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Variable Drive Vehicle

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Department of Mechanical Engineering

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ENTITLED

Variable Drive Vehicle

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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VARIABLE DRIVE VEHICLE

By

Christopher Clark, Michael D'Arrigo, Graham McClone, Joseph Sahyoun

SENIOR DESIGN PROJECT REPORT

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Abstract

The versatility of current rovers and exploratory vehicles is limited by a single drive system. The Variable Drive Vehicle (VDV) employs a actuated system capable of switching between wheeled and tracked drive modes. This allows the vehicle to travel quickly and efficiently over smooth terrain and to traverse more arduous terrain by switching between these two systems. The small scale prototype built over the course of this project is equipped with two modular wheel driven track units to demonstrate the viability of the system. Electric linear actuators and servo motors allow for simple control and a smooth transition between each drive system. These devices allow the modular tracks to be rotated out from under the wheels, and stowed on the vehicle when not in use. Finite element analysis ensured that the VDV's switching mechanism maintains safe loading at its most critical points during a drive system transition. The VDV was tested on smooth concrete to determine its maximum wheel speed, track speed, and how fast the drive system could be switched. Experiments yielded a top speed of 11.5 mph in the wheel mode, 0.8 mph in the track mode, and a switching time of 6.4 seconds. The vehicle's maximum obstacle clearance, 1 inch in track mode and 2 inches in wheel mode, and slope, 5 degrees in track mode and 22 degrees in wheel mode, fell short of expected values. These shortcomings resulted from a poor frictional power transfer when attempting to power the tracks using the wheels. However, this prototype provides a proof of concept for a variable drive system successfully incorporating two drive systems, and future improvements may yield a promising platform for future robotics research.

Keywords: Modular tracks, wheels, mobile platform, all-terrain, radio control, small scale prototype

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1 Introduction

1.1 Background/Motivation of Subject Matter

Drive system selection is an important engineering consideration when designing mobile platforms. Vehicles that utilize a wheel-based drive system tend to be limited in the terrain that they can easily traverse, for example cars struggle to drive on ice, or sand. Vehicles that utilize a track-based drive system, such as tanks, have increased terrain capability at the loss of speed and efficiency. There is a distinct need for a vehicle drive system having the capability to drive quickly, efficiently, and be able to conquer any terrain it encounters. Such a system would enhance the capabilities of vehicles in a variety of applications:

- Military personnel extraction
- Natural disaster relief
- Autonomous robotics research

1.2 Review of Field Literature

Günter H Hohl's book entitled *Off Road Vehicles* (Wheeled and Tracked) [1] discusses how vehicles with each type of drive system handle obstacles and terrain differently. Most vehicles that can traverse rough terrain are unable to reach high speeds. Additionally, the composition of the ground beneath a vehicle is frequently a determining factor in the vehicle's ability to move quickly. Drive systems with increased ground contact surface area, like continuous tracks, are better suited for applications where the terrain is soft. The information found in this book focuses on the various factors that can affect a vehicle's ability to travel using either a wheeled or tracked drive system.

When evaluating different drive systems, one important factor to be considered is the method of steering that is required. For a vehicle with full-length continuous tracks, skid steering is necessary. Skid steering is a method of turning a vehicle by creating a velocity differential between the two sides of the vehicle. Wheels or modular track units tend to be better suited for explicit steering. Explicit steering is where the intended vehicle heading is determined by using a mechanism to change the direction of the wheels. Important design factors including power draw, individual wheel torque, and position information can be radically different for wheeled and tracked systems. Benjamin Shamah's work indicates that, as the turn radius decreases to a point turn, greater power and torque are required for a skid steering turn than an explicit turn [2].

Spotts, Shoup, Lee, and Hornberger's *Design of Machine Elements* discusses performing drive train and structural calculations [3]. The capabilities of the vehicle will be determined by the torque, power, and traction capabilities of each respective drive system. Proper sizing and material selection for motors, gears, shafts, structural components, and batteries are required in order to complete a successful design. Utilizing this resource properly throughout this design process has resulted in a mechanically-sound prototype.

In the design and prototyping of a variable drive mobile platform, extensive computer modeling are useful because test various design parameters without building a physical prototype. This limits the number of build iterations necessary to complete a project. The Finite Element Analysis software Abaqus will be utilized for structural modeling. Traction capability modeling is feasible through the work of Akcabay, Perkins, and Zheng-Dong [4]. Their methods utilize a multi-body model for predicting mobility in robotic vehicles driven by continuous tracks. Both off road and urban terrains can be modeled using this method, which is ideal given the scope of this project.

The electronics for this robotics project are wired through an Arduino microcontroller. Information on how to utilize Arduino microcontrollers for mechatronics projects and write functional code was found in *Getting Started With Arduino* [5]. This book contains circuit schematics and hardware interfacing information for Arduino microcontrollers. The Arduino platform is open-source and ideal for prototyping.

A previously developed vehicle built by Ph.D candidate Yi Li was used as a case study for this project [6]. The thesis paper for this robotics platform addresses a similar drive system incorporating wheeled and tracked units that rotate 90 degrees so that one system is in use at a time. The system is configured in order to minimize loss of time while switching between drive systems (see Figure 1.1).

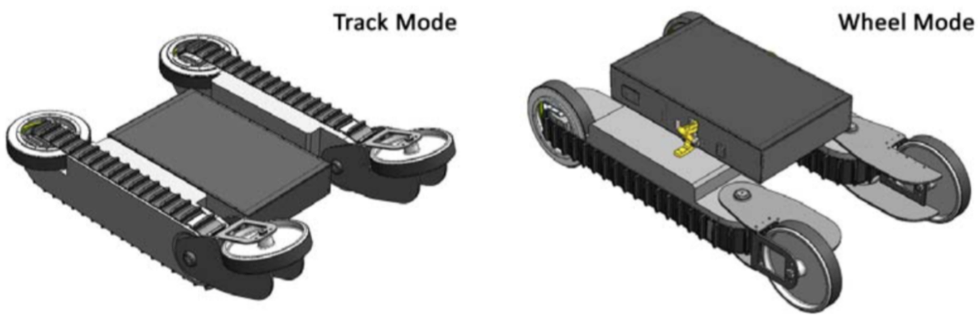


Figure 1.1: Adaptable drive system designed by Yi Li [6]. Reproduced without permission.

1.3 Existing Tactical Robotic Vehicles

Robotic rovers are currently used in a variety of applications. On a smaller scale, tactical robots are utilized by police departments and SWAT teams to mitigate hostile situations. These robots use special configurations to assist in overcoming common indoor obstacles such as stairs. It's crucial for these robots to be able to be able to move regardless of obstacles in order to be of any use in applications such as hostage protection and bomb threats. Larger robotic systems are often used in the exploration of areas that are not conducive to human life, such as other planets or environments on earth with hazardous conditions.

In order to accomplish tasks within these fields, current rover models incorporate unconventional drive systems. For instance, omni-directional drive systems provide more maneuverability by being able to translate in any direction. Other systems utilize movable members or arms to push the vehicle up and over an obstacle. Systems like these have proven to be very useful in climbing stairs and overcoming challenging obstacles. Table 1.1 outlines some specifications of existing tactical robotic vehicles. [7, 8, 9, 10]

Table 1.1: Existing Tactical Robotic Vehicles

Vehicle	**Speed (mph)**	**Weight (pounds)**	**Obstacle Clearance**	**Drive System**	**Special Features**	**Price ($)**
SDR Tactical (*Mastiff*)	1.36	110-150	Climb stairs, open doors	Continuous Tracks	Manipulator arm, hazmat sensors, audio video	25,000 - 40,000
Avatar III Tactical Robot	3	25	Climb stairs	Continuous Tracks	Manipulator arm, hazmat sensors, audio video	60,000
AMBOT Wheel	1.36	550	Climb stairs, open doors	Wheels	N/A	100,000
AMBOT Track	1.36	500	Climb stairs, open doors	Continuous Tracks	N/A	100,000

1.4 Project Objectives and Goals

The goal of this project is to develop a small-scale prototype for a vehicle chassis that incorporates two drive systems: one with wheels and one with tracks. This vehicle must have the capability of switching between each drive system without manual user intervention by engaging or disengaging selection mechanisms. Because of the temporal and monetary constraints of this project, the feasibility of the drive system switching mechanism was demonstrated on the rear wheels of a purchased remote control vehicle.

This required the design of mechanically sound, yet clever systems, (discussed in chapters 2 and 3), in order to achieve the benefits of utilizing a dual drive system. Retrofitting an existing vehicle requires a large number of custom parts; therefore, design for low cost and manufacturability was incorporated in an effort to decrease the material and machining cost of the development process.

The final objective was to evaluate the efficacy of the final design. This was first done theoretically by conducting a Finite Element Analysis to ensure that the vehicle would not fail under intended loading, which is discussed in chapter 3.3. This result was confirmed by fabricating and operating the physical prototype. Lastly, the performance of the system was evaluated by measuring the vehicle's speed and obstacle clearance capabilities on various terrains, as discussed in chapter 4.

2 Systems

2.1 Customer Needs

The Variable Drive Vehicle, at its most basic level, must be able to travel between two locations, no matter the terrain, in order to reach objectives in a timely manner. In order to do so, the vehicle was designed to overcome steep, slippery, or soft terrain, while still being capable of driving quickly and efficiently over a smooth surface. It must be able to quickly switch between these drive systems via user input to a control system.

2.2 User Scenario

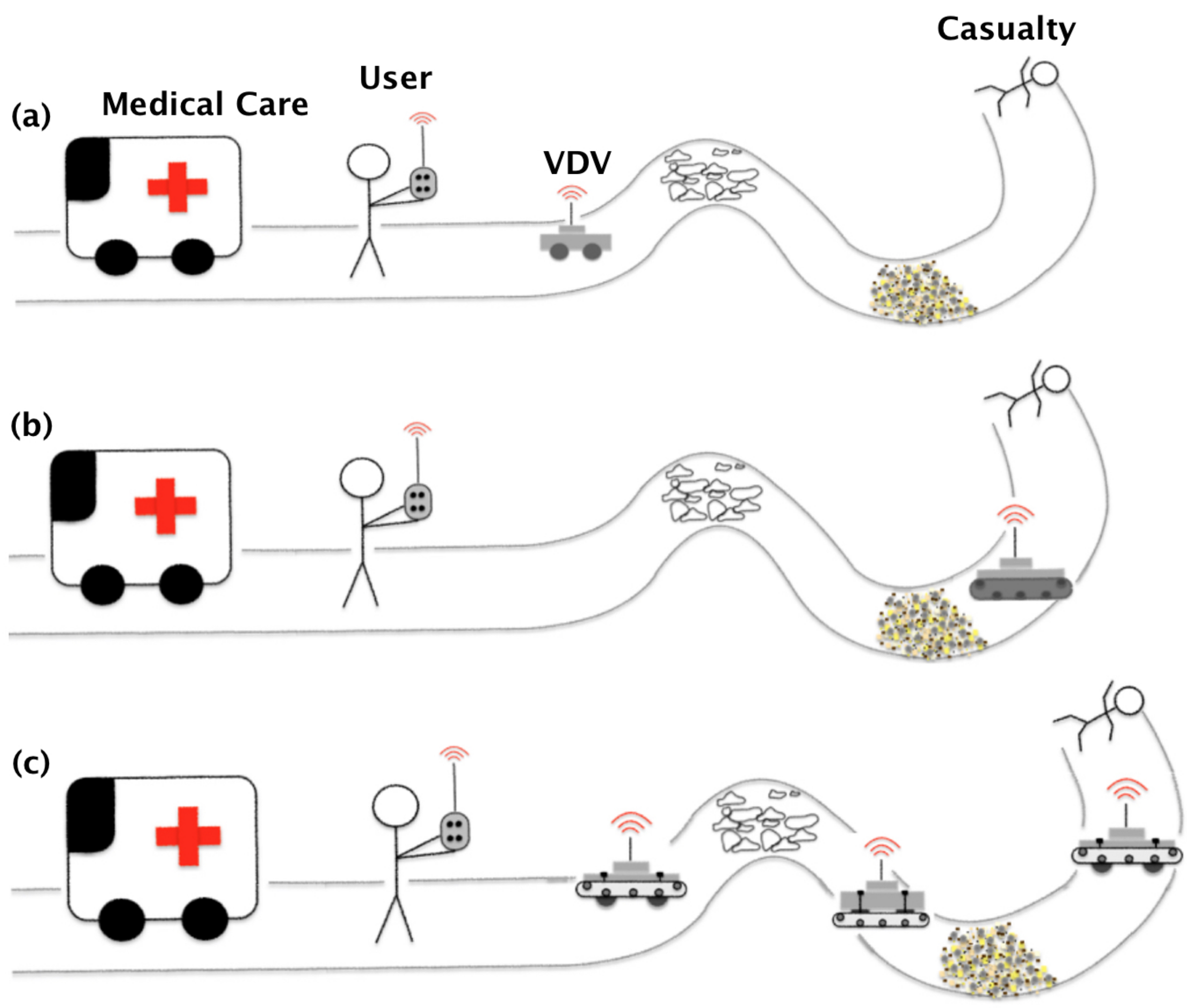


Figure 2.2: Vehicle access to hard-to-reach locations.

Figure 2.2 depicts a scenario where the VDV would be valuable. For example, in the military, a soldier may be harmed on the battle field with the surrounding terrain too difficult for most wheeled vehicles to overcome, as seen in Figure 2.2(a). While some tracked vehicles may be capable of reaching the injured soldier, they likely will take a long time in doing so, and in critical situations such as this one, time is frequently a crucial and decisive factor. This is illustrated by Figure 2.2(b). If the soldier is harmed and there is a live-fire situation, then it's likely that a helicopter would be unable to retrieve the soldier. In a case like this, a vehicle that is capable of traversing difficult terrain and traveling quickly when on smooth surfaces would be advantageous for the soldier's retrieval and survival. This is depicted in Figure 2.2(c).

A full-sized version of this vehicle would have potential uses in a wide variety of applications that could include military personnel extraction and land exploration. A smaller-scale version would still have great applicability in autonomous vehicle research as well as in police, SWAT, and military environments where tactical robots are currently used.

More quantitative goals for the small-scale prototype were developed based on competitive robotics vehicles in order to direct the project. A list of Product Design Specifications (PDS) was created from the performance characteristics of vehicles on the market today (see Appendix G). For the VDV to be successful, it needed to outperform the competition. Therefore, the Product Design Specifications were translated into Customer Needs for a hypothetical entity that would be interested in purchasing the VDV. These are summarized in Table 2.2.

2.3 Overall System

2.3.1 Roles and Requirements

The overall system must be able to scale difficult terrain and travel quickly over smooth surfaces. The off-road speed, top speed, vehicle weight, obstacle clearance, slope, ease of use, and terrain scaling capabilities were accounted for when rating the different designs considered for the overall system. They take into account the terrain for which the vehicle will be used in and what those situations may require. Specifications for these constraints were derived from the performance of existing robotic vehicles of similar size and can are outlined in the PDS in Appendix B. All these factors were input into selection matrices to rank the different design considerations (see Appendix E).

2.3.2 System Level Options and Trade-Offs

The preliminary design consisted of two separate chassis each with their own drive motor connected via an actuated switching system (see Figure G.2). Each drive system would be powered by its own drive system in order to preserve system redundancy. This was done in an effort to retain functionality of one drive system should the other fail. One would switch between the two systems by either extending or contracting the actuators until the desired drive system is in contact with the ground. This met the necessary speed and terrain scaling requirements but the larger weight and bulky geometry of the vehicle limited its obstacle clearance capabilities. This design was improved upon by utilizing an existing chassis and equipping it with a dual drive system powered by a single drive motor. Eliminating the separate drive motors reduced weight while maintaining versatility. The use of an existing chassis also

Table 2.2: Customer needs.

Customer Need	**Interpreted Requirement**	**Design Constraint**
VDV moves quickly to desired location	5 mph track speed 12 mph wheel speed	Minimize weight and frictional losses in both drive systems
VDV must switch drive systems without manual user intervention	Utilize electronically actuated switching mechanisms	All systems automated
Switching between drive systems must not interfere with mission time	10 second switching time	(Mission time for wheel mode + track mode + switch time) < (total mission time in track mode)
VDV must be easy to use and operate	User interface must be intuitive	Single drive controller
VDV must be able to traverse steep slopes	Overcome slope of 33 degrees	Low center of gravity, weight balanced, large track surface area to prevent slipping
VDV must be able to overcome obstacles	7 inch obstacle clearance	Size of track unit & size of wheels
VDV must be lightweight	20 pound maximum	Minimize material weight
VDV must be low-cost	Cost less than $2000	Minimize material cost

saved on build time and demonstrated the adaptability of the drive system across a range of vehicles. This updated design scored highest in the selection matrices and was chosen for the final design.

2.4 All-Terrain Drive System

2.4.1 Roles and Requirements

The all-terrain drive system must be able to maneuver through different terrains that require increased traction, such as sand or gravel. This system will mostly be used in off-road scenarios and the judging criterion were selected based off of this purpose. Similar to the overall system, slope, speed, obstacle clearance, weight, and terrain scaling capabilities were considered. However, those criterion that are more crucial to off-road vehicles, such as slope and obstacle clearance, were given larger scoring weights. Ultimately, the all-terrain drive system design should be able to scale an incline of around 33 degrees, which is the standard incline of stairs. It should also minimize weight and power consumption and must not sacrifice durability and reliability for mechanical complexity.

2.4.2 System Level Options and Trade Offs

The options for the all-terrain drive system included those currently in use in industry. The rocker-bogie system, used on NASA's *Curiosity* Rover, incorporates durable tires and a chassis known as a "rocker" (see Figure 2.3). This three wheeled chassis can scale objects while keeping all wheels in contact with the ground. Advantages of this system include its speed and payload carrying capabilities. However, wheels are not as durable as track and are prone to puncture. The rocker-bogie system cannot scale as large of slopes, topping out at 32 degrees, as the traditionally tracked system limiting its capabilities in rough terrain [11].

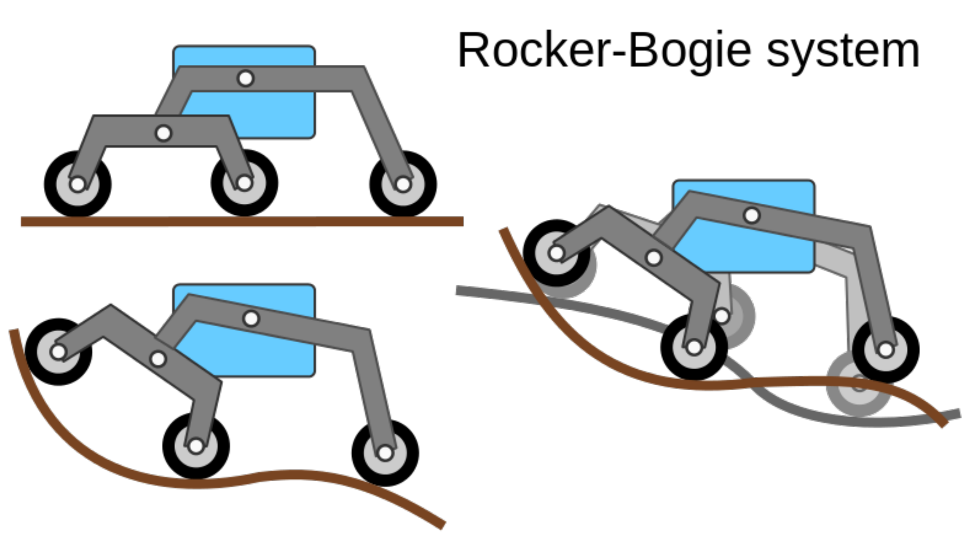


Figure 2.3: Rocker-bogie system [12]. Reproduced under Creative Commons License. Created by Facepunch.com

Full length tank tracks increase contact area with the ground, increasing traction and preventing the vehicle from sinking. Section A.2 provides hand calculations that show a 96% decrease in contact pressure from wheels to tracks. While full length continuous tracks provide traction advantages over wheels, they weigh much more and require more power. To reduce the system weight and losses in power, the implementation of four modular tracks were also considered. Modular tracked systems are smaller than full length tracks as they are often designed as a replacement for wheels. They are lightweight and provide sufficient traction but also require a longer build time.

Modular tracks powered by a shared drive motor scored highest in the selection matrices. Sharing the drive motor of the all-terrain system with that of the wheeled system closely integrated the two systems such that the increase in weight did not significantly impede the capabilities of the original drive system. The reduced track size also provided more space under the vehicle for clearing obstacles without large losses in traction.

2.5 Wheeled Chassis

2.5.1 Roles and Requirements

In order to move quickly over smooth terrain, the VDV must be able to switch into a wheeled mode and store the all-terrain mode. When considering which type of wheeled chassis would best accommodate these requirements, ride height, mobility, overhead clearance, torque, and top speed were determined to be the most crucial criterion affecting this decision. It must have a large ride height and plenty of overhead clearance so that it is able to clear obstacles and store the all-terrain drive system above the wheels. Because the drive motor will be shared with the all-terrain drive system, it must have a large enough torque to overcome the frictional and mechanical power losses inherent with the all-terrain design. Lastly, the ability to modify the chassis of the purchased vehicle was an important criterion for selecting a final model.

2.5.2 System Level Options and Trade Offs

Remote control vehicles come in various types for different applications. "Drift" and street cars focus on high accelerations and speeds across flat and smooth terrains. They have a low ride height to reduce air resistance as well as improve balance. Overhead clearance and mobility are also insufficient rendering this option unusable. Buggies have are designed for off-road driving at high speeds, but still implement a low ride-height to increase stability. Rock Crawlers proved to be the optimal choice as they incorporate a high-torque motor and a chassis that can be completely replaced. They also have a larger ride height with plenty of overhead clearance to accommodate stowage space [13].

2.6 Electronics

2.6.1 Roles and Requirements

For the electronics system, two main design options were considered: integrating the actuation mechanisms with the main vehicle power supply and keeping both systems separate. The key issues that were considered were size, complexity, and added functionality. Complexity was determined to be the most important criterion, followed by added functionality, and size. While an integrated design would be more elegant, it would significantly increase build time and make troubleshooting far more difficult. The criterion weights correspond to this trade-off prioritizing modularity and ease of design.

2.6.2 System Level Options and Trade-offs

An integrated electronics system would combine the electronics that power and operate the switching system with those that drive the vehicle. While this design reduces the overall size of the electronics system on-board the vehicle, it is significantly more complex than separating the two electronics systems. A separate configuration was decided to be the best for the scope of this project and an integrated electronics was left for future work.

2.7 Controls

2.7.1 Roles and Requirements

The controls must be able to operate both drive systems and the switching system. The three criteria used to rate each control design were its level of integration, remote capabilities, and ease of use. Level of integration and remote capabilities were equally weighted while ease of use was given less weight. While ease of use is important for customers, this proof of concept project is not concerned with the consumer market and thus, easy to use controls are not as significant for this initial prototype. Instead, the focus is on successfully demonstrating the switching between two different drive systems.

2.7.2 System Level Options and Trade-offs

Four control system designs were considered and evaluated. A remote controlled driving system with an integrated automated switching system scored highest in regards to the criterion but was set back by its cost and its design and build times. A fully integrated remote control system would require additional complex programming that would increase test and troubleshoot times. The simplest design consisted of separate controls for driving and switching. Driving is controlled by the existing vehicle controller and the switching system is operated by on-board push buttons. This increases the number of steps required to complete switching but also allows for a much simpler setup. This system also costs less as it eliminates the need for purchasing an Arduino compatible RF transmitter.

2.8 System Level Design and Main Subsystems

The Variable Drive Vehicle consists of five major subsystems: Wheel-based drive system, a track based drive system, a switching system, controller system, and an electronics system. Figure 2.4 shows the system block diagram for the final design. The wheel-based drive system powers the modular track units and is controlled remotely. An on-board microcontroller controls the switching subsystem which consists of three different actuated locking and clamping systems that each contribute to the manipulation of the (4) modular track units. These are labeled the contact lock, rotation clamp, and stowage lock. Each of these subsystems will be further explained in the following chapter. It should be noted that the viability of the switching system was demonstrated upon the rear wheels of the vehicle. The front wheels have an added degree of freedom used to turn and thus require more intricate mechanism designs. The power sources for each of these systems are also labeled.

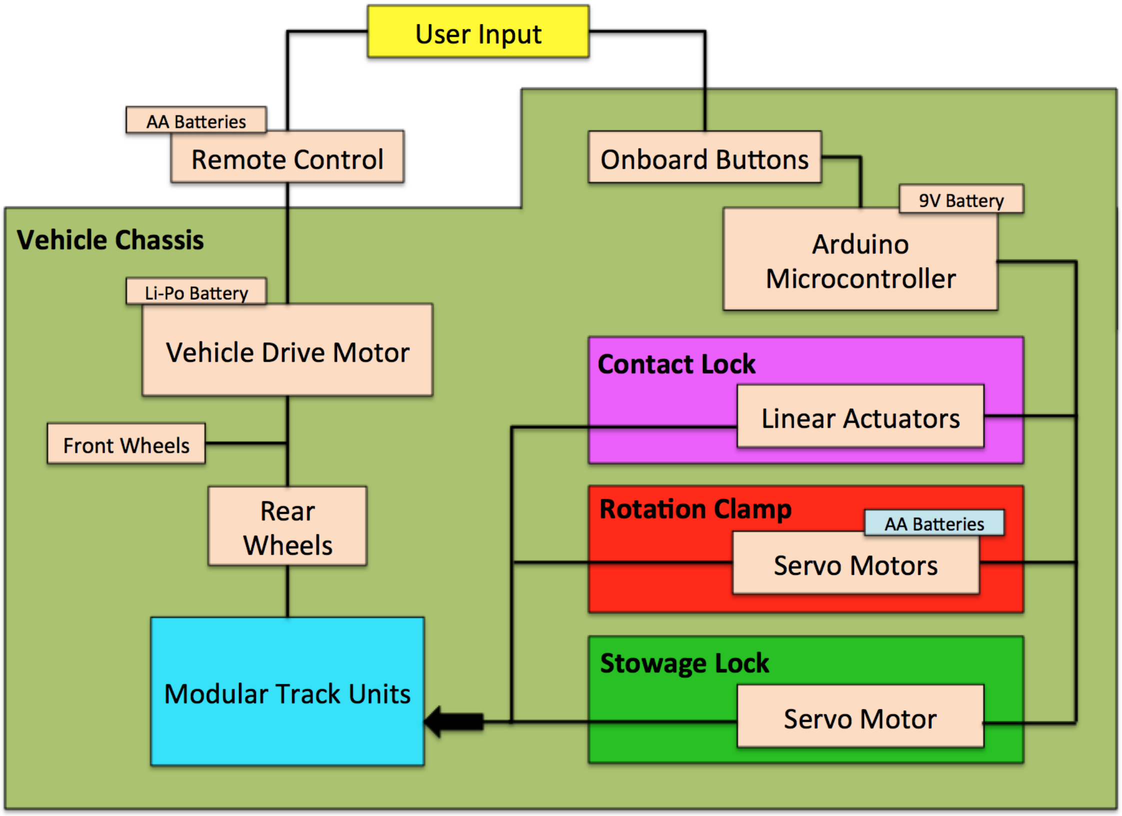


Figure 2.4: System level block diagram.

2.9 Project Management

2.9.1 Challenges

A variety of challenges arose during the design and manufacture of the VDV. In some cases, a compromise was necessary to the VDV's original design in order to compensate for system functionality or manufacturing capability. The majority of these problems arose as mechanism design difficulties associated with achieving a high level of functionality within a compact package. Interference of mechanical parts throughout the drive system switching process was a problem that constantly needed to be avoided.

Budget constraints were an additional challenge faced by the VDV team. The large number of motions required resulted in a need for several different types of electronic actuators. Selecting the most cost effective solution sometimes meant redesigning the mechanism altogether to avoid the purchase of more expensive components. Additionally, aluminum components were machined from larger pieces of aluminum bar stock, in order to reduce the overall number and cost of raw materials purchased.

Lastly, the manufacturing challenges faced by VDV team members were extensive. Extra care was required during parts of the redesign process in order to ensure that previously fabricated parts would still function properly. Additionally, parts were designed in a way that minimized the number of machining operations necessary for completion in order to reduce the already extensive manufacturing time. One major challenge during the manufacturing process was the structural weakness of the purchased remote controlled vehicle's chassis after parts of the frame were removed in order to accommodate the augmented system. This problem was addressed by machining aluminum reinforcements.

2.9.2 Budget

The project had an overall budget of $2000 provided by University funding. This sum was used to purchase the remote controlled base vehicle and all of the raw materials and electronic components required to construct each track unit. A cost break down can be found in Appendix F. Overall, the project used only 88% of the allotted budget, totaling $1750. This was the amount of money spent over the course of the entire project. The current final cost of the prototype hardware itself was $1200.

2.9.3 Time-line

The project time-line for the VDV can also be found in Appendix F. The project as a whole experienced a major set back with the first design choice. A redesign was required and took up a large portion of time that had initially been intended for manufacturing the VDV. Despite the vehicle's redesign, the manufacturing and some of the testing was completed prior to the Santa Clara University Design Conference.

2.9.4 Design Process

The VDV design process began by identifying a need for a vehicle drive system with enhanced mobility characteristics. It was then decided that this problem would be approached on the level of a small-scale prototype. Product design specifications were developed based on existing tactical and robotic vehicles. These were translated into customer requirements for an entity with the need for a vehicle that could outperform current technology. Selection matrices showed that combining the strengths of wheeled and tracked drive systems would achieve this goal. The subsequent design process for the VDV was iterative as the initial design did not meet all the project's requirements. Therefore, the way in which each drive system would be implemented was reevaluated. This second design has individual track units for each wheel of the vehicle. From this point, several additional subsystems had to be developed to allow the vehicle to function properly.

The first major part of this design was creating a system that allowed the wheels on the purchase remote controlled car to rotate the track on each unit in the proper direction. Additionally, various subsystems were designed to facilitate the switching between tracks and wheels and stowage of the tracked drive system. Each subsystem required various custom components and actuation mechanisms.

2.9.5 Risk Mitigation

There were considerable safety risks associated with the manufacture, assembly, test/operation, and storage of the Variable Drive Vehicle. Measures were taken to mitigate these risks and ensure that those interfacing with the vehicle, including developers, users and bystanders, remained safe. Each of the safety risks applicable to this project are discussed in the subsections below.

2.9.5.1 Manufacture Machining and fabricating the frame and chassis for this vehicle required the use of dangerous shop equipment including mills, lathes, drills, and bandsaws. All four engineers on this team took MECH 101L, a machine shop lab offered by SCU. MECH 101L covered the safe use of all machines necessary to complete this project as well as general shop safety protocol. Shop safety protocol included wearing short sleeves when working on mills and lathes so that clothes did not become entangled in the machines. Additionally, protective eye-wear was required when working on all machines in the machine shop. Potential safety risks and solutions have been listed below in Table 2.3.

Table 2.3: Manufacturing safety risks and mitigations.

Safety Risk	**Solution**
Rotating Mechanical Parts/ Machine Shop Equipment	Remove any loose articles of clothing or jewelry.
Airborne Debris	Use protective eyewear when working with mills, lathes, drills and bandsaws.
Electrical Shock	Shut off power to electrical devices when changing wiring.

2.9.5.2 Assembly Risks related to the assembly of the VDV were primarily electrical risks. The Occupational Health and Safety Administration (OSHA) identifies electrical current as the single most dangerous aspect of electronic devices [14]. Actuators that are capable of supporting the loads necessary to lift and lower the VDV's switching mechanism draw current exceeding 1 Amp. Current that exceeds 1 Amp has the potential to severely injure human beings. To mitigate the risk of overloading a power source, which could lead to a dangerous high current discharge, each major electrical system has its own power supply. The electrical components used in the VDV operate at voltages under 50V DC.

The power to the vehicle was always turned off when any engineer was working on the vehicle, or any of its subsystems. This ensured that body parts were not caught between the moving track unit and that electrical shock did not occur. Potential safety risks and solutions have been listed below in Table 2.4.

Table 2.4: Assembly safety risks and mitigations.

Safety Risk	**Solution**
Electrical Shock	Shut off power to electrical devices when changing wiring.

2.9.5.3 Test/Operation The most significant potential safety hazard regarding this vehicle was during the testing process. Any time a vehicle was moving it had the potential of running into people, wildlife, or property. Additionally, the operator must be mindful of differences in speed capabilities between drive systems during testing. To minimize the potential for the vehicle to cause damage, it was tested in a controlled environment where people other than the engineers testing the VDV were not present. In addition, the vehicle was always turned off when an engineer was working on the vehicle or during transport to the testing location.

The actuators that rotate the tracked drive system relative to the wheeled drive system create areas between the tracked chassis and wheeled chassis that can be defined as pinch points by the OSHA. A pinch point is defined as a point at which it is possible for a part of the body to be caught between the moving parts [15]. For this reason, body parts were kept away from pinch points while the VDV was in use.

A lithium-polymer battery powers the main electrical systems in this vehicle. It is recommended that lithium-polymer batteries be used between 32°F and 113°F for best charging and discharging performance. Lithium-polymer batteries can self ignite if they are subjected to temperatures above 302°F [16]. Ignition at this temperature is known as thermal runaway, and energy stored in the battery's cells is released in the form of heat causing a chain reaction that often consumes the whole battery. Thermal runaway can also be caused by a major mechanical deformation of the battery cells. For this reason, the battery has been housed in a protective container. When ignition due to thermal runaway occurs, the battery can make a hissing sound and the protective sleeve on the battery may visibly rupture [17].

In the event of a lithium-polymer battery ignition, the battery should be placed outdoors on a non-combustible surface to die out. The fumes from a lithium-polymer battery fire are toxic and should not be breathed in. If the fire must be put out immediately, using water as an extinguisher will suffice [18]. Potential safety risks and solutions have been listed below in Table 2.5.

Table 2.5: Test/operation safety risks and mitigations.

Safety Risk	**Solution**
Collision with Human	Create designated testing area.
Rotating Mechanical Parts	Shut off power to vehicle when handling.
Battery Fire	Charge/operate batteries within correct temperature range. In event of fire, use water as suppressant and do not inhale fumes.
Electrical Shock	Shut off power to electrical devices when changing wiring.

2.9.5.4 Storage The Variable Drive Vehicle was stored in the machine lab during the manufacturing and testing process when it is not being worked on or operated. The vehicle will be covered and stored in a locked cabinet with a "Do Not Touch: Safety Hazard" placard affixed to the top of the device. These measures are aimed at avoiding potential accidents involving pinch points in the actuation mechanism. Protection from moving parts and electrical shock will be ensured by disconnecting the power to the vehicle when it is to be stored.

When storing lithium-polymer batteries for a prolonged period of time, they should be discharged and stored between -4°F and 77°F to ensure no changes occur within the battery's molecular structure [19]. Potential safety risks and solutions have been listed below in Table 2.6.

Table 2.6: Storage safety risks and mitigations.

Safety Risk	**Solution**
Rotating Mechanical Parts	Shut off power to vehicle when handling.
Electrical Shock	Shut off power to electrical devices when changing wiring.
Batteries	Disconnect from vehicle, discharged and stored within correct battery temperature range (-4°F to 77°F).

2.9.5.5 Disposal The VDV will be handed over to the SCU Mechanical Engineering Department for use in future VDV senior design continuation projects. However, proper disposal and recycling techniques will be implemented should the Variable Drive Vehicle need to be disposed of. Batteries and disposable plastics and electrical components will be taken to a waste removal plant to ensure that the components are discarded with as little environmental impact as possible. Recyclable plastics, metal components, and electrical components will be taken to appropriate recycling facilities. Potential safety risks and solutions have been listed below in Table 2.7.

Table 2.7: Disposal safety risks and mitigations.

Safety Risk	**Solution**
Metals	Recycle at San Jose Metals Recycling facility.
Plastics	Recycle at Ranch Town Recycling facility in San Jose.
Electrical Components	Recycle at Green E-Waste Recycling center.
Batteries	Recycle at Green E-Waste Recycling center.

2.9.6 Team Management

A team management system was set in place at the initiation of the project. There was no team leader for the VDV project; the small team size deemed it unnecessary. Each task was assigned to a team member, but approval of all team members was necessary before the task was considered complete. Discussion often allowed each for each team member to focus on areas where they had a particular interest or expertise. More important decisions about the direction of the project were made with all four members of the team present in order to allow for equal input. Disputes over design choices were handled in a pragmatic manner where each solution was discussed thoroughly and the decision was made by simple majority.

3 Subsystems

3.1 Wheeled Chassis

The purpose of the wheeled chassis is to drive quickly and efficiently over smooth terrain. It also must be advantageous over the tracked system by being able to reach higher speeds on these terrains. The wheeled chassis must also have 4 wheel drive so that it is able to power the individual modular track units and be able to provide high torque. Most importantly, the wheels of the chassis need to be able to power the track units and therefore have a motor capable of providing a significant torque. The axles of the wheeled chassis must also be easily accessible to accommodate mounting the various mechanisms necessary for the augmented drive system. The chassis must also be easily modifiable to accommodate stowage of the track units on the vehicle. Additionally, a suspension system should be integrated into the chassis to provide support for any payload that may be added to later iterations of the project. Because the scope of the project is focused on the switching system, an already developed “plug-and-play” remote control system is advantageous. For these reasons, a rock crawler chassis was selected. As previously mentioned in Section 2.5.2, rock crawlers are RC cars with high-torque motors and easily modifiable chassis. They are also capable of great axle articulation, thanks to their sophisticated suspension. Out of the box, many rock crawler motors also offer a four wheel drive configuration. Designed for scaling more extreme terrains, rock crawlers utilize a frame raised high off the ground, and large clearances between components. This provides an excellent platform for modification. Lastly, the axles of rock crawler vehicles often extend out past the body of the car. This results in increased clearance above the wheel, which was determined to be the ideal location for track system stowage.

The Axial Wraith RC vehicle (See Figure 3.5 was chosen because it met these requirements. It includes a high torque 20-Turn DC motor that can power the four wheel drive system at speeds of up to 12 mph. The frame is constructed of composite plastic tubing held together by button head socket cap screws, requiring only hex keys for disassembly and modification. The electronic components are housed in protective casing and a skid plate underneath the transmission protects it from wear. The 4-Link suspension provides optimal axle articulation used to clear uneven terrains. The shocks include a spring tensioning system and a damper with replaceable fluid. This level of customization was deemed sufficient for the scope of this project.

Figure 3.5: The Axial Wraith rock racer.

3.2 Track Units

The VDV incorporates a wheel driven track system that is able to engage and disengage from the wheel. This provides the vehicle with added traction and terrain-scaling capabilities when desired. A wheel driven track system requires the motion of the wheel to power the track, thus eliminating the need for two drive motors. Modular track units were determined to be the best option for accomplishing this. They are lightweight when compared to full tracks and are able to maintain spatial and height clearance between the wheels.

Figure 3.6 shows a Solidworks assembly model of the track units. Tracked systems generally use an arrangement of axle mounted rollers with a belt wrapped around them to allow for the controlled rotation of the track belt around a specified path. The positions of these axles and rollers are fixed by the track plates. However, the track plates incorporate a series of slots that allow for tension adjustment of the track belt. A total of five track plates are used to accommodate for the existing geometry of the wheeled chassis and facilitate attachment of the track units to the axle. The complex shape and hole arrangement significantly reduces the machinability of these parts. Therefore, this component was laser-cut out of 3/8" acrylic sheet. Plastics were deemed to be a suitable material because of the small scale of the VDV prototype. The three inner track plates (two on the inside and one on the outside of each wheel) have larger holes and slots to allow the axles to rest inside of them. These push up against the outer track plates on each end. The outer track plates have smaller holes, which allow for screws to pass through and fasten the axles in place. The bottom center axle, and the axles of the two splined drive rollers on each track unit are not screwed in place. They passes through the inner track plates and are held in place by the outer track plates on either side. At the center of the outer most track plate is a cut away for an

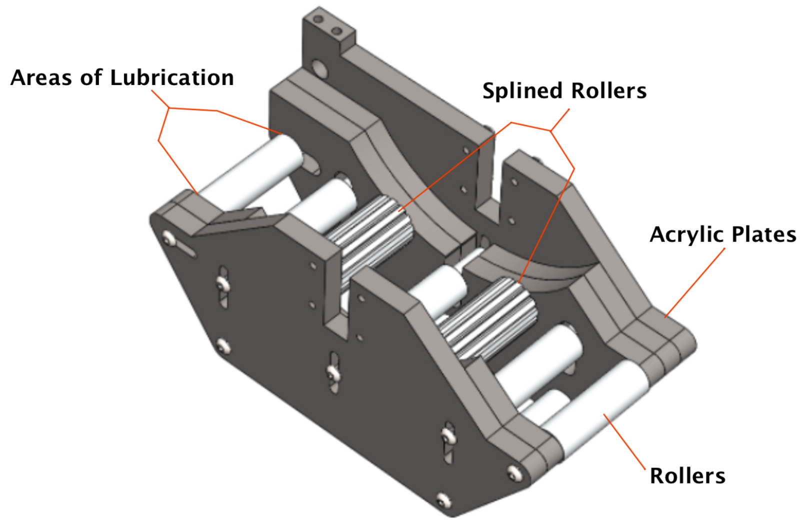


Figure 3.6: 3D CAD model of the modular track units.

aluminum insert. The purpose of this insert will be explained later.

To facilitate the free spinning motion of the rollers, solid graphite lubricant was applied to the mated surface between the inside of the roller and the outside of the axle. This uses less space than a bearing and costs less. The solid graphite lubricant also does not attract dust or dirt which could accumulate and compromise the rotation of the track belt. Each roller and axle were machined out of 6061-Aluminum. Simplifying load calculations showed that the minimum allowable axle radius for a worst case loading of 14 lbs was 0.01 inches. The actual axle diameter sizes of 0.375 inches and 0.25 inches were implemented due to the constraints associated with machining small parts. An axle with a diameter of 0.01 inches would deflect when placed in a lathe and cannot easily be properly machined.

In order to ensure that the forward rotation of the wheel corresponds to the forward motion of the track belt, intermediary splined rollers were used. These splined rollers were machined out of aluminum pulley bar stock and the splined profile provided added traction between the wheel and the splined roller. The track belt is a timing belt with the same pitch as splined rollers providing a mated drive interface. Figure 3.7 shows a schematic of the motion of the wheel relative to that of the track. As the wheel rotates clockwise, it grips the intermediary splined rollers turning them in the opposite direction. These rollers then rotate the track in the same direction as the wheel.

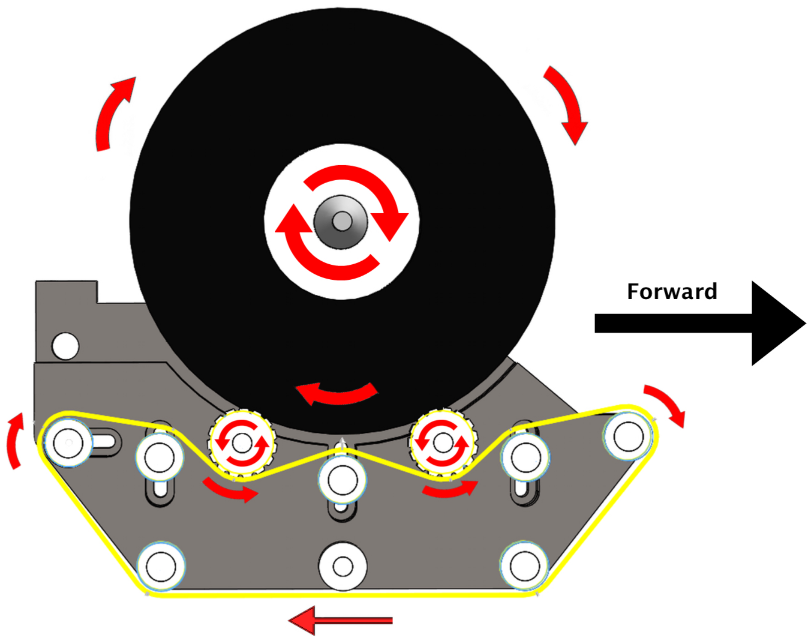


Figure 3.7: Belt diagram demonstrating the motion of the wheel relative to the track.

3.3 Rotation Clamp

In order to accommodate a variable drive system, the modular track units needed to be mounted to the vehicle in a way that facilitates stowage on board the vehicle. A rotational system was deemed the simplest and most effective way to achieve this goal. The track units can be positioned beneath the wheels when in use and rotated into a position above the wheels when stowed. This subsystem is called the rotation clamp and can be seen in Figure 3.8.

This rotational capability first needed to be enabled, before it was controlled. The track units also had to be attached to the vehicle on both the inside and outside of each wheel for stability and ruggedness in all terrain conditions. On the inside of each wheel, the unit was mounted by press-fitting a 15 mm bearing onto the axle housing of the base vehicle. An aluminum collar (Part Number: C2) was then press-fit to the outer ring of this bearing to facilitate the additional hardware required to attach the modular tracks. The specifics of this hardware connecting the bearing collars to the acrylic track plates will be discussed in a later subsystem. On the outside of each wheel, an extension for the axle was required. This aluminum extension was then threaded onto the end of the factory axle, and fit with its own 0.25 inch bearing and collar (Part Number: C1). Figure 3.9 shows where these are bearings incorporated into the VDV system.

Most importantly, with this rotation enabled, it then needed to be controlled. It was also important to utilize the the main drive motor of the car to control the position of the modular tracks, because of its high torque capabilities. This was achieved by clamping the track unit to the wheel, so that a rotation of the wheel corresponds to a rotation of the track unit.

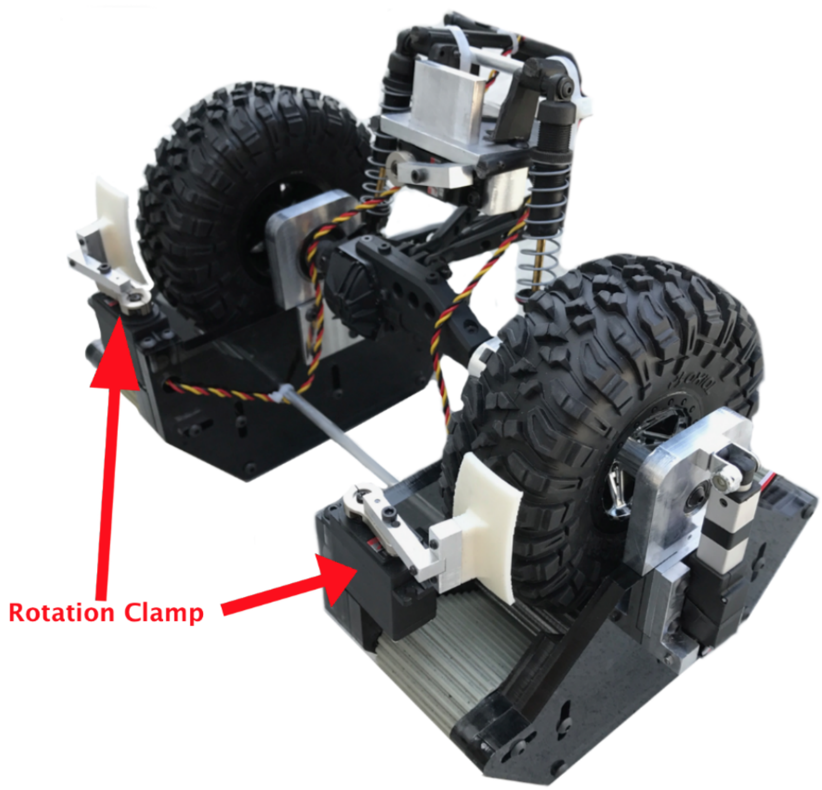


Figure 3.8: Photograph of VDV rear wheels with rotation clamp call-out.

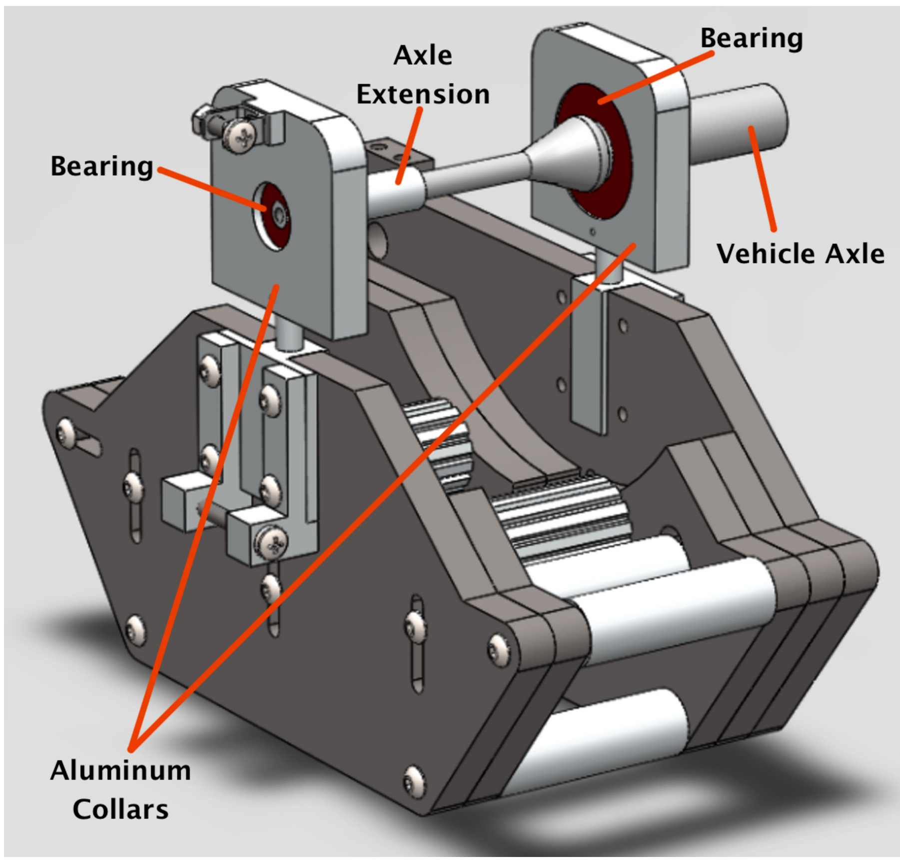


Figure 3.9: Mounting bearings and aluminum collars.

To achieve this goal, a Hitec HS645MG servo was used. This is a high torque model that incorporates a metal gear train. This servo was fitted with an aluminum servo horn, which was attached to a machined aluminum brake arm. (Assembly Number: A4) At the end of this arm was a 3D printed braking surface. This concave shell was designed to mate to the convex wheel when engaged, thereby locking into the tread pattern. This assembly can be seen in Figure 3.10. With the two components clamped together, the user can then rotate the entire device up into the desired stowage position using only the vehicle's throttle control. The track drive configuration can be seen in Figure 3.11(a), and 3.11(b) shows the wheel drive stowage position.

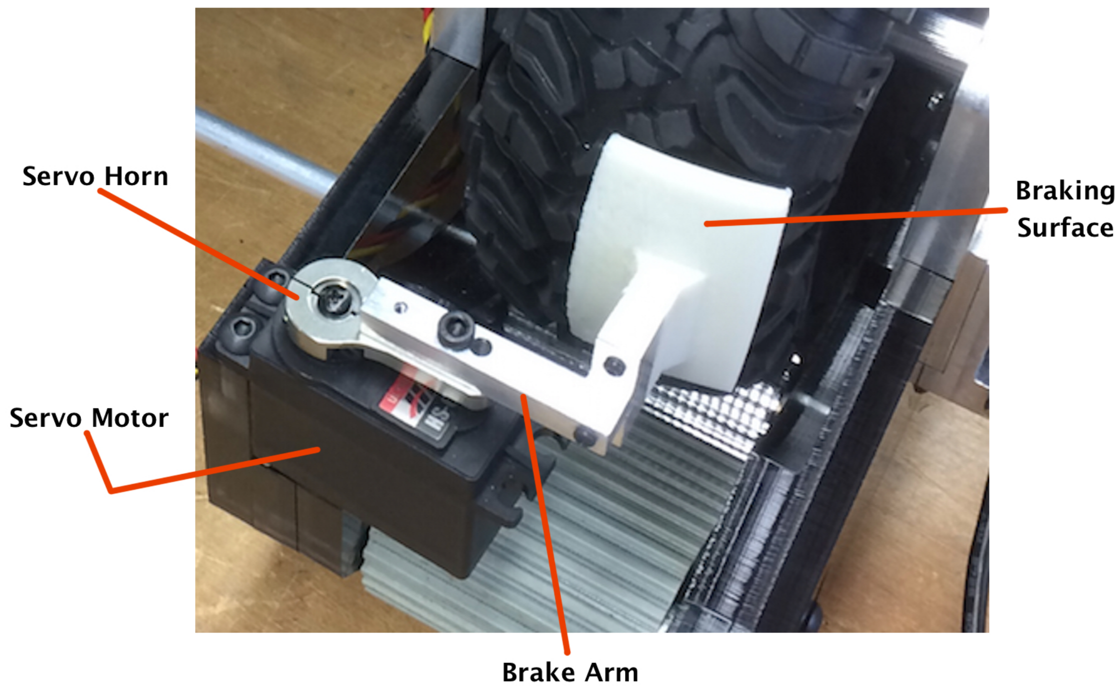


Figure 3.10: Rotation clamp servo, aluminum arm, and 3D printed braking surface.

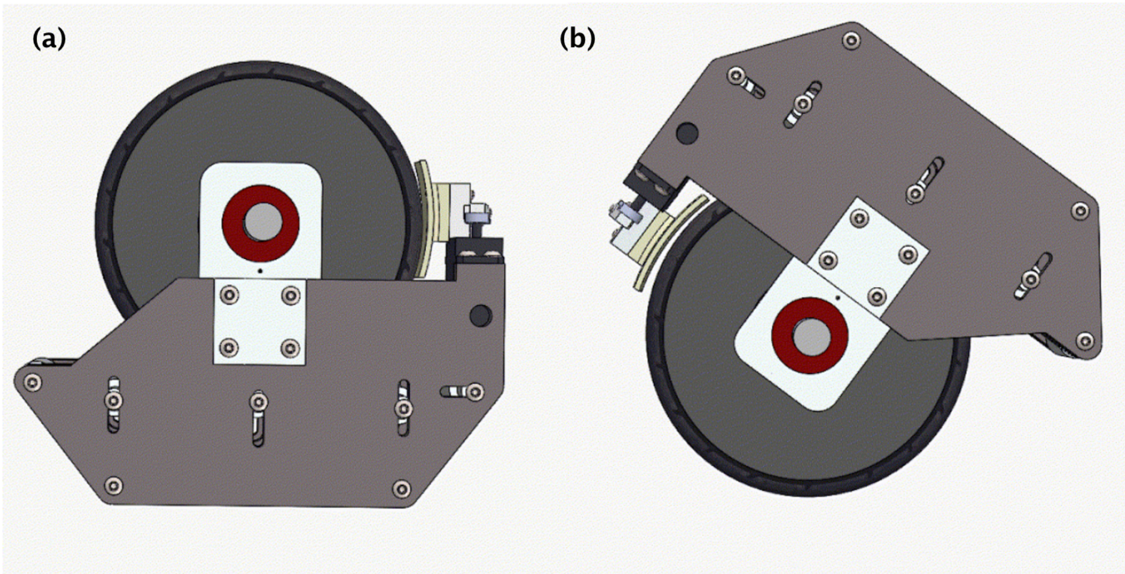


Figure 3.11: Use of the rotation clamp.
a) Tracked configuration.
b) Wheeled configuration.

3.3.1 Supporting FEA Analysis

Abaqus Finite Element Analysis software was used to gain a better understanding of the stresses acting on the track unit during peak loading. Peak loading occurred when the track assembly contacted the ground in order to switch the vehicle from driving on wheels to driving on tracks (see Figure 3.12).

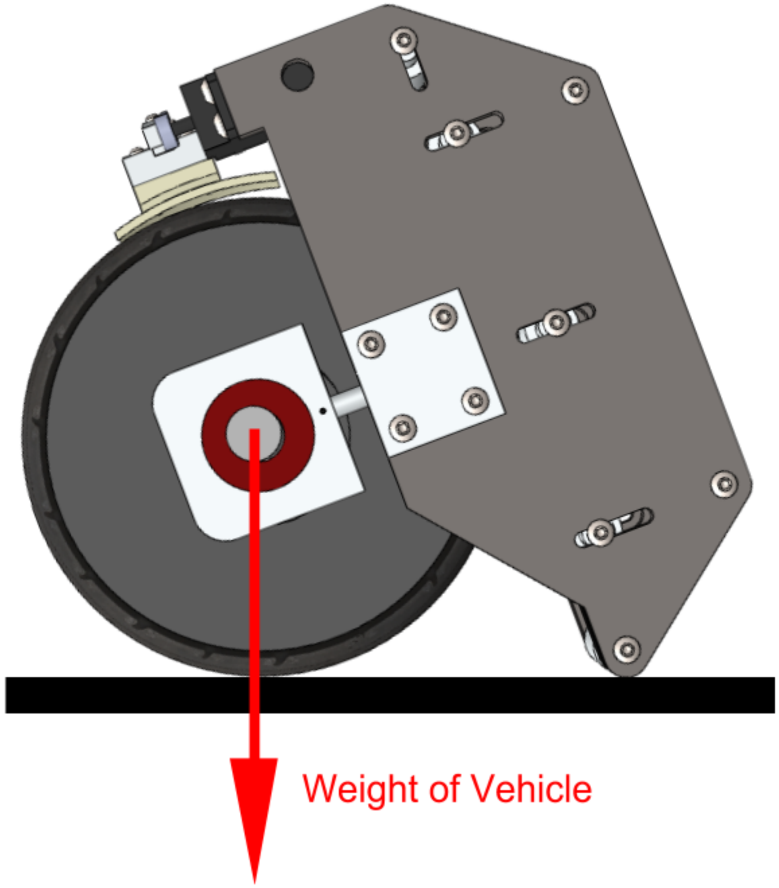


Figure 3.12: Free body diagram of peak loading scenario.

During this action, a servo arm brake is brought into contact with the wheel, effectively locking the rotation of the track assembly and wheel together. The vehicle reverses slowly resulting in a rotation of the wheel backwards and a rotation of the track assembly from the stowed position above the wheel towards the ground. Upon coming into contact with the ground, the track unit pushes the vehicle up onto the tracks and the vehicle will come to rest on top of the tracks, which are now in contact with the ground. When the track unit rotates from the stowed position above the wheel to the ground under the wheel, the vehicle's weight is momentarily transferred to two critical locations on the track unit. The location where the axle of the vehicle attaches to an axle extension shaft was considered to be critical due to varying shaft diameters and the resulting stress concentrations (see Figure 3.13). Additionally, the subassembly of components that attach the track unit to the vehicle's axle, named the axle collar mount, was considered to be critical because of the potential for large bending loads occurring at the junctions between the two cylindrical shafts and the side plates of the track assembly (see Figure 3.13).

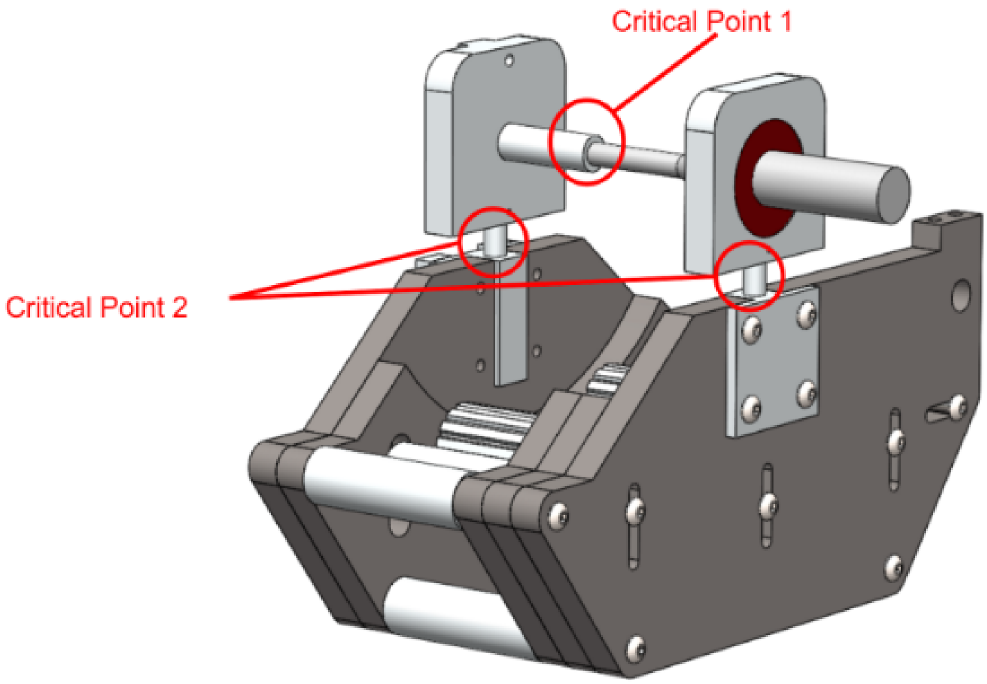
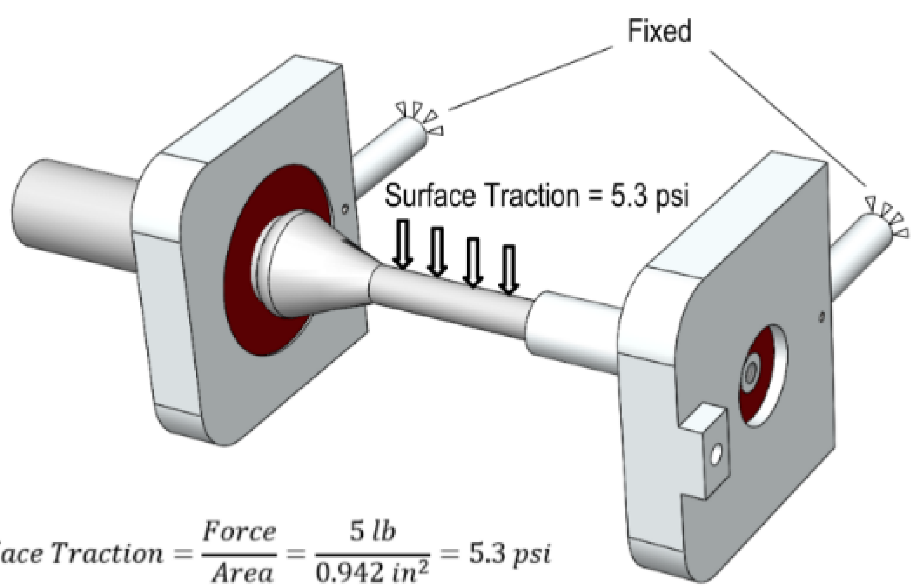


Figure 3.13: Critical points during drive system transition.

Before performing FEA, a free body diagram was used to gain an understanding of the boundary and loading conditions acting on the axle collar mount (see Figure 3.14).



$$Surface\ Traction = \frac{Force}{Area} = \frac{5\ lb}{0.942\ in^2} = 5.3\ psi$$

Figure 3.14: Free body diagram of FEA boundary and loading conditions.

In Figure 3.14, the acting load is due to the weight of the vehicle momentarily transferring from the wheels of the vehicle to the axle collar mount, before the load finally comes to rest on the tracks and bottom rollers. Referring to the design specifications listed in Appendix B, a maximum vehicle weight of 20lbs was expected. Assuming that this weight was evenly distributed among each of the 4 wheels or track units, then a 5 lb load would be acting upon the axle collar mount. In Abaqus, this load was prescribed as a surface traction, which is the load divided by the surface area where the load acts on the axle collar mount. Additionally, the junction between the axle collar mount and the track frame was assumed to be fixed with zero displacement allowed.

Several assumptions were made to simplify this model, including that all components were modeled as one homogeneous material with solid, homogeneous, quadratic, tetrahedral elements in Abaqus. Second, the loads were assumed to be static. In reality these loads will be applied dynamically. Additionally, since the axle collar mount was modeled as an isolated system that does not actually come into contact with the ground, the rest of the track unit was assumed to be rigid without deformation. This is a necessary assumption to make in order to fix the displacement of the axle collar mount at the junctions between the two cylindrical shafts on the axle collar mount and the side plates of the track frame. Lastly, the external conditions were assumed to be normal atmospheric pressure and temperature of 14.7 psi and 69°F.

The material chosen for the axle collar mount was 6061 Aluminum due to its high strength to weight ratio and ease of machinability. In Abaqus, the material properties, assumed at normal atmospheric pressure and temperature, were input as follows: Poisson's ratio of 0.33 and Modulus of Elasticity of 1.03+07 psi. After importing the Solidworks CAD file into Abaqus, a mesh convergence study was performed. This consisted of increasing the number of elements in our mesh, until the output solution did not change significantly. The final mesh on the part consisted of 162,000 elements (see Figure 3.15).

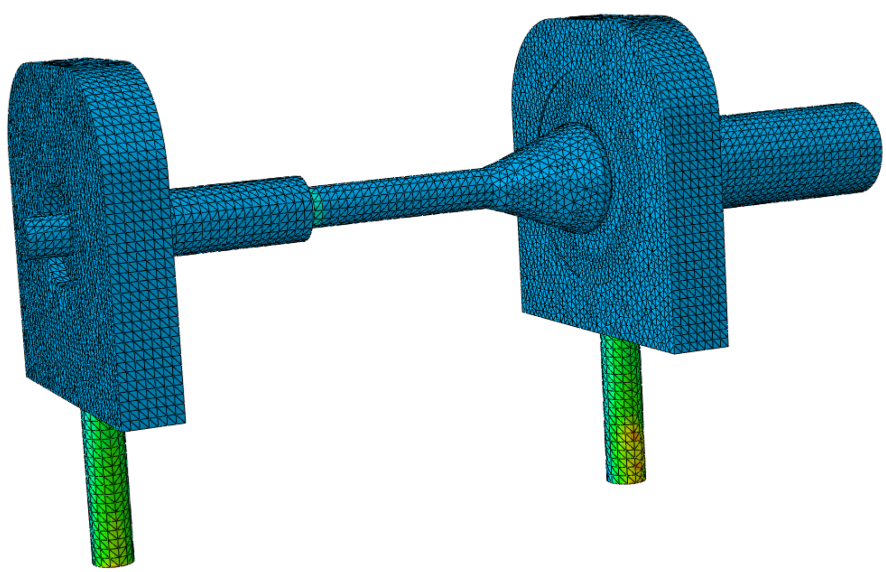


Figure 3.15: Mesh with quadratic tetrahedral elements.

Hand calculations assuming the same material properties, boundary and loading conditions as the FEA simulation were also used to determine the stresses at each critical point. The formulas and procedures for hand calculations can be found in Appendix B. Hand calculations found maximum principal stresses of 3.614e+03 psi at critical point 1 and 2.908e+03 psi at critical point 2, both below the yield stress of 6061 Aluminum 4.0e+04 psi. FEA results found maximum principal stresses of 3.243e+03 psi at critical point 1 and 2.554e+03 psi at critical point 2. Because the results from hand calculations were close in value to the FEA results, the FEA results and the assumptions used to formulate the FEA simulation were validated. The contour plots from the FEA simulation have been included in Figure 3.16 below. Figure 3.16(a) shows critical point 1, and 3.16(b) shows critical point 2. It should be noted that the deformations have been multiplied by a deformation scale factor because they would not otherwise be perceptible.

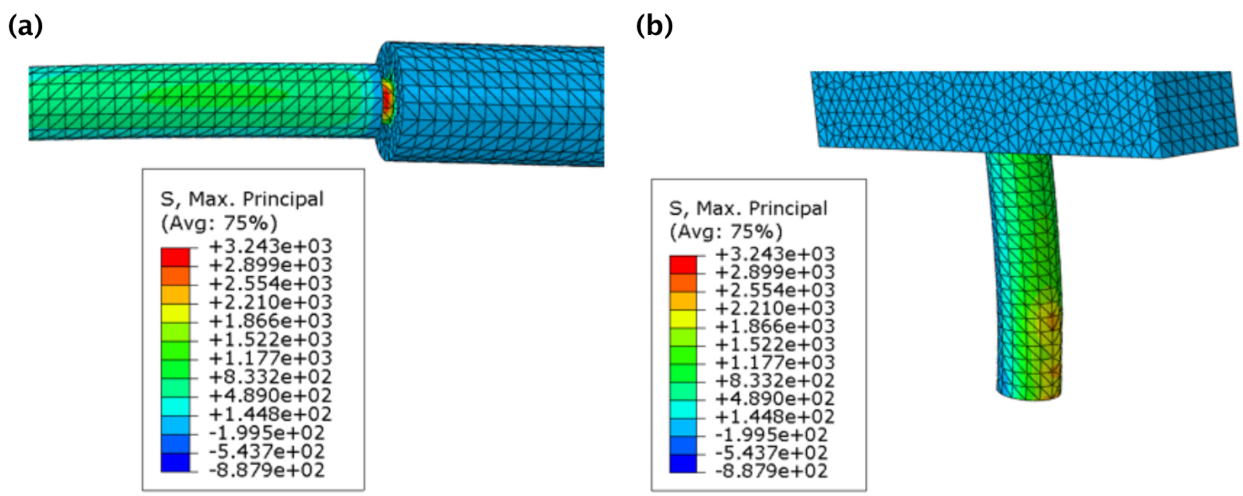


Figure 3.16: FEA simulation results at both critical points.
a) Critical point 1.
b) Critical point 2.

3.4 Stowage Lock

After the modular track units were rotated to the stowage position above the wheel, they needed to be locked in this position, in order to utilize the wheeled drive system. This subsystem is called the Stowage Lock, and consists of two main components, an aluminum crossbar and a latching mechanism. These components are shown in Figure 3.17.

Figure 3.17: VDV prototype photograph with stowage lock call-out

The first component is the aluminum crossbar (Part Number: S8) connecting the two rear track units, which was incorporated to simplify the stowage process in two ways. It not only ensures that the track units rotate simultaneously but provides a single surface to latch onto instead of locking each side individually. The latch is integrated on several aluminum chassis reinforcements, integrated to provide increased rigidity over the plastic vehicle frame components. Another Hitec servo motor, an HS425BB, is mounted on these components, and actuates an aluminum arm, which rotates up to constrain the motion of the crossbar, when engaged.

Interestingly, the crossbar included in the stowage lock also serves as an axle for the rear splined roller in each track unit. This reduced the overall number of machined parts in the final prototype for the project. Instead of fabricating two axles and a crossbar, one continuous bar was made to fit all three purposes. A model of the Stowage Lock, as well as a photograph of the system can be found in Figures 3.18 and 3.19.

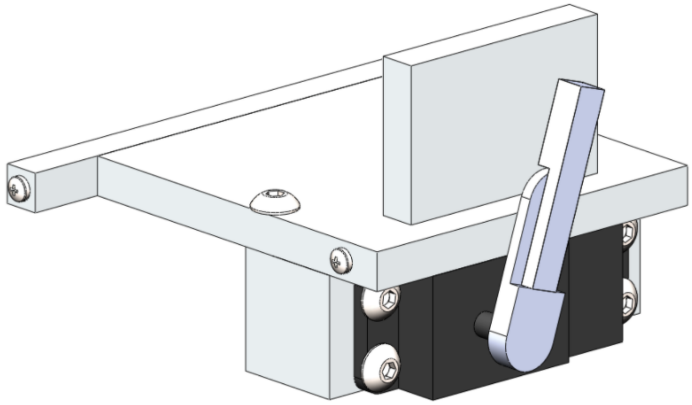


Figure 3.18: Stowage lock model showing aluminum frame reinforcements and latch.

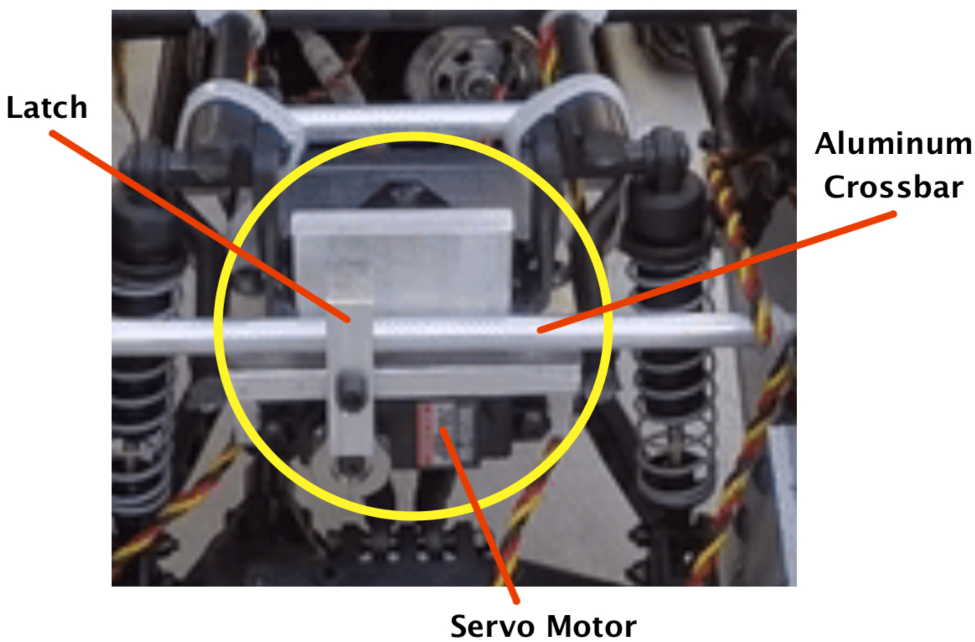


Figure 3.19: Labeled Prototype Photograph of the Stowage Lock Engaged

3.5 Contact Lock

The last important mechanical design consideration stems from the need to fully disengage the track drive system when the wheeled system is in use. With the modular tracks above the wheels and locked in place, the wheels are still in contact with the splined rollers without any additional mechanisms. Thus, the drive motor would still be powering the tracks. Not only is this unnecessary, because the tracks are pointed up in the air, but frictional losses inherent to the track units waste limited power and they significantly inhibit the performance of the wheeled system. To solve this problem, a Contact Lock was designed. It was named for its ability to hold the wheel in contact with the splined rollers, or disengage this functionality altogether, depending on which drive system is being used at the time. Figure 3.20(a) shows the wheel in contact with the splined rollers in order to drive the track. Figure 3.20(b) shows the splined rollers disengaged when driving in wheel mode.

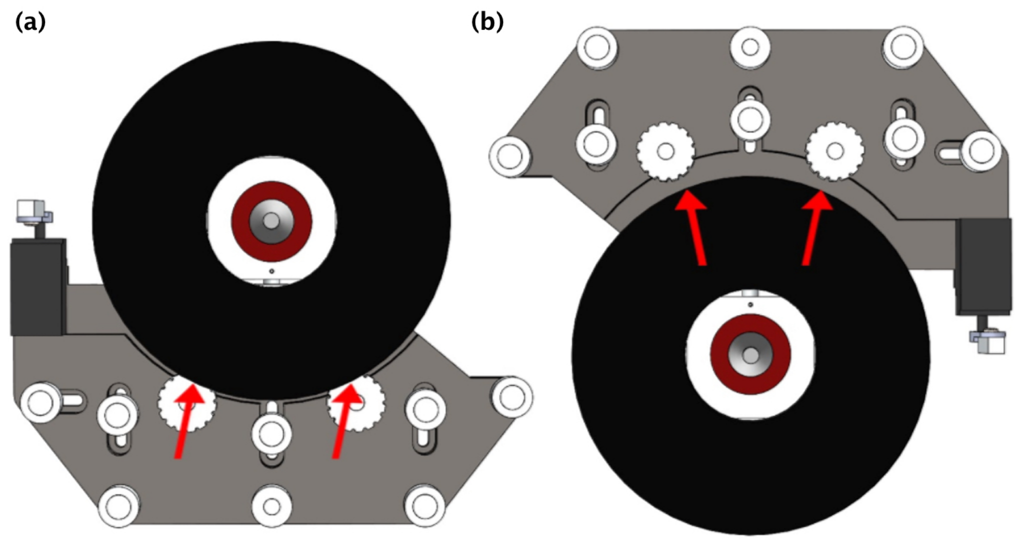


Figure 3.20: Section view diagram of the contact lock functionality. a) Tracked configuration, wheels are in contact with splined rollers. b) Tracks are stowed above wheels, the splined rollers are disengaged from the wheels.

This subsystem includes an aluminum shaft that extends from an inset in the bearing collars mounted to the axle of the VDV. These parts are pinned together by means of a spring pin. (Assembly Number: A3) This shaft enters into a sleeve, machined into an aluminum inset mounted in the track plates (Part Number: T10) This tight-tolerance fit provides for smooth motion of the track unit away from the axle of the vehicle to prevent the driving of the track. The aluminum inset sleeve was selected over incorporating the hole into the acrylic plate itself to avoid binding in the mechanism. Additionally, the thin wall on either side of the hole in the acrylic plate would be much more prone to failure.

An electronic linear actuator was then incorporated in order to control the extension and contraction of the shaft in the sleeve. A model of this hardware is shown in Figure 3.21. An Actuonix L12-R was selected for several reasons. Its compact design and 30 mm stroke met the VDV application, while also being both lightweight and strong. With a 210:1 gear ratio, it can provide over 80 Newtons of force, about 17 pounds, more than enough to lift the modular tracks. Springs were initially placed in the bottom of each sleeve in order to assist in extending the mechanism. However, the springs caused significant binding issues in the mechanism and were removed. Successful operation without them proved the springs to be unnecessary. Lastly, this particular model is operated using the same control algorithm as the other servo motors used in this project, which will be discussed in the controls subsystem. By expanding the actuator, the aluminum shaft is guided to an extended position, slightly lifting the splined rollers off of the wheel. Bringing these two components out of contact disengages the driving functionality of the modular track system. The track units become completely stowed and nonoperational, allowing the wheeled drive system to operate freely.

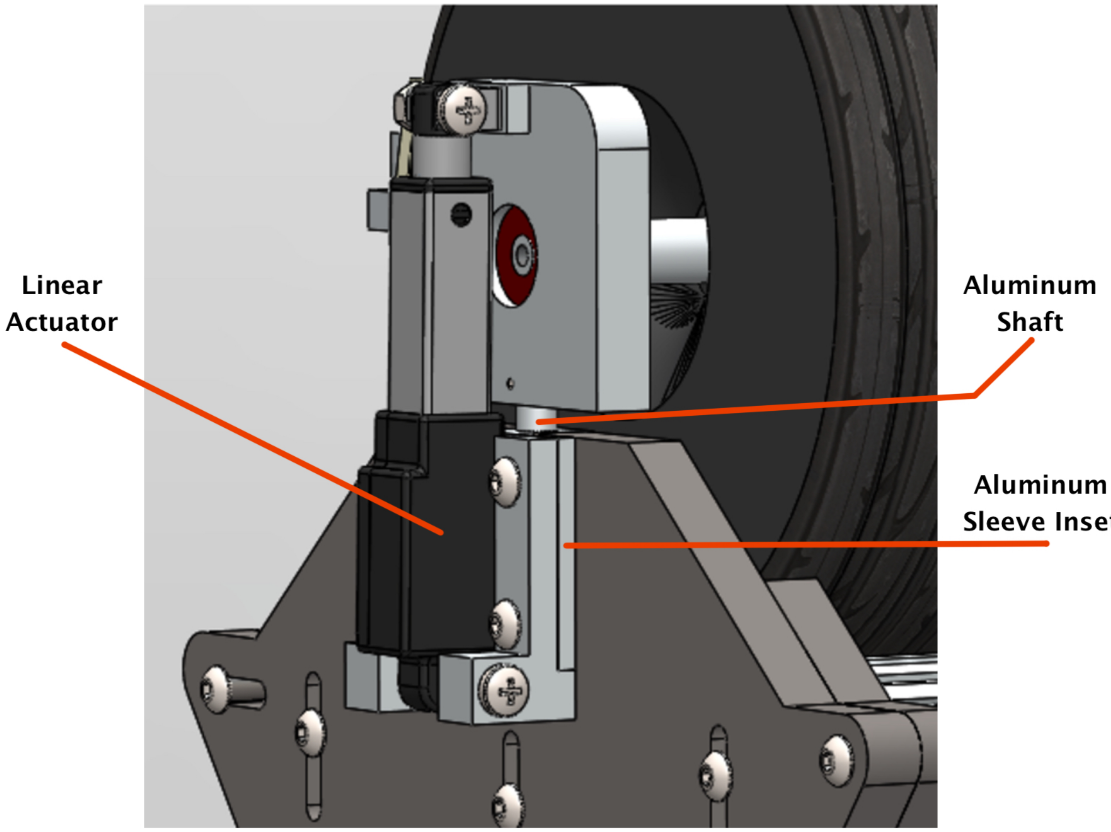


Figure 3.21: Contact lock model showing aluminum shaft and linear actuator.

3.6 Control Subsystem

In order to control the VDV's mechanical subsystems, a centralized control subsystem needed to be developed. This centers around an Arduino Uno microcontroller. While Arduino requires use of its own code language, this language is easy to use and very high level and function-based. The Arduino Uno is one of the simplest, lowest cost solutions for prototyping projects like the VDV on the market today.

Most importantly, the Arduino is particularly well suited for our project because of its open source code libraries for controlling servos. Servo motors operate using PWM, which stands for pulse width modulation control. Essentially, the microcontroller sends the servo a 5 V square wave for a specified number of microseconds, which corresponds to an angular position. Arduino makes it very easy to relate these two parameters and quickly obtain a functional system. As previously mentioned, both our servos and linear actuators operate via the same control algorithm, PWM. However, in the case of the linear actuators, the length of the pulses sent to the device corresponded to a certain level of extension, rather than an angle.

All of the wiring for this project was done using a breadboard. This was deemed sufficient given that the project is a proof of concept that subject to change drastically with subsequent work. Therefore, it would have been inappropriate to solder a permanent solution. The Arduino and the breadboard are both housed in a 3D printed box that mounts to the frame of the vehicle via screws and 3D printed clips (see Figure 3.22). For simplicity, a diagram of the control wiring will be included with the electrical diagram in the electrical subsystem section.

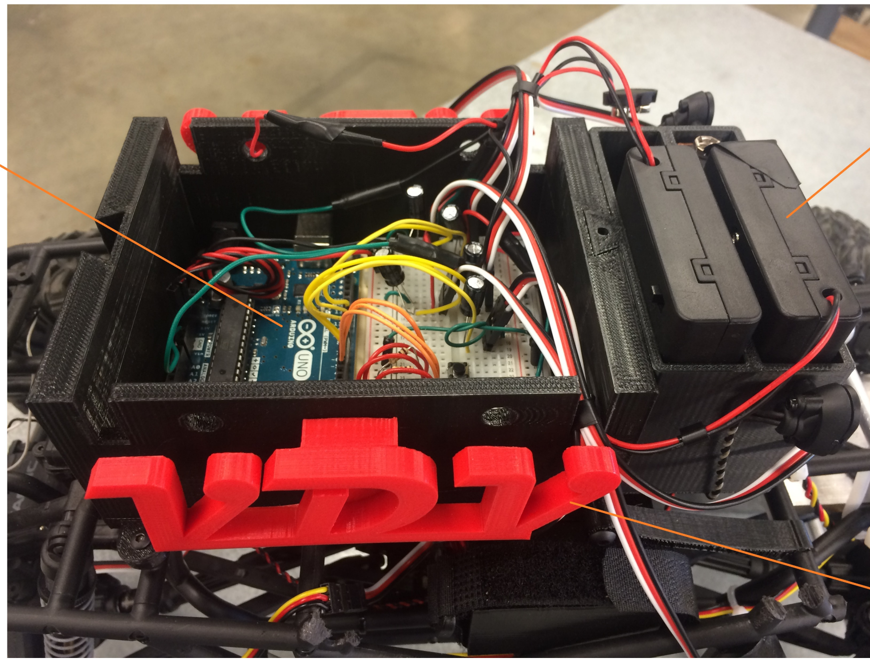


Figure 3.22: 3D printed controls housing box.

The subsystems of the VDV are operated via onboard push-buttons. The alternative would have been to implement a radio control module with our Arduino, and possibly to integrate the mechanism controls onto the car's own remote. However, this process was deemed non-essential for achieving the core functionalities of the project. The push-buttons were included in the Arduino kit that was originally purchased, and therefore there was no need to purchase additional hardware. One interesting facet about the implementation of the momentary push buttons is that code effectively changes them into on/off toggle switches. This is the ideal configuration to match the VDV's physical actuation. For example, this enables the user to push the rotation clamp button once to turn on and again to turn it off, instead of holding the button down the entire time the clamp needs to be engaged. This was achieved by reading the Arduino's inputs looking for two conditions and using these conditions to cycle a variable between zero and one: off and on. First, a change in the button's state was required, and second, the change needed to be from high to low. This combination ensures that holding a button down does not register multiple presses, and that letting go of a button does not register as a change. A delay of 20 milliseconds was also implemented in this loop in order to ensure that a press could not be missed by the microcontroller. These parameters together resulted in very reliable operation of the VDV's actuation systems. (See Appendix I)

Once control over the servo motors and linear actuators was established, their optimal positions were determined experimentally. For the rotation clamp, the servo was rotated until the braking surface slightly depressed the tire. When turned off, the specified angle was reduced by 20 degrees, leaving a small gap between the wheel and the braking surface. A similar process was utilized to find the vertical and horizontal positions corresponding to the on and off positions, respectively, for the stowage lock. The contact lock engaged position was specified when the bearing collar interferes with the acrylic track plate, and the aluminum shaft is fully inserted in its sleeve. The actuator was then used to extend the mechanism until the wheel fully disengaged from the splined rollers and could rotate freely.

3.7 Electronic Subsystem

In order to retain modularity of the prototype at this stage, the vehicle's drive motor and steering power supply were powered separately from the added systems. The Axial Wraith is powered using a manufacturer-recommended 7.4 V, 4100 mAh Lithium Polymer battery, which was more than adequate for the extent of the VDV's testing.

The Arduino Uno was initially powered via a USB cable connected to a laptop computer. This enabled testing of the system while retaining the ability to manipulate control parameters. Once the actuation positions were determined, the Arduino was then powered with a 9 V battery, allowing for untethered operation and testing. 9 V batteries are cheap, readily available, and right in the middle of the acceptable 5 V to 12 V range for powering the board properly.

Because the Arduino Uno can only supply 450 mA, an external power source was necessary to supply all of the subsystem actuators. AA batteries were selected to power the servo motors and linear actuators because they are cheap, readily available, and have better current capacity than the 9 V. Each of these cells provides 1.5 Vs. In to provide the necessary 6 Vs to operate the components at optimal levels, 4 AA batteries were needed in series. This configuration was made possible by purchasing Adafruit battery holders.

The main electrical concern for the VDV project was the current that the AA's could supply in light of the requirements for the servo motors and linear actuators. Each HS645MG high torque servo motor requires up to 450 mA, the HS425BB standard servo draws 150 mA, and each linear actuators needs 300 mA at full load. The total current draw sums to 1.65 A. Alkaline AA batteries are capable of supplying over 2 A each, but only for roughly 45 minutes. To avoid having to change batteries frequently during testing, 2 AA battery packs were incorporated. This configuration is more than capable of powering all of the actuators at the same time if necessary. In order to split the loading, the first power pack was connected to one high torque servo, the standard servo and one linear actuator. The second power pack was connected to the other high torque servo and linear actuator. A 100 microfarad was also placed in parallel with the power supply for each component in order to stabilize the system. This helped to combat the slight dip in voltage commonly caused by servo motors short peaks in current draw, by acting as a "reservoir." Lastly, it was important to connect the grounds of each circuit in order to ensure that the PWM control would operate correctly. Without this, the servo motors and actuators behave erratically. Detailed manufacturers information for the servos, linear actuators, and AA's batteries can be found in Appendix H. Figure 3.23 contains a visual representation of the wiring for the VDV's electrical system.

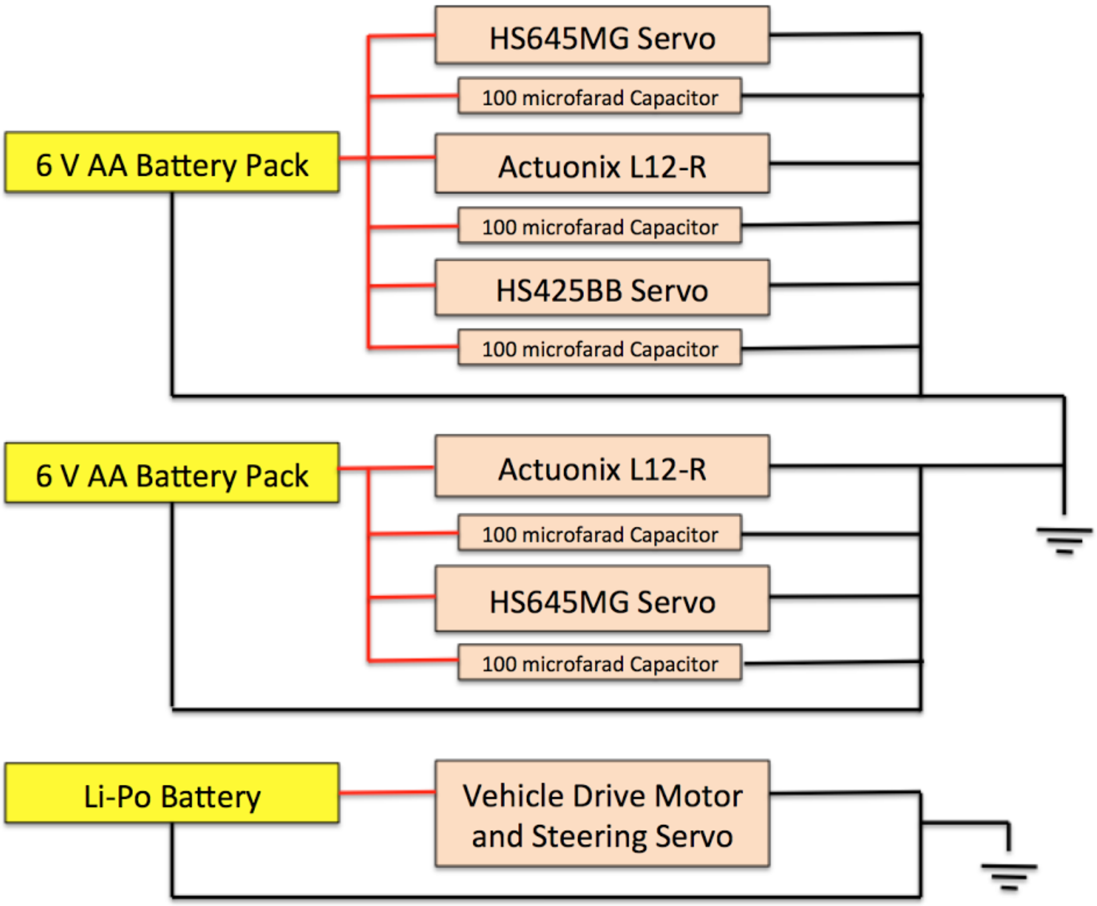


Figure 3.23: High level wiring diagram of the VDV's electronics.

4 Testing and Results

4.1 Experimental Protocol

The experimental protocol used to test and verify each criteria from the PDS (see Appendix B) can be seen in Table 4.8 below.

Table 4.8: Experimental protocols.

Evaluation	**Location/ Time**	**Equipment**	**Accuracy**	**Trials**	**Requirements**	**Formulae/ Assumptions**	**Man Hours**
Track Speed (Concrete)	Engineering Quad, 5/9 1pm	Stopwatch, long tape, cones	0.1 mph	10	5 mph	Constant velocity between cones at 10 ft	0.5
Wheel Speed (Concrete)	Engineering Quad, 5/9 1:30pm	Stopwatch, long tape, cones	0.1 mph	10	12 mph	Constant velocity between cones at 10 ft	0.5
Switch Time	Engineering Quad, 5/9 2pm	Stopwatch	0.1 sec	5	10 sec	n/a	0.25
Weight	Machine Shop, 5/8 5pm	Scale	0.5 lbs	3	20 lbs	n/a	0.25
Max. Slope	Engineering Quad, 5/19 11:30am	Cinder blocks, plywood sheet	1 degree	10	33 degrees	$\tan^{-1}(\frac{opp}{adj})$ = degrees	0.5
Obstacle Height Clearance	Engineering Quad, 5/9 12pm	Plywood sheets	0.1 in	10	7 in	n/a	0.5

4.2 Testing Procedure and Results

4.2.1 Track Speed

The track speed was measured by driving the vehicle in track mode a known distance between two cones in our testing area. A team member drove the vehicle at top speed past the two cones starting a sufficient distance before the first cone so that the vehicle had time to achieve maximum speed. A second team member used a stopwatch to time how long the vehicle took to travel from the first cone to the second cone. The known distance between the two cones was be divided by the travel time to determine velocity.

On concrete, the average track speed of the VDV was 0.8 mph. Unfortunately, the VDV was not able to move when in track mode on grass, gravel or sand. These surfaces provide less traction than concrete and during testing, the contact between the VDV's wheels and splined rollers was not sufficient to transmit power to turn the tracks on these surfaces. As a result, the wheels spun continuously without gripping the splined rollers and the tracks did not move (see Figures 4.24 and 4.25).

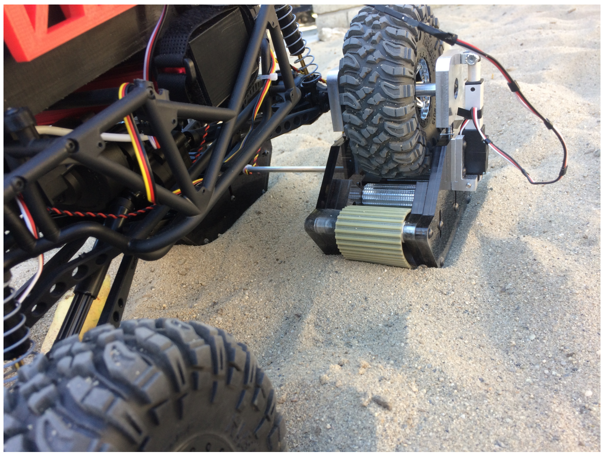


Figure 4.24: Tracks sinking in sand.

Figure 4.25: Tracks sinking in grass.

4.2.2 Wheel Speed

The wheel speed was measured in the same manner as the track speed, however the vehicle was in wheel mode.

Table 4.9: Wheel speeds on different surfaces.

Surface	**Average Speed**
Concrete	11.48 mph
Grass	4.05 mph
Gravel	3.24 mph
Sand	2.71 mph

4.2.3 Switch Time

The vehicle switched from wheel mode to track mode by engaging the brake arm and contact lock, disengaging the rotation lock, and slowly reversing the vehicle until the tracks are fully engaged with the ground (180 degrees from their starting point), then the contact lock was released. The vehicle switched from track mode to wheel mode by engaging the brake arm, releasing the contact lock, and slowly driving the vehicle forward until the tracks come into contact with the rotation lock above the vehicle (180 degrees from their starting point on the ground), then the brake arm was disengaged. The switch time was then calculated by timing the full transformation of wheel to track mode and track to wheel mode and taking the average of the two actions.

Averaging 5 switch times each, the time to transition from wheel mode to track mode was found to be 5.79 seconds, and from track mode to wheel mode 6.79 seconds. The total average of switching times was then calculated to be 6.29 seconds.

4.2.4 Maximum Slope

The maximum slope that the vehicle could surmount was measured by placing one end of a plywood sheet on top of cinder blocks, and the other end on the ground, effectively making a ramp. More cinder block were be added to increase the slope of the ramp until the vehicle slipped when trying to travel up it. Using measuring tape, the slope was measured by measuring the opposite and adjacent legs of the triangle made by the plywood sheet ramp with the ground. The inverse tangent relationship between opposite and adjacent legs of the triangle was then used to define the slope angle.

In wheel mode, the VDV was able to climb a slope of 21.59 degrees. In track mode, it was able to climb a slope of 5.06 degrees. Poor contact between the VDV's wheels and splined rollers resulted in the wheels spinning continuously without gripping the splined rollers on slopes greater than 5.06 degrees, resulting in no track movement (see Figure 4.26). Theoretically, the VDV should be able to overcome greater slopes when in track mode because of increased surface traction, however, for this to be accomplished, the contact between the VDV's wheels and splined rollers must be improved.

Figure 4.26: VDV traveling up 5 degree slope in track mode.

4.2.5 Obstacle Height Clearance

The maximum height that the vehicle could surmount was measured by placing plywood sheets on the ground. More sheets were added to increase the height of the obstacle until the vehicle could not surmount it (see Figures 4.27 and 4.28). The height was measured using a measuring tape.

In wheel mode, the VDV was able to surmount an obstacle 2 inches high. In track mode, it was able to surmount an obstacle 1 inch high. Theoretically, the VDV should be able to overcome greater obstacles when in track mode, however, for this to be accomplished, the contact between the VDV's wheels and splined rollers must be improved.

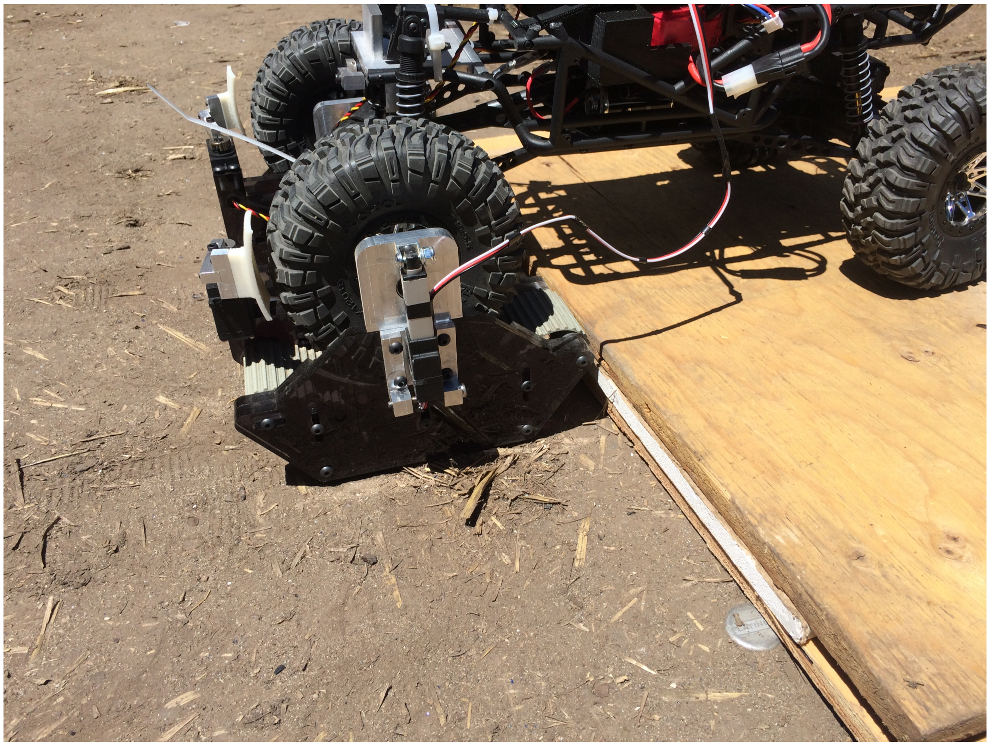


Figure 4.27: Approaching obstacle.

Figure 4.28: Overcoming obstacle.

4.3 Benchmarking Results

Table 4.10: Experimental results.

Evaluation	Requirements	Measured Results
Track Speed (Concrete)	5 mph	0.8 mph
Wheel Speed (Concrete)	12 mph	11.48 mph
Switch Time	10 sec	6.29 sec
Weight	20 lbs	14 lbs
Max. Slope	33 degrees	5.06 degrees (track mode) 21.59 degrees (wheel mode)
Obstacle Height Clearance	7 in	1 in (track mode) 2 in (wheel mode)

5 Costing Analysis

5.1 Chassis Cost

The wheel-based chassis for the VDV was the base of the entire project. The remote control car was $450.88, which included the cost of the controller, and the batteries required for the car and the controller. This was a large purchase with a budget of only $2000.

5.2 Track Unit Cost

Each track unit was constructed from custom designed machined components. Major components for the cost of each unit included the linear actuators on each unit, the high torque servo motor on each unit and the aluminum bar stock within each track unit. The overall cost for each track unit was $315.57.

The VDV's stowage lock was the cheapest subsystem costing only $25.46. The final cost-contributing component was the Arduino Starter Kit, which cost $63.83.

5.3 Overall Cost Breakdown

Table 5.11: Cost breakdown.

Total Vehicle Analysis	Individual Cost	Quantity	Total
Track Unit, Rotation Lock, and Contact Lock	$315.77	2	$631.54
Stowage Lock	$25.46	1	$25.46
Vehicle Chassis	$450.88	1	$450.88
Electrical Components	$94.04	1	$94.04
			$1201.92

The cost for the components and materials on the VDV was $1201.92. However, this isn't the total sum spent on the vehicle's parts. The total for all of the raw materials and components for the VDV is $1716.90. This cost includes shipping for each component as well as the cost for materials that went unused. The project as a whole was well below the $2000 budget allocated to it. The specific cost break down for each item used for the fabrication of the VDV is provided in Appendix F with a total budget breakdown in F.3.

6 Patent Search

6.1 Summary

A thorough patent investigation demonstrated the merit of patenting the Variable Drive Vehicle. This search showed that the integration of wheels and tracks into one drive system is not a novel concept and has an established classification. However, the implementation of the combined drive system is unique. Prior art claims ownership of significantly different manipulation mechanisms for integration of multiple drive systems. The VDV proved to have a unique mechanism design from that of other patents and in turn differed in its claims.

6.2 Introduction

The variable drive vehicle has various components that contribute to the vehicle's capability of switching between two drive systems. With this said, the vehicle's capability and design for having two drive systems and being able to switch between them make up the entirety of the VDV's patent disclosure. While the track units had a highly customized design, the ability of storing the track units above the wheel when not in use, and an actuator electronics transformation system that allow the tracks to remain attached to the vehicle when not in use are what set it apart from adaptable drive system platforms or vehicles that are able to switch between drive systems that utilize alternative means of doing so.

While the concept of the Variable Drive Vehicle is rooted in the ability of utilizing multiple drive systems to move between two locations as quickly as possible, another crucial aspect of this project was the design of a system that allowed this to happen by actuating the change from one drive mode to the other and visa versa. In this sense, there are three characteristics of the VDV that distinguish it from other vehicles. The first two are the capability of driving on wheels or tracks. This in and of itself doesn't distinguish the VDV from other adaptable platforms, the final component is the switching system, which is the crucial difference setting it apart from other platforms.

6.3 Invention Description

The invention to be patented is the Integrated Wheel and Track System that is part of the VDV. This system aims to solve the problem of getting a vehicle between two locations as quickly as possible no matter how much challenging terrain is in the way. The general description of this system follows: it must have the capability of driving on wheels. The vehicle must have the capability of driving on a tracked system that is powered by the main wheel rotation. Finally the vehicle must utilize a hands-free "switching system" that allows the vehicle to rotate the tracks from the stowage location above the wheels to below the wheels, and it must be able to do the reverse, rotating the tracks from under the wheels up into the stowage location over the wheels. The system is comprised of three main components: the first is a contact lock which consists of some type of linear actuation that serves to either separate the tracks from the wheels or bring the track units into contact with the wheels. The second major component is a rotation clamp or rotation lock, that locks the rotation of the track unit to the rotation of the wheel. This subsystem is crucial in positioning the track units so that they can be stored when they are not in use and rotated back under the wheels when difficult terrain is encountered. Finally, a stowage subsystem is required so that the vehicle can lock the track units in the correct position above the wheel when not in use.

Two major competing ideas were evaluated and compared to the VDV's switching system. The first is the Track 'n Go traction supplement for modern cars. While this system has the incredible ability to increase traction on a variety of vehicles, the Track 'n Go system requires physical user input in order to add or remove the tracks from the vehicle. The Variable Drive Vehicle design increases the general usability of an additive track system by allowing the user to have no physical input while switching between the drive systems. From this design, the VDV differs greatly in that Track 'n Go does not have an ability to utilize an on-board microcontroller to assist in this process. Another competing design is the "Adaptable Mobility System" designed and built by Yi Li. This system utilizes two drive systems that rotate 90 degrees between wheeled and tracked drive systems. While this design is a creative way to implement two drive systems into one compact vehicle, it requires the use of at least two separate motors in order to move not counting the motors required to rotate the track and wheeled units between the two systems. The VDV has an advantage over this drive system in that the VDV utilizes a single motor to drive both the wheeled and tracked systems.

The VDV was invented by Joseph Sahyoun, Michael D'Arrigo, Christopher Clark and Graham McClone. It was designed between January and April of 2017 with its first completed build finalized Friday May 5, 2017. The VDV was initially publicized at the Santa Clara University School of Engineering Senior Design Conference on Thursday May 11, 2017. Initial testing for the VDV was conducted May 6-9, 2017 with additional testing conducted on Friday May 19, 2017. Detailed part drawings, a Bill of Materials and assembly drawings for the VDV can be found in Appendix C.

6.4 Classifications

The combined nature of this design places it under Class 305: Wheel Substitutes for Land Vehicles.

"This class relates to apparatus intended to be substituted for the wheel or runner of a land vehicle. The apparatus of this class bears the same general relationship to a land vehicle as a wheel or runner and serves generally the same function but is so constructed that it can be called neither a wheel nor a runner. The apparatus of the class, however, may include wheels or runners as sub-combination portions thereof." [20]

The VDV cannot be considered solely a wheeled vehicle nor solely a tracked vehicle. It has the capabilities of both and must therefore be classified as such. This classification references others that pertain to robots and vehicles. For the scope of this project, these other classifications include Class 188 (Brakes), Class 384 (Bearings), and Class 474 (Endless Belt Power Transmission Systems or Components). Mechanisms and components included within the design may utilize other patents or have patents on themselves. These can be found within these related classifications.

The VDV can more specifically be listed in Class 305 under subclass 15 (Combined or Convertible) and subclass 20 (Wheel on Top of Upper Track Run). These pertain to two very crucial aspects of the project and its potential patentability. It is both a convertible drive system with wheel drive track capabilities. These allow it to scale various terrains and give it more versatility within the field.

6.5 Review of Prior Art

6.5.1 Hybrid Wheel and Track Vehicle Drive System - US 20040216932 A1

This patent describes a tracked and wheeled vehicle drive system that utilizes a series of drive and idler wheels surrounded by a track belt. The track units rotate like cantilever arms that allow the contact area to be reduced or increased as desired. The specific claim states:

> "The vehicle drive system of claim 1, the cantilever beam being rotatably shiftable to at least selectively present a portion of the track that is only supported by the idler wheel to a ground surface, to present a portion of the track that is only supported by the drive wheel to a ground surface, and to present a portion of the track that is supported by both the idler wheel and the drive wheel to a ground surface" [21]

The rotatable cantilever beams are the key mechanisms that allow the robotic vehicle to overcome difficult obstacles. They mimic robotic legs that can lift the entire robot when needed. One aspect that is similar to the VDV design is the coupled motive source for both the wheels and the tracks. By implementing these drive and idler wheels, this vehicle is able to power its track system. The VDV instead utilizes a series of rollers between the wheel and track interface to allow the wheel to rotate the track forward. While conceptually similar, the implementation of the two designs differ. The track system for the Hybrid Wheel and Track Drive System can behave like a wheel through the rotation of the cantilever leg. The VDV stores a modular track unit above the wheel for use when necessary.

6.5.2 Hybrid Robotic Vehicle - US4977971A

The Hybrid Robotic Vehicle incorporates a drive system capable of switching between three drive modes: wheeled, tracked, and legged. The vehicle has four appendages which can be oriented to operate in each of the three modes, and each leg has three degrees-of-freedom that facilitate changes in orientation. Their claim is that this vehicle contains,

> "a plurality of legs, each of said plurality of legs (1) comprising a strut assembly having a proximal end and a distal end, said proximal end being pivotable about a first horizontal axis independently of rotation of a wheel, and wherein a track assembly on each of said legs is pivotably connected to said distal end of said strut assembly" [22]

The strut assembly combined with the linear actuators comprise the switching system. Similar to the VDV, this design stores the tracked drive system onboard the vehicle and is able to engage it when necessary. However, their system offers a third method of motion with legs in which the tracked platforms are utilized as cantilever beams that lift the vehicle up and over obstacles of various height. Two separate drive motors are used for the wheels and tracks while actuators perform the manipulation of the legs. The VDV does not incorporate this third drive system and combines the drive motors for both systems. Doing so reduced overall weight which in turn reduced losses in power.

The Hybrid Robotic Vehicle has a shared vision with the VDV in that its purpose is to be used in hazardous situations that may put human lives at risk. By combining different drive systems, the vehicle is able to navigate through various types of terrains that may not be accessible by single drive system robotic vehicles. This increased versatility expands the breadth of application for this robotic vehicle and could potentially reduce risk of life in dangerous scenarios. What is most distinguishable between this design and the VDV is the implementation of the switching system and the mechanisms that perform the action.

6.5.3 Hybrid Mobile Robot - US20080277172A1

This patent is based on the design of an all-terrain vehicle that utilizes a pair of mechanical links that serve as arms with the intended purpose of pushing the vehicle up and over any obstacles that the vehicle might encounter. In utilizing this device, this vehicle would be capable of overcoming significant obstacles, however, the vehicle's main focus is obstacle clearance as opposed to speed. While the Hybrid Mobile Robot does utilize what could be considered to be an alternative drive system that is based in the additional mechanical arms, it doesn't use a wheeled platform at any time. Another major difference is that the tracked drive system on the VDV was designed to be compatible with a range of different vehicles. The Hybrid Mobile Robot, simply by the nature of how its robotic arms are stored, would be very challenging to turn into an adaptable platform that is able to adjust to different vehicles.

The first claim discusses the links that are designed as rotating arms to lift the Hybrid Mobile Robot over obstacles. The first claim is as follows,

> "a base link having a drive system, the base link adapted to function as a traction device and a turret; and a second link attached to the base link at a first joint, the second link having a drive system and being adapted to function as a traction device and to be deployed for manipulation" [23]

The links on the Hybrid Mobile Robot can be deployed as an additional means of traction, increasing the vehicle's capability of clearing challenging obstacles.

6.5.4 All Terrain Mobile Robot - US4932831A

This patent describes a vehicle that utilizes a tracked drive system in order to assist humans in dangerous situations. This vehicle is designed to be capable in various terrain circumstances but doesn't address the issue of speed nor the time required to complete a task. In addition, the vehicle has no alternative drive system on which it is able to drive under differing circumstances. This mobile robot was designed for use as a robot in addition to a vehicle, it's ability to utilize built in robotic arms sets it apart from the VDV as well.

The claims for this robot design focus on the use of a main track unit and two alternative track units on either side of a main chassis. In addition, the claims discuss the specific design features of multiple robotic arms for the vehicle to utilize during a mission. The first part of the first claim is as follows:

> "An all terrain vehicle adapted for remote control operation in potentially hostile environments, which comprises: a main chassis having a forward end and a rearward end, said main chassis equipped with a pair of rotatable sprockets on each side thereof, at least one of said sprockets being driven, said pair of sprockets on each side of said main chassis having a flexible main track engaged therewith, said main track supporting said vehicle on said terrain and moving said vehicle across said terrain;" [24]

In addition to the “flexible main tracks” this patent includes additional track systems on the front and rear of the vehicle that have the capability of rotating to allow it to scale difficult types of terrain such as stairs. The Variable Drive Vehicle doesn’t have such components, but rather is intended to utilize its main and only track units to scale challenging terrain on its own.

6.5.5 Dual Mode Mobile Robot US9096281

The dual mode robot utilizes a dual drive system comparable to the VDV in that it utilizes both tracks and wheels in a way that is easy to switch between the two drive systems. This vehicle has the capability of rotating the wheels or tracks as to use an alternative drive system. The robot is able to do this without user input, either via remote control or through the use of an autonomous system. The robot is different from the VDV in its switching mechanism, its method of steering and the number of motors required to run the vehicle. The dual mode mobile robot utilizes in line tracks that extend the entire length of the vehicle, as opposed to the modular track systems that are found on the Variable Drive Vehicle. The first claim is as follows:

> "A mobile robot comprising:
>
> a platform;
>
> a pair of track wheel driving modules attached to opposing sides of the platform, each of the track wheel driving modules having:
>
> a track assembly;
>
> a wheel assembly;
>
> a pair of a swing arm mechanisms each operably pivotally attached to the platform, each swing arm mechanism having a swing arm, a front wheel operably attached to the swing arm and a front roller operably attached to a distal end of the swing arm and an arm drive motor operably connected to each swing arm and the arm drive motor drives and controls the angle between the platform and the swing arm, and each swing arm having a wheel position and a track position; and
>
> wherein each of the track wheel driving modules is moveable from a track position to a wheel position and wherein in the wheel position the pair of swing arm mechanisms are pivotally used for independent steering of the mobile robot and in the track position the swing arm acts like a flipper."[25]

This robot also has additional features that the VDV isn’t equipped with that do not address the issue of traction and speed that the VDV addresses. Overall, the dual mode mobile robot is very similar to the VDV.

6.6 Patent Search Conclusions

The patent search yielded several different patents with shared objectives and goals similar to that of the VDV. Most of these hybrid all terrain vehicles are designed to increase the terrain scaling capabilities of the robotic vehicle so that it can be used in hazardous scenarios not accessible by a single drive system vehicle. However, each of these vehicles incorporate different mechanisms that distinguish the designs. Some designs incorporate shared drive motors while others separate them. The use of cantilever beams is also popular amongst these designs as they can behave like legs when necessary. Thus, the VDV shares in the vision of these designs but differs in the implementation making the VDV a patentable idea. To patent the VDV, the claims must differ from that of prior art. Therefore, descriptions of the switching mechanisms must be incorporated in this claim. For the scope of this project:

> "We claim:
>
> A dual drive system vehicle consisting of:
>
> A single chassis;
>
> Modular track units connected along the same axle of the wheel that can be engaged under the wheel or stored above the wheel.
>
> A series of locking and clamping mechanisms connected to modular track units, of which consist of three parts, (i) a contact locking mechanism that engages and disengages the wheel with the track unit via linear actuation, (ii) a rotation clamp system which engages a brake mounted on the track unit with the wheel, locking the rotational degree of freedom of the track unit with that of the wheel, (iii) and a stowage lock that utilizes a servo to hold a connect member between the track units in place above the rear wheels.
>
> Means of actuating each mechanism via onboard electronic push buttons;"

These claims describe the unique nature of the switching system and distinguish it from prior patents. They outline the specific mechanisms involved, describing their contribution to the overall system.

7 Engineering Standards and Realistic Constraints

7.1 Health and Safety

As mentioned in Section 2.10.5, our team has recognized considerable safety risks associated with the manufacture, assembly, test/operation, and storage of the Variable Drive Vehicle. However, measures have been taken to mitigate some of these risks, and ensure that those interfacing with the vehicle are confident in the safeguards put in place. Each of the safety risks applicable to this project are in further detail in 2.10.5.

7.2 Economic

Developing a highly versatile robotic vehicle at a relatively low cost compared to existing vehicles is very valuable. The cost of a device determines who is capable of purchasing it and therefore using it. For the VDV to be marketable to a wide audience, it was designed and manufactured to be as inexpensive as possible. Many current robotic vehicles that are used to traverse rough terrain come at a hefty price tag (see Figure 1.1).

A low cost robotic platform makes it easier for students to perform autonomous vehicle research. Instead of building a vehicle from scratch, researchers could purchase our platform and add any modifications necessary. In this way, more time can be spent on designing an autonomous control system. Robotic vehicles are also attractive for many law enforcement agencies. These agencies often have tight budget restrictions. The addition of a low cost robotic vehicle to their departments can potentially enhance the effectiveness of their day to day field operations.

In order to ensure that the vehicle could be produced at a low cost, it was essential that our team adhered to our budget plan. The greatest expense in this budget was the purchasing of an existing wheeled RC vehicle. It was necessary to purchase an existing drive system so that our team had sufficient time to focus on designing an actuated system to switch between drive systems.

Engineering projects often require iteration and improvement before project goals are met, for this reason, additional funding was alotted in the beginning of the project to enable minor design changes that were deemed necessary during the testing process.

7.3 Usability

A product's ease of use determines how much functionality users are able to extract from a device. A state of the art, well equipped rescue vehicle would not be able to realize its full potential if it was exceedingly difficult to operate. There are many factors that can dictate how easy a robotic platform is to operate. These include the difficulty to transport the vehicle, the time it takes to prepare the vehicle before each mission and the user interface or remote control. The VDV weighs less than 20 lbs and therefore can be transported easily by the operator. Additionally, the VDV requires little set-up time and can be fully operational within a minute. As referenced in section 3.6, creating a universal hand-held remote control to operate all functions of the VDV was outside of the scope for this project. Onboard push-buttons were implemented to control the actuated subsystems of the VDV, while the pre-existing RC vehicle remote was used to drive the VDV.

7.4 Environmental Impact

The environmental impact of this vehicle was carefully considered in this project. The vehicle does not directly cause harm to the environment through its operation. Furthermore, the materials used in the construction of the vehicle were chosen so as to lessen negative environmental impact. Lithium-polymer batteries were selected to power the electronic components instead of cheaper lead-acid batteries because of the increased level of risk associated with the manufacturing, handling, and disposal of lead-acid [19]. Since the VDV is powered by electricity, it does not emit carbon into the atmosphere during operation.

As mentioned in Section 2.10.5.5, The VDV will be handed over to the SCU Mechanical Engineering Department for use in future VDV senior design continuation projects. However, proper disposal and recycling techniques will be implemented should the Variable Drive Vehicle need to be disposed of. These strategies are outlined in 2.10.5.5.

7.5 Societal Impact

Engineers are obliged to consider the societal impact of their work, and the VDV project is no exception. In addition, it aligns with Jesuit values and SCU's 3C's (Competence, Conscience and Compassion). By using engineering *competence*, the VDV team has designed a system that can be integrated into wheeled robots in order to increase their terrain-scaling abilities. On a larger scale, this can be used *compassionately* in search and rescue for injured military personnel, and for victims of natural and man-made disasters. While it is recognized that the VDV could also be utilized as a robotic weaponized vehicle, this would not align with good *conscience*. Therefore, in a commercial setting, the VDV team would refuse to sell their product for these uses. Robotic research facilities could also modify the VDV to be implemented in planetary exploration. All these areas must be taken into account when attempting to evaluate the societal impact of this vehicle.

The main goal of the VDV project is to demonstrate an improved augmented drive system that can increase the versatility of vehicles. The idea was inspired by a need to transport wounded soldiers in combat situations while reducing the risk to medical personnel. The VDV has a drive system that is capable of accessing these frequently difficult-to-reach situations. In the case of natural disasters, the VDV drive system can scale across debris and search for survivors. This enhanced accessibility can increase the search area and reduce the response time of rescuers. It must be noted that the intent of the VDV is not to replace rescue workers. It is designed to aid workers and reduce the risk associated with rescue work.

7.5.1 Background on Impacted Areas

The use of robots in the event of disasters, whether natural or man-made, has been discussed since the early-1990s. Robin Murphy, the director of CRASAR (Center for Robot-Assisted Search and Rescue) at Texas A&M, has been at the forefront of this discussion, conducting research as well as participating in disaster relief organizations. She states that quicker response times in disaster situations can cut total reconstruction time by 1000 days. Through the use of robots, she believes that responders can locate survivors more quickly and efficiently allowing for restoration and reconstruction to begin earlier. The military has multiple autonomous robots currently in use for both search and rescue and attack. They are used to patrol bases and alert the operator of an intruder in an unauthorized area [26]. UAVs can provide aerial surveillance on unexplored areas and help detect threats without having a pilot risk his or her life. Cluster control of ground units could provide a closer look as some search areas undetectable by a UAVs sensor[27]. Cluster control describes the control of multiple autonomous robots whose relative spatial awareness is maintained. They could thus be programmed to perform a “sweep” of an area and provide updates on certain events that may occur in the process. These types of applications are used as a defense mechanisms in a manner that is meant to reduce the risk of death for soldiers. Improvement in ground accessibility could significantly increase the capability of these robots.

7.5.2 Scope of Influence

The scope of influence is heavily dependent on the size and application of the Variable Drive Vehicle. This analysis assumes that the technology will be used exclusively in situations where human lives may be put at risk and not be used for destructive purposes. It is also assumed that the vehicle will be produced for specific customers and not be available commercially. The influence under these assumptions extends to research, rescue, and utility applications. If a task that requires human participation cannot be performed with the VDV, then enhancements would have to be made to the vehicle or a different mechanism be retrofitted upon it. In this case, robotic researchers would add improvements to the vehicle to make it more versatile. There are still developments to be made in the robotic industry as technology improves and autonomous control becomes more developed. The VDV is a start to this further development and aims to prove the effectiveness of such a device. In the instance of cardiac arrest, the responders have 10 minutes to reach the patient before serious damage may result [28]. It is assumed that two humans can travel 4 miles per hour while carrying an injured person. A full-sized VDV is expected to be able to travel around 7 mph in track mode and 14 mph in the wheeled mode. Therefore we assume an average of 9 mph between track and wheeled mode, which includes speed lost due to switching between modes. If the distance from point of injury to a safe location with more advanced medical supplies is 1 mile, then the VDV will be able to complete this journey in 0.11 hours or 6.67 minutes, within the 10 minute limit. In contrast, it would take two humans 0.25 hours or 15 minutes to transport the injured person to safety, over the 10 minute limit.

7.5.3 Potential Impact

In Iraq and Afghanistan there were 16,235 reports of soldiers wounded in action (WIA). Of that number, 383 died of wounds (DOW). DOWs are those deaths that occur after reaching a Medical Treatment Facility (MTF). There were also a reported 1,266 soldiers killed in action (KIA). These numbers bring into question the immediate treatment process used in these combat areas as well as the evacuation processes [29].There has been a significant reduction in these numbers since WWII. However, treatment and evacuation methods can always be improved. With the VDV, injured soldiers can be reached quickly and safely without the need for a Medic to risk his or her life to retrieve the soldier. The onboard supplies could also increase the lifespan of the injured person until he or she reaches an MTF. This could greatly reduce loss of life. With regards to patrolling an area, robots are much more effective than humans as they do not get tired or influenced by their environment. According to Major Kenneth Rose, “Machines don’t get tired. They don’t close their eyes. They don’t hide under trees when it rains and they don’t talk to their friends ... A human’s attention to detail on guard duty drops dramatically in the first 30 minutes ... Machines know no fear.” Not only are robots advantageous during patrol, but, should an attack occur, the robotic patrol unit will likely be the first to encounter it and allow soldiers to respond more quickly to the imminent danger.

Response time is also a crucial factor in disaster relief scenarios. According to Robin Murphy, for each day saved in the initial response, the total number of days till recovery is reduced by 1000 (see Figure 7.29) [30]. The potential for the VDV to hasten response times could therefore yield significant reductions in recovery time after a disaster. They could also aid in the reconstruction process as robots can be used to search buildings that look prone to collapsing.

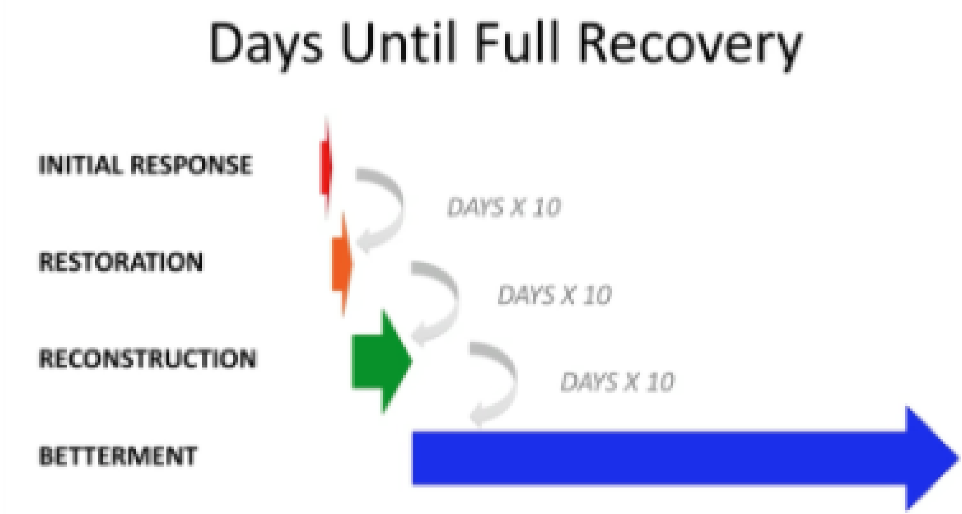


Figure 7.29: Relative times for each step of recovery after a disaster [30]. Reproduced without permission.

7.6 Manufacturability

The design process for the VDV consisted of purchasing an existing wheeled RC vehicle and equipping it with a modular wheel driven tracked drive system. This limited the size and scale of the design to what was already available on the market. Simple modifications had to be made to the chassis in order to accommodate a storage location for the track units. Manufacturability of the VDV is mainly focused in the switching system and its individual components. Each subsystem required custom built components, which greatly increased machining time. In order to reduce overall manufacturing time, the electronics housing was 3-D printed out of PLA and ABS plastics. 3D printing is able to construct intricate components within a day without many limitations on shape. This made it easier to mount the electronics onto the existing wheeled chassis. The most difficult component to machine were the shaft collars that facilitated rotation of the track unit. The corner fillets required a cutting path to be programmed on the mill and the variety of holes added more steps to the process.

8 Future Work and Summary

8.1 Future Work

Looking forward there is a possibility that future senior design teams could continue this project. One could optimize modular track units by reducing frictional losses when driving in track mode. To do this it is necessary to improve the traction between wheel and splined rollers. The wheels on the RC vehicle used in this small scale prototype were deformable and therefore did not apply sufficient pressure to the splined rollers. A future senior design team may seek to replace deformable wheels with air filled wheels to increase the pressure applied on the splined rollers. Additionally, once all rollers are in optimal positions for track tension, the adjustable features of the track plates can be removed, leading to a reduction in material and weight. A future senior design team could also design modular track units for front wheels. Because the front wheels turn to steer the vehicle, a new mechanism needs to be designed to attach the front track units to the inside of the vehicle's axle. Lastly, a larger prototype would have increased value in military and disaster relief applications by having the ability to carry larger payloads and overcome larger obstacles and difficult terrain more easily.

8.2 Summary

In the military and disaster relief scenarios, medical personnel risk their lives to save the injured. In these situations, time is of the essence, and a quick retrieval can be the difference between life or death. To complete this task without additional risk would require a vehicle traverse various types of terrains. Many existing robotic vehicles capable of traversing difficult terrain utilize track based drive systems and have limited top speeds on smooth terrain. Wheel based drive systems have the ability to traverse smooth terrain quickly but may fail to perform in loose or steep terrain. By integrating both drive systems into a single vehicle, the advantages of each may be utilized whenever desired based on local terrain.

The VDV employs a actuated system capable of switching between wheeled and tracked drive modes, enabling the vehicle to travel quickly and efficiently over smooth terrain as well as traveling over rough terrain by switching between these two drive modes. This small scale prototype is equipped with two modular wheel driven track units to demonstrate the viability of the actuated switching mechanism. Electric linear actuators and servo motors allow the modular track units to be rotated out from under the wheels, and stowed on the vehicle when not in use. Finite element analysis ensured that the VDV's switching mechanism maintains safe loading at its most critical points during a drive system transition. The VDV was tested on smooth concrete to determine its maximum wheel speed, track speed, and how fast the drive system could be switched. Experiments yielded a top speed of 11.5 mph in the wheel mode, 0.8 mph in the track mode, and a switching time of 6.4 seconds. The vehicle's maximum obstacle clearance, 1 inch in track mode and 2 inches in wheel mode, and slope, 5 degrees in track mode and 22 degrees in wheel mode, fell short of expected values. These shortcomings resulted from a poor frictional power transfer when attempting to power the tracks using the wheels. However, this prototype provides a proof of concept for a variable drive system successfully incorporating two drive systems, and future improvements may yield a promising platform for future robotics research.

Figure 8.30: Variable Drive Vehicle.

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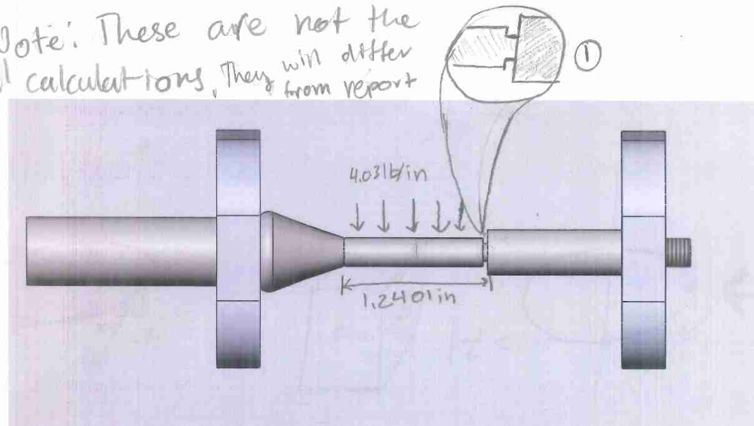
Appendices

A Detailed Calculations

A.1 Hand Calculations to Verify FEA

*Note: These are not the final calculations, They will differ from report



Critical point # 1

- Change in shaft diameter creates a stress concentration
- The radius of the fillet is so small that
- Assume point load of 5lbs at middle of shaft

$D = 0.25in$, $d = 0.15748in$, M

$D/d = 1.5875$

$r = 0$ in radius

$K_t = 3$

$M = 5lbs \cdot 0.6401 = 3.2005$ in·lbs

$$\sigma_{nom} = \frac{M}{\frac{\pi d^3}{32}} = 253,007 \text{ psi}$$

$$\sigma_{max} = K_t \sigma_{nom} = 759,021 \text{ psi}$$

Max normal stress Theory of failure

$\sigma_{max} \leq \frac{\sigma_y}{N_{fs}}$ both ABS & Aluminum Pass

Due to the lack of radius, the stress concentration factor was assumed to be $K_t = 3$. However, the equations and tables are only accurate when $0.01 \leq r/d \leq 0.30$.

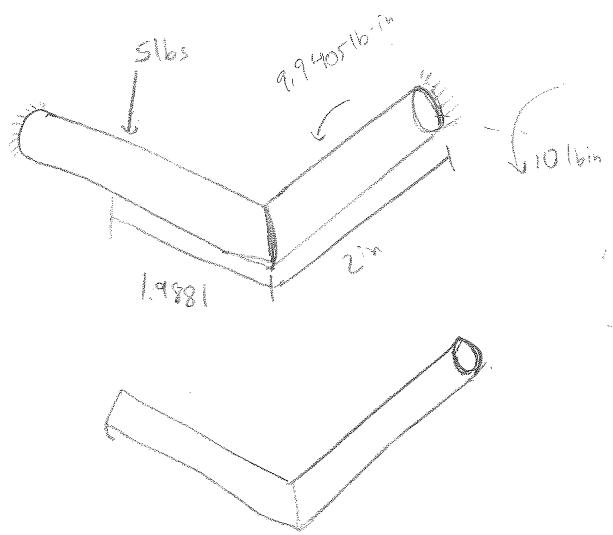
$\tau_2 = 3240.099$

$\tau_1 = 810.0248$

$\sigma_1 = 1629.75$

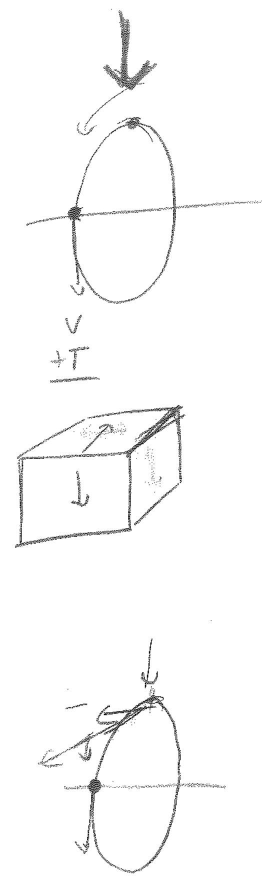
$\sigma_2 = 6518.98$

3259.49

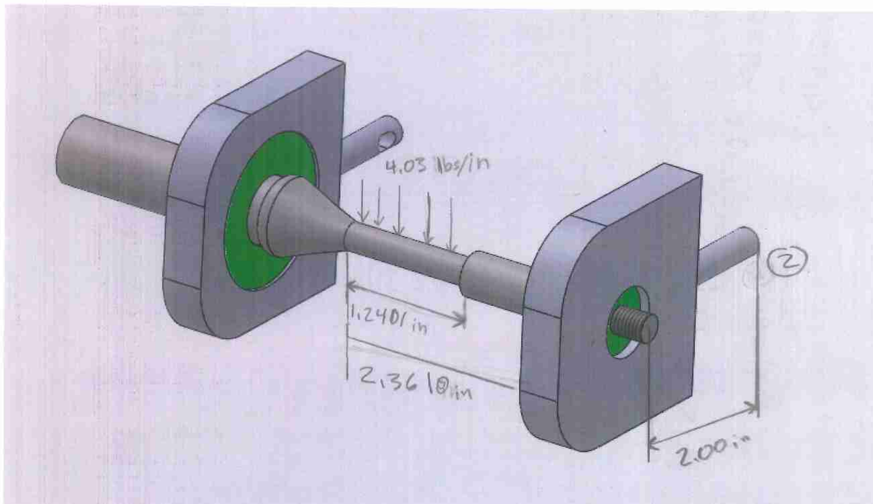


4600

46,000

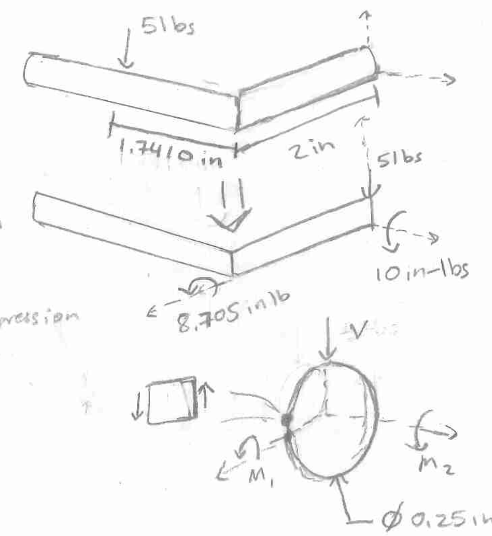


Note: These are not the final calculations.
They will differ from report results



Critical point #2 $N_{fs} = 1.3$

- Assuming load is evenly distributed, represent as point load in middle



- Materials: ABS plastic & 6061 Aluminum

$\sigma_{u_{ABS}} = 6500$ psi $\sigma_{y_{Al}} = 40$ ksi

- Assume same yield stress in tension or compression

$\tau_{max} = \tau_{Torsion} + \tau_{shear}$

$= \frac{2M_1}{\pi r^3} + \frac{4V}{3A} = 2973.2\ lb/in^2$

$\sigma_{bending} = \frac{4M_2}{\pi r^3} = 6518.98\ lb/in^2$

Max Normal stress theory of failure

$\sigma_{bending} \leq \frac{\sigma_y}{N_{fs}}$

$6518.98 \leq \frac{8790}{1.5}$ ABS Passes

$6518.98 \leq \frac{40{,}000}{1.5}$ Aluminum Does not Fail

Max Shear Stress Theory of failure

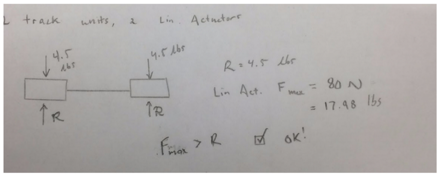
$\tau_{max} \leq \frac{S_{yp}}{2N_{fs}}$

ABS passes

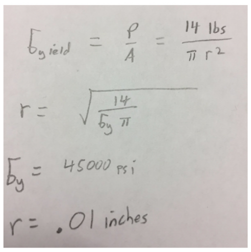
Aluminum passes

A.2 Supporting Mechanical Design Hand Calculations

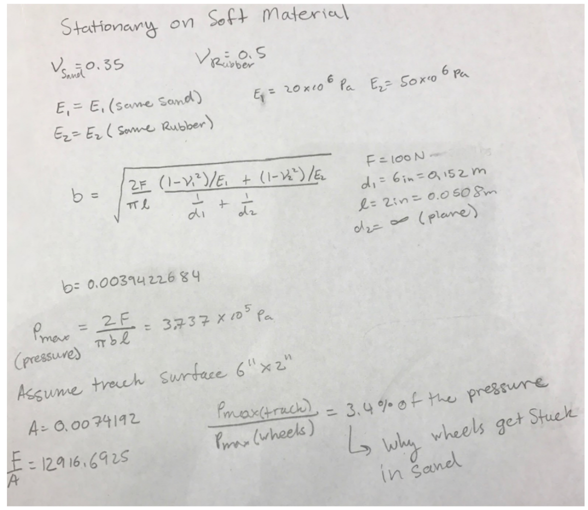
Linear Actuator Force



Minimum Required Axle Size



Tendency of Wheels to Sink in Sand



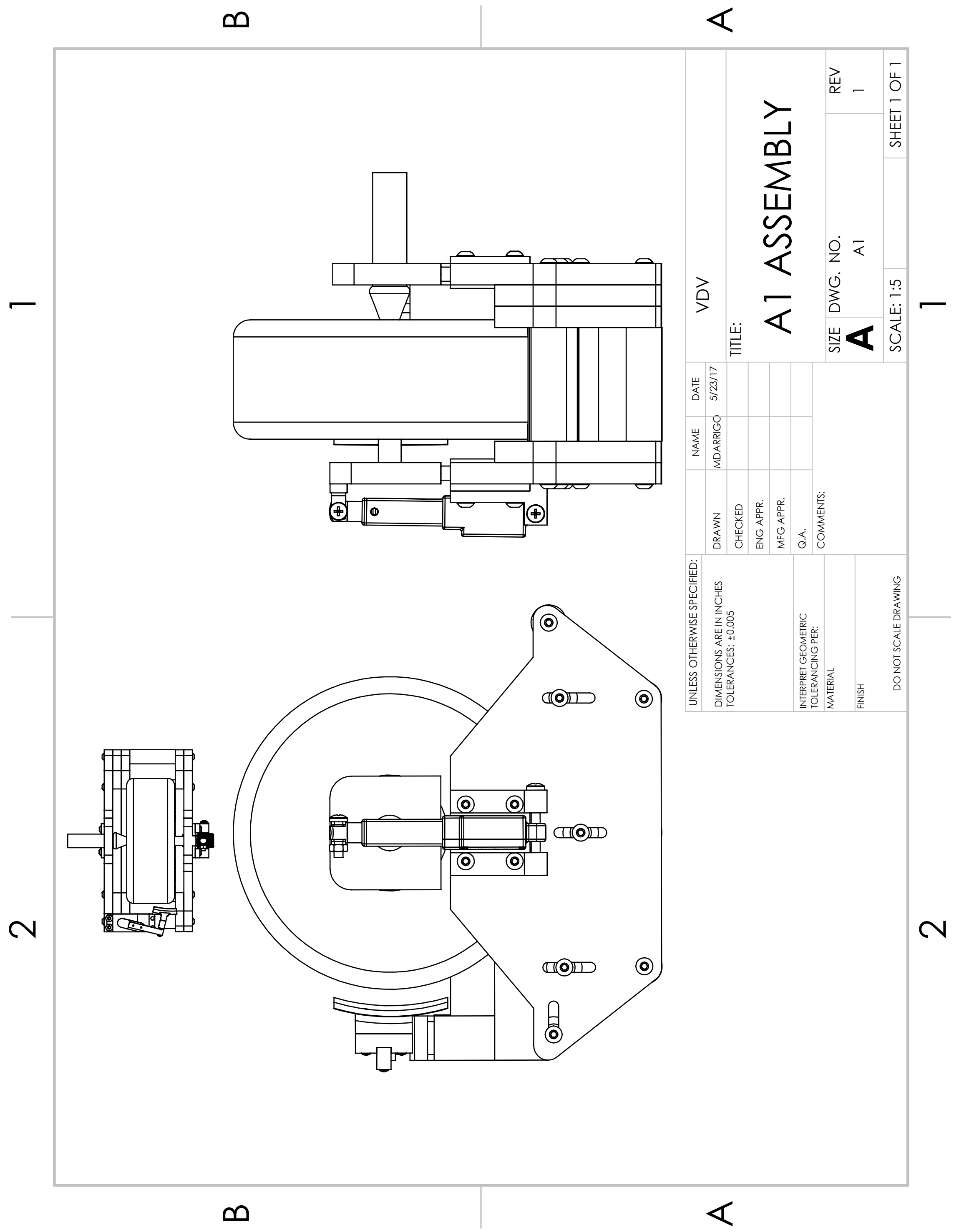
B Product Design Specifications (PDS)

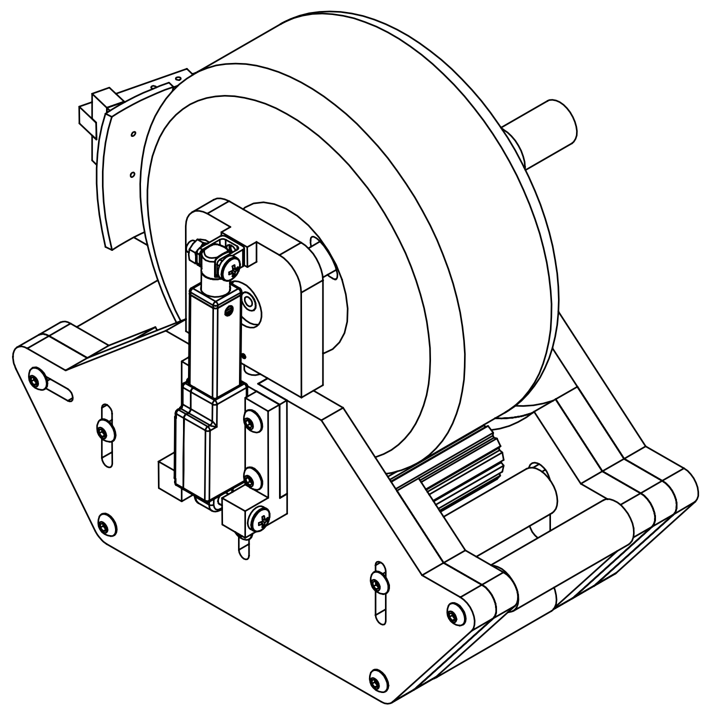
Table B.1: PDS (Version 5, 9 May 2017).

Elements/ Requirements	**Parameters**		
Performance)	**Units**	**Datum**	**Target/Range**
Track Speed (Concrete)	mph	AMBOT Track	5
Wheel Speed (Concrete)	mph	AMBOT Wheel	12
Switch Time	seconds	N/A	10
Weight	pounds	Avatar III	20
Maximum Slope	degrees	Typical Stair Slope	33
Obstacle Height Clearance	inches	Typical Stair Height	7
Cost	$	N/A	2,000

C Assemblies, Detailed Parts Drawings, and Bill of Materials

C.1 Assembly Drawings





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	ENG APPR.			
	MFG APPR.			
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MATERIAL	COMMENTS:			
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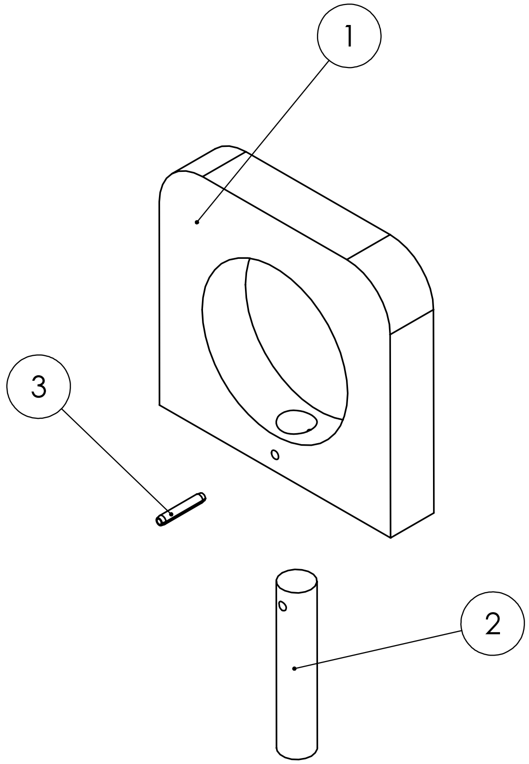


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	C1, C2	AXLE COLLAR (LARGE OR SMALL HOLE)	1
2	C3	MECHANISM SHAFT	1
3	N/A	1/16 X 3/8 SPRING PIN	1

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ±.005	DRAWN	MDARRIGO	5/22/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

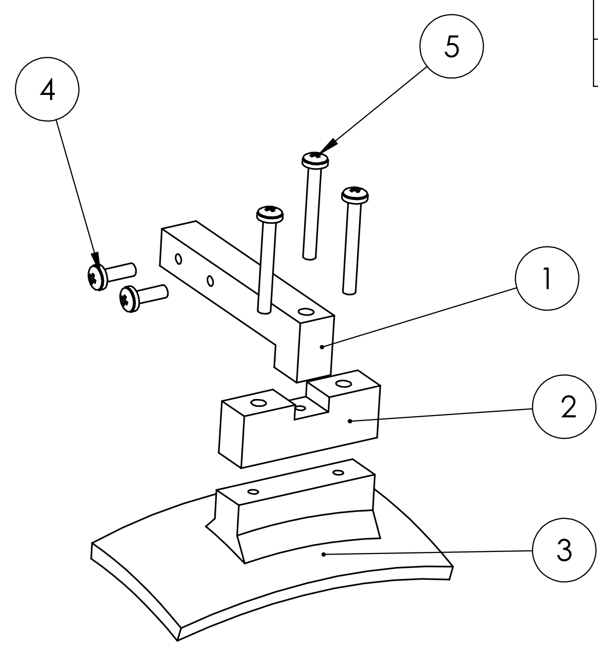
VDV

TITLE:

AXLE COLLAR
SHAFTCOLLARASSEMBLY

SIZE	DWG. NO.	REV
A	A3	1
SCALE 1:1		SHEET 1 OF 1

ITEM NO.	PART NUMBER	PART NAME	QTY.
1	B1	Brake Arm	1
2	B2	Brake Bracket	1
3	B3	Brake Plate (L or R)	1
4	N/A	M2 X 6 mm	2
5	N/A	M2 X 16 mm	3



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	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
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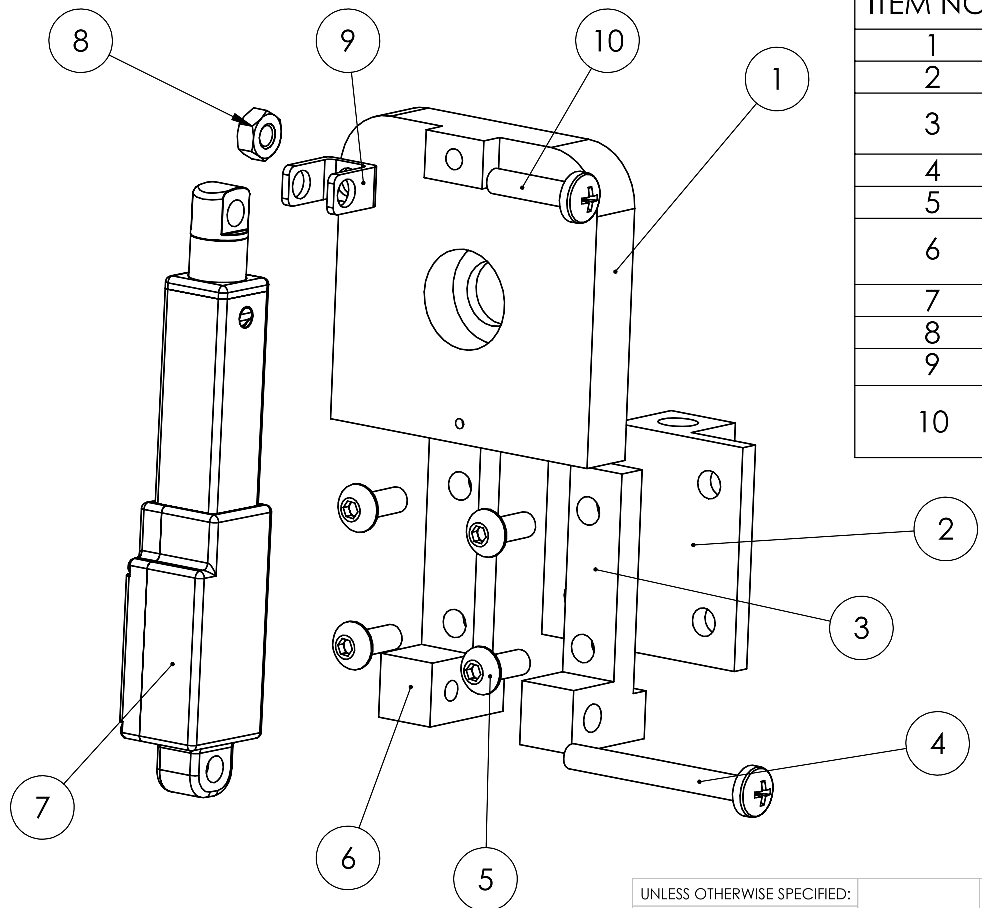


ITEM NO.	PART NUMBER	PART NAME	QTY.
1	C1	Axle Collar Small Hole	1
2	T10	Shaft Receiver Inset	1
3	T11	Lower Actuator Bracket Clearance	1
4	N/A	M4 X 35 mm	1
5	N/A	M4 X 10 mm	4
6	T12	Lower Actuator Bracket Tap	1
7	N/A	Actuonix L12-R	1
8	N/A	M4 Hex Nut	1
9	N/A	Upper Actuator Bracket	1
10	N/A	M4 X 16 mm	1

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MDARRIGO	5/22/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

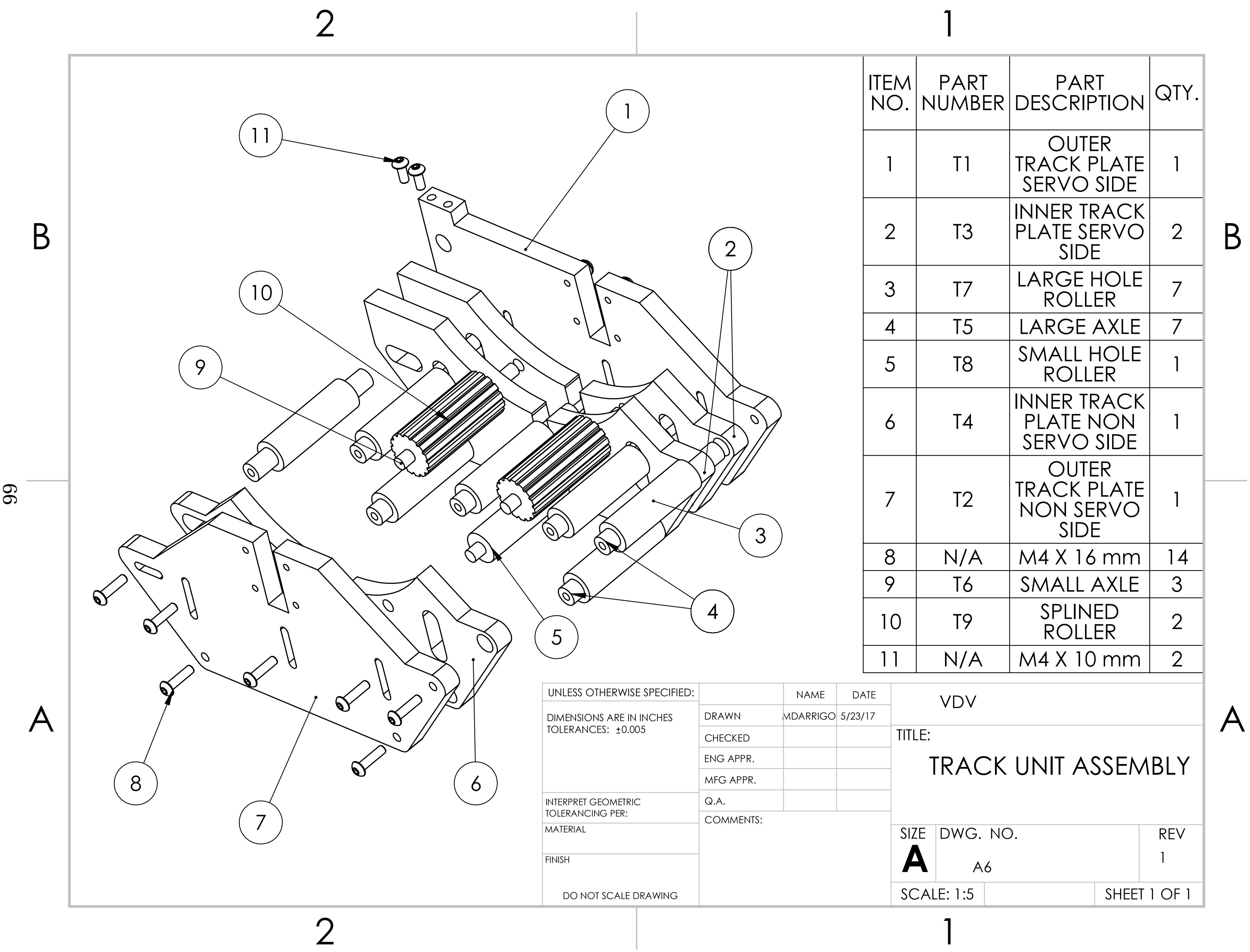
VDV

TITLE:

ACTUATOR ASSEMBLY

SIZE A | DWG. NO. A5 | REV 1

SCALE: 1:10 | SHEET 1 OF 1



ITEM NO.	PART NUMBER	PART DESCRIPTION	QTY.
1	T1	OUTER TRACK PLATE SERVO SIDE	1
2	T3	INNER TRACK PLATE SERVO SIDE	2
3	T7	LARGE HOLE ROLLER	7
4	T5	LARGE AXLE	7
5	T8	SMALL HOLE ROLLER	1
6	T4	INNER TRACK PLATE NON SERVO SIDE	1
7	T2	OUTER TRACK PLATE NON SERVO SIDE	1
8	N/A	M4 X 16 mm	14
9	T6	SMALL AXLE	3
10	T9	SPLINED ROLLER	2
11	N/A	M4 X 10 mm	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
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CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

VDV

TITLE:
TRACK UNIT ASSEMBLY

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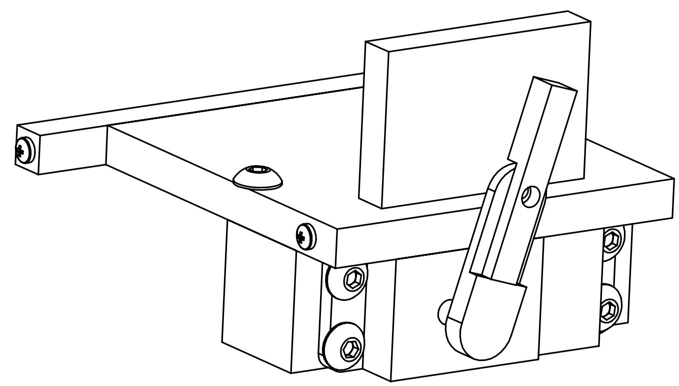

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	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

VDV

TITLE:

STOWAGE LOCK ASSEMBLY

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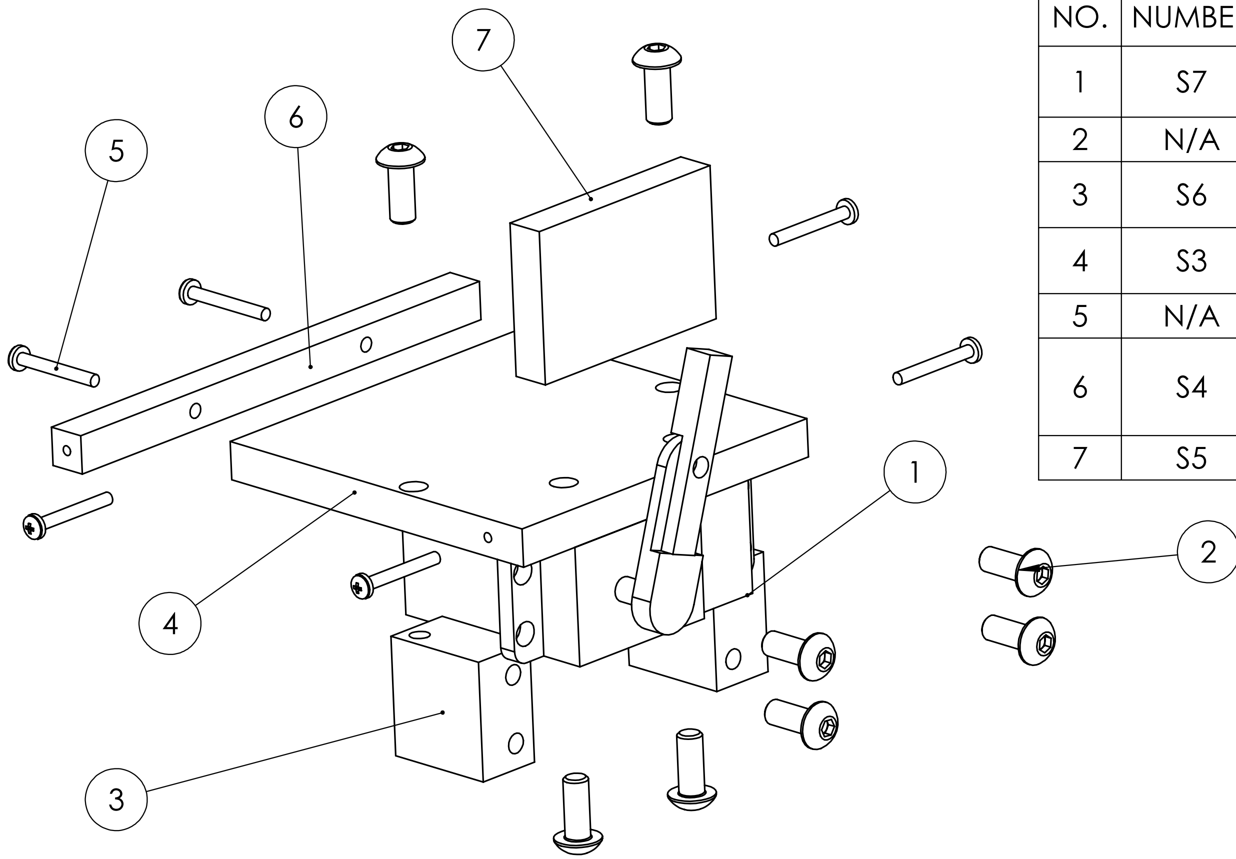

ITEM NO.	PART NUMBER	PART DESCRIPTION	QTY.
1	S7	SERVO MOUNT RIGHT	1
2	N/A	M4 X 10 mm	8
3	S6	SERVO MOUNT LEFT	1
4	S3	MOUNTING FRAME	1
5	N/A	M2 X 16 mm	6
6	S4	FRAME ATTACHMENT BRACE	1
7	S5	BACK STOP	1

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.005	DRAWN	MDARRIGO	5/22/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

VDV

TITLE:

STOWAGE LOCK ASSEMBLY

SIZE	DWG. NO.	REV
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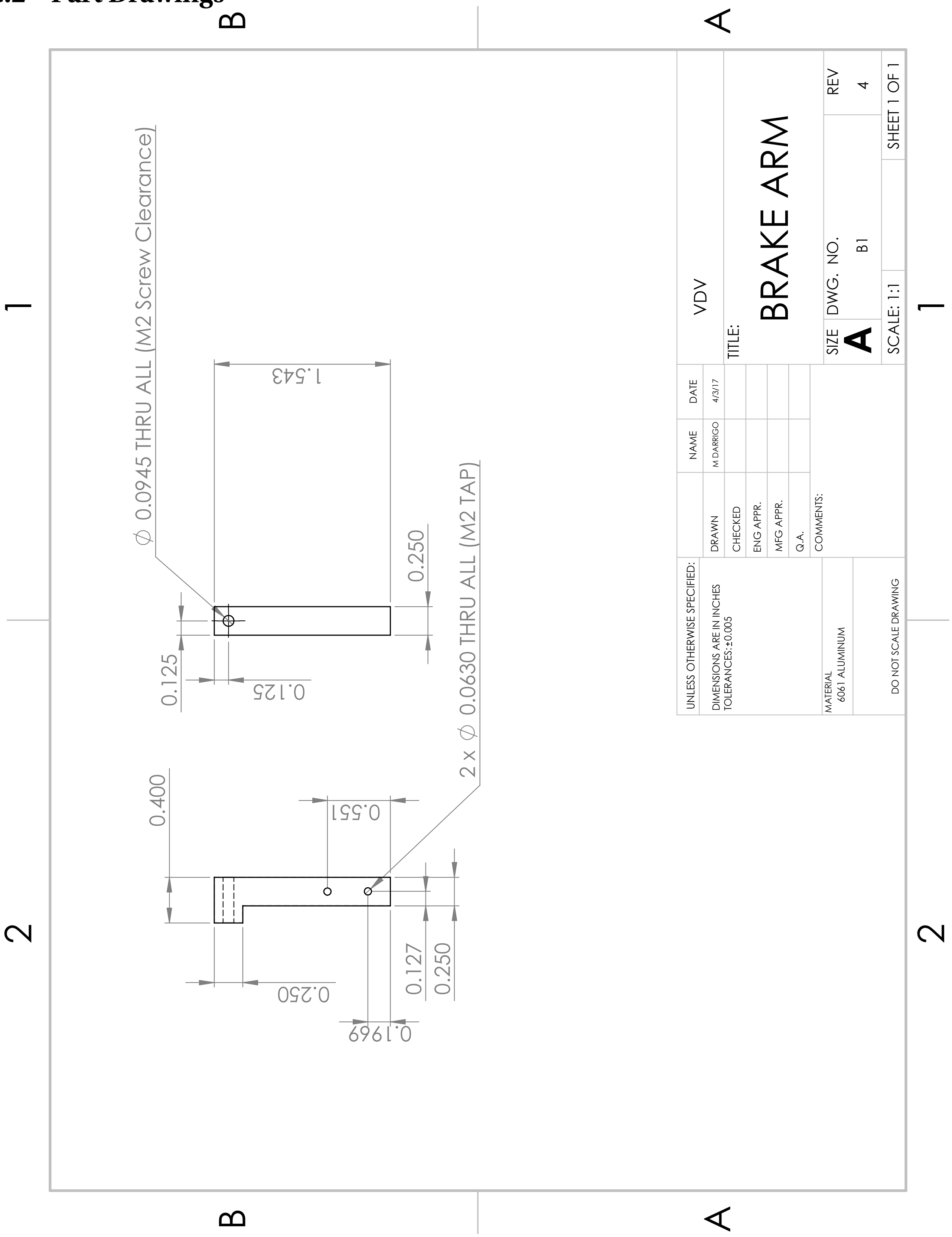
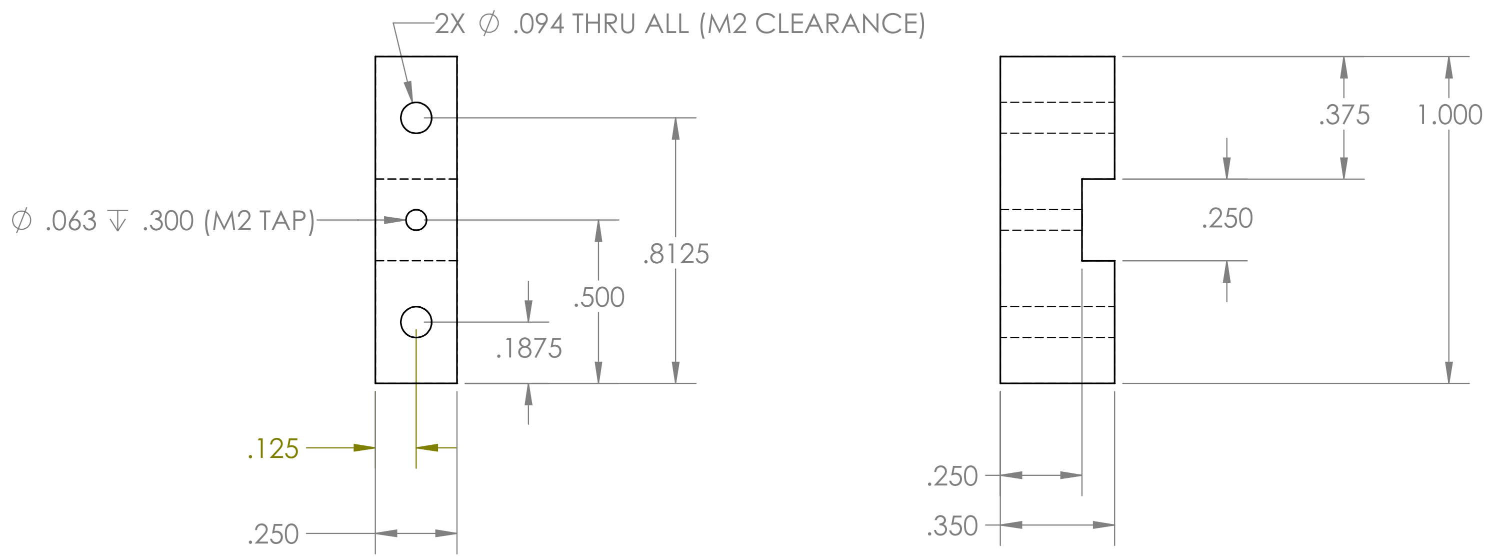
SCALE: 1:2 | SHEET 1 OF 1

C.2 Part Drawings





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	MFG APPR.			
	Q.A.			
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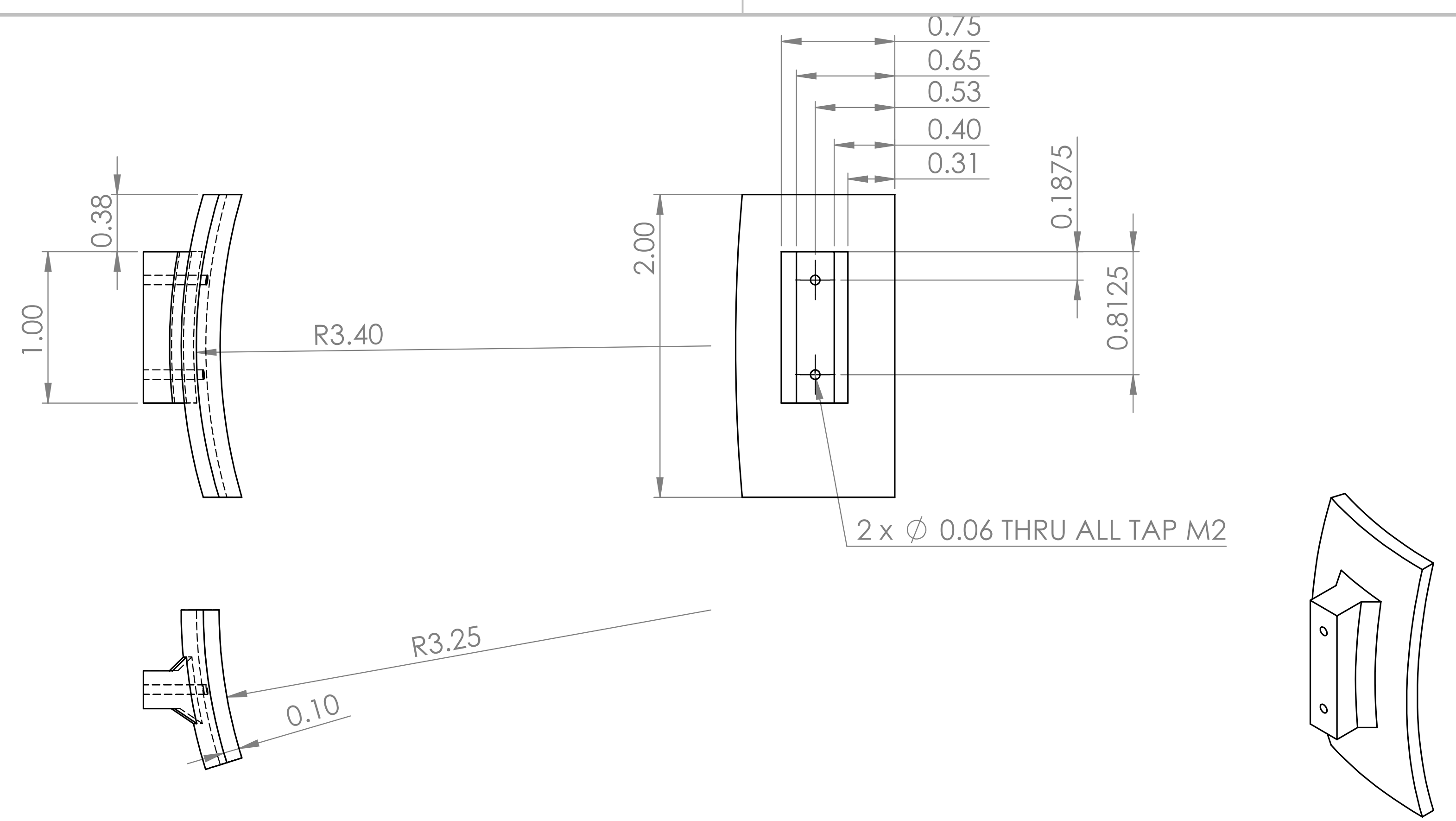

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	CHECKED			BRAKE PLATE LEFT		
	ENG APPR.					
	MFG APPR.					
	Q.A.					
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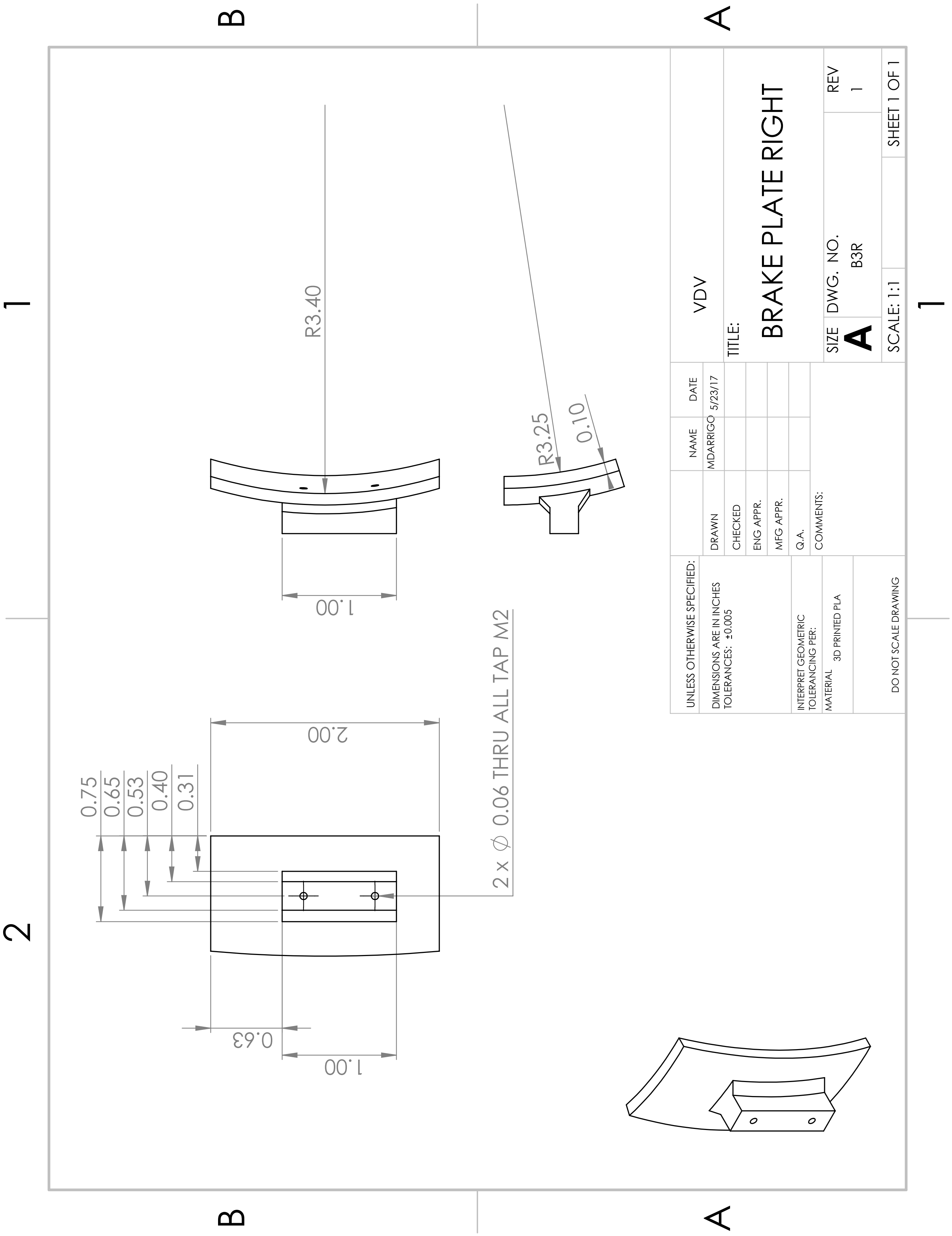
B
A
1
2
R3.40
R3.25
0.10
1.00
2.00
2 x Ø 0.06 THRU ALL TAP M2
0.75
0.65
0.53
0.40
0.31
0.63
1.00
VDV
TITLE:
BRAKE PLATE RIGHT
SIZE A
DWG. NO. B3R
REV 1
SCALE: 1:1
SHEET 1 OF 1
NAME DATE
DRAWN MDARRIGO 5/23/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
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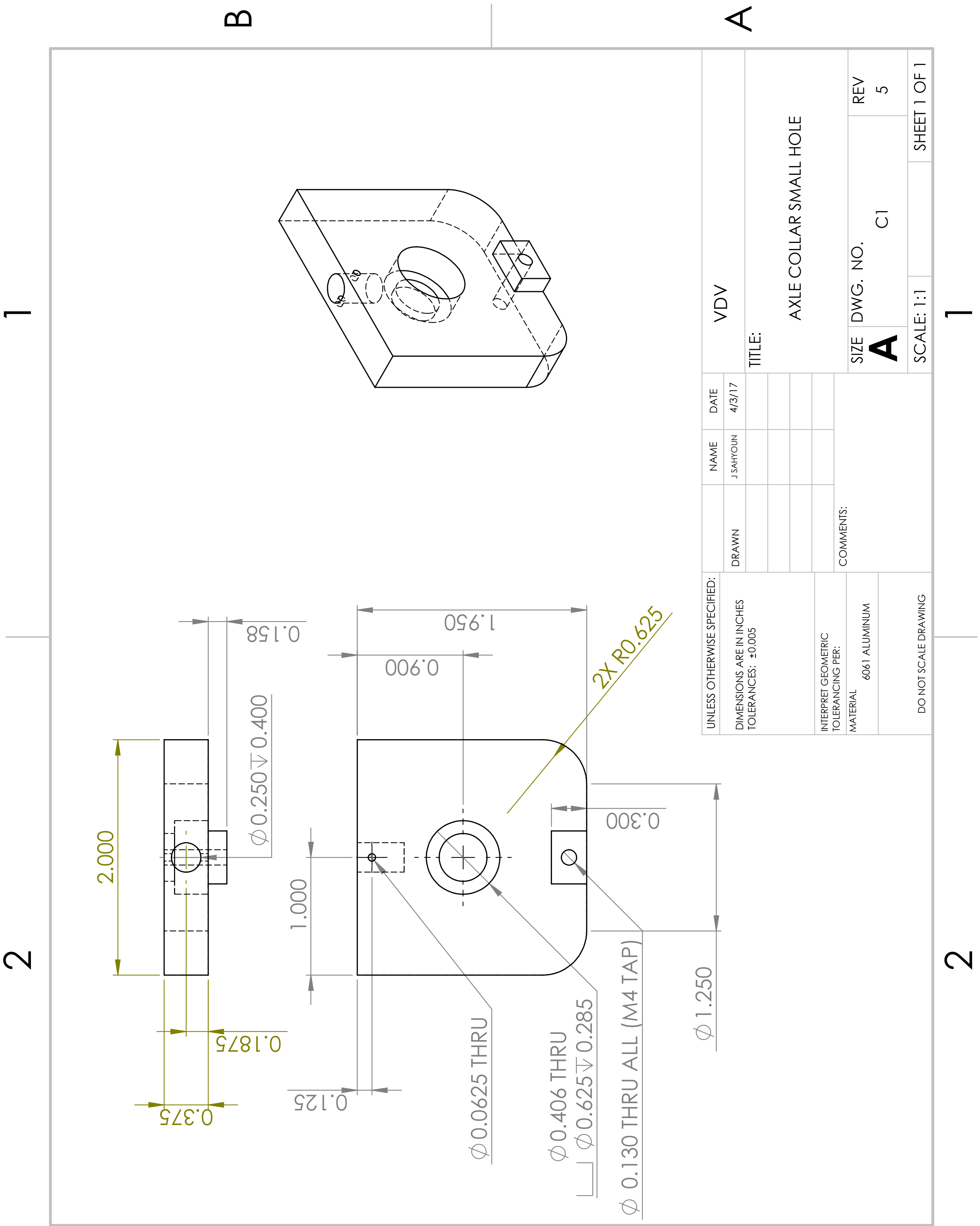
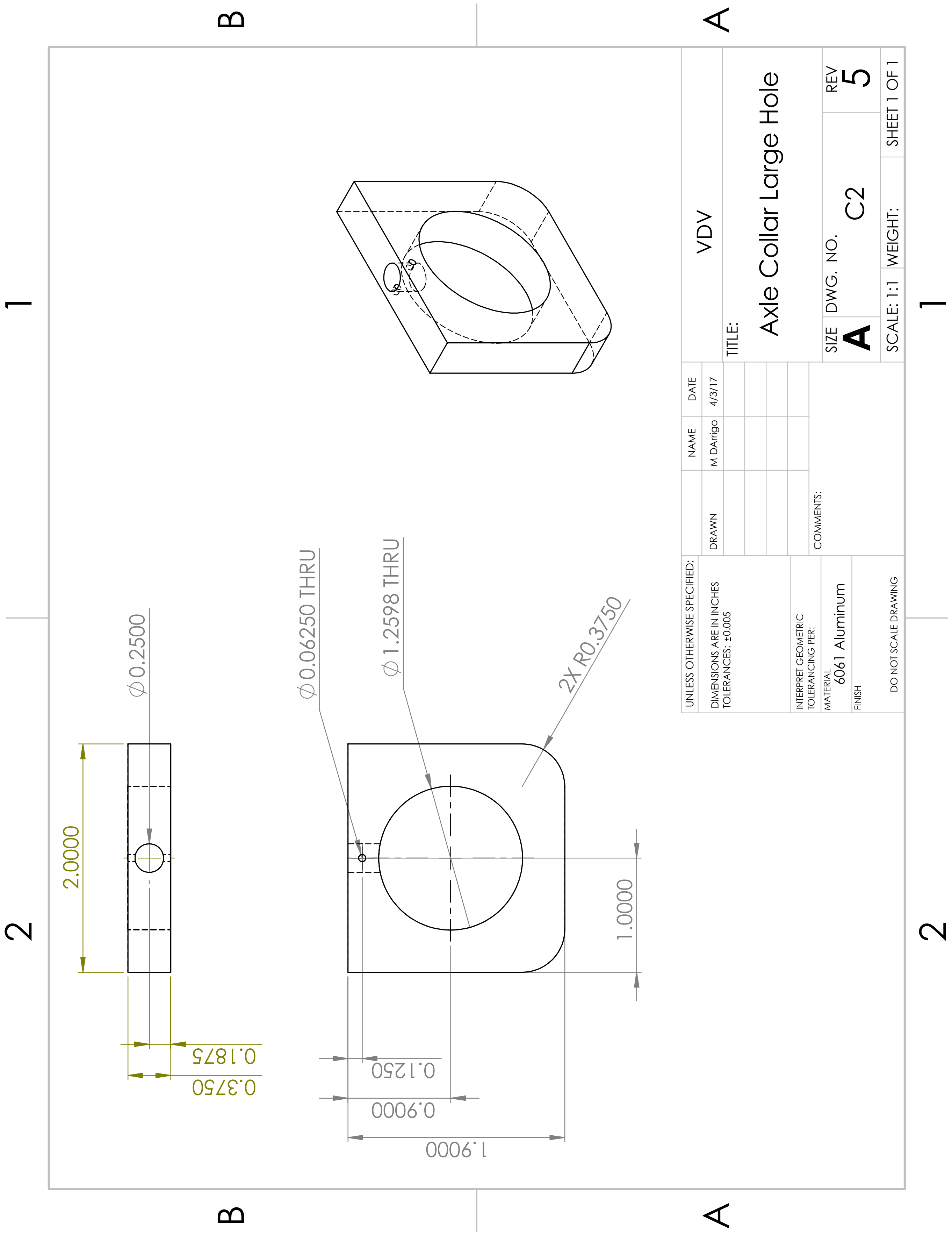
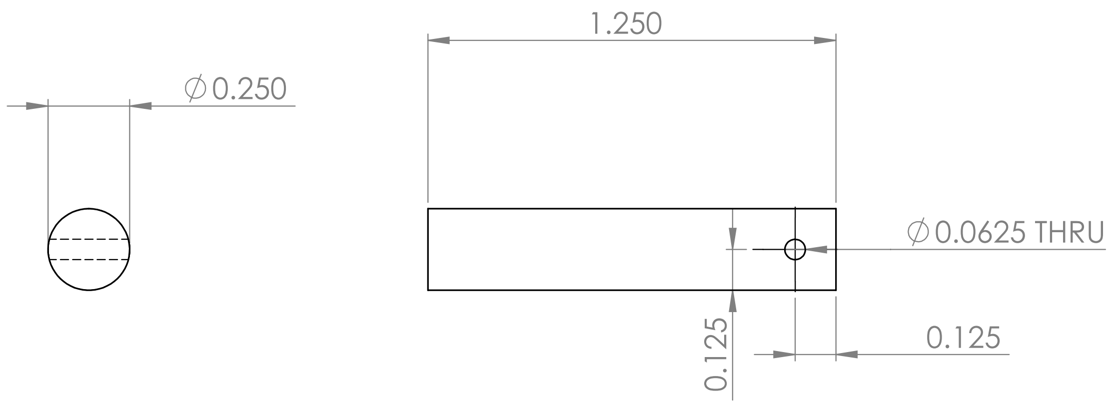
MATERIAL 3D PRINTED PLA
DO NOT SCALE DRAWING


AXLE COLLAR SMALL HOLE
VDV
TITLE:
SIZE A
DWG. NO. C1
REV 5
SCALE: 1:1
SHEET 1 OF 1
DRAWN J SAHYOUN 4/3/17
NAME
DATE
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL 6061 ALUMINUM
DO NOT SCALE DRAWING
2.000
0.158
⌀0.250 ↧ 0.400
1.950
0.900
2X R0.625
0.300
1.000
⌀1.250
0.1875
0.375
0.125
⌀0.0625 THRU
⌀0.406 THRU
⌴ ⌀0.625 ↧ 0.285
⌀ 0.130 THRU ALL (M4 TAP)



B
A
1
2
Ø 0.2500
2.0000
0.1875
0.3750
Ø 0.06250 THRU
Ø 1.2598 THRU
2X R0.3750
1.0000
0.1250
0.9000
1.9000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Aluminum
FINISH
DO NOT SCALE DRAWING
DRAWN
NAME
M DArrigo
DATE
4/3/17
COMMENTS:
VDV
TITLE:
Axle Collar Large Hole
SIZE
A
DWG. NO.
C2
REV
5
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ± 0.005

MATERIAL
6061 ALUMINUM

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	M DARRIGO	3/30/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

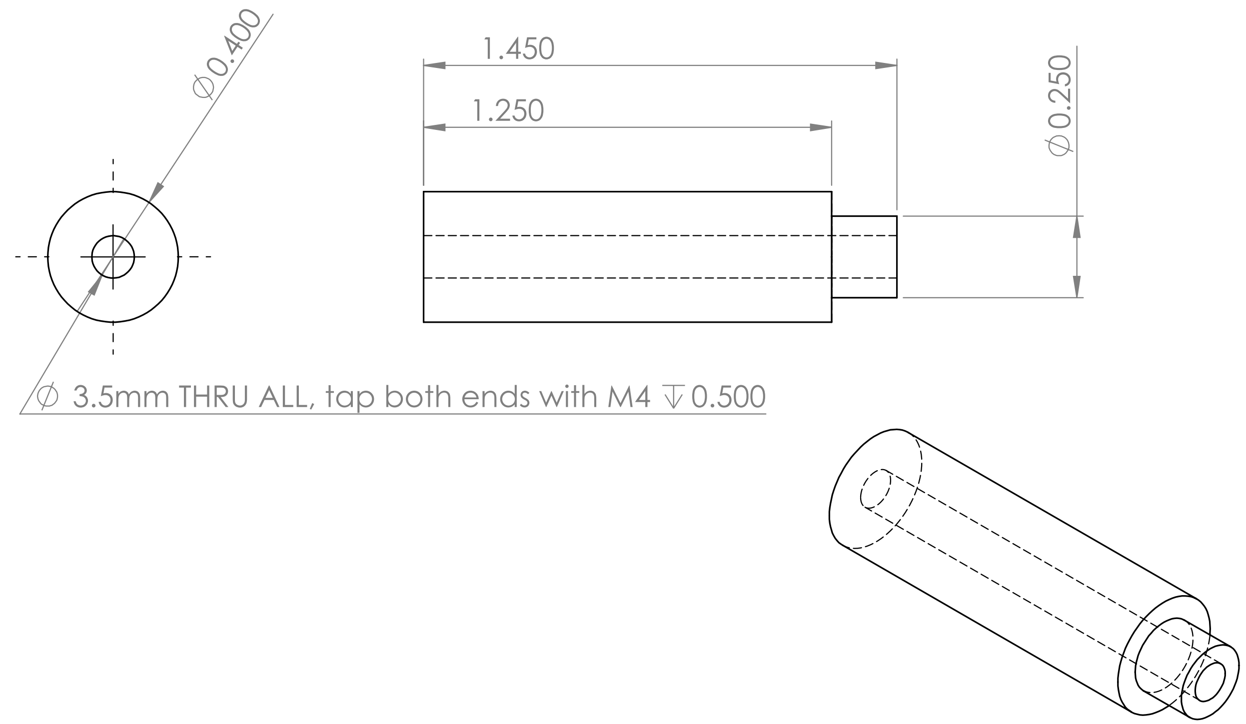
VDV

TITLE:

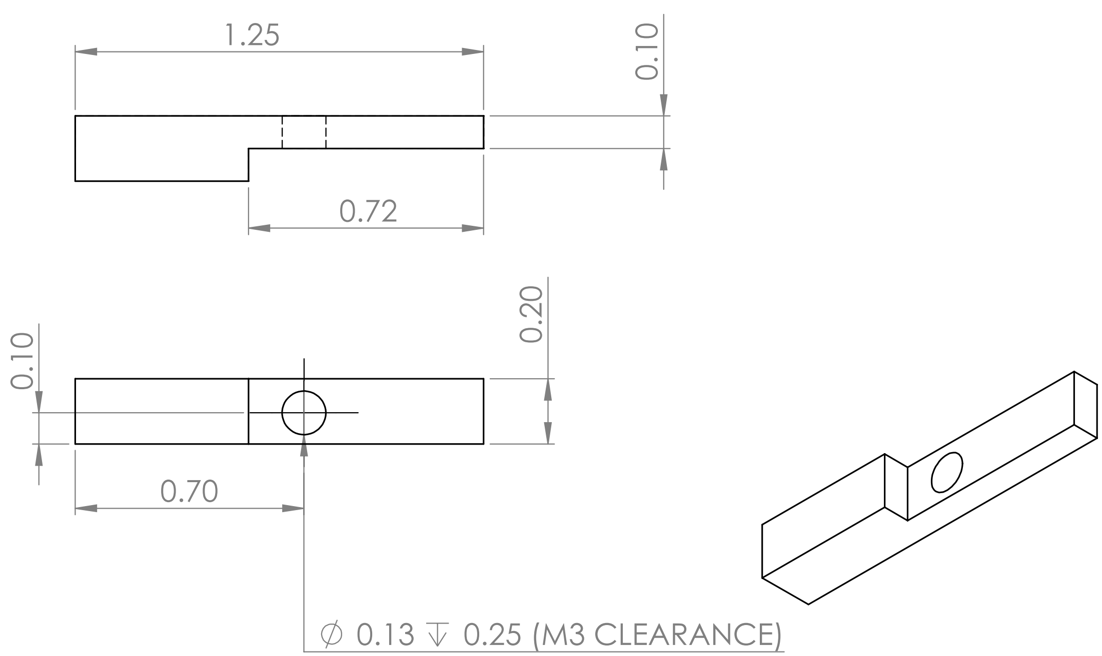
MECHANISM SHAFTS

SIZE A | DWG. NO. C3 | REV 3

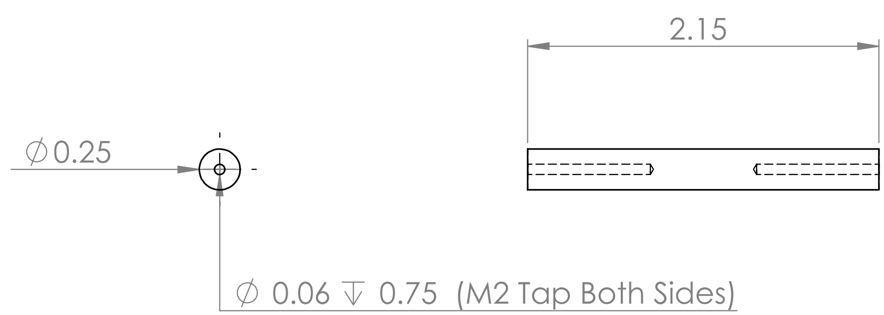
SCALE: 2:1 | SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	VDV
DIMENSIONS ARE IN INCHES TOLERANCES:±0.005	DRAWN	C Clark	4/3/17	TITLE:
	CHECKED			AXLE EXTENSION
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 6061 ALUMINUM	COMMENTS:			SIZE A · DWG. NO. C4 · REV 2
DO NOT SCALE DRAWING				SCALE: 2:1 · WEIGHT: · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	VDV
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.005	DRAWN	MDARRIGO	5/22/17	TITLE:
	CHECKED			STOWAGE LOCK ARM
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL 6061 ALUMINUM	COMMENTS:			SIZE A · DWG. NO. S1 · REV 2
FINISH				
DO NOT SCALE DRAWING				SCALE: 2:1 · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES: ±.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6061 ALUMINUM

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MDARRIGO	5/3/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

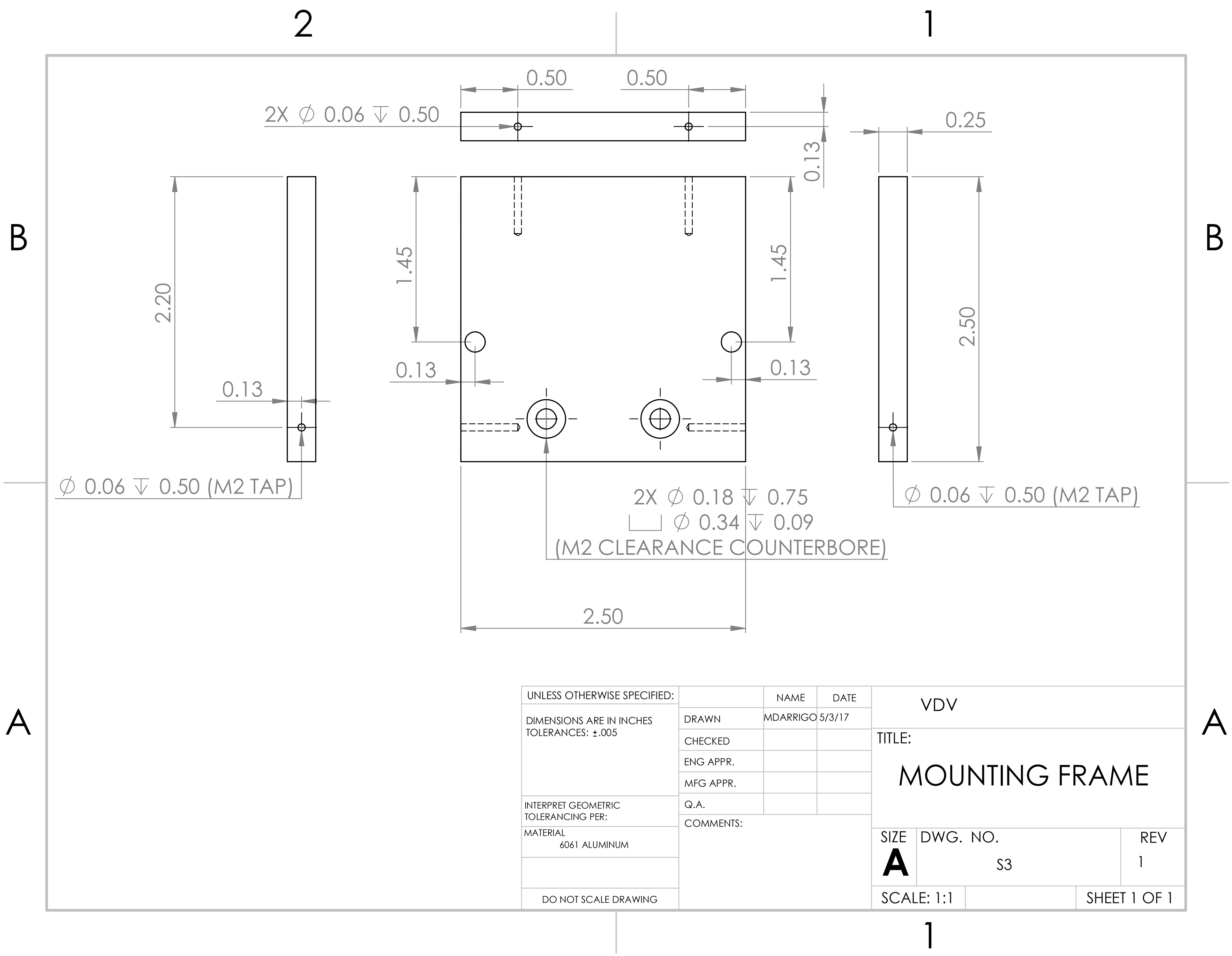
VDV

TITLE:

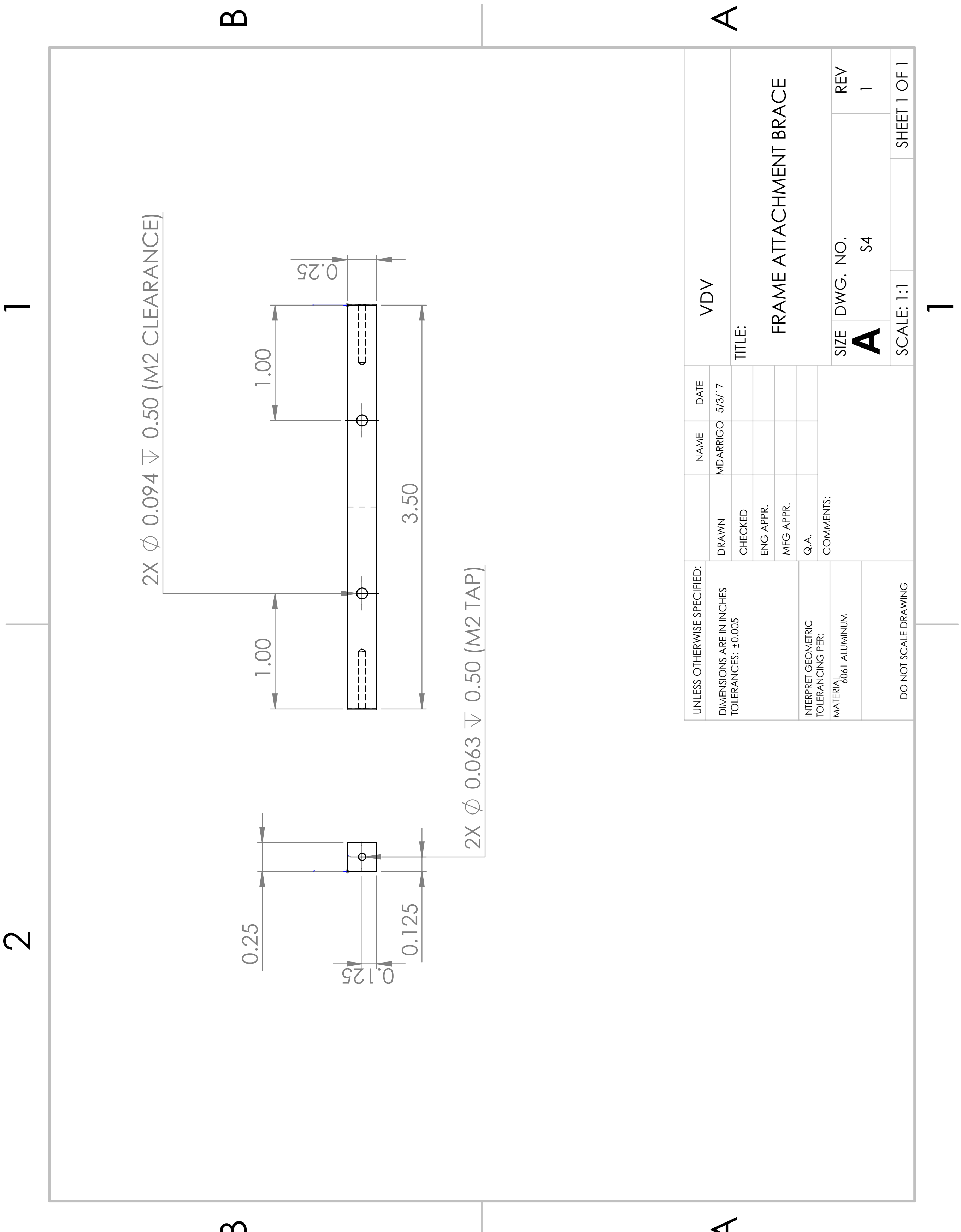
STRUT TOWER BRACE

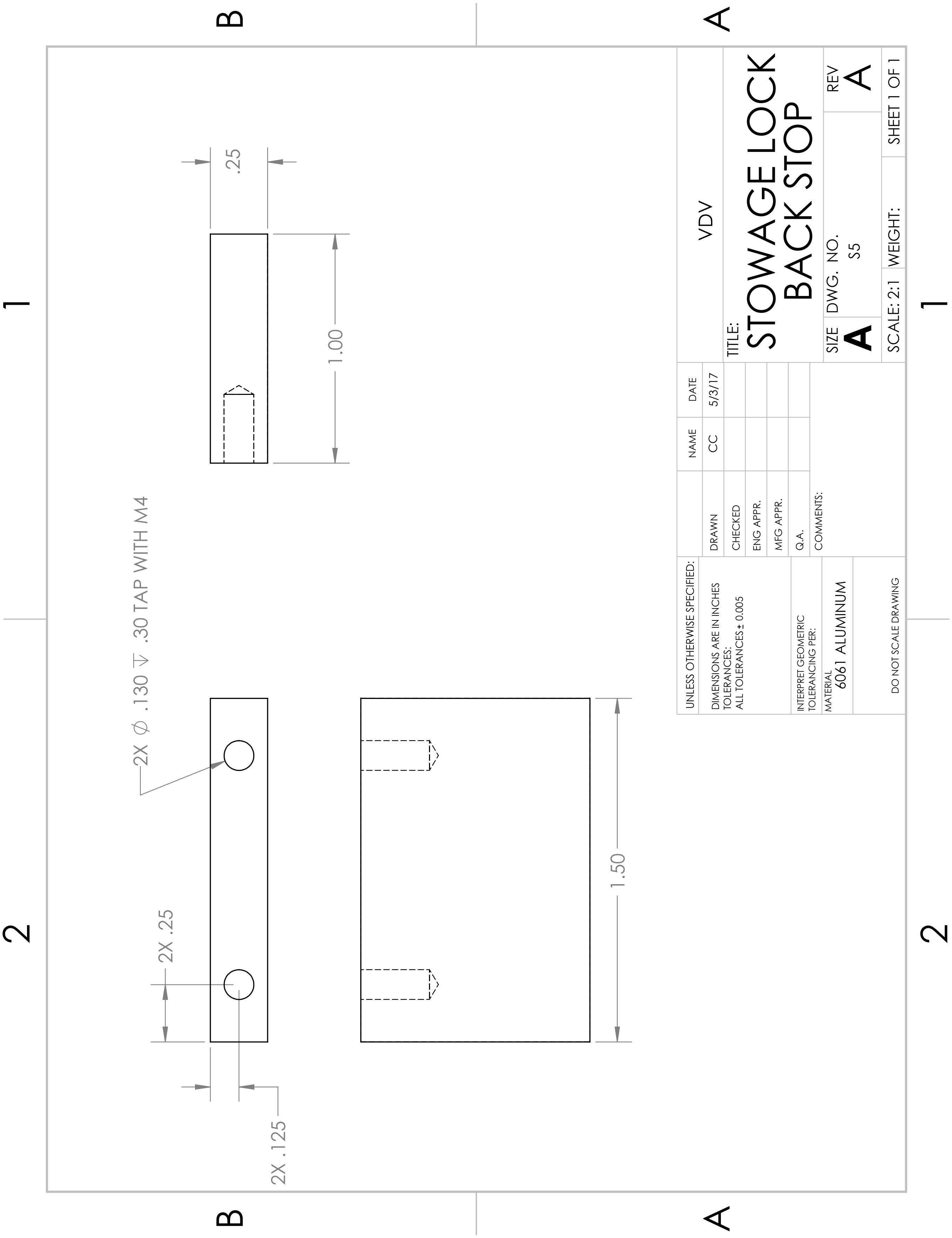
SIZE A | DWG. NO. S2 | REV 1

SCALE: 1:1 | SHEET 1 OF 1

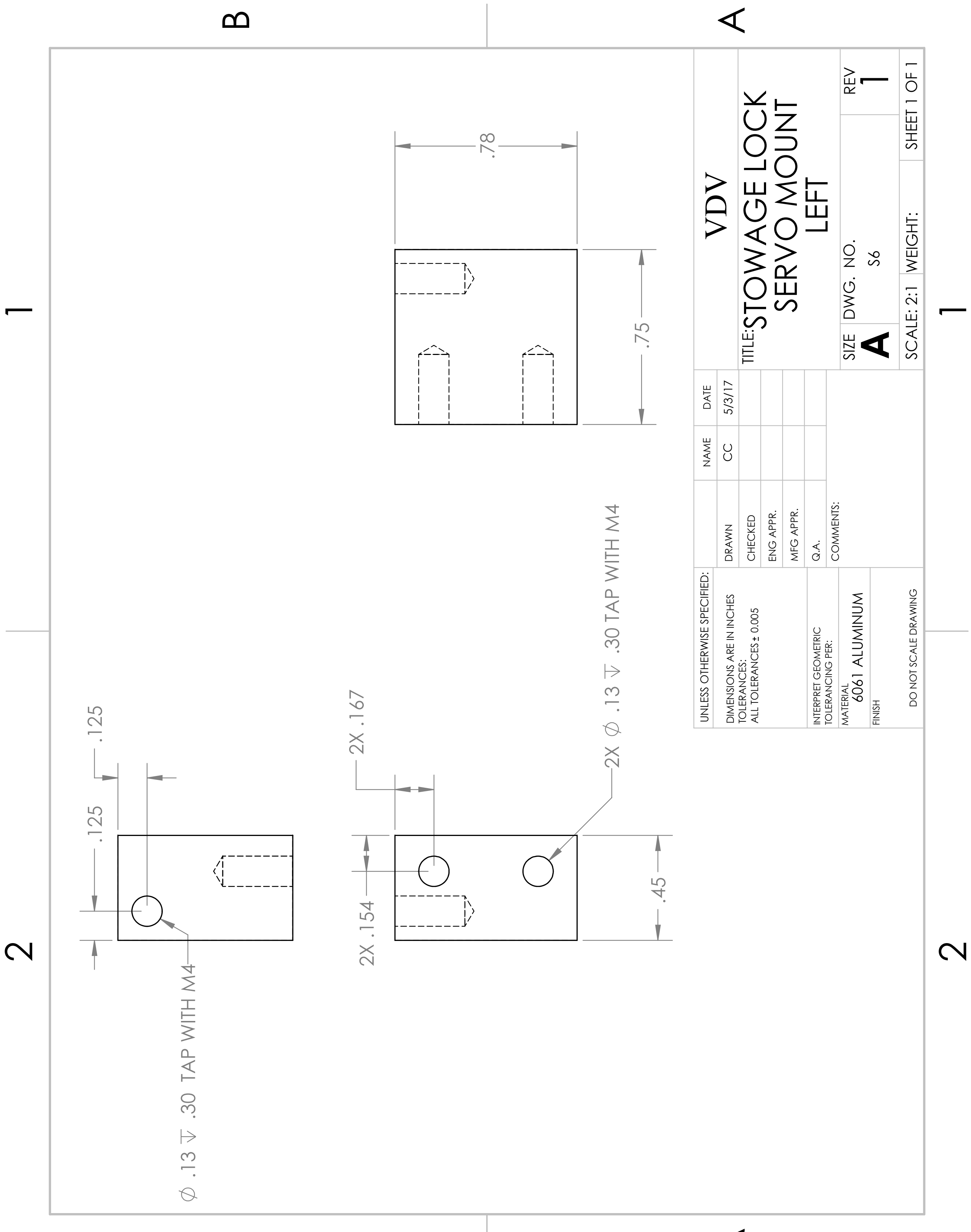


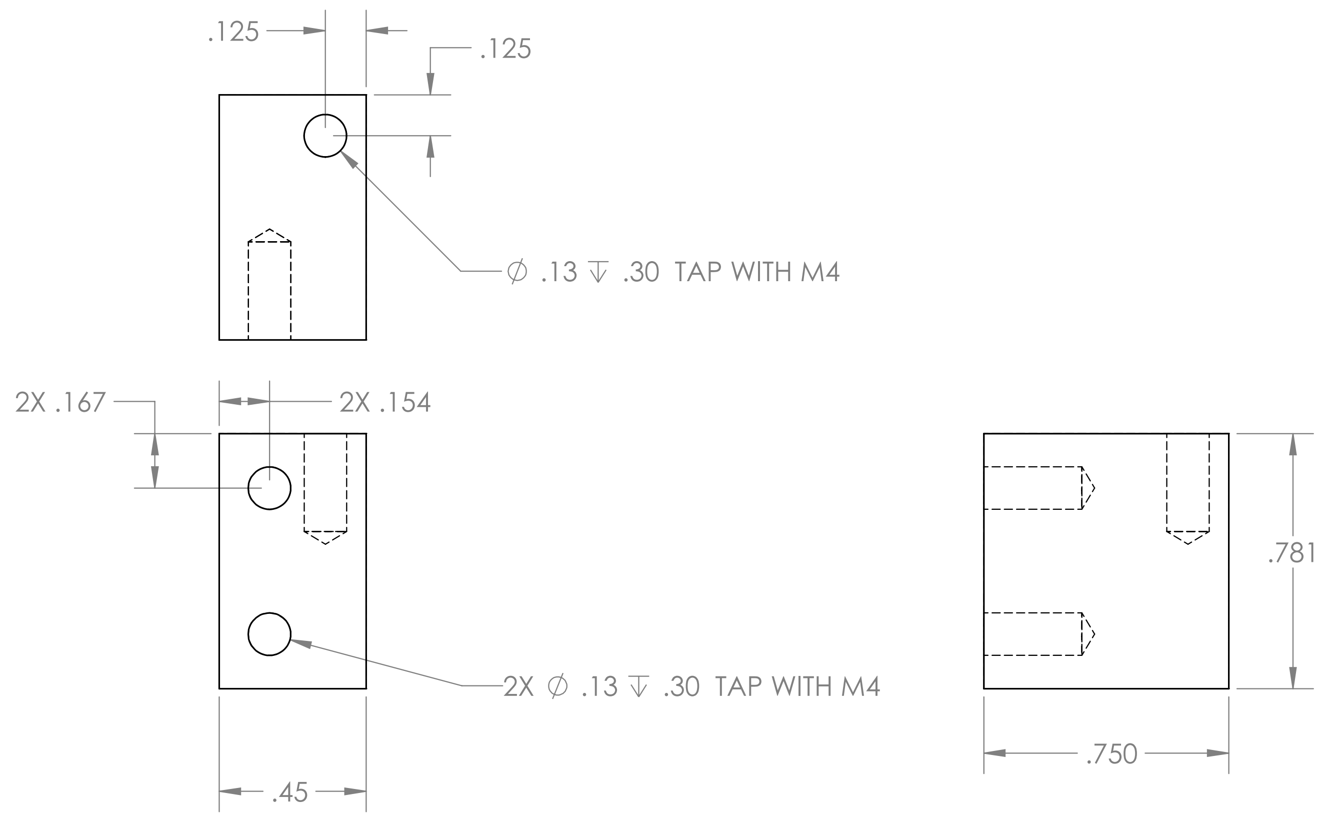
2X ∅ 0.06 ↧ 0.50
0.50
0.50
0.13
0.25
2.20
1.45
1.45
2.50
0.13
0.13
0.13
∅ 0.06 ↧ 0.50 (M2 TAP)
∅ 0.06 ↧ 0.50 (M2 TAP)
2X ∅ 0.18 ↧ 0.75
⌴ ∅ 0.34 ↧ 0.09
(M2 CLEARANCE COUNTERBORE)
2.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 ALUMINUM
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MDARRIGO
5/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
VDV
TITLE:
MOUNTING FRAME
SIZE
A
DWG. NO.
S3
REV
1
SCALE: 1:1
SHEET 1 OF 1


2X ⌀ 0.094 ↧ 0.50 (M2 CLEARANCE)
2X ⌀ 0.063 ↧ 0.50 (M2 TAP)
0.25
1.00
3.50
1.00
0.25
0.125
0.125
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 ALUMINUM
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MDARRIGO
5/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
VDV
TITLE:
FRAME ATTACHMENT BRACE
SIZE
A
DWG. NO.
S4
REV
1
SCALE: 1:1
SHEET 1 OF 1



2X ∅ .130 ↧ .30 TAP WITH M4
.25
1.00
2X .25
2X .125
1.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ALL TOLERANCES ± 0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 ALUMINUM
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CC
5/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
VDV
TITLE:
STOWAGE LOCK BACK STOP
SIZE
A
DWG. NO.
S5
REV
A
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1


VDV
TITLE: STOWAGE LOCK SERVO MOUNT LEFT
SIZE A
DWG. NO. S6
REV 1
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
ALL TOLERANCES ± 0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CC
5/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
.78
.75
.45
2X .154
2X .167
.125
.125
∅ .13 ↧ .30 TAP WITH M4
2X ∅ .13 ↧ .30 TAP WITH M4
A
B
1
2



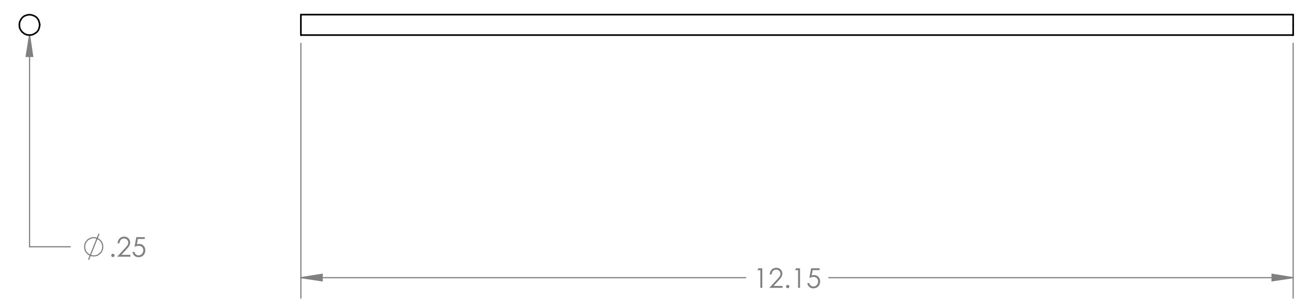
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ALL TOLERANCES ± 0.005	DRAWN	CC	5/3/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL 6061 ALUMINUM	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

VDV

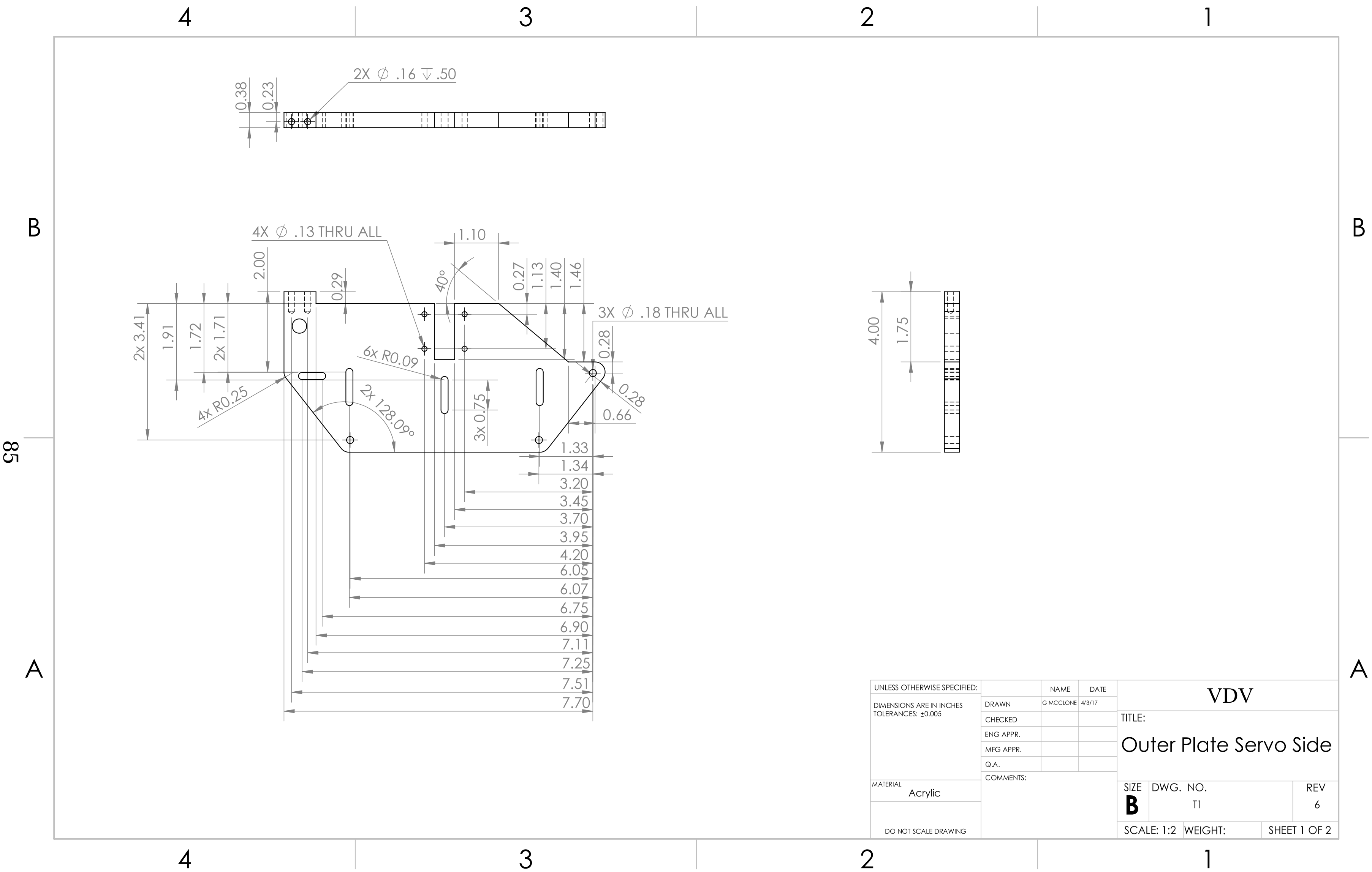
TITLE: STOWAGE LOCK SERVO MOUNT RIGHT

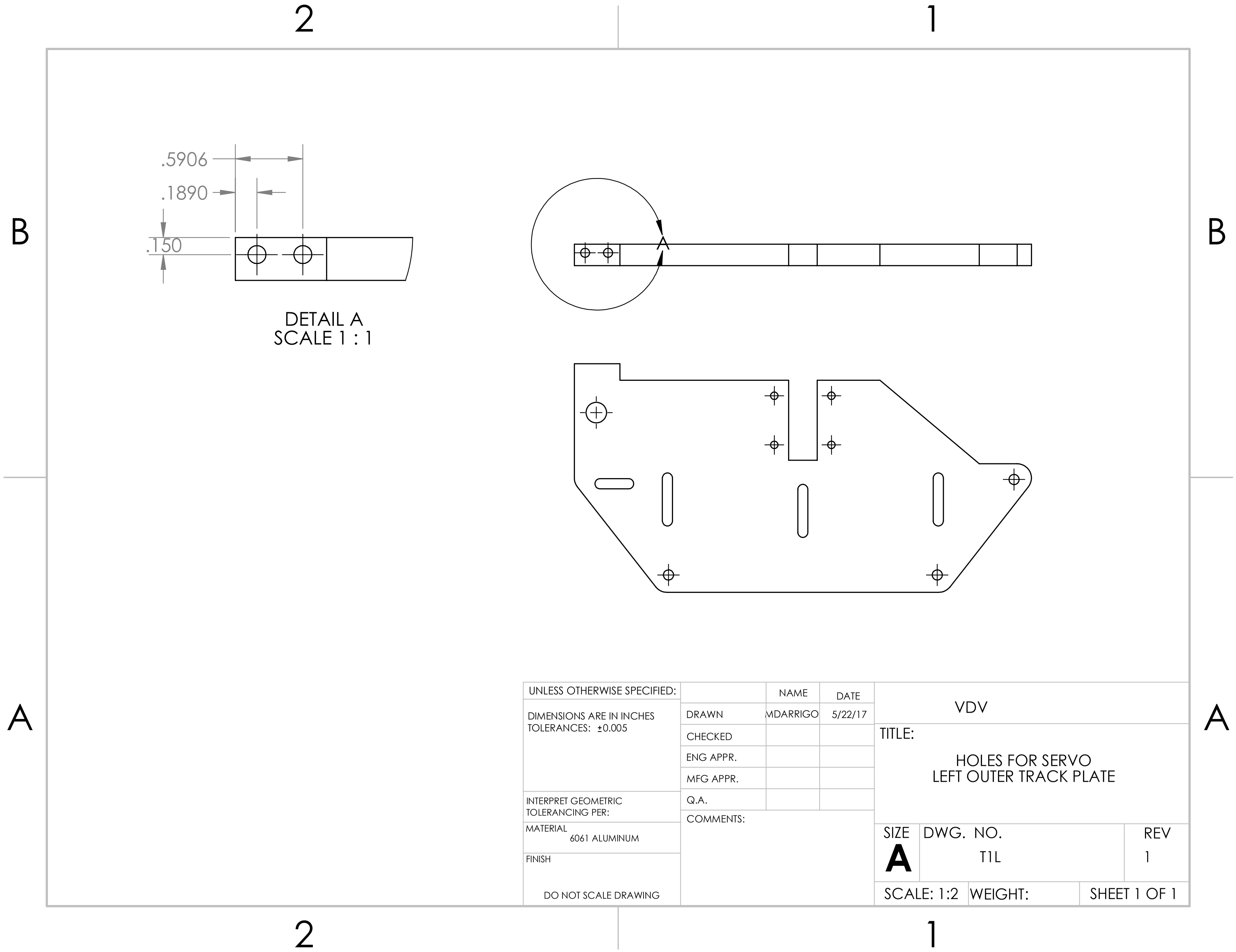
SIZE	DWG. NO.	REV
A	S7	1

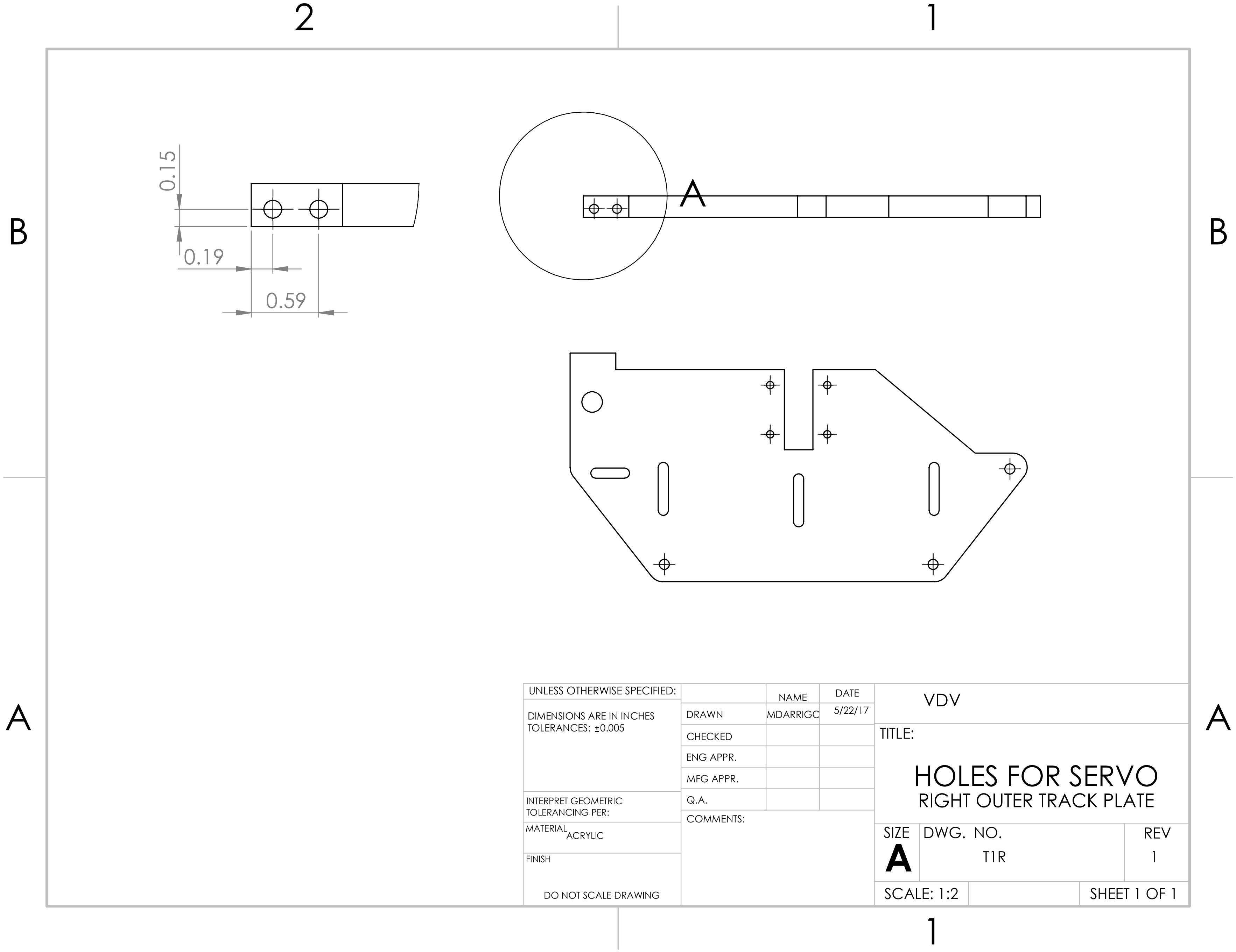
SCALE: 2:1 WEIGHT: SHEET 1 OF 1



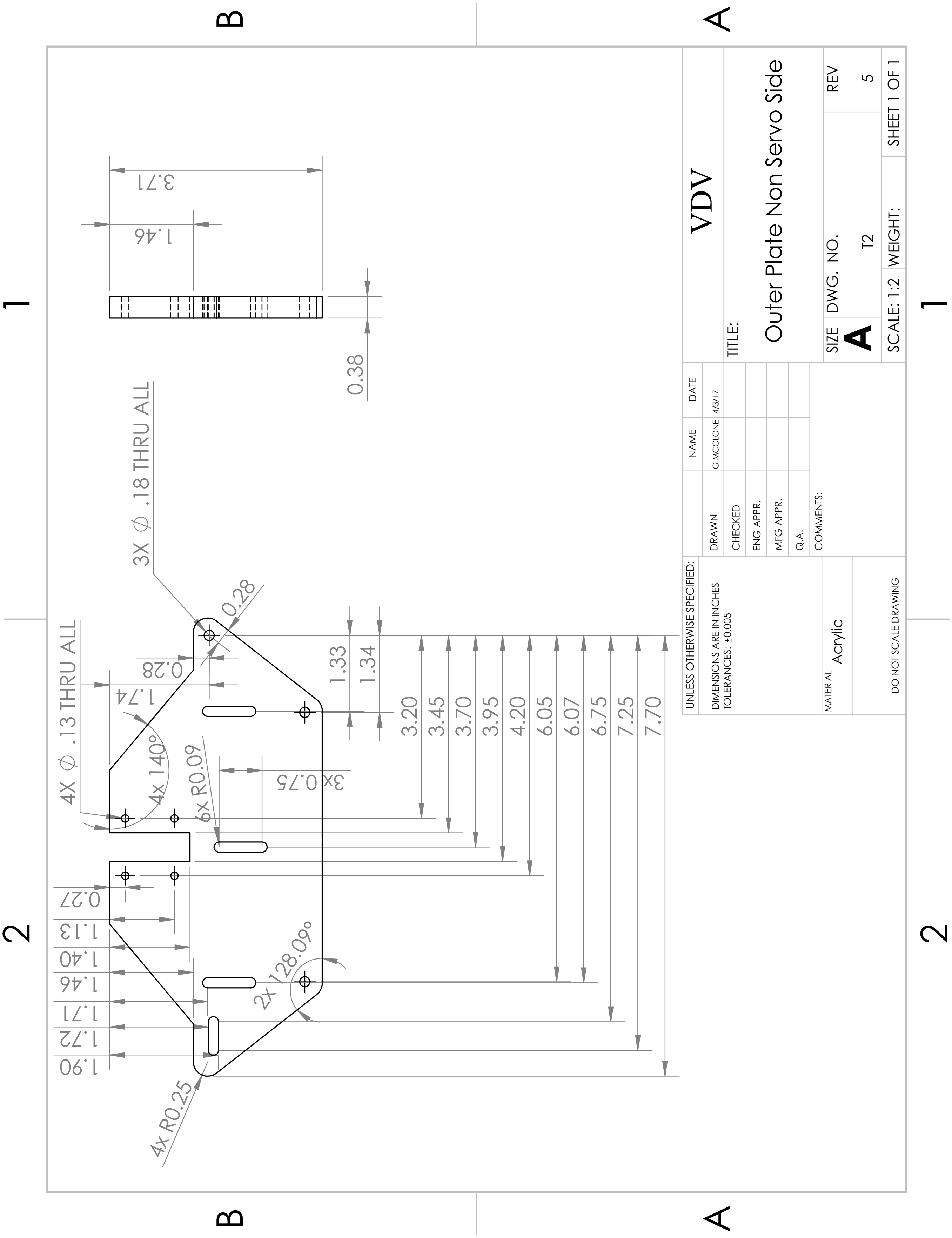
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	VDV
DIMENSIONS ARE IN INCHES TOLERANCES: ALL TOLERANCES ± .005	DRAWN	CC	5/3/17	TITLE:
	CHECKED			TRACK CONNECTOR BAR
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL 6061 ALUMINUM	COMMENTS:			SIZE A · DWG. NO. S8 · REV 1
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:4 · WEIGHT: · SHEET 1 OF 1


2X ∅ .16 ↧ .50
0.38
0.23
4X ∅ .13 THRU ALL
2.00
0.29
1.10
40°
0.27
1.13
1.40
1.46
3X ∅ .18 THRU ALL
0.28
0.28
0.66
6x R0.09
2x 128.09°
3x 0.75
4x R0.25
2x 3.41
1.91
1.72
2x 1.71
1.33
1.34
3.20
3.45
3.70
3.95
4.20
6.05
6.07
6.75
6.90
7.11
7.25
7.51
7.70
4.00
1.75
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
NAME
DATE
DRAWN
G MCCLONE
4/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
Acrylic
DO NOT SCALE DRAWING
VDV
TITLE:
Outer Plate Servo Side
SIZE
B
DWG. NO.
T1
REV
6
SCALE: 1:2
WEIGHT:
SHEET 1 OF 2

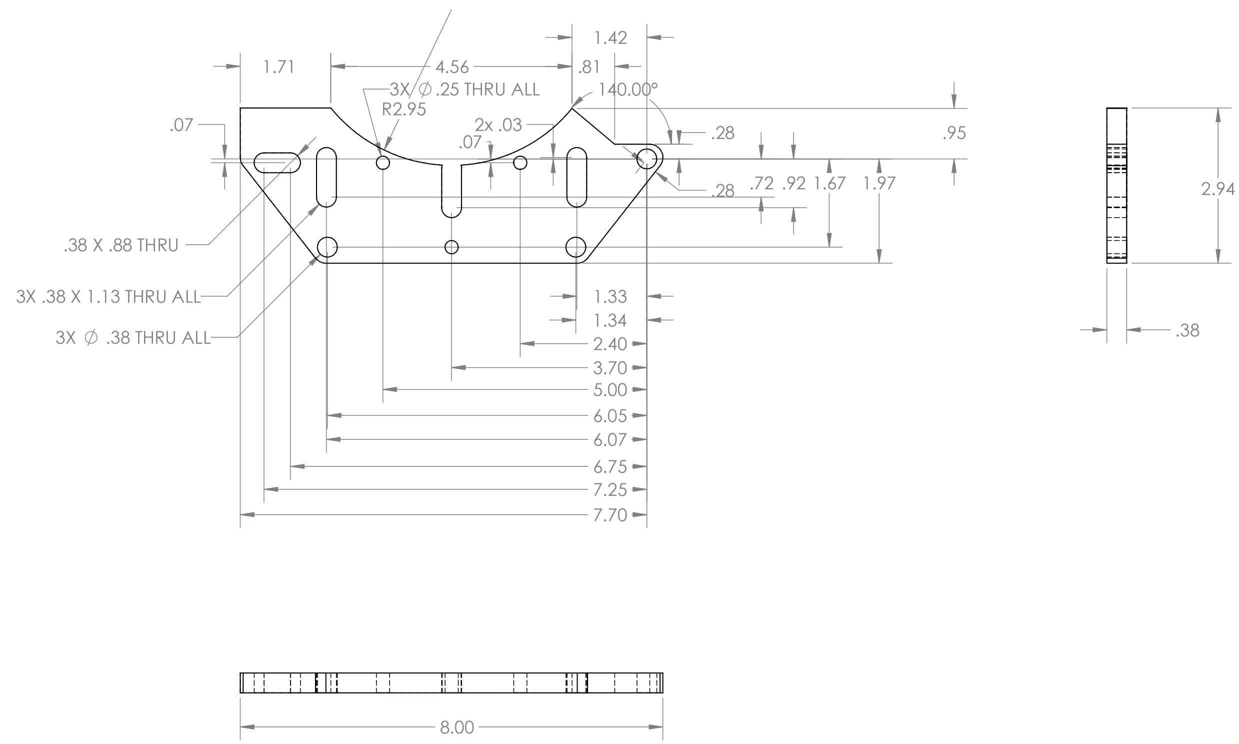

.5906
.1890
.150
DETAIL A
SCALE 1 : 1
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MDARRIGO
5/22/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
VDV
TITLE:
HOLES FOR SERVO
LEFT OUTER TRACK PLATE
SIZE
A
DWG. NO.
T1L
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1



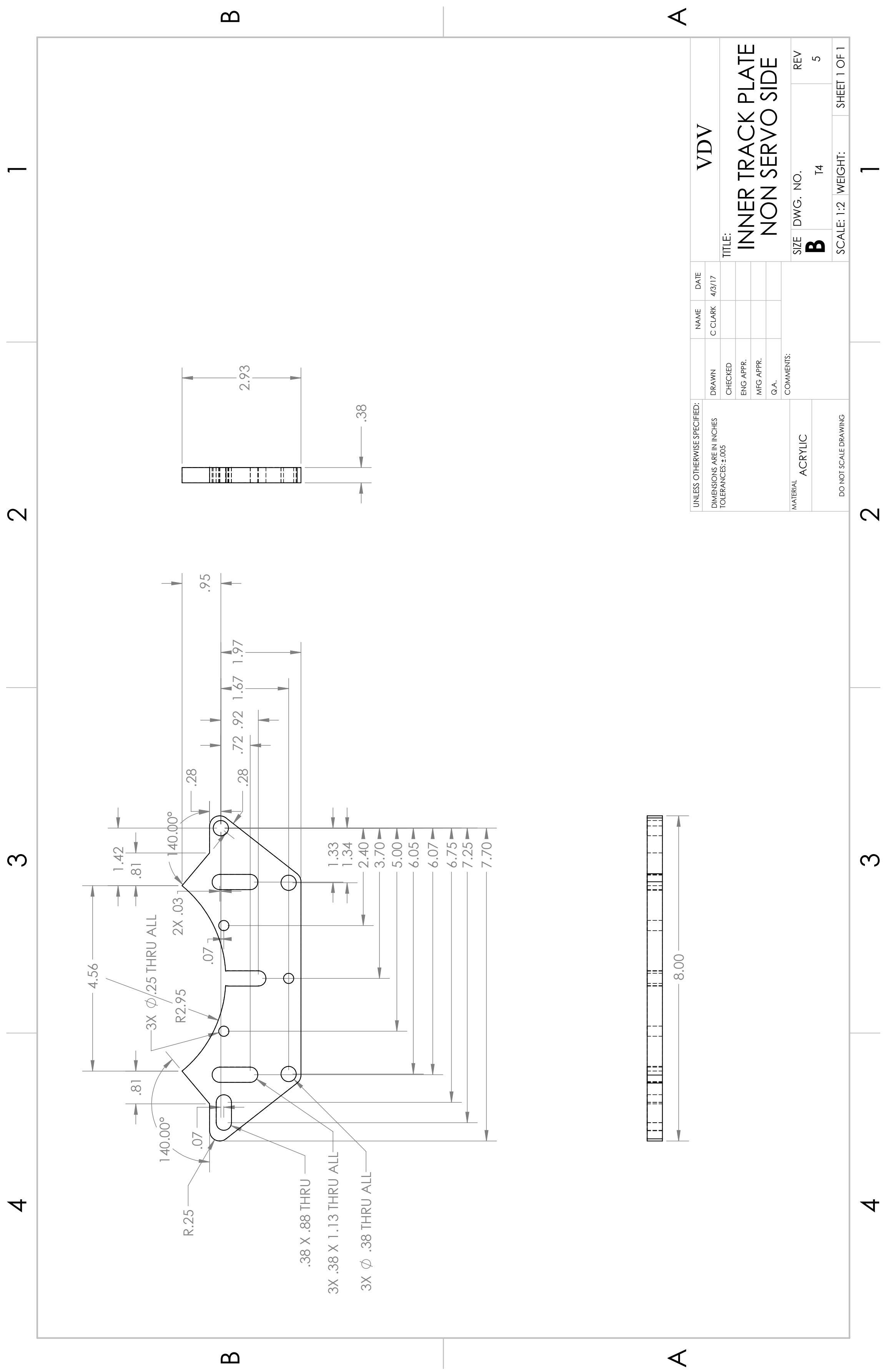
2
1
B
A
0.15
0.19
0.59
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL ACRYLIC
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN MDARRIGC 5/22/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
VDV
TITLE:
HOLES FOR SERVO
RIGHT OUTER TRACK PLATE
SIZE A
DWG. NO. T1R
REV 1
SCALE: 1:2
SHEET 1 OF 1

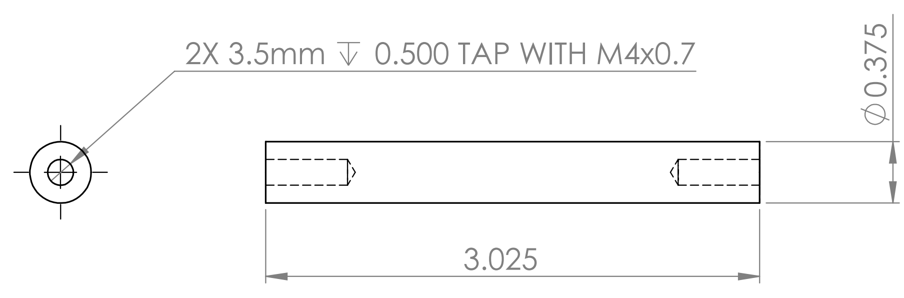


VDV
TITLE:
Outer Plate Non Servo Side
SIZE A
DWG. NO. T2
REV 5
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
NAME
DATE
DRAWN
G MCCLONE
4/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
Acrylic
DO NOT SCALE DRAWING
4X ⌀ .13 THRU ALL
3X ⌀ .18 THRU ALL
4x 140°
6x R0.09
3x 0.75
2x 128.09°
4x R0.25
0.28
0.28
1.74
1.33
1.34
0.38
1.46
3.71
0.27
1.13
1.40
1.46
1.71
1.72
1.90
3.20
3.45
3.70
3.95
4.20
6.05
6.07
6.75
7.25
7.70

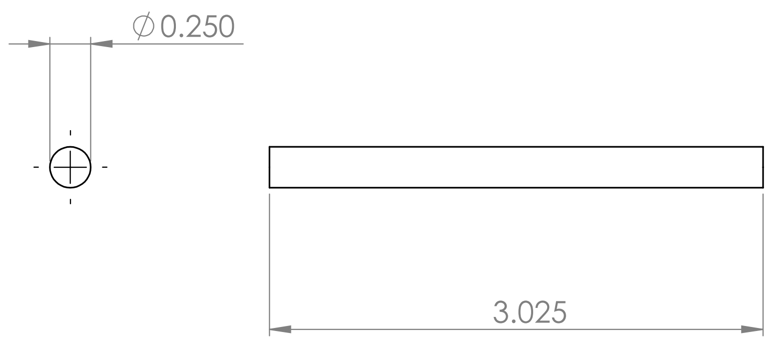


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	VDV
DIMENSIONS ARE IN INCHES TOLERANCES: ±.005	DRAWN	C CLARK	4/3/17	TITLE: INNER TRACK PLATE SERVO SIDE
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			SIZE **B** DWG. NO. T3 REV 3
MATERIAL ACRYLIC	COMMENTS:			
DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 1 OF 1

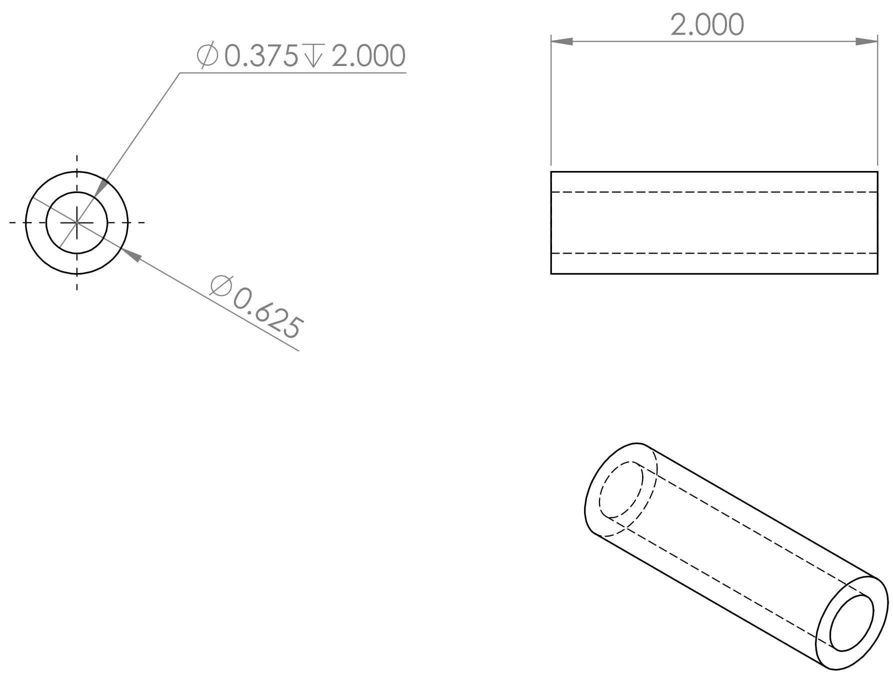

VDV
TITLE:
INNER TRACK PLATE
NON SERVO SIDE
SIZE
B
DWG. NO.
T4
REV
5
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±.005
NAME
DATE
DRAWN
C CLARK
4/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
ACRYLIC
DO NOT SCALE DRAWING
2.93
.38
8.00
.95
1.97
1.67
.92
.72
.28
.28
140.00°
1.42
.81
2X .03
.07
4.56
3X ⌀.25 THRU ALL
R2.95
.81
140.00°
.07
R.25
.38 X .88 THRU
3X .38 X 1.13 THRU ALL
3X ⌀ .38 THRU ALL
1.33
1.34
2.40
3.70
5.00
6.05
6.07
6.75
7.25
7.70



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	VDV
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.005	DRAWN	J SAHYOUN	4/3/17	TITLE:
	CHECKED			LARGE AXLES
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 6061 ALUMINUM	COMMENTS:			SIZE A · DWG. NO. T5 · REV 2
DO NOT SCALE DRAWING				SCALE: 1:1 · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	VDV		
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.005	DRAWN	C CLARK	4/3/17	TITLE:		
	CHECKED			SMALL AXLES		
	ENG APPR.					
	MFG APPR.					
	Q.A.					
MATERIAL 6061 ALUMINUM	COMMENTS:			SIZE A	DWG. NO. T6	REV 3
DO NOT SCALE DRAWING				SCALE: 1:1		SHEET 1 OF 1



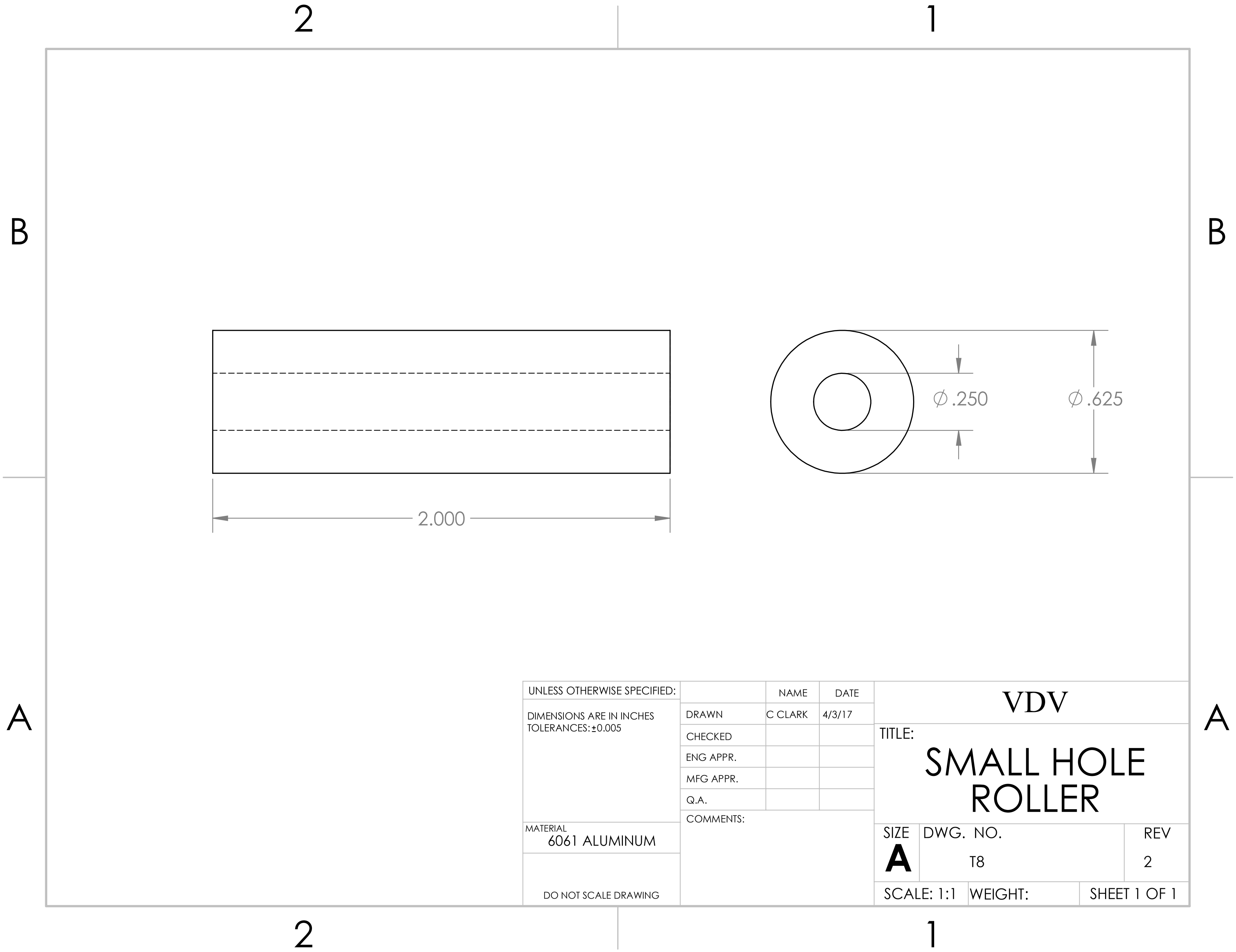
UNLESS OTHERWISE SPECIFIED:		NAME / DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.005	DRAWN	G MCCLONE / 3/15/17
	CHECKED	
	ENG APPR.	
	MFG APPR.	
	Q.A.	
MATERIAL 6061 ALUMINUM	COMMENTS:	
DO NOT SCALE DRAWING		

VDV

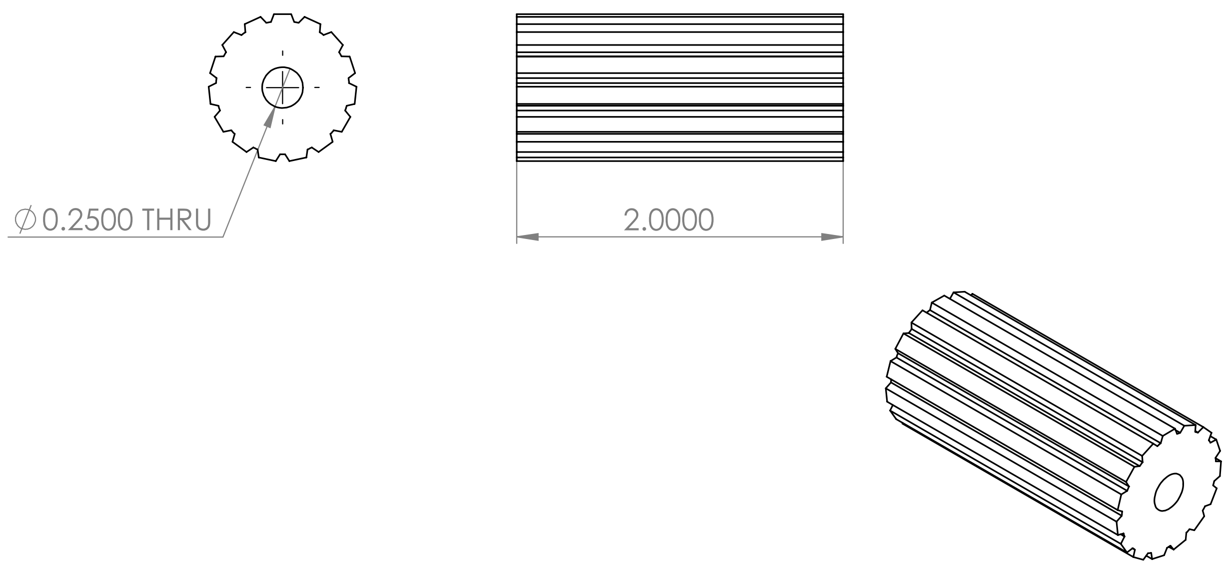
TITLE:

LARGE HOLE ROLLER

SIZE	DWG. NO.	REV
A	T7	2
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

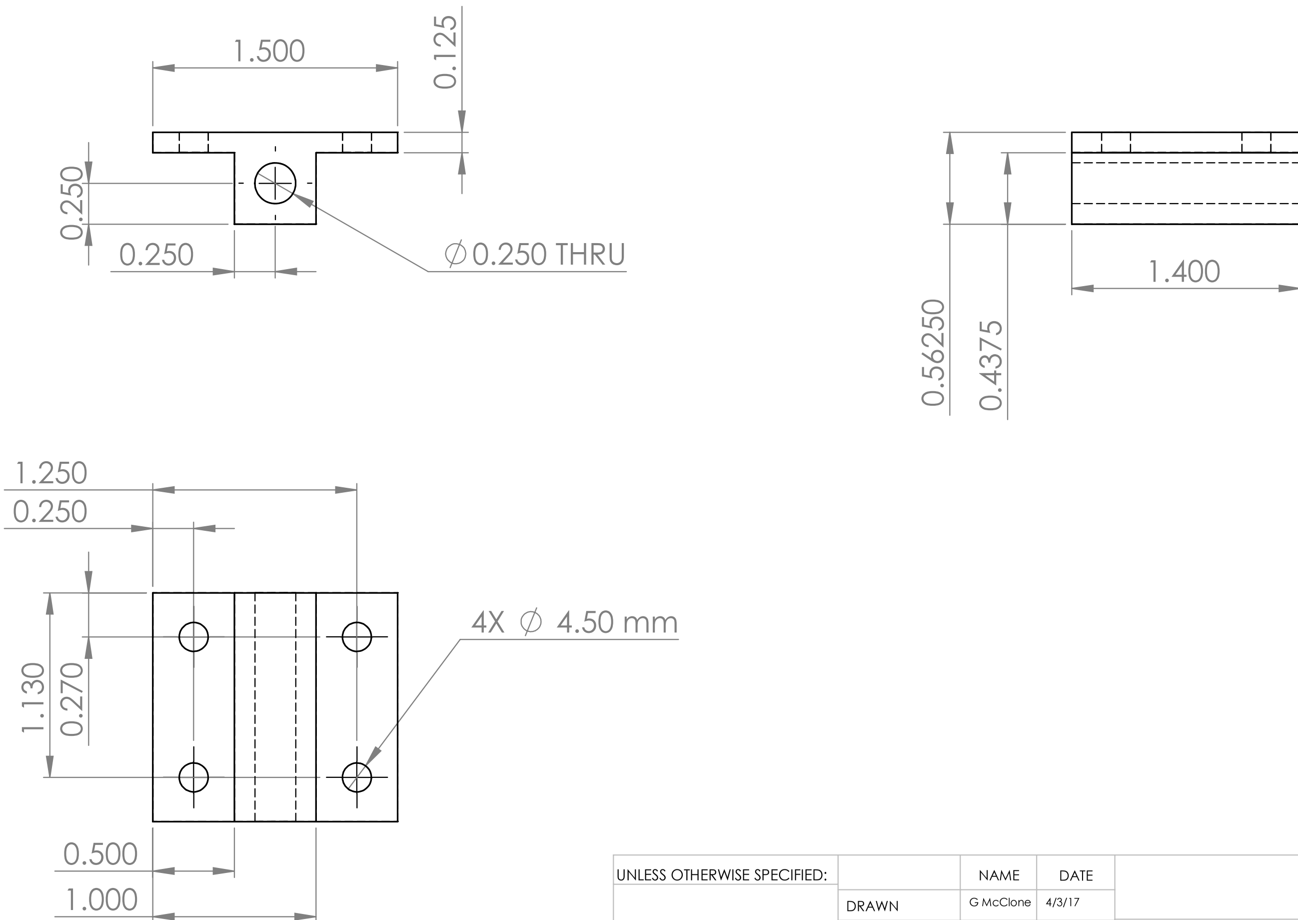


2.000
⌀.250
⌀.625
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
MATERIAL
6061 ALUMINUM
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
C CLARK
4/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
VDV
TITLE:
SMALL HOLE ROLLER
SIZE
A
DWG. NO.
T8
REV
2
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1



MODIFIED 15 Tooth Roller with T5 tooth profile
PD: 23.88 mm OD: 23.05mm
Polytech.com

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	VDV
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.005	DRAWN	J SAHYOUN	3/18/17	TITLE:
	CHECKED			SPLINED ROLLER
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 6061 ALUMINUM	COMMENTS:			SIZE A · DWG. NO. T9 · REV 3
DO NOT SCALE DRAWING				SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1



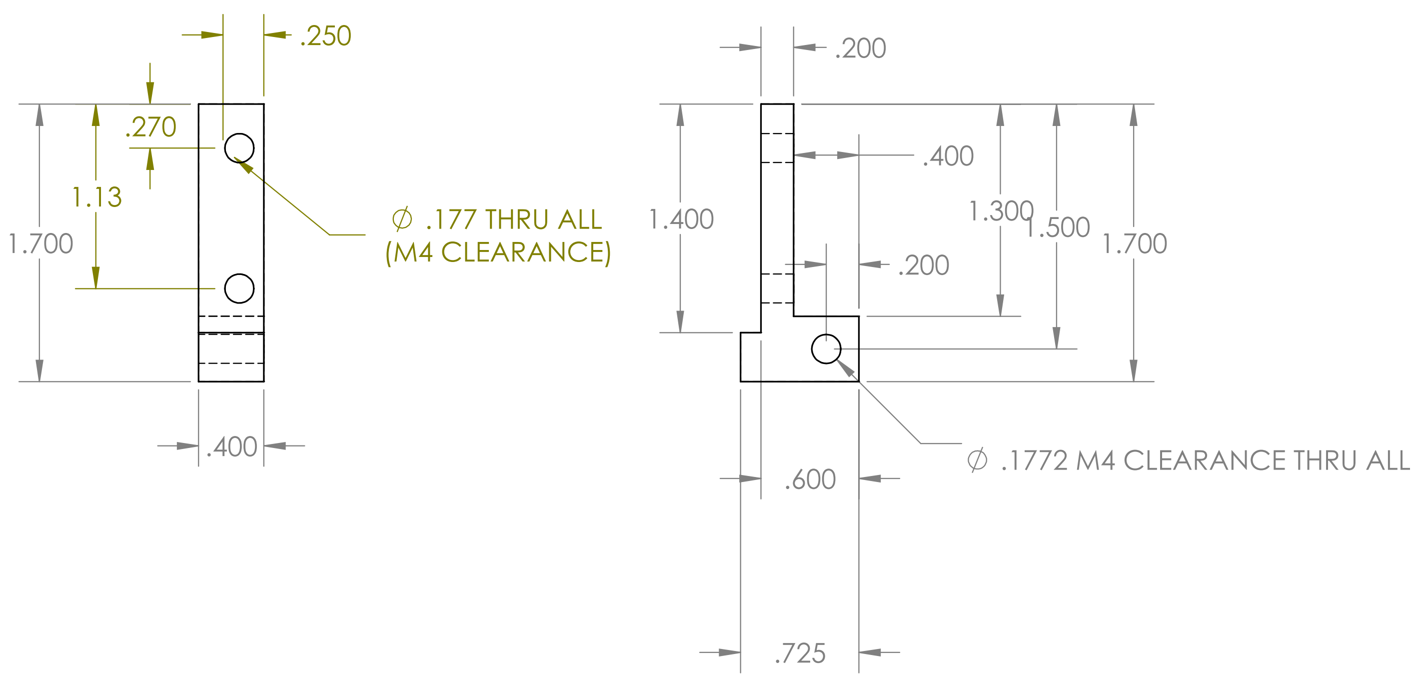
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ±0.005	DRAWN	G McClone	4/3/17
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL 6061 Aluminum	COMMENTS:		
DO NOT SCALE DRAWING			

VDV

TITLE:

Shaft Receiver Inset

SIZE	DWG. NO.	REV
A	T10	2
SCALE: 2:1	WEIGHT:	SHEET 1 OF 1



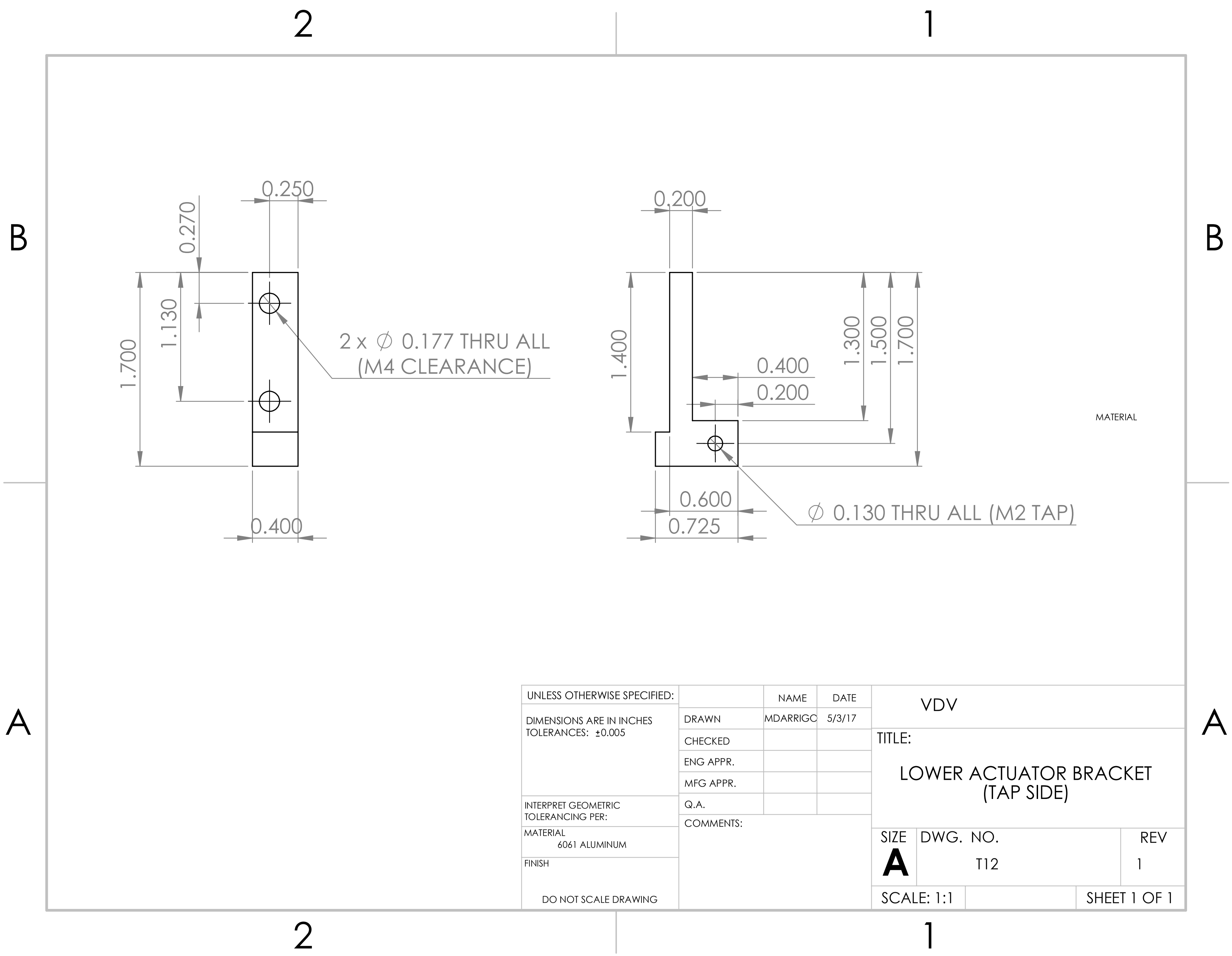
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: ALL TOLERANCES ± .005	DRAWN	CC	4/10
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL ALUMINUM	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

VDV

TITLE:
LOWER ACTUATOR BRACKET
(CLEARANCE SIDE)

SIZE	DWG. NO.	REV
A	T11	A

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1


0.250
0.270
1.130
1.700
0.400
2 x ∅ 0.177 THRU ALL
(M4 CLEARANCE)
0.200
1.400
0.400
0.200
1.300
1.500
1.700
0.600
0.725
∅ 0.130 THRU ALL (M2 TAP)
MATERIAL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
6061 ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
MDARRIGC
5/3/17
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
VDV
TITLE:
LOWER ACTUATOR BRACKET
(TAP SIDE)
SIZE
A
DWG. NO.
T12
REV
1
SCALE: 1:1
SHEET 1 OF 1

C.3 Bill of Materials

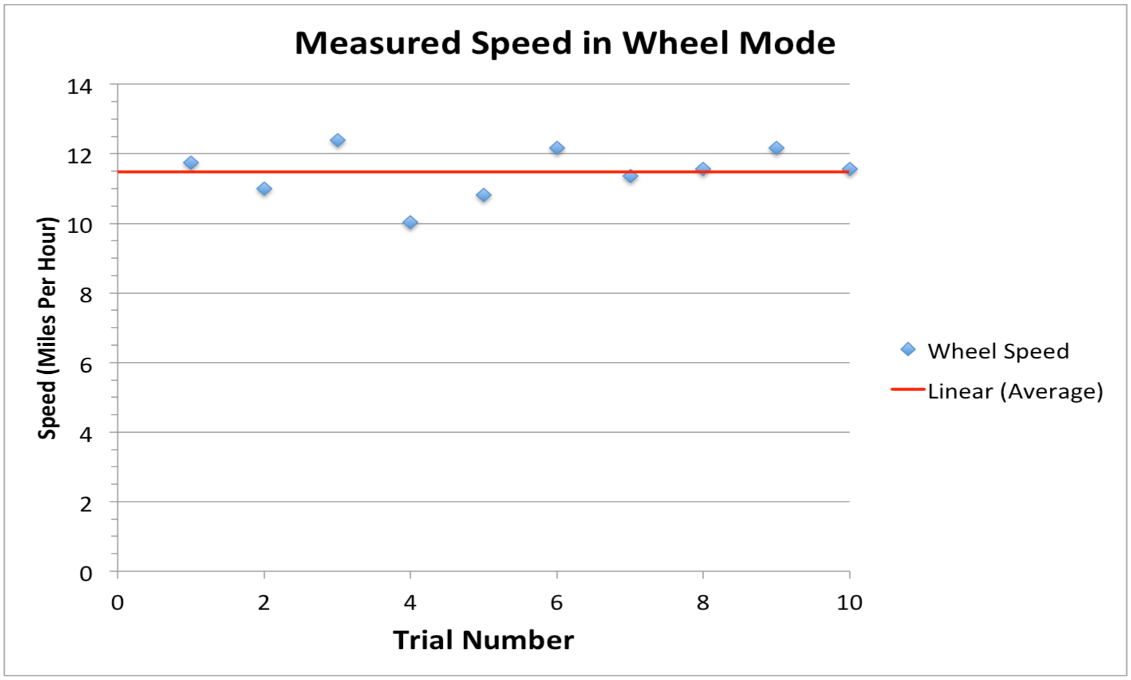
Track Unit, Rotation Lock, And Contact Lock Components	Part Number	Quantity	Material	Manufacture
Outer Track Plate Non-Servo Side	T2	1	Acrylic	Laser Cut
Outer Track Plate Servo Side	T1	1	Acrylic	Laser Cut
Inner Track Plate Non-Servo Side	T4	1	Acrylic	Laser Cut
Inner Track Plate Servo Side	T3	2	Acrylic	Laser Cut
HS 645 MG Servo	N/A	1	N/A	Purchased
Aluminum Servo Arm	N/A	1	Aluminum	Purchased
Splined Rollers	T9	2	6061-Aluminum	Machined
Large Hole Rollers	T7	7	6061-Aluminum	Machined
Small Hole Roller	T8	1	6061-Aluminum	Machined
Small Axle	T6	2	6061-Aluminum	Machined
Large Axle	T5	7	6061-Aluminum	Machined
Axle Collar Large Hole	C2	1	6061-Aluminum	Machined
Axle Collar Small Hole	C1	1	6061-Aluminum	Machined
Mechanism Shaft	C3	2	6061-Aluminum	Machined
Shaft Receiver Inset	T10	2	6061-Aluminum	Machined
Brake Arm	B1	1	6061-Aluminum	Machined
Brake Bracket	B2	1	6061-Aluminum	Machined
Axle Extension	C4	1	6061-Aluminum	Machined
Brake Plate	B3L, B3R	1	ABS-Plastic	3D Printed
Bearing ID 15mm OD 32mm	N/A	1	N/A	Purchased
Bearing ID 0.25" OD 0.625"	N/A	1	N/A	Purchased
Lower Actuator Bracket	T11, T12	2	6061-Aluminum	Machined
Timing Belt	N/A	1	Polyurethane	Purchased
Slotted Spring Pin	N/A	2	Stainless Steel	Purchased
M2 Screws 6mm	N/A	2	Alloy Steel	Purchased
M2 Screws 16mm	N/A	3	Alloy Steel	Purchased
M3 Screw 12mm	N/A	2	Alloy Steel	Purchased
M4 Screws 10mm	N/A	10	Alloy Steel	Purchased
M4 Screws 16mm	N/A	14	Alloy Steel	Purchased
M4 Screws 35mm	N/A	2	Alloy Steel	Purchased
Actuonix L12-R Linear Actuators	N/A	2	N/A	Purchased

Stowage Lock Components	Part Number	Quantity	Material	Manufacture
Track Connector Bar	S8	1	6061-Aluminum	Machined
HS 425 BB Servo	N/A	1	N/A	Purchased
Aluminum Servo Arm	N/A	1	Aluminum	Purchased
M2 Screws 16mm	N/A	3	Alloy Steel	Purchased
M3 Screw 12mm	N/A	1	Alloy Steel	Purchased
M4 Screws 10mm	N/A	6	Alloy Steel	Purchased
Frame Attachment Brace	S4	1	6061-Aluminum	Machined
Stowage Lock Servo Mount	S6,S7	2	6061-Aluminum	Machined
Stowage Lock Backstop	S5	1	6061-Aluminum	Machined
Mounting Frame	S3	1	6061-Aluminum	Machined
Stowage Lock Arm	S1	1	6061-Aluminum	Machined
Strut Tower Brace	S2	2	6061-Aluminum	Machined

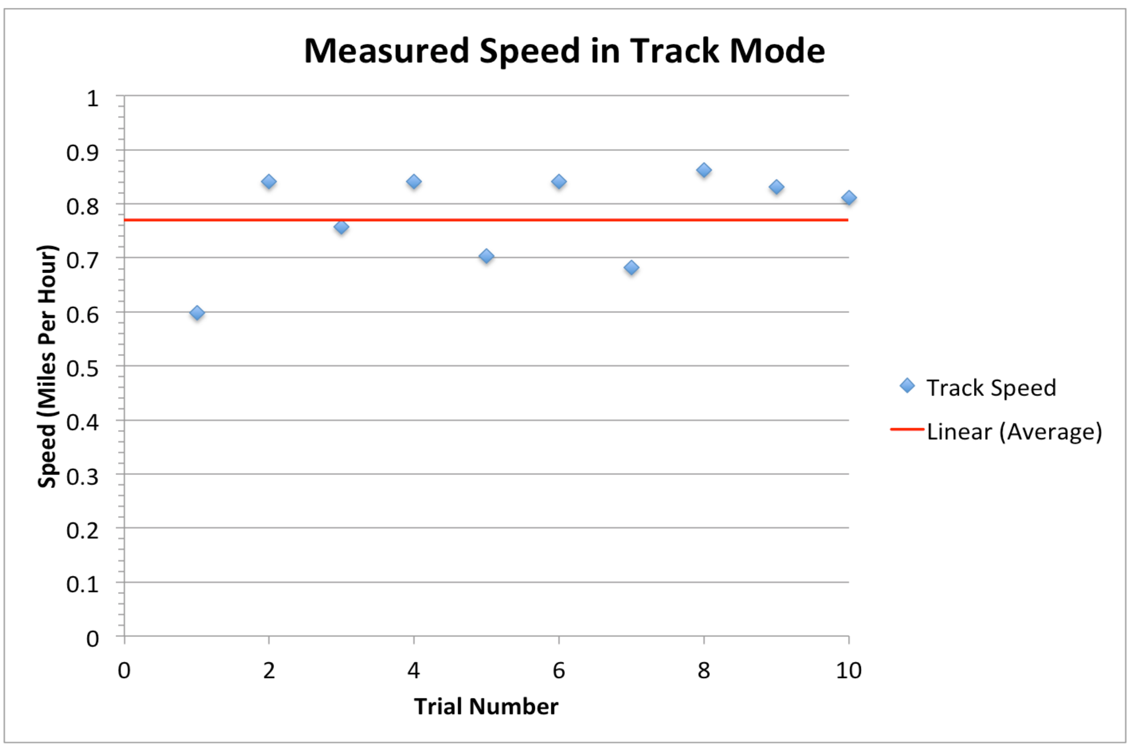
Vehicle Chassis	Part Number	Quantity	Material	Manufacture
Axial Wraith 1/10th Scale Radio Controlled Car (And Controller)	N/A	1	N/A	Purchased
Venom 7.4V 4100 mAh Lithium Polymer Battery	N/A	1	N/A	Purchased
AA Batteries	N/A	2	N/A	Purchased

Electronic Components	Part Number	Quantity	Material	Manufacture
Arduino Starter Kit (Arduino Uno, Assorted Wires, Capacitors, Switch)	N/A	1	N/A	Purchased
9V Battery	N/A	1	N/A	Purchased
AA Batteries	N/A	10	N/A	Purchased
Battery Holders	N/A	2	N/A	Purchased
Electronics Housing	N/A	1	ABS-Plastic	3D Printed

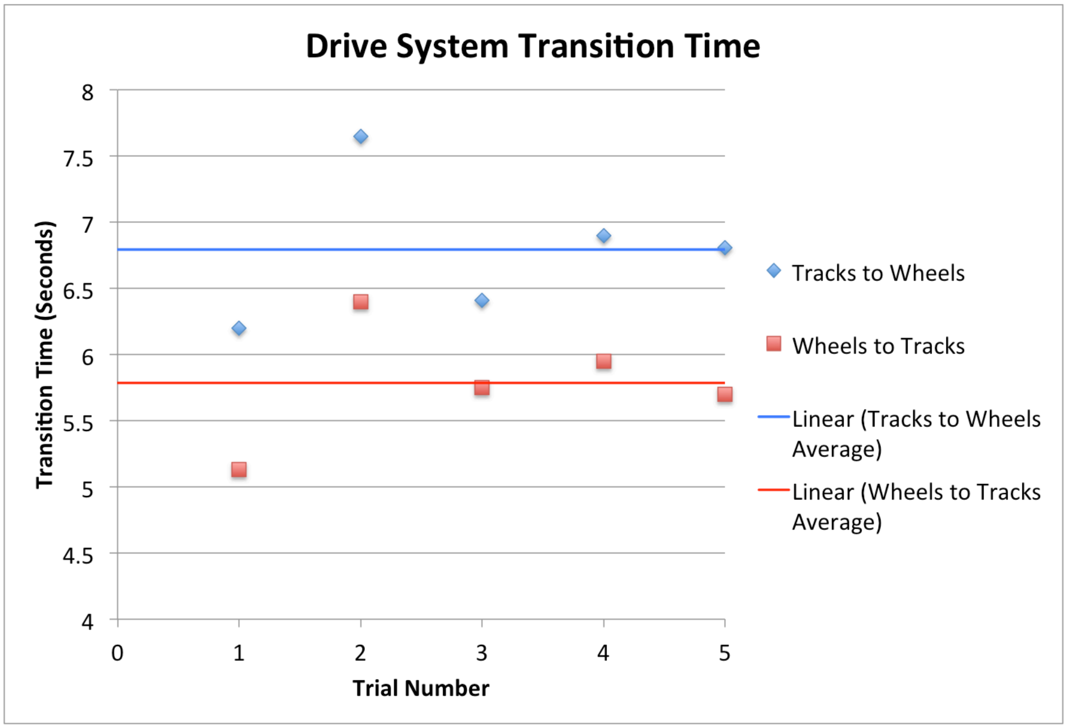
D Experimental Data



Average Maximum Wheel Speed: 11.5 MPH



Average Maximum Track Speed: 0.8 MPH



Average Tracks to Wheels Transition Time: 6.8 Seconds
Average Wheels to Tracks Transition Time: 5.8 Seconds

	Grass Speed Test					
	Wheels			**Tracks**		
	Time for 10 ft	**fps**	**mph**	**Time for 1 ft**	**fps**	**mph**
1	1.67	5.988023952	4.082743604	0	0	0
2	1.69	5.917159763	4.034427111	0	0	0
3	1.79	5.586592179	3.809040122	0	0	0
4	1.62	6.172839506	4.208754209	0	0	0
5	1.66	6.024096386	4.107338445	0	0	0
6	1.66	6.024096386	4.107338445	0	0	0
7	1.68	5.952380952	4.058441558	0	0	0
8	1.7	5.882352941	4.010695187	0	0	0
9	1.73	5.780346821	3.94114556	0	0	0
10	1.65	6.060606061	4.132231405	0	0	0
		Average	4.049215565		**Average**	0

	Gravel Speed Test					
	Wheels			Tracks		
	Time for 10 ft	fps	mph	Time for 1 ft	fps	mph
1	2.16	4.62962963	3.156565657	0	0	0
2	1.998	5.005005005	3.412503413	0	0	0
3	2.23	4.484304933	3.057480636	0	0	0
4	2.2	4.545454545	3.099173554	0	0	0
5	1.9	5.263157895	3.588516746	0	0	0
6	2.17	4.608294931	3.142019271	0	0	0
7	2.15	4.651162791	3.171247357	0	0	0
8	2.21	4.524886878	3.085150144	0	0	0
9	2	5	3.409090909	0	0	0
10	2.1	4.761904762	3.246753247	0	0	0
		Average	3.236850093		Average	0

	Sand Speed Test					
	Wheels			Tracks		
	Time for 10 ft	fps	mph	Time for 1 ft	fps	mph
1	2.46	4.06504065	2.771618625	0	0	0
2	2.69	3.717472119	2.534640081	0	0	0
3	2.39	4.184100418	2.85279574	0	0	0
4	2.4	4.166666667	2.840909091	0	0	0
5	2.5	4	2.727272727	0	0	0
6	2.66	3.759398496	2.563226247	0	0	0
7	2.72	3.676470588	2.506684492	0	0	0
8	2.3	4.347826087	2.964426877	0	0	0
9	2.65	3.773584906	2.572898799	0	0	0
10	2.47	4.048582996	2.760397497	0	0	0
		Average	2.709487018		Average	0

Obstacle Clearance	
Tracks	Wheels
1 in	2 in

Maximum Slope	
Tracks	Wheels
5.06 degrees	21.59 degrees

E Decision Matrices

Project: Variable Drive Vehicle
System: Overall System
Date: 8-Nov-16

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Offroad Speed		0	0	0.5	0	0.5	0.5						1.5	1
2	Top Speed	1		0.5	0	0.5	1	0						3	2
3	Terrain Capabilites	1	0.5		0.5	1	1	0.5						4.5	3
4	Max Slope	0.5	1	0.5		1	1	0.5						4.5	2
5	Weight	1	0.5	0	0		1	0						2.5	2
6	Ease of Use	0.5	0	0	0	0		0						0.5	1
7	Obstacle Clearance	0.5	1	0.5	0.5	1	1							4.5	3
8		1	1	1	1	1	1	1						7	
9		1	1	1	1	1	1	1	1					8	
10		1	1	1	1	1	1	1	1	1				9	
11		1	1	1	1	1	1	1	1	1	1			10	
12		1	1	1	1	1	1	1	1	1	1	1		11	

Fill in Purple squares above

Fill in upper triangle of the matrix

Working across each row, determine if the criterion in that row is more important (1), same importance (0.5) or less important (0) than the criterion in that column

Assign weighting factors for each criterion in the Yellow squares

Design Project = Variable Drive Vehicle **System=** Overall System **Date=** 8-Nov-16

CRITERIA	TARGET or FACTOR	DESIGN IDEAS: 1 = Baseline		Tracks		Two Separate Chassis		Single chassis w/ single		five		six		seven		eight		nine		ten	
Time – Design	30	30		40		50		60													
Time – Build	30	30		40		50		50													
Time – Test	20	20		20		20		20													
Time Score	10		10		12.22		14.44		15.56		0.00		0.00		0.00		0.00		0.00		0.00
Cost – Prototype	1000	$ 1,000.00		$ 1,000.00		$ 1,500.00		$ 1,200.00													
Cost – Production	1	$ 1.00																			
Cost Score	10		10		5.00		7.50		6.00		0.00		0.00		0.00		0.00		0.00		0.00
Offroad Speed	1	3	3	4	4	4	4	5	5		0		0		0		0		0		0
Top Speed	2	3	6	2	4	3	6	4	8		0		0		0		0		0		0
Terrain Capabilites	3	3	9	5	15	5	15	5	15		0		0		0		0		0		0
Max Slope	2	3	6	4	8	5	10	5	10		0		0		0		0		0		0
Weight	2	3	6	1	2	1	2	2	4		0		0		0		0		0		0
Ease of Use	1	3	3	2	2	1	1	2	2		0		0		0		0		0		0
Obstacle Clearance	3	3	9	3	9	4	12	4	12		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
	TOTAL		42.0		46.8		48.1		54.4		20.0		20.0		20.0		20.0		20.0		20.0
	RANK																				
	% MAX		77.1%		85.9%		88.3%		100.0%		36.7%		36.7%		36.7%		36.7%		36.7%		36.7%
	MAX	54.4																			

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Wheels

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(B) + TT(i)/TT(B))/3
Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(i)/Cprot(B))/2
Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescore(B)-Timescore(i)) + (Costscore(B) - Costscore(i))

Comparison(i,j) = 5 if idea "i" is much better than baseline for criteria "j"
Comparison(i,j) = 4 if idea "i" is better than baseline for criteria "j"
Comparison(i,j) = 3 if idea "i" is same as baseline for criteria "j"
Comparison(i,j) = 2 if idea "i" is worse than baseline for criteria "j"
Comparison(i,j) = 1 if idea "i" is much worse than baseline for criteria "j"

Design Idea Descriptions

2	Tracks
3	Two Separate Chassis w/ separate motors
4	Single chassis w/ single motor
5	five
6	six
7	seven
8	eight
9	nine
10	ten

Project: Variable Drive Vehicle
System: Wheeled Chassis
Date: 8-Nov-16

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Ride Height		0.5	0.5	0.5	1								2.5	2
2	Modability	0.5		1	0.5	1								3	3
3	Overhead Clearance	0.5	0		0.5	1								2	2
4	Torque	0.5	0.5	0.5		1								2.5	2
5	Speed	0	0	0	0									0	1
6		1	1	1	1	1								5	
7		1	1	1	1	1	1							6	
8		1	1	1	1	1	1	1						7	
9		1	1	1	1	1	1	1	1					8	
10		1	1	1	1	1	1	1	1	1				9	
11		1	1	1	1	1	1	1	1	1	1			10	
12		1	1	1	1	1	1	1	1	1	1	1		11	

Fill in Purple squares above

Fill in upper triangle of the matrix

Working across each row, determine if the criterion in that row is more important (1), same importance (0.5) or less important (0) than the criterion in that column

Assign weighting factors for each criterion in the Yellow squares

Design Project = Variable Drive Vehicle **System=** Wheeled Chassis **Date=** 8-Nov-16

CRITERIA	TARGET or FACTOR	1 = Baseline		Drift		Buggies		Rock Crawlers	
Time – Design	1	1		1		1		1	
Time – Build	1	1		1		1		1	
Time – Test	1	1		1		1		1	
Time Score	10		10		10.00		10.00		10.00
Cost – Prototype	500	$ 500.00		$ 500.00		$ 500.00		$ 500.00	
Cost – Production	1	$ 1.00		$ 1.00		$ 1.00		$ 1.00	
Cost Score	10		10		10.00		10.00		10.00
Ride Height	2	3	6	1	2	4	8	5	10
Modability	3	3	9	4	12	5	15	5	15
Overhead Clearance	2	3	6	1	2	4	8	5	10
Torque	2	3	6	1	2	4	8	5	10
Speed	1	3	3	5	5	4	4	2	2
0	0	3	0	2	0		0		0
0	0	3	0	3	0		0		0
0	0	3	0		0		0		0
0	0	3	0		0		0		0
0	0	3	0		0		0		0
0	0	3	0		0		0		0
0	0	3	0		0		0		0
	TOTAL		30.0		23.0		43.0		47.0
	RANK								
	% MAX		63.8%		48.9%		91.5%		100.0%
	MAX	47.0							

CRITERIA	five		six		seven		eight		nine		ten	
Time – Design												
Time – Build												
Time – Test												
Time Score		0.00		0.00		0.00		0.00		0.00		0.00
Cost – Prototype												
Cost – Production												
Cost Score		0.00		0.00		0.00		0.00		0.00		0.00
Ride Height		0		0		0		0		0		0
Modability		0		0		0		0		0		0
Overhead Clearance		0		0		0		0		0		0
Torque		0		0		0		0		0		0
Speed		0		0		0		0		0		0
0		0		0		0		0		0		0
0		0		0		0		0		0		0
0		0		0		0		0		0		0
0		0		0		0		0		0		0
0		0		0		0		0		0		0
0		0		0		0		0		0		0
0		0		0		0		0		0		0
TOTAL		20.0		20.0		20.0		20.0		20.0		20.0
RANK												
% MAX		42.6%		42.6%		42.6%		42.6%		42.6%		42.6%

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Street RC Cars

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(B) + TT(i)/TT(B))/3
Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(i)/Cprot(B))/2
Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescore(B)-Timescore(i)) + (Costscore(B) - Costscore(i))

Comparison(i,j) = 5 if idea "i" is much better than baseline for criteria "j"
Comparison(i,j) = 4 if idea "i" is better than baseline for criteria "j"
Comparison(i,j) = 3 if idea "i" is same as baseline for criteria "j"
Comparison(i,j) = 2 if idea "i" is worse than baseline for criteria "j"
Comparison(i,j) = 1 if idea "i" is much worse than baseline for criteria "j"

Design Idea Descriptions

2	Drift
3	Buggies
4	Rock Crawlers
5	five
6	six
7	seven
8	eight
9	nine
10	ten

Project: Variable Drive Vehicle
System: All-Terrain Subsystem
Date: 8-Nov-16

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Speed		0	0	0.5	0	0	1						1.5	1
2	Slope	1		0.5	1	0.5	0.5	1						4.5	2
3	Obstacle Clearance	1	0.5		1	0.5	0.5	1						4.5	1.5
4	Weight	0.5	0	0		0	0	0.5						1	2
5	Terrain Capabilities	1	0.5	0.5	1		0.5	1						4.5	1.5
6	Mechanical Complexity	1	0.5	0.5	1	0.5		1						4.5	2
7	Power Consumption	0	0	0	0.5	0	0							0.5	1
8		1	1	1	1	1	1	1						7	
9		1	1	1	1	1	1	1	1					8	
10		1	1	1	1	1	1	1	1	1				9	
11		1	1	1	1	1	1	1	1	1	1			10	
12		1	1	1	1	1	1	1	1	1	1	1		11	

Fill in Purple squares above

Fill in upper triangle of the matrix
Working across each row, determine if the criterion in that row is more important (1), same importance (0.5) or less important (0) than the criterion in that column

Assign weighting factors for each criterion in the Yellow squares

Design Project = Variable Drive Vehicle **System=** All-Terrain Subsystem **Date=** 8-Nov-16

	TARGET or	DESIGN IDEAS																			
CRITERIA	**FACTOR**	**1 = Baseline**		**Modular (dedicated)**		**Full length (shared**		**Modular (shared)**		**Rocker Bogie**		**six**		**seven**		**eight**		**nine**		**ten**	
Time – Design	30	30		30		30		30		40											
Time – Build	30	30		40		30		40		40											
Time – Test	30	30		30		30		30		30											
Time Score	10		10		11.11		10.00		11.11		12.22		0.00		0.00		0.00		0.00		0.00
Cost – Prototype	500	$ 500.00		$ 500.00		$ 500.00		$ 500.00		$ 500.00											
Cost – Production	1	$ 1.00		$ 1.00		$ 1.00		$ 1.00		$ 1.00											
Cost Score	10		10		10.00		10.00		10.00		10.00		0.00		0.00		0.00		0.00		0.00
Speed	1	3	3	4	4	3	3	4	4	4	4		0		0		0		0		0
Slope	2	3	6	3	6	3	6	3	6	2	4		0		0		0		0		0
Obstacle Clearance	1.5	3	4.5	4	6	3	4.5	4	6	4	6		0		0		0		0		0
Weight	2	3	6	4	8	4	8	5	10	4	8		0		0		0		0		0
Terrain Capabilities	1.5	3	4.5	3	4.5	3	4.5	3	4.5	1	1.5		0		0		0		0		0
Mechanical Complexity	2	3	6	2	4	3	6	2	4	1	2		0		0		0		0		0
Power Consumption	1	3	3	3	3	4	4	5	5	3	3		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
	TOTAL		33.0		34.4		36.0		38.4		26.3		20.0		20.0		20.0		20.0		20.0
	RANK																				
	% MAX		86.0%		89.6%		93.8%		100.0%		68.5%		52.1%		52.1%		52.1%		52.1%		52.1%
	MAX	38.4																			

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Full length track treads with dedicated drive motor

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(B) + TT(i)/TT(B))/3
Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(i)/Cprot(B))/2
Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescore(B)-Timescore(i)) + (Costscore(B) - Costscore(i))

Comparison(i,j) = 5 if idea "i" is much better than baseline for criteria "j"
Comparison(i,j) = 4 if idea "i" is better than baseline for criteria "j"
Comparison(i,j) = 3 if idea "i" is same as baseline for criteria "j"
Comparison(i,j) = 2 if idea "i" is worse than baseline for criteria "j"
Comparison(i,j) = 1 if idea "i" is much worse than baseline for criteria "j"

Design Idea Descriptions

2	Modular (dedicated)
3	Full length (shared drive motor)
4	Modular (shared)
5	Rocker Bogie
6	six
7	seven
8	eight
9	nine
10	ten

Project: Variable Drive Vehicle
System: Switching System
Date: 8-Nov-16

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Ease of use		0	0.5	0	1								1.5	1
2	Switch Time	1		0.5	1	1								3.5	2
3	Pinch Points	0.5	0.5		0	1								2	1.5
4	Mechanism Complexity	1	0	1		0.5								2.5	2
5	Weight	0	0	0	0.5									0.5	1
6		1	1	1	1	1								5	
7		1	1	1	1	1	1							6	
8		1	1	1	1	1	1	1						7	
9		1	1	1	1	1	1	1	1					8	
10		1	1	1	1	1	1	1	1	1				9	
11		1	1	1	1	1	1	1	1	1	1			10	
12		1	1	1	1	1	1	1	1	1	1	1		11	

Fill in Purple squares above

Fill in upper triangle of the matrix

Working across each row, determine if the criterion in that row is more important (1), same importance (0.5) or less important (0) than the criterion in that column

Assign weighting factors for each criterion in the Yellow squares

Design Project = Variable Drive Vehicle **System=** Switching System **Date=** 8-Nov-16

CRITERIA	TARGET or FACTOR	DESIGN IDEAS: 1 = Baseline		Actuated platform (two		Onboard Installation		Combined drive system		five		six		seven		eight		nine		ten	
Time – Design	30	30		30		40		50													
Time – Build	30	30		25		40		40													
Time – Test	20	20		20		20		20													
Time Score	10		10		9.44		12.22		13.33		0.00		0.00		0.00		0.00		0.00		0.00
Cost – Prototype	1000	$ 1,000.00		$ 1,700.00		$ 1,200.00		$ 1,500.00													
Cost – Production	1	$ 1.00		$ 1.00		$ 1.00		$ 1.00													
Cost Score	10		10		13.50		11.00		12.50		0.00		0.00		0.00		0.00		0.00		0.00
Ease of use	1	3	3	5	5	5	5	4	5		0		0		0		0		0		0
Switch Time	2	3	6	4	8	5	10	4	6		0		0		0		0		0		0
Pinch Points	1.5	3	4.5	3	4.5	3	4.5	2	3.5		0		0		0		0		0		0
Mechanism Complexity	2	3	6	5	10	4	8	2	4		0		0		0		0		0		0
Weight	1	3	3	1	1	3	3	2	3		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
	TOTAL		22.5		25.6		27.3		15.7		20.0		20.0		20.0		20.0		20.0		20.0
	RANK		3.0		2.0		1.0		4.0												
	% MAX		82.5%		93.7%		100.0%		57.4%		73.3%		73.3%		73.3%		73.3%		73.3%		73.3%
	MAX	27.3																			

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Manual Installation

Design Idea Descriptions

2 Actuated platform (two vertical actuators)
3 Onboard Installation and Stowage
4 Combined drive system rotation (Yi Li)
5 five
6 six
7 seven
8 eight
9 nine
10 ten

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(B) + TT(i)/TT(B))/3
Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(i)/Cprot(B))/2
Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescore(B)-Timescore(i)) + (Costscore(B) - Costscore(i))

Comparison(i,j) = 5 if idea "i" is much better than baseline for criteria "j"
Comparison(i,j) = 4 if idea "i" is better than baseline for criteria "j"
Comparison(i,j) = 3 if idea "i" is same as baseline for criteria "j"
Comparison(i,j) = 2 if idea "i" is worse than baseline for criteria "j"
Comparison(i,j) = 1 if idea "i" is much worse than baseline for criteria "j"

Project: Variable Drive Vehicle
System: Controller Subsystem
Date: 8-Nov-16

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Integration		0.5	1										1.5	3
2	Remote	0.5		1										1.5	3
3	Ease of use	0	0											0	1
4		1	1	1										3	
5		1	1	1	1									4	
6		1	1	1	1	1								5	
7		1	1	1	1	1	1							6	
8		1	1	1	1	1	1	1						7	
9		1	1	1	1	1	1	1	1					8	
10		1	1	1	1	1	1	1	1	1				9	
11		1	1	1	1	1	1	1	1	1	1			10	
12		1	1	1	1	1	1	1	1	1	1	1		11	

Fill in Purple squares above

Fill in upper triangle of the matrix
Working across each row, determine if the criterion in that row is more important (1), same importance (0.5) or less important (0) than the criterion in that column

Assign weighting factors for each criterion in the Yellow squares

Design Project = Variable Drive Vehicle **System=** Controller System **Date=** 8-Nov-16

CRITERIA	TARGET or FACTOR	1 = Baseline		Remote Driving and		Remote operated		Onboard push button		five		six		seven		eight		nine		ten	
		DESIGN IDEAS																			
Time – Design	50	50		70		50		30													
Time – Build	10	10		20		20		10													
Time – Test	30	30		50		20		5													
Time Score	10		10		16.89		12.22		5.89		0.00		0.00		0.00		0.00		0.00		0.00
Cost – Prototype	40	$ 40.00		$ 100.00		$ 60.00		$ 40.00													
Cost – Production	1	$ 1.00		$ 1.00		$ 1.00		$ 1.00													
Cost Score	10		10		17.50		12.50		10.00		0.00		0.00		0.00		0.00		0.00		0.00
Integration	3	3	9	5	15	4	12	3	9		0		0		0		0		0		0
Remote	3	3	9	5	15	4	12	3	9		0		0		0		0		0		0
Ease of use	1	3	3	5	5	3	3	2	2		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
	TOTAL		21.0		20.6		22.3		24.1		20.0		20.0		20.0		20.0		20.0		20.0
	RANK																				
	% MAX		87.1%		85.5%		92.4%		100.0%		82.9%		82.9%		82.9%		82.9%		82.9%		82.9%
	MAX	24.1																			

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Onboard Automated Switching and Remote driving

Design Idea Descriptions

2 Remote Driving and automated Switching
3 Remote operated manual switching and driving
4 Onboard push button manual switch/ remote driving
5 five
6 six
7 seven
8 eight
9 nine
10 ten

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(B) + TT(i)/TT(B))/3
Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(i)/Cprod(B))/2
Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescore(B)-Timescore(i)) + (Costscore(B) - Costscore(i))

Comparison(i,j) = 5 if idea "i" is much better than baseline for criteria "j"
Comparison(i,j) = 4 if idea "i" is better than baseline for criteria "j"
Comparison(i,j) = 3 if idea "i" is same as baseline for criteria "j"
Comparison(i,j) = 2 if idea "i" is worse than baseline for criteria "j"
Comparison(i,j) = 1 if idea "i" is much worse than baseline for criteria "j"

Project: Variable Drive Vehicle
System: Electronics Subsystem
Date: 8-Nov-16

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Size		0	0.5										0.5	1
2	Functionality	1		1										2	2
3	complexity	0.5	0											0.5	2
4		1	1	1										3	
5		1	1	1	1									4	
6		1	1	1	1	1								5	
7		1	1	1	1	1	1							6	
8		1	1	1	1	1	1	1						7	
9		1	1	1	1	1	1	1	1					8	
10		1	1	1	1	1	1	1	1	1				9	
11		1	1	1	1	1	1	1	1	1	1			10	
12		1	1	1	1	1	1	1	1	1	1	1		11	

Fill in Purple squares above

Fill in upper triangle of the matrix

Working across each row, determine if the criterion in that row is more important (1), same importance (0.5) or less important (0) than the criterion in that column

Assign weighting factors for each criterion in the Yellow squares

Design Project = Variable Drive Vehicle **System=** Electronics System **Date=** 8-Nov-16

CRITERIA	TARGET or FACTOR	1 = Baseline		Separate from existing		three		four		five		six		seven		eight		nine		ten	
						DESIGN IDEAS															
Time – Design	50	50		30																	
Time – Build	10	10		10																	
Time – Test	30	30		10																	
Time Score	10		10		6.44		0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00
Cost – Prototype	40	$ 40.00		$ 40.00																	
Cost – Production	1	$ 1.00		$ 1.00																	
Cost Score	10		10		10.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00
Size	1	3	3	1	1		0		0		0		0		0		0		0		0
Functionality	2	3	6	3	6		0		0		0		0		0		0		0		0
complexity	2	3	6	5	10		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
0	0	3	0		0		0		0		0		0		0		0		0		0
	TOTAL		15.0		20.6		20.0		20.0		20.0		20.0		20.0		20.0		20.0		20.0
	RANK																				
	% MAX		73.0%		100.0%		97.3%		97.3%		97.3%		97.3%		97.3%		97.3%		97.3%		97.3%
	MAX	20.6																			

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Integrated with existing motor(s)

Design Idea Descriptions

2 Separate from existing motor(s)
3 three
4 four
5 five
6 six
7 seven
8 eight
9 nine
10 ten

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(B) + TT(i)/TT(B))/3
Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(i)/Cprot(B))/2
Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescore(B)-Timescore(i)) + (Costscore(B) - Costscore(i))

Comparison(i,j) = 5 if idea "i" is much better than baseline for criteria "j"
Comparison(i,j) = 4 if idea "i" is better than baseline for criteria "j"
Comparison(i,j) = 3 if idea "i" is same as baseline for criteria "j"
Comparison(i,j) = 2 if idea "i" is worse than baseline for criteria "j"
Comparison(i,j) = 1 if idea "i" is much worse than baseline for criteria "j"

F Timeline and Budget

F.1 Project Timeline

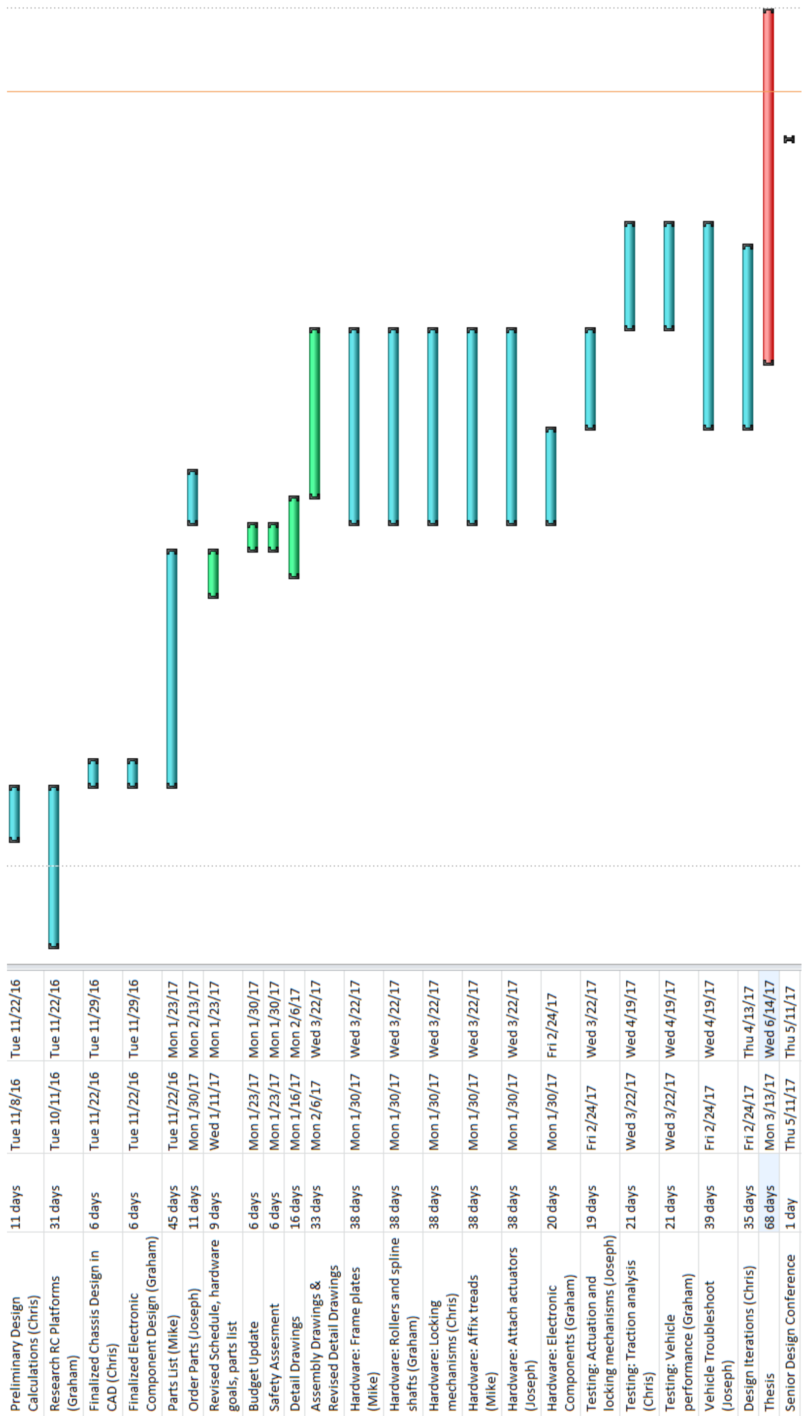


Figure F.1: Gantt chart of project timeline.

F.2 Bill of Materials with Cost Analysis

Track Unit, Rotation Lock, And Contact Lock Components	Quantity	Material	Manufacture	Cost Per Unit	Cost
Outer Track Plate Non-Servo Side	1	Acrylic	Laser Cut	$2.33	$2.33
Outer Track Plate Servo Side	1	Acrylic	Laser Cut	$2.33	$2.33
Inner Track Plate Non-Servo Side	1	Acrylic	Laser Cut	$2.33	$2.33
Inner Track Plate Servo Side	2	Acrylic	Laser Cut	$2.33	$4.66
HS 645 MG Servo	1	N/A	Purchased	$32.37	$32.37
Aluminum Servo Arm	1	Aluminum	Purchased	$3.40	$3.40
Splined Rollers	2	6061-Aluminum	Machined	$25.45	$50.90
Large Hole Rollers	7	6061-Aluminum	Machined	$0.73	$5.11
Small Hole Roller	1	6061-Aluminum	Machined	$0.73	$0.73
Small Axle	2	6061-Aluminum	Machined	$0.66	$1.32
Large Axle	7	6061-Aluminum	Machined	$1.01	$7.07
Track Plate Shaft Collar ID 0.625”	1	6061-Aluminum	Machined	$1.60	$1.60
Track Plate Shaft Collar ID 1.375”	1	6061-Aluminum	Machined	$1.60	$1.60
Mechanism Shaft	2	6061-Aluminum	Machined	$0.26	$0.52
Shaft Receiver Inset	2	6061-Aluminum	Machined	$1.12	$2.24
Brake Arm	1	6061-Aluminum	Machined	$0.90	$0.90
Brake Bracket	1	6061-Aluminum	Machined	$0.30	$0.30
Axle Extension	1	6061-Aluminum	Machined	$0.34	$0.34
Brake Pad	1	ABS-Plastic	3D Printed	$0.00	$0.00
Bearing ID 15mm OD 32mm	1	N/A	Purchased	$9.06	$9.06
Bearing ID 0.25” OD 0.625”	1	N/A	Purchased	$6.56	$6.56
Timing Belt	1	Polyurethane	Purchased	$33.97	$33.97
Slotted Spring Pin	2	Stainless Steel	Purchased	$0.08	$0.16
M2 Screws 6mm	2	Alloy Steel	Purchased	$0.41	$0.82
M2 Screws 16mm	3	Alloy Steel	Purchased	$0.39	$1.17
M3 Screw 12mm	2	Alloy Steel	Purchased	$0.20	$0.40
M4 Screws 10mm	10	Alloy Steel	Purchased	$0.09	$0.90
M4 Screws 16mm	14	Alloy Steel	Purchased	$0.09	$1.26
M4 Screws 35mm	2	Alloy Steel	Purchased	$0.71	$1.42
Actuonix L12-R Linear Actuators	2	N/A	Purchased	$70	$140
					$315.77

Stowage Lock Components	Quantity	Material	Manufacture	Cost Per Unit	Cost
Stowage Lock Cross Bar	1	6061-Aluminum	Machined	$2.57	$2.57
HS 425 BB Servo	1	N/A	Purchased	$14.98	$14.98
Aluminum Servo Arm	1	Aluminum	Purchased	$3.40	$3.40
M2 Screws 16mm	3	Alloy Steel	Purchased	$0.39	$1.17
M3 Screw 12mm	1	Alloy Steel	Purchased	$0.20	$0.20
M4 Screws 10mm	6	Alloy Steel	Purchased	$0.09	$0.54
3.5x.25 square extruded bar	1	6061-Aluminum	Machined	$0.30	$0.30
Stowage Lock Servo Mount	2	6061-Aluminum	Machined	$0.22	$0.44
Stowage Lock Backstop	1	6061-Aluminum	Machined	$0.19	$0.19
Mounting Frame	1	6061-Aluminum	Machined	$0.66	$0.66
Stowage Lock Arm	1	6061-Aluminum	Machined	$0.09	$0.09
Strut Tower Brace	2	6061-Aluminum	Machined	$0.46	$0.92
					$25.46

Vehicle Chassis	Quantity	Material	Manufacture	Cost Per Unit	Cost
Axial Wraith 1/10th Scale Radio Controlled Car (And Controller)	1	N/A	Purchased	$399.99	$399.99
Venom 7.4V 4100 mAh Lithium Polymer Battery	1	N/A	Purchased	$49.99	$49.99
AA Batteries	2	N/A	Purchased	$0.45	$0.90
					$450.88

Electronic Components	Quantity	Material	Manufacture	Cost Per Unit	Cost
Arduino Starter Kit (Arduino Uno, Assorted Wires, Capacitors, Switch)	1	N/A	Purchased	$63.83	$63.83
9V Battery	1	N/A	Purchased	$3.48	$3.48
AA Batteries	10	N/A	Purchased	$0.45	$4.50
Battery Holders	2	N/A	Purchased	$8.95	$17.90
Electronics Housing	1	ABS-Plastic	3D Printed	$4.33	$4.33
					$94.04

Total Vehicle Analysis	Individual Cost	Quantity	Total
Track Unit, Rotation Lock, and Contact Lock	$315.77	2	$631.54
Stowage Lock	$25.46	1	$25.46
Vehicle Chassis	$450.88	1	$450.88
Electronic Components	$94.04	1	$94.04
			$1,201.92

F.3 Total Project Spending and Final Budget Summary

Item Description	Vendor	Amount
4in x 2ft ABS Pipe	Home Depot	$10.95
3/4 x 48 in Dowel	Home Depot	$2.54
.75x.75x48 in Wood	Home Depot	$10.16
3/4x2ft PVC pipe	Home Depot	$2.86
1/4 Hex Bolts	Home Depot	$0.85
1/4 Hex Nuts	Home Depot	$0.30
Sales Tax	Home Depot	$2.52
CA Lumber Fee	Home Depot	$0.10
Foam Board	Office Max	$12.29
Sales Tax	Office Max	$1.12
AA Battery holders	Amazon	$17.90
9V Batteries	Amazon	$6.95
AA Batteries	Amazon	$9.65
Arduino Starter Kit	Amazon	$63.83
HS645 MG Servos	Amazon	$64.74
Sales Tax	Amazon	$5.50
Aluminum Pulley Bar Stock	Polytech	$42.34
Shipping	Polytech	$8.55
Acrylic Sheet	Estreetplastics	$69.99
Shipping	Estreetplastics	$33.62
1/4 in Aluminum Rod	McMaster Carr	$15.18
3/8 in Aluminum Rod	McMaster Carr	$23.28
5/8 in Aluminum Rod	McMaster Carr	$26.09
3/4x1.5x2ft Aluminum Bar	McMaster Carr	$19.17
1/4 Ball Bearings	McMaster Carr	$13.12
5/8 Ball Bearings	McMaster Carr	$18.12
5/8x2.5x2ft Aluminum Bar	McMaster Carr	$22.09
1/16 Spring Pins	McMaster Carr	$7.58
M4 Tap	McMaster Carr	$15.40
M4 16mm Screws	McMaster Carr	$9.63
M4 10mm Screws	McMaster Carr	$9.47
Sales Tax	McMaster Carr	$15.23
Shipping	McMaster Carr	$13.07
Timing Belt	Polytech	$66.96
Shipping	Polytech	$15.00
HS645MG Servo	Amazon	$30.14
Sales Tax	Amazon	$2.22
M2 6mm screws	McMaster Carr	$10.25
M2 16mm screws	McMaster Carr	$9.76
M2 Tap	McMaster Carr	$15.76
15mm Bearings	McMaster Carr	$16.48
Compression Springs	McMaster Carr	$6.52
Graphite Lubricant	McMaster Carr	$6.34
Sales Tax	McMaster Carr	$5.86
Shipping	McMaster Carr	$6.09
M2 Taps	Advanced Tool and Supply	$25.80
Sales Tax	Advanced Tool and Supply	$2.32
Linear Actuators	Actuonix	$140.00
Shipping	Actuonix	$25.96
Servo Extension Wires	Amazon	$7.99
HS425BB Servo	Amazon	$14.98
Aluminum Servo Horns	Amazon	$16.99
Sales Tax	Amazon	$1.35
Linear Actuators	Actuonix	$140.00
Shipping	Actuonix	$26.21
Plastic Epoxy	Home Depot	$5.47
Electrical Tape	Home Depot	$1.97
Sales Tax	Home Depot	$0.67
Axial Wraith Model RC Truck	Sheldon's Hobbies	$399.99
7.4 V Lipo Battery	Sheldon's Hobbies	$49.99
Battery Charger	Sheldon's Hobbies	$25.99
Charger Adapter	Sheldon's Hobbies	$7.99
Sales Tax	Sheldon's Hobbies	$43.56
36x48 Board	Bronco Corner Bookstore	$9.98
Sales Tax	Bronco Corner Bookstore	$0.85
M3 12mm screws	Fastenal	$3.00
County Tax	Fastenal	$0.09
State Tax	Fastenal	$0.18
Total Project Spending		**$1,716.90**

Budget Quantity	Amount
Total Budget	$2,000.00
Spending	$1,716.90
Surplus	$283.10

G Design Sketches

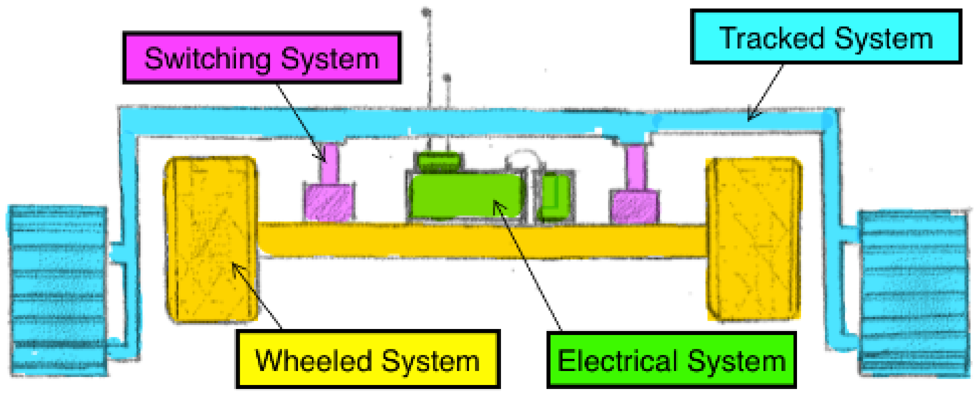


Figure G.2: Initial design with subsystems labeled (by Christopher Clark).

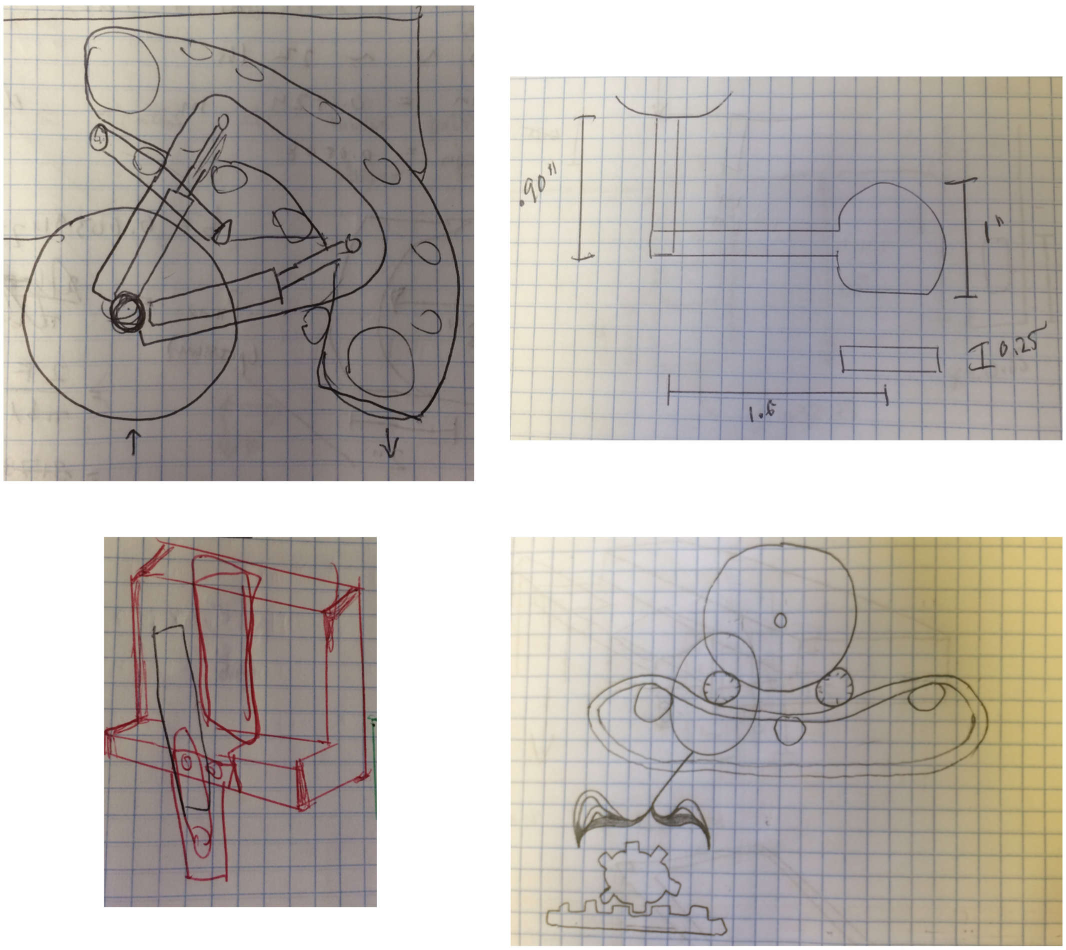


Figure G.3: Design sketches for modular tracks and switch systems (by Michael D'Arrigo).

H Information from Manufacturers

ANNOUNCED SPECIFICATION OF HS-645MG STANDARD DELUXE HIGH TORQUE SERVO

1.TECHNICAL VALUES

CONTROL SYSTEM	:+PULSE WIDTH CONTROL 1500usec NEUTRAL	
OPERATING VOLTAGE RANGE	:4.8V TO 6.0V	
OPERATING TEMPERATURE RANGE	:-20 TO +60° C	
TEST VOLTAGE	:AT 4.8V	:AT 6.0V
OPERATING SPEED	:0.24sec/60° AT NO LOAD	:0.2sec/60° AT NO LOAD
STALL TORQUE	:7.7kg.cm(106.93oz.in)	:9.6kg.cm(133.31oz.in)
OPERATING ANGLE	:45°/ONE SIDE PULSE TRAVELING 400usec	
DIRECTION	:CLOCK WISE/PULSE TRAVELING 1500 TO 1900usec	
IDLE CURRENT	:8.8mA	:9.1mA
RUNNING CURRENT	:350mA	:450mA
DEAD BAND WIDTH	:8usec	
CONNECTOR WIRE LENGTH	:300mm(11.81in)	
DIMENSIONS	:40.6x19.8x37.8mm(1.59x0.77x1.48in)	
WEIGHT	:55.2g(1.94oz)	

Figure H.4: Rotation clamp high torque servo motor specifications [31].

HS-425BB Servo Specifications

Performance Specifications	
Operating Voltage Range (Volts DC)	4.8V ~ 6.0V
Speed (Second @ 60°)	0.21 ~ 0.16
Maximum Torque Range oz. / in.	46 ~ 57
Maximum Torque Range kg. / cm.	3.3 ~ 4.1
Current Draw at Idle	8 mA
No Load Operating Current Draw	150 mA
Stall Current Draw	800 mA
Dead Band Width	8 µs
Physical Specifications	
Dimensions (Inches)	1.59 x 0.77 x 1.44
Dimensions (Metric)	40.6 x 19.8 x 36.6
Weight (Ounces)	1.60
Weight (Gram)	45.5
Circuit Type	HT7003 Analog SMT
Motor Type	3 Pole Metal Brush Ferrite
Gear Material	Nylon
Bearing Type	Dual Ball Bearing
Output Shaft (type / Ømm)	Standard 24
Case Material	Plastic
Dust / Water Resistance	N / A
Connector Gauge (AWG) / Strand Count	25 / 40

Figure H.5: Stowage lock servo motor specifications [32].

L12 Specifications

Gearing Option	50:1	100:1	210:1	
Peak Power Point	17N @ 14mm/s	31N @ 7mm/s	62N @ 3.2mm/s	
Peak Efficiency Point	10N @ 19mm/s	17N @ 10mm/s	36N @ 4.5mm/s	
Max Speed *(no load)*	25mm/s	13mm/s	6.5mm/s	
Max Force *(lifted)*	22N	42N	80N	
Back Drive Force *(static)*	12N	22N	45N	
Stroke Option	**10 mm**	**30mm**	**50mm**	**100mm**
Mass	28 g	34 g	40 g	56 g
Repeatability *(-I,-R,-P&LAC)*	±0.1 mm	±0.2 mm	±0.3 mm	±0.5 mm
Max Side Load *(extended)*	50N	40N	30N	15N
Closed Length *(hole to hole)*	62mm	82mm	102mm	152mm
Potentiometer *(-I, -R, -P)*	1kΩ±50%	3kΩ±50%	6kΩ±50%	11kΩ±50%
Voltage Option		**6VDC**		**12VDC**
Max Input Voltage		7.5V		13.5V
Stall Current		460mA		185mA
Standby Current *(-I/-R)*		7.2mA		3.3mA
Operating Temperature	-10°C to +50°C			
Potentiometer Linearity	Less than 2.00%			
Max Duty Cycle	20 %			
Audible Noise	55dB @ 45cm			
Ingress Protection	IP-54			
Mechanical Backlash	0.2mm			
Limit Switches *(-S)*	Max. Current Leakage: 8uA			
Maximum Static Force	200N			

Figure H.6: Actuonix L12-R specifications [33].

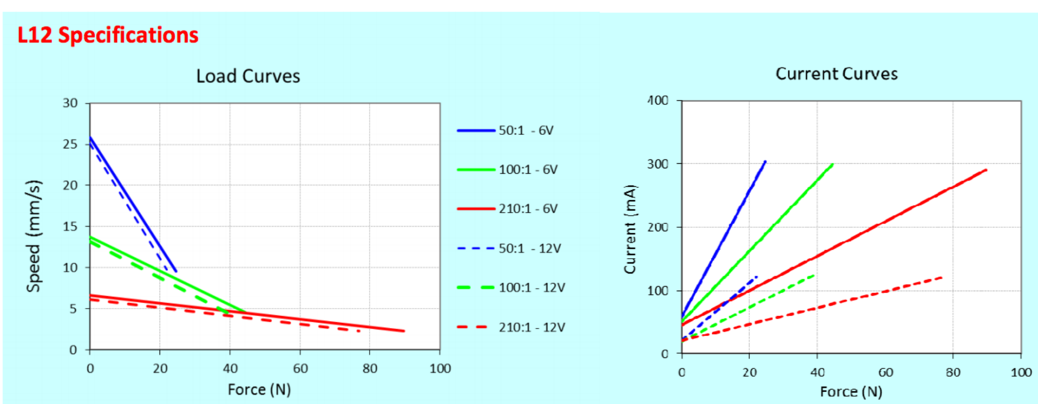


Figure H.7: Actuonix L12-R current draw [33].

Summary of tests, see discharge curves below										
Size	Brand	Code in Charts	Date of Test	Sell By Date	Termination voltage used in test	Amp-Hours at 100 mA Discharge rate	Amp-hours at 500 mA Discharge Rate	Amp-hours at 1 Amp Discharge Rate	Amp-hours at 2 Amps Discharge Rate	Amp-Hours at 5 Amps Discharge Rate
AA Alkaline	Radio Shack Enercell Plus	RS	April 2006	2010	0.1 Volt	2.13 AH	1.31 AH	0.98 AH	0.72 AH	
AA Alkaline	Duracell Coppertop	DC	April 2006	2012	0.1 Volt	2.20 AH	1.30 AH	0.83 AH	0.54 AH	
AA Alkaline	Energizer Titanium	ET	May 2006	2012	0.1 Volt		1.84 AH	1.41 AH	1.18 AH	
AA Alkaline	Energizer Max	EM	May 2006	2012	0.1 Volt		1.17 AH	0.93 AH	0.70 AH	
AA Alkaline	Eveready Gold	EG	May 2006	2012	0.1 Volt		1.28 AH	0.95 AH	0.78 AH	
AA Lithium Metal	Energizer Lithium	E2	May 2006	2013	0.1 Volt				2.8 AH	
AA NiMH	PowerStream 2000 mAH Rechargeable		April 2006		0.1 Volt	2.04 AH (200 mA)			1.94 AH	2.11 AH (see curve)

Figure H.8: AA battery current supply testing data [34].

AX90018

Axial Wraith 1/10th Scale Electric 4WD - RTR

OVERVIEW | TECH SPECS | COMPATIBILITY | OPTION PARTS | PARTS | GALLERY | TECH TIPS | INSTRUCTIONS

Wheelbase:	353mm (13.9")
Ground Clearance:	80mm (3.15")
Height:	237mm (9.3")
Width:	280mm (11.02")
Weight:	2.48kg (5.44 lbs")
Length	482.6mm (19")

Figure H.9: Axial wraith vehicle specifications [35].

I Arduino Code

```
//add servo library
#include <Servo.h>

//name and initialize components
Servo leftServo;
Servo rightServo;
Servo leftLinAct;
Servo rightLinAct;
Servo rotationLock;

//variables
//brake servo control switch and specified positions (input in degrees)
int leftangleon=105; //left brake on position
int leftangleoff=80; //left brake off position
int rightangleon=40; //right brake on position
int rightangleoff=60; //right brake off position
int brakestate=0; //left brake button
int prevbrakestate=0; //temporary state variable to detect change
int i=0; //left brake hold on or off variable

//contact lock control switch and specified positions (input in microseconds)
int positionon=1050; // contact lock on position
int positionoff=1400; // contact lock off position
int contactstate=0; // contact button
int prevcontactstate=0; //temporary state variable to detect change
int j=0; // contact lock hold on or off variable

//rotation lock control switch and specified positions (input in degrees)
int angleon=90; //right brake on position
int angleoff=170; //right brake off position
int rotationstate=0; //left brake button
int prevrotationstate=0; //temporary state variable to detect change
int k=0; //left brake hold on or off variable

void setup() {
  //brake servos
  leftServo.attach(11); //default limits
  rightServo.attach(10); //default limits
  pinMode(7,INPUT); // brake switch

  //linear actuators
  leftLinAct.attach(6,1000,2000); //specified limits of motion
  rightLinAct.attach(5,1000,2000); //specified limits of motion
  pinMode(4,INPUT); //lin act switch

  //rotation lock
  rotationLock.attach(9); //default limits
  pinMode(3,INPUT); //rotation lock switch
}
```

Figure I.10: Arduino code for actuation of the VDV (1/2).

```
void loop() {
  //both brakes at once
  brakestate=digitalRead(7); //check button
  //check for button change from low to high
  if (brakestate!=prevbrakestate && prevbrakestate==LOW){
    switch (i){
      case 0:{ //if off
        i=1; //turn on
      break;}
      case 1:{ //if on
        i=0; //turn off
      break;}
    }
  }
  if (i==1){
    leftServo.write(leftangleon);
    rightServo.write(rightangleon);
  }
  if (i==0){
    leftServo.write(leftangleoff);
    rightServo.write(rightangleoff);
  }
  prevbrakestate=brakestate; //old state to recognize change

  //both contact locks at one time
  contactstate=digitalRead(4); //check button
  //check for button change from low to high
  if (contactstate!=prevcontactstate && prevcontactstate==LOW){
    switch (j){
      case 0:{ //if off
        j=1; //turn on
      break;}
      case 1:{ //if on
        j=0; //turn off
      break;}
    }
  }
  if (j==1){
    leftLinAct.writeMicroseconds(positionon);
    rightLinAct.writeMicroseconds(positionon);
  }
  if (j==0){
    leftLinAct.writeMicroseconds(positionoff);
    rightLinAct.writeMicroseconds(positionoff);
  }
  prevcontactstate=contactstate;

  //rotation lock
  rotationstate=digitalRead(3); //check button
  //check for button change from low to high
  if (rotationstate!=prevrotationstate && prevrotationstate==LOW){
    switch (k){
      case 0:{ //if off
        k=1; //turn on
      break;}
      case 1:{ //if on
        k=0; //turn off
      break;}
    }
  }
  if (k==1){
    rotationLock.write(angleon);
  }
  if (k==0){
    rotationLock.write(angleoff);
  }
  prevrotationstate=rotationstate;

  delay(20); //functional waiting
}
```

Figure I.11: Arduino code for actuation of the VDV (2/2).

J Patents Referenced

US 20040216932A1

(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2004/0216932 A1**
Giovanetti et al. (43) **Pub. Date: Nov. 4, 2004**

(54) **HYBRID WHEEL AND TRACK VEHICLE DRIVE SYSTEM**

(75) Inventors: **Anthony J. Giovanetti**, San Jose, CA (US); **Lorin C. Dueck**, San Jose, CA (US); **Raymond L. Hickman**, Gilroy, CA (US)

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Minneapolis, MN 55402-2100 (US)

(73) Assignee: **United Defense, LP**, Arlington, VA

(21) Appl. No.: **10/851,346**

(22) Filed: **May 21, 2004**

Related U.S. Application Data

(63) Continuation of application No. 10/192,573, filed on Jul. 9, 2002.

(60) Provisional application No. 60/304,213, filed on Jul. 9, 2001.

Publication Classification

(51) **Int. Cl.**[7] **B62D 55/06**
(52) **U.S. Cl.** **180/9.1**

(57) **ABSTRACT**

A vehicle drive system includes a hybrid wheel and track system, having a drive wheel operably coupled to a motive source, the motive source for imparting rotational motion to the drive wheel, the drive wheel having an axis of rotation, an idler wheel displaced from the drive wheel and rotationally coupled to the drive wheel by a continuous track; and a cantilever beam supporting the idler wheel and being rotatable as desired about the drive wheel axis of rotation. A device and method for controlling a suspension are further included.

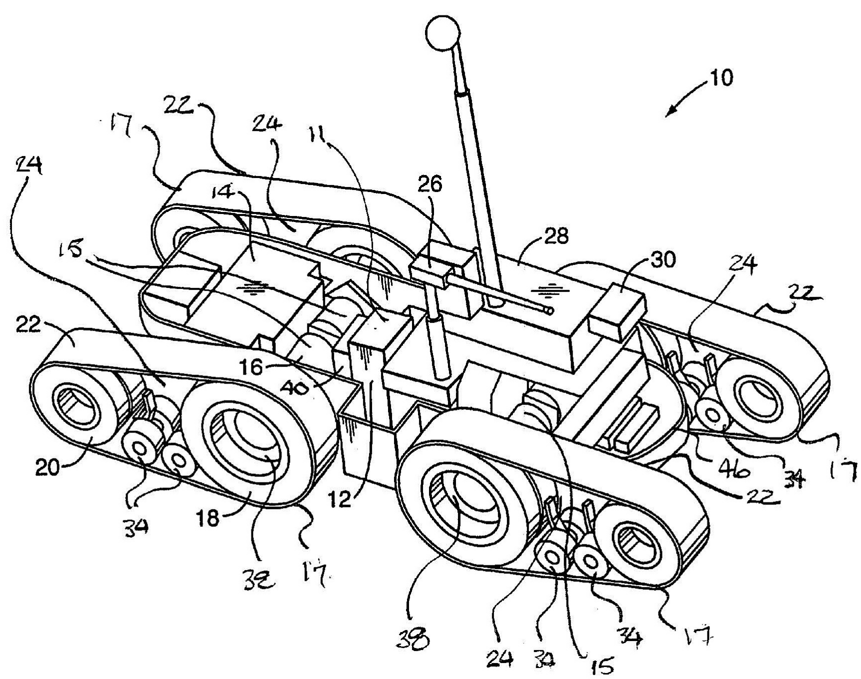

Figure J.12: Hybrid Wheel and Track Vehicle Drive System Patent

United States Patent [19]

Crane, III et al.

[11] **Patent Number: 4,977,971**

[45] **Date of Patent: Dec. 18, 1990**

[54] **HYBRID ROBOTIC VEHICLE**

[75] Inventors: **Carl D. Crane, III,** Gainesville, Fla.; **Dana S. Haukoos,** Fountain Valley, Calif.

[73] Assignee: **University of Florida,** Gainesville, Fla.

[21] Appl. No.: **353,027**

[22] Filed: **May 17, 1989**

[51] **Int. Cl.**[5] **B62D 63/02;** B62D 55/075

[52] **U.S. Cl.** **180/8.3;** 180/9.3; 180/9.32; 280/840; 33/356; 901/1; 901/46

[58] **Field of Search** 180/8.1, 8.2, 8.3, 8.4, 180/8.5, 8.6, 9.28, 9.3, 9.32, 9.33, 9.34, 9.35, 9.36; 280/840; 901/1, 46, 50, 27, 28, 29; 33/356, 327

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4,855,822	8/1989	Narendra	901/1

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0191673	11/1983	Japan	180/8.2
0229680	10/1986	Japan	180/8.3
2236695	10/1987	Japan	901/1
0203484	8/1988	Japan	180/8.2

Primary Examiner—Charles A. Marmor
Assistant Examiner—Mitchell Bompey
Attorney, Agent, or Firm—Kerkam, Stowell, Kondracki & Clarke

[57] **ABSTRACT**

A hybrid robotic vehicle is provided for use in environments which are hazardous to humans, the vehicle being adapted to carry a payload for use in viewing the area or acquiring other types of sensory data. The hybrid robotic vehicle has a main body and four appendages or legs, each of which has a wheel assembly and a track assembly, and is configured to operate having three degrees-of-freedom about one vertical and two horizontal axes, the three degrees-of-freedom permitting improved capability to cross obstacle-strewn terrain, as well as to traverse inclined surfaces while maintaining the main body and its payload in an upright and level attitude. The vehicle may operate in any of wheeled, tracked, or legged modes, with actuators controlling each of the three joint angles on each leg, and having separate motors for driving the wheels and the tracks, the control being effected by a human operator through a control panel computer interface, and a computer relaying commands through a cable tether connected to the vehicle.

25 Claims, 9 Drawing Sheets

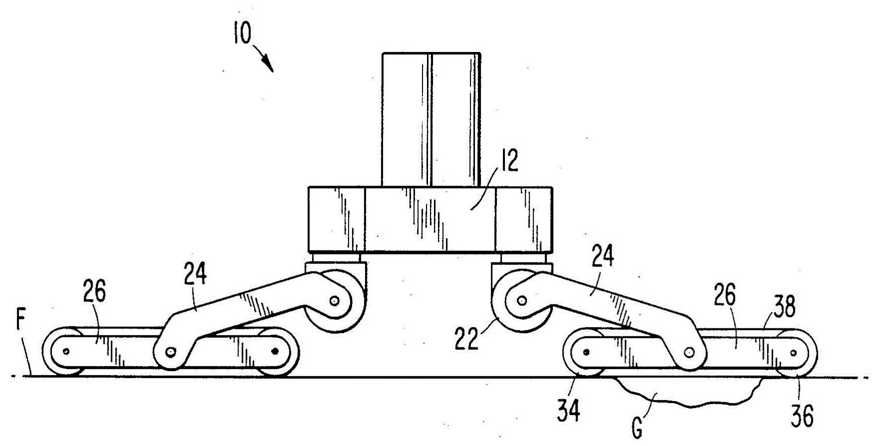

Figure J.13: Hybrid Robotic Vehicle Patent

US 20080277172A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2008/0277172 A1**

Ben-Tzvi et al. (43) **Pub. Date: Nov. 13, 2008**

(54) **HYBRID MOBILE ROBOT**

(76) Inventors: **Pinhas Ben-Tzvi**, Toronto (CA); **Andrew A. Goldenberg**, Toronto (CA); **Jean W. Zu**, Mississauga (CA)

Correspondence Address:
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2111 Eisenhower Ave, Suite 406
Alexandria, VA 22314 (US)

(21) Appl. No.: **11/980,782**

(22) Filed: **Oct. 31, 2007**

Related U.S. Application Data

(60) Provisional application No. 60/924,380, filed on May 11, 2007.

Publication Classification

(51) **Int. Cl.**
B62D 55/00 (2006.01)
G06F 19/00 (2006.01)

(52) **U.S. Cl.** **180/9.1**; 700/245

(57) **ABSTRACT**

A hybrid mobile robot includes a base link and a second link. The base link has a drive system and is adapted to function as a traction device and a turret. The second link is attached to the base link at a first joint. The second link has a drive system and is adapted to function as a traction device and to be deployed for manipulation. In another embodiment an invertible robot includes at least one base link and a second link. In another embodiment a mobile robot includes a chassis and a track drive pulley system including a tension and suspension mechanism. In another embodiment a mobile robot includes a wireless communication system.

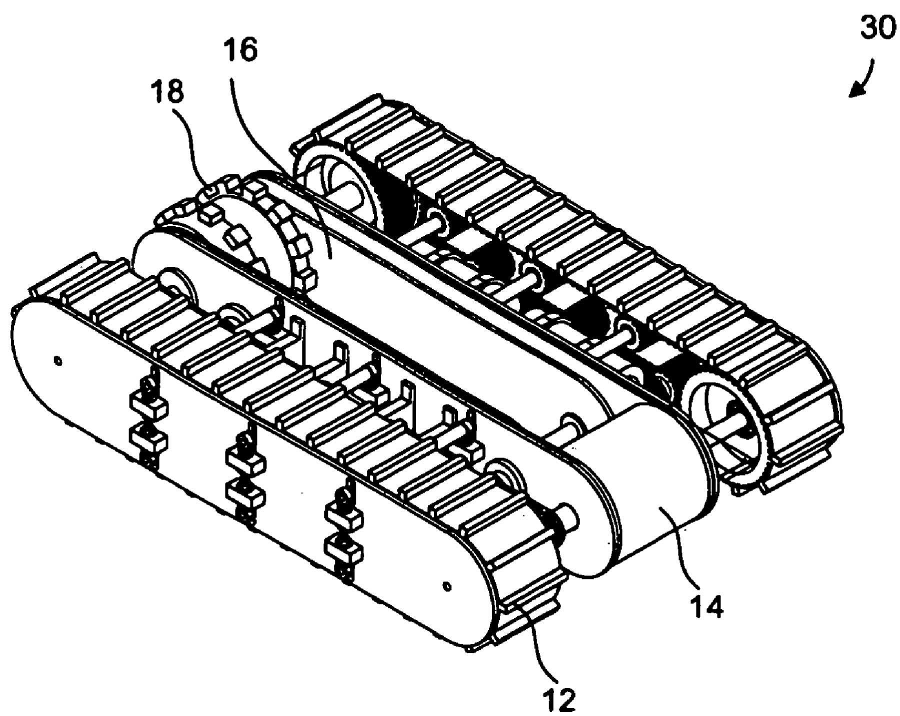

Figure J.14: Hybrid Mobile Robot Patent

United States Patent [19]

White et al.

[11] **Patent Number: 4,932,831**

[45] **Date of Patent: Jun. 12, 1990**

[54] **ALL TERRAIN MOBILE ROBOT**

[75] Inventors: **John R. White,** Oak Ridge; **Kenneth L. Walker,** Clinton; **Joel B. Coughlan,** Oak Ridge; **R. Glen Upton,** Oak Ridge; **Kenneth A. Farnstrom,** Oak Ridge; **Howard W. Harvey,** Oak Ridge, all of Tenn.

[73] Assignee: **Remotec, Inc.,** Oak Ridge, Tenn.

[21] Appl. No.: **248,973**

[22] Filed: **Sep. 26, 1988**

[51] **Int. Cl.⁵** **B66C 9/00**

[52] **U.S. Cl.** **414/732;** 180/2.1; 180/9.32; 901/1

[58] **Field of Search** .... 414/732; 901/1; 180/8.1, 9.32, 9.62, 2.1, 6.5; 242/54 R; 89/41.01, 41.05; 248/278

[56] **References Cited**

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4,817,653	4/1989	Krajicek et al.	901/1 X

FOREIGN PATENT DOCUMENTS

98822	8/1964	Denmark	901/1

Primary Examiner—Frank E. Werner

Assistant Examiner—Donald W. Underwood

Attorney, Agent, or Firm—Pitts and Brittian

[57] **ABSTRACT**

A remotely controlled vehicle for traversing various terrains to accomplish missions in a hostile environment. This remotely controlled vehicle has a main chassis with rotatable tracks on either side thereof that supports a central body of the vehicle. Auxiliary chassis in a forward and rearward direction also carry tracks on either side, with these auxiliary chassis being pivotable to raised or lowered positions to accomplish movement over uneven terrain. The body carriers a deployable arm including a shoulder, an elbow and a wrist, with this arm being provided with five degrees of motion. The drive means throughout the vehicle for the main tracks and for the essential components of the arm are carried out through the use of motor driven planetary gear assemblies to achieve the necessary torque and speed. The body in one embodiment carries a cable drum and provision is made to rotate the drum, to allow it to be free reeling or to lock the same, in order to control the desired feed to or from the drum of a cable carrying signals to and from the vehicle. All of the motions are controlled remotely from a control station. Except for the shoulder and elbow joints, all wiring of the components is internal, and the position of various elements is determined using potentiometers and the like resistive elements.

11 Claims, 14 Drawing Sheets

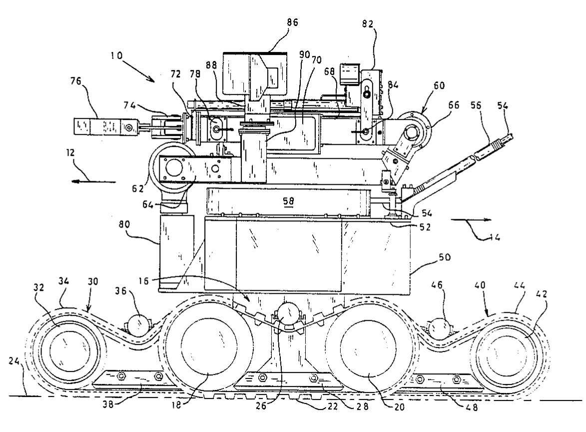

Figure J.15: All Terrain Mobile Robot Patent

K SDC Executive Summary and Presentation Slides

Santa Clara University
School of Engineering

VDV

Variable Drive Vehicle

A multi-drive system for tactical and scientific applications

Senior Design Conference
May 11th, 2017

Graham McClone, Michael D'Arrigo, Joseph Sahyoun, Chris Clark
gmcclone@scu.edu mdarrigo@scu.edu jasahyoun@scu.edu, cmclark@scu.edu

Advised By
Professor Michael Taylor

In the military, soldiers often risk their lives retrieving and tending to wounded soldiers on the battlefield. Unmanned rovers could retrieve wounded soldiers, but are frequently limited by difficult terrain. In these situations, time is of the essence, and a quick retrieval can be the difference between life or death. A wheel based drive system can traverse smooth terrain quickly but can fail to perform in loose or steep terrain. A track based drive system provides more traction but travels much slower, and is less efficient. Most current rovers and exploratory vehicles utilize a single drive system limiting their versatility and overall capability. Our goal is to combine the strengths of a track based drive system and a wheel based drive system into a single integrated system, the Variable Drive Vehicle (VDV).

The VDV employs a actuated system capable of switching between wheeled and tracked drive modes. This allows the vehicle to travel quickly and efficiently over smooth terrain and to traverse more arduous terrain by switching between these two systems. The small scale prototype built over the course of this project is equipped with two modular track units to demonstrate the viability of the system. Electric linear actuators and servo motors allow for simple control and a smooth transition between each drive system. These devices allow the modular tracks to be rotated out from under the wheels, and stowed on the vehicle when not in use. Finite element analysis ensured that the VDV's switching mechanism maintains safe loading at its most critical points during a drive system transition. The VDV was tested on smooth concrete to determine its maximum wheel speed, track speed, and how fast the drive system could be switched. Experiments yielded a top speed of 11.5 mph in the wheel mode, 0.8 mph in the track mode, and a switching time of 6.4 seconds. Future testing will consist of velocity tests on various terrain and other performance characteristics include maximum slope and obstacle clearance. The prototype that has been developed provides a proof of concept for a variable drive system incorporating both wheels and tracks, and is and promising platform for future robotics research.

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VDV

Variable Drive Vehicle

A multi-drive system for tactical and scientific applications

Graham McClone
Michael D'Arrigo
Joseph Sahyoun
Chris Clark

Advised by Dr. Michael James Taylor

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Today's Agenda:

1. Project Overview
2. Objectives
3. Component Design
4. Testing and Results
5. Key Takeaways and Next Steps
6. Q & A

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The Need for Tactical and Scientific Vehicles

- **Disaster Relief Scenarios**
  - Damage Assessment
  - Search and Rescue
- **Military Applications**
  - Weapons systems
  - Supply
  - Casualty Extraction

- **Mobility**
  - Well-designed vehicles are suitable for a wide range of applications

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Problem Statement

The versatility of robotic vehicles is limited by a single drive system.

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Existing Tactical Robotic Vehicles




Description:	SDR Mastiff	Avatar III	AMBOT Wheel	AMBOT Track
Drive System	Tracks	Tracks	Wheels	Tracks
Speed (mph)	1.4	~3	12	6
Weight (lbs)	~130	25	550	500
Cost	~$30,000	~$60,000	~$100,000	~$100,000

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Objectives

- Build a small-scale prototype to determine the viability of integrating two drive systems into an augmented RC vehicle
  - Switch between drive systems based on local terrain
  - Low-cost to increase application potential
  - Increases a vehicle's versatility

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Product Design Specifications

Specification:	Value:
Top Speed	12 mph*
Weight	20 lbs
Switching Time	10 seconds
Material Cost	$2,000

* On a smooth surface

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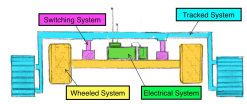
Design Iterations

Fall 2016



Multi-Chassis VDV

- Two Drive Motors
  - Redundant
- Heavy
- Poor Obstacle Clearance
- Requires custom-built vehicle chassis

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Design Iterations

Winter/Spring 2017

- **Reduces vehicle weight**
  - Integrated modular track units
- **Utilizes a single drive motor**
  - Wheel Driven Track System
- **Built on an existing wheeled chassis**
- **Focus on rear wheels**
  - Proof of Concept

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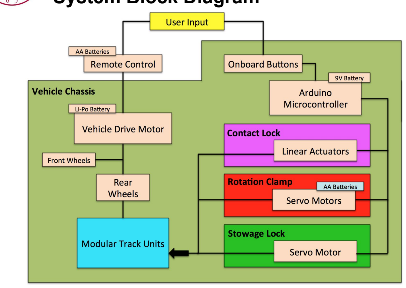
System Block Diagram



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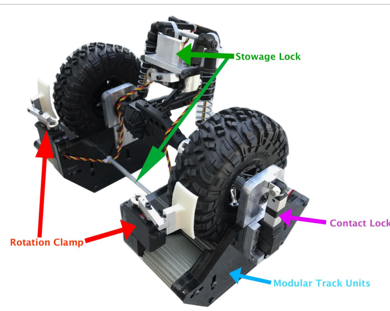

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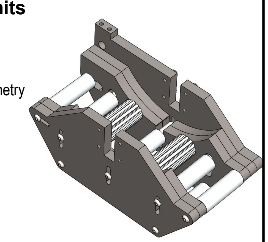
Wheeled Vehicle Chassis

- **Model: Axial Wraith**
  - Radio Controlled
  - Customizable frame
  - 5 pounds base weight
- **Motor: High Torque 20 Turn D/C**
  - All Wheel Drive
  - Top Speed: 12 mph

Modular Track Units

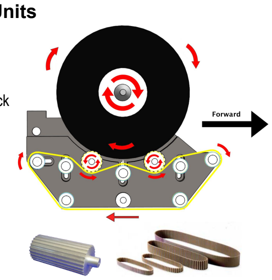
Modular Track Units

- Acrylic side-plates
  - Laser-cut due to complex geometry
- Aluminum Axles and Rollers
  - Adjustable positions
- Graphite lubricant
- Power the track using the wheels



Modular Track Units

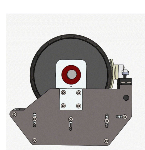
- Directional Change
  - Wheels drive splined rollers
  - Splined rollers drive the track
- Aluminum Pulley Bar Stock
  - Spline Rollers
- Timing Belt Track
  - Mated drive interface
  - Increased Traction

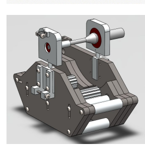


Rotation Clamp

Rotation Clamp

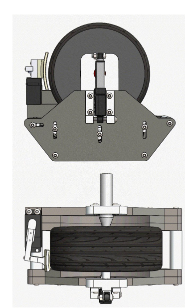
- Stowage position
  - Above the wheel
- Mounted to the axle using bearings
  - Press fit
  - Axle extension
- Utilize main drive motor to rotate track units out from under the wheels



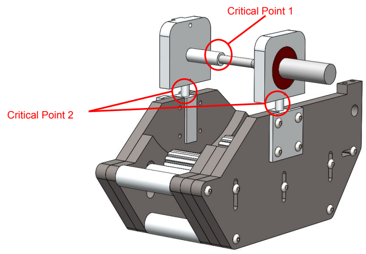


Rotation Clamp

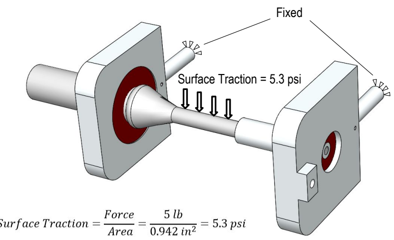
- Fix wheel to track unit
- High-torque Servo - HS645MG
  - Metal gear train
  - Aluminum horn and arm
  - 3D-Printed brake surface mated to wheel



Critical Points During Switching

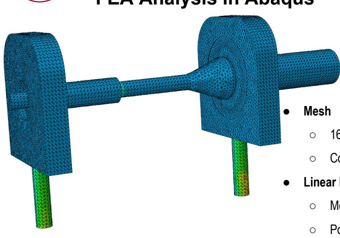


FEA Analysis in Abaqus



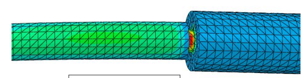
$$Surface\ Traction = \frac{Force}{Area} = \frac{5\ lb}{0.942\ in^2} = 5.3\ psi$$

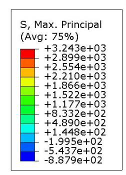
FEA Analysis in Abaqus



- **Mesh**
  - 162,000 Quad. Tet. Elements
  - Convergence Study
- **Linear Elastic Material: 6061 AL**
  - Modulus of Elasticity: 1.0e+07 psi
  - Poisson's Ratio: 0.33
- **Static Loading**

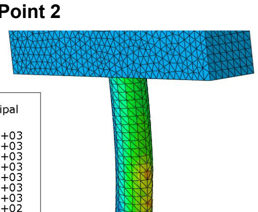
Critical Point 1

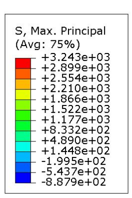




Max. Stress: 3.2e+03 psi
6061 Aluminum Yield: 4.0e+04 psi

Critical Point 2





Max. Stress: 2.6e+03 psi
6061 Aluminum Yield: 4.0e+04 psi

Comparing FEA with Hand Calculations

Loading Information		Maximum Principal Stress	
Loading	Critical Point	FEA Simulation	Hand Calculation
5.3 psi	1	3.243e+03 psi	3.614e+03 psi
	2	2.554e+03 psi	2.908e+03 psi

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Stowage Lock

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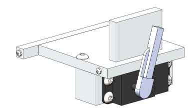
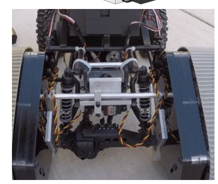
Stowage Lock

- Hold track units in stowed position above wheels
- Aluminum crossbar
  - Axle of splined roller
  - Connects track units
- Latch Mechanism
  - Aluminum frame reinforcement
  - Servo motor





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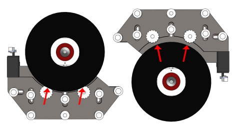
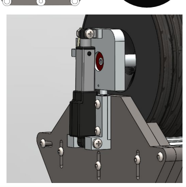
Contact Lock

- Disengage wheels from driving the splined rollers
- Aluminum shaft and sleeve
- Linear Actuators
  - Actuonix L12-R
  - 210:1 gear ratio





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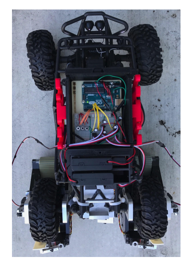
Control System

- 3D printed housing
  - Mounted directly to vehicle frame
- Arduino Microcontroller
  - PWM for Linear Actuators/Servos
- Momentary Push-Buttons
  - Onboard vehicle
  - Code registers button presses to manipulate an “on/off” toggle variable



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Electrical Power Supplies

- 7.4 V 4100 mAh Li-Po Battery
  - Vehicle drive motor and steering servo
- Two 4xAA 6V Battery Packs
  - Rotation clamp servos
  - Contact lock linear actuators
  - Stowage lock servo
- 9V Battery
  - Arduino

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Testing

- Speed Tests: Ten trials on a straight line course
  - Wheeled
  - Tracked
- Switching Time: Five trials per configuration
  - Track-to-wheel transition
  - Wheel-to-track transition

Benchmarking Results

Evaluation:	Goal:	Measured Values:
Track Speed	5 mph	0.8 mph
Wheel Speed	12 mph	11.5 mph
Switching Time	10 seconds	6.3 seconds
Weight	20 lbs	14 lbs
Cost	$2000	$1265

Cost

Item	Cost
Track Units (2)	$631
Stowage Lock	$25
Wheeled Chassis	$545
Arduino and Electrical Components	$64
Total	$1,265

Looking Forward

- **Current VDV Team**
  - Performance Testing
    - Speed on different terrain, slope, obstacle clearance
- **Potential Continuation Projects**
  - Optimize track units
    - Reduce frictional losses
    - Reduce weight
  - Design modular track units for front wheels
    - Accommodate steering
  - Expand to larger wheeled chassis
    - Military and disaster relief applications

Conclusion

- Small-scale prototype:
  - Integrated two drive systems into an augmented RC vehicle
  - Utilize single drive motor and existing wheeled chassis
  - Switch between drive systems in just 6.3 seconds
  - Low-cost and lightweight, increases the vehicle's versatility
- Platform for future research, disaster relief, and military applications

Acknowledgement

We would like to thank Dr. Michael Taylor for his continued support as our project advisor.

We would also like to thank the School of Engineering for making this vision a reality.

Thank You!

Questions?

Appendix

Testing

Experimental Protocol (9 May. 2017)

Variable Drive Vehicle

Evaluation	Equipment	Formulae and Assumptions	Accuracy	Trials	Expected Outcome	Measured Outcome
Track Speed (Concrete)	Stopwatch, long tape, cones	Constant velocity between cones at 10 ft., V(mph) = 10 ft / (sec*0.6818)	0.1 mph	10	5 mph	0.8 mph
Wheel Speed (Concrete)	Stopwatch, long tape, cones	Constant velocity between cones at 10 ft., V(mph) = 10 ft / (sec*0.6818)	0.1 mph	10	12 mph	11.5 mph
Switch Time	Stopwatch	n/a	0.1 sec	5	10 secs	6.3 secs
Weight	Scale	Vehicle can be balanced on scale	0.5 lbs	3	20 lbs	14 lbs
Max Slope	Cinder blocks, 2x4s, plywood sheet	tan^-1(opp/adj) = degrees	2 degrees	10	33 degrees	
Obstacle Height Clearance	Plywood	n/a	1 in	10	7 in	

Testing

Experimental Protocol (9 May. 2017) cont...

Variable Drive Vehicle

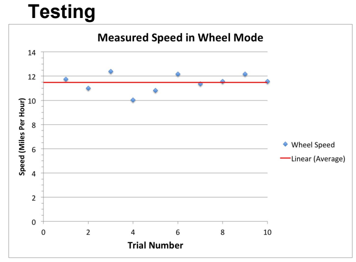
Evaluation	Equipment	Formulae and Assumptions	Accuracy	Trials	Expected Outcome	Measured Outcome
Turning Radius	Long tape, chalk	Low speed circles	1 in	3	3 ft	
Track Speed (Sand, Gravel, Grass)	Stopwatch, long tape, cones	Constant velocity between cones at 10 ft., V(mph) = 10 ft / (sec*0.6818)	0.1 mph	10	5 mph	
Wheel Speed (Sand,Gravel, Grass)	Stopwatch, long tape, cones	Constant velocity between cones at 10 ft., V(mph) = 10 ft / (sec*0.6818)	0.1 mph	10	12 mph	

Experimental Data

	Speed Test					
	Wheels			Tracks		
	Time for 10 ft	fps	mph	Time for 1 ft	fps	mph
1	0.58	17.24137931	11.7554859	11.4	0.877192982	0.59808612
2	0.62	16.12903226	10.9970674	8.1	1.234567901	0.84175084
3	0.55	18.18181818	12.3966942	9	1.111111111	0.75757576
4	0.68	14.70588235	10.026738	8.1	1.234567901	0.84175084
5	0.63	15.87301587	10.8225108	9.7	1.030927835	0.70290534
6	0.56	17.85714286	12.1753247	8.1	1.234567901	0.84175084
7	0.6	16.66666667	11.3636364	10	1	0.68181818
8	0.59	16.94915254	11.5562404	7.9	1.265822785	0.86306099
9	0.56	17.85714286	12.1753247	8.2	1.219512195	0.83148559
10	0.59	16.94915254	11.5562404	8.4	1.19047619	0.81168831
		Average	11.4825263		Average	0.77718728

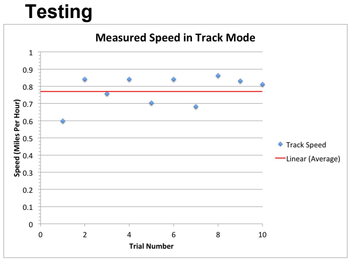
	Switch Time	
	Tracks to Wheels	Wheels to Tracks
1	6.2	5.13
2	7.65	6.4
3	6.41	5.75
4	6.9	5.95
5	6.81	5.7
Average	6.794	5.786

Testing



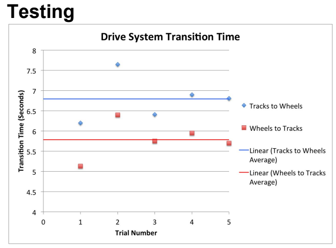
Average Maximum Wheel Speed: 11.5 MPH

Testing



Average Maximum Track Speed: 0.8 MPH

Testing



Average Tracks to Wheels Transition Time: 6.8 Seconds
Average Wheels to Tracks Transition Time: 5.8 Seconds

Track N Go

- **Pros:** Able to use both wheel and track drive systems
- **Cons:** Switching between systems takes 15 min and requires manual installation

Current Supply of AA Batteries

Summary of tests, see discharge curves below

Size	Brand	Code in Charts	Date of Test	Sell By Date	Termination voltage used in test	Amp-Hours at 100 mA Discharge rate	Amp-hours at 500 mA Discharge Rate	Amp-hours at 1 Amp Discharge Rate	Amp-hours at 2 Amps Discharge Rate	Amp-Hours at 5 Amps Discharge Rate
AA Alkaline	Radio Shack Enercell Plus	RS	April 2006	2010	0.1 Volt	2.13 AH	1.31 AH	0.98 AH	0.72 AH	
AA Alkaline	Duracell Coppertop	DC	April 2006	2012	0.1 Volt	2.20 AH	1.30 AH	0.83 AH	0.54 AH	
AA Alkaline	Energizer Titanium	ET	May 2006	2012	0.1 Volt		1.84 AH	1.41 AH	1.18 AH	
AA Alkaline	Energizer Max	EM	May 2006	2012	0.1 Volt		1.17 AH	0.93 AH	0.70 AH	
AA Alkaline	Eveready Gold	EG	May 2006	2012	0.1 Volt		1.28 AH	0.95 AH	0.78 AH	
AA Lithium Metal	Energizer Lithium	E2	May 2006	2013	0.1 Volt				2.8 AH	
AA NiMH	PowerStream 2000 mAH Rechargeable		April 2006		0.1 Volt	2.04 AH (200 mA)			1.94 AH	2.11 AH (see curve)

Source: Powerstream Technology

ANNOUNCED SPECIFICATION OF HS-645MG STANDARD DELUXE HIGH TORQUE SERVO

1.TECHNICAL VALUES

CONTROL SYSTEM	:+PULSE WIDTH CONTROL 1500usec NEUTRAL	
OPERATING VOLTAGE RANGE	:4.8V TO 6.0V	
OPERATING TEMPERATURE RANGE	:-20 TO +60°C	
TEST VOLTAGE	:AT 4.8V	:AT 6.0V
OPERATING SPEED	:0.24sec/60° AT NO LOAD	:0.2sec/60° AT NO LOAD
STALL TORQUE	:7.7kg.cm(106.93oz.in)	:9.6kg.cm(133.31oz.in)
OPERATING ANGLE	:45°/ONE SIDE PULSE TRAVELING 400usec	
DIRECTION	:CLOCK WISE/PULSE TRAVELING 1500 TO 1900usec	
IDLE CURRENT	:8.8mA	:9.1mA
RUNNING CURRENT	:350mA	:450mA
DEAD BAND WIDTH	:8usec	
CONNECTOR WIRE LENGTH	:300mm(11.81in)	
DIMENSIONS	:40.6x19.8x37.8mm(1.59x0.77x1.48in)	
WEIGHT	:55.2g(1.94oz)	

Source: Hitec

HS-425BB Servo Specifications

Performance Specifications	
Operating Voltage Range (Volts DC)	4.8V ~ 6.0V
Speed (Second @ 60°)	0.21 ~ 0.16
Maximum Torque Range oz. / in.	46 ~ 57
Maximum Torque Range kg. / cm.	3.3 ~ 4.1
Current Draw at Idle	8 mA
No Load Operating Current Draw	150 mA
Stall Current Draw	800 mA
Dead Band Width	8 μs
Physical Specifications	
Dimensions (Inches)	1.59 x 0.77 x 1.44
Dimensions (Metric)	40.6 x 19.8 x 36.6
Weight (Ounces)	1.60
Weight (Gram)	45.5
Circuit Type	HT7003 Analog SMT
Motor Type	3 Pole Metal Brush Ferrite
Gear Material	Nylon
Bearing Type	Dual Ball Bearing
Output Shaft (type / Ømm)	Standard 24
Case Material	Plastic
Dust / Water Resistance	N / A
Connector Gauge (AWG) / Strand Count	25 / 40

Source: Hitec

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L12 Specifications

Gearing Option	50:1	100:1	210:1
Peak Power Point	17N @ 14mm/s	31N @ 7mm/s	62N @ 3.2mm/s
Peak Efficiency Point	10N @ 19mm/s	17N @ 10mm/s	36N @ 4.5mm/s
Max Speed *(no load)*	25mm/s	13mm/s	6.5mm/s
Max Force *(lifted)*	22N	42N	80N
Back Drive Force *(static)*	12N	22N	45N

Stroke Option	10 mm	30mm	50mm	100mm
Mass	28 g	34 g	40 g	56 g
Repeatability *(-I,-R,-P&LAC)*	±0.1 mm	±0.2 mm	±0.3 mm	±0.5 mm
Max Side Load *(extended)*	50N	40N	30N	15N
Closed Length *(hole to hole)*	62mm	82mm	102mm	152mm
Potentiometer *(-I, -R, -P)*	1kΩ±50%	3kΩ±50%	6kΩ±50%	11kΩ±50%

Voltage Option	6VDC	12VDC
Max Input Voltage	7.5V	13.5V
Stall Current	460mA	185mA
Standby Current *(-I/-R)*	7.2mA	3.3mA

Operating Temperature	-10°C to +50°C
Potentiometer Linearity	Less than 2.00%
Max Duty Cycle	20 %
Audible Noise	55dB @ 45cm
Ingress Protection	IP-54
Mechanical Backlash	0.2mm
Limit Switches *(-S)*	Max. Current Leakage: 8uA
Maximum Static Force	200N

Source: Actuonix

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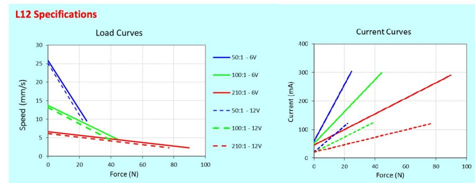
Linear Actuator Current Draw VS Load



Source: Actuonix

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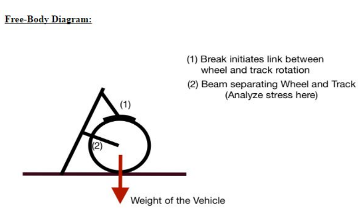
FBD of Drive System Switching



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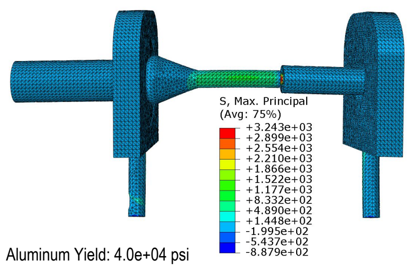
Track Extension Analysis in Abaqus



6061 Aluminum Yield: 4.0e+04 psi

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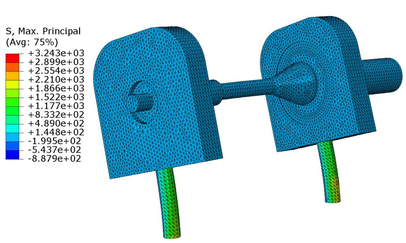
Shaft Collar Analysis in Abaqus



6061 Aluminum Yield: 4.0e+04 psi

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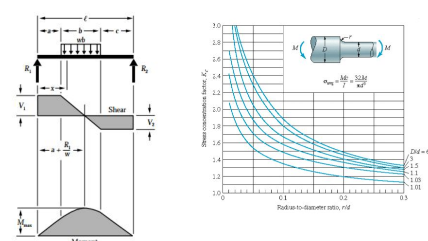
Equations Used for Switching Stress Hand Calculations



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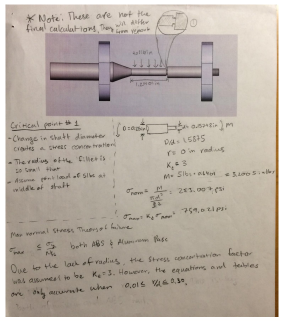
Switching Action Stress Hand Calculations



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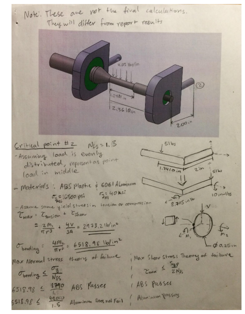
Switching Action Stress Hand Calculations



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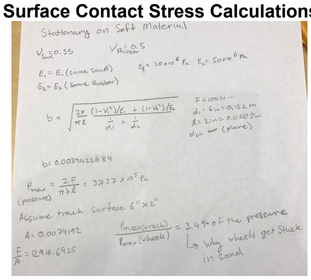
Surface Contact Stress Calculations - Sand



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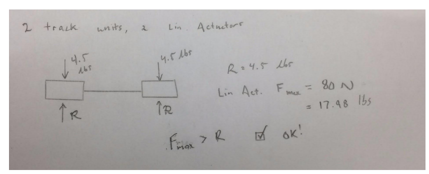
Linear Actuator Force Calculations



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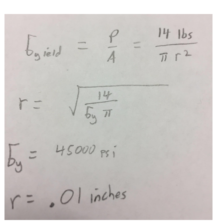
Minimum Axle Size Calculations



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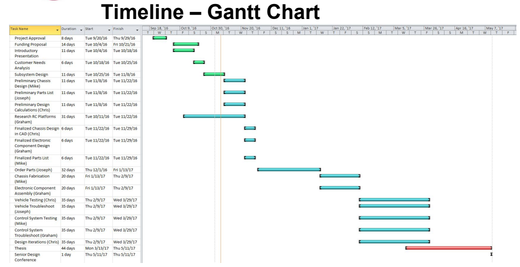
Timeline – Gantt Chart



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Safety Risks and Mitigations

Risk	Description	Mitigation Strategy
Electrical Components	Electrical shock, potential fire or explosion	Properly size all components including batteries, motors, and wires
Rotating and Moving Mechanical Parts	Pinch points within the actuated frame	Disconnect power to the machine while working on or touching the vehicle
Dangerous and Harmful Chemicals	Lithium ion batteries	Use batteries within correct temperature range and house them for protection

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Safety Risks and Mitigations

Risk	Description	Mitigation Strategy
Fabrication Equipment	Working with mills, lathes, power tools	All team members are enrolled in MECH 101L (Machine Shop Lab) to learn safe shop practices
Testing Procedures	Collisions, personal injury	Standardized testing procedures including a clearly defined testing area

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VDV Photo Links

Mastiff
http://www.basicknowledge101.com/resources/robots.html
http://sdrtactical.com/HD2Arm-Mastiff/

AMBOT
http://www.ambot.com/ip-wheel.shtml
http://www.ambot.com/ip-tank.shtml

AVATAR III
http://robotex.com/products/

Soldiers Carrying Injured
https://s-media-cache-ak0.pinimg.com/564x/4f/22/e0/4f22e034ff1fe3a8db1576bfbefb9e61.jpg

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VDV Photo Links

HS-425BB Deluxe Servo

https://www.google.com/search?q=hitec+servos&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjZypeH1-PTAhVL4WMKHTmYDN8Q_AUICygC&biw=1295&bih=1047#tbm=isch&q=hitec+425bb+servos&imgrc=WNQsdbduREuGhM:

AA Battery Pack

https://images-na.ssl-images-amazon.com/images/I/41oLsULv1AL._SX355_.jpg

LiPo Battery

https://www.venompower.com/collections/lipo-car-truck-buggy-batteries/products/venom-25c-2s-4100mah-7-4v-hard-case-lipo-battery-with-universal-plug-system

9V Battery

http://www.conboyelectrical.com/images/9v.jpg

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VDV Photo Links

Bar stock

http://www.polytechdesign.com/images/t10bi.jpg

Timing Belts

http://www.polytechdesign.com/flexbelt.php

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Additional Resources

Equations Used for Hand Calculations

Spotts, M. F., T. E. Shoup, and L. E. Hornberger. *Design of Machine Elements*. 8th ed. Upper Saddle River, NJ: Pearson, Prentice Hall, 2004. Print.

Wheels vs. Tracks Efficiency
http://www.comw.org/pda/0007wheels.html

L Media

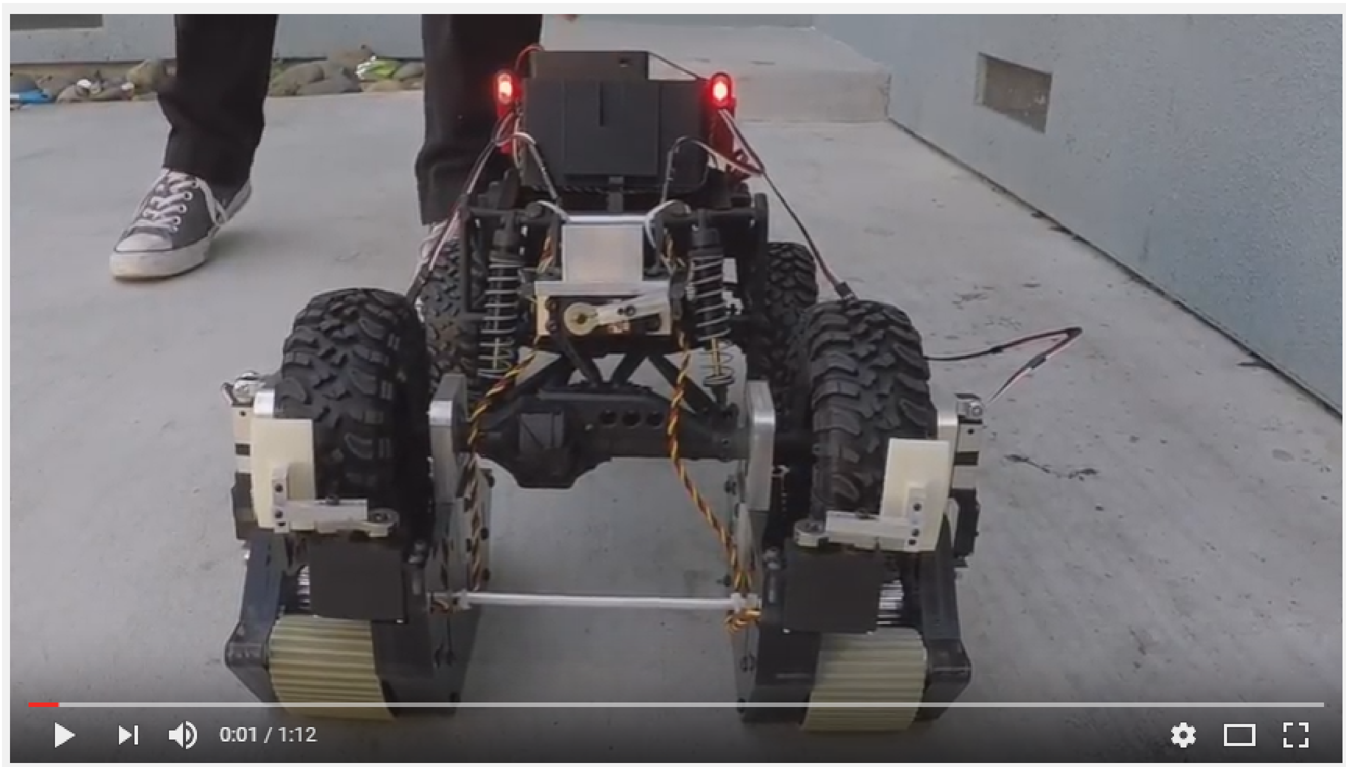

Figure L.16: YouTube video of VDV.

https://www.youtube.com/watch?v=E6DFoAOU6MA