988 | -201.089 | -187.869 | -189.564 |
| Effectiveness <br> of <br> $\mathbf{R}_{z}$ <br> $(\%)$ | -133.085 | -111.517 | -180.746 | -144.756 | -186.607 | -171.208 | -257.988 |

Table A.23: Mixture A: One Pass: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture A |  |  |  |
| One Pass |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 0.988 | 1.07 | 1.845 |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ | 6.472 | 6.31 | 9.58 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.049 | -0.119 | -0.914 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -0.455 | -0.293 | -3.563 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.044 | 0.127 | 0.902 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 0.455 | 0.293 | 3.563 |
| Effectiveness of $\mathrm{R}_{a}$ with respect to the Potential Thickness (\%) | -0.773 | -0.379 | 3.551 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Potential Thickness (\%) | 0.11 | -0.285 | 7.691 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | -13.443 | -6.583 | 61.728 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 0.7 | -1.815 | 49.066 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | -104.77 | -113.074 | -195.76 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | -107.562 | -104.875 | -159.224 |

Table A.24: Mixture A: Two Passes: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture A |  |  |  |
| Two Passes |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.14 | 1.883 | 1.918 |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ | 7.818 | 11.495 | 11.792 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.062 | -0.812 | -0.847 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -1.633 | -5.31 | -5.607 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.197 | 0.939 | 0.974 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 1.802 | 5.478 | 5.775 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | -0.003 | 12.704 | 13.302 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Potential Thickness (\%) | 5.759 | 20.972 | 22.2 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | -0.015 | 65.085 | 68.151 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 21.655 | 78.864 | 83.48 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | -105.385 | -174 | -177.231 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | -126.408 | -185.853 | -190.649 |

Table A.25: Mixture B: One Pass: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture B |  |  |  |
| One Pass |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.105 | 1.738 | 1.89 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 7.625 | 11.207 | 10.427 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.045 | -0.68 | -0.815 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -1.222 | -4.803 | -4.023 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathrm{m})$ | 0.162 | 0.794 | 0.947 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathrm{m})$ | 1.608 | 5.19 | 4.41 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | -0.45 | 7.228 | 8.98 |
| Effectiveness of $\mathrm{R}_{z}$ with respect to the Potential Thickness (\%) | 51.357 | 204.857 | 171.429 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | -3.226 | 51.803 | 64.356 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 18.646 | 74.378 | 62.241 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | -104.245 | -163.522 | -177.044 |
| Effectiveness of $R_{z}$ with respect to the Dirt Layer (\%) | -119.079 | -175.013 | -162.832 |

Table A.26: Mixture B: Two Passes: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture B |  |  |  |
| Two Passes |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.293 | 1.768 | 2.023 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 9.015 | 11.308 | 12.072 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.235 | -0.718 | -0.96 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -2.612 | -4.905 | -5.668 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.349 | 0.824 | 1.079 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathrm{m})$ | 2.998 | 5.292 | 6.055 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | 1.851 | 7.697 | 10.731 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Potential Thickness (\%) | 110.929 | 209.214 | 241.929 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 13.268 | 55.16 | 76.908 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 40.275 | 75.96 | 87.837 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | -122.013 | -167.138 | -190.566 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | -140.786 | -176.601 | -188.522 |

Table A.27: Mixture C: One Pass: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture C |  |  |  |
| One Pass |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.233 | 1.578 | 1.883 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 8.39 | 10.412 | 10.992 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.185 | -0.53 | -0.843 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -2.257 | -9.362 | -9.942 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.289 | 0.634 | 0.939 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 2.373 | 4.395 | 4.975 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | 0.978 | 4.717 | 8.074 |
| Effectiveness of $\mathrm{R}_{z}$ with respect to the Potential Thickness (\%) | 6.693 | 30.915 | 32.892 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 7.867 | 37.936 | 64.939 |
| Effectiveness of $\mathrm{R}_{z}$ with respect to the Clean Reference (\%) | 30.55 | 62.007 | 71.032 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | -117.302 | -150 | -179.365 |
| Effectiveness of $\mathrm{R}_{z}$ with respect to the Dirt Layer (\%) | -136.793 | -252.636 | -262.092 |

Table A.28: Mixture C: Two Passes: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture C |  |  |  |
| Two Passes |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.333 | 1.82 | 1.988 |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ | 8.835 | 11.958 | 11.82 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.293 | -0.768 | -0.94 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -2.71 | -5.833 | -5.695 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.389 | 0.877 | 1.044 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 2.818 | 5.942 | 5.803 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | 2.103 | 8.308 | 10.344 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Potential Thickness (\%) | 7.983 | 18.337 | 17.878 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 16.917 | 59.539 | 74.135 |
| Effectiveness of $\mathrm{R}_{z}$ with respect to the Clean Reference (\%) | 37.474 | 86.074 | 83.921 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | -127.143 | -171.855 | -187.579 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | -144.245 | -195.238 | -192.98 |

Table A.29: Mixture D: One Pass: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture D |  |  |  |
| One Pass |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.205 | 1.733 | 1.843 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 8.115 | 10.678 | 10.68 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | 0.058 | -0.484 | -0.589 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -0.81 | -3.373 | -3.375 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.262 | 0.789 | 0.899 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 2.098 | 4.662 | 4.663 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | -0.52 | -4.896 | -5.774 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Potential Thickness (\%) | -1.922 | -4.841 | -4.843 |
| Effectiveness of $R_{a}$ with respect to the Clean Reference (\%) | 5.532 | 52.095 | 61.436 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 26.271 | 66.157 | 66.183 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | -95.383 | -137.467 | -145.91 |
| Effectiveness of $R_{z}$ with respect to the Dirt Layer (\%) | -111.088 | -146.178 | -146.201 |

Table A.30: Mixture D: Two Passes: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture D |  |  |  |
| Two Passes |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.285 | 1.663 | 1.813 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 9.503 | 11.092 | 11.42 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.362 | -0.613 | -0.763 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -4 | -5.588 | -5.917 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.342 | 0.719 | 0.869 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 3.487 | 5.075 | 5.403 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | 0.678 | 1.842 | 2.528 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Potential Thickness (\%) | 3.332 | 5.052 | 5.408 |
| Effectiveness of $R_{a}$ with respect to the Clean Reference (\%) | 12.684 | 45.964 | 58.809 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 47.873 | 72.588 | 77.697 |
| Effectiveness of $R_{a}$ with respect to the Dirt Layer (\%) | -138.6 | -165.35 | -181.149 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | -172.683 | -201.545 | -207.511 |

Table A.31: Mixture E: One Pass: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture E |  |  |  |
| One Pass |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.048 | 1.645 | 1.86 |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ | 7.075 | 9.967 | 10.795 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.147 | -0.764 | -1.009 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -1.337 | -4.228 | -5.057 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.104 | 0.702 | 0.917 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathbf{m})$ | 1.058 | 3.95 | 4.778 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | -0.391 | 2.08 | 3.004 |
| Effectiveness of $R_{z}$ with respect to the Potential Thickness (\%) | 0.942 | 5.143 | 6.346 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | -8.335 | 44.358 | 64.064 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 10.088 | 55.083 | 67.972 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Dirt Layer (\%) | -116.512 | -183.488 | -208.534 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | -123.294 | -173.686 | -188.121 |

Table A.32: Mixture E: Two Passes: Average

| Average |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture E |  |  |  |
| Two Passes |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 115 | 150 |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ | 1.36 | 1.77 | 2.008 |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ | 9.575 | 11.487 | 12.887 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.213 | -0.636 | -0.871 |
| $\mathbf{R}_{z e, w, c}(\mu \mathbf{m})$ | -2.682 | -4.593 | -5.993 |
| $\mathbf{R}_{\text {a clean }}(\mu \mathbf{m})$ | 0.417 | 0.827 | 1.064 |
| $\mathbf{R}_{z \text { clean }}(\mu \mathrm{m})$ | 3.558 | 5.47 | 6.87 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Potential Thickness (\%) | 1289 | 3779 | 5189 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Potential Thickness (\%) | -6.746 | -10.843 | -13.843 |
| Effectiveness of $\mathbf{R}_{a}$ with respect to the Clean Reference (\%) | 18.815 | 55.16 | 75.741 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Clean Reference (\%) | 48.989 | 78.734 | 100.519 |
| Effectiveness of $\mathrm{R}_{a}$ with respect to the Dirt Layer (\%) | -118.832 | -155.182 | -175.766 |
| Effectiveness of $\mathbf{R}_{z}$ with respect to the Dirt Layer (\%) | -138.902 | -166.634 | -186.944 |

## A.4.4 Tables for Each Trial

Table A.33: Clean: Reference One: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference One |  |  |  |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 10 | 50 | 100 | 150 | 200 | 300 | 400 | 500 | 750 | 1000 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.500 | 0.530 | 0.790 | 0.840 | 1.180 | 1.340 | 1.620 | 1.710 | 1.820 | 1.570 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.550 | 1.610 | 1.940 | 2.340 | 2.550 | 2.760 | 3.060 | 3.560 | 3.000 | 3.040 |
| Average ( $\mu \mathrm{m}$ ) | 1.025 | 1.070 | 1.365 | 1.590 | 1.865 | 2.050 | 2.340 | 2.635 | 2.410 | 2.305 |
| $\begin{gathered} \mathbf{R}_{a e, w, c} \\ (\mu \mathbf{m}) \end{gathered}$ | 0.759 | 0.712 | 0.417 | 0.192 | -0.083 | -0.268 | -0.558 | -0.853 | -0.628 | -0.523 |
| Effectiveness (\%) | -33.52 | -37.64 | -63.48 | -83.18 | -107.26 | -123.47 | -148.86 | -174.70 | -154.99 | -145.80 |

Table A.34: Clean: Reference One: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference One |  |  |  |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |  |  |  |
| $\begin{gathered} \text { Energy } \\ (\mu \mathbf{J}) \\ \hline \end{gathered}$ | 10 | 50 | 100 | 150 | 200 | 300 | 400 | 500 | 750 | 1000 |
| Parallel to the Path of the laser-beam ( $\mu \mathbf{m}$ ) | 0.500 | 0.530 | 0.810 | 0.850 | 1.200 | 1.310 | 1.600 | 1.700 | 1.780 | 1.580 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.550 | 1.600 | 1.960 | 2.390 | 2.580 | 2.790 | 3.090 | 3.570 | 3.040 | 3.030 |
| Average ( $\mu \mathrm{m}$ ) | 1.025 | 1.065 | 1.385 | 1.620 | 1.890 | 2.050 | 2.345 | 2.635 | 2.410 | 2.305 |
| $\begin{gathered} \mathbf{R}_{a e, w, c} \\ (\mu \mathrm{~m}) \end{gathered}$ | -1.025 | -1.065 | -1.385 | -1.620 | -1.890 | $-2.050$ | $-2.345$ | -2.635 | $-2.410$ | $-2.305$ |
| Effectiveness (\%) | -189.76 | -193.27 | -221.29 | -241.87 | -265.52 | -279.53 | -305.37 | -330.76 | -311.06 | -301.86 |

Table A.35: Clean: Reference One: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference One |  |  |  |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |  |  |  |  |  |  |  |
| $\begin{gathered} \text { Energy } \\ (\mu \mathbf{J}) \\ \hline \end{gathered}$ | 10 | 50 | 100 | 150 | 200 | 300 | 400 | 500 | 750 | 1000 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.500 | 0.530 | 0.820 | 0.860 | 1.200 | 1.300 | 1.590 | 1.680 | 1.770 | 1.580 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.550 | 1.610 | 1.960 | 2.420 | 2.600 | 2.800 | 3.110 | 3.550 | 3.040 | 3.030 |
| Average ( $\mu \mathbf{m}$ ) | 1.025 | 1.070 | 1.390 | 1.640 | 1.900 | 2.050 | 2.350 | 2.615 | 2.405 | 2.305 |
| $\begin{gathered} \mathbf{R}_{a e, w, c} \\ (\mu \mathrm{~m}) \end{gathered}$ | -1.025 | -1.070 | -1.390 | -1.640 | -1.900 | -2.050 | $-2.350$ | -2.615 | -2.405 | $-2.305$ |
| Effectiveness (\%) | -189.76 | -193.70 | -221.73 | -243.62 | -266.39 | -279.53 | -305.80 | -329.01 | -310.62 | -301.86 |

Table A.36: Clean: Reference One: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference One |  |  |  |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |  |  |  |  |  |  |  |
| $\begin{gathered} \text { Energy } \\ (\mu \mathbf{J}) \\ \hline \end{gathered}$ | 10 | 50 | 100 | 150 | 200 | 300 | 400 | 500 | 750 | 1000 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 3.170 | 3.600 | 6.270 | 5.420 | 7.110 | 10.090 | 11.890 | 12.310 | 12.840 | 10.920 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.120 | 10.040 | 12.440 | 14.910 | 14.310 | 15.890 | 16.610 | 19.890 | 18.530 | 17.520 |
| Average ( $\mu \mathbf{m}$ ) | 6.145 | 6.820 | 9.355 | 10.165 | 10.710 | 12.990 | 14.250 | 16.100 | 15.685 | 14.220 |
| $\begin{gathered} \mathbf{R}_{a e, w, c} \\ (\mu \mathrm{~m}) \end{gathered}$ | -6.145 | -6.820 | -9.355 | -10.165 | -10.710 | -12.990 | -14.250 | -16.100 | -15.685 | -14.220 |
| Effectiveness (\%) | -195.61 | -206.12 | -245.56 | -258.16 | -266.64 | -302.12 | -321.73 | -350.51 | -344.061 | -321.26 |

Table A.37: Clean: Reference One: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference One |  |  |  |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |  |  |  |  |  |  |  |
| $\begin{gathered} \text { Energy } \\ (\mu \mathbf{J}) \\ \hline \end{gathered}$ | 10 | 50 | 100 | 150 | 200 | 300 | 400 | 500 | 750 | 1000 |
| Parallel to the Path of the laser-beam ( $\mu \mathbf{m}$ ) | 3.160 | 3.630 | 6.330 | 5.360 | 7.120 | 9.970 | 11.770 | 12.010 | 12.360 | 11.000 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathbf{m}$ ) | 9.140 | 10.030 | 12.520 | 14.930 | 14.330 | 2.790 | 16.690 | 19.970 | 18.540 | 17.650 |
| $\begin{gathered} \text { Average } \\ (\mu \mathbf{m}) \end{gathered}$ | 6.150 | 6.830 | 9.425 | 10.145 | 10.725 | 6.380 | 14.230 | 15.990 | 15.450 | 14.325 |
| $\begin{gathered} \mathbf{R}_{a e, w, c} \\ (\mu \mathbf{m}) \end{gathered}$ | -6.150 | $-6.830$ | -9.425 | -10.145 | -10.725 | -6.380 | -14.230 | -15.990 | -15.450 | -14.325 |
| Effectiveness (\%) | -195.69 | -206.27 | -246.65 | -257.85 | -266.88 | -199.27 | -321.42 | -348.81 | -340.41 | -322.89 |

Table A.38: Clean: Reference One: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference One |  |  |  |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |  |  |  |
| $\begin{gathered} \text { Energy } \\ (\mu \mathbf{J}) \end{gathered}$ | 10 | 50 | 100 | 150 | 200 | 300 | 400 | 500 | 750 | 1000 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 3.150 | 3.630 | 6.350 | 5.330 | 7.140 | 9.850 | 11.710 | 11.920 | 12.110 | 10.980 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.150 | 10.030 | 12.540 | 14.970 | 14.370 | 16.360 | 16.670 | 19.890 | 18.510 | 17.630 |
| Average ( $\mu \mathbf{m}$ ) | 6.150 | 6.830 | 9.445 | 10.150 | 10.755 | 13.105 | 14.190 | 15.905 | 15.310 | 14.305 |
| $\begin{gathered} \mathbf{R}_{a e, w, c} \\ (\mu \mathrm{~m}) \end{gathered}$ | -6.150 | $-6.830$ | -9.445 | -10.150 | -10.755 | -13.105 | -14.190 | -15.905 | -15.310 | -14.305 |
| Effectiveness (\%) | -195.69 | -206.27 | -246.96 | -257.93 | -267.35 | -303.92 | -320.79 | -347.48 | -338.22 | -322.58 |

Table A.39: Clean: Reference Two: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 2.270 | 2.850 | 2.290 | 2.510 | 2.400 | 2.820 | 0.840 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.880 | 1.320 | 1.890 | 1.220 | 1.780 | 2.600 | 2.340 |
| Average ( $\mu \mathrm{m}$ ) | 1.575 | 2.085 | 2.090 | 1.865 | 2.090 | 2.710 | 1.590 |
| $\mathbf{R}_{a e, w, c}(\mu \mathrm{~m})$ | -0.503 | -1.013 | -1.018 | -0.793 | -1.018 | -1.638 | 0.192 |
| Effectiveness (\%) | -146.967 | -194.557 | -195.023 | -174.028 | -195.023 | -252.877 | -83.185 |

Table A.40: Clean: Reference Two: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 2.260 | 2.850 | 2.300 | 2.510 | 2.420 | 2.820 | 0.850 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.900 | 1.330 | 1.900 | 1.270 | 1.800 | 2.650 | 2.390 |
| Average ( $\mu \mathrm{m}$ ) | 1.580 | 2.090 | 2.100 | 1.890 | 2.110 | 2.735 | 1.620 |
| $\mathbf{R}_{a e, w, c}(\mu \mathrm{~m})$ | -0.508 | -1.018 | -1.028 | -0.818 | -1.038 | -1.663 | -1.620 |
| Effectiveness (\%) | -147.434 | -195.023 | -195.956 | -176.361 | -196.890 | -255.210 | -241.877 |

Table A.41: Clean: Reference Two: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 2.260 | 2.840 | 2.310 | 2.500 | 2.420 | 2.830 | 0.860 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.900 | 1.330 | 1.870 | 1.270 | 1.810 | 2.660 | 2.420 |
| Average ( $\mu \mathbf{m}$ ) | 1.580 | 2.085 | 2.090 | 1.885 | 2.115 | 2.745 | 1.640 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.508 | -1.013 | -1.018 | -0.813 | -1.043 | -1.673 | -1.640 |
| Effectiveness (\%) | -147.434 | -194.557 | -195.023 | -175.894 | -197.356 | -256.143 | -243.629 |

Table A.42: Clean: Reference Two: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 12.840 | 16.100 | 14.670 | 16.000 | 14.070 | 17.430 | 5.420 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.320 | 10.160 | 12.420 | 8.860 | 10.670 | 11.780 | 14.910 |
| Average ( $\mu \mathrm{m}$ ) | 10.580 | 13.130 | 13.545 | 12.430 | 12.370 | 14.605 | 10.165 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -4.097 | -6.647 | -7.062 | -5.947 | -5.887 | -8.122 | -10.165 |
| Effectiveness (\%) | -163.188 | -202.519 | -208.920 | -191.722 | -190.797 | -225.270 | -258.169 |

Table A.43: Clean: Reference Two: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 12.840 | 16.190 | 14.870 | 16.010 | 14.130 | 17.600 | 5.360 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.460 | 10.260 | 12.470 | 9.730 | 10.750 | 11.950 | 14.930 |
| Average ( $\mu \mathrm{m}$ ) | 10.650 | 13.225 | 13.670 | 12.870 | 12.440 | 14.775 | 10.145 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -4.167 | -6.742 | -7.187 | -6.387 | -5.957 | -8.292 | -10.145 |
| Effectiveness (\%) | -164.267 | -203.985 | -210.848 | -198.509 | -191.877 | -227.892 | -257.858 |

Table A.44: Clean: Reference Two: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 12.830 | 16.160 | 14.900 | 16.240 | 14.300 | 17.630 | 5.330 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.420 | 10.450 | 11.320 | 9.170 | 10.730 | 11.990 | 14.970 |
| Average ( $\mu \mathrm{m}$ ) | 10.625 | 13.305 | 13.110 | 12.705 | 12.515 | 14.810 | 10.150 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -4.142 | -6.822 | -6.627 | -6.222 | -6.032 | -8.327 | -10.150 |
| Effectiveness (\%) | -163.882 | -205.219 | -202.211 | -195.964 | -193.033 | -228.432 | -257.936 |

Table A.45: Clean: Reference Two: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.060 | 0.830 | 1.630 | 1.020 | 1.870 | 1.780 | 0.840 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.010 | 0.480 | 2.160 | 2.270 | 2.380 | 2.200 | 2.340 |
| Average ( $\mu \mathrm{m}$ ) | 1.035 | 0.655 | 1.895 | 1.645 | 2.125 | 1.990 | 1.590 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | 0.037 | 0.417 | -0.823 | -0.573 | -1.053 | -0.918 | 0.192 |
| Effectiveness (\%) | -96.579 | -61.120 | -176.827 | -153.499 | -198.289 | -185.692 | -83.185 |

Table A.46: Clean: Reference Two: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.060 | 0.840 | 1.660 | 1.050 | 1.900 | 1.800 | 0.850 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.020 | 0.480 | 2.190 | 2.310 | 2.440 | 2.240 | 2.390 |
| Average ( $\mu \mathrm{m}$ ) | 1.040 | 0.660 | 1.925 | 1.680 | 2.170 | 2.020 | 1.620 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | 0.032 | 0.412 | -0.853 | -0.608 | -1.098 | -0.948 | -1.620 |
| Effectiveness (\%) | -97.045 | -61.586 | -179.627 | -156.765 | -202.488 | -188.491 | -241.877 |

Table A.47: Clean: Reference Two: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| One Pass |  |  |  |  |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.070 | 0.840 | 1.660 | 1.050 | 1.900 | 1.810 | 0.860 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.020 | 0.480 | 2.200 | 2.330 | 2.440 | 2.250 | 2.420 |
| Average ( $\mu \mathrm{m}$ ) | 1.045 | 0.660 | 1.930 | 1.690 | 2.170 | 2.030 | 1.640 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | 0.027 | 0.412 | -0.858 | -0.618 | -1.098 | -0.958 | -1.640 |
| Effectiveness (\%) | -97.512 | -61.586 | -180.093 | -157.698 | -202.488 | -189.425 | -243.629 |

Table A.48: Clean: Reference Two: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| Two Passes |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.320 | 7.100 | 11.600 | 6.660 | 10.520 | 10.400 | 5.420 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.900 | 7.290 | 11.610 | 11.960 | 13.400 | 11.590 | 14.910 |
| Average ( $\mu \mathrm{m}$ ) | 8.610 | 7.195 | 11.605 | 9.310 | 11.960 | 10.995 | 10.165 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.127 | -0.712 | -5.122 | -2.827 | -5.477 | -4.512 | -10.165 |
| Effectiveness (\%) | -132.802 | -110.977 | -178.997 | -143.599 | -184.473 | -169.589 | -258.169 |

Table A.49: Clean: Reference Two: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| Two Passes |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.370 | 7.180 | 11.750 | 6.730 | 10.640 | 10.420 | 5.360 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.900 | 7.290 | 11.770 | 12.080 | 13.720 | 11.840 | 14.930 |
| Average ( $\mu \mathrm{m}$ ) | 8.635 | 7.235 | 11.760 | 9.405 | 12.180 | 11.130 | 10.145 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.152 | -0.752 | -5.277 | -2.922 | -5.697 | -4.647 | -10.145 |
| Effectiveness (\%) | -133.188 | -111.594 | -181.388 | -145.064 | -187.866 | -171.671 | -257.858 |

Table A.50: Clean: Reference Two: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Clean: Reference Two |  |  |  |  |  |  |  |
| Two Passes |  |  |  |  |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |  |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 85 | 95 | 105 | 115 | 125 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.360 | 7.290 | 11.800 | 6.750 | 10.690 | 10.440 | 5.330 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.920 | 7.230 | 11.780 | 12.130 | 13.620 | 11.910 | 14.970 |
| Average ( $\mu \mathrm{m}$ ) | 8.640 | 7.260 | 11.790 | 9.440 | 12.155 | 11.175 | 10.150 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.157 | -0.777 | -5.307 | -2.957 | -5.672 | -4.692 | -10.150 |
| Effectiveness (\%) | -133.265 | -111.979 | -181.851 | -145.604 | -187.481 | -172.365 | -257.936 |

Table A.51: Mixture: A: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.470 | 1.630 | 1.810 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.490 | 0.520 | 1.840 |
| Average ( $\mu \mathrm{m}$ ) | 0.980 | 1.075 | 1.825 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.037 | -0.132 | -0.882 |
| Effectiveness with respect to Potential Thickness (\%) | -0.815 | -0.337 | 3.442 |
| Effectiveness with respect to Clean Reference (\%) | -14.173 | -5.853 | 59.831 |
| Effectiveness with respect to Dirt Layer (\%) | -103.887 | -113.958 | -193.463 |

Table A.52: Mixture: A: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.480 | 1.640 | 1.820 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.500 | 0.480 | 1.880 |
| Average ( $\mu \mathrm{m}$ ) | 0.990 | 1.060 | 1.850 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.047 | -0.117 | -0.907 |
| Effectiveness with respect to Potential Thickness (\%) | -0.765 | -0.412 | 3.568 |
| Effectiveness with respect to Clean Reference (\%) | -13.297 | -7.167 | 62.020 |
| Effectiveness with respect to Dirt Layer (\%) | -104.947 | -112.367 | -196.113 |

Table A.53: Mixture: A: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3
Trial 3 Mixture: A
One Pass
$\mathbf{R}_{a}(\mu \mathbf{m})$

| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |
| :---: | :---: | :---: | :---: |
| Energy $(\mu \mathbf{J})$ | $\mathbf{7 5}$ | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 1.480 | 1.640 | 1.830 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 0.510 | 0.490 | 1.900 |
| Average $(\mu \mathbf{m})$ | 0.995 | 1.065 | 1.865 |
| $\left.\mathbf{R}_{a \text { e,w,c} \boldsymbol{(})} \mu \mathbf{m}\right)$ | -0.052 | -0.122 | -0.922 |
| Effectiveness with respect to Potential Thickness (\%) | -0.740 | -0.387 | 3.643 |
| Effectiveness with respect to Clean Reference (\%) | -12.859 | -6.729 | 63.334 |
| Effectiveness with respect to Dirt Layer (\%) | -105.477 | -112.898 | -197.703 |

Table A.54: Mixture: A: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.500 | 8.750 | 10.140 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 4.440 | 5.060 | 8.920 |
| Average ( $\mu \mathrm{m}$ ) | 6.470 | 6.905 | 9.530 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.453 | -0.888 | -3.513 |
| Effectiveness with respect to Potential Thickness (\%) | 0.106 | 1.167 | 7.569 |
| Effectiveness with respect to Clean Reference (\%) | 0.674 | 7.443 | 48.288 |
| Effectiveness with respect to Dirt Layer (\%) | -107.535 | -114.765 | -158.393 |

Table A.55: Mixture: A: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.540 | 8.830 | 10.120 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 4.410 | 3.140 | 9.060 |
| Average ( $\mu \mathrm{m}$ ) | 6.475 | 5.985 | 9.590 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.458 | 0.032 | -3.573 |
| Effectiveness with respect to Potential Thickness (\%) | 0.118 | -1.077 | 7.715 |
| Effectiveness with respect to Clean Reference (\%) | 0.752 | -6.872 | 49.222 |
| Effectiveness with respect to Dirt Layer (\%) | -107.618 | -99.474 | -159.391 |

Table A.56: Mixture: A: One Pass: $\mathrm{R}_{z}(\mu \mathrm{M})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.500 | 8.780 | 10.120 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 4.440 | 3.300 | 9.120 |
| Average ( $\mu \mathrm{m}$ ) | 6.470 | 6.040 | 9.620 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.453 | -0.023 | -3.603 |
| Effectiveness with respect to Potential Thickness (\%) | 0.106 | -0.943 | 7.789 |
| Effectiveness with respect to Clean Reference (\%) | 0.674 | -6.017 | 49.689 |
| Effectiveness with respect to Dirt Layer (\%) | -107.535 | -100.388 | -159.889 |

Table A.57: Mixture: A: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.640 | 2.130 | 2.100 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.630 | 1.600 | 1.700 |
| Average ( $\mu \mathrm{m}$ ) | 1.135 | 1.865 | 1.900 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.052 | -0.782 | -0.817 |
| Effectiveness with respect to Potential Thickness (\%) | -0.117 | 12.362 | 12.960 |
| Effectiveness with respect to Clean Reference (\%) | -0.598 | 63.334 | 66.399 |
| Effectiveness with respect to Dirt Layer (\%) | -104.769 | -172.154 | -175.385 |

Table A.58: Mixture: A: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.670 | 2.120 | 2.110 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.620 | 1.660 | 1.740 |
| Average ( $\mu \mathrm{m}$ ) | 1.145 | 1.890 | 1.925 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.062 | -0.807 | -0.842 |
| Effectiveness with respect to Potential Thickness (\%) | 0.054 | 12.789 | 13.387 |
| Effectiveness with respect to Clean Reference (\%) | 0.277 | 65.523 | 68.589 |
| Effectiveness with respect to Dirt Layer (\%) | -105.692 | -174.462 | -177.692 |

Table A.59: Mixture: A: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{M})$ : Trial 3
Trial 3 Mixture: A Two Passes $\mathbf{R}_{a}$ ( $\mu \mathbf{m}$ )

| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |
| :---: | :---: | :---: | :---: |
| Energy $(\mu \mathbf{J})$ | $\mathbf{7 5}$ | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 1.670 | 2.130 | 2.110 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 0.620 | 1.670 | 1.760 |
| Average $(\mu \mathbf{m})$ | 1.145 | 1.900 | 1.935 |
| $\mathbf{R}_{a \text { e,w,c}}(\mu \mathbf{m})$ | -0.062 | -0.817 | -0.852 |
| Effectiveness with respect to Potential Thickness (\%) | 0.054 | 12.960 | 13.558 |
| Effectiveness with respect to Clean Reference (\%) | 0.277 | 66.399 | 69.464 |
| Effectiveness with respect to Dirt Layer (\%) | -105.692 | -175.385 | -178.615 |

Table A.60: Mixture: A: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{M})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.170 | 13.260 | 12.210 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 6.710 | 9.880 | 11.540 |
| Average ( $\mu \mathrm{m}$ ) | 7.940 | 11.570 | 11.875 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.755 | -5.385 | -5.690 |
| Effectiveness with respect to Potential Thickness (\%) | 6.262 | 21.283 | 22.545 |
| Effectiveness with respect to Clean Reference (\%) | 23.548 | 80.031 | 84.777 |
| Effectiveness with respect to Dirt Layer (\%) | -128.375 | -187.065 | -191.997 |

Table A.61: Mixture: A: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| Two Passes |  |  |  |
| ( $\mathbf{R}_{\boldsymbol{z}}(\mu \mathbf{m})$ | $\mathbf{1 1 5}$ |  |  |
| Energy $(\mu \mathbf{J})$ | $\mathbf{7 5}$ | $\mathbf{1 1 5}$ |  |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 9.550 | 12.850 | 12.300 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 5.940 | 9.990 | 11.180 |
| Average $(\mu \mathbf{m})$ | 7.745 | 11.420 | 11.740 |
| $\mathbf{R}_{a}$ e,w,c$(\mu \mathbf{m})$ | -1.560 | -5.235 | -5.555 |
| Effectiveness with respect to Potential Thickness (\%) | 5.455 | 20.662 | 21.986 |
| Effectiveness with respect to Clean Reference (\%) | 20.513 | 77.697 | 82.676 |
| Effectiveness with respect to Dirt Layer (\%) | -125.222 | -184.640 | -189.814 |

Table A.62: Mixture: A: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{M})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: A |  |  |  |
| Two Passes |  |  |  |
| Energy $(\mu \mathbf{J}) \quad \mathbf{R}_{\boldsymbol{z}}(\mu \mathbf{m})$ | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |  |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 9.540 | 12.870 | 12.310 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 6.000 | 10.120 | 11.210 |
| Average $(\mu \mathbf{m})$ | 7.770 | 11.495 | 11.760 |
| $\mathbf{R}_{a}$ e,w,c$(\mu \mathbf{m})$ | -1.585 | -5.310 | -5.575 |
| Effectiveness with respect to Potential Thickness (\%) | 5.559 | 20.972 | 22.069 |
| Effectiveness with respect to Clean Reference (\%) | 20.902 | 78.864 | 82.988 |
| Effectiveness with respect to Dirt Layer (\%) | -125.627 | -185.853 | -190.137 |

Table A.63: Mixture: B: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.650 | 1.780 | 1.710 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.560 | 1.660 | 2.050 |
| Average ( $\mu \mathrm{m}$ ) | 1.105 | 1.720 | 1.880 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.045 | -0.660 | -0.820 |
| Effectiveness with respect to Potential Thickness (\%) | -0.450 | 7.065 | 9.020 |
| Effectiveness with respect to Clean Reference (\%) | -3.226 | 50.635 | 64.647 |
| Effectiveness with respect to Dirt Layer (\%) | -104.245 | -162.264 | -177.358 |

Table A.64: Mixture: B: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.650 | 1.750 | 1.720 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.560 | 1.700 | 1.980 |
| Average ( $\mu \mathrm{m}$ ) | 1.105 | 1.725 | 1.850 |
| $\mathbf{R}_{a e, w, c}(\mu \mathrm{~m})$ | -0.045 | -0.665 | -0.790 |
| Effectiveness with respect to Potential Thickness (\%) | -0.450 | 7.126 | 8.654 |
| Effectiveness with respect to Clean Reference (\%) | -3.226 | 51.073 | 62.020 |
| Effectiveness with respect to Dirt Layer (\%) | -104.245 | -162.736 | $-174.528$ |

Table A.65: Mixture: B: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3
Trial 3
Mixture: B
One Pass
$\mathbf{R}_{a}(\mu \mathbf{m})$

| Energy $(\mu \mathbf{J})$ | $\mathbf{R}_{a}(\mu \mathbf{m})$ | 75 | 115 |
| :---: | :---: | :---: | :---: |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 1.650 | 1.800 | 1.730 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 0.560 | 1.710 | 2.070 |
| Average $(\mu \mathbf{m})$ | 1.105 | 1.755 | 1.900 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.045 | -0.695 | -0.840 |
| Effectiveness with respect to Potential Thickness (\%) | -0.450 | 7.493 | 9.265 |
| Effectiveness with respect to Clean Reference (\%) | -3.226 | 53.700 | 66.399 |
| Effectiveness with respect to Dirt Layer (\%) | -104.245 | -165.566 | -179.245 |

Table A.66: Mixture: B: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 10.780 | 11.780 | 10.870 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 4.680 | 10.880 | 10.030 |
| Average ( $\mu \mathrm{m}$ ) | 7.730 | 11.330 | 10.450 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.327 | -4.927 | -4.047 |
| Effectiveness with respect to Potential Thickness (\%) | 55.857 | 210.143 | 172.429 |
| Effectiveness with respect to Clean Reference (\%) | 20.280 | 76.297 | 62.604 |
| Effectiveness with respect to Dirt Layer (\%) | -120.718 | -176.939 | -163.196 |

Table A.67: Mixture: B: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 10.790 | 11.660 | 10.870 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 4.340 | 10.530 | 9.910 |
| Average ( $\mu \mathrm{m}$ ) | 7.565 | 11.095 | 10.390 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.162 | -4.692 | -3.987 |
| Effectiveness with respect to Potential Thickness (\%) | 48.786 | 200.071 | 169.857 |
| Effectiveness with respect to Clean Reference (\%) | 17.713 | 72.640 | 61.670 |
| Effectiveness with respect to Dirt Layer (\%) | -118.142 | -173.269 | -162.259 |

Table A.68: Mixture: B: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 3
Trial 3
Mixture: B
One Pass
$\mathbf{R}_{z}(\mu \mathbf{m})$

| Energy $(\mu \mathbf{J})$ | $\mathbf{R}$ |  |  |
| :---: | :---: | :---: | :---: |
| $\boldsymbol{z}(\mu \mathbf{m})$ | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |  |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 10.810 | 11.830 | 10.900 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 4.350 | 10.560 | 9.980 |
| Average $(\mu \mathbf{m})$ | 7.580 | 11.195 | 10.440 |
| $\mathbf{R}_{a \text { e }, w, c}(\mu \mathbf{m})$ | -1.177 | -4.792 | -4.037 |
| Effectiveness with respect to Potential Thickness (\%) | 49.429 | 204.357 | 172.000 |
| Effectiveness with respect to Clean Reference (\%) | 17.946 | 74.196 | 62.448 |
| Effectiveness with respect to Dirt Layer (\%) | -118.376 | -174.831 | -163.040 |

Table A.69: Mixture: B: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.770 | 1.960 | 2.020 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.810 | 1.550 | 2.020 |
| Average ( $\mu \mathrm{m}$ ) | 1.290 | 1.760 | 2.020 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.230 | -0.700 | -0.960 |
| Effectiveness with respect to Potential Thickness (\%) | 1.811 | 7.554 | 10.731 |
| Effectiveness with respect to Clean Reference (\%) | 12.976 | 54.138 | 76.908 |
| Effectiveness with respect to Dirt Layer (\%) | -121.698 | -166.038 | -190.566 |

Table A.70: Mixture: B: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.770 | 1.970 | 1.980 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.820 | 1.590 | 2.050 |
| Average ( $\mu \mathrm{m}$ ) | 1.295 | 1.780 | 2.015 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.235 | -0.720 | -0.955 |
| Effectiveness with respect to Potential Thickness (\%) | 1.872 | 7.798 | 10.670 |
| Effectiveness with respect to Clean Reference (\%) | 13.414 | 55.890 | 76.471 |
| Effectiveness with respect to Dirt Layer (\%) | -122.170 | -167.925 | -190.094 |

Table A.71: Mixture: B: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.770 | 1.960 | 1.980 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.820 | 1.590 | 2.070 |
| Average ( $\mu \mathrm{m}$ ) | 1.295 | 1.775 | 2.025 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.235 | -0.715 | -0.965 |
| Effectiveness with respect to Potential Thickness (\%) | 1.872 | 7.737 | 10.792 |
| Effectiveness with respect to Clean Reference (\%) | 13.414 | 55.452 | 77.346 |
| Effectiveness with respect to Dirt Layer (\%) | -122.170 | -167.453 | -191.038 |

Table A.72: Mixture: B: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |
| :---: | :---: | :---: | :---: |
| Mixture: B |
| Two Passes |

Table A.73: Mixture: B: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 10.580 | 12.090 | 12.360 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 7.400 | 10.400 | 11.270 |
| Average ( $\mu \mathrm{m}$ ) | 8.990 | 11.245 | 11.815 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.587 | -4.842 | -5.412 |
| Effectiveness with respect to Potential Thickness (\%) | 109.857 | 206.500 | 230.929 |
| Effectiveness with respect to Clean Reference (\%) | 39.886 | 74.974 | 83.843 |
| Effectiveness with respect to Dirt Layer (\%) | -140.396 | -175.612 | -184.513 |

Table A.74: Mixture: B: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: B |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 10.590 | 12.060 | 12.370 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 7.460 | 10.500 | 11.300 |
| Average ( $\mu \mathrm{m}$ ) | 9.025 | 11.280 | 11.800 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.622 | -4.877 | -5.397 |
| Effectiveness with respect to Potential Thickness (\%) | 111.357 | 208.000 | 230.286 |
| Effectiveness with respect to Clean Reference (\%) | 40.430 | 75.519 | 83.610 |
| Effectiveness with respect to Dirt Layer (\%) | -140.942 | -176.158 | -184.279 |

Table A.75: Mixture: C: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.740 | 1.700 | 1.870 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.710 | 1.430 | 1.860 |
| Average ( $\mu \mathrm{m}$ ) | 1.225 | 1.565 | 1.865 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.175 | -0.515 | -0.815 |
| Effectiveness with respect to Potential Thickness (\%) | 0.906 | 4.608 | 7.875 |
| Effectiveness with respect to Clean Reference (\%) | 7.284 | 37.060 | 63.334 |
| Effectiveness with respect to Dirt Layer (\%) | -116.667 | -149.048 | -177.619 |

Table A.76: Mixture: C: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.740 | 1.710 | 1.880 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.720 | 1.430 | 1.890 |
| Average ( $\mu \mathrm{m}$ ) | 1.230 | 1.570 | 1.885 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.180 | -0.520 | -0.835 |
| Effectiveness with respect to Potential Thickness (\%) | 0.960 | 4.662 | 8.093 |
| Effectiveness with respect to Clean Reference (\%) | 7.722 | 37.498 | 65.085 |
| Effectiveness with respect to Dirt Layer (\%) | -117.143 | -149.524 | -179.524 |

Table A.77: Mixture: C: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.750 | 1.710 | 1.890 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.730 | 1.470 | 1.910 |
| Average ( $\mu \mathrm{m}$ ) | 1.240 | 1.590 | 1.900 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.190 | -0.540 | -0.850 |
| Effectiveness with respect to Potential Thickness (\%) | 1.069 | 4.880 | 8.256 |
| Effectiveness with respect to Clean Reference (\%) | 8.597 | 39.250 | 66.399 |
| Effectiveness with respect to Dirt Layer (\%) | -118.095 | -151.429 | -180.952 |

Table A.78: Mixture: C: One Pass: $\mathrm{R}_{z}(\mu \mathrm{M})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 10.770 | 10.750 | 10.880 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 5.890 | 10.220 | 11.040 |
| Average ( $\mu \mathrm{m}$ ) | 8.330 | 10.485 | 10.960 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.197 | -9.435 | -9.910 |
| Effectiveness with respect to Potential Thickness (\%) | 6.489 | 31.165 | 32.784 |
| Effectiveness with respect to Clean Reference (\%) | 29.616 | 63.148 | 70.539 |
| Effectiveness with respect to Dirt Layer (\%) | -135.815 | -253.832 | -261.576 |

Table A.79: Mixture: C: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 10.860 | 10.830 | 10.910 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 5.970 | 10.220 | 11.090 |
| Average ( $\mu \mathrm{m}$ ) | 8.415 | 10.525 | 11.000 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.282 | -9.475 | -9.950 |
| Effectiveness with respect to Potential Thickness (\%) | 6.778 | 31.301 | 32.920 |
| Effectiveness with respect to Clean Reference (\%) | 30.939 | 63.771 | 71.162 |
| Effectiveness with respect to Dirt Layer (\%) | -137.201 | -254.484 | -262.228 |

Table A.80: Mixture: C: One Pass: $\mathrm{R}_{z}(\mu \mathrm{M})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 10.850 | 10.830 | 10.900 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 6.000 | 9.620 | 11.130 |
| Average ( $\mu \mathrm{m}$ ) | 8.425 | 10.225 | 11.015 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.292 | -9.175 | -9.965 |
| Effectiveness with respect to Potential Thickness (\%) | 6.813 | 30.278 | 32.972 |
| Effectiveness with respect to Clean Reference (\%) | 31.094 | 59.103 | 71.395 |
| Effectiveness with respect to Dirt Layer (\%) | -137.364 | -249.592 | -262.473 |

Table A.81: Mixture: C: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.510 | 2.030 | 2.080 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.130 | 1.590 | 1.850 |
| Average ( $\mu \mathrm{m}$ ) | 1.320 | 1.810 | 1.965 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.270 | -0.750 | -0.905 |
| Effectiveness with respect to Potential Thickness (\%) | 1.940 | 8.165 | 10.059 |
| Effectiveness with respect to Clean Reference (\%) | 15.604 | 58.517 | 72.092 |
| Effectiveness with respect to Dirt Layer (\%) | -125.714 | -170.755 | -185.377 |

Table A.82: Mixture: C: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{M})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.520 | 2.010 | 2.090 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.160 | 1.640 | 1.890 |
| Average ( $\mu \mathrm{m}$ ) | 1.340 | 1.825 | 1.990 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.290 | -0.765 | -0.930 |
| Effectiveness with respect to Potential Thickness (\%) | 2.158 | 8.348 | 10.365 |
| Effectiveness with respect to Clean Reference (\%) | 17.355 | 59.831 | 74.281 |
| Effectiveness with respect to Dirt Layer (\%) | -127.619 | -172.170 | -187.736 |

Table A.83: Mixture: C: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.520 | 2.020 | 2.100 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.170 | 1.640 | 1.920 |
| Average ( $\mu \mathrm{m}$ ) | 1.345 | 1.830 | 2.010 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.295 | -0.770 | -0.950 |
| Effectiveness with respect to Potential Thickness (\%) | 2.212 | 8.409 | 10.609 |
| Effectiveness with respect to Clean Reference (\%) | 17.793 | 60.269 | 76.033 |
| Effectiveness with respect to Dirt Layer (\%) | -128.095 | -172.642 | -189.623 |

Table A.84: Mixture: C: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.240 | 12.820 | 12.790 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.110 | 11.700 | 10.960 |
| Average ( $\mu \mathrm{m}$ ) | 8.675 | 12.260 | 11.875 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.550 | -6.135 | -5.750 |
| Effectiveness with respect to Potential Thickness (\%) | 7.453 | 19.337 | 18.061 |
| Effectiveness with respect to Clean Reference (\%) | 34.984 | 90.768 | 84.777 |
| Effectiveness with respect to Dirt Layer (\%) | -141.633 | -200.163 | -193.878 |

Table A.85: Mixture: C: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.540 | 11.990 | 12.570 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.240 | 11.630 | 11.010 |
| Average ( $\mu \mathrm{m}$ ) | 8.890 | 11.810 | 11.790 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.765 | -5.685 | -5.665 |
| Effectiveness with respect to Potential Thickness (\%) | 8.166 | 17.845 | 17.779 |
| Effectiveness with respect to Clean Reference (\%) | 38.330 | 83.766 | 83.454 |
| Effectiveness with respect to Dirt Layer (\%) | -145.143 | -192.816 | -192.490 |

Table A.86: Mixture: C: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: C |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.610 | 11.990 | 12.550 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 8.270 | 11.620 | 11.040 |
| Average ( $\mu \mathrm{m}$ ) | 8.940 | 11.805 | 11.795 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.815 | -5.680 | -5.670 |
| Effectiveness with respect to Potential Thickness (\%) | 8.331 | 17.829 | 17.796 |
| Effectiveness with respect to Clean Reference (\%) | 39.108 | 83.688 | 83.532 |
| Effectiveness with respect to Dirt Layer (\%) | -145.959 | -192.735 | -192.571 |

Table A.87: Mixture: D: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.740 | 2.010 | 2.030 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.670 | 1.420 | 1.620 |
| Average ( $\mu \mathrm{m}$ ) | 1.205 | 1.715 | 1.825 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | 0.058 | -0.452 | -0.562 |
| Effectiveness with respect to Potential Thickness (\%) | -0.520 | -4.717 | -5.623 |
| Effectiveness with respect to Clean Reference (\%) | 5.532 | 50.197 | 59.831 |
| Effectiveness with respect to Dirt Layer (\%) | -95.383 | -135.752 | -144.459 |

Table A.88: Mixture: D: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Mixture: D |  |  |  |
| :---: | :---: | :---: | :---: |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |
| Energy $(\mu \mathbf{J})$ | $\mathbf{7 5}$ | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 1.740 | 2.010 | 2.030 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathbf{m})$ | 0.670 | 1.480 | 1.660 |
| Average ( $\mu \mathbf{m})$ | 1.205 | 1.745 | 1.845 |
| $\mathbf{R}_{a}$ e,w,c$(\mu \mathbf{m})$ | 0.058 | -0.482 | -0.582 |
| Effectiveness with respect to Potential Thickness (\%) | -0.520 | -4.964 | -5.787 |
| Effectiveness with respect to Clean Reference (\%) | 5.532 | 52.824 | 61.582 |
| Effectiveness with respect to Dirt Layer (\%) | -95.383 | -138.127 | -146.042 |

Table A.89: Mixture: D: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.740 | 2.020 | 2.040 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.670 | 1.480 | 1.680 |
| Average ( $\mu \mathrm{m}$ ) | 1.205 | 1.750 | 1.860 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | 0.058 | -0.487 | -0.597 |
| Effectiveness with respect to Potential Thickness (\%) | -0.520 | -5.005 | -5.911 |
| Effectiveness with respect to Clean Reference (\%) | 5.532 | 53.262 | 62.896 |
| Effectiveness with respect to Dirt Layer (\%) | -95.383 | -138.522 | -147.230 |

Table A.90: Mixture: D: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.720 | 11.710 | 11.080 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 6.420 | 9.550 | 10.310 |
| Average ( $\mu \mathrm{m}$ ) | 8.070 | 10.630 | 10.695 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.765 | -3.325 | -3.390 |
| Effectiveness with respect to Potential Thickness (\%) | -1.871 | -4.786 | -4.860 |
| Effectiveness with respect to Clean Reference (\%) | 25.571 | 65.405 | 66.416 |
| Effectiveness with respect to Dirt Layer (\%) | -110.472 | -145.517 | -146.407 |

Table A.91: Mixture: D: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| One Pass |  |  |  |
| ( $\mathbf{R}_{\boldsymbol{z}}(\mu \mathbf{m})$ | $\mathbf{1 1 5}$ |  |  |
| Energy $(\mu \mathbf{J})$ | $\mathbf{7 5}$ | $\mathbf{1 5 0}$ |  |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 9.780 | 11.740 | 11.080 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathbf{m})$ | 6.490 | 9.640 | 10.210 |
| Average $(\mu \mathbf{m})$ | 8.135 | 10.690 | 10.645 |
| $\mathbf{R}_{a}$ e,w,c$(\mu \mathbf{m})$ | -0.830 | -3.385 | -3.340 |
| Effectiveness with respect to Potential Thickness (\%) | -1.945 | -4.854 | -4.803 |
| Effectiveness with respect to Clean Reference (\%) | 26.582 | 66.338 | 65.638 |
| Effectiveness with respect to Dirt Layer (\%) | -111.362 | -146.338 | -145.722 |

Table A.92: Mixture: D: One Pass: $\mathrm{R}_{z}(\mu \mathrm{M})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| One Pass |  |  |  |
| Energy $(\mu \mathbf{J})$ | $\mathbf{R}_{\boldsymbol{z}}(\mu \mathbf{m})$ | $\mathbf{7 5}$ |  |
| Earallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 9.750 | 11.750 | 11.150 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 6.530 | 9.680 | 10.250 |
| Average $(\mu \mathbf{m})$ | 8.140 | 10.715 | 10.700 |
| $\mathbf{R}_{a}$ e $, \boldsymbol{w}, \boldsymbol{c}(\mu \mathbf{m})$ | -0.835 | -3.410 | -3.395 |
| Effectiveness with respect to Potential Thickness (\%) | -1.951 | -4.882 | -4.865 |
| Effectiveness with respect to Clean Reference (\%) | 26.660 | 66.727 | 66.494 |
| Effectiveness with respect to Dirt Layer (\%) | -111.431 | -146.680 | -146.475 |

Table A.93: Mixture: D: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.700 | 1.790 | 1.740 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.860 | 1.520 | 1.850 |
| Average ( $\mu \mathrm{m}$ ) | 1.280 | 1.655 | 1.795 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.352 | -0.595 | -0.735 |
| Effectiveness with respect to Potential Thickness (\%) | 0.647 | 1.787 | 2.443 |
| Effectiveness with respect to Clean Reference (\%) | 12.100 | 44.942 | 57.203 |
| Effectiveness with respect to Dirt Layer (\%) | -137.882 | -164.093 | -179.174 |

Table A.94: Mixture: D: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.700 | 1.780 | 1.730 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.880 | 1.570 | 1.900 |
| Average ( $\mu \mathrm{m}$ ) | 1.290 | 1.675 | 1.815 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.362 | -0.615 | -0.755 |
| Effectiveness with respect to Potential Thickness (\%) | 0.694 | 1.881 | 2.536 |
| Effectiveness with respect to Clean Reference (\%) | 12.976 | 46.694 | 58.955 |
| Effectiveness with respect to Dirt Layer (\%) | -138.959 | -166.248 | -181.329 |

Table A.95: Mixture: D: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{M})$ : Trial 3
Trial 3 Mixture: D Two Passes $\mathbf{R}_{a}$ ( $\mu \mathbf{m}$ )

| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |
| :---: | :---: | :---: | :---: |
| Energy $(\mu \mathbf{J})$ | 75 | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 1.700 | 1.770 | 1.740 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 0.880 | 1.570 | 1.920 |
| Average $(\mu \mathbf{m})$ | 1.290 | 1.670 | 1.830 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.362 | -0.610 | -0.770 |
| Effectiveness with respect to Potential Thickness (\%) | 0.694 | 1.857 | 2.607 |
| Effectiveness with respect to Clean Reference (\%) | 12.976 | 46.256 | 60.269 |
| Effectiveness with respect to Dirt Layer (\%) | -138.959 | -165.709 | -182.944 |

Table A.96: Mixture: D: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 11.190 | 11.150 | 12.170 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 7.540 | 11.420 | 10.910 |
| Average ( $\mu \mathrm{m}$ ) | 9.365 | 11.285 | 11.540 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -3.862 | -5.782 | -6.037 |
| Effectiveness with respect to Potential Thickness (\%) | 3.182 | 5.262 | 5.538 |
| Effectiveness with respect to Clean Reference (\%) | 45.721 | 75.596 | 79.564 |
| Effectiveness with respect to Dirt Layer (\%) | -170.170 | -205.058 | -209.691 |

Table A.97: Mixture: D: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 11.240 | 11.040 | 11.810 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 7.870 | 11.200 | 10.940 |
| Average ( $\mu \mathrm{m}$ ) | 9.555 | 11.120 | 11.375 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -4.052 | -5.617 | -5.872 |
| Effectiveness with respect to Potential Thickness (\%) | 3.388 | 5.083 | 5.359 |
| Effectiveness with respect to Clean Reference (\%) | 48.677 | 73.029 | 76.997 |
| Effectiveness with respect to Dirt Layer (\%) | -173.622 | -202.059 | -206.693 |

Table A.98: Mixture: D: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: D |  |  |  |
| Two Passes |  |  |  |
| Energy $(\mu \mathbf{J}) \quad \mathbf{R}_{z}(\mu \mathbf{m})$ | $\mathbf{7 5}$ | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |
| Earallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 11.250 | 10.950 | 11.820 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 7.930 | 10.790 | 10.870 |
| Average $(\mu \mathbf{m})$ | 9.590 | 10.870 | 11.345 |
| $\mathbf{R}_{a}$ e,w,c$(\mu \mathbf{m})$ | -4.087 | -5.367 | -5.842 |
| Effectiveness with respect to Potential Thickness (\%) | 3.426 | 4.812 | 5.327 |
| Effectiveness with respect to Clean Reference (\%) | 49.222 | 69.139 | 76.530 |
| Effectiveness with respect to Dirt Layer (\%) | -174.258 | -197.517 | -206.148 |

Table A.99: Mixture: E: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.540 | 1.680 | 1.740 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.560 | 1.560 | 1.870 |
| Average ( $\mu \mathrm{m}$ ) | 1.050 | 1.620 | 1.805 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.152 | -0.722 | -0.907 |
| Effectiveness with respect to Potential Thickness (\%) | -0.377 | 1.964 | 2.723 |
| Effectiveness with respect to Clean Reference (\%) | -8.043 | 41.877 | 58.079 |
| Effectiveness with respect to Dirt Layer (\%) | -116.883 | -180.334 | -200.928 |

Table A.100: Mixture: E: One Pass: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.530 | 1.690 | 1.880 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.560 | 1.620 | 1.920 |
| Average ( $\mu \mathrm{m}$ ) | 1.045 | 1.655 | 1.900 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.147 | -0.757 | -1.002 |
| Effectiveness with respect to Potential Thickness (\%) | -0.398 | 2.107 | 3.114 |
| Effectiveness with respect to Clean Reference (\%) | -8.481 | 44.942 | 66.399 |
| Effectiveness with respect to Dirt Layer (\%) | -116.327 | -184.230 | -211.503 |

Table A.101: Mixture: E: One Pass: $\mathrm{R}_{a}(\mu \mathrm{M})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| One Pass |  |  |  |
| Energy $(\mu \mathbf{J}) \quad \mathbf{R}_{a}(\mu \mathbf{m})$ | $\mathbf{7 5}$ | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |
| Earallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 1.530 | 1.710 | 1.900 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 0.560 | 1.630 | 1.930 |
| Average $(\mu \mathbf{m})$ | 1.045 | 1.670 | 1.915 |
| $\mathbf{R}_{a}$ e,w,c$(\mu \mathbf{m})$ | -0.147 | -0.772 | -1.017 |
| Effectiveness with respect to Potential Thickness (\%) | -0.398 | 2.169 | 3.175 |
| Effectiveness with respect to Clean Reference (\%) | -8.481 | 46.256 | 67.713 |
| Effectiveness with respect to Dirt Layer (\%) | -116.327 | -185.900 | -213.173 |

Table A.102: Mixture: E: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.550 | 10.720 | 10.850 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 4.530 | 8.930 | 10.680 |
| Average ( $\mu \mathrm{m}$ ) | 7.040 | 9.825 | 10.765 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.302 | -4.087 | -5.027 |
| Effectiveness with respect to Potential Thickness (\%) | 0.891 | 4.937 | 6.303 |
| Effectiveness with respect to Clean Reference (\%) | 9.544 | 52.879 | 67.505 |
| Effectiveness with respect to Dirt Layer (\%) | -122.684 | -171.217 | -187.598 |

Table A.103: Mixture: E: One Pass: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathbf{m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.540 | 10.750 | 11.130 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 4.620 | 8.860 | 10.500 |
| Average ( $\mu \mathrm{m}$ ) | 7.080 | 9.805 | 10.815 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.342 | -4.067 | -5.077 |
| Effectiveness with respect to Potential Thickness (\%) | 0.949 | 4.908 | 6.375 |
| Effectiveness with respect to Clean Reference (\%) | 10.166 | 52.567 | 68.283 |
| Effectiveness with respect to Dirt Layer (\%) | -123.381 | -170.868 | -188.469 |

Table A.104: Mixture: E: One Pass: $\mathrm{R}_{z}(\mu \mathrm{M})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| One Pass |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 9.520 | 11.610 | 11.290 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 4.690 | 8.930 | 10.320 |
| Average ( $\mu \mathrm{m}$ ) | 7.105 | 10.270 | 10.805 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -1.367 | -4.532 | -5.067 |
| Effectiveness with respect to Potential Thickness (\%) | 0.985 | 5.584 | 6.361 |
| Effectiveness with respect to Clean Reference (\%) | 10.555 | 59.803 | 68.128 |
| Effectiveness with respect to Dirt Layer (\%) | -123.816 | -178.972 | -188.295 |

Table A.105: Mixture: E: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.950 | 1.790 | 2.230 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.770 | 1.730 | 1.760 |
| Average ( $\mu \mathrm{m}$ ) | 1.360 | 1.760 | 1.995 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.218 | -0.618 | -0.853 |
| Effectiveness with respect to Potential Thickness (\%) | 1309.000 | 3709.000 | 5119.000 |
| Effectiveness with respect to Clean Reference (\%) | 19.107 | 54.138 | 74.719 |
| Effectiveness with respect to Dirt Layer (\%) | -119.124 | -154.161 | -174.745 |

Table A.106: Mixture: E: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{a}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 1.930 | 1.790 | 2.230 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 0.770 | 1.760 | 1.780 |
| Average ( $\mu \mathrm{m}$ ) | 1.350 | 1.775 | 2.005 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.208 | -0.633 | -0.863 |
| Effectiveness with respect to Potential Thickness (\%) | 1249.000 | 3799.000 | 5179.000 |
| Effectiveness with respect to Clean Reference (\%) | 18.231 | 55.452 | 75.595 |
| Effectiveness with respect to Dirt Layer (\%) | -118.248 | -155.474 | -175.620 |

Table A.107: Mixture: E: Two Passes: $\mathrm{R}_{a}(\mu \mathrm{~m})$ : Trial 3
Trial 3 Mixture: E
Two Passes

| $\mathbf{R}_{a}(\mu \mathbf{m})$ |  |  |  |
| :---: | :---: | :---: | :---: |
| Energy $(\mu \mathbf{J})$ | $\mathbf{7 5}$ | $\mathbf{1 1 5}$ | $\mathbf{1 5 0}$ |
| Parallel to the Path of the laser-beam $(\mu \mathbf{m})$ | 1.940 | 1.790 | 2.250 |
| Perpendicular to the Path of the laser-beam $(\mu \mathbf{m})$ | 0.780 | 1.770 | 1.790 |
| Average $(\mu \mathbf{m})$ | 1.360 | 1.780 | 2.020 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -0.218 | -0.638 | -0.878 |
| Effectiveness with respect to Potential Thickness (\%) | 1309.000 | 3829.000 | 5269.000 |
| Effectiveness with respect to Clean Reference (\%) | 19.107 | 55.890 | 76.908 |
| Effectiveness with respect to Dirt Layer (\%) | -119.124 | -155.912 | -176.934 |

Table A.108: Mixture: E: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 1

| Trial 1 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 12.420 | 11.520 | 14.050 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 7.280 | 11.620 | 12.280 |
| Average ( $\mu \mathrm{m}$ ) | 9.850 | 11.570 | 13.165 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.957 | -4.677 | -6.272 |
| Effectiveness with respect to Potential Thickness (\%) | -7.336 | -11.021 | -14.439 |
| Effectiveness with respect to Clean Reference (\%) | 53.268 | 80.031 | 104.850 |
| Effectiveness with respect to Dirt Layer (\%) | -142.892 | -167.843 | -190.982 |

Table A.109: Mixture: E: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{M})$ : Trial 2

| Trial 2 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathbf{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 12.010 | 11.420 | 14.900 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 6.770 | 11.510 | 11.170 |
| Average ( $\mu \mathrm{m}$ ) | 9.390 | 11.465 | 13.035 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.497 | -4.572 | -6.142 |
| Effectiveness with respect to Potential Thickness (\%) | -6.350 | -10.796 | -14.161 |
| Effectiveness with respect to Clean Reference (\%) | 46.110 | 78.397 | 102.827 |
| Effectiveness with respect to Dirt Layer (\%) | -136.219 | -166.320 | -189.096 |

Table A.110: Mixture: E: Two Passes: $\mathrm{R}_{z}(\mu \mathrm{~m})$ : Trial 3

| Trial 3 |  |  |  |
| :---: | :---: | :---: | :---: |
| Mixture: E |  |  |  |
| Two Passes |  |  |  |
| $\mathbf{R}_{z}(\mu \mathrm{~m})$ |  |  |  |
| Energy ( $\mu \mathrm{J}$ ) | 75 | 115 | 150 |
| Parallel to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 12.220 | 11.350 | 13.770 |
| Perpendicular to the Path of the laser-beam ( $\mu \mathrm{m}$ ) | 6.750 | 11.500 | 11.150 |
| Average ( $\mu \mathrm{m}$ ) | 9.485 | 11.425 | 12.460 |
| $\mathbf{R}_{a e, w, c}(\mu \mathbf{m})$ | -2.592 | -4.532 | -5.567 |
| Effectiveness with respect to Potential Thickness (\%) | -6.554 | -10.711 | -12.929 |
| Effectiveness with respect to Clean Reference (\%) | 47.588 | 77.775 | 93.880 |
| Effectiveness with respect to Dirt Layer (\%) | -137.597 | -165.740 | -180.754 |

## A. 5 Appendix:Testing

## A.5.1 Testing:Ultrasonic Proximity Sensor

Table A.111: Trial 1:Ultrasonic Proximity Sensor

| Trial 1 |  |  |
| :---: | :---: | :---: |
| Actual Distance (in) | Measured Distance (in) | Percent Error (\%) |
| 1 | 1.1811 | 18.110 |
| 2 | 1.9685 | 1.575 |
| 3 | 3.1496 | 4.987 |
| 4 | 3.937 | 1.575 |
| 5 | 5.1181 | 2.362 |
| 6 | 6.2992 | 4.987 |
| 7 | 7.0866 | 1.237 |
| 8 | 8.2677 | 3.346 |
| 9 | 9.0551 | 0.612 |
| 10 | 10.2362 | 2.362 |
| 11 | 11.0236 | 0.215 |
| 12 | 11.811 | 1.575 |

Table A.112: Trial 2:Ultrasonic Proximity Sensor

| Trial 2 |  |  |
| :---: | :---: | :---: |
| Actual Distance (in) | Measured Distance (in) | Percent Error (\%) |
| 1 | 1.1811 | 18.110 |
| 2 | 1.9685 | 1.575 |
| 3 | 3.1496 | 4.987 |
| 4 | 3.937 | 1.575 |
| 5 | 5.1181 | 2.362 |
| 6 | 6.2992 | 4.987 |
| 7 | 7.0866 | 1.237 |
| 8 | 8.2677 | 3.346 |
| 9 | 9.0551 | 0.612 |
| 10 | 10.2362 | 2.362 |
| 11 | 11.0236 | 0.215 |
| 12 | 11.811 | 1.575 |

Table A.113: Trial 3:Ultrasonic Proximity Sensor

| Trial 3 |  |  |
| :---: | :---: | :---: |
| Actual Distance (in) | Measured Distance (in) | Percent Error (\%) |
| 1 | 1.1811 | 18.110 |
| 2 | 1.9685 | 1.575 |
| 3 | 3.1496 | 4.987 |
| 4 | 3.937 | 1.575 |
| 5 | 5.1181 | 2.362 |
| 6 | 6.2992 | 4.987 |
| 7 | 7.0866 | 1.237 |
| 8 | 8.2677 | 3.346 |
| 9 | 9.0551 | 0.612 |
| 10 | 10.2362 | 2.362 |
| 11 | 11.0236 | 0.215 |
| 12 | 11.811 | 1.575 |

## A.5.1.1 Test Form 1.2

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 1.2) Ultrasonic Proximity Sensor |
| Test Date: | $3 / 27 / 18$ |
| Test Iteration: | 1 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: |  |
| Test Parameter | See Tables in Appendix |
| Fixed Distance (in) | 3 |
| Number of Trials | See Tables in Appendix |
| Average Reading | See Tables in Appendix |
| Accuracy | 4.8221(with outlier) 1.5945 (without outlier) |
| Standard Deviation | One outlier in the test at 1in. All other measurements were <br> within 5\% error. The device is very precise, the readings on <br> all 3 trials were the same. The accuracy varies. <br> Observation Notes: <br> Resolutions if Needed: |


| Primary Test Executor Signature: | Mkrtich Arslanyan |
| :--- | :--- |
| Second in Command Signature: |  |
| Test End Time (hh:mm) |  |
| Further Attachments? (file location) | Ultrasonic Sensor excel sheet |

## A.5.2 Laser Proximity Sensor

Table A.114: Trial 1:Laser Proximity Sensor

| Trial 1 |  |  |
| :---: | :---: | :---: |
| Actual Distance (in) | Measured Distance (in) | Percent Error (\%) |
| 1 | 1.1417 | 14.170 |
| 2 | 1.9685 | 1.575 |
| 3 | 2.9528 | 1.573 |
| 4 | 4.0157 | 0.392 |
| 5 | 5.0787 | 1.574 |
| 6 | 6.1024 | 1.707 |
| 7 | 7.0866 | 1.237 |
| 8 | 8.3071 | 3.839 |
| 9 | 9.3307 | 3.674 |
| 10 | 10.5906 | 5.906 |
| 11 | 11.5748 | 5.225 |
| 12 | 12.7953 | 6.627 |

Table A.115: Trial 2:Laser Proximity Sensor

| Trial 2 |  |  |
| :---: | :---: | :---: |
| Actual Distance (in) | Measured Distance (in) | Percent Error (\%) |
| 1 | 1.1417 | 14.170 |
| 2 | 2.0472 | 2.360 |
| 3 | 3.1102 | 3.673 |
| 4 | 3.937 | 1.575 |
| 5 | 5.0394 | 0.788 |
| 6 | 5.9449 | 0.918 |
| 7 | 7.2441 | 3.487 |
| 8 | 8.3858 | 4.823 |
| 9 | 9.4094 | 4.549 |
| 10 | 10.6693 | 6.693 |
| 11 | 11.6142 | 5.584 |
| 12 | 12.874 | 7.283 |

Table A.116: Trial 3:Laser Proximity Sensor

| Trial 3 |  |  |
| :---: | :---: | :---: |
| Actual Distance (in) | Measured Distance (in) | Percent Error (\%) |
| 1 | 1.1811 | 18.110 |
| 2 | 2.0866 | 4.330 |
| 3 | 3.0709 | 2.363 |
| 4 | 4.0551 | 1.378 |
| 5 | 5.0787 | 1.574 |
| 6 | 6.0236 | 0.393 |
| 7 | 7.1654 | 2.363 |
| 8 | 8.2283 | 2.854 |
| 9 | 9.3701 | 4.112 |
| 10 | 10.5512 | 5.512 |
| 11 | 11.5748 | 5.225 |
| 12 | 12.6378 | 5.315 |

## A.5.2.1 Test Form 1.1

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 1.1) Laser Proximity Sensor |
| Test Date: | $3 / 27 / 18$ |
| Test Iteration: | 1 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: |  |
| Test Parameter | See Tables in Appendix |
| Fixed Distance (in) | 3 |
| Number of Trials | See Tables in Appendix |
| Average Reading | Y |
| Bolt Hole Recognized (Y/N) | N/A |
| Spoke Hole Recognized (Y/N) | See Tables in Appendix |
| Accuracy | 4.03 with outlier. 2.04 without outlier |
| Standard Deviation | Device is not accurate under one inch. Starts to lose <br> accuracy as distance increases. Best range to use in is 2-7 <br> inches away from target. |
| Observation Notes: |  |
| Resolutions if Needed: |  |
| Primary Test Executor Signature: | Mkrtich Arslanyan |
| Second in Command Signature: |  |
| Test End Time (hh:mm) | $10: 08 p m$ |

## A.5.3 Cycle Time

## A.5.3.1 Test Form 2.3

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 2.3) Cycle Time |
| Test Date: | 4 -27-2018 |
| Test Iteration: | 21 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Name of Test Supporter 2: |  |
| Test Parameter | $05: 06$ |
| Total Cycle Time (mm:ss) | $01: 48$ |
| Run Time (mm:ss) |  |
| Down Time (mm:ss) |  |
| Observation Notes: |  |
| Resolutions if Needed: |  |

## A.5.4 Over-Heating Protection

## A.5.4.1 Test Form 4.3

| MCE 402 Team \#14 <br> Team B.E.E.M. | Record of Individual Test |
| :--- | :--- |
| Test Description (refer to Test Matrix): | 4.3 ) Over-Heating Protection |
| Test Date: | $04-27-2018$ |
| Test Iteration: | 1 |
| Name of Primary Test Executor: | Mkrtich Arslanyan |
| Name of Second in Command: |  |
| Name of Test Supporter 1: |  |
| Test Parameter |  |
| Name of Test Supporter 2: | $97 \%$ |
| Temperature Accuracy | N/A |
| Activates System Shutdown Procedure <br> (Y/N) |  |


| Observation Notes: | Temperature never reached the limit of 35 degrees Celsius. <br> Shutdown procedure could not be tested. |
| :--- | :--- |
| Resolutions if Needed: |  |
| Primary Test Executor Signature: | Mkrtich Arslanyan |
| Second in Command Signature: |  |
| Test End Time (hh:mm) | $06: 45$ PM |
| Further Attachments? (file location) |  |

