CRANFIELD UNIVERSITY

Qingming Song

The simulation of Automated Leading Edge Assembly

SCHOOL OF AEROSPACE, TRANSPORT AND

MANUFACTURING

MSc by Research Thesis

Academic Year: 2014-2015

Supervisor: Prof. Phil Webb

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ABSTRACT

Aircraft manufacturers are experiencing a fierce competition worldwide. Improving productivity, increasing throughput and reducing costs are influencing aircraft manufacturer's future development. In order to improve competitiveness and provide sufficient and high quality products, it should reduce operations of aircraft assembly，majority of which are still in manual process, which limit production output. In contrast, these processes can be automated to replace manual operations. Much more attention should be placed on automated application.

This project aims to propose a methodology to develop the automated assembly based on robotics and use this methodology to develop a new concept of Automated Leading Edge Assembly. The research selects an automated assembly process for further evaluation and brackets assembled on the front spar of Leading Edge are chosen to be automated assembly with robot assistant. The software DELMIA is used to develop and simulate the automated assembly process of brackets based on 3-D virtual aircraft Leading Edge models. The research development is mainly divided into three phases which are: (1) The state of art on Manual Leading Edge Assembly; (2) Automated Leading Edge Assembly framework development; (3) Automated Leading Edge Assembly framework evaluation including automated assembly process simulation based on DELMIA robotics workbench and automated assembly cost estimation.

The research has proposed a methodology to develop the automated assembly based on robotics, proposed a new concept of Automated Leading Edge Assembly: using robots to replace workers to finish the assembly applications in the Leading Edge, and proposed a new automated bracket assembly process with laser ablation, adhesive bonding, drilling, riveting, and robot application. These applications can attract more and more engineers' attention and provide preliminary knowledge for further study and detail research in the future.

Key words:

Automation application, Automated Leading Edge Assembly, robotics, automated assembly process, laser ablation, adhesive bonding, simulation, cost estimation.

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LIST OF ABBREVIATIONS

ALEA	Automated Leading Edge Assembly
AO	Assembly Outline
APD	Assembly Precedent Diagram
ASP	Assembly Sequence Planning
AWBA	Automated Wing Box Assembly
CAE	Computer Aided Engineering
DELMIA	Digital Enterprise Lean Manufacturing Interactive Application
DOF	Degrees Of Freedom
DPE	DELMIA Process Engineer
DPM	Digital Process Manufacturing
ECS	Environment Control System
EWIS	Electrical Wire Interconnection System
FAL	Final Assembly Line
FCS	Flight Control System
HSS	High Speed Steel
HVLP	High Volume Low Pressure
OLP	Off-line Programming
PB	Payback Period
PPR	Product, Process, and Resource
SB	System Bracket
SCFM	Standard Cubic Feet per Minute
TCP	Tool Center Point
TO	Tooling Outline

1. Introduction

1.1 Background

Aircraft manufacturers are experiencing a fierce competition worldwide. Improving productivity, increasing throughput and reducing costs are influencing aircraft manufacturer’s future development. In order to improve competitiveness and provide sufficient and high quality products, it should reduce operations of aircraft assembly，majority of which are still in manual process, which limit production output. In contrast, these processes can be automated to replace manual operations.

Aircraft wing Leading Edge assembly is a labor intensive and time consuming process. It may be replaced by automation applications in the future. Automated assembly based on robot is a suitable choice. Leading Edge is a metal 'D' nosed structure attached to the front spar of the main wing box housing the slat actuators, torque tubes, bleeding air deicing tubes, and electrical wiring system.

Until now there is limited study of Automated Leading Edge Assembly (ALEA) in the literature. This project chose typical brackets used to attach aircraft systems such as bleed air deicing pipe, torque tube and electrical wiring bundles to investigate the simulation of automated bracket assembly on the Leading Edge.

1.2 Project Aim and Objectives

1.2.1 Project aim

This research aims to propose a methodology to develop the automated assembly based on robotics and apply this to develop a new concept of Automated Leading Edge Assembly: using robots to replace workers to finish the assembly applications in the Leading Edge. The methodology is used to select an automated assembly process for further evaluation. Brackets assembled on the front spar of Leading Edge are chosen to be automated assembly with robot assistant. The software of DELMIA is used to develop and simulate the automated assembly process of brackets based on 3-D virtual aircraft Leading Edge models.

1.2.2 Research objectives

The objectives are divided into six steps which focus on how to develop the automated process and apply it to bracket assembly and how to evaluate the process

1) To investigate manual Leading Edge assembly process, research automated assembly process and choose component to be automatically assembled.

2) To develop Product (Leading Edge components and involved brackets models).

3) To develop Process (automated brackets assembly process).

4) To develop Resource (end-effectors, robot, fixture and involved resources).

5) To simulate the automated brackets assembly process and optimize.

6) Automated brackets assembly cost estimation.

1.3 Research motivation

In recent years, robots are widely used in aero structure drilling and aircraft inspection. In order to improve the productivity and meet soaring market requirement and competition, to fill the gaps of automated system assembly of aircraft.

Aircraft wing Leading Edge assembly is a compact process which means many component parts are crowded together, also a labor intensive and time consuming process. It is a better choice to choose aircraft wing Leading Edge to do research on its automation. Robotic Automated Leading Edge Assembly is a major challenge but it must be overcome. Robot automation advantages are listed below [1]:

- Ability to reprogram equipment to accommodate design changes and product varieties, thus affording even for small-to-medium production lot sizes;
- Programming of new assembly tasks can be done off-line without disrupting production;
- Reduce operating costs: reduce overheads and direct costs, improved competitiveness;
- Improve product quality and consistency: avoid tiredness and distraction, high quality finish for every product produced;
- Improve quality of work for employees: robots are ideal for jobs in dusty, hot, hazardous environments, employees can learn valuable robot programming skills;
- Increase production output rates: use robot to achieve continuous production;
- Increase product manufacturing flexibility: one robot can handle a variety of jobs or tasks;
- Reduce material waste and increase yield: reduce breakages, scrap and wastage;
- Comply with safety rules and improve workplace health and safety: robots can take over unpleasant or health threatening tasks;
- Reduce labor turnover and difficulty of recruiting workers: offer greater flexibility with robots;
- Reduce capital costs: save energy, reduce waste and the cost of consumables used, ensure a fast, efficient order turnaround;
- Save space in high value manufacturing areas: variety of mounting

options helps save space, robots are ideal for confined space;

All the benefits listed above are driving force to realize robotic Automated Leading Edge Assembly.

1.4 Theoretical fundamental

This dissertation draws insights from eight major technical areas (Fig1-1): Leading Edge, manual assembly, automated assembly, process planning, CATIA and DELMIA are demonstrated in chapter literature review; end-effector, adhesive bonding, robotics and metrology are illustrated in Appendices.

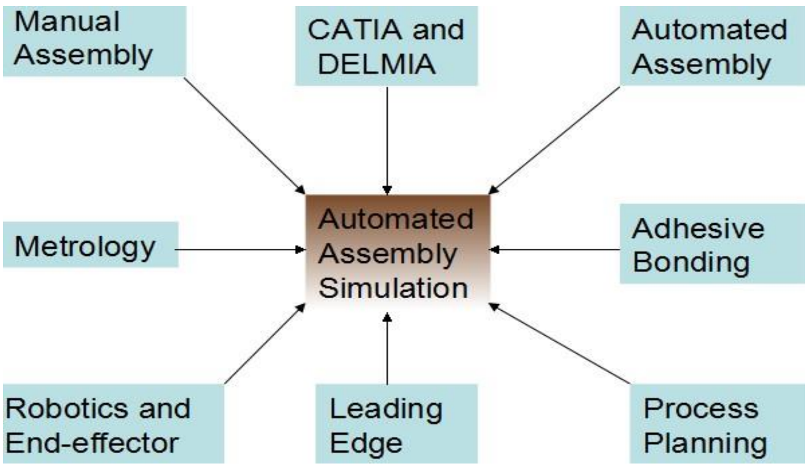


Fig 1- 1. The technology areas covered in this dissertation

1.5 Thesis structure

The thesis is presented in 7 chapters, summarized as follows.

Chapter 1 – Introduction:

This chapter initially describes the background to the project; afterwards, the project aim and objectives are elaborated; moving on to project motivation and a brief introduction to the theoretical fundamental covered in this project; the structure of the thesis is then presented. The information presented in this chapter provides an overview of the whole project;

Chapter 2 – Literature Review

A comprehensive literature review on how to arrange automated Leading Edge assembly is carried out in this chapter. This helps to lay out solid theoretical foundations and techniques applied in assembly operations in the whole project.

Chapter 3 – Research Methodology

This chapter firstly describes the research approach, and methods applied to develop engineering research project about how to develop manual assembly to robotic automated assembly especially in aerospace. The next part is about the approach used for development of automated Leading Edge assembly.

Chapter 4 –The state of art on Manual Leading Edge Assembly

This chapter introduces the Leading Edge components including bleeding air deicing tubes, electrical wiring system and slat actuators & torque tubes. Brackets installed in the Leading Edge are also illustrated. Then Leading Edge assembly process is proposed, the research gap is finally confirmed.

Chapter 5 – ALEA Framework Development

This chapter demonstrates how to select critical area to be used for simulation at the beginning; three key tasks which are assembly product development, process development and resource development are illustrated in the following parts.

Chapter 6 – ALEA Framework Validation

This chapter mainly describes how to evaluate the framework of ALEA. It should have been evaluated from three approaches, robotic automated bracket assembly process simulation, cost estimation and test in reality. However, just assembly process simulation and cost estimation are introduced in this chapter for reasons.

Chapter 7 –Discussions and Conclusions

This chapter mainly focuses on discussion of the methodology, research work, achievements, and conclusions. The contribution to knowledge, research limitations and the recommendations for future work are also presented.

2. Literature Review

2.1 Introduction

Assembly is the final process for product realization, which means component parts and subassemblies are integrated together to obtain the desired product.

Recent years, the competition among aircraft manufacturers is fierce. Productivity, capital investment, cost are the key factors while meeting high quality requirements, labor intensive and time consuming operations of aircraft wing Leading Edge assembly may be replaced by automation in the future. Automated assembly based on robot is a suitable choice.

2.2 Leading Edge

There are mainly three kinds of wing aircraft; fixed, flapping and rotary wing aircraft, as shown in Fig 2-1.This chapter mainly illustrates the fixed wing aircraft, focusing on the fixed Leading Edge of the wing.

Fig 2- 1. Fixed, flapping and rotary wing aircraft (From Google)

The wing Leading Edge is the headmost edge of wing and is the first part to contact the air [2-3]. It consists of complicated structures (Fig 2-2) that are wing front spar, nose ribs and some supports and involved systems (Fig 2-3). Leading Edge is a metal 'D' nosed structure attached to the front spar of the main wing box housing the slat actuators, torque tubes, bleeding air deicing tubes, and electrical wiring system.

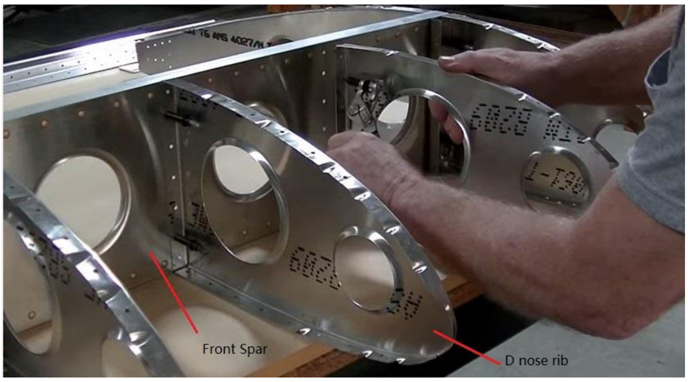


Fig 2- 2. Leading Edge simplified structure (From Google)

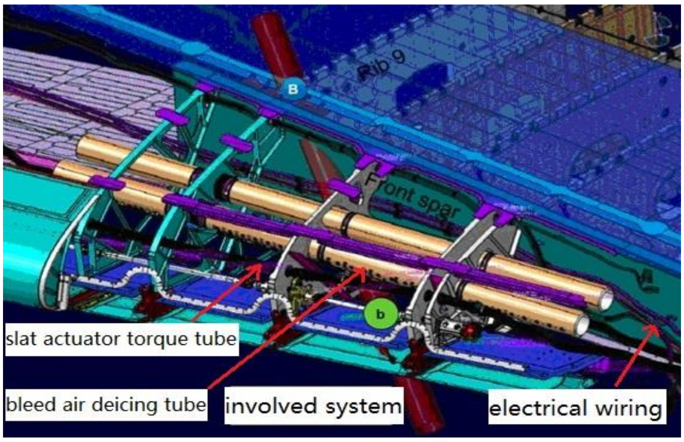


Fig 2- 3. Involved systems of Leading Edge (Courtesy Airbus A380)

2.3 Aircraft assembly

2.3.1 Manual assembly

2.3.1.1 Introduction

Aircraft assembly consumes up to around 40-50% of total manufacturing cost [4]. However, most of tasks are finished manually with tooling. Approximately 80% of aircraft wing’s holes are drilled manually [5]. There are many kinds of sheet metal parts in aircraft manufacturing, these parts are assembled using essentially the same technique/method as were used for decades.

2.3.1.2 Assembly tooling

Aircraft assembly tooling can be divided into two different groups which are fixtures and jigs. Fixture is used to position and hold parts during assembly, jig is used not only to position and hold parts, but also to guide other tools as cutting, drilling. When aircraft parts have been attached to the fixture clamps, the assembly process is engaged.

2.3.1.3 Current manual assembly

The Leading Edge of wing is currently assembled manually with jig and fixture. Jig is utilized to control assembly accuracy. Firstly, the parts are clamped in the fixture. Then, rivet holes are located and drilled using drilling jigs or tools. De-burring is done finally.

Today, human factors still play a dominated role in manual assembly. To some degrees, an individual's professional skill levels, working style, attitude and experience determine the quality of products and productivity. Training an experienced worker takes much time and budget. Meanwhile the assembly process planning engineers need to finish majority of tasks, such as compile Assembly Outline (AO), Tooling Outline (TO) and Process Specification, to guide the worker. Most of operations need fixtures to guarantee the accuracy.

2.3.1.4 Future manual assembly

The majority of fixtures create tremendous storage problem, which need a large capital investment to store fixture and the process is also very labor intensive and time consuming and lower productivity. Meanwhile, manual operations may cause certain health or safety risk and increase likelihood of components damage or rework [6, 7]. So in the future human factors will be liberated and robot will play a dominated role in (semi)automated assembly.

2.3.2 Automated assembly

2.3.2.1 Introduction

The current automated solution applied in the assembly of aerospace structure, mainly large sections, take fuselage and wing box for example, are based on large specialized machines as auto-riveters and auto-spray gun, with large number of individual components being manually assembled. Automation application in aircraft Final Assembly Line especially.

2.3.2.2 Automated Final Assembly Line

2.3.2.2.1 The Final Assembly Line of Boeing

The Final Assembly Line (FAL) of Boeing was firstly utilized in Boeing717 and famous for its moving line, which is composed of a center moving line and several feed lines. It is utilized in Boeing 737 afterwards. The Final Assembly Line of Boeing 737, as shown in Fig 2-4, helps Boeing increase their production rate significantly up to 30 ship sets per month [8, 9].

Fig 2- 4. Boeing 737 Final Assembly Line (Courtesy Boeing)

2.3.2.2.2 The Final Assembly Line of Airbus

Airbus Final Assembly Line with flow line principle was utilized in A320. The FAL ensures that most of tasks can be executed without influencing each other. For achieving this aim, sophisticated and dedicated tools are applied by integrating with mobile working platforms.

With advanced FAL, as shown in Fig 2-5, Airbus intends to produce 42 ships A320 per month in 2015, and expects to increase to 50 ships per month in 2017, and possibly 60 [10].

Fig 2- 5. Airbus A320 Final Assembly Line (Courtesy Airbus)

2.3.2.2.3 The Final Assembly Line of COMAC

For the C919, she is a new comer. However, a Final Assembly Line, as shown in Fig 2-6, with five platforms consisting of fuselage connecting and wing body joining tooling and equipment is employed. It is a path from nose filling, wing assembly, rear fuselage assembly, full fuselage assembly to the final wing-to-body and tail join assembly [11].

Fig 2- 6. COMAC C919 Final Assembly Line (Courtesy COMAC)

2.3.2.3 Advantages of Automation

The advantages of automation were derived from [12], as shown below.

1) Execute hard physical, strenuous or monotonous work.

2) Finish tasks in unsafe conditions as heat, fire.

3) Undertake jobs like carrying heavy and bigger objects which are difficult to perform by human beings

4) Increase consistency and reduce component damage or rework.

2.3.2.4 Robot automation

Recent years, robots play an important role in the aerospace automation industry, for robots can finish the same operation with the same quality. Robots were utilized to aero structure drilling and aircraft inspection. Several UK companies perform a project of the Automated Wing Box Assembly (AWBA), which produces noticeable advancements in the robotic assembly [13]. However, the robot application has so far been confined to small and low volume [16]. For meeting the productivity and broadening the market, the smaller, lower volume and more precise assembly technology will still be major challenge in automated assembly in the future [14].

2.3.3 Assembly development

Modern aircraft assembly consist of large number of complex shape components which have different property, there are so many assembly features to ensure. Assembly procedure, typical assembly operations and assembly sequence planning methods are simply addressed below.

2.3.3.1 Assembly procedure

For developing a feasible assembly, there is a main procedure need to be followed considering several main key factors [15].

Procedure:

1) To develop a suitable representation of assembly
2) To develop a representation of the resource
3) To generate the sequence of assembly operations
4) To reason about accessibility, feasibility, using the model and resource

Key factor:

1) Mating face between mating parts
2) Part connectivity relationships
3) Mating direction for part assembly
4) Part collision information
5) Constraints
6) Equipment and tooling choice

2.3.3.2 Assembly operation

Typical operations for the assembly process of aircraft structures are shown below [16].

1) Pre-assembly
2) Drilling
3) Temporary fastening
4) De-burring
5) Sealant application
6) Fastening

2.3.3.3 Assembly sequence planning methods

Assembly Sequence Planning (ASP) is an essential course for aircraft assembly process design. The current aircraft assembly contains a large number of feasible assembly sequences [17]. So an optimal assembly sequence needs to be sought in aircraft assembly.

In general, assembly sequence planning can be defined considering several major aspects based on AND/OR graphs, on directed graphs, on precedence relationships, and on establishment conditions.

1) The method to generate sequences based on precedence relationships in two steps: creating the precedence relations and verifying liaison sequence [18].

2) The method to assembly by disassembling, for instance, reversing the disassembling sequence is an assembly sequence [19].

3) The method to use directed graph-based procedures with traditional representations to reduce sorting operations [20].

- As an example, Fig 2-8 demonstrates the directed graph of feasible assembly sequences for the assembly shown in Fig 2-7.Each node of the graph in Fig 2-8 is labeled by a partition of the set of parts that represents a stable assembly state. In this route, the edges are equal to the proper sequence of tasks, while the nodes are equal to the proper sequence of states of the assembly process. For example, one feasible assembly sequence is 1, 2, 7, and 13 [21].

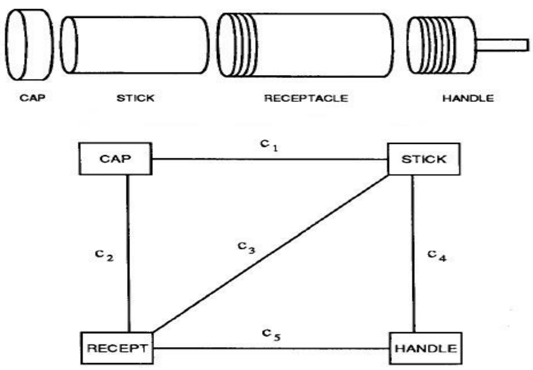


Fig 2- 7. The graph of four-part assembly exploded and connections view

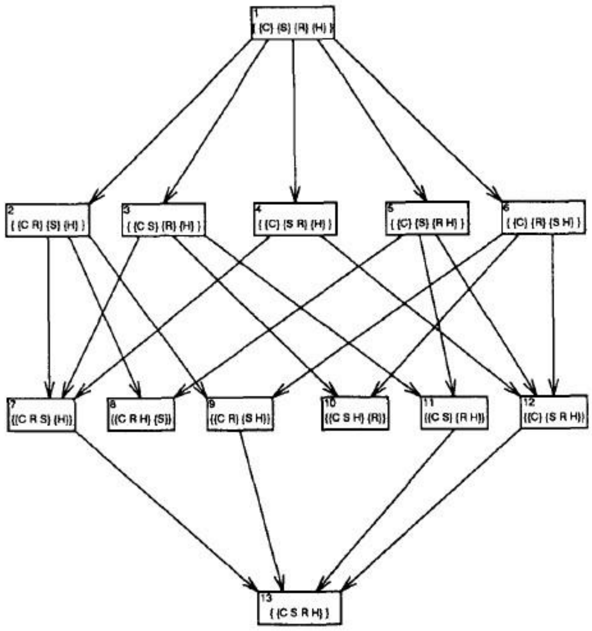


Fig 2- 8. Directed graph of feasible assembly sequences

4) The method based on the directed, AND/OR graphs to develop feasible assembly sequences [22].

- For example, Fig 2-9 shows part of the AND/OR graph for the assembly shown in Fig 2-7.Each node of the graph in Fig 2-9 is equal to a subset of parts that related to a subassembly. The subassembly of the cap, the receptacle, and the handle, and the subassembly of the cap, the stick, and the handle are not included in this graph. Because these subassemblies do not occur in any feasible assembly sequence.

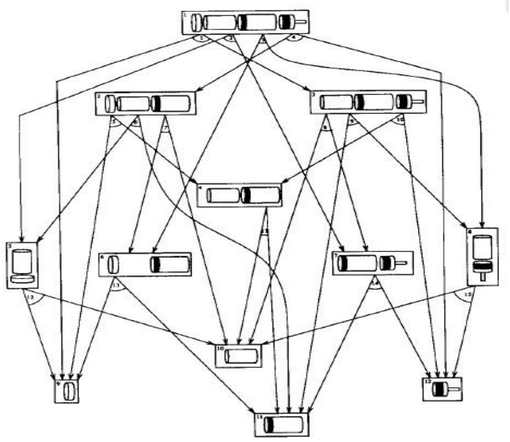


Fig 2- 9. AND/OR graph of feasible assembly sequences

However, in reality, few people know exactly how to develop a proper relational model graph or incident matrix of the product, draw a correct explosion graph or develop a proper assembly precedent diagram (APD) to achieve an optimal assembly plan [23]. If an assembly plan include all of them, it will be much more effective. Take a three-stage integrated approach [24] for example, in the first stage, develop a proper explosion graph. In the second stage, develop a correct relational model graph and an incidence matrix. In the third stage, generate the back-propagation neural network.

2.4 End-effector

2.4.1 Introduction

In robotics, end effector is a device or tool at the end of a robotic arm and designed to execute activities. Take gripper for instance, it is an end effector or tool which may be similar with a human hand to grasp physical thing [4-6]. According to different tasks, end effectors are various, such as for drilling, picking and placing, riveting. All of which need to have some characteristics to be an effective end effector [25-29]:

- Stiff / Rigid
- Light
- Cheap
- Durable
- Flexible
- Easily produce and mount

2.4.2 Gripper types

There are three common types of grippers as magnetic grippers, vacuum and jaw-type. It can also be sorted into another three main groups: single surface grippers, clamping grippers and flexible grippers [30].

2.4.2.1 Single surface grippers

Single-surface grippers are used for gripping components of which only one surface is available. The single surface gripper can be sorted to magnetic grippers, vacuum grippers and adhesive grippers who grasp the items by pulling force rather than pushing force.

2.4.2.1.1 Magnetic grippers

The magnetic grippers are only suitable for ferrous objects. There are two common magnetic grippers, permanent magnets and electromagnets. The permanent magnet is an object that is made from a magnetized material. The electromagnetic grippers can pick and drop objects at any time.

2.4.2.1.2 Vacuum grippers

Vacuum-grippers mainly consist of two parts that are suction cup and under-pressure device. The under-pressure can be generated with the device consisting of vacuum pump, ejector, suction bellow and pneumatic cylinder. The vacuum grippers pick up device is suction cup which is usually made from rubber and can be sorted into four different types [31]: universal suction cups, flat suction cups with bars, suction cups with bellow and depth suction cups as shown in Fig 2-10.

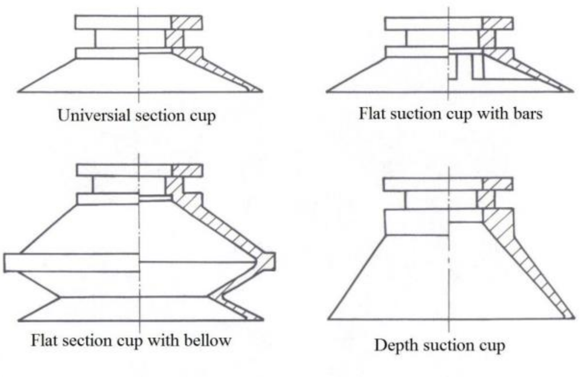


Fig 2- 10. Suction cups

The universal suction cups are suitable for flat and slightly arched surfaces. The flat suction cups with bars are suitable for flat or flexible items that need assistance when they are lifted. Suction cups with bellows are usually used for curved surfaces. The depth suction cup can be used for surfaces that are very irregular and curved or when an item needs to be lifted over an edge. However, an item with holes, slots and gaps on the surfaces is not recommended to be handled with vacuum grippers.

2.4.2.1.3 The adhesive gripper

The adhesive type of gripper are usually used to pick up fabric or similar material [32].

2.4.2.2 Clamping grippers

Clamping grippers are usually two-jaw or three-jaw grippers which are applied frequently in manufacturing factories. The two-jaw grippers can be suitable to small and large objects. The mechanics motion of the jaw-fingers is composed of linkage, actuators pinion, cams, pneumatic and hydraulic cylinders.

2.4.2.3 Flexible grippers

Every finger of flexible grippers equips with several linkages, each of which has an individual steering. Flexible grippers seem to be human hand. This gripper can grasp different shape of objects because the linkages can be controlled individually [32].

2.4.3 Robotic tool changer

Robotic tool changers are used to change end effectors or tools for robots. Tool changer is equipment that is composed of two sides which are used to standardize the interface between the robot and different robot tools [33].

3. Research Methodology

3.1 Introduction

This chapter focuses on the engineering research methodology, which will be followed step by step to complete the whole project. It firstly describes the research approach, and methods applied to develop engineering research project about how to develop manual assembly to robotic automated assembly especially in aerospace.

Then the next part is about the approach used for development of automated Leading Edge assembly. The research approach for this project can be defined as a detailing of engineering research methodology and the author used several research tools to assist during the research period.

3.2 Project methodology

3.2.1 Methodology for engineering project development

The engineering design process is a series of steps that engineers follow to come up with a solution to a problem. Usually, the solution involves designing a product (like a machine or components) and planning manufacturing or/and assembly process that meet certain criteria and/or accomplish a certain task. With results analysis, judge whether the solution or method works and figure out the useful information which can be used later by others. Fig 3-1 shows Methodology for engineering project development. The flow chart given here is summarized based on this project development and the book of “A framework for integrated assembly systems”.

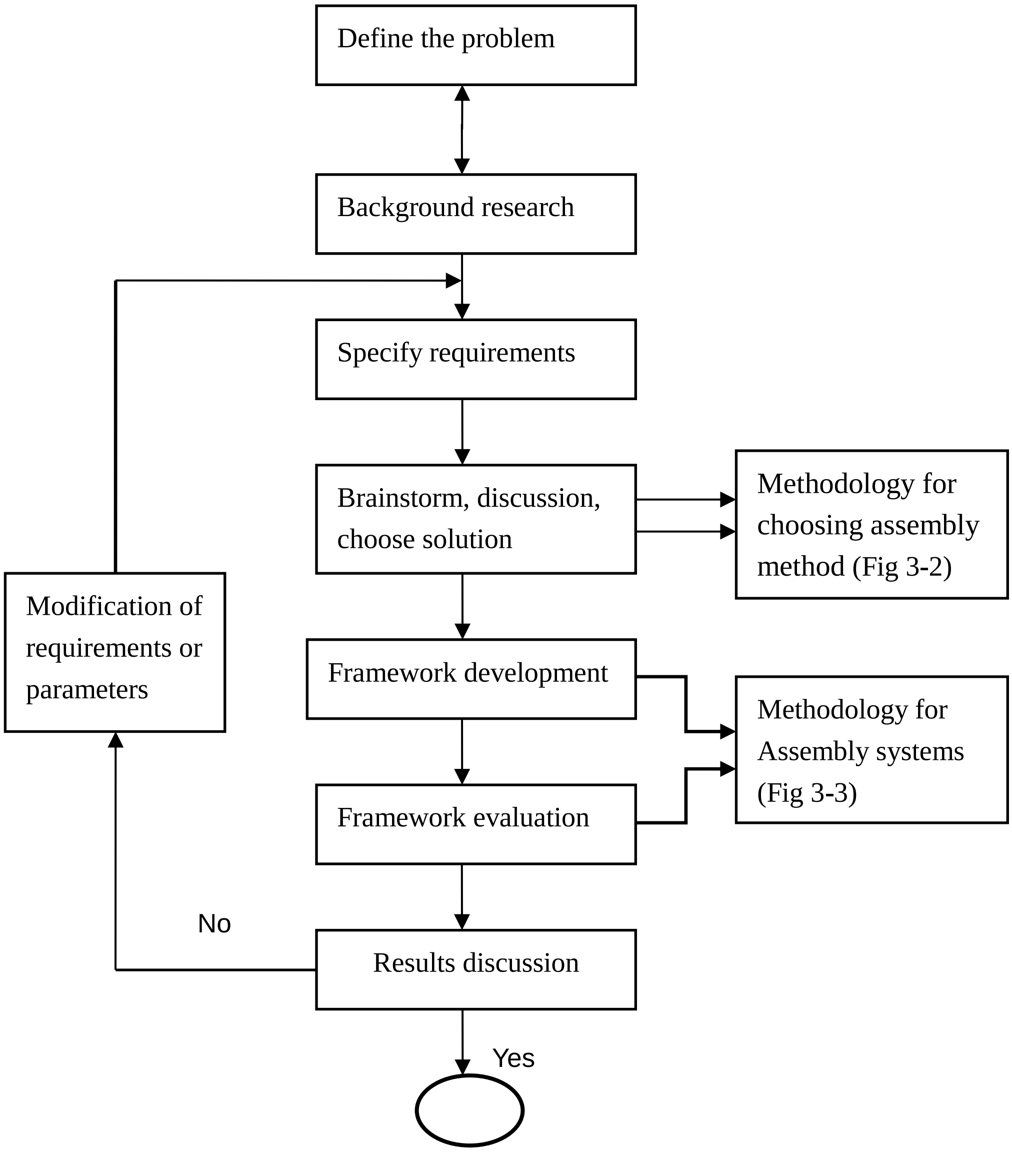


Fig 3- 1. Methodology for engineering project development [34]

Define the Problem. The engineering design process starts with a problem definition. It must make clear that the research area, what is the problem, why is it important to solve or observe.

Do Background Research: Learn about the research area and learn from the previous experiences. Study what the researcher need to help the project develop smoothly. Find out about existing solutions to similar problems, and avoid mistakes that were made in the past.

Specify Requirements: Design requirements state the important characteristics that the solution must meet to succeed. One of the best ways to identify the design requirements for the solution is to analyze the concrete example of a similar, existing product, noting each of its key features, and the customers' demand.

Brainstorm, discussion, chooses solution: There are always many good ways to solve problems. Look at whether each possible solution meets the design requirements. Reject solutions that do not meet the requirements. Considering all the factors, choose a better method. Fig3-2 illustrates how to develop this work.

Framework development: It is an operating version of a solution. Often it consists of several steps to develop the framework. Many key sections are in this stage, and the details can be drawn from Fig 3-3.

Framework evaluation: It is to evaluate whether the framework developed in last stage works. The project results can be drawn in this stage. Find new problems, make changes, and test new solutions before settling on a final design. Fig 3-3 illustrates how to develop this work.

Results discussion: To complete the project, communicate the results with others, talk about what the project has found and what need to be further research. Summarize a feasible method to provide guidelines for further study.

3.2.2 Methodology for choosing assembly method

Table 3-1 compares the abilities /behavior and limitations of robot, human and automation. There are some of the important factors to think about while developing a task to robot, automated machine or human. The robot-human-automation charts are developed (Fig 3-2) to provide procedures for determining which method will be suitable for product assembly, and automation here can be defined as implement with other machines except robot.

Table 3- 1. Comparation of robot, human and automation abilities and behavior [34]

Robot, human and automation abilities and behavior			
Characteristic	Robot	Human	Automation
Manipulation abilities	Good	Limited	Limited
Strength and power	Medium	Low	High
Consistency	Absolute consistency	Low	Perfect, very reliable
Overload performance	Constant performance up to a designed limit load	Performance declines smoothly	Constant performance until a breakdown
Computational capability	Fast	Slow	No computational ability
Memory	Good	Limitation	No memory
Intelligence	No	Good	No
Fatigue	No fatigue	Need rest	No fatigue
Environmental constraints	Can be fitted to hostile environments	Normal environments	Can be fitted to hostile environments
Training	Required programming	Requires training	No
Social and psychological needs	None	Need	None
Individual differences	Only if designed to be different	100-150% variation may be expected	Only if designed to be different
Energy efficiency	High	Low	Needs a lot of power
Positioning accuracy	Good	Poor	Good
Productivity	High	Low	High
Repeatability	Perfect	Good	Perfect
Suitable area	Large volumes, small-to-medium size, need space	Most areas	Aero structure, large section

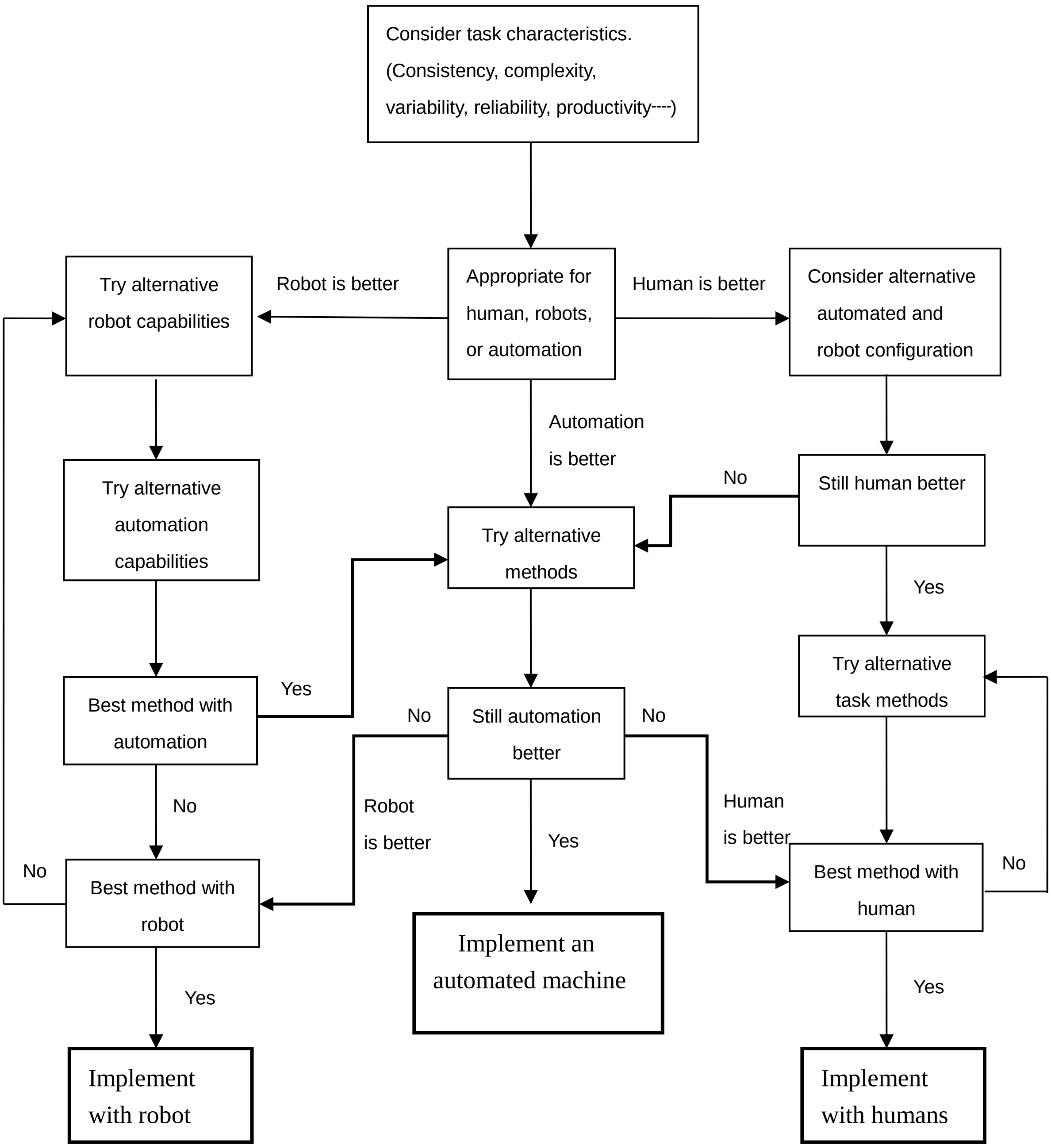


Fig 3- 2. Methodology for choosing assembly method [34]

3.2.3 Methodology for assembly systems

Fig 3-3 shows a step by step systematic progress of assembly system development. The progress is divided into five stages. The methodology here should be seen as an abstract form of the actual procedures followed when assembly operations are being planned. The flow chart given here is summarized based on this project development and is intended as a guideline and aid for a systematic approach. The details will be discussed below.

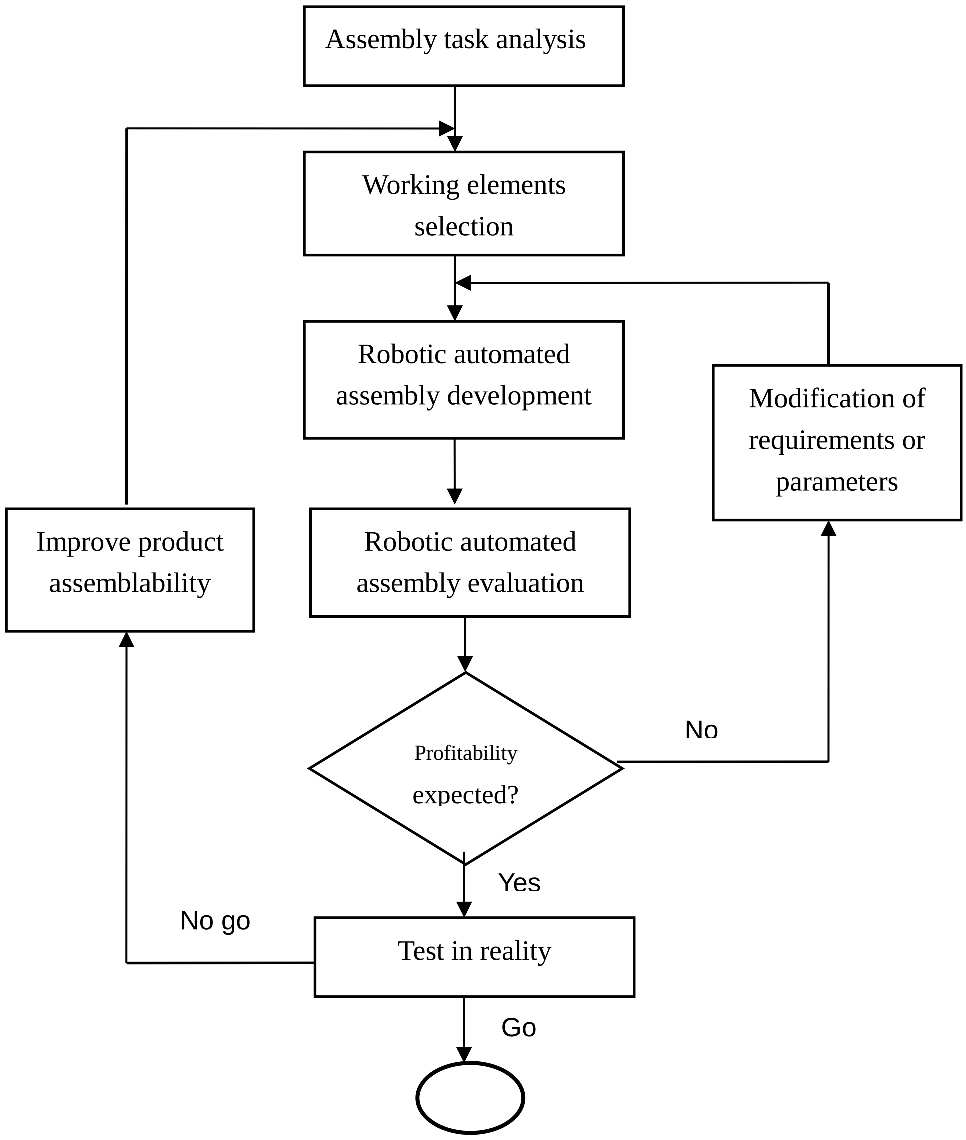


Fig 3- 3. Methodology for Assembly systems

First stage: Assembly task analysis	
Part stages	Aids and results
● Analysis of range of parts ● Analysis of assembly process ● Analysis of peripheral conditions ● Setting up target criteria	➢ Types, Volumes ➢ Priority chart, Process flow chart ➢ Obstacle to robotic automation ➢ Customer requirements

Assembly task analysis

This stage mainly illustrates the state of art on the research area, analysis of range of parts, assembly process, peripheral conditions and target criteria and provides much important information about product types, volumes, process flow chart, degree of flexibility and customer requirements for the following stages development about gap definition, framework development and evaluation.

In order to be able to determine which assembly operation is most suitable for flexibility assembly, which is suitable for manual assembly, a priority chart can provide some guidelines for making decision. Fig 3-4 shows the objective and structure of a priority chart for assembly process development. For those unsuitable for flexibility assembly products, according to the researcher's selection of assembly method, flexibility-oriented redesign is a better choice.

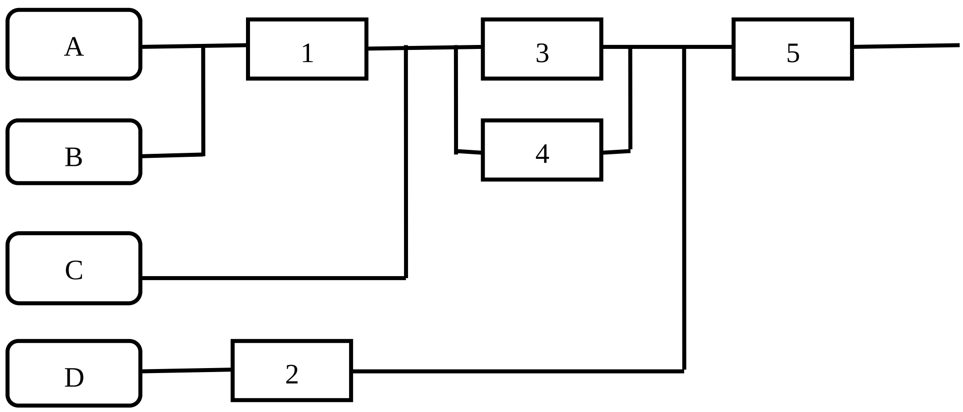


Fig 3- 4. Explanation of an assembly priority chart [35]

The priority chart indicates:

- Which assembly activities (1) have priority over other activities (3 4 5) and which parts are needed (A B).

- The earliest point when an assembly activity can be carried on (2).
- Which assembly activities can be performed in parallel or in any desired order (3 4).
- The latest assembly step 5 at which preassembly (2) of a part D must be completed.

Second stage: Working elements selection	
Part stages	Aids and results
● Elements selection principle ● Determining scope of simulation ● Analysis of working elements	➢ Guidelines, considerations ➢ Decision matrix ➢ Recommendations for flexibility-oriented design

Working elements selection

The research area stated in last area may be a large scope, for many reasons such as time limited, labor limited, resource limited, a small quantity or critical area is chosen for detail study. This stage will demonstrate key area selection principle; determine method and analysis of the elements. The appropriate working elements can be matched with the various subassemblies and convenient to work with. Once the working elements have been identified, the framework development can start.

Third stage: Robotic automated assembly development	
Part stages	Aids and results
● Product development ● Process development ● Resource development	➢ Product requirements and modelling ➢ Process requirements, Process flow chart ➢ Types, Volumes

Robotic automated assembly development

Although a robotic automation assembly was chosen for this project, the methodology is also suitable for the other two methods.

This stage mainly shows how to develop a framework of robotic automation assembly, illustrates product requirements, work piece date confirmation, product develop methodology, process develop methodology, resources needed for assembly, etc. Based on the procedures above, the product modelling, robotic automated assembly process, and equipment/tooling used to assist robot in product assembly were finally developed.

3.2.3.1 Methodology for product development

Fig 3-5 shows a step by step systematic process of product development. The methodology here should be seen as a procedure for product automation oriented development. Based on different conditions of company, some may have the existing products which can be used to automated assembly, some may have the existing products which can't be suitable for automation, and others do not have products, they all can follow this methodology. The final aid is to develop products complying with automation-oriented design rules which can be seen in Table 3-2.

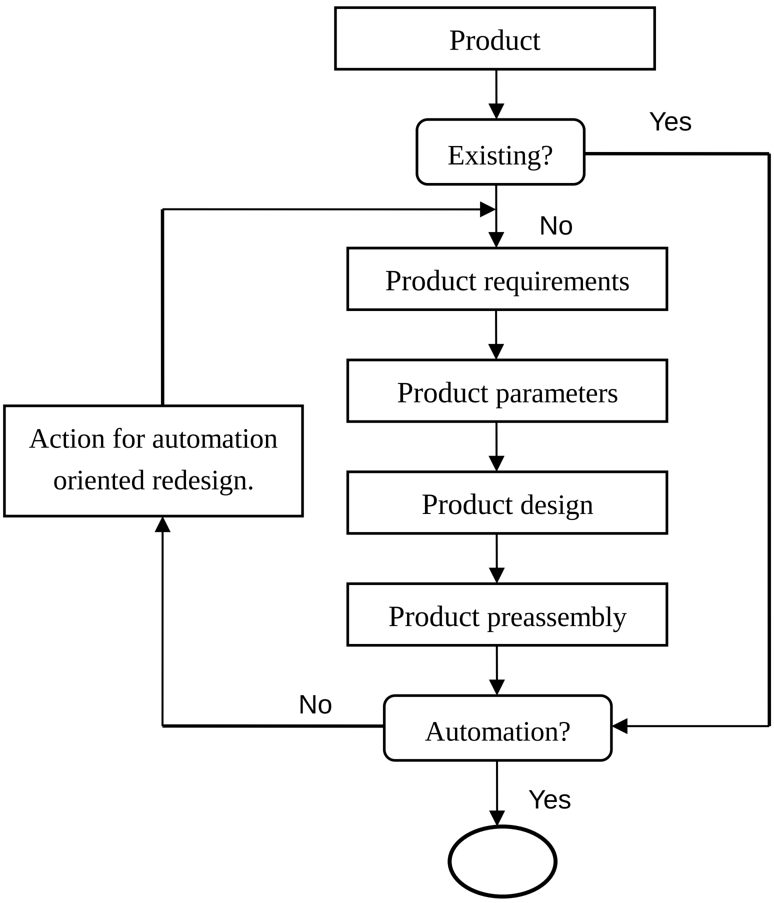


Fig 3- 5. Methodology for product development

Table 3- 2. General objectives and issues in design for assembly (DFA) [38]

	Strategic	Operational	Guidelines
Product	Customer needs Market structure Volume trends Quality, reliability, safety Economics: make or buy Assemble to order or stock Lifecycle issues	Subassemblies, components Part form and functions Part features, characteristics Assembly sequences Assembly operations Tolerations, clearances Tests, inspections	Symmetry No tangling No jamming Suitable fastening Modularity Base part Locating features
Assembly facility	Cost, quality, productivity Organization, labor needs Location, space needs Degree of automation Flow, control interfaces	Equipment selection Layout Task allocation Material handling Part feeding, Fixturing	Part handling(less accuracy) No repositioning Shortest distance No adjustment One-way assembly

Table 3-2 shows techniques for assembly-oriented product design must therefore consider the handling of product components and the joining/fastening of these components. Similarly, the system and organization of assembly must also be designed for cost-effective, reliable operation. Objective and issues of design for assembly are summarized in Table for companies' strategic and operational objectives.

3.2.3.2 Methodology for resource development

Fig 3-6 shows a step by step systematic process of resource development. The process is divided into six steps. The methodology here should be seen as a procedure for resource developing. According to the information presented in last several stages, resources type can be confirmed, resource requirements can be identified, after calculation of resource parameters, resources design work can start. According to different demands, considering whether it is better to produce or purchase resources. If bought, the resource parameters and requirements should be discussed with supplier and supplier will provide resource specifications which meet the project demand. After these works have been finished, resource evaluation should be in progress. If the resource works, this stage work is finished, if not, modification of requirements or parameters where is a problem will be redesigned.

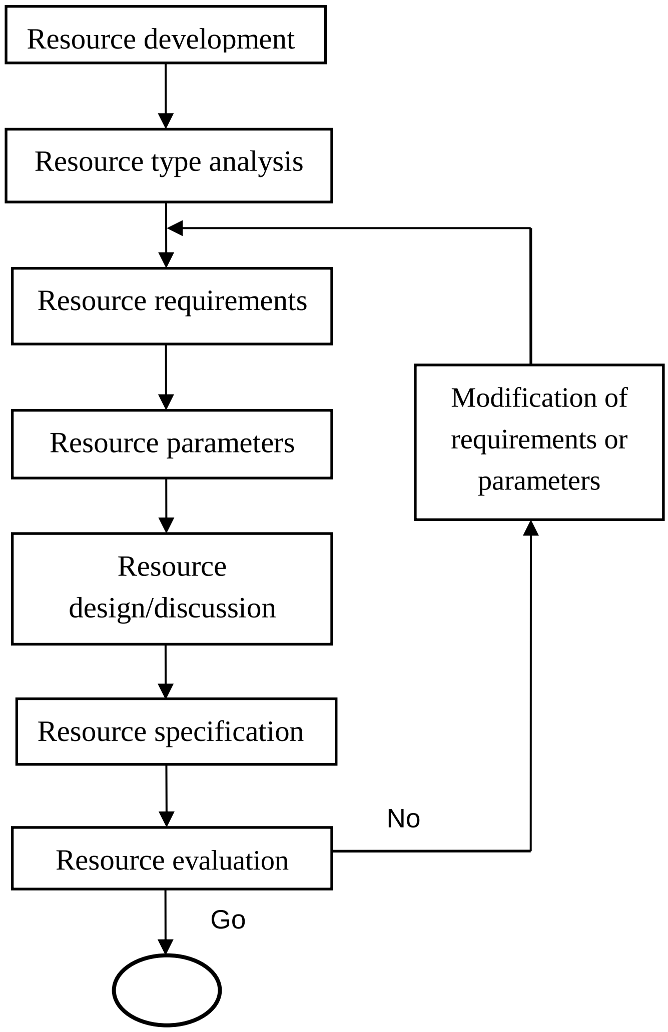


Fig 3- 6. Methodology for resource development

Fourth stage: Robotic automated assembly evaluation	
Part stages	Aids and results
● Process simulation(based on DELMIA) ● Process analysis ● Cost estimation	➢ Work content/simulation ➢ Collision/clash detection, feasibility ➢ Cost modelling

Robotic automated assembly evaluation

It is mainly to evaluate the framework developed in this stage. It will evaluate the framework from two different sides, process simulation and cost estimation. In process simulation section, software DELMIA was used to allocate PPR and simulate assembly process to test whether the process is feasible or detect problems for further optimization. The methodology for process simulation is shown in Fig 3-7. In cost estimation section, manual assembly cost and robotic automated assembly cost were calculated based on proposed method, and payback period was also calculated from two various production rate. According to different company production rates, different decisions will be drawn.

3.2.3.3 Methodology for process simulation

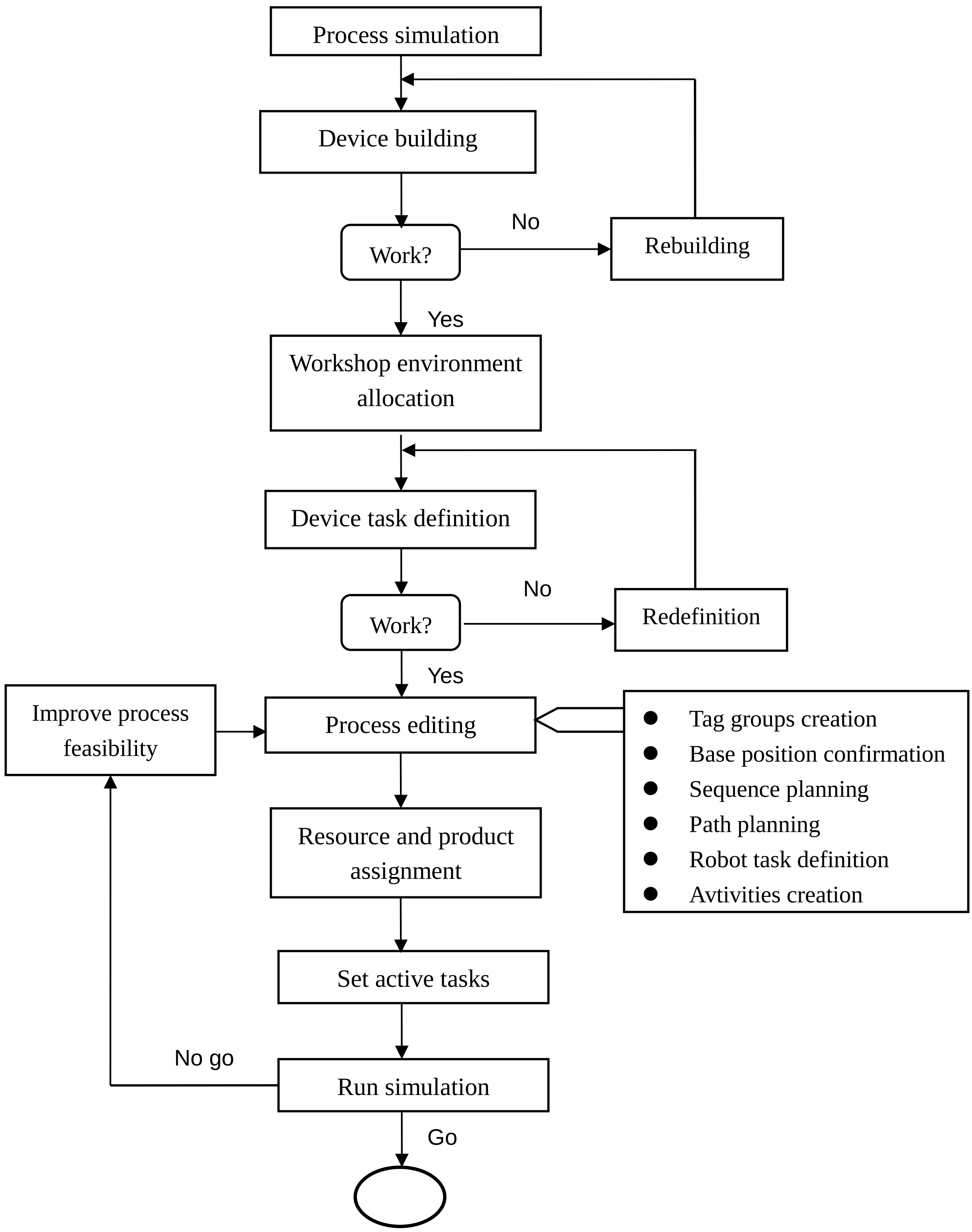


Fig 3- 7. Methodology for process simulation

Fig 3-7 demonstrates a step by step systematic process of robotic assembly simulation. The process is divided into seven steps. The methodology here should be seen as a procedure for assembly process simulation. This stage mainly shows how to prepare for simulation step by step, because there are many works before simulation, such as device building, workshop environment layout, device task definition, process editing, resources and products assignment, and set active tasks. Here devices are end effectors, robot rail which have properties of mechanical movements, TCP (Tool Center Point). All these work must be done in DELMIA, so skillfully applying DELMIA will be helpful in project development.

Fifth stage: Test in reality	
Part stages	Aids and results
● Resource purchase/manufacturing ● Product manufacturing/purchase ● Test outline editing ● Operator training ● Test and inspection ● Results and conclusions	➢ Physical resources ➢ Physical products ➢ Outline ➢ Skilled worker ➢ Datum collection ➢ Conclusions

Test in reality

Test can be considered as a technical operation or procedure that consists of determination of one or more characteristics of a developed product, process or service according to a specified procedure. After virtual simulation and cost estimation, the project will be in the final stage. This stage provides what should be prepared for test, how to arrange test, how to test and inspect the results, and how to analyze the datum and draw conclusions. Establish a procedure for managing test results. Describe roles and responsibilities of testers. It is recommended that experienced testers execute this task. Usually the test will be deployed in the laboratory or in the supplier's workshop.

3.3 Research steps

The research started with understanding the problem of Automated Leading Edge Assembly. Through problem definition the project theme was confirmed. Literature review was carried out to understand the technical areas covered in this project. Based on methodology presented in chapter 3.2, a proposed research step is demonstrated in Fig 3-8.

Robotic Automated Assembly Steps			
Phases	Tools	Key tasks	Deliverables
1.The state of art on manual Leading Edge assembly	Flow chart;	1.1 Introduce Leading Edge components. 1.2 Study Leading Edge assembly process. 1.3 Research gap identification.	Manual process
2.Automated Leading Edge Assembly framework development	Decision matrix; CATIA;	2.1 Working elements selection. 2.2 Product Development. 2.3 Process Development. 2.4 Resource Development.	Modelling, Automated Process
3.Automated Leading Edge Assembly framework evaluation	DELMIA; Flow chart;	3.1 Environment layout. 3.2 Perform PPR (Process, Product and Resource). 3.3 Automated assembly simulation. 3.4 Analysis and Optimization. 3.5 Cost estimation.	Simulation, Payback period

Fig 3- 8. The proposed Robotic Automated Assembly Steps

Phase 1

This phase starts with studying the aircraft Leading Edge. What does Leading Edge consist of? What function does each system have and how to install these components. It mainly illustrates the state of art on manual Leading Edge assembly, analysis of range of parts, assembly process. Discussed with experienced engineers worked in involved areas, assembly process of part of systems was developed in form of process flow chart. Considering the state of art on manual Leading Edge assembly and future manufacturing requirement, research gap was identified.

Phase 2

In this phase, with analysis of most of products assembled on the Leading Edge, referred to involved engineer’s advice, the critical area and product used to be simulated were chosen. In the following stage, many key factors affecting the project were studied including the CATIA and Robotics. Then robotic automated assembly process was developed, finally the modelling of products and resources were drawn.

Phase 3

In this phase, software DELMIA was utilized throughout. It was used to allocate PPR and simulate assembly process to test whether the process is feasible or detect problems for further optimization. After simulation, manual assembly cost and robotic automated assembly cost were calculated based on proposed method, and payback period was also calculated from two various production rates.

3.4 Software application

This chapter will demonstrate the main software used in this project. CATIA is going to be used to develop models as Leading Edge structure and involved fixture models, components used to be simulated. DELMIA is utilized to plan and simulate the automated assembly process.

DELMIA (Digital Enterprise Lean Manufacturing Interactive Application) helps global customers re-imagine their planning, management and optimization of industrial operations, and provides connection between the real and virtual worlds. One ideal tool can make digital manufacturing come true in the aerospace industry is DELMIA Process Engineer (DPE) [36], which assists process planning by integrating PPR information from initial design to the end of production phase. It contains all of the planning information and logical relationships among the PPR tree. More intelligently, DPE can integrate with other digital manufacturing modules as CATIA and digital process manufacturing (DPM), as shown in Fig 2-11.

Fig 3- 9. DELMIA Digital Product Manufacturing [37]

DELMIA V5 Robotics is an off-line programming (OLP) system which is compatible with many industrial robots from different manufacturers. It is an integrated solution which enables engineers to develop, plan, simulate, optimize process in a 3D digital factory environment [38].In this project DELMIA V5-6R2012 is employed. The following workbenches are applied: Device Building, Device Task Definition, Fastening Process Planner, and Work cell Sequencing.

4. The state of art on Manual Leading Edge Assembly

4.1 Introduction

The wing Leading Edge is a metal 'D' nosed structure attached to the front spar of the main wing box housing the bleed air deicing system, electrical wiring system and slat actuators & torque tubes, as shown in Fig 4-1. This chapter is mainly demonstrated bracket and systems assembled in the front spar.

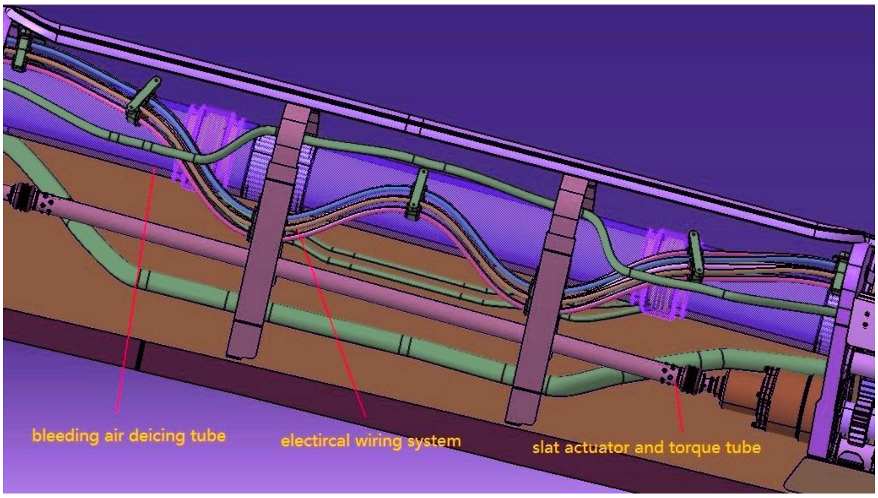


Fig 4- 1. Systems installed in the Leading Edge

4.2 Metal bracket

Bracket is a small fitting or support used to attach system parts, such as bleed air deicing tube, wiring bundles, cable, and other kind of ducts and to keep them in the correct position. Generally, the brackets are made from metallic material and cut to size before configured to the required shape by bending operation. And then the brackets are heat-treated to obtain the desired surface properties.

The brackets are designed to be that they will not damage systems, structure and insulation brackets during the life span of aircraft. Their weight shall be minimized as much as possible thus reducing the overall weight leading to indirect cost saving.

Fig 4-2 demonstrates the typical configurations of brackets [39].

A- Bracket is attached directly to the primary structure with permanent fasteners.

B- Bracket is a removable bracket attached on to A-brackets or directly on to the structure.

C- Bracket is attached to either A or B ones, usually they are glued on to the A and B brackets.

In reality, the shape of brackets may be not the same as brackets shown above. But they have similar configuration, manufacturing process and function.

Fig 4-3 addresses typical brackets distribution on the Leading Edge, just shows two kinds of brackets assembled on different surfaces or directions. There are many brackets which are used to attach systems as piccolo tube, torque tube and electrical wiring bundle. These brackets must be assembled firstly and then systems can be installed.

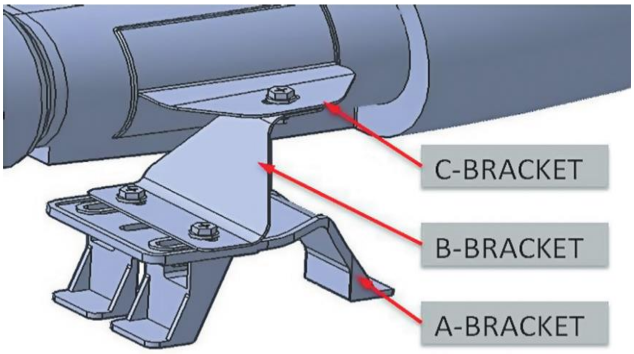


Fig 4- 2. Types of brackets [39]

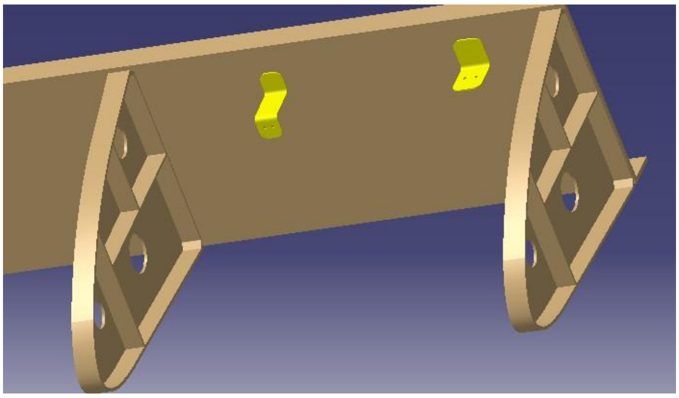


Fig 4- 3. Typical brackets distribution on the Leading Edge

4.3 Assembly process analysis

As known, the Leading Edge consists of structures and systems. This section gives a description of systems installed on the Leading Edge. The structure assembly is not discussed in this dissertation. There are mainly three systems as shown in Fig 4-1, before installing these systems, brackets used to fix or support systems must be assembled first. Bracket assembly based on the condition that wing slat and systems have not been installed. Fig 4-4 explains the systems installation process. Usually, SB is firstly assembled, then ECS and EWIS are installed, finally FCS is installed. Where SB, ECS, EWIS, FCS are System Bracket, Environment Control System, Electrical Wiring Interconnection System, Flight Control System respectively.

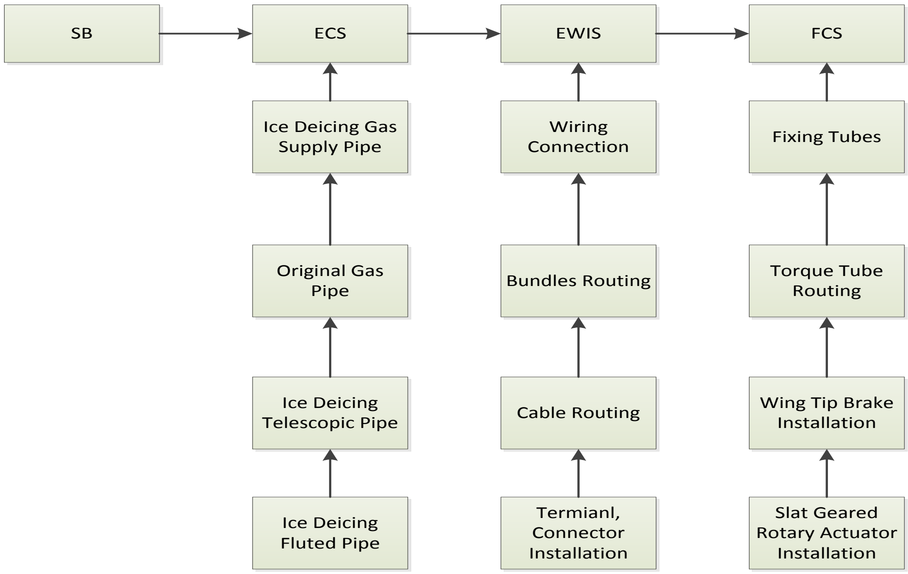


Fig 4- 4. System installation process

According to the proposed system installation process, each system consists of several subassemblies, which can be generally divided into three stages.

Stage 1 include drilling and subassembly of involved connectors, slide supports, slat actuators and terminals, which are attached to the structures of D-nose ribs, front spat or brackets.

Stage 2 assemblies focus on routing involved pipes, tubes, electrical wiring, and valves going across the components assembled in previous stage.

Stages 3 adjust the components to optimal position and use clamps, connectors or fasteners to fix them.

Assembly requirements:

1) The process of slat geared rotary actuator installation:

Besmear grease on actuator external spline and slat pinion internal spline before Install the geared rotary actuator which is going through the slat pinion. It should be careful to put geared rotary actuator into slat pinion to prevent spline from damaging. After installation of geared rotary actuator, actuator should be rolled smoothly. And then fix the actuator with bolts and screws, which need to be screwed up with specified force.

2) In the process of deicing pipe, torque tubes installation, make sure that the space between deicing pipes or torque tubes and surrounding structure or other systems is enough. Be careful to routing the pipes or tubes as the Leading Edge consists of a series of hollow chambers and the space in the Leading Edge is limited.

3) Wing tip brake should be installed with lubricated bolts and screws, which need to be screwed up with specified force. Whilst wing tip brake and bracket contact surface should be sealed.

4) Fixture needed: Fixture used to position the deicing pipe orifice. Fixture used to rotate the torque tube to match the spline.

4.3 Research gap identification

The volume of air traffic has soared in the past few decades. For meeting the airplane demand and customer’s requirement, automation may be a better way to increase the production rate. However those are applied in large aircraft section, small, complicated, space compact, are also manual assembly. In certain cases automation can be achieved easily, but wing assembly remains a major challenge, especially wing Leading Edge. Why is this so? The main reason lies in the complicated internal structure of the wings, which consist of a series of hollow chambers. It’s clear that the system installation on the Leading Edge is a very complicated and difficult process, even for manual assembly.

Automated Leading Edge assembly is a new concept and there is limited literature study about it. It is a major challenge to realize automated Leading Edge assembly. In order to increase productivity and fill the blank in this field, the challenge should not be ignored. In contrast, people must start to study and overcome it.

5. ALEA Framework Development

5.1 Working elements selection

As known, there are many systems installing in the Leading Edge, this project will not research them all for several reasons such as time limited, labor limited, resource limited, a small quantity or critical area would be chosen for detail study to evaluate the project aim.

Considering large number of pipes, tubes, cable harnesses going through the complicated Leading Edge which make the assembly high complexity and difficulty, and with the suggestions from experienced workers, the decision matrix is proposed accordingly. Table 5-1 shows the factors which affect the decision for working elements selection. The project is to realize the robotic automated assembly, and the affecting factors are shown below:

- Product volume: the larger the better
- Assembly space: the larger the better
- Installation degree of difficulty or ease: the easier the better
- Part handling: the easier the better
- Robot: basic is better, special will increase the robot cost

Table 5- 1. Decision matrix

Requirements	Product Volume	Assembly Space	Installation degree of difficulty or ease	Part handling	Robot
bleeding air deicing tubes	medium	medium	medium	medium	special
slat actuator & torque tubes	medium	small	hard	hard	special
electrical wiring system	large	medium	medium	hard	special
brackets	large	large	medium	easy	basic

From the decision matrix, the brackets is proposed to be researched on automated assembly firstly, and then bleeding air deicing tubes and electrical wiring system, the last step is to install slat actuator & torque tubes. The assembly sequence is still the same as the assembly process presented in chapter 4.2.

Considering the characters from the decision matrix, brackets should be assembled before other systems assembly. So brackets used to attach involved systems are chosen to be automated assembly based on robotic first. Others can be done in the future.

5.2 Product Development

Referring to dimensions of the wing Leading Edge of COMAC C919, the researcher developed the Leading Edge front spar, D nose ribs and involved brackets. The model is not the whole spar section, just 2700 millimeter long and 270 millimeter width as shown in Fig 5-1. There are distributing five ribs, the internal between each two ribs is the same and 600 millimeter. The products here are just used for simulation, not for manufacturing, so the requirements for products are very simple, the geometry and the dimensions of the products are similar to real parts, and the material of front spar and bracket is proposed to be aluminum alloy 7075-T7451 and 2024-T351 respectively.

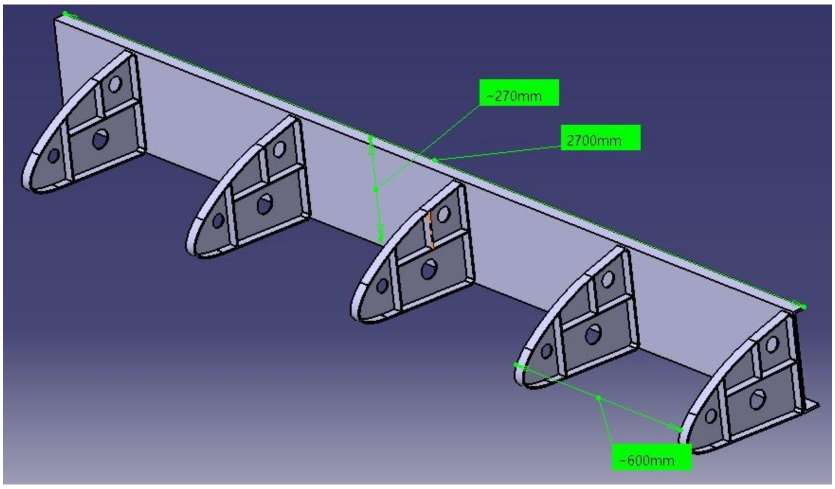


Fig 5- 1. Front spar and D nose ribs model

There are two types of brackets which can be defined as Z and L shape as shown in Fig 5-2. The holes used to fix systems are predrilled during the brackets manufacturing period, the other side holes used to fix brackets and the front spar will be drilled in robot operations.

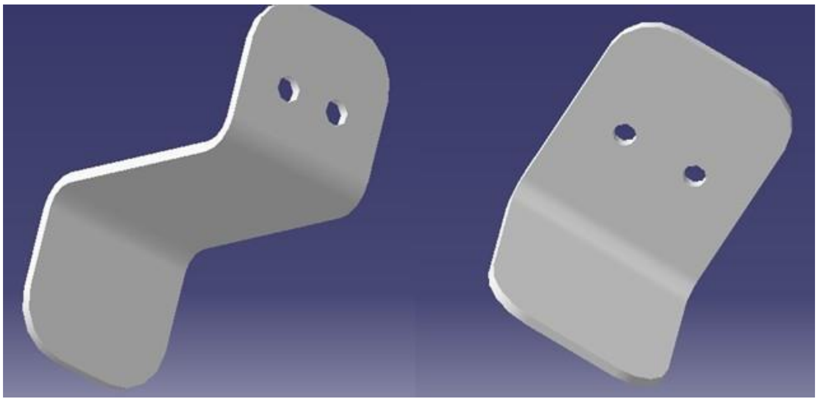


Fig 5- 2. The brackets model

5.3 Process Development

The brackets assembly process was planned based on workbench of DELMIA Process Engineer, in which Product, Process and Resource information can be logically integrated. Where Product consists of involved front spar, D nose ribs, brackets and fasteners, Process is mainly about the operations and sequence of bracket assembly and Resource are something used to run and support the operations, such as the station stand, robot, end effector, robot rail, and work shop floor.

Fig 5-3 shows the bracket assembly operations which are mainly supposed to be five steps. This process is mainly about how a bracket is located, fixed, drilled and riveted.

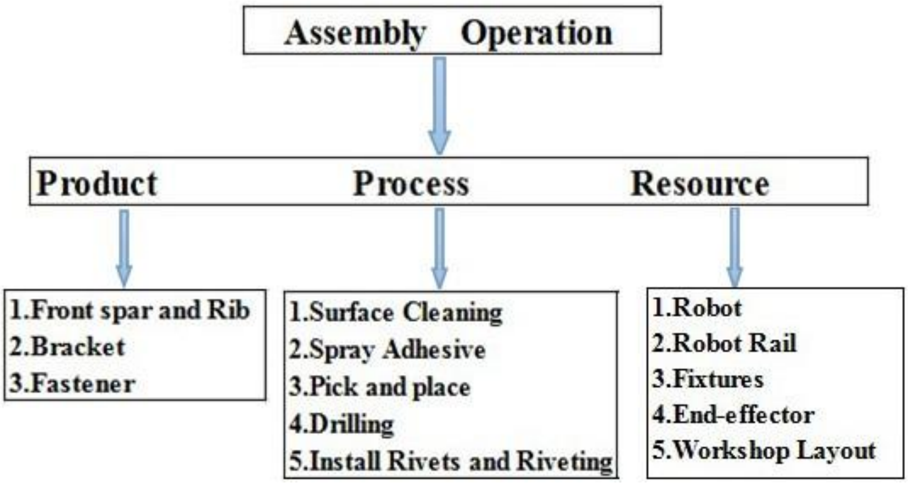


Fig 5- 3. Bracket assembly operation

5.3.1 Process operations:

Operation 1: Surface Cleaning is to clean the mating surface of front spar. The size of cleaning area should be larger than the contact surface of bracket. The method of Laser Ablation is proposed to clean the surface.

Operation 2: Spray Adhesive is to spray adhesive on the mating surface where was cleaned in last step.

Operation 3: Adhesive Bonding in this project is to temporarily fix the bracket on the front spar before they are drilled. As known, usually bracket is fixed with jig or fixture, and adhesive bonding is used to fix special product permanently. But in this project, adhesive bonding is an alternative method to fix component to replace the traditional fixture method.

Operation 4: Drilling is to drill the holes of the bracket and front spar together.

Operation 5: Install fasteners is to install rivets to the holes for connection of bracket and front spar, and riveting is to fix the bracket and front spar permanently.

5.3.2 Operations technology selection

Table 5-2 shows the technology can be applied in each operations, there are three options for each operation to choose. All the operations would be finished by robot arms with end-effectors. Considering the innovation, feasibility and robotic automation, the project deploys the technology below to develop an innovative assembly process.

Operation 1: Laser ablation is chosen for cleaning the mating surface of the front spar.

Operation 2: Adhesive bonding is chosen for temporarily fixing brackets.

Operation 3: Vacuum grippers are chosen for picking and placing brackets.

Operation 4: End-effector for drilling is chosen to drill the bracket and the front spar together.

Operation 5: End-effector for riveting is chosen to rivet the bracket and the front spar permanently.

Table 5- 2. Operations technology

Operations	Option 1	Option 2	Option 3
Surface cleaning	Laser ablation	Plasma	Detergent
Temporarily fixed	Adhesive	Jig & fixture	Manual fix
Pick and place	Vacuum grippers	Clamping grippers	Magnetic grippers
Drilling	End-effector	Pneumatic drill	Manual drill
Riveting	End-effector	Riveter	Manual squeezer

5.4 Resource Development

As known, if bracket assembly operations can be done smoothly, resource can be seen as equipment which is used to run operations and tooling which is used to support the tasks are needed. The project proposed a robotic assembly cell including robot and its sliding rail, end-effectors, station stand and components storage fixture.

5.4.1 Robot and its sliding rail

- Robot

Table 5- 3. Robot requirements

Features	Requirement

DOF	6
Capacity	60kg (132 lbs.)
Repeatability	0.20mm (0.0079 in)
Reach	2540mm (100 in)
Metrology system	Yes
Power	Electric power

Table 5-3 illustrates general requirements for robot. As presented in literature review and robot requirements, there are many robots which are available in this project. The robot IRB_6400 belong to ABB Company is chosen to perform the whole process. IRB 6400RF is the most accurate and rigid robot in its class, it has six degrees of freedom and is excellent for picking and placing, welding and drilling. Table 5-4 demonstrates the merits of this kind of robot.

In the virtual environment of robotics DELMIA simulation, five robots were deployed in this project, as they will execute five different operations respectively and the robot end-effectors may not be changed in the simulation course. In reality, one robot can finish these five different operations with robot tool changer assisting. Tool changer is used to change an end-effector mounted on robot arm to another.

Table 5- 4. IRB_6400 Robot merits

Features	Reliability	Security	Fast	Accurate	Robust
Advantage	High production up time	A safe investment	Short cycle times	Consistent parts quality	Harsh production environment
Explaination	well-proven design, minimum of maintenance	Advanced motion control, collision detection, low risk of tool and work piece damage	Unique control, the robot always optimizes the acceleration and retardation to actual load	Best in class regarding path accuracy and position repeatability (RP=1.0 mm) and with ABB's True Move, the robot always follow the same path, independent.	All-steel construction with high material strength. The arms are mechanically balanced and equipped with double bearings. The Foundry Plus protection has IP67 tightness on the complete mechanical arm and

- Robot sliding rail

In this project, according to the different robot motion paths and robot interface, simple robot sliding rail is proposed. As shown in Fig 6-1.

5.4.2 End-effector development

DELMIA Robotic provides virtual robot and its motion, but the involved end-effectors need to be developed based on various tasks, so different end-effectors were developed. There are five kinds of end-effectors deploying in this project.

5.4.2.1 End-effector for surface cleaning:

5.4.2.1.1 End-effector requirements

Laser ablation is selected to be integrated with end-effector for surface cleaning. The requirements for the end-effector are shown below.

1) Can be mounted on robot arm
2) Lightweight and stiffness
3) Suitable for aluminum alloy surface cleaning
4) Suitable for small area (2 inch x 2 inch) cleaning
5) Standard interface (changeover)
6) Not interfere with robot's motion
7) Durable– long life, low maintenance
8) No residues. No damage to the substrate
9) Cycle time: 2s

5.4.2.1.2 End-effector development

- Introduction

Laser cleaning technology is a safe, low maintenance, no damage to the substrate and pretty much cost effective way for surface cleaning or preparation.

Thousands of focused laser pulses per second will be distributed onto a contamination layer. Most of the laser energy is being absorbed by the contamination layer and is directly transformed into thermal energy, which vaporizes existing contamination and removes them away from the substrate. If the absorption factor is higher, the cleaning process will be faster. The material of substrate does not absorb as much laser beam as the contamination but reflects it.

Metallic surfaces are especially suitable for laser ablation as their high reflection. The substrate will not be stained by laser cleaning process. Fig 5-4 illustrates Laser ablation process principle.

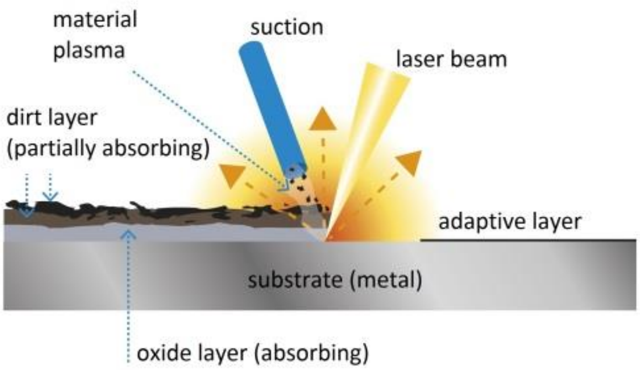


Fig 5- 4. Laser ablation process [40]

- Laser ablation application:

The laser ablation is one of the most effective surfaces cleaning method. It may also be the lowest operating cost of various cleaning methods. The laser ablation is easy to be integrated with robotics and widely used in automation. One way is to attach the optical head to a robot arm.

Fig 5-5 shows Laser ablation applications in industrial. The automated laser ablation provides large potential of cost saving, high reliability and the consistent product quality.

Fig 5- 5. Laser ablation applications [41]

5.4.2.1.3 Modeling

According to the above information presented about laser ablation and requirements for laser ablation, the end-effector modelling is proposed, as show in Fig 5-6.

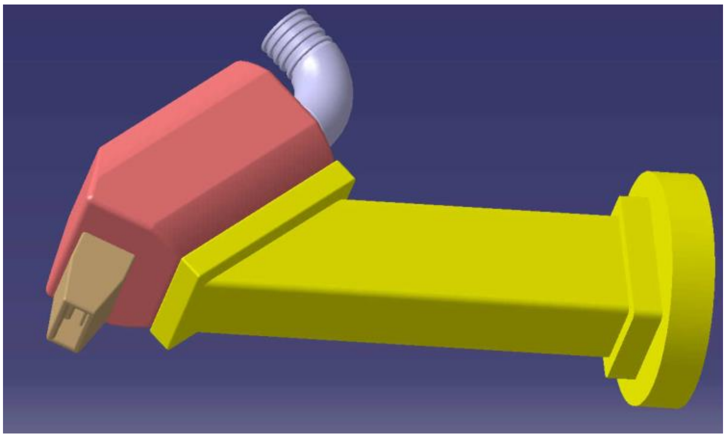


Fig 5- 6. End-effector for surface cleaning

5.4.2.2 End-effector for adhesive spraying

5.4.2.2.1 End-effector requirements:

Adhesive bonding is selected for bracket temporary fixing. This end-effector is used to spray adhesive on the mating surface. The requirements for the end-effector are shown below.

1) Can be mounted on robot arm

2) Lightweight and stiffness

3) Suitable for small area (2 inch x 2 inch) spraying

4) Standard interface (changeover)

5) Not interfere with robot's motion

6) Durable– long life, low maintenance

7) Cycle time: 0.3s

8) Nozzle size: 1.3 mm (0.051 in)

9) Fluid flow: 0.0355 L/min (1.25 oz/min)

5.4.2.2.2 End-effector development

- Adhesive bonding stress

Fig 5-7 shows adhesive bonding joints. Bonded joints may be subjected to several stresses including tension, cleavage, compression, shear or peel and often a combination of part of them.

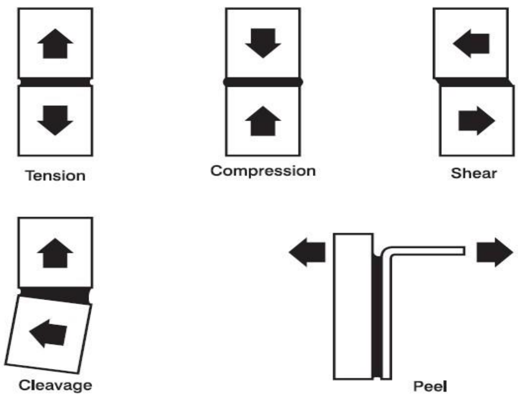


Fig 5- 7. Adhesive bonding joint

Adhesives perform best in shear; next will be compression and tension. Take aluminum alloy for example, a simple sheet of metal lap joint, 1.63 mm thick with 12.5 mm overlap (adhesive area), using the standard test method at room temperature. The mean breaking stress of shear will be various from 15 to 50 MPa, depending on the adhesive [42].

It has also been proven that the shear stress of aluminum applied two-part epoxy in normal environment condition is very strong in "Design Guide for Bonding Metal" [43].

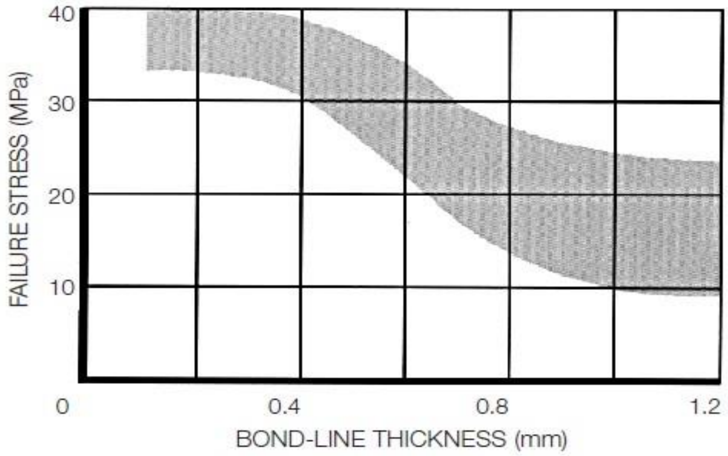


Fig 5- 8. Shear strength changing trend [44]

Fig 5-8 shows shear strength decreases with the thickness of layer of adhesive increasing. The diagram shows that strength is significant drop in the range 0.4 to 1.0 mm. When thicknesses of adhesive are greater than 1.0 mm, shear strength is approximately constant. The exact curve shape depends on the characteristics of the adhesive. Tough adhesives will have higher values in thicker bond-lines while rigid adhesives will reduce much more quickly.

The optimum bond-line thickness is in the range 0.1 to 0.3mm. If the thickness is less than 0.1mm there will be a risk of incomplete filling of the joint [44].

Overlaps in this project are supposed to be 30x30mm and 40x20mm, and thickness to be 0.2mm; Cycle time less than 0.3s. So the adhesive flow is 0.0355 l/min.

- Adhesive spray gun:

There are more and more automatic adhesive spray applications in industrial, which can be seen in Fig 5-9.

Fig 5- 9. Automatic adhesive spray application

A comprehensive range of nozzles ensures excellent results with virtually all types of spraying media. Available nozzle sizes (Φ mm): 0.3, 0.5, 0.8, 1.0, 1.3, 1.5, 1.8, 2.0, 2.2, and 2.5.

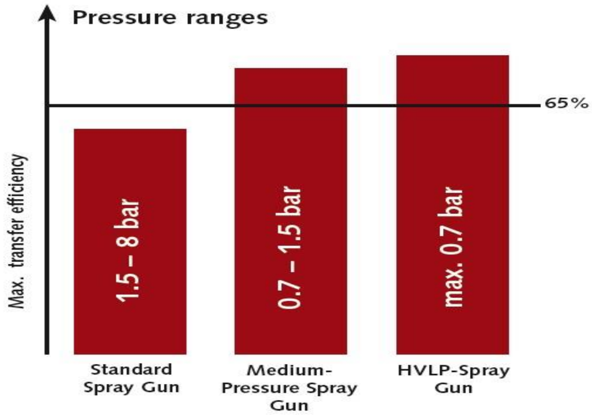


Fig 5- 10. Supply pressure of automatic spray guns [45]

Fig 5-10 shows different supply pressure of automatic spray guns.

Conventional method: Air pressure is typical 30 to 60 psi (2 to 4 bar) with air consumption of 6 to 25 cfm (170 to 700 l/min).

High Volume Low Pressure (HVLP): It uses larger air volumes (11 to 30 cfm or 300 to 840 l/min) at low pressure, a maximum of 10 psi (0.7 bar) [46].

In this project, it is recommended spray type is HVLP and nozzle size is: Φ=1.3 mm (0.051 in).

5.4.2.2.3 Modeling

According to the above information presented about adhesive spray and requirements, the end-effector modelling is proposed, as show in Fig 5-11.

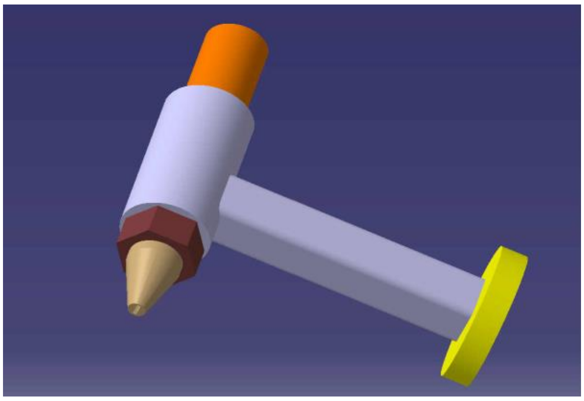


Fig 5- 11. End-effector for adhesive spraying

5.4.2.3 End-effector for picking and placing:

5.4.2.3.1 End-effector requirements

This end-effector is used to pick and place the brackets, which are made from aluminum. Because of the brackets' lightweight and regular shape, vacuum suction cup is employed. The requirements for the end-effector are shown below.

1) Can be mounted on robot arm
2) Not interfere with robot's motion
3) Durable– long life, low maintenance
4) Standard interface (changeover)
5) Lightweight and compact
6) Will not damage parts
7) Handling capacity: at least 0.1kg (0.22 lbs.)
8) Adjustable systems available
9) Flat surface (aluminum alloy brackets)
10) Venturi power consumption

5.4.2.3.2 End-effector development

- Introduction：

Vacuum generators are not new technology. They have been existed for decades and can be used for various areas from evacuation, pick-up to work-holding. There are two basic methods of producing vacuum. The most widely used way is utilizing electric-motor-driven. Another way is using a no-moving-part venturi.

If constant vacuum flow is required, vacuum pumps may be much more efficient device compared to venturis. Also if a large vacuum flow at high vacuum is needed, a vacuum pump is also the first choice. Except these two conditions, the venturi may be the best method. In this project, venturi is selected for vacuum generating and its advantages [47] are shown below.

1) Fast cycling: suitable for applications as pick & place and labeling.
2) Harsh environments: can operate in high temperature and corrosive environments.
3) Noise levels: can be minimized by using noise reducing mufflers.
4) Ease of mounting: they can be mounted on robot arm, very close to the work station.
5) Lower Cost: Due to their simplicity, the venturis are low cost components.

Compressed air is basic requirements of a venturi vacuum generator. If compressed air is unavailable, vacuum pump will be an alternative.

- Principle of venturi vacuum:

As shown in Fig 5-12, compressed air is throttled when the air flows into the nozzle and then into the diffuser. It will increase the velocity of air flow and reduce the pressure in the diffusion chamber. As known, air in closed vacuum system flows from high pressure area into low pressure area of the diffusion chamber and finally will be exhausted via the diffuser. The effect of this action increases the vacuum level and discharges most of the air within the closed vacuum system at supersonic speeds.

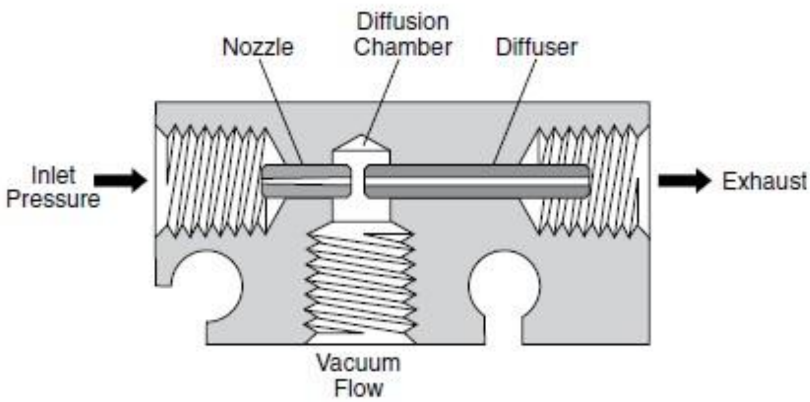


Fig 5- 12. Principle of venturi vacuum [48]

- Venturi vacuum generator:

The size of the venturi vacuum generator is generally decided by either the

Vacuum Flow Rates or the Evacuation Time, and varies according to the size of the diffuser / nozzle.

➢ Nozzle size:

As a general guide, the nozzle diameter can be selected for most non-porous vacuum applications from the Table 5-5 as follows. Suction cup diameter is supposed to be 25 mm, so nozzle diameter is 1.0mm

Table 5- 5. Nozzle diameter reference to suction cup diameter [48]

Nozzle Diameter	Maximum Suction Cup Diameter inches (mm)
0.5mm	.79 (20)
1.0mm	1.79 (50)
1.5mm	2.36 (60)
2.0mm	4.72 (120)
2.5mm	5.91 (150)
3.0mm	7.87 (200)

➢ Evacuation Time

Evacuation Time is the time required to evacuate the air out to specific vacuum level. It is also viewed as response time of the system.

Table 5-6 shows a typical Evacuation Time chart for a generator series.

Table 5- 6. Evacuation time [48]

Nozzle Diameter	Air Supply Pressure	Air Consumption	Evacuation Time in sec/ ft^3, to reach different Vacuum Level (inHg)								
	PSI	SCFM	3	6	9	12	15	18	21	24	27
05HS	70	0.46	24.3	57.3	101.9	160.5	231.1	305.1	433.1	597.7	—
05LS	70	0.46	11.0	23.4	40.0	64.4	110.2	—	—	—	—
10HS	70	1.55	4.8	9.9	16.0	24.9	35.9	51.4	77.4	117.5	226.0
10LS	70	1.55	3.7	7.6	13.0	20.3	33.1	—	—	—	—
15HS	70	3.53	2.5	4.8	7.0	11.0	15.5	22.0	31.9	46.6	112.1
15LS	70	3.53	2.0	3.1	5.0	7.6	12.1	—	—	—	—

* 1 ft^3=28.31 liters

➢ Vacuum Flow

Table 5-7 lists a typical Vacuum Flow chart for a generator series. The vacuum flow rate at different vacuum levels is listed in SCFM. This chart is used to give the reference for the change of the vacuum flow rate in different degree of vacuum.

Table 5- 7. Vacuum flow [48]

Nozzle Dia.	inHg										
	0	3	6	9	12	15	18	21	24	27	30
05HS	.21	.19	.17	.15	.13	.11	.09	.07	.05	.03	—
05LS	.32	.27	.22	.17	.12	.06	—	—	—	—	—
10HS	.95	.85	.75	.65	.55	.45	.35	.25	.15	.05	—
10LS	1.27	1.05	.83	.59	.38	.17	—	—	—	—	—
15HS	2.22	1.98	1.74	1.5	1.26	1.01	.76	.51	.25	.10	—
15LS	3.35	2.79	2.23	1.67	1.10	.53	—	—	—	—	—

Fig 5-13 shows the model number index regarding nozzle diameter codes in table 5-6 and 5-7.

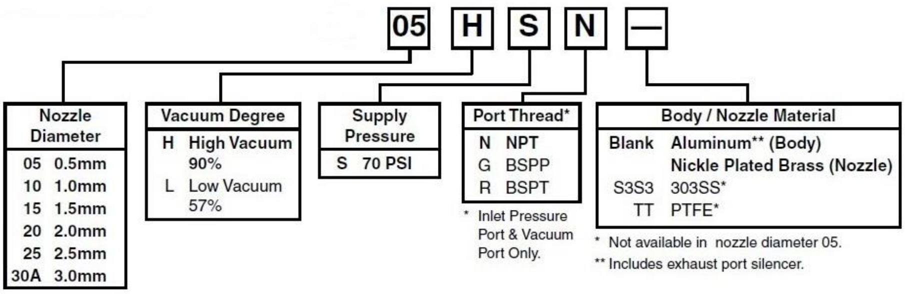


Fig 5- 13. Model number index [48]

Example: A pick up and drop down application requires a less than 0.25 seconds response time for creating18 inHg of vacuum system including tubes and cups, the vacuum volume is 0.002 ft^3 , so the evacuation time is 0.25 x 1/0.002 =125 secs.

As shown in the evacuation time table, any kind of vacuum generator with less than 125 seconds response time to achieve 18 inHg can be selected for this application, and considering the nozzle diameter, it is also available.

- Parameter confirmation:

General suction cup lift product has two directions, horizontal lift and vertical lift as shown in Fig 5-14. Different lift direction requires different force. Safety factors should be considered. It's recommended that safety factors are 2 when suction cup surface is in horizontal position and 4 when cup face is in vertical position respectively [49]. Considering moving robot the safety factors should plus 1.

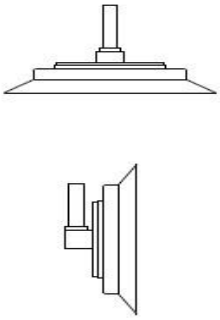


Fig 5- 14. Suction cup lift direction

Table 5-8 shows the conversion between desired vacuum level and pressure.

Table 5- 8. Conversion chart between vacuum and pressure [49]

% Vacuum	Hg inches	mmHg	bar	PSI
10	3	76.92	-0.1	-1.47
20	6	153.85	-0.2	-2.94
30	9	230.77	-0.3	-4.41
40	12	307.69	-0.4	-5.88
50	15	384.62	-0.5	-7.35
60	18	461.54	-0.6	-8.82
70	21	538.46	-0.7	-10.29
80	24	615.38	-0.8	-11.76
90	27	692.31	-0.9	-13.23
100	30	769.23	-1.0	-14.70

The device is used to pick and place brackets used in this project. The heaviest one expanded dimensions are: Long=106mm, Thickness=2mm, and Width= 30mm. ρ =2.73 x10^3 kg/m^3 .

So $G = mg = \rho v g$=0.171N.

Where G=the weight of the objects, N

Force = Area x Pressure

Where:

F = the weight of the objects $\times$ Safety factor.

P = the expected vacuum level

A = the area of the vacuum cup

Suction cup diameter is d=25 mm. Nozzle diameters is 1.0mm. Safety factor is 4+1=5.

P=F/A= $\frac{5G}{\pi \frac{d^2}{4}} = \frac{20G}{\pi d^2} = \frac{20 \times 0.171}{3.14 \times 25^2 \times 10^{-6}} =$ 1743pa $\approx$ 0.18bar.

According to the table 5-8, the vacuum level is 6"Hg at least.

So the end effectors in this project are powered by compressed air and employ the venturi principle to achieve at least a 6” Hg vacuum. Requiring response time at most 0.3 seconds, providing millisecond attach and release. As shown in the evacuation time table, every generator can meet the requirement.

5.4.2.3.3 Modelling

According to the above parameters calculated about vacuum generator and requirements, the end-effector modelling is proposed, as show in Fig 5-15.

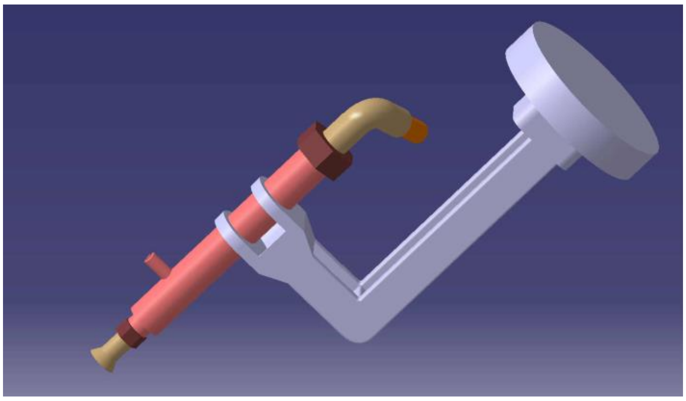


Fig 5- 15. End-effector for picking and placing

5.4.2.4 End-effector for drilling:

5.4.2.4.1 End-effector requirements

This end-effector is used to drill holes going through bracket and spar. The requirements for the end-effector are shown below.

1) Can be mounted on robot arm
2) Lightweight and stiffness
3) Suitable for aluminum alloy drilling
4) Standard interface (changeover)
5) Not interfere with robot's motion
6) Durable– long life, low maintenance
7) Easy to change drill
8) Electric power
9) Twist drill
10) Spindle motor power: 1.1kw
11) The rotational velocity of the tool: 5400 rpm
12) Thrust force: at least 500 N (112.5 lbf.)
13) Feed rate: 0.006 in/rev (0.15mm/rev)

5.4.2.4.2 End-effector development

- Introduction:

Drilling is a commonly hole-making process which uses a drill as a cutting tool for producing round holes of various sizes and depths. The most common tool material for drills is high-speed steel, and the most common kind of tool used in drilling is twist drill (Fig 5-16).

Table 5-9 shows the drill geometry of high-speed steel twist drills for various work piece materials.

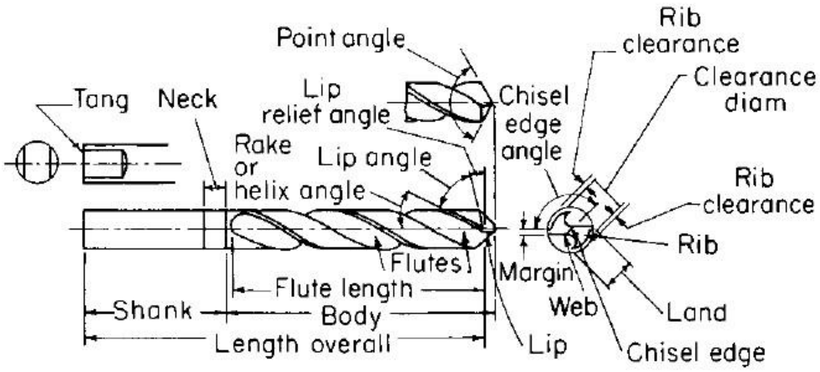


Fig 5- 16. Straight shank twist drill [50]

Table 5- 9. Recommended Drill Geometry for High-Speed Steel Twist Drills [50]

Material	Point angle, deg	Lip relief angle, deg	Chisel edge angle, deg	Helix angle, deg	Point grind
Aluminum alloys	90–118	12–15	125–135	24–48	Standard
Magnesium alloys	70–118	12–15	120–135	30–45	Standard
Copper alloys	118	12–15	125–135	10–30	Standard
Steels	118	10–15	125–135	24–32	Standard
High strength steels	118–135	7–10	125–135	24–32	Crankshaft
Stainless steels, low-strength	118	10–12	125–135	24–32	Standard
Stainless steels, high-strength	118–135	7–10	120–130	24–32	Crankshaft
High-temperature alloys	118–135	9–12	125–135	15–30	Crankshaft
Refractory alloys	118	7–10	125–135	24–32	Standard
Titanium alloys	118–135	7–10	125–135	15–32	Crankshaft
Cast irons	118	8–12	125–135	24–32	Standard
Plastics	60–90	7	120–135	29	Standard

SOURCE: "Machining Data Handbook," published by the Machinability Data Center, Metcut Research Associates Inc.

Obtaining maximum economy in the use of drills requires consideration of many factors. One important factor is selecting the proper drill for a specific application.

While a drill of almost any design can be used to produce a hole in almost any materials, lower costs for production applications necessitate use of the correct drill. Variables influencing the selection of the proper drill include the composition, hardness, and surface condition of the material to be drilled; the diameter and depth of the hole to be drilled; the accuracy, surface finish, and production requirement; the type and condition of the machine to be used. Standard drills should be used whenever possible because of reduced costs, interchangeability, better availability and proven designs.

Once a drill has been selected, many operating parameters must be established. These include power requirement, cutting speed, feed rate and spindle speed.

- Power requirement

In order to provide suitable equipment for any drilling operation, it is necessary to determine the torque and thrust required to rotate and feed the drill at the desired rate. Torque and speed set the power requirement; thrust determines the machine rigidity and strength requirement.

Researches and analysis indicate that drill torque and thrust are functions of drill diameter, drill chisel edge length, feed per revolution, and work piece material.

Reasonable estimates of torque and thrust requirement of sharp twist drills of various sizes and designs can be made from the following formulas [51]:

For torque:

$$M = Kf^{0.8}d^{1.8}A$$

For thrust:

$$T = 2Kf^{0.8}d^{0.8}B + Kd^{2}E$$

Where:

M= torque, in.lbf.

T= thrust force, lb.

K= work-material constant

f= drill feed, ipr.

d= drill diameter, in.

A, B, E= Drill design constant shown in Table 5-10.

For metric usage, the torque in N.m can be obtained by multiplied in.-lbf by 0.113. Thrust force in newton is determined by multiplied the force in pounds by 4.448.

Table 5- 10. Constant Values for Thrust Force and Torque [51]

Work material	k	C/d	W/d	A	B	E
Steel, 200 Bhn	24000	0.03	0.025	1.000	1.100	0.001
Steel, 300 Bhn	31000	0.05	0.045	1.005	1.140	0.003
Steel, 400 Bhn	34000	0.08	0.070	1.015	1.200	0.006
Aluminum alloys	7000	0.10	0.085	1.020	1.235	0.010
Most brasses	14000	0.15	0.130	1.080	1.310	0.022

* C= chisel edge length, inch d= drill diameter, inch W= web thickness, inch

The most important drill design feature affecting torque and thrust is the ratio of the chisel edge length, c, to the drill diameter, d.

The formulas yield torque and thrust requirement for sharp drills, an extra 30-50% should be provided to allow for drills dulling.

If the operating speed is known, the torque can be converted to approximate horsepower requirement by means of the following formula:

$$hp = \frac{MS}{62500}$$

Where:

hp =approximate horsepower required

M= torque, in.-lbf

S= drill speed, rpm

Or

$$kw = \frac{MS}{9524}$$

Where M= torque, N.m

To allow for machine transmission losses, the power (based on dull drills) should be multiplied by about 1.25. Alternatively, power requirement for sharp drills could be multiplied by about 1.7, thus allowing for both dulling and machine losses.

- Drilling speeds and feeds:

Drilling speed refers to a drill's peripheral or surface speed in feet per minute (sfm) or meters per minute (m/min). Drill speed is related to spindle speed (rpm) as follow:

$$S = \frac{3.82 \times V}{D}$$

Where

S = the rotational velocity of the tool, rpm

V=drill surface speed, fpm

D= drill diameter, in

Feed rate is expressed as inches per revolution (ipr) or millimeters per revolution (mm/rev), as well as inches per minute (ipm) or millimeters per minute (mm/minute).

The parameters of cutting speed and feed rate control metal removal rate, hole quality, and drill life. Any increase in these parameters generally increase metal removal rate, but decrease tool life. While an increase in speed usually has a larger effect in reducing drill life than an increase in feed rate. As a result, the highest feed rate should be used for drilling, with moderate cutting speed to provide satisfactory holes and economical tool life, balanced against production requirement.

Table 5-11 .5-12 and 5-13 show the cutting speed and feed rate of different material drilled.

Table 5- 11. Suggested operating conditions in various material with twist drill [51]

Material Drilled	Hardness		Cutting Tool Material*	Peripheral Speed, sfm (m/min)	Feed Rate**
	Brinell	Rockwell			
Aluminum and its alloys	45-105	to R_B62	HSS	350 (107)	Z
Asbestos	---	---	WC	55 (17)	Y
Bakelite	---	---	WC	80 (24)	Y
Carbon	---	---	HSS	60-70 (18-21)	W
Copper and its alloys					
High machinability	to 124	R_B10-70	HSS	200 (61)	Z
Low machinability	to 124	R_B10-70	HSS	70 (21)	Z
Fiberglass-epoxy	---	---	WC	650 (198)	0.0025-0.0050″ (0.063-0.127 mm)
Glass	---	---	WC	15-25 (4.6-7.6)	Light hand
High-temperature alloys					
Cobalt based	180-230	R_B89-99	HSS-Co	20 (6.1)	W
Iron based	180-230	R_B89-99	HSS-Co	25 (7.6)	X
Nickel based	150-300	to R_C32	HSS-Co	20 (6.1)	W

Table 5- 12. Suggested feed rate [51]

* Feed Rate, ipr (mm/rev)	Drill Diameter				
	1/8" (3.2)	1/4" (6.4)	1/2" (12.7)	3/4" (19.1)	1" (25.4)
W	0.0015 (0.038)	0.0003 (0.08)	0.0035 (0.089)	0.0045 (0.114)	0.005 (0.13)
X	0.002 (0.05)	0.0035 (0.089)	0.006 (0.015)	0.085 (0.216)	0.0105 (0.267)
Y	0.003 (0.08)	0.005 (0.13)	0.008 (0.20)	0.0105 (0.267)	0.0125 (0.317)
Z	0.003 (0.08)	0.006 (0.15)	0.010 (0.25)	0.0155 (0.394)	0.0190 (0.483)

Table 5- 13.High Speed Steel & Cobalt Drills Speed and Feed Recommendations [52]

Workpiece material	Brinell hardness BHN	Surface speed SFM	Feed per revolution by drill diameter				
			1/8"	1/4"	1/2"	3/4"	1"
Low carbon steel	≤120	110	0.0030	0.0040	0.0080	0.0100	0.0110
Medium carbon steel	120-150	65	0.0040	0.0060	0.0110	0.0130	0.0140
Aluminum alloys	≤150	325	0.0040	0.0060	0.0110	0.0130	0.0140
Cooper alloys	≤200	80	0.0040	0.0060	0.0110	0.0130	0.0140

In this research, materials drilled are aluminum alloys (front spar: 7075-T7451, bracket: 2024-T351). The thickness of front spar is 5.5-6 mm and bracket is 2mm. The total height is 7.5-8mm. Twist drill is selected to drill the holes, twist drill is made from high speed steel, and the diameter of the drill is 1/4 in.

According to the recommended parameters: V=325-350fpm, D=1/4 in, f=0.006 ipr, K=7000, A=1.02, B=1.235, E=0.01.

$S = \frac{3.82 \times V}{D} = 3.82 \times 350 \times 4 = 5348$ rpm;

$M = Kf^{0.8} d^{1.8} A = 7000 \times 0.006^{0.8} \times 0.25^{1.8} \times 1.02 = 9.95316$ in.-lbf = 1.125 N.m;

$T = 2Kf^{0.8} d^{0.8} B + Kd^2 E \quad = 2 \times 7000 \times 0.006^{0.8} \times 0.25^{0.8} \times 1.235 + 7000 \times 0.25^2 \times 0.01 =$

101.3719 lb = 450.9 N;

$kw = \frac{MS}{9524} = \frac{1.125 \times 5348}{9524} = 0.632$ kw

And the motor power is 0.632×1.7=1.0744 kw

So the end effector for drilling electric driven should meet these requirements above at least.

5.4.2.4.3 Modelling

According to the above parameters calculated about drilling and requirements, the end-effector modelling is proposed, as show in Fig 5-17.

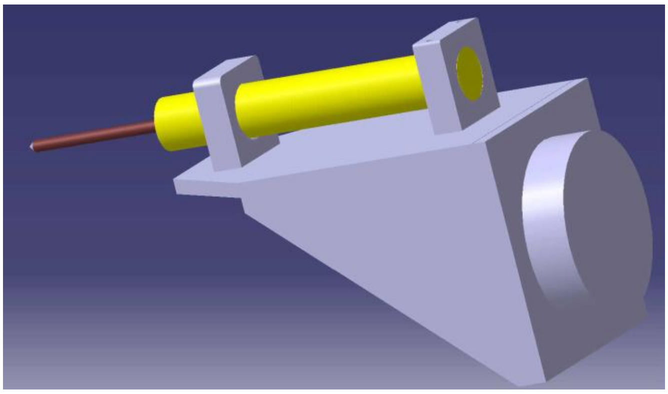


Fig 5- 17. End-effector for drilling

5.4.2.5 End-effector for rivet feeding and riveting:

5.4.2.5.1 End-effector requirements

This end effector is used to transport rivets to the holes and make the tail of the rivet deformed to demand shop head. Rivets are pre-stored in storage which is driven by air pushing force.

The requirements for the end-effector are shown below.

1) Can be mounted on robot arm
2) Lightweight and stiffness
3) Standard interface (changeover)
4) Not interfere with robot's motion
5) Durable– long life, low maintenance
6) Axial force: at least 35535 N (8000 lbf)

7) Will not damage parts
8) Universal head rivet
9) Cycle time: max 1s

5.4.2.5.2 End-effector development

- Introduction:

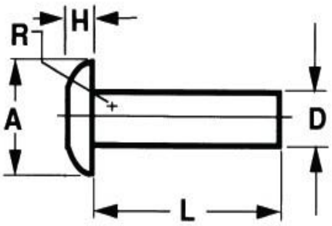
The riveting process consists of inserting the rivet and forming a head, inserting is to insert the rivet into matching holes of the pieces to be joined, and forming is to form a head on the protruding end of the shank. The head is formed by continuous squeezing with a pressure riveter or by rapid forging with a pneumatic hammer.

The amount of squeeze force to apply depends on rivet material, type and geometry of rivet and hole, and variants associated with rivet installation process.

The rivet selected in this project is universal head rivet, as shown in Fig 5-18. There are several kinds of solid rivet material:

• A – 1100 – Pure aluminum
• B – 5056 – Magnesium
• AD – 2117 – Most common type
• D – 2017 – “Ice box”
• DD – 2024 – “Ice box”

For example: Universal head, 2117 T4, 3/32 diameter, 5/16 length, can be seen as AN470AD3-5 or MS20470AD3-5.



UNIVERSAL HEAD RIVETS

Nominal diameter (D)		A	H	R
Fraction	Decimal	Head Diameter	Head Height	Head Radius
3/32	0.094	0.187	0.045	0.082
1/8	0.125	0.250	0.059	0.108
5/32	0.156	0.312	0.072	0.135
3/16	0.187	0.375	0.085	0.164
1/4	0.250	0.500	0.112	0.217
5/16	0.312	0.625	0.138	0.272
3/8	0.375	0.750	0.166	0.328

Notes: 1. Approximate proportions: A = 2.00 x D
H = 0.465 x D
R = 0.872 x D

Fig 5- 18. Universal head rivet [53]

- Rivets used in this project

As described previously, universal head rivet, 2117 T4, 1/4 diameter, 10/16 length is selected, AN470AD8-8 or MS20470AD8-8.

Table 5- 14. Universal shop head [53]

Rivet	Shank Diameter	Shop Head Diameter		Head Height	
		Min.	Max.	Min.	Max.
1/16	.063	.08	.11	.02	.04
3/32	.094	.12	.16	.03	.06
1/8	.125	.16	.21	.04	.08
5/32	.156	.20	.27	.05	.10
3/16	.188	.24	.32	.06	.12
1/4	.250	.33	.43	.08	.17
5/16	.313	.41	.53	.11	.21
3/8	.375	.49	.64	.12	.25

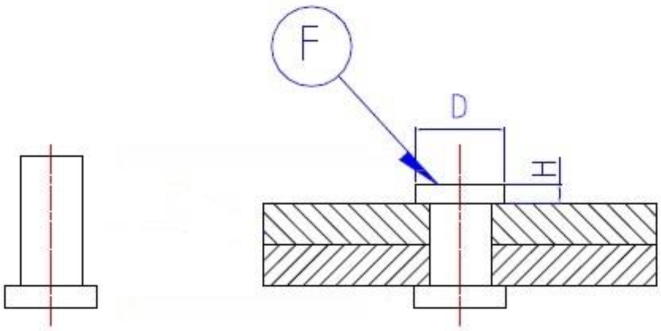


Fig 5- 19. Finished riveting index

Riveting axial force calculation empirical formula [84]:

$$P = Z \times n \times \sigma_b \times \left(1 + a \times \mu \times \frac{D}{4H}\right) \times F$$

Where:

P= axial force, N

H= shop head height, mm

D= shop head diameter, mm

F= tool contact square, mm^2

D, H, and F can be seen in Table 5-14 and Fig 5-19.

Riveting material σ_b and other constant values can be seen in Table 5-16.

Table 5- 15. Material condition number index

CLASS	MATERIAL BEING MACHINED	MATERIAL EXAMPLES	BRINELL HARDNESS	DESCRIPTION
20	**ALUMINUM ALLOY** CAST AND WROUGHT	308.0, 356.0, 360.0, 380.0, 383.0, 390.0, 2024, 3003, 4032, 5052, 6061, 7075	30-150 (500 kg)	DISCONTINUOUS FLAKY OR LONG STRINGY
	COPPER ALLOY TOUGH	101, 110, 115, 120, 130, 142, 155, 170, 172, 175, 195, 425, 610, 630, 655, 725, 805, 826, 910	40-200 (500 kg)	LONG CONTINUOUS
	LEAD ALLOY	Alloys 7, 8, 13, 15 1Sb, 4Sb, 6Sb, 8Sb, 9Sb	10-20 (500 kg)	DISCONTINUOUS TIGHTLY CURLED
	PLASTIC	ABS, Acrylic, Allyl, Bakelite, Epoxy, Furan, Nylon, Polyethylene, Polystyrene, PVC	–	CONTINUOUS
	ZINC ALLOY	AC41A, AG40A, AMS4803, ILZRO 12, ZDC NO. 7, GRADES 903, 925	80-100	LONG TIGHTLY CURLED
40	**ALUMINUM BRONZE**	614, 952-958	40-175	SHORT LOOSELY CURLED
	COPPER ALLOY/BRASS/BRONZE FREE MACHINING	268, 270, 314, 332, 335, 340, 342, 353, 356, 360, 370, 464-467, 485, 838, 945	10-100 Rb	FLAT SMALL
	MAGNESIUM ALLOY	AM60A, AZ21A, AZ91B-C, HM31A, K1A, ZE41A, ZK40A	50-90 (500 kg)	FLAT SMALL
	NICKEL SILVER	745, 752, 754, 757, 700, 973-978	10-100 Rb	LOOSELY CURLED
60	**CAST IRON-DUCTILE** AUSTENITIC (NI-RESIST)	TYPES D-2, D-2B, D-2C, D-2M, D-3, D-3A, D-4, D-5, D-5B	120-275	DISCONTINUOUS TIGHTLY CURLED
	CAST IRON-DUCTILE FERRITIC & FERRITIC-PEARLITIC	GRADES 60-40-18, 65-45-12, 80-55-06, D4018, D4512, D5506	140-270	DISCONTINUOUS TIGHTLY CURLED
	CAST IRON-DUCTILE MARTENSITIC & PEARLITIC-MARTENSITIC	GRADES 100-70-03, 120-90-02, D7003, DQ&T	270-400	DISCONTINUOUS TIGHTLY CURLED
	CAST IRON-GRAY FERRITIC & FERRITIC-PEARLITIC	CLASSES 20, 25, 30, 35, 40 GRADES G1800, G2500, G3000	120-220	DISCONTINUOUS
	CAST IRON-GRAY PEARLITIC	CLASSES 45, 50, 55, 60 GRADES G3500, G4000	220-320	DISCONTINUOUS
	CAST IRON-MALLEABLE FERRITIC & PEARLITIC	CLASSES 32510, 35018, 40010, 45008 GRADES M3210, M4504, M5003	110-240	DISCONTINUOUS
	CAST IRON-MALLEABLE TEMPERED MARTENSITE	GRADES 60004, 70003, 80002 GRADES M5003, M8501	200-320	DISCONTINUOUS
80	**STEEL-LOW & MEDIUM STRENGTH** FREE MACHINING	1108-1119, 1132-1151, 10L17, 10L18, 10L50, 11L44, 12L13, 12L14, 12L15	100-250	DISCONTINUOUS LOOSELY CURLED
	STEEL-LOW & MEDIUM STRENGTH WROUGHT	1005-1029, 1030-1050, 1513, 1518, 1524, 1552	100-375	CONTINUOUS STRINGY

Table 5- 16. Constant Values for axial force [54]

Symbol	**Item**	**Condition**		**Value**
σ_b	Brinell Hardness	20#		350
		40#		400
		60#		500
		80#		550
Z	Deformation Coefficient	**Process**	**Shape**	**Coefficient**
		pre-riveting	simple	1.0-1.2
		lean-riveting	simple	1.2-1.5
		lean-riveting	complex	1.5-1.8
n	Tool Deformation Coefficient	**Lumpy**	**Pointedness**	**Coefficient**
		no	no	1
		yes	no	1.75-2.0
		yes	yes	2.5
a	Shop Head Shape Coefficient	Cylinder		1.3
		Hexagon		2
		Rectangle		2.3
		Complex Shape		2.5-3.0
μ	Friction Coefficient	**Face**	**Lubrication**	**Coefficient**
		grind	Graphite	0.05-0.10
		grind	no	0.10-0.15
		lean machining		0.15-0.20
		rough machining		0.20-0.30

As known, the rivet material is aluminum and rivet diameter is 1/4 in, according to Table 5-15 and 5-16. σ_b =350, Z=1.5, n=1, a=1.3, μ =0.10, D=0.35×25.4,

H= 0.125×25.4, F= $\pi\times\left(\frac{0.35\times25.4}{2}\right)^2$.

$$P = Z \times n \times \sigma_b \times \left(1 + a \times \mu \times \frac{D}{4H}\right) \times F$$

$$= 1.5 \times 1 \times 350 \times \left(1 + 1.3 \times 0.1 \times \frac{0.35 \times 25.4}{4 \times 0.125 \times 25.4}\right) \times \pi \left(\frac{0.35 \times 25.4}{2}\right)^2$$ =35535 N ≈ 8000 lbs.

- Squeezer

The principal parts of air squeezer are the cylinder, the throttle valve, the blow off valve, the piston, moving jaw and anvil set. A typical C yoke squeezer is shown in Fig 5-20.

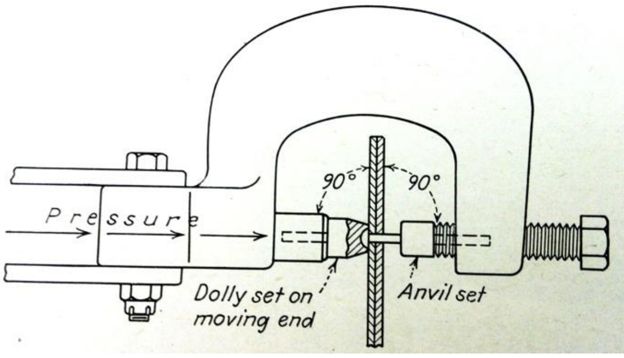


Fig 5- 20. C yoke squeezer operations [55]

Fig 5-21 and Table 5-17 show different riveters' parameters about the force they can provide.

Tri-Cylinder				
Part Number	Reach	Capacity	O.A.L.	Weight
34-820C	1-1/2"	1/4" Alum. 3/16" Steel	18-3/4" (47.6 cm)	8.5 lbs (3.9 kgs)

Fig 5- 21. High power c-yoke riveter [56]

Table 5- 17. Tandem compression riveters [57]

Tandem Compression Riveters, "Alligator" Yoke

Model No.	Rivet Capacity		Yoke Reach	Yoke Gap	Closed Height	Shank Diameter	Max. Force	Max. Travel
	Alum.	Steel						
MP-351A-TAN-918	3/16"	5/32"	9-1/8"	2-3/16"	3/4"	0.187"	6000 lbs.	1-11/16"
MP-351A-TAN-7	3/16"	5/32"	7"	2"	1-1/2"		6000 lbs.	1-11/16"
MP-351A-TAN-5	3/16"	5/32"	5"	1-5/8"	7/8"		6800 lbs.	1-3/8"
MP-351A-TAN-278	1/4"	3/16"	2-7/8"	1-5/8"	7/8"		10400 lbs.	5/8"

Tandem Compression Riveters, "C" Yoke

Model No.	Rivet Capacity		Yoke Reach	Yoke Gap	Closed Height	Shank Diameter	Max. Force	Max. Travel
	Alum.	Steel						
MP-351C-TAN-218	1/4"	7/32"	2-1/8"	1-3/16"	25/32"	0.187"	12000 lbs.	9/16"

From the riveters shown above, the force for 1/4 in rivet is 9000-12000 lbs. They all meet this project requirement as calculated 8000 lbs.

5.4.2.5.3 Modelling

According to the above parameters calculated about riveting and requirements, the end-effector modelling is proposed, as show in Fig 5-22.

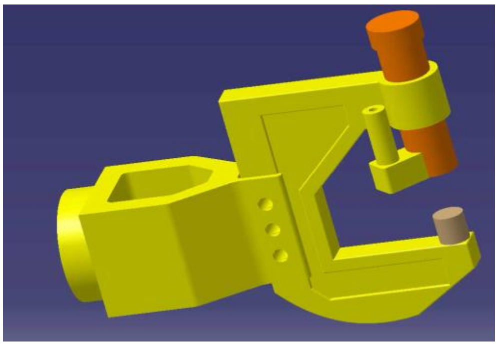


Fig 5- 22. End-effector for feeding rivets and riveting

5.4.3 End-effector specification

When the project will be tested in reality, the end-effectors and other resource specifications will be very useful information. In this project, the work of test in reality hasn't been done, but the specifications have been prepared below.

5.4.3.1 Robot Specification

Table 5-18 shows the robot specification and the robot photo can be seen in Fig 5-23.

Table 5- 18. Robot specification

Feature	Specification
Type	IRB 6400 M98 3.0-75, 2100kg
Control	S4C
Axes	6
Capacity	75kg (165 lbs)
Repeatability	0.15mm (0.006 in)
Reach	3000mm (118 in)
Power	Electric power

Fig 5- 23. IRB robot (From ABB)

The robots of ABB IRB 6400 M98 are used worldwide. They were deployed in automotive manufacturing 20 years ago. They are famous for reliability, capability and the industry standard [58].

5.4.3.2 Laser ablation end-effector Specification

Table 5-19 shows the Laser ablation end-effector specification and the Laser ablation end-effector photo can be seen in Fig 5-24.

Table 5- 19. Laser ablation specification

Feature	Specification
Laser system	CL 50
Average laser power	up to 100 Watt
Laser class	4
Electrical requirement	115 or 230V
Flexible fiber optic beam delivery	up to 12 ft
Optic	OSA 70
Optics operating distance	up to 20 in
Beam width	up to 4 in
Cycle time	variable

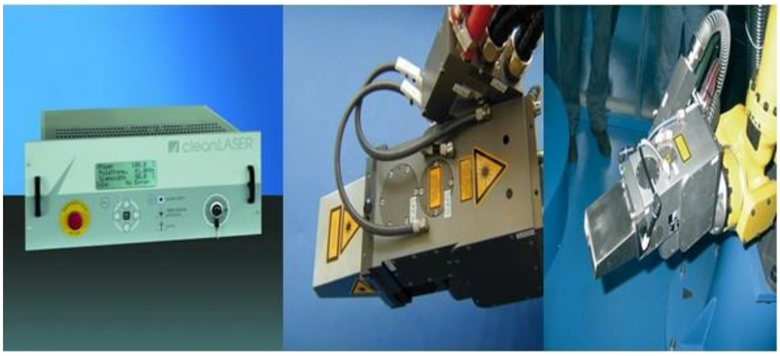


Fig 5- 24. Laser system and optic (From Clean Laser)

The laser ablation equipment consists of the laser source and a fiber optic.

The CL 50 is air-cooled q-switched pulsed laser systems. Compact and versatile, it has an excellent reputation for the cost-effective treatment and using in small areas where need to meet requirements of high precision cleaning.

The OSA 70 optic was designed for robotic applications. The optic can easily be attached to all common robotic systems [59].

5.4.3.3 Spray adhesive end-effector Specification

Table 5-20 shows the Spray adhesive end-effector specification and the Spray adhesive end-effector photo can be seen in Fig 5-25.

Table 5- 20. Spray adhesive specification

Feature	Specification
Maximum working fluid pressure	100 psi (0.7 MPa, 7 bar)
Maximum working air pressure	100 psi (0.7 MPa, 7 bar)
Maximum HVLP Inbound Air Pressure	10 psi (0.07 MPa, 0.7 bar)
Maximum Working Fluid Temperature	120° F (49° C)
Minimum Air Cylinder Actuation Pressure	50 psi (0.34 MPa, 3.4 bar)
Spray type	HVLP
Nozzle size	Φ=1.3 mm (0.051 in)
Cycle time	variable (0.1s - 2s)
Fluid flow	35 - 350 cc/min (1.2 - 11.8 oz/min)

Fig 5- 25. Spray adhesive end-effector

Automatic HVLP spray gun, it can spray on small areas and meet precision requirement [60].

5.4.3.4 Venturi vacuum end-effector Specification

Table 5-21 shows the Venturi vacuum end-effector specification and the Venturi vacuum end-effector picture can be seen in Fig 5-26.

Table 5- 21. Venturi vacuum specification

Feature	Specification
Type	VSA-ARV
Speed to vacuum	0.2-0.3 seconds
Speed to release	0.02 seconds
Air supply pressure	60 psi
Vacuum level	27inhg (-0.88bar)
Air consumption	Vacuum=1.4scfm or 40l/m during vacuum Blow off = 0 Noise level: 68dBA
Handling capacity	3.2kg-10.3kg (7lbs-22.7lbs)
Cycle time	150 plus cycles per minute

Fig 5- 26. Venturi vacuum end-effector

DE-STA-CO's patented Auto-Release Venturi Vacuum Generator with a single air line offers users the fastest vacuum and blowoff in the industry. Vacuum levels will reach as high as 27inhg or -0.88bar at airline pressures of 60psi or 4 bar [61].

5.4.3.5 Drilling end-effector Specification

Table 5-22 shows the drilling end-effector specification and the drilling end-effector photo can be seen in Fig 5-27.

Table 5- 22. Drilling specification

Feature	Specification
Stroke	Max. 6 in (150mm)
Thrust capacity	2,000 lbs. (907 kg)
RPM	Max. 10000
Spindle motor capacity	7.5 HP (5.6 kW)
Power	Electric servo
Spindle nose	HSK
Quill diameter	4.72 in (120mm)
Feed rate	0.003-0.008 in/rev (0.075-0.20mm/rev)

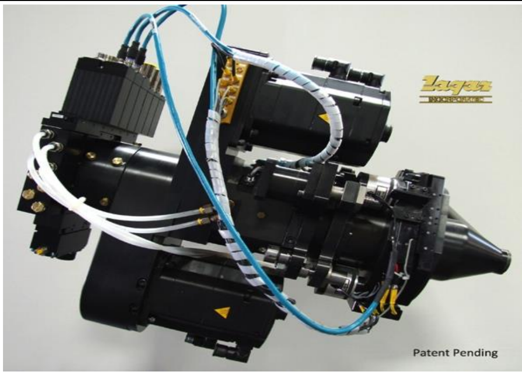


Fig 5- 27. Drilling end-effector

Zagar Inc's. Robotic End Effectors can be mounted on robot arm and finish precision drilling, milling, counter sinking, counter-boring, and trimming [62].

5.4.3.6 Riveting end-effector Specification

Table 5-23 shows the riveting end-effector specification and the riveting end-effector photo can be seen in Fig 5-28.

Table 5- 23. Riveting specification

Feature	Specification
Stroke	Max. 6 in (150mm)
Rivet Compatibility	up to diameter 1/4in (6.4 mm), length 0.157-0.551 in (4-14mm)
Throat depths	from 60mm to 1500mm
Thrust Capacity	53333 N (12000 lbf)
Cycle time	less than 0.75s
Power	Electric Servo

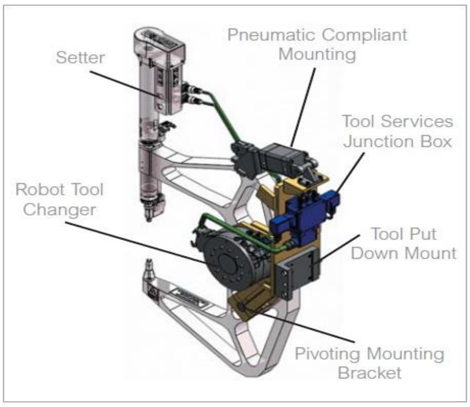


Fig 5- 28. Electric Servo Riveting for Robot Mounting

Henrob electric rivet setter can meet market demand for full range of rivets and material combinations, robot mounted servo tool capable of fast cycle times with high reliability, and provide a high level of control [63].

5.4.3.7 Automatic tool changer

5.4.3.7.1 Tool changer requirement

Just like end-effector specifications presented above, the tool changer will be play an important role on end-effectors changing in reality. In order to fit the interface between robot arm and end-effector, the tool changer should meet the requirements below.

1) Can be mounted on robot arm

2) Accurate, repeatable mounting of robotic end-of-arm tooling.
3) Rigid and Lightweight
4) Standard interface
5) Durable– long life, low maintenance
6) Handles capacity: up to 150 lbf.
7) Collision sensor

5.4.3.7.2 Tool changer Specification

Table 5-24 shows the tool changer specification and the tool changer photo can be seen in Fig 5-29.

Table 5- 24. Tool changer Specification

Feature	Specification
Type (Robot Half)	QC-150
Type (Tool Half)	TP-150
Payload	150 lbs (68 Kg)
Moment Rating	1900 in-lbs (215 Nm)
Pressure Range (locked cylinder)	40-100 psi (3-7 bar)
Temperature Range	-30°~180° F (-35°~80° C)
Repeatability	± 0.001 in. (±0.025 mm)

Fig 5- 29. Tool changer

The tool half is inserted into the robot half. The tool half and robot half are mounted on end effector and robot respectively [64].

5.4.4 Station stand

According to the developed Leading Edge components and the robot work-envelop, and considering the end-effector working directions, station stand was developed, as shown in Fig 5-30. And the distribution of the Leading Edge on station stand can be seen in Fig 5-31.

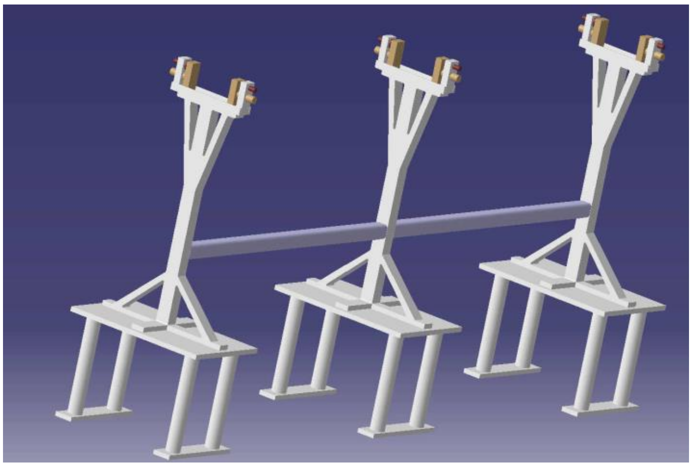


Fig 5- 30. The station stand model

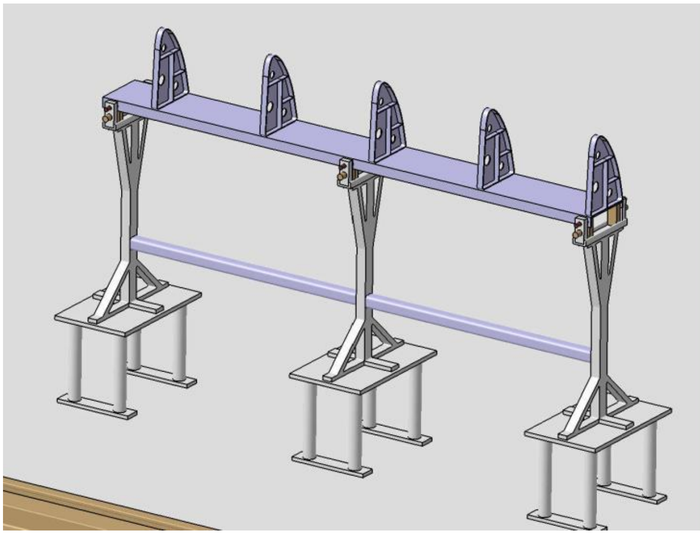


Fig 5- 31. The models distribution

5.4.5 Components storage fixture

In order to pick and place bracket conveniently, a suitable storage fixture is developed, as shown in Fig 5-32. The brackets are placed perpendicularly and there is enough space for robot arm to handling the mating surface.

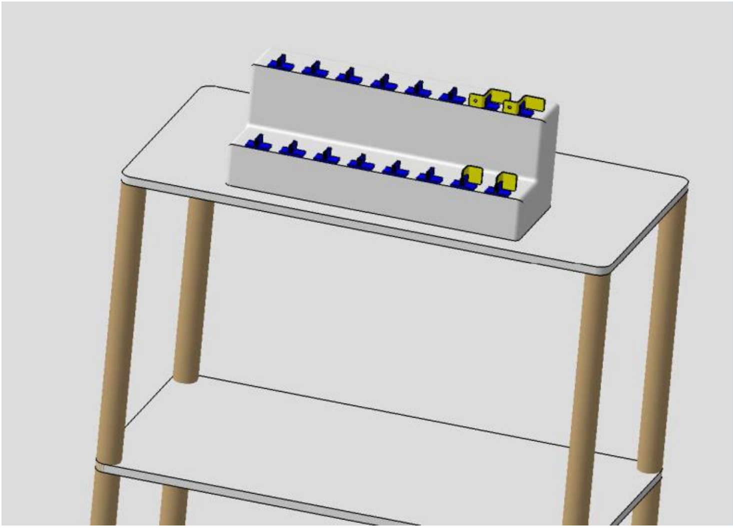


Fig 5- 32. The storage fixture

6. ALEA Framework Evaluation

6.1 Introduction

This chapter mainly describes how to evaluate the framework of ALEA. It should have been evaluated from three approaches, robotic automated bracket assembly process simulation, cost estimation and test in reality. But, the researcher did not develop the last step which can be done in the future for reasons, such as limited of time and resources. So process simulation and cost estimation are developed in this chapter.

6.2 Simulation

The bracket assembly process was proposed before. The task of simulation started with robotic workcell environment construction in DELMIA. Then followed the most important work which is allocation of the PPR, next step is to simulate the whole process, and the final task is to analyze the simulation and optimize the tasks if necessary.

6.2.1 Workcell environment layout

In order to make the simulation more realistic, the robotic workcell environment should be designed and distributed in DELMIA. It is simply developed and consists of floor, walls, warning lamps, component storage and involved equipment. Fig 6-1 shows the distribution of the robotic workcell.

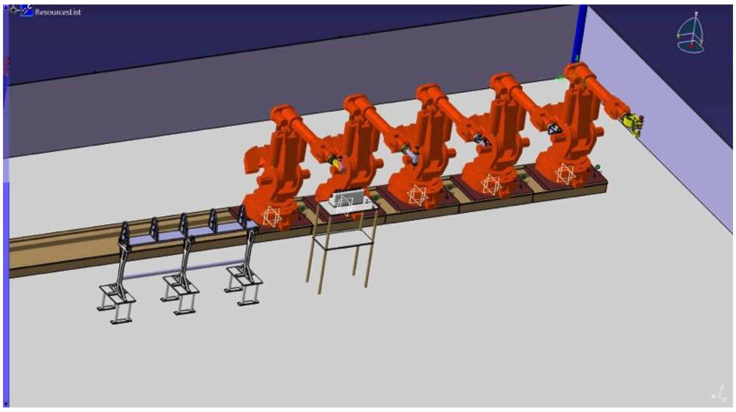


Fig 6- 1. The distribution of the robotic workcell

6.2.2 Perform PPR

In order to be sure that the resource is working as required, and to detect any errors before beginning the simulation process. Many times tests have been operated. The allocation of PPR is proposed to be divided into four stages

- Stage 1 Device building

Device building which gives tools life through setting up mechanism for them provides a complete set of tools for modeling mechanical systems that are typically used in the manufacturing process. Such systems include robotic end-effectors, positioning devices, tracks, etc. The target is generic modeling forward-kinematic devices that can be driven using joint coordinates.

Robot sliding rail can be seen as a linear track and be built as an auxiliary device for robot. Except robot sliding rail, there are also five end-effectors need to be built in this simulation. If there is a problem in the course of device building, optimization work is necessary until the device has been built successfully. After device building as required, the properties of the resources like TCP, mechanical motion and piston motion have been setup. Just like the resources are alive like a human. Without these properties, the robots can't finish the desired tasks.

- Stage 2 Device task definition

Robot task definition provides an interactive sequencing tool that enables users to create complete workcell logic by sequencing different robot or device programs. A rich library of hundreds of robots and controllers for all major industrial robot manufacturers is provided to support programmers in their layout and programming tasks. In this interactive 3D environment, devices are mounted on the robot arms. Then the robot can be seen as a waiting for command human, she can do what the master tell her, as shown in Fig 12.

- Stage 3 Process planning

In this step, all works are to let robot move and work complying with the automated bracket assembly process proposed in chapter 5.3. There are five operations need to be created, and each operation follows the same steps presented below.

1) Create tags

Tags points are created to give the robot a path to follow perform the job at hand. The job may be surface treatment, adhesions, pick and place or other tasks. The tag points need to be stored somewhere and this is where robot tasks come in. A robot task is a storage area for multiple tag points or groups. By creating tag points a path is created, this path can be numbered and named. Fig 6-2 shows the tag groups. Base position points such as place points, drilling points and riveting points are stored in Tag group 0, and other tag groups represent robot task paths.

Fig 6- 2. The tag groups

2) Create robot tasks

A robot task is a linear sequence of activities called operations; each operation can contain a motion and a set of actions. Tag group created is assigned to a robot task in sequence, and the robot can move to the selected locations (tag points) to finish the required tasks. Now a robot can work separately and a single robot task is created.

3) Create activities

After single robot task creation, to start to create station activities that can be seen as assembly operations. An activity can be a storage area for steps in the process. The activities should be in sequence which is the same as assembly process presented in chapter 5.3. Fig 6-3 demonstrates the station activities (assembly operations) in sequence. And the sequence can be adjusted in PERT chart which is a project management tool used to schedule, organize, and coordinate tasks within a project. A PERT chart presents a graphic representation of the process flow. It allows for modification of the process plan in a dynamic manner. The bracket assembly process PERT chart is shown in Fig 6-4.

Creation of activities is done to store the resources and products necessary to complete a task or activity. These tasks or activities may then be coordinated to create a correctly sequenced simulation of an overall process.

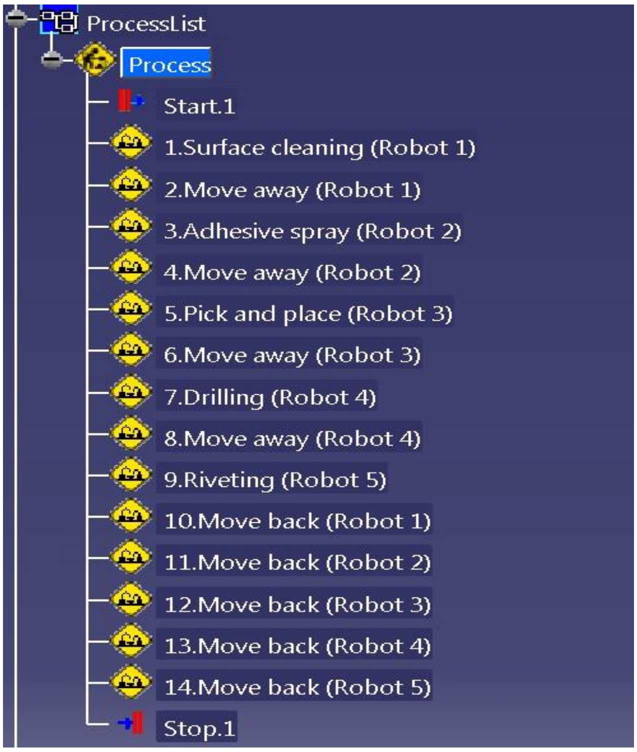


Fig 6- 3. The assembly operations

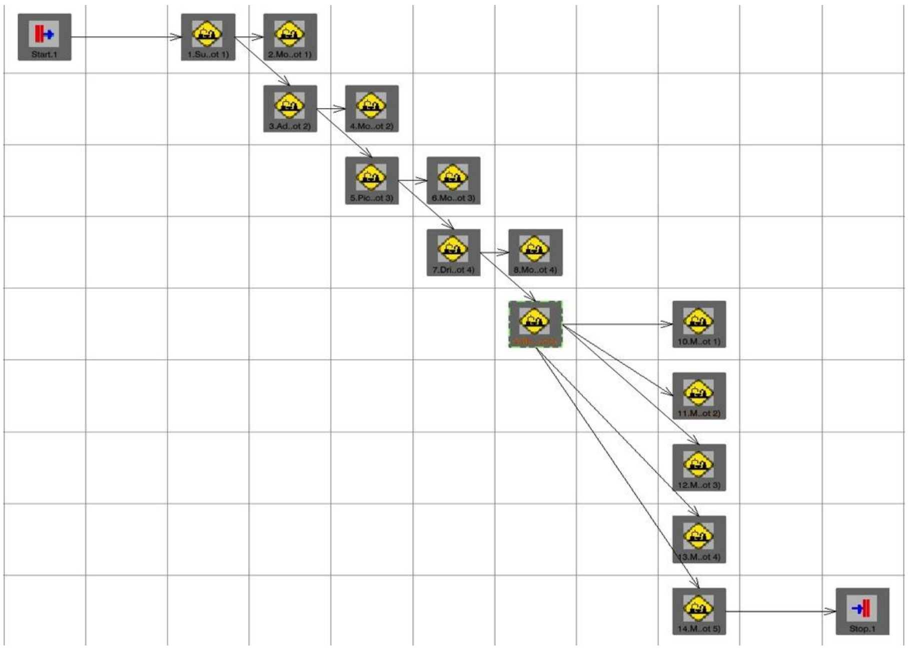


Fig 6- 4. Assembly process PERT chart

- Stage 4 Assignment and set tasks active

Both products and associated resources will be assigned to the process activities. Without them, the simulation can't take place. After the work of assignment, the finished goods is created.

Product assignment is usually assigned as process first process product and process processes product, process first process product is an input process which should be selected when a product is first processed by a process; process processes product is also an input process which is selected when a product is processed in a further process.

Resources assignment is usually assigned as process uses resource and process runs resource, process uses resource is used for Labor, Tools, Fixtures, and any auxiliary resource used during the processing; process runs resource is used for main resources such as stations, robots and machines.

After product and resource assignment, robot tasks can be assigned to the corresponding process activities, concurrently, set tasks active, and then the final process is created.

6.2.3 Automated assembly simulation

After setting active task, the simulation can be run. Robot 1 is responsible for activity 1, 2 and 10; Robot 2 is responsible for activity 3, 4 and 11; Robot 3 is responsible for activity 5, 6 and 12; Robot 4 is responsible for activity 7, 8 and 13; Robot 5 is responsible for activity 9 and 15;

Firstly, robot 1 executes activity 1 (as shown in Fig 6-5).

Secondly, robot 1 executes activity 2, robot 2 executes activity 3 concurrently (as shown in Fig 6-6).

Thirdly, robot 2 executes activity 4, robot 3 executes activity 5 concurrently.

Finally, all the robots move back to the initial position (as shown in Fig 6-7).

And all the robots work as required.

All the activities' sequence, begin time, end time, and the duration time are illustrated, the relationship between activities is also presented in the process Gantt chart (as shown in Fig 6-8).

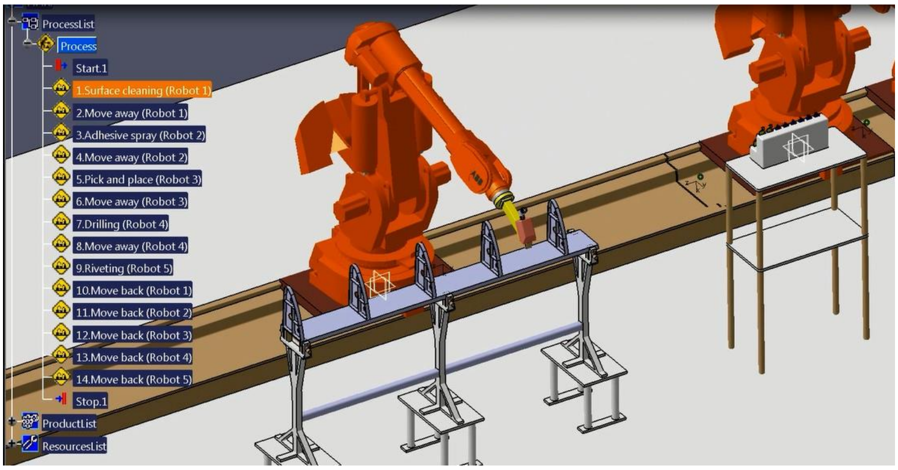


Fig 6- 5. Surface cleaning operation

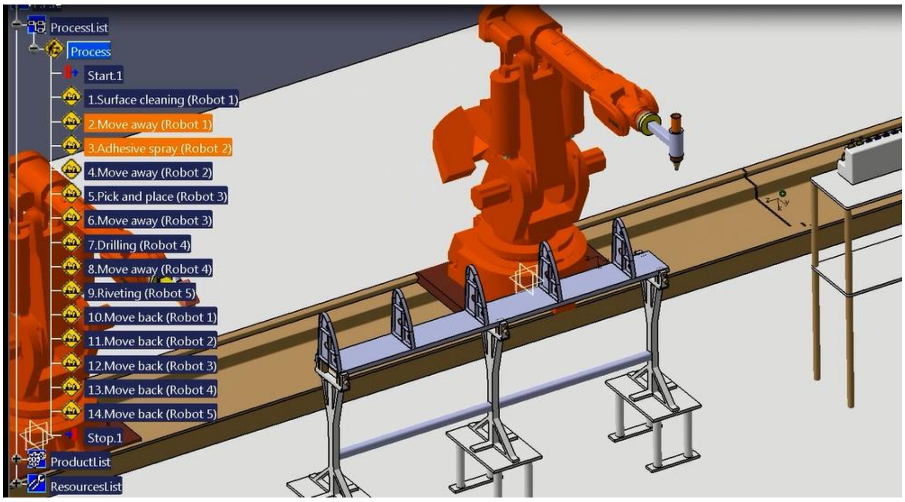


Fig 6- 6. Operations concurrently

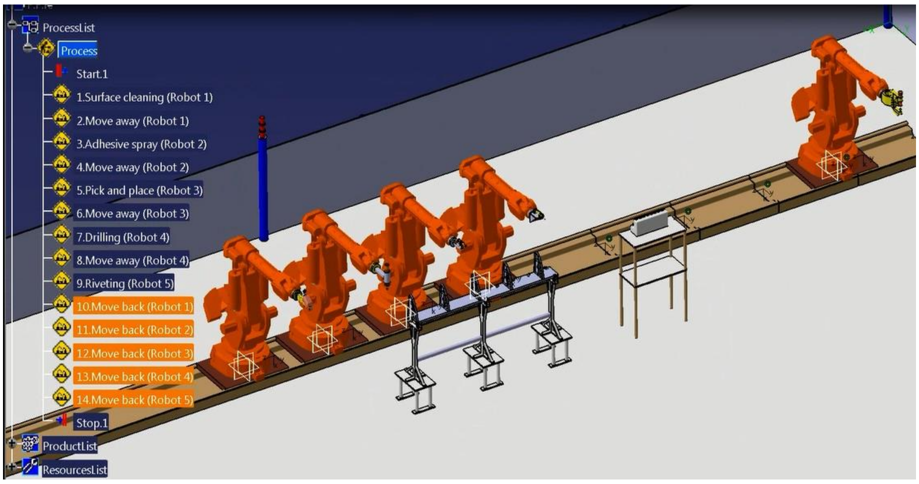
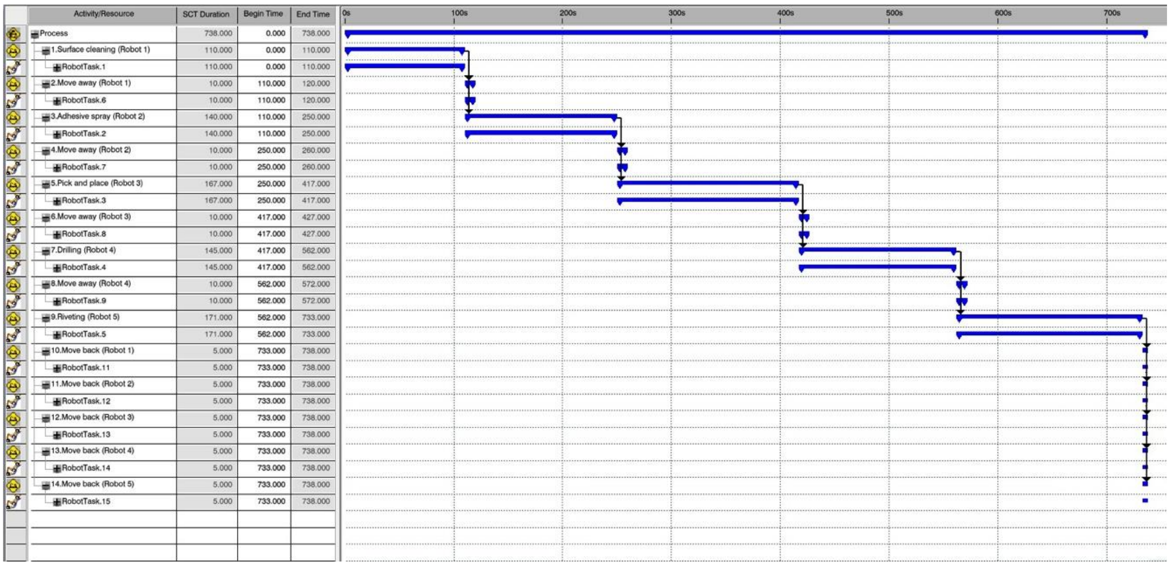


Fig 6- 7. Robots move back



Activity/Resource	SCT Duration	Begin Time	End Time
Process	738.000	0.000	738.000
1.Surface cleaning (Robot 1)	110.000	0.000	110.000
RobotTask.1	110.000	0.000	110.000
2.Move away (Robot 1)	10.000	110.000	120.000
RobotTask.6	10.000	110.000	120.000
3.Adhesive spray (Robot 2)	140.000	110.000	250.000
RobotTask.2	140.000	110.000	250.000
4.Move away (Robot 2)	10.000	250.000	260.000
RobotTask.7	10.000	250.000	260.000
5.Pick and place (Robot 3)	167.000	250.000	417.000
RobotTask.3	167.000	250.000	417.000
6.Move away (Robot 3)	10.000	417.000	427.000
RobotTask.8	10.000	417.000	427.000
7.Drilling (Robot 4)	145.000	417.000	562.000
RobotTask.4	145.000	417.000	562.000
8.Move away (Robot 4)	10.000	562.000	572.000
RobotTask.9	10.000	562.000	572.000
9.Riveting (Robot 5)	171.000	562.000	733.000
RobotTask.5	171.000	562.000	733.000
10.Move back (Robot 1)	5.000	733.000	738.000
RobotTask.11	5.000	733.000	738.000
11.Move back (Robot 2)	5.000	733.000	738.000
RobotTask.12	5.000	733.000	738.000
12.Move back (Robot 3)	5.000	733.000	738.000
RobotTask.13	5.000	733.000	738.000
13.Move back (Robot 4)	5.000	733.000	738.000
RobotTask.14	5.000	733.000	738.000
14.Move back (Robot 5)	5.000	733.000	738.000
RobotTask.15	5.000	733.000	738.000

Fig 6- 8. The process Gantt chart

6.2.4 Analysis and Optimization

Robot task analysis has many different meanings because of the various methods which can be used. Here researcher will analyze tasks for collisions/clashes; automatic task clash function (Fig 6-9) is deployed. It keeps open when running the process simulation. If a collision appears, the simulation will stop, and then find out what is the problem and solve it.

The final process simulation runs well, the process model is valid (Fig 6-10) and there is no clash. So it is supposed that the process is feasible in space because of no clash, and is feasible in logic because the process model is valid. But the final evaluation of other factors like techniques used in the process should be tested further in reality.

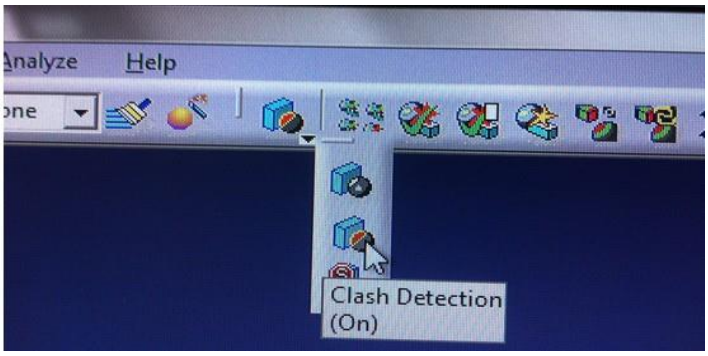


Fig 6- 9. Clash detection

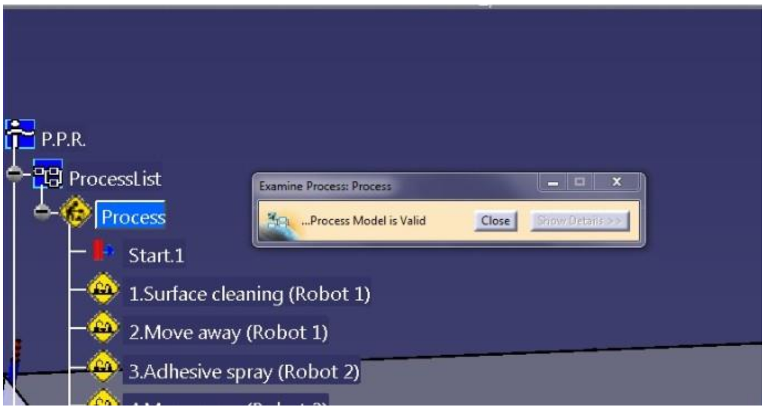


Fig 6- 10. Process model validation

6.3 Cost estimation

6.3.1 Introduction

It is a very difficult work to do assembly costs estimation accurately. However, it is very important to make decisions on overall cost and manufacturability. The recommended method for assembly cost estimation is to sum overhead, equipment cost (based on the worker's experiences), labor cost, and tolerance levels specified.

- Overhead/ Labor /Equipment cost [65] = (total time to complete operations) x (the operations' labor rate) x [1 + (Basic overhead factor) + (Equipment factor) + (Special operation/tolerance factor)]

1. Total time to complete operation(s): including setup, pick and place, fix, the actual assembly operation, cleanup, and packaging (if applicable).
2. Labor rate for the operation: hourly rate based on information about "National Occupational Employment and Wage Estimates" [66] for different job classifications available from the US Department of Labor.
   Production occupations:
   $24.43 for Aircraft Structure, Surfaces, Rigging, and Systems Assemblers.
   $14.61 for Miscellaneous Assemblers and Fabricators.
   $24.13 for specialized skills, Robot operator. Computer Numerically Controlled (CNC) Machine Tool Programmers, Metal and Plastic.

3. Basic overhead factor: It is recommended that basic overhead factor (worker benefits, buildings, utilities, training, and maintenance) is 100% (or a value of 1).
4. Equipment factor: It is recommended that assembly and manufacturing operations which require equipment or tooling is 50% (or a value of 0.5).
5. Special operation / tolerance factor: It is recommended that special case operations (laser welding, CNC machining, robot operating) and / or tight tolerance requirements (due to increased cost of equipment and personnel, levels of scrap) is 25% (or a value of 0.25).

In this project, the objective is to evaluate automated assembly is feasible in reality. So component cost will not be considered. And the condition of assembly is that there is one robot, five end effectors and involved tool changers, and other auxiliary tools.

6.3.2 Cost calculation

- **Manual assembly cost:**

There are three people to finish this tasks, two skilled people finish operations 1-3, and another people finish the operation 4.

Operation 1: 0.05 hour (Bracket holes position confirmation: 0.05 hour, Bracket holes drill: 0.05 hour);

Operation 2: 0.075 hour (Bracket assembly position confirmation: 0.05 hour, Front spar holes drill: 0.1 hour);

Operation 3: 0.05 hour (Riveting);

Operation 4: 0.05 hour (Cleaning up);

According to the information presented before, the workers hourly average wages are $24.43/hr and $14.61/hr respectively. So the cost details for bracket assembly manually are shown in Table 6-1 below.

Table 6- 1. Cost details for manual bracket assembly

Process	Operation 1	Operation 2	Operation 3	Operation 4
Details	Confirm bracket holes position, and then drill the holes	Confirm front spar holes position, fix the involved components and then drill the holes of spar	Rivet bracket and front spar together	Clean up
A. Total time to complete operation(s) in hours	0.05 hour per bracket	0.075 hour per bracket	0.05 hour per bracket	0.05 hour per bracket
B. labor rate for the operation	$24.43/hr	$24.43/hr	$24.43/hr	$14.61/hr
C. Labor cost ($)= A x B	1.222	1.831	1.222	0.731
D. basic overhead factor	1	1	1	1
E. Equipment factor	0.5	0.5	0.5	0.5
F. Special operation , tolerance factor	0	0	0	0
G. labor/overhead/equipment cost($) = C x (1+D+E+F)	3.054	4.581	3.054	1.827
Overall cost ($)	12.516			

- **Automated assembly cost:**

As presented in chapter 6.2.3, it takes about 738 seconds (12 minutes) to finish assembling four brackets, so it may need about 3 minutes (0.05 hour) to assemble one bracket. Two people are needed to assist this task, what are they responsible for is shown below. The total time to complete operation(s) in hours per bracket for each people is an average time, for example, people works in operation 2 can clean up the workplace one time when 20 brackets have been assembled, other time he can feed brackets or do other assistant works.

➢ Operation 1: 0.05 hour (robots are responsible for cleaning front spar surface, spraying adhesive, picking and placing bracket, drilling bracket and spar together, and riveting permanently; the skilled people is responsible for programming tasks, watching the robot working condition and dealing with emergency as necessary);

- Operation 2: 0.05 hour (people here is responsible for cleaning up the workplace, feeding brackets and other assistant tasks);

According to the information presented before, the workers hourly average wages are \$24.13/hr and \$14.61/hr respectively. So the part of cost details for bracket assembly automatically is shown in table below. The total cost of automatic assembly is sum the Machines cost and the labor/overhead/equipment cost.

Table 6- 2. Cost details for automated bracket assembly

Process	Operation 1	Operation 2
Details	Robot operations	Feed brackets and Clean up
A. Total time to complete operation(s) in hours	0.05 hour per bracket	0.05 hour per bracket
B. labor rate for the operation	\$24.13/hr	\$14.61/hr
C. Labor cost (\$)= A x B	1.207	0.731
D. basic overhead factor	1	1
E. Equipment factor	0.5	0.5
F. Special operation/tolerance factor	0.25	0
G. labor/overhead/equipment cost(\$) = C x (1+D+E+F)	3.018	1.827
Overall cost (\$)	4.845	

If want to know which method is cost effective between manual assembly and automated assembly based on different stages. So the critical value of the quantity of bracket assembled need to be figured out.

The recommended (From experienced workers) equation is: Manual assembly cost = Automated assembly cost.

- Manual labor/overhead/equipment cost X N + R1 X N X manufacturing cost/per bracket + R2 X N X reassembly cost/per bracket = Machine cost + Automated labor/overhead/equipment cost X N

Where,

N is quantity of bracket assembled.

R1 is scrappage before bracket is assembled.

R2 is scrappage after bracket is assembled

Here,

R1≈0.3%

R2≈0.2%

Manufacturing cost/per bracket ≈ manual labor/overhead/equipment cost.

Reassembly cost/per bracket ≈2 manual labor/overhead/equipment cost.

Machine cost (as shown in Table) = Robot cost + End effectors cost + Tool changers cost + other tools cost.

So, $12.516 \times N + 0.3\% \times N \times 12.516 + 0.2\% \times N \times 2 \times 12.516 = 150000 + 4.845 \times N$

N≈20000.

The quantity of 20000 is a balance point, if a company plans to produce less than this quantity of items, manual assembly will be a cost effective method, if the company can produce more than this quantity of items, and automated assembly will be a better choice. For aerospace industry, there is large quantity of brackets, and it is a better way to utilize robotic automated assembly technology.

Table 6- 3. Estimated machine cost

Machines	Estimated unit price ($)	Quantity	Total cost ($)
Robot	70000	1	70000
Laser ablation	30000	1	30000
Spray gun	3000	1	3000
Pick and place	2000	1	2000
Drilling	15000	1	15000
Riveting	15000	1	15000
Tool changer	10000	1	10000
Others	5000	1	5000
Overall cost($)	150000		

6.3.3 Payback period calculation

Payback period (PB) measures the time when cash outflows is equal to total cash inflows, which is, the time required to break even.

1). Take an airplane company A for example, select automation to assemble the brackets. This company's airplane output is about 20 ships/per month (Boeing output is about 60 ships/per month), and about 200 brackets are assembled on each airplane's wing, so 4000 brackets will be assembled per month.

Cash outflows = 150000+ 4.845N,

Cash inflows = QN,

Where,

Cash outflows here account for machine cost and labor cost;

Cash inflows here account for product cost and product profit;

Q is each bracket price including the bracket cost and profit (Q is a various value according to different companies, and here is assumed as $15); N is the quantity of bracket.

According to the equation above, the table can be shown below:

Table 6- 4. Cash flow condition

Expected Cash Flow	Month 0	Month 1	Month 2	Month 3	Month 4
Bracket quantity	0	4000	4000	4000	4000
Cash Inflows ($)	0	60000	60000	60000	60000
Cash Outflows($)	-150000	-20000	-20000	-20000	-20000
Net Cash Flow($)	-150000	40000	40000	40000	40000
Cumulative Cash Flow($)	-150000	-110000	-70000	-30000	10000

Net cash flow: Sum cash inflows and outflows together for each month.

Cumulative cash flow: Sum cash inflows and outflows for all previous months and the current month.

When will the investment break even? According to cumulative cash flow at the bottom row in Table 6-4, it is clear that PB occurs sometime in Month 4 because cumulative cash flow is negative at Month 3 end and positive at end of Month 4. The Fig 6-11 shows when cumulative cash flow crosses from negative to positive:

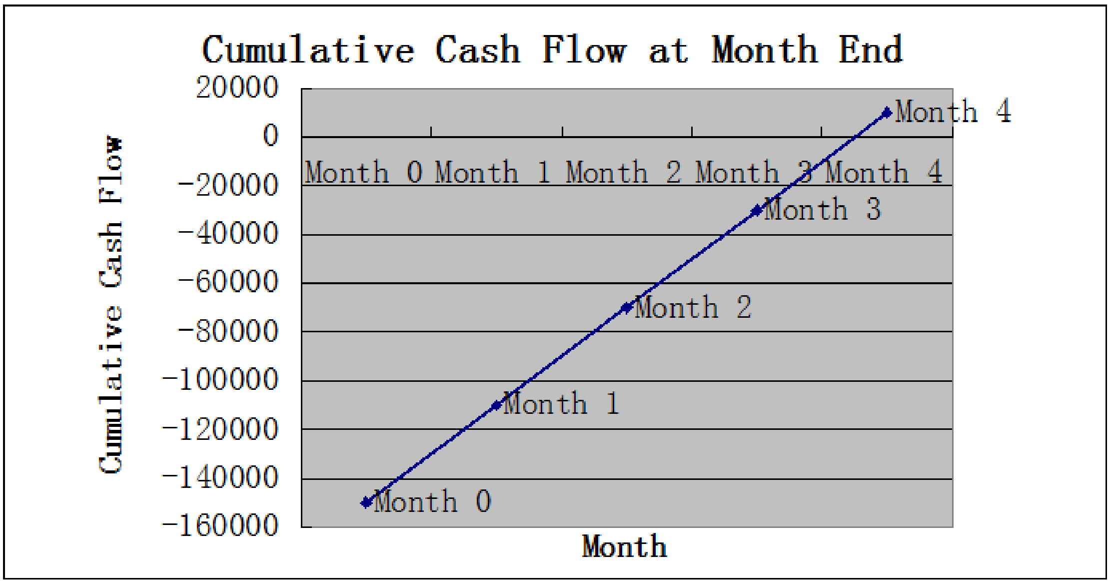


Fig 6- 11. Cumulative cash flow condition

Usually break even may happen at any time when the cumulative cash flow becomes 0 in month 4, if there is only per month cash flow data to work with and no further information about when cash flow appears within month 4. It must assume that the month's cash flows are spread evenly through the month.

Using the datum in table above, where cumulative cash flow clearly reaches 0 in Month 4, PB can be calculated (estimated) as follows;

Y=40000X-150000

Where

Y=cumulative cash flow,

X=month

When Y=0,

It can be calculated X=3.75 Months. So Payback period=3.75 Months.

2). Take another airplane company C for example, this company's airplane output is about 4 ships/per month (Boeing output is about 60 ships/per month), and about 200 brackets are assembled on each airplane’s wing, so 800 brackets will be assembled per month.

Table 6-5 shows Cumulative Cash Flow, Fig 6-12 shows when cumulative cash flow crosses from negative to positive.

Table 6- 5. Cash flow condition

Expected Cash Flow	Month 0	Month 1	Month 2	Month 3	......	Month 18	Month 19
Bracket quantity	0	800	800	800	800	800	800
Cash Inflows ($)	0	12000	12000	12000	12000	12000	12000
Cash Outflows($)	-150000	-4000	-4000	-4000	-4000	-4000	-4000
Net Cash Flow($)	-150000	8000	8000	8000	8000	8000	8000
Cumulative Cash Flow($)	-150000	-142000	-134000	-126000	......	-6000	2000

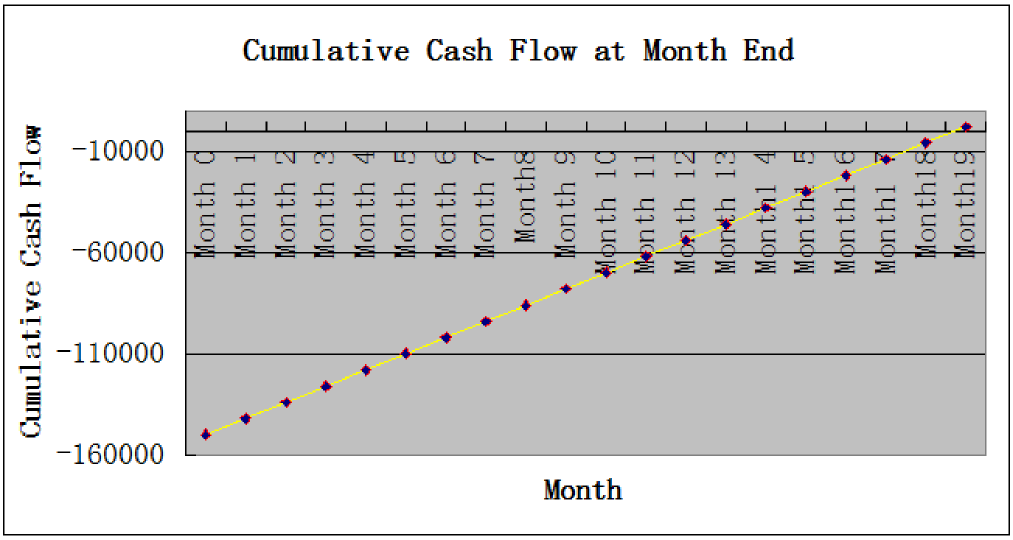


Fig 6- 12. Cumulative cash flow condition

Applying the same method as the method above, it can be calculated that Payback period=18.75 Months.

As known, shorter payback period is better than a longer payback. The payback period is very important for engineer to make decisions. It can reveal the risk of project investment to some extent, because it gives a quick chart of the amount of time when it will break even. A shorter payback period is seemed to be less risky. Investment or action costs are recovered sooner and can be used for further investment.

7. Discussions and Conclusions

7.1 Introduction

This chapter will firstly discuss the research work implemented and achievements of this project, and then the contribution to knowledge, research limitations and recommendations for future work are clarified in the following sections.

7.2 Discussion

The aims of research are to propose a methodology to develop the automated assembly based on robotics and to develop a new concept of Automated Leading Edge Assembly: using robots to replace workers to finish the assembly applications in the Leading Edge. All these are to replace manual assembly by automated assembly, to reduce cost and increase the productivity without affecting products quality.

This part will discuss the research work implemented from three aspects: Project methodology, Automated Leading Edge Assembly concept and automated bracket assembly process development. The methodology will be used as guidance for automated assembly development, the new concept of ALEA will be the key to open the area of automated system assembly, and automated bracket assembly process development can be seen as a case study.

7.2.1 Project methodology

The project methodology presented in this research has provided an effective process to guide the project step by step. The logic steps provide proper information for the research development at the proper stage. This methodology has led to automated bracket assembly process development and its evaluation including DELMIA simulation and cost estimation. And it will provide guidance for other projects about how to develop assembly from manual to automated assembly in some extent.

The methodology is developed based on a rule which is developed from the most general to the most specific. Firstly, Methodology for engineering project development is generally proposed, it consists of two key sections which are methodology for choosing assembly method and methodology for assembly systems development including methodology for assembly development and methodology for assembly evaluation. Secondly, the two key methodologies are proposed one by one. Finally, methodology for product development, resource development, process simulation and cost estimation are developed specifically under the guidance of methodology of assembly system development.

- In the stage of choosing assembly method, there are three kinds of assembly methods, which are implementing with humans, implement with robot and implement with automated machines. There are some important factors presented in chapter 3 to think about while developing a task to robot, automated machine or human. Robot is selected to finish the mission of automated bracket assembly in this project.
- In the stage of assembly system development, there are mainly five steps to develop. Project scope is generally defined, so the first thing is to analyze assembly tasks to learn about the art of involved components installation, and then to decide a specify area to do research, which is working elements selection. The decision matrix is helpful in this step. The following two stages are automated assembly development and evaluation in virtual. Finally it is the test in reality.

In this stage, methodology for product development is to provide procedure for product design for automated assembly, and there are lots of key factors need to be considered; methodology for resource development is to provide guidance for equipment, tooling and simulation environment development; and methodology for process simulation is to provide a step by step systematic process of robotic assembly simulation, and to demonstrate how to allocate product, process, and resource and how to simulate the assembly process.

7.2.2 ALEA concept and automated bracket assembly

ALEA concept is proposed to play a role of the key to a door to the automated aerospace system assembly and the concept is throughout the whole project. This project studied the automated bracket assembly to explore whether the assembly process is feasible and to evaluate the new concept of ALEA.

Automated bracket assembly is divided into two stages which are automated bracket assembly development and automated bracket assembly evaluation.

In the stage of automated assembly development, the three key tasks are product development, process development and resource development. Product development is very important, it is the heart of the whole project, and the product should be design for automated assembly, usually there is a design team to finish this task. For limited of time and resources, product used in this project is simply developed based on the size and geometry of real part and just used for DELMIA simulation, the dimensions and geometry of products can be seen in chapter 5.2. Process development is also an important task, it will affect whether the project can success. The most important purpose is to explore a way to realize the automated Leading Edge assembly and develop an innovative automated bracket assembly process, so the technology of laser ablation and adhesive bonding are applied in this process. Resource development is to develop equipment and tooling for assembly, types and specifications of resource may be various according to different technology applied in the assembly process. The work of resource requirements, parameters and specifications must be done. In this research, resource models were developed simply, as the models are used for simulation, not for manufacturing. Resource requirements are proposed based on the procedure of considering their durableness, cost, safety, and foresight. In the course of resource parameter calculation, according to the empirical formula, professional date table and information of the size of drilling holes, product material, the size of mating surface, robot envelop and so on, the basic parameters of resource were calculated, as presented in chapter 5.4.2. The parameters are minimum requirements, if resources can meet minimum requirements, the resource can work. Usually, the physical resources are provided by special manufacturing companies which can meet resource requirements. Specification of resource is always seen as physical resource parameter, and it is always provide by resource manufacturing company.

In the stage of automated assembly evaluation, as discussed before the assembly process should be evaluated from two aspects which are theory and practice, the assembly process is evaluated by the theory including process simulation and cost estimation in this project. The practice evaluation may be done by other researchers in future. In the process simulation, the duration time of assembly operations, assembly path and sequence are clarified. In the cost estimation, manual assembly and automated assembly cost were estimated based on the empirical formula. The quantity of product and the productivity of the company are discussed, the two key factors will affect manager’s decision, and the payback period will be various according to different companies.

7.3 Conclusion

It has been possible to find out the method to increase the productivity of wing Leading Edge bracket assembly by using robot to execute the assembly operations to reduce the cycle time and researching an innovative assembly process.

Basically there are two aspects of this thesis i.e. Academic and Industrial. On Academic front by using simulation as a tool to analyze the assembly path, sequence, duration time, collision/clash, and other activities; and applying cost estimation to calculate the payback period, author has been successful in studying current technologies and addressing the Literature gap and showing how to apply simulation for complex, compact, and manual assemblies, most of all, author has also proposed a methodology for developing assembly from manual to automated assembly in some extent. On the Industrial front particularly for the companies which want to increase productivity, gap analysis with respect to best assembly practices, process simulation and cost estimation show the importance and advantages of automation, this thesis provides an insight for how to use simulation and cost estimation for similar complex and compact assemblies to analyze the activities.

Through the thesis, the research has achieved the aim and objectives set up initially. Three mainly findings are drawn as follows:

- The project methodology has been developed with intention to provide systematic guidance for other theoretical and practice researches, and this methodology has guided this project development smoothly.
- A new concept of ALEA (Automated Leading Edge Assembly) has been proposed initially, this project has finished studying part of ALEA, which is Leading Edge bracket assembly.
- An innovative automated bracket assembly process has been developed,

technology of laser ablation and adhesive bonding has been applied in the assembly process, and the two operations of rivet feeding and riveting has been integrated together to be one operation. All of these have been evaluated in theory.

7.4 Contribution to knowledge

Automated application in aerospace has been developed for many years, however, it is limited in automated system assembly, and there is limited literature about it. All those presented below may be the contribution to the knowledge.

- This project provides a methodology for developing aerospace assembly from manual to automation, although the project has just selected bracket assembly for evaluation, the methodology is still suitable for other systems assembly development.
- New concept of ALEA has been proposed successfully, and it can be seen as the key to open the area of automated system assembly, more and more researchers may pay attention to it, which will enhance the depth of involved areas study and extend the literature reference.
- The application of technology of laser ablation and adhesive bonding will help researchers develop more and more innovative assembly process, for laser ablation and adhesive bonding alone, each of them could not be an innovative or new technique, but deploying them in automated bracket assembly is an innovative try, from which people may get some ideas.
- This thesis has also summarized enough theoretical fundament which would be helpful in aerospace automated Leading Edge assembly study.

7.5 Research limitation and recommendations

7.5.1 Research limitation

An individual research project covering several different fields may result in a limited research depth of each field as limitation of time and resources. But the researcher can achieve much more knowledge from the course, and know how to arrange a project logically in the future. The project limitations are drawn as follows:

- The methodology has been discussed by several experts initially, and they gave a positive judgement, and the simulation and cost estimation proof that the method is feasible in theory. In the future, this method should be validated by aerospace companies and experts in this area.
- The models developed in this project are simplified and limited, so models may be further developed in future as necessary. The automated bracket assembly needs to be evaluated in practice as well.
- The automated bracket assembly process deployed five robots which has been deployed in DELMIA to finish five different tasks, but in reality one robot can finish what five robots have done in DELMIA, so in reality five robots would be replaced by one robot assistant with tool changer.
- Some activities (e.g. drilling holes, riveting, spraying adhesive) may not be simulated realistically in DELMIA, and they need to be done in reality.
- The geometry and dimensions of end effectors are not realistic; the physical ones need to be discussed with the resource manufacturer.
- Some datum was estimated empirically, the accuracy of datum need to be further evaluated.

7.5.2 Recommendations for future work

Based on the research results, discussion and limitation, some recommendations are given below to the readers who are interested in aerospace automated assembly.

- The automated bracket assembly process needs to be tested in reality.
- Optimize the process assembly path and cycle time.
- The products and end-effectors can be designed by details.
- The researcher should study involved software such as CATIA and DELMIA.
- Theoretical fundaments should be studied further.
- Do further research about automated system assembly such as automated electrical wiring assembly and automated bleeding air deicing tube assembly.

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APPENDICES

Appendix A. Robotics

A.1 Introduction

Recent years witness a significant increase in the aerospace industry, especially in Asian market such as China and India. For meeting the increased demand and getting much more market, productivity and cost-effectiveness need to be improved. The best way to improve productivity is to implement automation based on robot [67].

A.2 Robot application and construction

A.2.1 Robot application

Automation is a common method for optimizing manufacturing output and quality. More than 60% of the total robots are working in automotive, food manufacturers and electronics industries [68]. It is really a new concept of implementing automation in aerospace manufacturing, in recent years, many aerospace companies have attempted to utilize robot for drilling, inspection and so on, as shown in Fig A-1.

Fig A- 1. Robot application in aerospace industry (From Google)

Because of robot's flexibility and applicability for different applications, robot based automation has been a popular method to many manufacturers, whereas it is much less common in the aerospace industry which is highly specialized [69]. But it is a tendency that robot will play a much more important role in the future. It may be a feasible way to attempt to employ robot in more areas of aerospace in the long run. So this project attempts to research the simulation of automated Leading Edge assembly based on industrial robot and virtual models.

A.2.2 Robot construction

An industrial robot which is consisted of four major components, the manipulator, power source, control system and end-effector is defined by ISO 8373 [70] as an automatically controlled, multipurpose reprogrammable, manipulator programmable in no less than three axes [71].Multifunctional robot manipulator is designed to move material, products, end-effectors through variable programmed motions.

A.3 Robot division

There are commonly three kinds of robot: Parallel, Cartesian, and Articulated–arm.

- Parallel robot: Tricept, Delta, Hexapod

Most Tricept robots are designed to be medium to heavy payload and high precision. However, there are very few suppliers manufacturing this type of robot.

Majority of Delta robots are designed for food packaging with payloads below 5kg, so they are not suitable for aerospace manufacturing.

Hexapod is available with the highest accuracy and repeatability. However, because of majority of these robots are designed to be used in groups, it has very limited reach and payload.

- Cartesian robot

The Cartesian robot is also known as Gantry robot. It typically contains three linear axes based the rule of right angles. Some have the capability of an axis for the rotation of work pieces. In general, gantry robots are usually used in conjunction with an articulated-arm robot, which benefits from the flexibility, accuracy of the articulated-arm robot and the expanded work envelope provided by the gantry robot.

- Articulated-arm robot

Articulated-arm robots are open-loop kinematic chain mechanisms which look like the human arm. Most of these robots which have at least three or more rotary joints are driven by servo motors. Articulated-arm robots consist of a waist, shoulder, upper arm, forearm, and wrist connecting to the end effector. For the ability to rotate all the joints, a majority of these robots have six degrees of freedom (DOF).

A.4 Robot capability

A.4.1 Introduction

As is known that robots positioning accuracy is not good as repeatability. Usually robot repeatability accuracy can reach around 0.1 to 0.2 mm but the positioning inaccuracy is worse, may be up to 15 mm or even more if it is not properly built and calibrated [72]. So the best way to improve the accuracy is to optimize the robot structure and metrology system.

A.4.2 Robot metrology system

After proper calibration, robot is able to perform better. Visual measurement (Fig A-2) is a non-contact measuring methodology for 3D data acquisition. Stereo camera integrated with (multiple) laser stripes can supply the information for converting data from 2D image coordinate to 3D world coordinate.

A researcher [14] made a test that robot integrated with metrology system moved from position P1 to P5 for five times surround the measuring workspace, the calibrated results are shown in Fig A-3 and Fig A-4.The maximum standard deviation of repeatability is 0.095mm and the maximum positioning inaccuracy is 0.57mm. These data can be used for robot spatial position compensation.

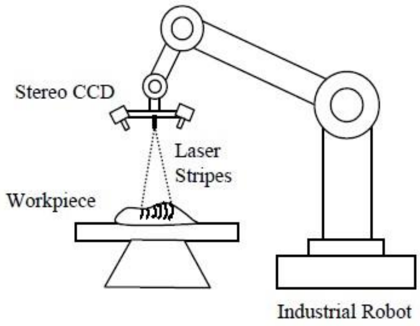

Fig A- 2. System Construction [72]

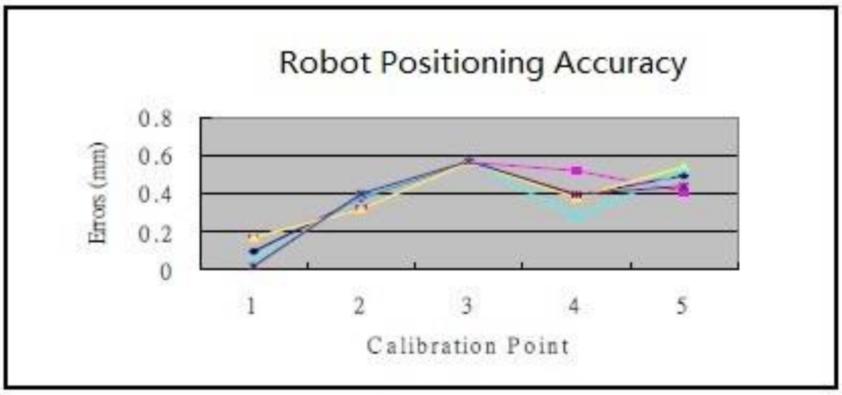

Fig A- 3. Robot Positioning Accuracy [73]

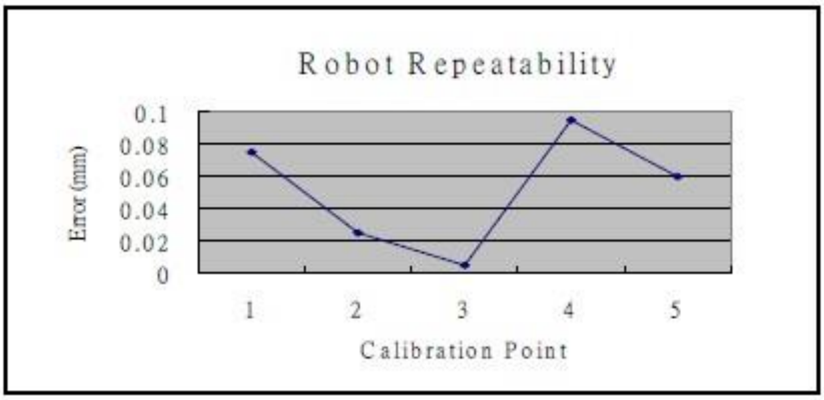

Fig A- 4. Robot Repeatability Accuracy [73]

Another researcher [74] shows the similar result that Industrial Robots can reach extreme absolute accuracy down to +/-50 micrometer with metrology system. Some other researchers [75, 76] can also support that: the robot integrated with advanced metrology system can have a better performance on robot position accuracy and repeatability which can meet most of aircraft assembly requirements.

A.5 Coordinate Systems

A.5.1 Introduction

Although the robots have excellent mechanical features, their internal coordinate systems are complicated. The robot coordinate systems conversion, the coordinate system for optical design and actual processing are very important.

The coordinate systems of robot include the world coordinates, the base coordinates, the work-piece coordinates, the user coordinates, and the tool coordinates, all of which follow the right-hand rule, as shown in the Fig 2-11.

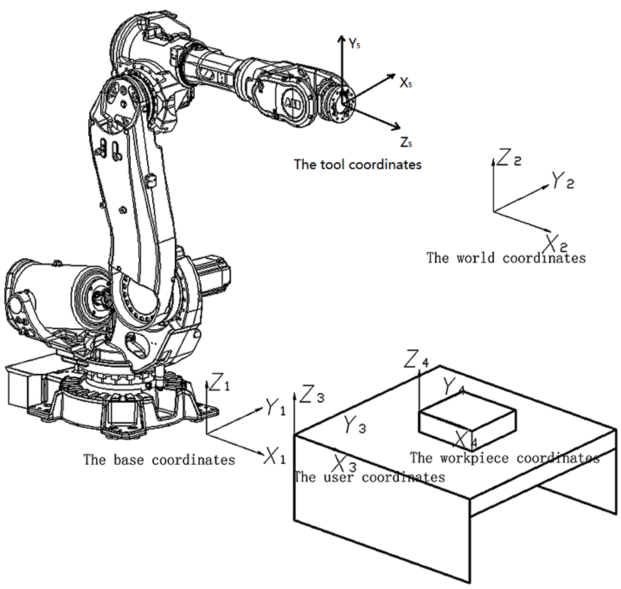

Fig A- 5. The robot coordinate system [77]

A.5.2 Coordinate transformation

The coordinate transformation is to describe the same space in different coordinate systems. Transformation between two coordinate systems (Fig A-6), can comply with Bursa wolf seven parameters formula given below [78].

$$\begin{pmatrix} X_T \\ Y_T \\ Z_T \end{pmatrix} = (S) \begin{pmatrix} 1 & \gamma & -\beta \\ -\gamma & +1 & \alpha \\ \beta & -\alpha & 1 \end{pmatrix} \times \begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} + \begin{pmatrix} dX \\ dY \\ dZ \end{pmatrix} \quad (0\text{-}1)$$

Here, XS, YS, ZS and XT, YT, ZT are coordinates of in source coordinate system and target coordinate system respectively; α, β, γ which are usually very small are rotation angles about the X, Y and Z axes respectively; dX, dY and dZ are the transformation of the origin. S is scale change from source coordinate to target coordinate datum. Change in scale δ is regarded as ppm value. So S = (1 + δ $*10^{-6}$) and above equation can also be rewritten as below [19].

$$\begin{pmatrix} X_T - X_S \\ Y_T - Y_S \\ Z_T - Z_S \end{pmatrix} = \begin{pmatrix} \delta & \gamma & -\beta \\ -\gamma & +\delta & \alpha \\ \beta & -\alpha & \delta \end{pmatrix} \times \begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} + \begin{pmatrix} dX \\ dY \\ dZ \end{pmatrix} \qquad (0\text{-}2)$$

dX, dY, dZ, α, β, γ ,and δ are seven unknown parameters, which are calculated based on common known points in both systems. If there are more than three common points, least square solutions can be obtained for the seven unknown parameters using matrix operation.

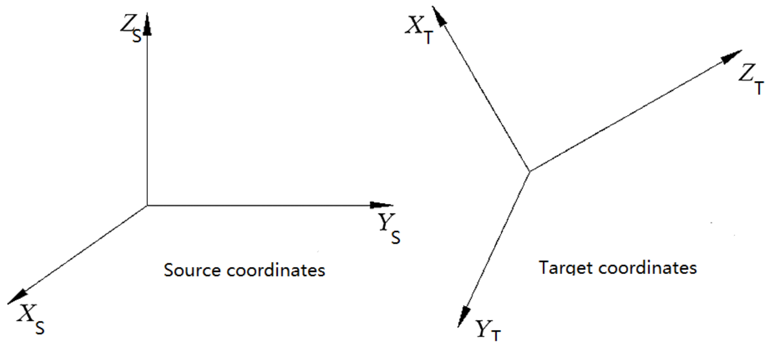

Fig A- 6. Two coordinate systems

A.6 Conclusion

Accordingly, articulated-arm robots can utilize in many areas and meet most of aerospace manufacturing requirements, in several special requirement areas, there are a number of Cartesian robots which are integrated with an articulated-arm and advanced metrology system. These robots have high flexibility, accuracy, repeatability and large working envelope which can meet requirements of a large number of tasks.

Appendix B. Adhesive bonding

B.1 Introduction

Adhesive bonding technology is to join two products which are plastics, metals, composites and many other materials by applying a substance to the surfaces of the two adherents. Adhesive bonding technology provides a great variety of design flexibility as it can be widely applied in most industrial assembly sequences [79].

This technology has been widely used as a direct alternative approach to riveting and will not stop on aircraft projects [80, 85]. It is viewed as a key technology used in aircraft structure to make it to be lightweight, rigid, durable and cost-effective [81].

B.2 Adhesive materials

Adhesives are materials that possess the capability of permanent joining elements of structures. An important feature of adhesives is their high strength when cured [82].

The influence of the adhesive ability to wet the substrate surface of host materials is the contact angle θ [83], as shown in Fig B-1. With the decrease of the contact angle, adhesion between the adhesive and substrate increases [84].

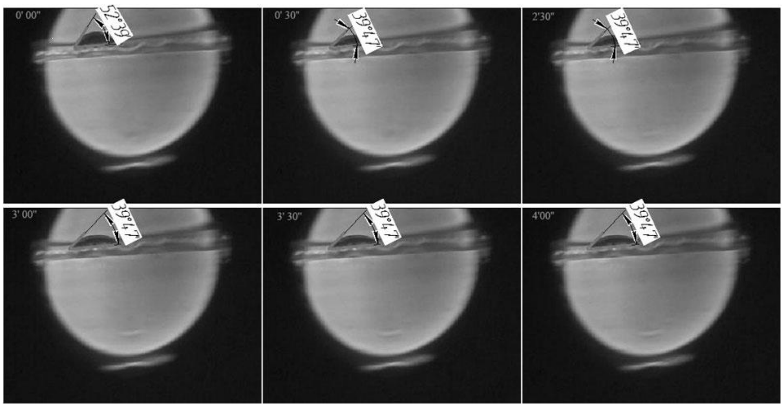

Fig B- 1. Photographs of K-153 adhesive contact angle [82]

B.3 Adhesive classification

These are mainly three groups adhesive materials used for aircraft construction [80].

1) Metal and metal substrates: applying hot cure
2) Metal and metal honeycomb substrates: applying hot cure
3) Metal and metal substrates: applying cold cure

B.3.1 Metal and metal substrates: applying hot cure

Phenolic and epoxy resin systems are mainly two kinds of adhesive materials applied to hot cure metal and metal substrates.

B.3.2 Metal and metal honeycomb substrates: applying hot cure

Only epoxy systems are suitable to these applications. When reached the cure temperature, epoxy adhesives turn to be mobile liquids and would run out of joints. So flow modifying additives or scrim should be contained. With the mobility of adhesive and reticulation characteristics of substrates it can form a stronger bonding.

B.3.3 Structural metal to metal: cold cure

Many two-part curing epoxy systems are available. The two epoxy systems of 3M Co. SW9323B/A-150and Hysol-Dexter EA9330.1 are widely used in aircraft structural bonding.

The Fig B-2 illustrates types of adhesives ranked with cure temperature changing. Higher cure temperature, more cross-linking and higher environmental resistance, less toughness.

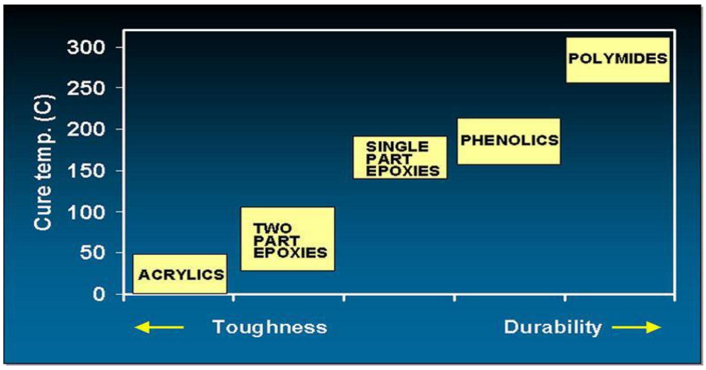

Fig B- 2. Adhesives ranked with cure temperature changing [81]

B.4 Bonding surfaces treatment

The adhesive must spread over bonding joints and wet the aluminum surface before good adhesion can occur. It should remove contaminants as dust, grease, dirt, oil and oxide caused by air corrosion what may create bonding problems, so surface treatment is very important.

Surface pre-treatment is very helpful for adhesive bonding [81].

B.4.1 Classification of surface treatment

Surface treatment may apply one or all of the following processes shown in Fig B-3.

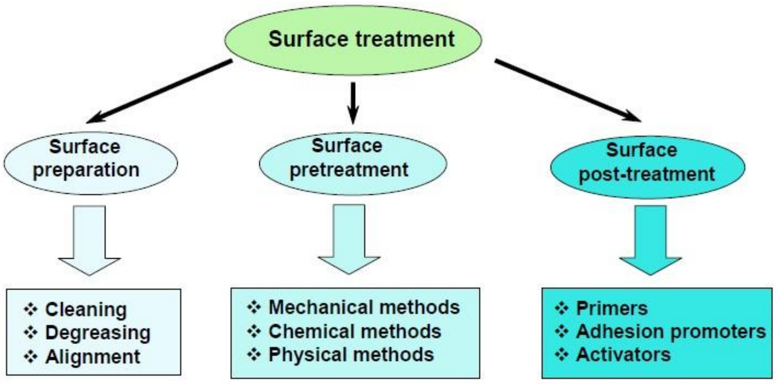

Fig B- 3. Proposed steps in surface treatment [86]

Surface Preparation: Use cleaning, degreasing or alignment to remove oil, dust, grease, dirty and other surface contaminants.

Surface Pretreatment: Use physical, chemical or mechanical methods to remove strongly absorbed surface layers and activate the surface.

Surface Post-treatment: Apply primers, adhesion promoters or activators to improve adhesion to the adhesive.

B.4.2 Surface treatment methods

Surface treatment consists of many methods according to different material of substrates; this chapter introduces three main types: detergent, plasma and laser ablation.

Detergent as soaps, alcohol and caustic soda are widely used cleaning agents which are applied by scrubbing, spraying, or ultrasonic agitated solution. These agents can remove certain kinds of contaminants as dirt and oil reasonably well. But they may react with some substrates, and it must be rinsed and dried thoroughly after cleaning.

Plasma [86] is usually generated in a low pressure chamber and created from inert gases as argon, ammonia, or nitrogen other than oxygen. Plasma generation equipment is shown in Fig B-4.

Fig B- 4. Plasma generation equipment [86]

Laser ablation (LA) is another cleaning method in which a laser beam (Fig B-5) concentrates on a sample surface to remove rubbish from the irradiated zone. In most metals and glasses/crystals the removal is by vaporization of the material due to heat [87].

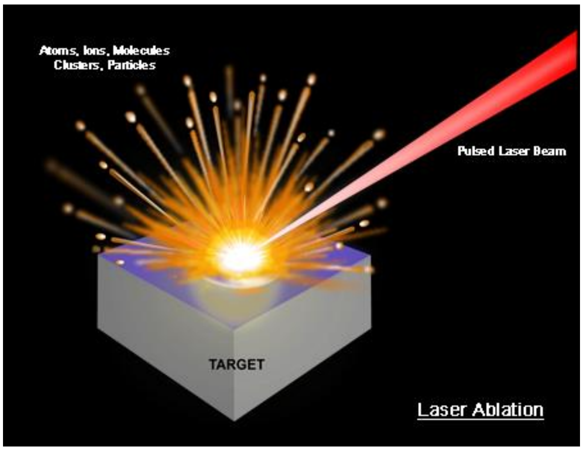

Fig B- 5. Laser ablation [87]