# Final Design Review Report

**Phoenix Robotics: PESA (Purdue Emergency Supply Assistant)**

Submitted To: Professor Jensen

Submitted By: Brian Rock, Sachit Puntambekar, Arnav Vast, Konrad Hrabina, Dhruv Lal

Date: 12/3/19

**<u>Executive Summary</u>:**

In mass casualty incidents (MCI) emergency responders often times need to carry large amounts of weight into the field to administer care to patients. While carrying these supplies the first responders have to travel between warm zones and triage to resupply. This repetitive process fatigues paramedics and takes resources away from patient care. The goal of Phoenix Robotics' PESA robot is to streamline resources towards patient care by reducing first responder fatigue in mass casualty incidents.

Speaking to the Tippecanoe County Emergency Management Department, a gap in the existing market was identified and performance metrics for a half scale robot with a limited budget were established: carry 50 lbs of supplies, traverse complex terrain, be remote controlled, and incorporate a vision system. To satisfy these requirements, the PESA robot was designed (Appendix G) and incorporates a continuous track system (Appendix G, Figure G.19), a UI to remote control the robot (Appendix I, J, L), and a vision system that has two cameras and ultrasonics (Appendix R, subassembly 3).

The business opportunities and target customers for the robot are vast and summarized below and documented more deeply in Appendix C. Currently there are no competitors and the market is in a prime position to receive our product with significant margins. In terms of projected units sold, there is around one MCI trailer per district in Indiana and about 10 districts in the whole state. Extrapolating to all 50 states in the US, it is estimated that there will be demand for about 490 PESA Robot units which projects to $5.8 million in gross profit and (Appendix C)..

There are several key design decisions and fabrications for the prototype. Starting from the bottom they include a custom made continuous track system with in house suspension design to traverse semi-complex terrain shown in Appendix G. Dynamic analyses were carried out for the tread system, links, and sprockets as well and can be found in Appendix H.3 for more detail. A drive-train to power the robot and a structurally sound chassis was designed to carry the weight of all the electronics (Appendices I-L) and the weight of a scaled down Stokes basket. with an FEA for all custom fabricated parts and can be found in more detail in Appendix H.

Testing and validation was conducted for both mechanical and electrical systems (Appendix N). While completing the prototype and doing testing and validation lessons were learned for future prototyping (Appendix M). After testing and validating the gaps between customer requirements and prototype, specs were identified (Appendix N). The lessons learned through the prototyping process will contribute greatly when pursuing a full-scale marketable product.

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## A: Team Members and Organization Structure

| Project Role | Position holder | Contact Information |
| --- | --- | --- |
| Project Director | Dhruv Lal | dlal@purdue.edu |
| Chief Engineer | Brian Rock | rockb@purdue.edu |
| Manufacturing Manager | Sachit Puntambekar | spuntamb@purdue.edu |
| Assembly Manager | Konrad Hrabina | khrabina@purdue.edu |
| Test & Validation Manager | Arnav Vast | avast@purdue.edu |
| Buyer/Business Manager/Customer Voice | Arnav Vast | avast@purdue.edu |

## B: Charter

# ME 463 Senior Design

**Project Title:** Purdue Emergency Medical Assistant (PESA)

**Team Name:** Phoenix Robotics

**Team Members:** Brian Rock, Anvav Vast, Konrad Hrabina, Sachit Puntambekar, Dhruv Lal

**Vision Statement:** Enable EMTs to provide better on-site treatment to patients by reducing their fatigue from trips to get more supplies and carrying those supplies.

### Problem Statement (Current State)

In Mass Casualty Incidents (MCIs) emergency responders need to carry approximately 100 lbs. of supplies with them when going to find patients. In MCIs multiple patients who need care are located in the warm zones. Constantly caring for patients while carrying all these supplies easily fatigues responders and their supplies can easily run out.

### Business / Society Benefit (Future State)

Society will benefit by more lives being saved and less permanent patient damage in mass casualty incidents where EMTs will become fatigued due to their work. The supply robot will reduce trips to and from the safe zone while also being able to reduce the weight EMTs need to carry making them more effective in patient

### Project Scope

| IN Scope | OUT of Scope |
|---|---|
| The "In Scope" is to create a remote control supply robot capable of carrying EMT's supplies to warm zones via Remote control using a vision and ultrasonic vision system. | The "Out" or future scope will be to transfer the robot from remote control to an autonomous system via tethering or beacon systems as well as being able to carry a normal stokes basket on top of the Robot Chassis. |

### Key Milestones

Low Fidelity Prototype, Written and Oral PDR, Mid-fidelity prototype, Written and Oral CDR, Purchase Orders Places, Final Prototype Built, Mallot Posters, Written and Oral FDR, Mallot Display, Public Display

### Key Assumptions & Risks

Operator can maneuver robot form triage to warm zone in a time effective manner being able to keep up with the pace of a normal EMT. The robot will stay located on first responders Mass Casualty Incident Trailer. Robot will include safety protocols to stop movement and prevent collision with patients, EMTs or obstacles.

### Team Members & Roles

Project Director: Dhruv Lal
Chief Engineer: Brian Rock
Manufacturing Manager: Sachit Puntambekar
Assembly Manager: Konrad Hrabina
Test & Validation Manager: Arnav Vast
Buyer/Business Manager/Voice of the Customer: Arnav Vast

### Key Resources Required

Professor Expertise, Emergency Management Customer Contacts, Manufacturing Tools, Work Rooms, Machine Shop Managers

Version: 2.1

Last Updated: 11/26/2019

## C: Business Case and Project Budget

In Mass Casualty Incidents (MCIs) emergency responders need to carry approximately 100 lbs of supplies with them when on a rescue mission. In MCIs multiple patients who need care are located in “warm zones”, areas with moderate risk of injury. Constantly caring for patients while carrying all these supplies greatly fatigues responders with the risk of their supplies running out, making them less capable of caring for themselves and their patients alike.

Currently there are no alternatives in place to carrying these supplies. Phoenix Robotics has developed a solution to fill this void, with the Purdue Emergency Supply Assistant, known as PESA. The vision of PESA is to enable emergency responders to provide the best quality on-site treatment by reducing the responder’s fatigue from carrying those supplies and taking trips back and forth to resupply.

The production cost of the fully scaled PESA robot comes from the current project budget being scaled to a larger and more robust design. The half-scaled PESA is currently costing $1,763.00, a breakdown of the cost can be seen in the bill of materials for the prototype in Appendix Q. As we scale to a larger design, many costs will increase by a scale of two, however some costs will increase by a larger factor. The increase of pricing will be due to improvements in parts, such as higher quality sensors, and more robust tank tread components. The sensors will be upgraded from the $4.00 ultrasonic sensors, to a $7,500 LiDAR system from Waymo. This upgrade will drastically improve the safety system of the PESA, while having the capability of being integrated with autonomous control. Also, the tank tread system will be upgraded from the Lynxmotion kits used in the prototype to a custom track and sprocket set. This will allow for the use of stronger materials for the sprocket and tread. Pricing for the tread was estimated using kits online that were out of the project budget when considered for the prototype. These kits ranged from $4,000 to $6,000. Finally, upgrading to custom shocks will improve the suspensions system. These custom shocks would cost around $400 each totalling to $3200 per PESA. Incorporating the price increase from doubling the scale of the prototype, as well as the mentioned improvements, the full-scale production cost is then estimated to be $18,433.76.

As directly competing products are not currently in existence, different products with similar functionalities were investigated to gauge a potential sales price. One product is the Strkyer Gurney, which helps emergency responders move patients. The comparable capability of this product is its ability to transport a load, up to 700 lbs. The Gurney sells for $18,000, but it is unable to navigate uneven terrain, and still requires responders to physically move the gurney in and out of buildings, as this option has no propulsion system. Another product is the Starship delivery robot, which can transport a load of up to 20 lbs, and navigate over curbs and stairs. The sales price of the Starship robot is not known exactly, but using data from the contracts with universities, we can roughly estimate the price to be between $10,000 and $16,000. The product we have deemed as our greatest competitor, as it has features that are closest to meeting our customer requirements, TUG by Aetheon. TUG is an autonomous medical material delivery robot that is used in hospitals only. The TUG robot can carry up to 1400 lbs and is able to navigate buildings using elevators, however it must be integrated into the building's wireless network. The sales price of the TUG robot is not known exactly, but using the $3.5 million price of a contract with a hospital for 25 TUG robots, we can roughly estimate the price to be $140,000. In discussions with the Director of Tippecanoe County Emergency Management, an estimated price for a product with PESA''s capabilities came out to be $70,000. With all these considerations in mind, we would like to sell PESA at a price of $32,000.

Thus, the projected profit per PESA sold is estimated to be $13,566.24. A minimum gross profit was calculated by projecting data gathered from the Executive Director of Tippecanoe County Emergency Management. There is at least 1 mass casualty incident trailer per every Homeland Security district in the state of Indiana. In Indiana there are a total of 10 districts, equating to 6,691,878 people. Using this ratio and the populations of all 50 states and Washington DC, we can project to place a robot in 492 state homeland security districts. This projection was verified with the Executive Director of Tippecanoe County Emergency Management. He deemed it viable, while noting that the number was probably smaller than reality due to population density in smaller states. Using this projection, the gross profit of PESA would be at least $5,819,916.96.

**Project Budget:**

PURDUE MECHANICAL ENGINEERING

## ME 463 Senior Design

PURDUE UNIVERSITY

**Team Name:** Purdue Emergency Supply Assistant **Date:** 23-Nov-2019

| COMPLETED ORDERS | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Item Description** | **How will the item be used for the project?** | **Vendor** | **Item Cost** | **Quantity Purchased** | **Shipping Cost** | **Total Cost** | **Purchase date** |
| Lynxmotion Track - 2" Wide x 21 Links TRK-01 | Tread for Tread System | RobotShop | $25.19 | 6 | $ - | $ 151.14 | 18-Oct-2019 |
| Lynxmotion Track Sprocket - 6 Tooth (Pair) SPRK-01 | Bottom sprockets and top tensioner for Tread System | RobotShop | $7.71 | 10 | $ - | $ 77.10 | 18-Oct-2019 |
| Lynxmotion Track Sprocket - 9 Tooth (Pair) SPRK-02 | The top sprocket and drive sproket for Tread System | RobotShop | $9.65 | 4 | $ - | $ 38.60 | 18-Oct-2019 |
| Lynmxotion HUB-02 Universal Hub - 6mm (Pair) | Connect sprockets to 6mm shaft | RobotShop | $7.65 | 14 | $ - | $ 107.10 | 18-Oct-2019 |
| LED Lights | Light area for working EMT and Driving vision | Amazon | $13.60 | 1 | $ - | $ 13.60 | 24-Oct-2019 |
| Pi Case with Cooling | Cools Raspberry Pi and protects it from damage | Amazon | $15.59 | 1 | $ - | $ 15.59 | 24-Oct-2019 |
| Raspberry Pi Expansion Board Power Relay | Power Relay Board | Amazon | $23.99 | 1 | $ - | $ 23.99 | 24-Oct-2019 |
| WINDCAMP Power Splitter Distributor | Power Splitter | Amazon | $57.99 | 1 | $ - | $ 57.99 | 24-Oct-2019 |
| Sheet Metal + Cutting | Tread Plates, Support Arms, Base Chassis | Purdue RMS | $140.00 | 1 | $ - | $ 140.00 | 28-Oct-2019 |
| Shocks | Shocks for other side fo tread assembly | Amazon | $25.99 | 2 | $ - | $ 51.98 | 4-Nov-2019 |
| Bearings FR188zz 6.350mm x12.700mm x 4.762mm | Reduce friction for wheel and suspension arm rotation | Amazon | $16.99 | 4 | $ - | $ 67.96 | 4-Nov-2019 |
| Springs | Stiffer springs for shocks | McMaster-Carr | $10.40 | 1 | $ - | $ 10.40 | 8-Nov-2019 |
| Drive Sprocket | Drive Train | McMaster-Carr | $11.94 | 1 | $ - | $ 11.94 | 8-Nov-2019 |
| Bearings FR6ZZ | Used for drive shaft alignment | Amazon | $9.94 | 1 | $ - | $ 9.94 | 8-Nov-2019 |
| Sheet Metal Bending | Base Chassis | Purdue RMS | $40.00 | 1 | $ - | $ 40.00 | 12-Nov-2019 |
| Shims 1/4" ID 3/8" OD | Allow bearings to operate smoothly without binding | McMaster-Carr | $3.82 | 10 | $ - | $ 38.20 | 11-Nov-2019 |
| | | | | | $ - | $ - | |
| | | **TOTAL** | | | | **$ 855.53** | |
| | | **GRAND TOTAL** | | | | **$ 855.53** | |
| | | **Remaining Budget** | | | | **$ 144.47** | |

## D: Project Schedule

The following is the team's project schedule up to the CDR. The team recognized the schedule was too vague and added detail to the schedule post CDR

| 2019 Fall Senior Design Schedule | | | | | |
|---|---|---|---|---|---|
| | TASK NAME | START DATE | END DATE | TEAM MEMBER | PERCENT COMPLETE |
| **PDR** | | | | | |
| **Low Fidelity Prototype** | | **9/5** | **9/10** | **All** | **100%** |
| | Meet with customer | 9/5 | 9/5 | All | 100% |
| | Prelim design meeting | 9/6 | 9/6 | All | 100% |
| | Prelim CAD Chassis | 9/7 | 9/8 | Brian | 100% |
| | Prelim Electrical Design | 9/7 | 9/8 | Dhruv | 100% |
| | Prelim CAD Drive train | 9/8 | 9/10 | Brian | 100% |
| | Build Prototype | 9/8 | 9/10 | All | 100% |
| **Report** | | **9/8** | **9/12** | All | **100%** |
| | Summarize activities | 9/8 | 9/12 | All | 100% |
| | Business case/budget | 9/8 | 9/12 | All | 100% |
| | Project Schedule | 9/8 | 9/12 | Sachit | 100% |
| | Risk Mitigation | 9/8 | 9/12 | Konrad | 100% |
| | Flow Charts | 9/8 | 9/12 | Brian | 100% |
| **Presentation** | | **9/8** | **9/12** | **All** | 100% |
| **CDR** | | | | | |
| **Mid-fidelity prototype** | | **9/18** | **10/9** | **All** | **100%** |
| | Re-asses with customer contact | 9/18 | 9/18 | All | **100%** |
| | Asses validity of subsystems | 9/19 | 9/20 | All | **100%** |
| | Finalize Design | 9/20 | 9/21 | All | **100%** |
| | Part Drawings | 9/21 | 9/24 | Brian | **100%** |
| | BOM List | 9/24 | 9/24 | All | **100%** |
| | Final Budget | 9/25 | 9/25 | Brian | **100%** |
| | Part analysis/procurement | 9/25 | 9/28 | All | **100%** |
| | Medium fidelity fabrication | 9/29 | 10/6 | Dhruv | **100%** |
| | Prototype Assembly | 10/6 | 10/9 | Dhruv | **100%** |
| **Written CDR** | | **10/8** | **10/10** | **All** | **100%** |
| | Summarize activities | 10/8 | 10/10 | All | **100%** |
| **Oral CDR** | | **10/8** | **10/10** | **All** | **100%** |

Project Schedule from start of semester to CDR

| | | | | |
|---|---|---|---|---|
| **Final Prototype/FDR** | | | | |
| Team Members and Organization Structure | - | - | Brian | 100% |
| Charter | - | - | Brian | 100% |
| Business Case Fix | 10/31 | 12/2 | Arnav | 100% |
| Project Budget | 10/31 | 11/19 | Brian | 100% |
| Project Schedule | 10/31 | 12/1 | Sachit/Brian | 100% |
| Update Risk Mitigation | 10/31 | 11/14 | Brian | 100% |
| Mechanical CAD | 10/31 | 11/26 | All | 100% |
| Motion Path Simulation | 10/31 | 11/20 | Brian | 100% |
| Shear Analysis Refinement | 12/1 | 12/2 | Sachit | 100% |
| Torque Analysis Refinement | 12/1 | 12/2 | Konrad | 100% |
| Spring Analysis Refinement | 12/1 | 12/2 | Konrad | 100% |
| FEA Front Arm Links | 11/9 | 11/9 | Sachit | 100% |
| FEA Bottom Arm Links | 12/1 | 12/2 | Sachit | 100% |
| FEA Chassis | 12/1 | 12/2 | Sachit | 100% |
| FEA Springs | 12/1 | 12/2 | Konrad | 100% |
| Electronics Schematic | 11/19 | 12/2 | Dhruv | 100% |
| Electronic Circuit Diagram | 11/19 | 12/2 | Dhruv | 100% |
| Electronic CAE | 11/19 | 12/2 | Dhruv | 100% |
| FlowChart of Control | 11/20 | 12/2 | Dhruv | 100% |
| Skeleton Code | 11/19 | 12/2 | Dhruv | 100% |
| Part Drawings | 10/31 | 12/2 | Brian | 100% |
| Manufaturing Drawings | 10/31 | 12/2 | Brian | 100% |
| Learned from Final Prototype | 12/1 | 12/2 | All | 100% |
| Validation Plan, Results, Conclusion | 10/31 | 12/2 | Brian/Dhruv | 100% |
| Market Analysis | 10/31 | 11/8 | Brian | 100% |
| Building Prototype | 10/31 | 12/2 | All | 100% |
| Purchase Orders/Returns | 10/31 | 12/2 | Arnav | 100% |
| Finish GearBox Design | 10/31 | 12/2 | Arnav | 100% |
| Finish Chassis Design | 11/24 | 12/2 | All | 100% |
| FEA Drive Shaft | 11/20 | 12/2 | Sachit | 100% |
| Bill of Materials (BOM) | 10/31 | 12/2 | Arnav | 100% |
| Waterjet Phase 1 (Arms, Tread Plates) | 10/31 | 11/4 | Sachit | 100% |
| Waterjet Phase 2 (Links 2, Tread Plate) | 10/31 | 12/2 | Sachit | 100% |
| Waterjet Phase 3 (Chassis) | 10/31 | 12/2 | Sachit | 100% |
| Chassis Work (bending & welding) | 11/13 | 11/13 | Sachit/Konrad | 100% |
| Assembly Manufacturing Plan | 12/1 | 12/2 | Arnav | 100% |
| Chassis Balance Analysis | 11/7 | 11/8 | Sachit | 100% |
| Prototype feasability, shortcomings, next phase plan | 12/1 | 12/2 | All | 100% |
| Parts Manufacturing Plan | | 12/2 | Sachit | 100% |
| Testing | 11/11 | 11/22 | All | 100% |
| Iteration - Mechanical | 11/11 | 11/22 | All | 100% |
| Iteration - Electrical | 11/11 | 11/22 | Dhruv | 100% |
| Report Executive Summary | 11/1 | 12/2 | All | 100% |
| **FDR** | | | | |
| Oral | 11/17 | 12/3 | All | 100% |
| Written | 11/17 | 12/3 | All | 100% |

Project Schedule from CDR to Present. More detail was added to the schedule and specific responsibilities were assigned to team members to establish ownership of the task

## E: Risk Mitigation

The following is the team's risk register spreadsheet. Most of these risks were avoided. The key setbacks we encountered from the risk register were the breaking of parts during assembly and the delay of incoming parts.

The breaking of parts during assembly came from the bearings and sprockets. The bearings selected were cheap and low quality. The bearings were selected due to the project's budget constraints and not having the money to 40 high quality bearings. Approximately, four bearings broke during press fitting them into our holes due to operator error as well as poor bearing quality. To mitigate this problem the team ordered new bearings from the business office and individually to ensure that we had enough working bearings for assembly and some extra incase more were broken. In the future, to prevent this the team would utilize higher quality bearings and better machining to ensure no bearings break.

The sprockets selected were part of Lynxmotion's tread system. They were selected because it was the best tread system the team could buy with our budget. A sprocket was broken while trying to remove it from the drive shaft. Uneven force was applied to the top and bottom of the sprocket and caused to to crack. To mitigate this the team used personal funds to express ship a new sprocket so the prototype could be tested. The sprockets purchased are made of ABS poly-carbonite and are fairly brittle. If more time was available the team could have manufactured metal sprockets to this could be avoided. In the future, the team would utilize a custom tread system for the "tank treads" of our supply robot.

The delay of incoming parts was caused by the business office messing up an order of our bearings and ordered 4 individual sets of 10 instead of 40 all at once. This created a staggered delivery and the team had to accept this delay and assembly was halted until the bearings were delivered. In a professional setting, this could also happen if the team is not the ones placing the order. The outcome would just have to be accepted.

The figure on the next page is the updated Risk Register:

| IDENTIFICATION | | | | | | CURRENT ASSESSMENT | | | TREATMENT | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | RAISED BY | DATE RAISED | CAUSE (IF...) | EFFECT (THEN...) | RISKOWNER | P | I | Current Risk Score | STRATEGY | TREATMENT DESCRIPTION |
| | *The originator of the risk* | *When the risk was first identified* | *If uncertain eventoccurs due to (or because of) specifiedroot cause(s).Tip: ask "why, why, why..." to drill down to root cause* | *then the ultimate impactto our objectives are. Tip: ask "so what, so what, ..."* | *Single named owner* | *Probability of the event occurring* | *Worst' impact* | *Calculated risk score* | *Select overall approach to treatment (Mitigate or Accept)* | *Summary of the treatment responses (actions, controls, fallbacks) that treat the risk.* |
| 1 | Arnav | 8-Sep-19 | Purchasing Request form is denied | Delay in project schedule | Arnav | L | M | 6 | Mitigate | Plan to submit orders so parts would come than needed as a buffer. |
| 2 | Konrad | 8-Sep-19 | If the design weighs more than 100lbs due to required weight capacity and material limitations | Robot cannot be safely lifted by first responders, requiring secondary device to lift system. | All | M | M | 10 | Accept | Plan to develop alternative loading methods to lifting |
| 3 | Arnav | 8-Sep-19 | We buy inadequate parts for the design | Delay in project schedule, waste of budget, waste of time to return items | All | L | L | 5 | Mitigate | Have the whole team inspect purchases prior to submitting a purchasing request form |
| 4 | Konrad | 8-Sep-19 | We exceed our $1000 budget due to project complexity and part cost | We can no longer proceed with the selected design and must reduce design cost. | All | L | H | 11 | Mitigate | Carefully plan builkd materials and associated costs |
| 5 | Konrad | 8-Sep-19 | Ordered parts don't come in on time | We cant operate according to schedule | All | L | M | 6 | Accept | Plan tasks we can do coccurently to allow for more flexibility building |
| 6 | Konrad | 8-Sep-19 | Components purchased get damaged during building due to poor handling | We need to purchase more parts which is both a time and financial burden | All | L | H | 11 | Mitigate | Ensure we understand component specifications to prevent damaging electronics or breaking compomnents |
| 7 | Konrad | 8-Sep-19 | Components purchased are no longer useful due to design changes/improvements | We utilize financial resources on things we no longer need | All | L | L | 5 | Mitigate | Ensure suppliers accept returns on components |
| 8 | Arnav | 9-Sep-19 | Inadequate mechanical analysis | PESA does not operate at the safety measures that we set | Sachit | L | H | 11 | Mitigate | Recalculate material limits and manufacture again |
| 9 | Brian | 25-Sep-19 | Electrical Componets don't perform to specifications | Robot will not be able to properly opperate | Dhruv | M | H | 15 | Accept | Try our best to meet requirements with what we have and buy other electronics to supplement |
| 10 | Brian | 25-Sep-19 | Robot is damaged during testing | Robot will need to be rebuilt and fixed delaying the project schedule and testing | All | M | H | 15 | Mitigate | Make testing safer in future to avoid accidents |
| 11 | Brian | 25-Sep-19 | Robot loses control during testing and harms team member | Depending on severity could lead to them going to the doctor and the robot damage | All | L | H | 10 | Mitigate | In future set limiters on motors and make sure individuals are a safe distance when operating |
| 12 | Brian | 22-Nov-19 | Purchased parts are messed up by the business office | Robot can't be assembled, tested, or demoed | Arnav | L | H | 10 | Mitigate | Worse case scenario use personal funds to express ship needed parts so testing can be conducted and assembly can be finished |

## F: Sketches

The following figures are the sketches generated in team design meetings pre the CDR where the problem was identified and concepts were generated to properly satisfy customer requirements.

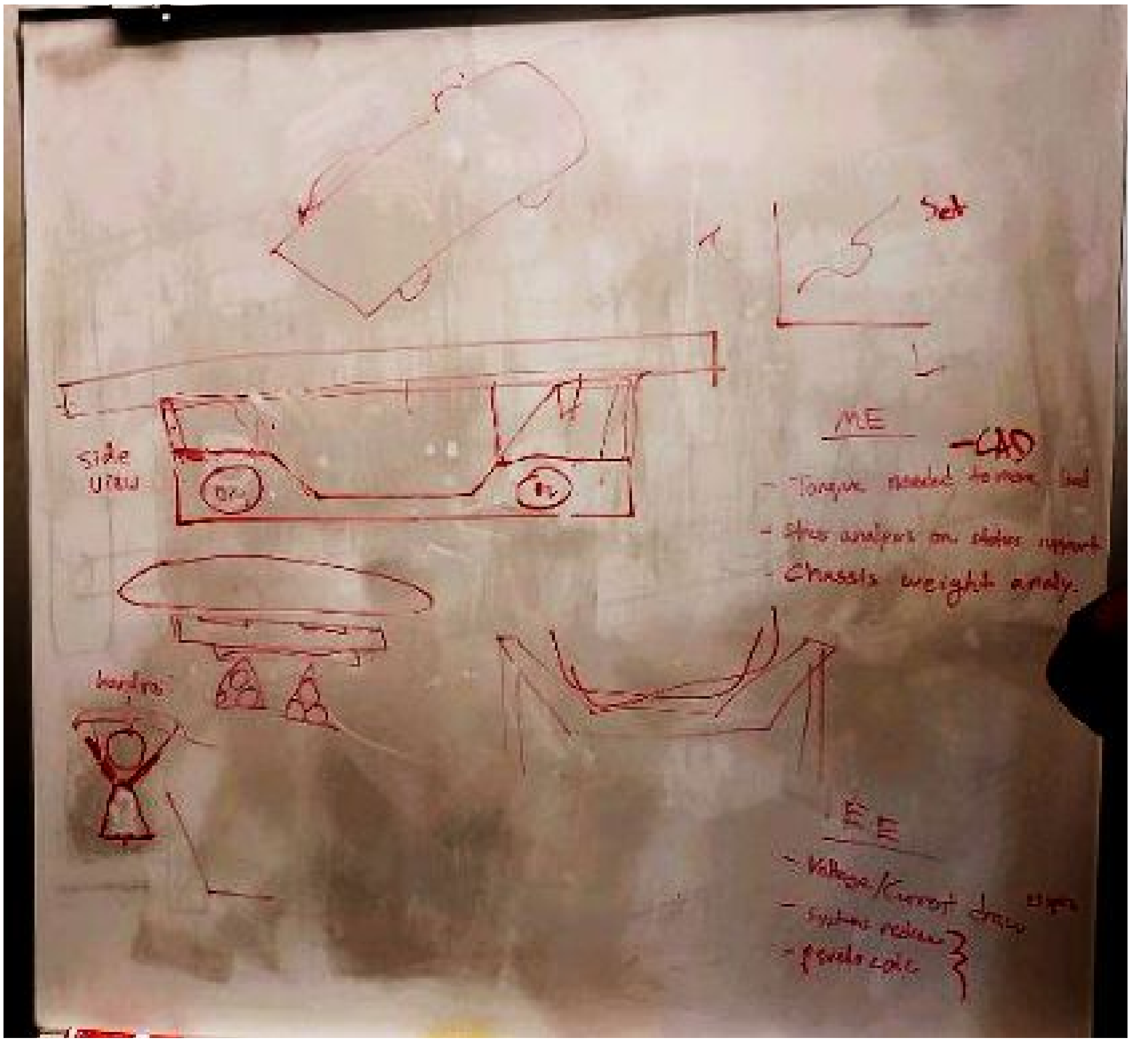



Figure F.1: Depicts the basic concepts for attaching stokes basket to chassis, using a gravity-aided locating system & latches

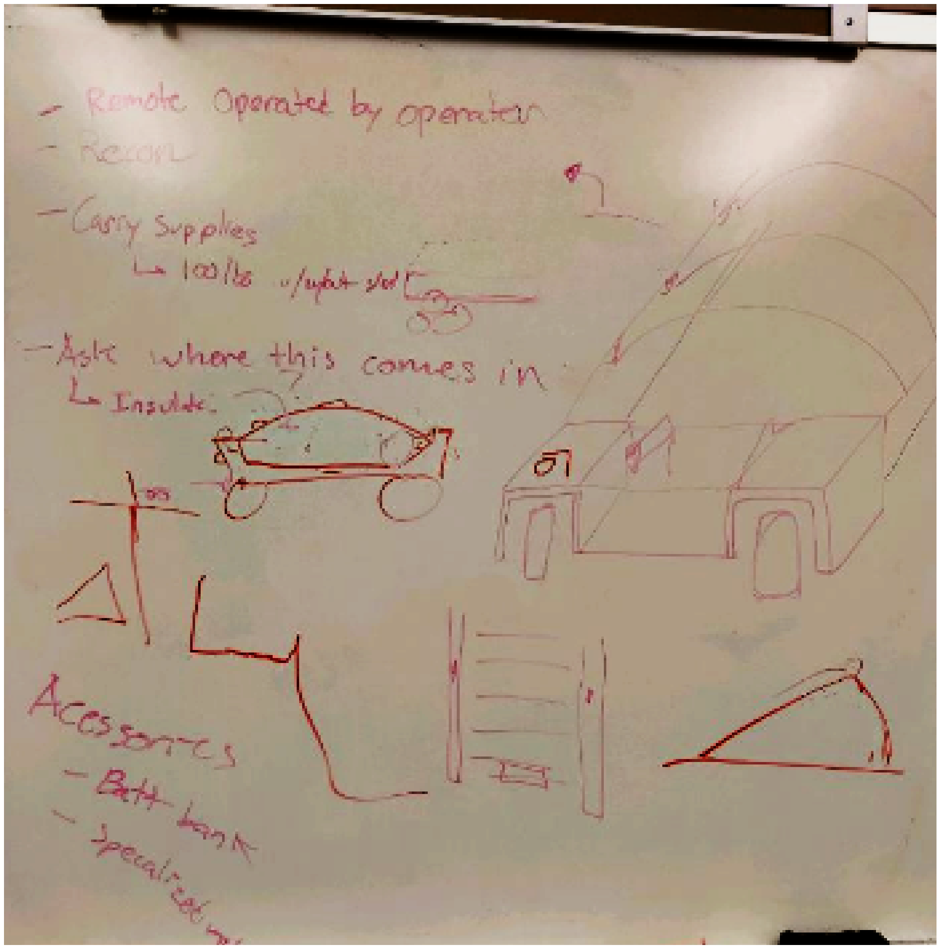



Figure F.2: Open bed concept for design without stokes basket

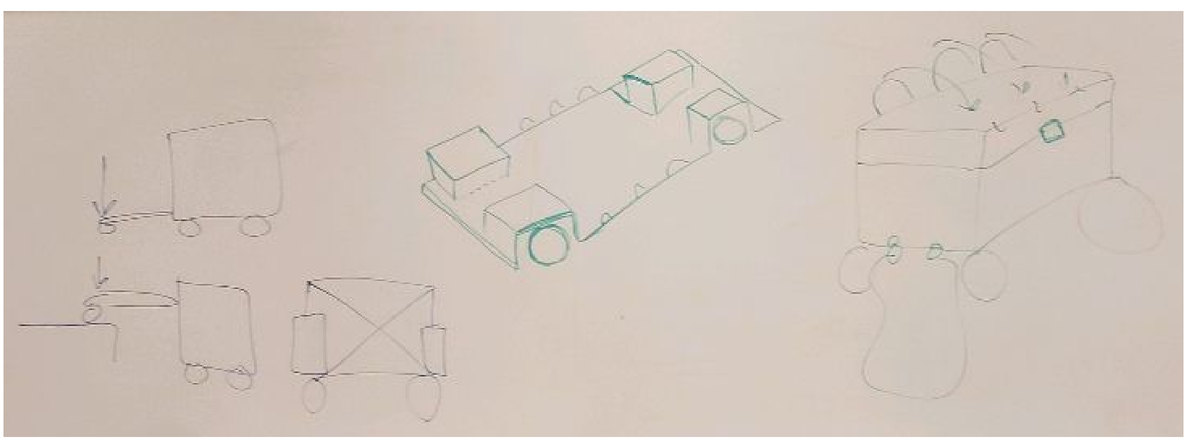


Figure F.3: Basic concepts for stair-scaling, and chassis design including open and enclosed designs

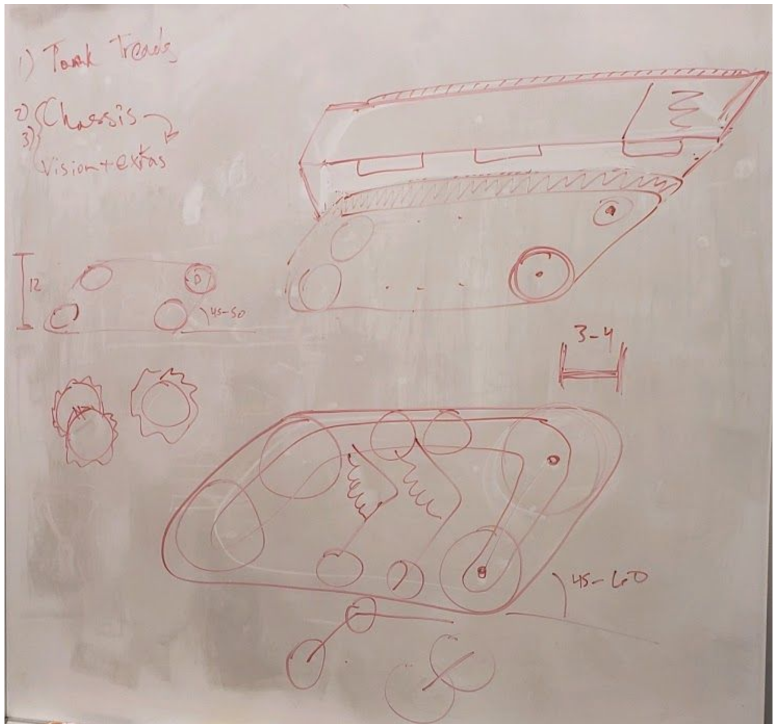



Figure F.4: Concepts for full chassis-length track system

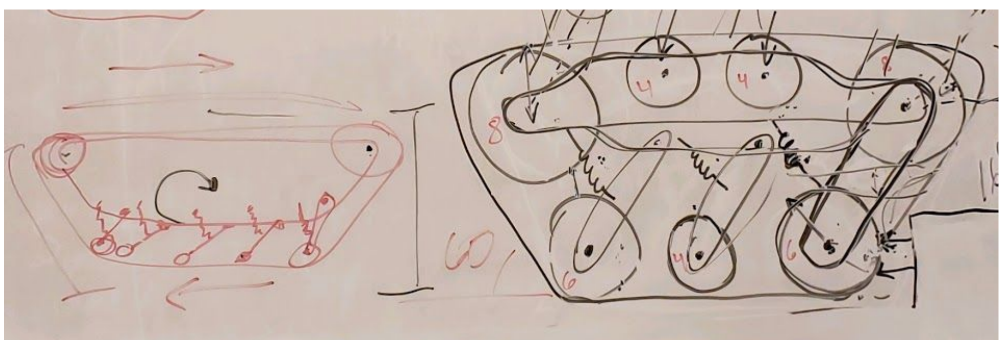



Figure F.5: Full length track concept with suspension

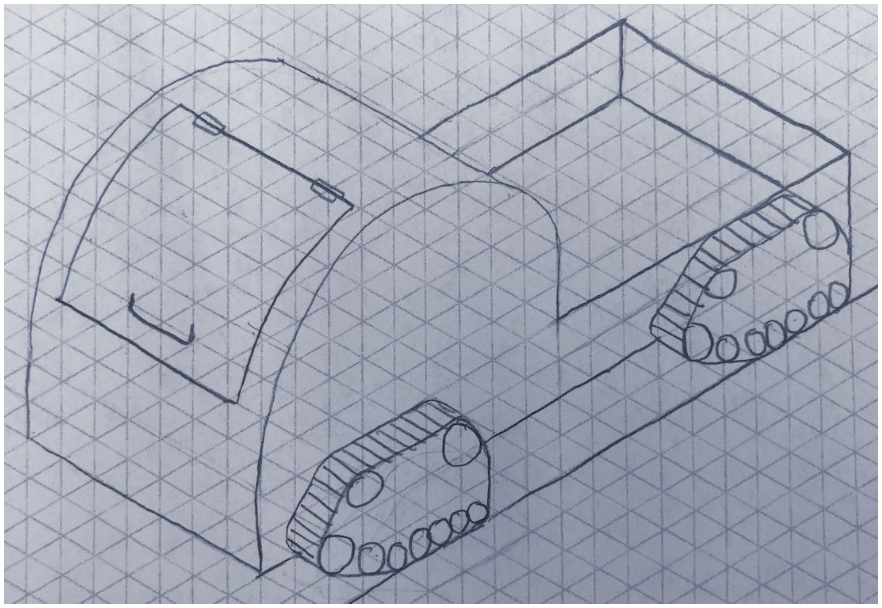


Figure F.6: Concept of combined designs, enclosed & insulated, open bed, and individual wheel tracks

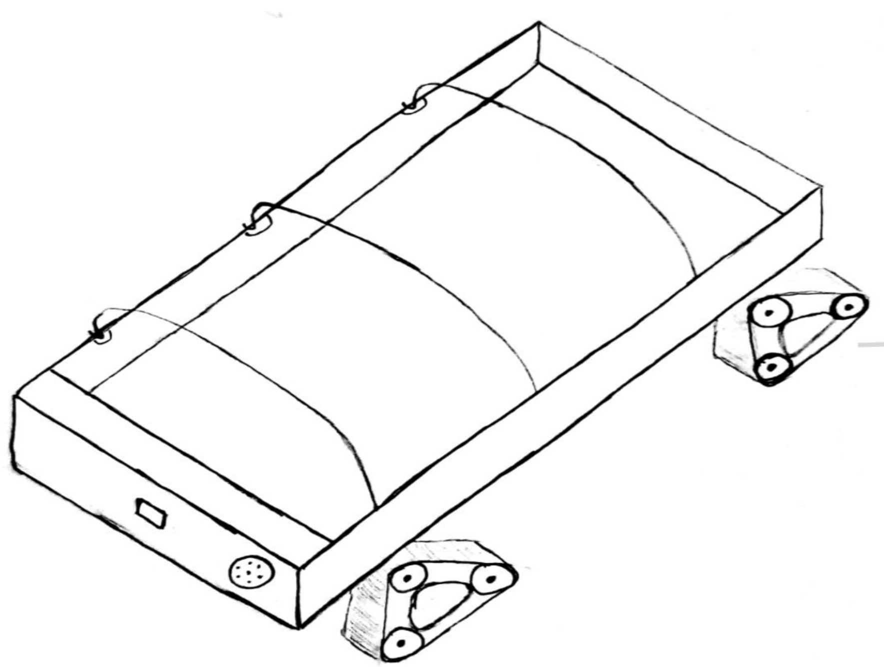


Figure F.7: Concept of combined designs, open bed, individual wheel tracks, accessory power. This was the design the customer liked the most and we moved forward with.

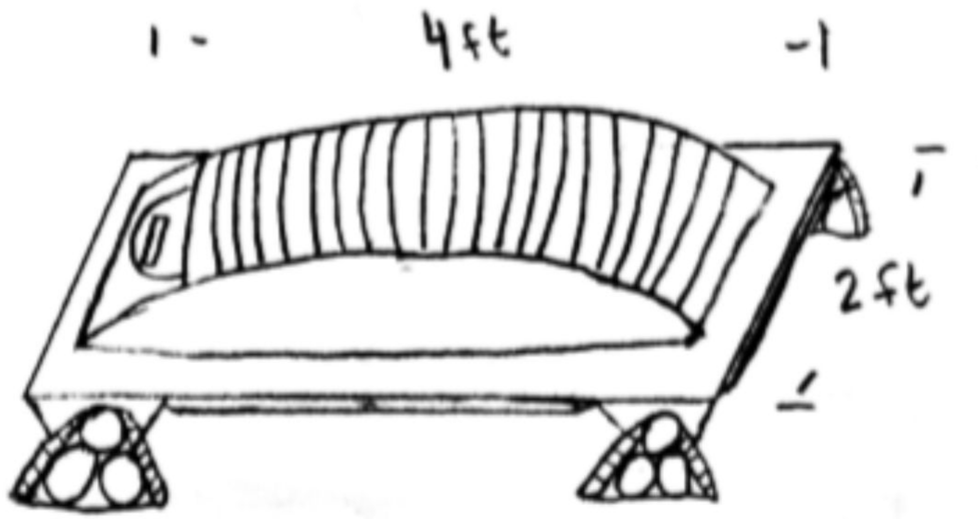



Figure F.8: Concept of combined designs, enclosed bed & wheel tracks

After the CDR our project had a clear vision and the team's sketches moved from designing on a white board to planning and sketching in CAD.

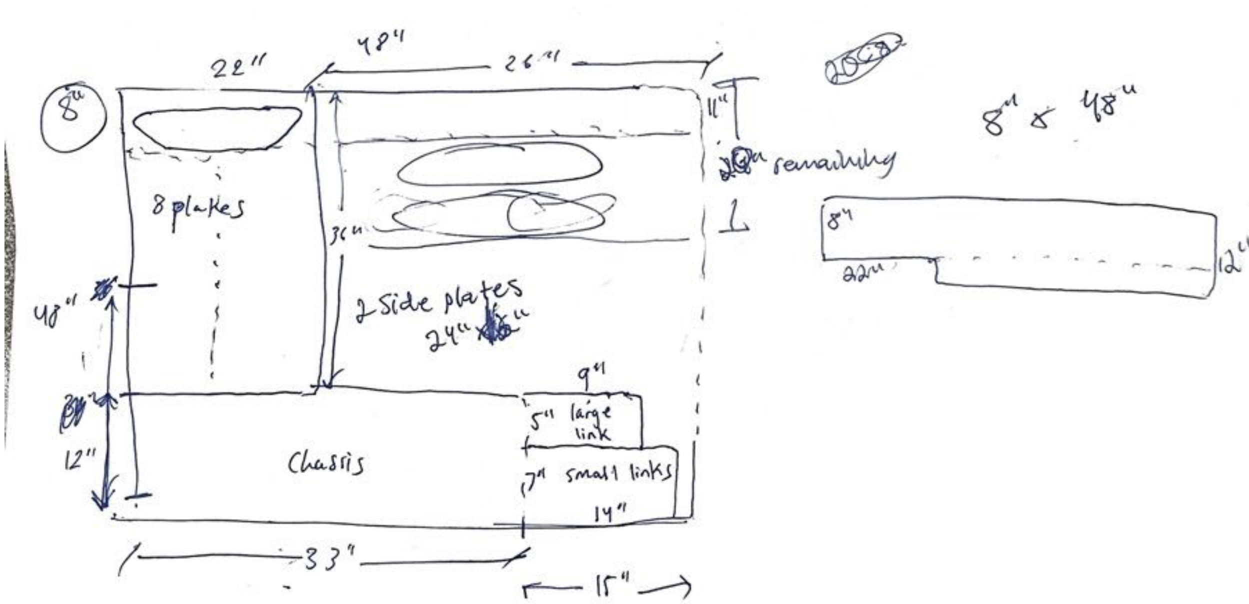



Figure F.9: Water jet cutting plan to reduce wasted material and maximize the amount of parts the team could cut out of the sheet metal

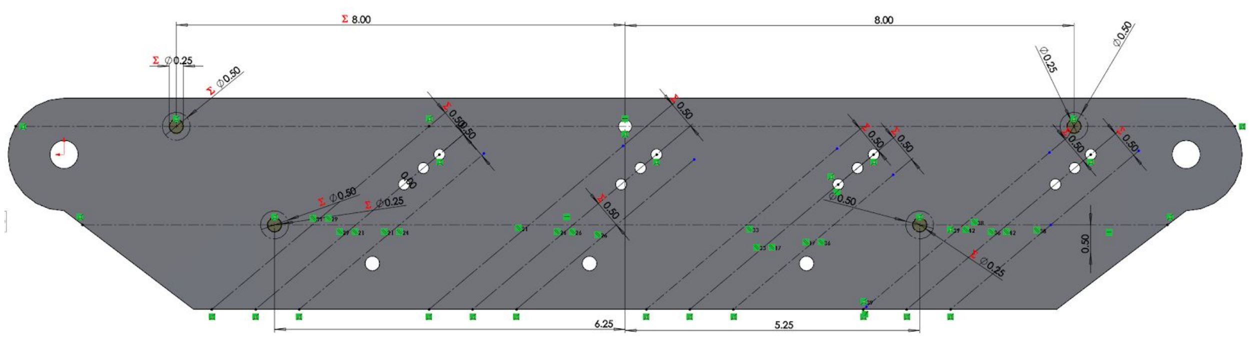



Figure F.10: Sketch used to verify mounting hole placements, so that spacers did not interfere with the suspension shocks.

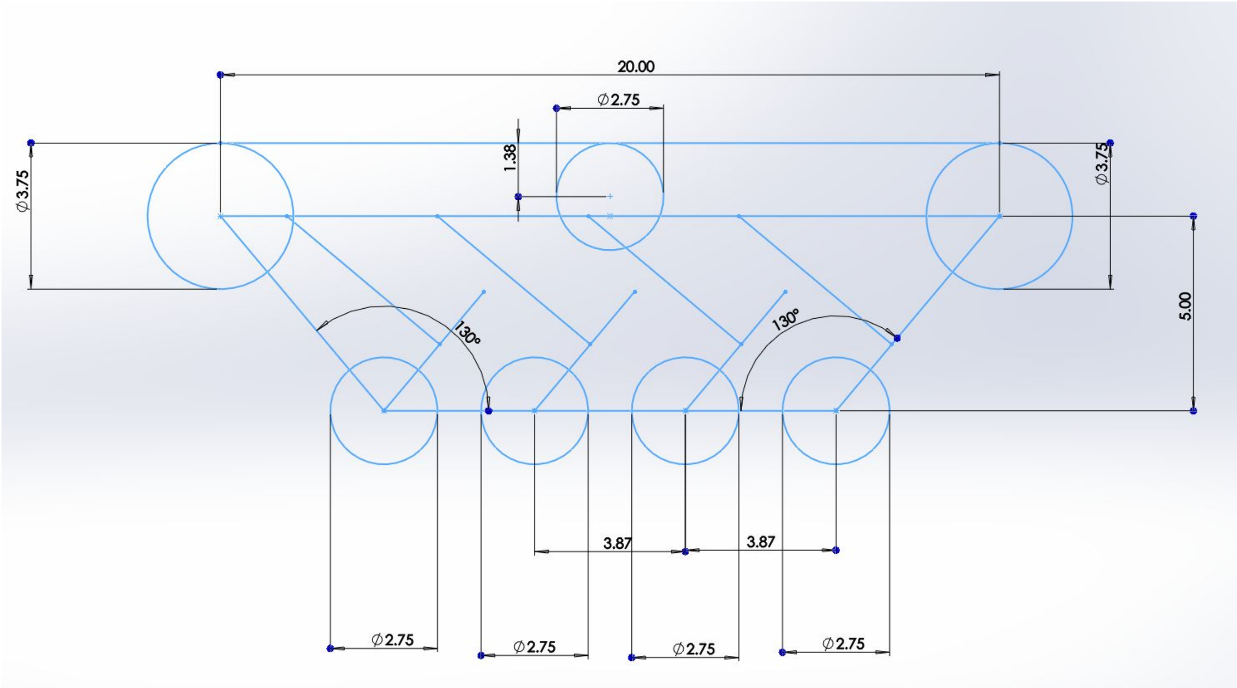



Figure F.11: Initial Drawing of Tank Tread System Design

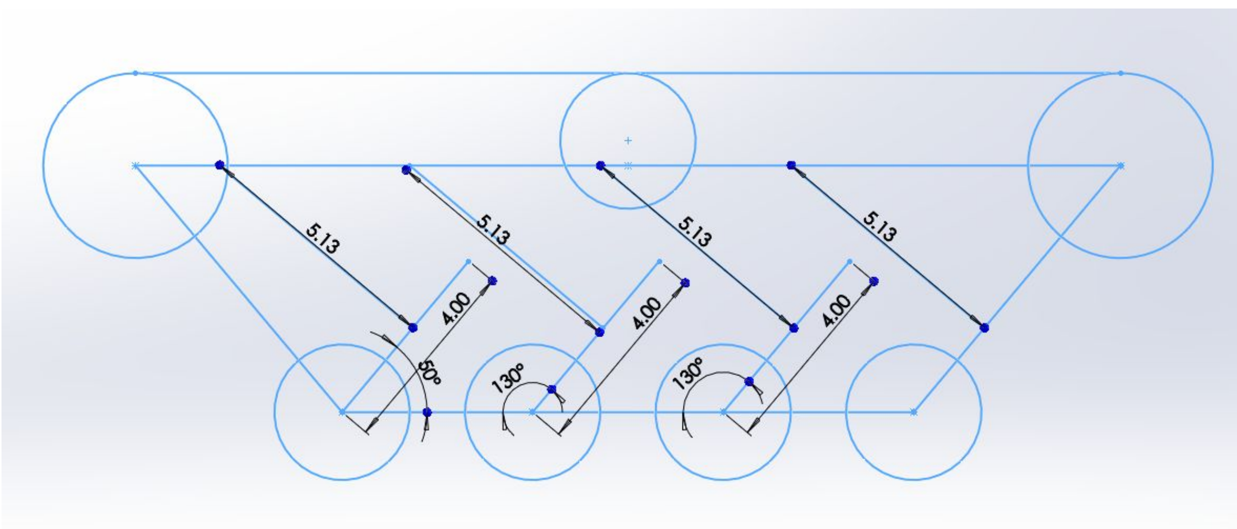



Figure F.12: Second View of Initial Tank Tread System Drawing

## G: Mechanical CAD

Figures G.1 to G.5 depict the preliminary CAD modeling done from the project updates post PDR to the CDR. After the CDR, figures G.3-G.5 were iterated and refined to get the final CAD models depicted in G.6-G.17.

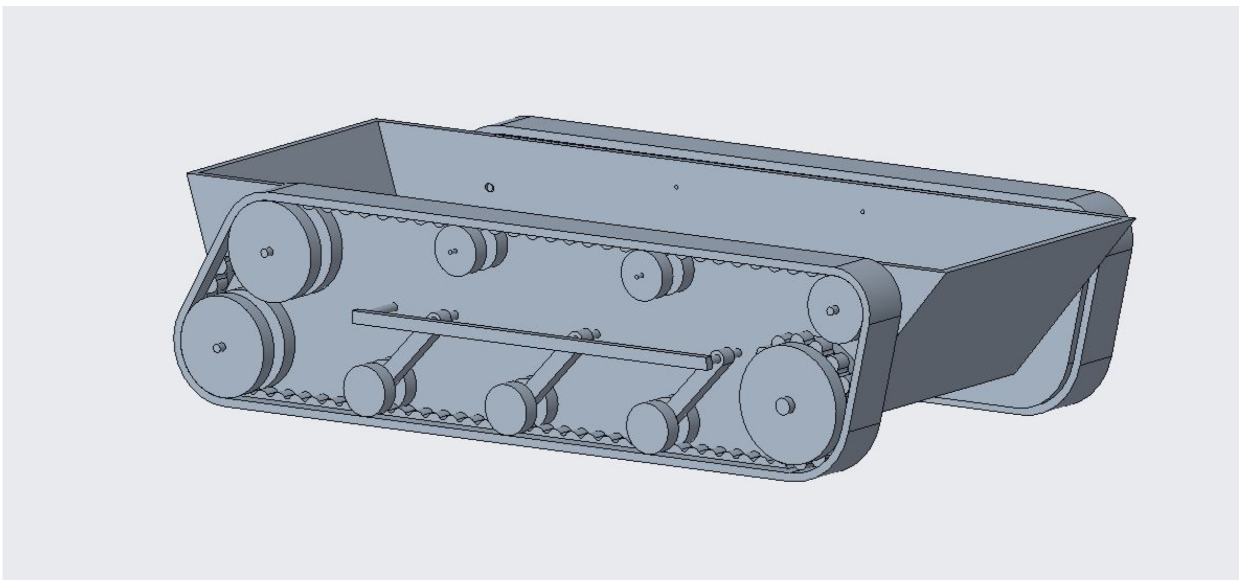


*Figure G.1: The initial conceptual CAD design of what tank tread system could look like on the final prototype.*

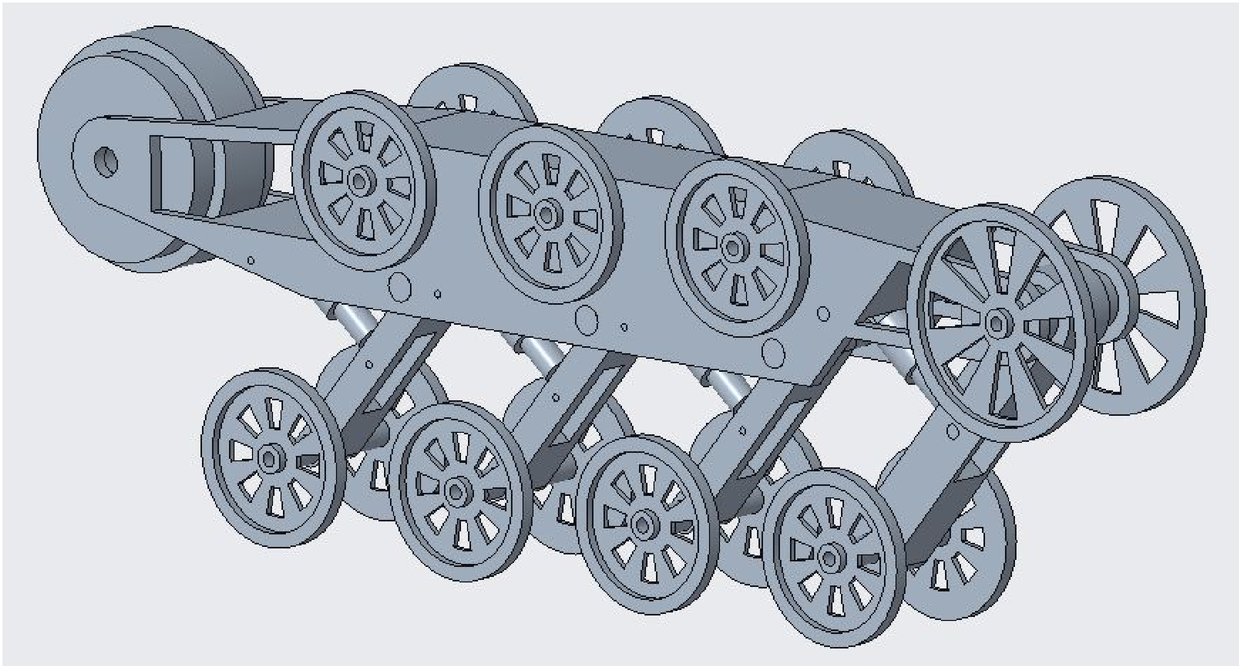


*Figure G.2: A more refined version of the initial CAD model. This CAD design shows the pistons and more accurate part design than G.1. Before looking into existing market parts was done this is potentially the design the team could have moved forward with. However, after the time to machine and availability of parts was considered. The team moved forward with a design focused around figure G.3*

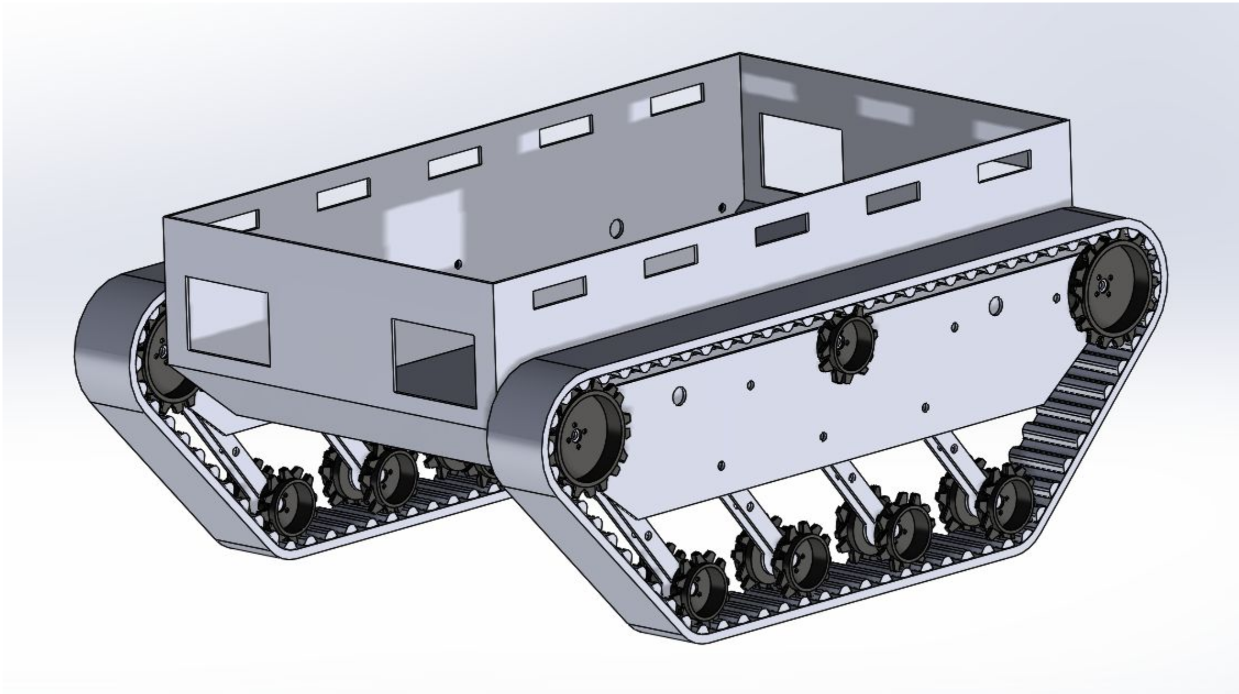


*Figure G.3: Final to scale prototype CAD design. It uses the purchased Lynxmotion motion sprockets and a completed chassis with provisions for sensors and cameras along with holes for a stokes basket strap. This is the design we iterated to get to the final design*

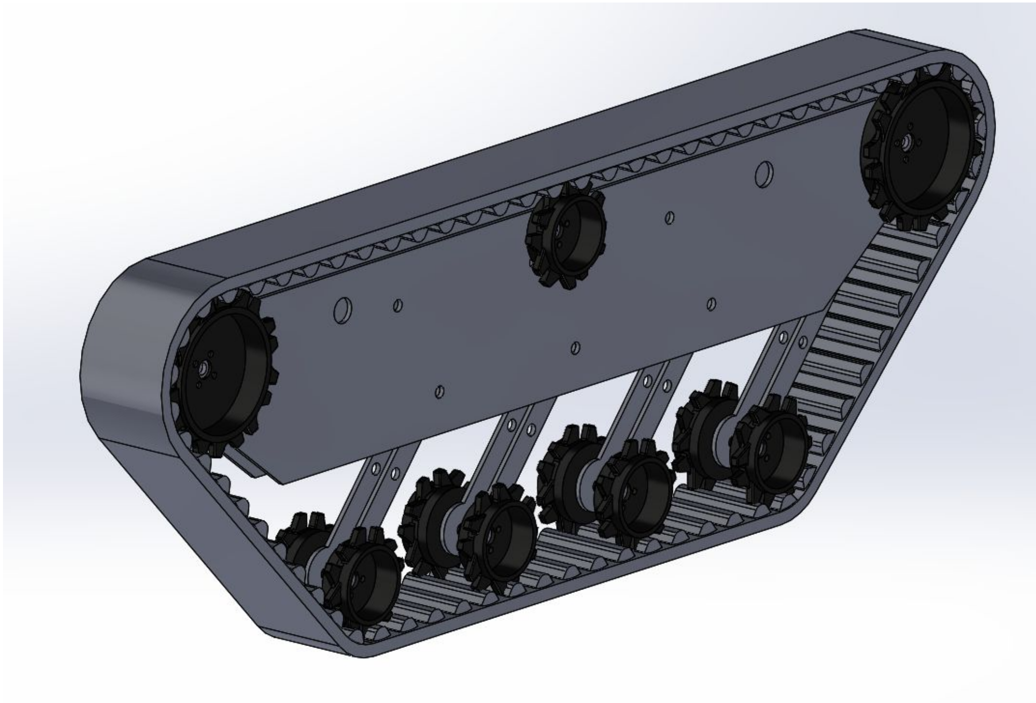


*Figure G.4: Tread system assembly*

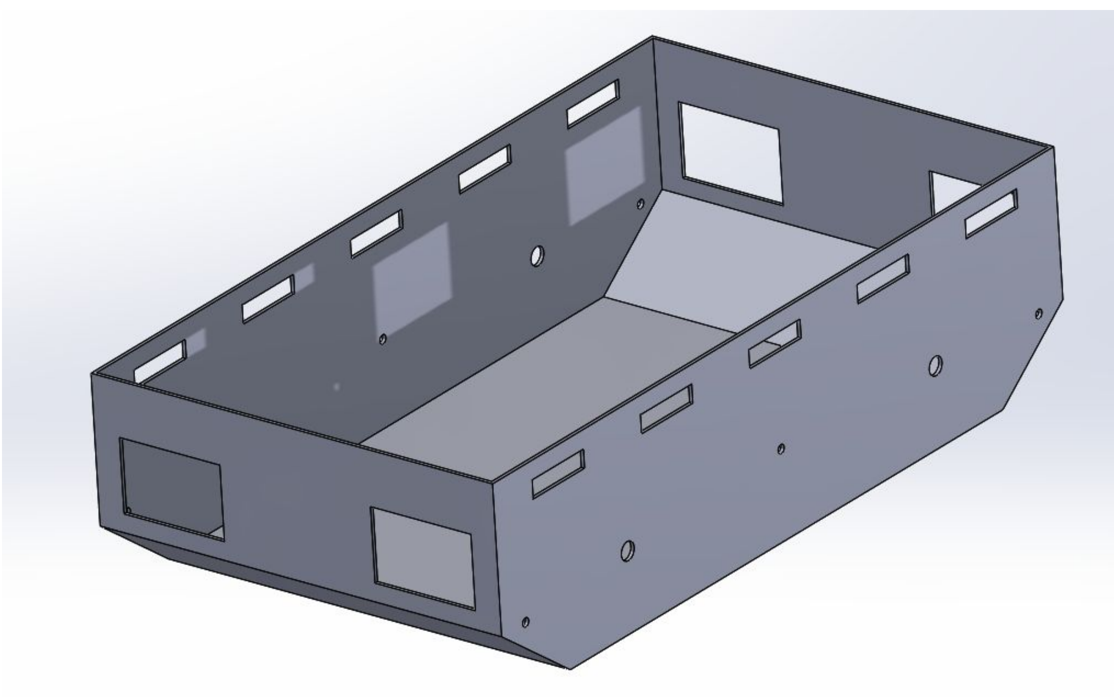


*Figure G.5: Base chassis and the holes it connects to the tread system with*

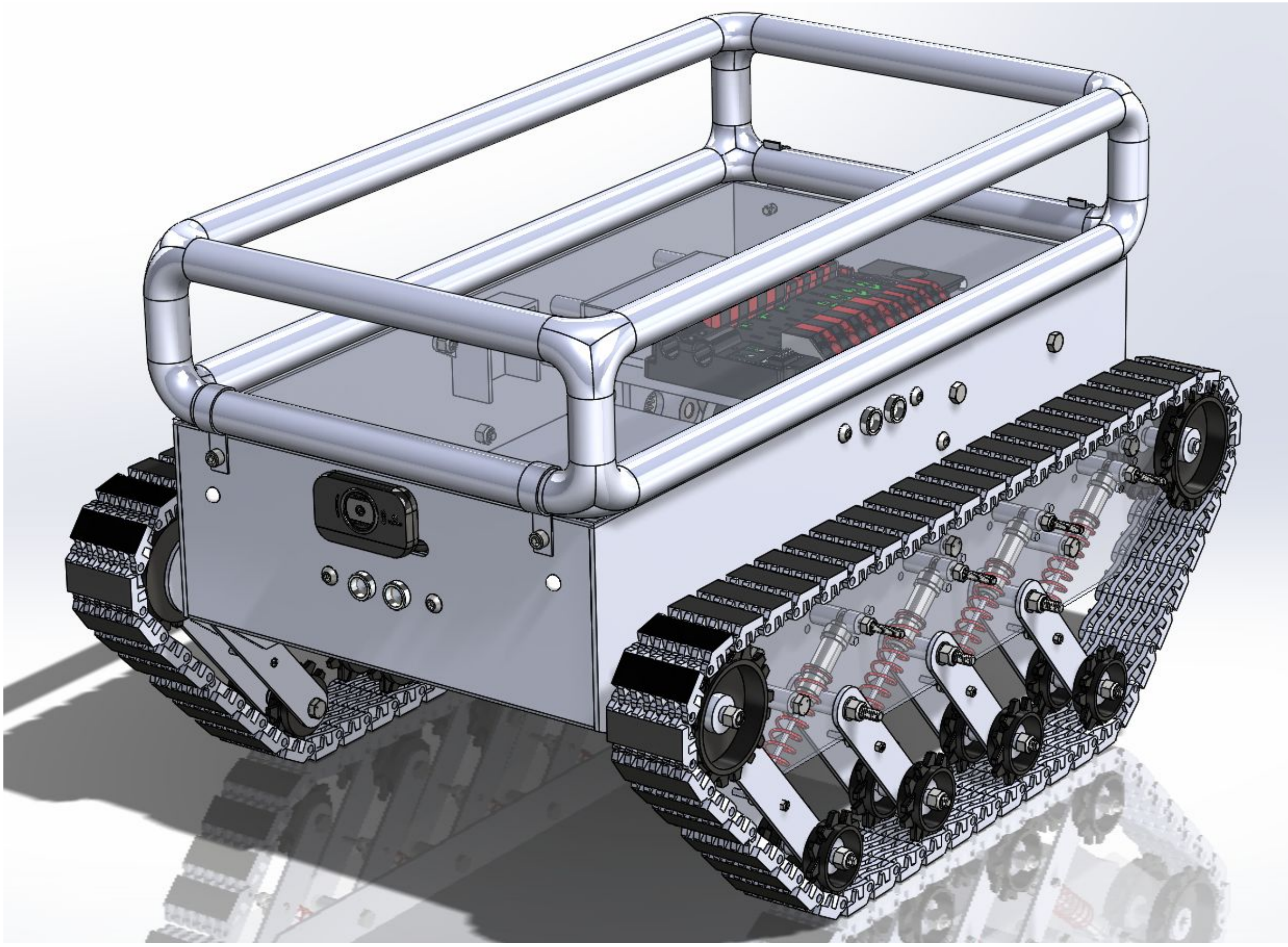


*Figure G.6: The assembly depicting our final prototype. The chassis top and tread plates have been made transparent to give some internal view*

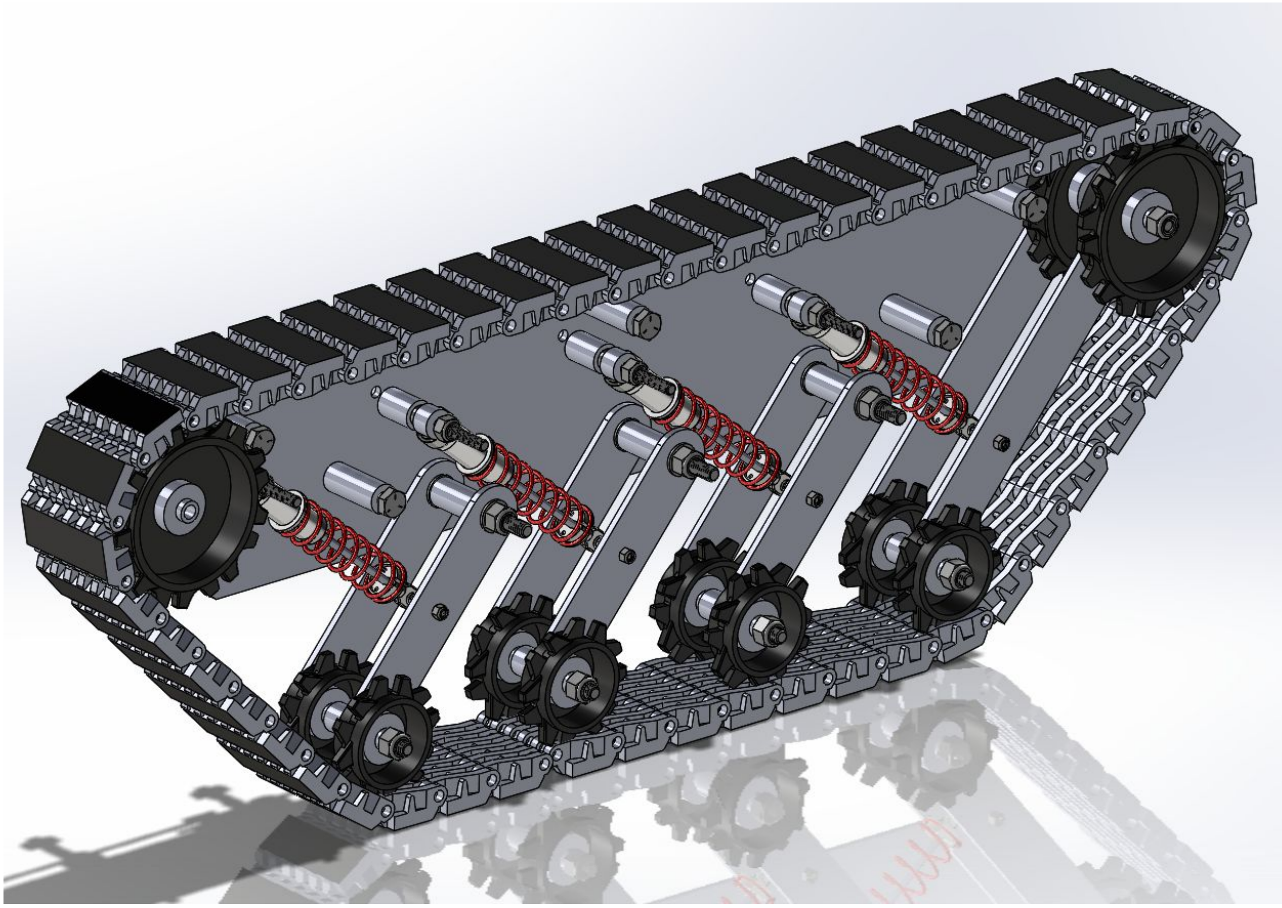


*Figure G.7: Final Tread System Sub-Assembly. Outer tread plate remove for inside view*

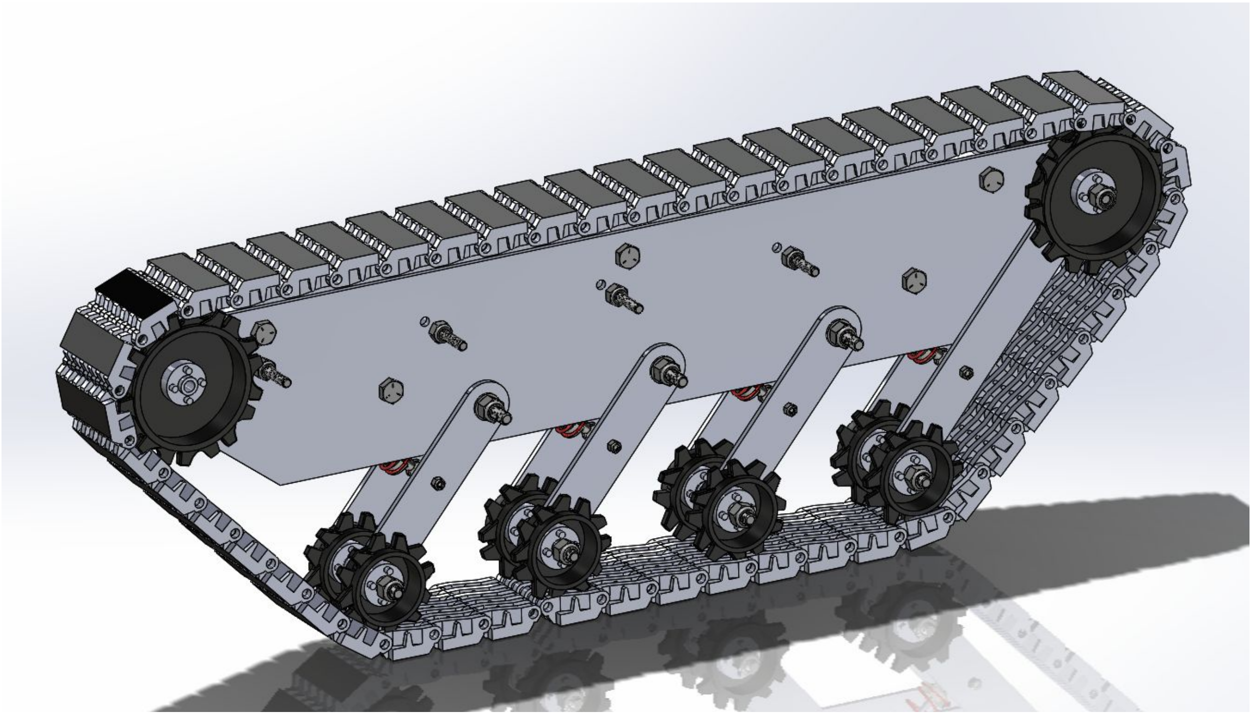


*Figure G.8: Final Tread Sub-Assembly with outer tread plate*

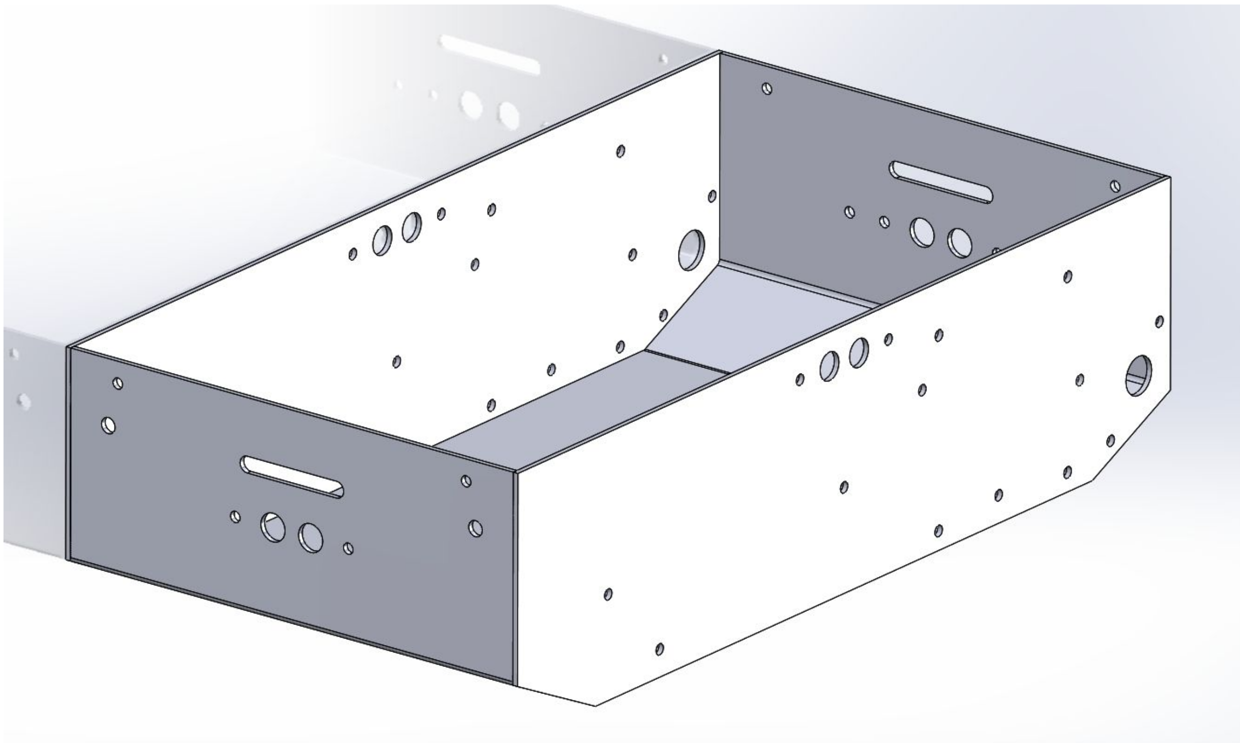


*Figure G.9: Base chassis and all the holes for mounting and connecting*

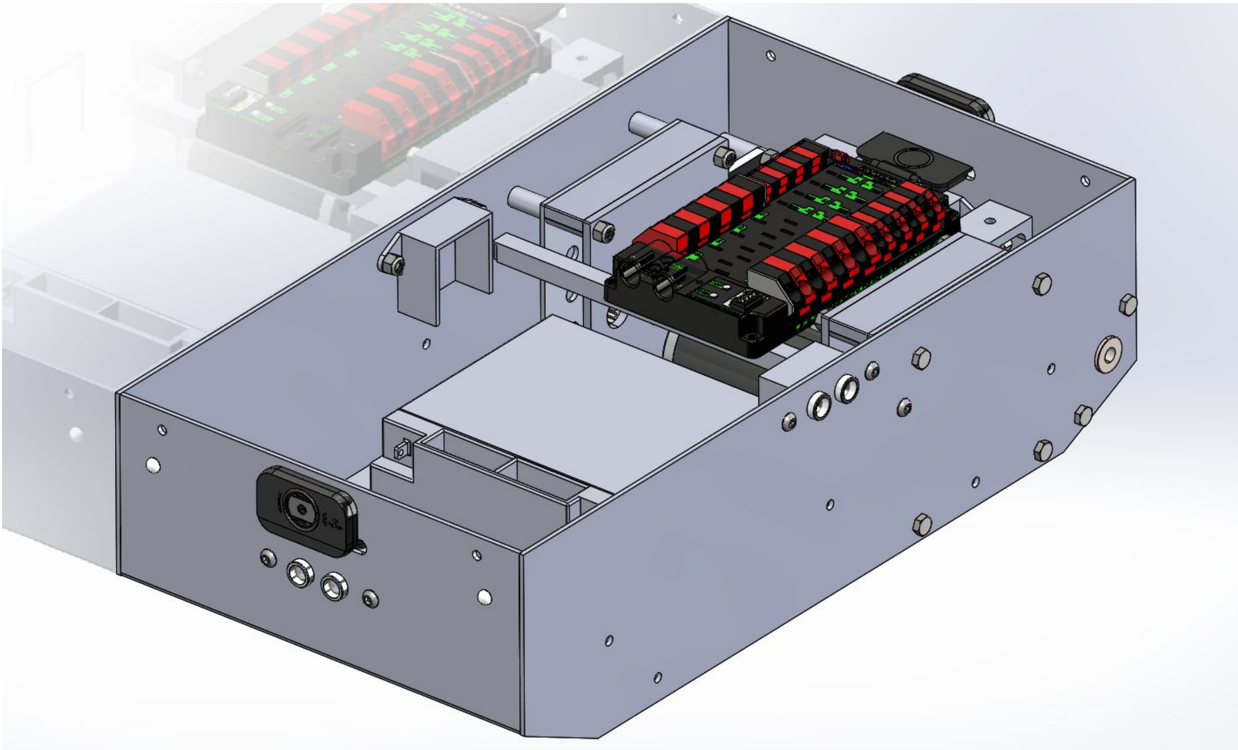


*Figure G.10: Base Chassis Sub-Assembly with internal components and sensors*

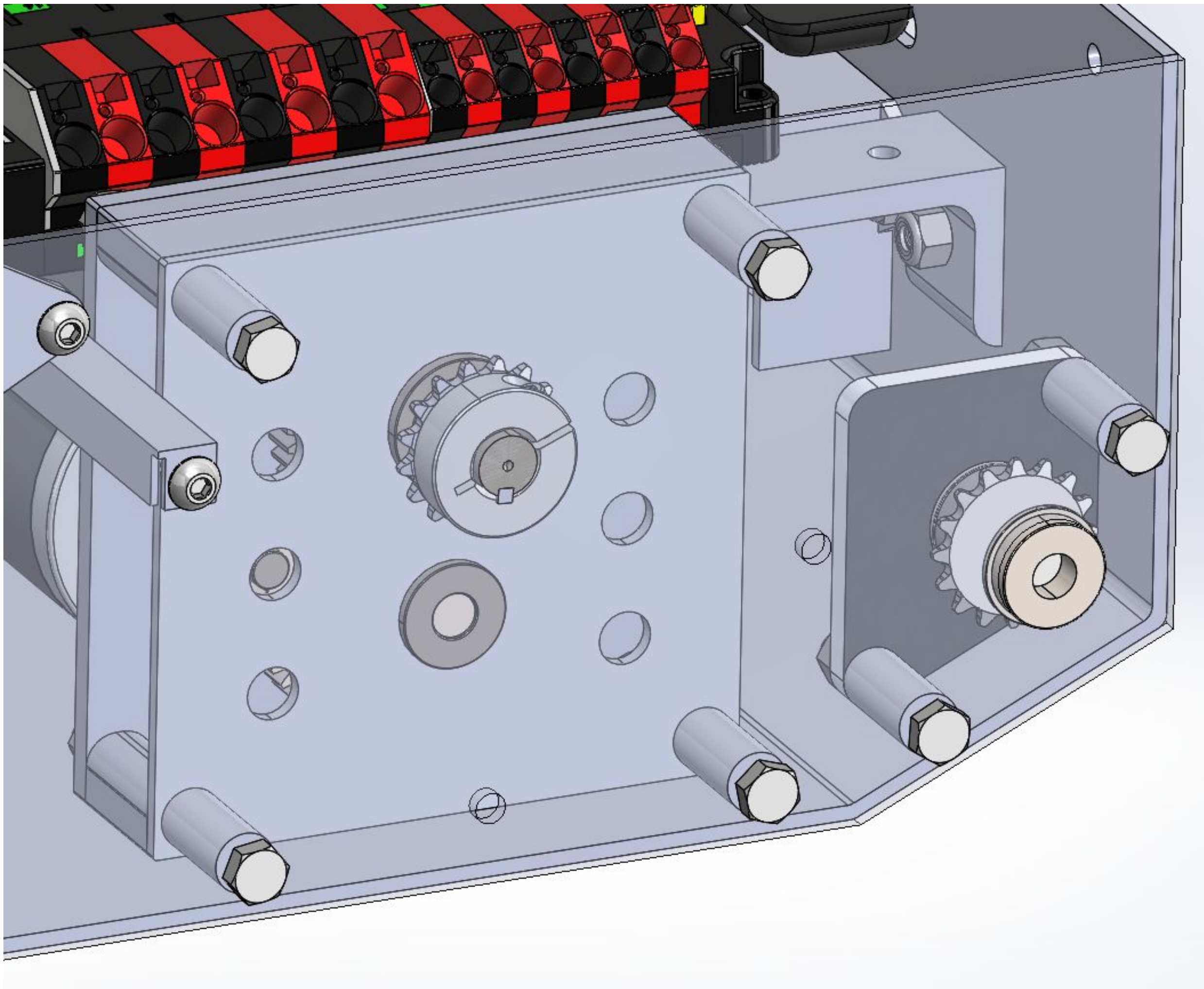


*Figure G.11: Close up of drive system. The figure depicts the sprocket connection from the gearbox to the output shaft.*

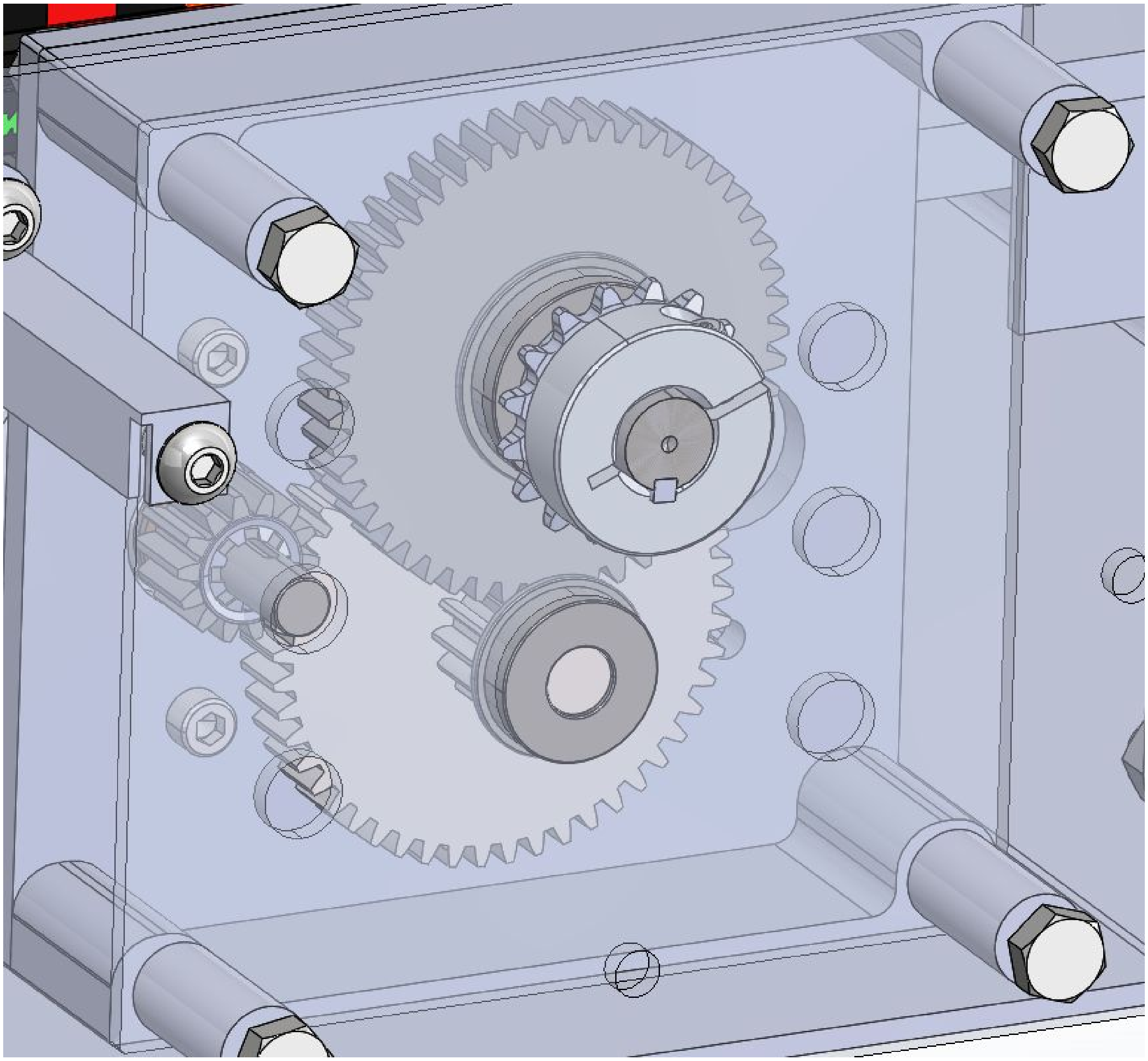


*Figure G.12: Gearbox to give gear ratio of 14.5 to 1*

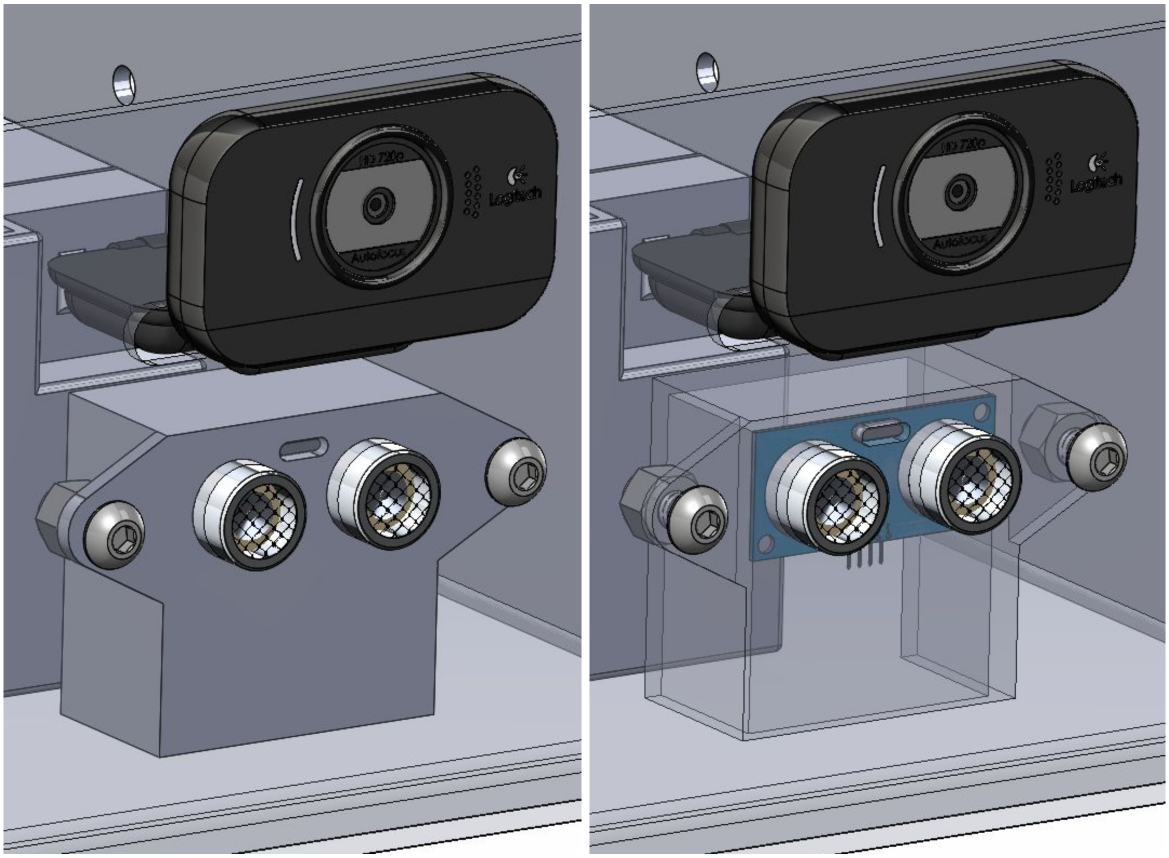



*Figure G.13: Ultrasonic and camera system*

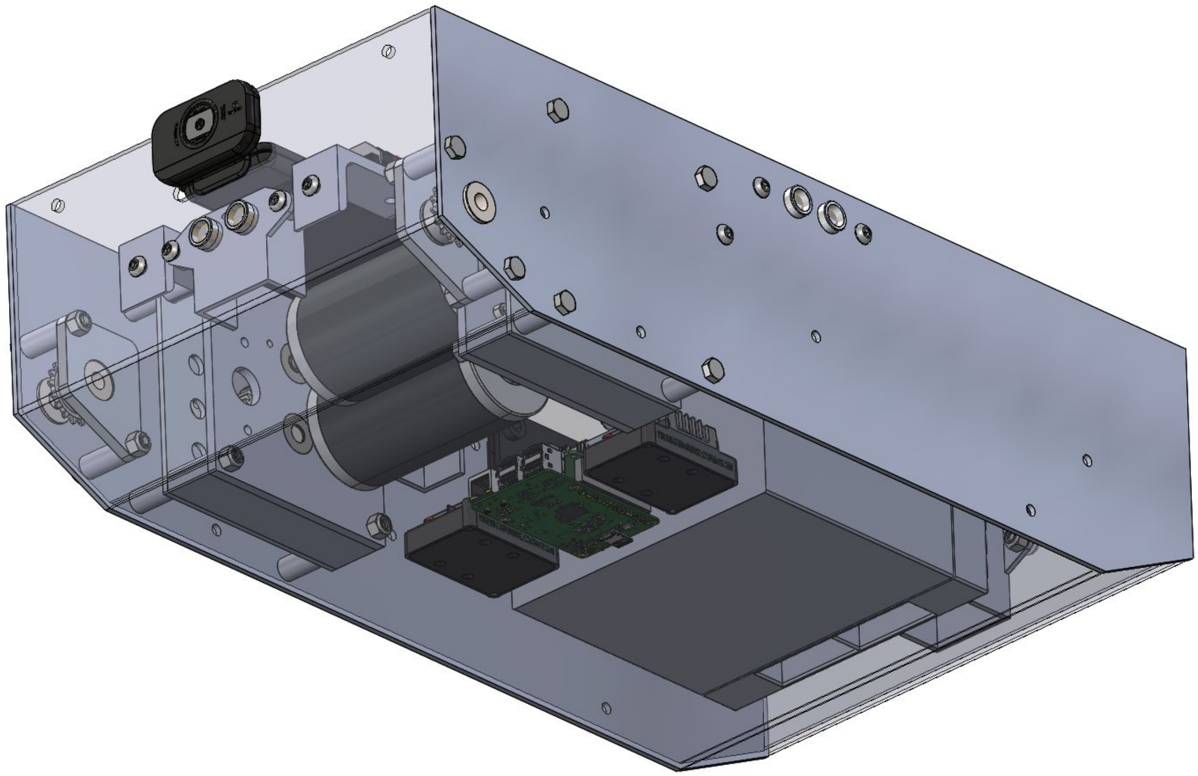


*Figure G.14: Bottom view of Chassis Sub-Assembly*

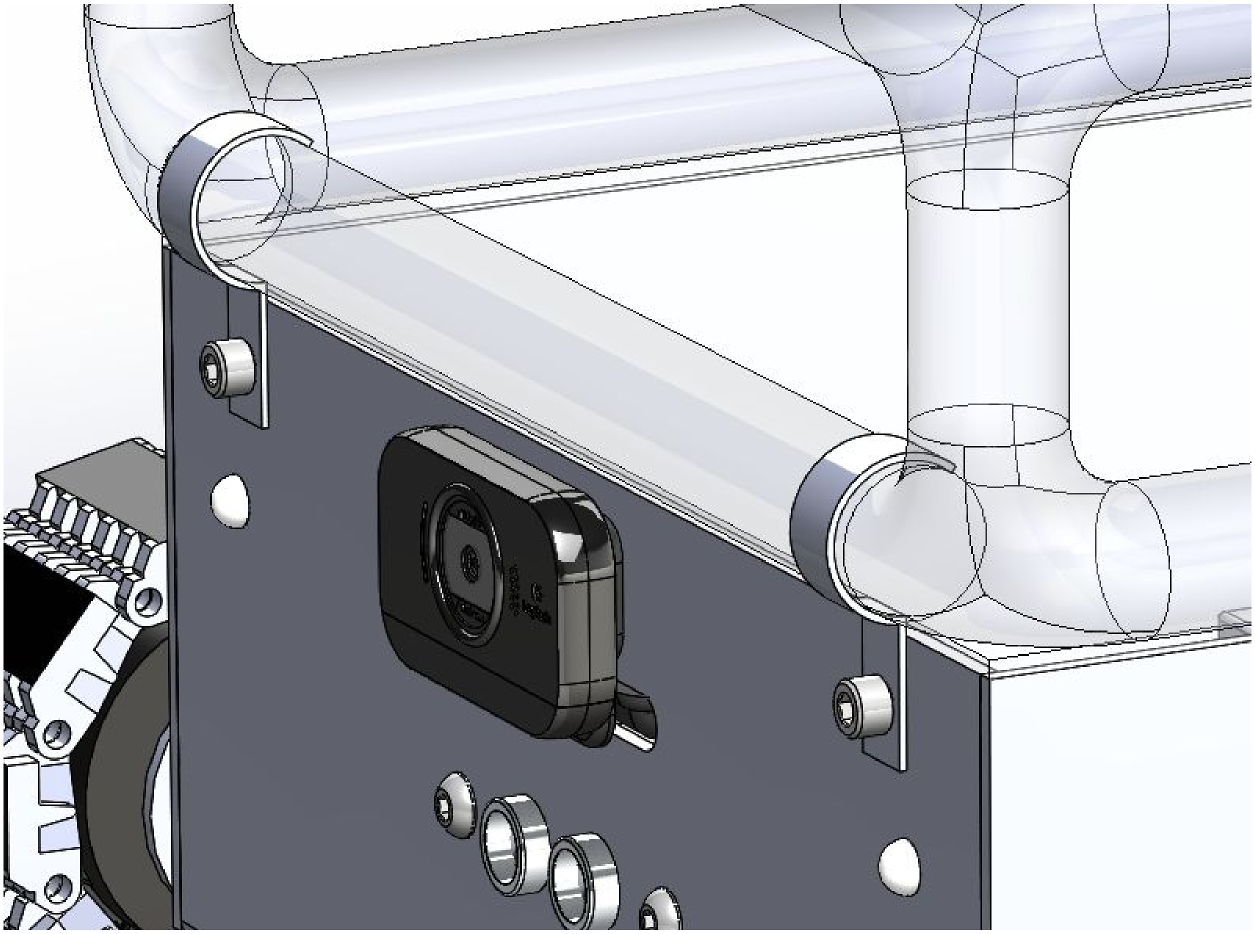


*Figure G.15: Chassis clips attached to the stokes basket*

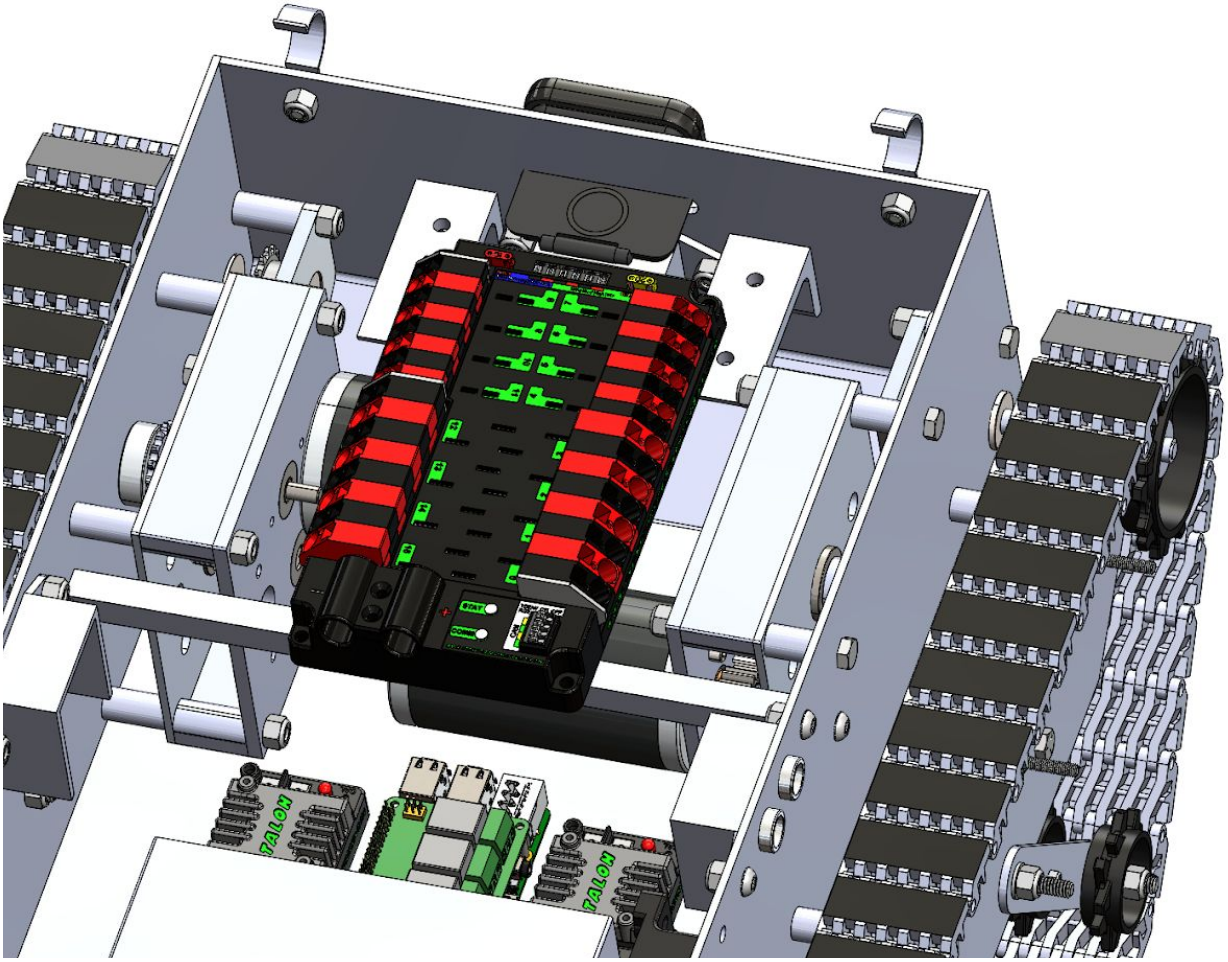



*Figure G.16: View under power distribution board*

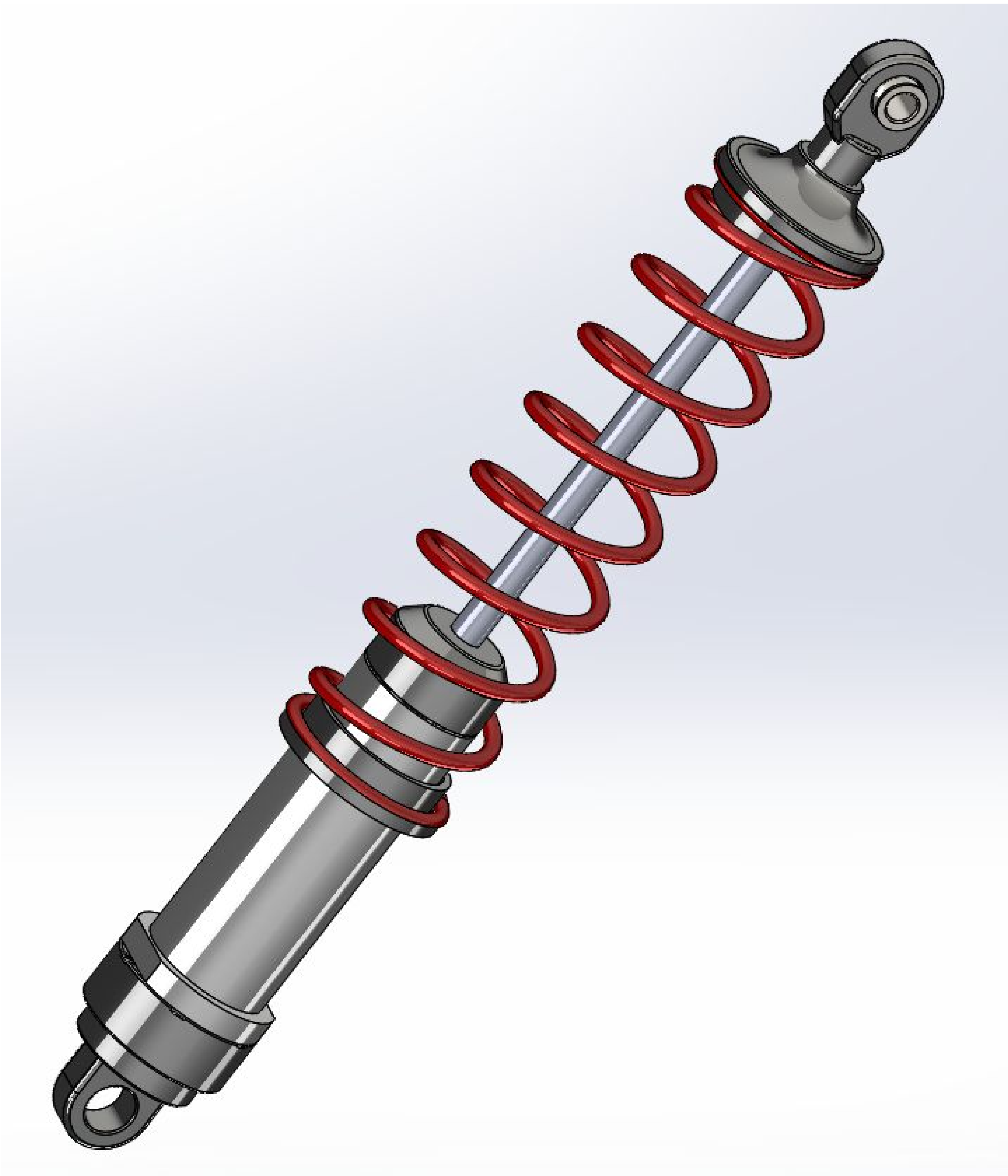


*Figure G.17: Shock Sub-Assembly*

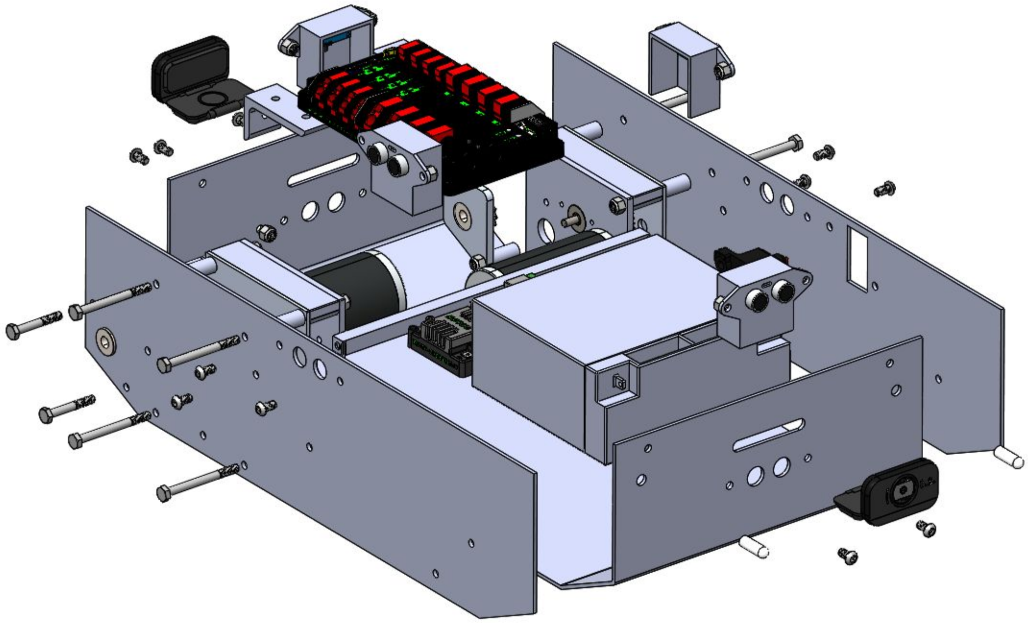


*Figure G.18: Chassis Sub-Assembly Exploded View*

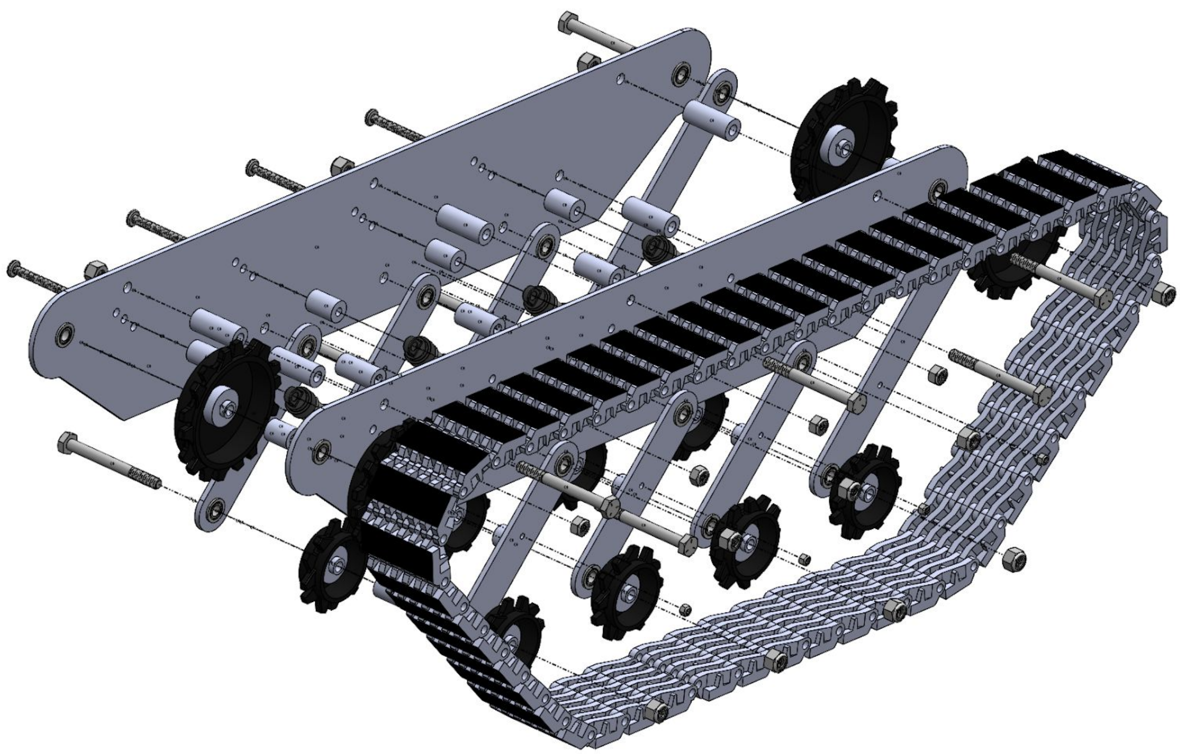


*Figure G.19: Tank Tread Sub-Assembly Exploded View*

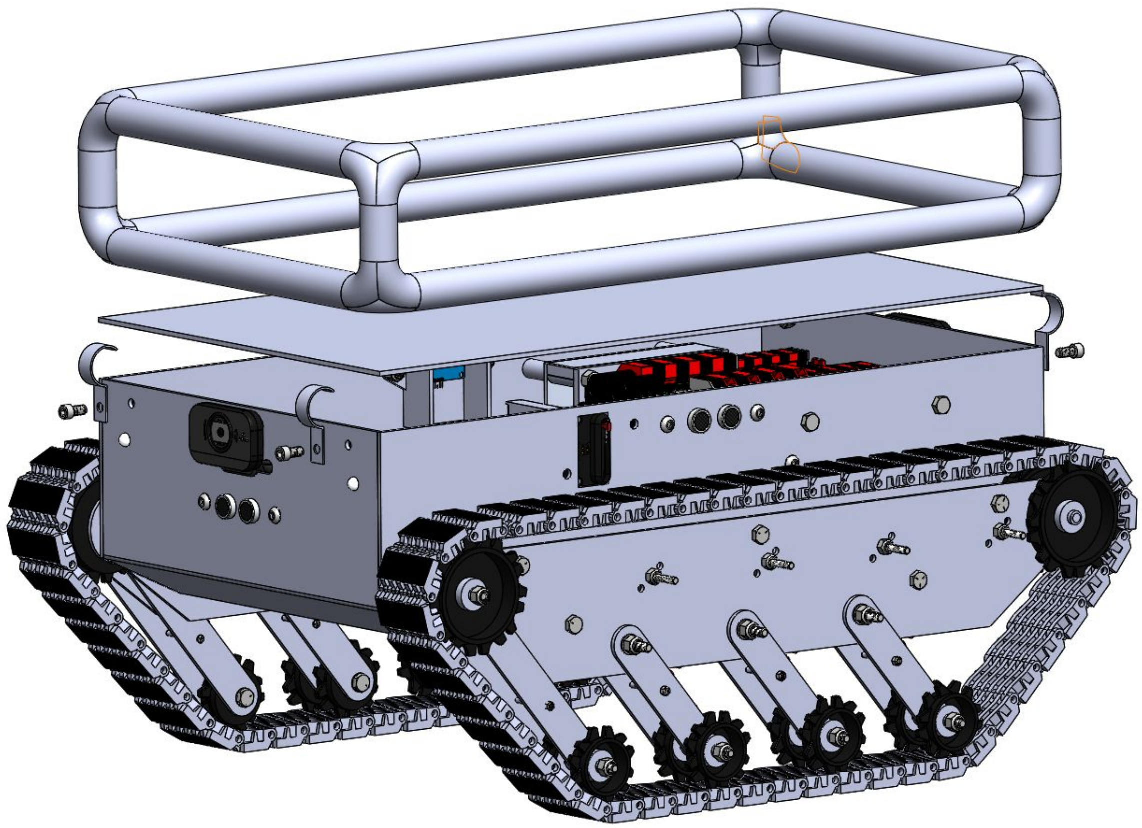


*Figure G.20: Full Robot Exploded View*

## H: Mechanical CAE (FEA, CFD, motion path simulation, … depending on your project)

*Note: All engineering analyses have been completed for the half scale design*

*Note: The words 'track' and 'tread' and used interchangeably and effectively mean the same thing; the entire sub assembly of the continuous track system. For reference see figure G.6.*

### H1. Chassis Balance Analysis

There were several things that needed to be placed inside the chassis. A simple moment analysis was conducted to determine where these components could be placed with respect to each other to cancel out any moments and stabilize the robot.

To begin with are several relationships between components that would not change:

- Distance between two motors (A1 - A2 = d)
- Distance between center of gearbox to center of CIM motor on it (B - x = A2)
- Total length of chassis 21.9 inches
- Location of power distribution board center mass known (will be placed vertically on chassis front)

Substituting these into the moment analysis gave an equation that related to the placement of the gearbox to the placement of the battery, the two heaviest and most flexible in terms of position.

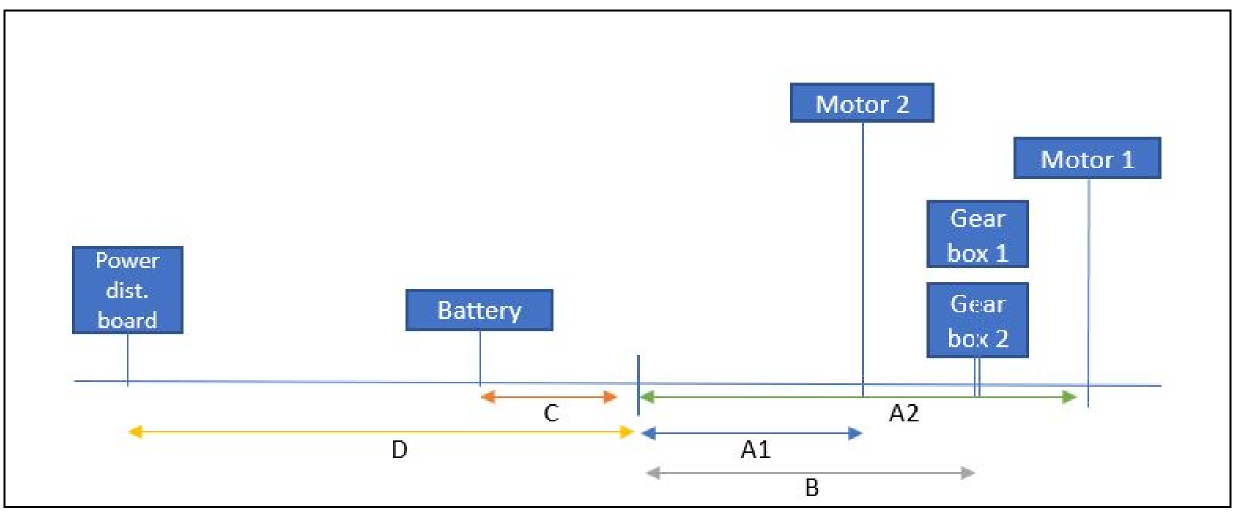



*Figure H.1.1: Schematic showing chassis and placement of each component inside*

$$D_1 = \frac{21.9}{2}$$

$$2(10.95) + 13.6C_1 = 2.8A_2 + 2.8A_1 + \overset{B_1}{3.1}B_1 + 3.1B_1$$

$$2(10.95) + 13.6C_1 = 2.8(A_2 + A_1) + 6.2B_1$$

$$= 2.8(A_2 + d + A_2) + 6.2B_1$$

$$2(10.95) + 13.6C_1 = 2.8(d + 2A_2) + 6.2B_1$$

$$= 2.8(d + 2(B_1 - x)) + 6.2B_1$$

$$2.8(d + 2B_1 - 2x) + 6.2B_1$$

$$2.8d + 5.6B_1 - 5.6x + 6.2B_1$$

$$2(10.95) + 13.6C_1 = 2.8d + 11.8B_1 - 5.6x$$

$$A_1 - A_2 = d \qquad B_1 - x = A_2$$

$$A_1 = d + A_2$$

$$13.6C_1 = 2.8d + 11.8B_1 - 5.6x - 2(10.95)$$

$$C_1 = \frac{2.8}{13.6}d_1 + \frac{11.8}{13.6}B_1 - \frac{5.6}{13.6}x - \frac{2(10.95)}{13.6}$$

battery pos.

input gearbox pos

*Figure H.1.2: Mathematical calculations for moment analysis*

| | All positions in inches | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Item | Weight (lb) | Quantity | Pos from center (in) | | (in) | constants | (in) | |
| A2 (closer) | Cim motor | 2.8 | | 3.5 | | 11.9 | | | |
| A1 (farther) | Cim motor | 2.8 | 2 | 6.51 | | 14.91 | d | 3.01 | motor to mo |
| B1 | Gear box | 3.1 | 2 | 5 | | 13.4 | x | 1.5 | motor to gea |
| C1 | Battery | 13.6 | 1 | 1.50 | | 6.90 | inner length | 21.9 | |
| D1 | power dist board | 2 | 1 | 10 | | 1.9 | | | |

*Figure H.1.3: Snippet of spreadsheet to automate calculations*

Yellow cell indicates an input and green cell indicates an output in figure H.1.3. All other distance values derive from these two cells.

The engineers chose a gearbox location most convenient for assembly and power train considerations and the placement of the 7lb battery could be determined along with the rest of the components.

## H2. Torque Analysis

| FULL SCALE | | | | | | |
|---|---|---|---|---|---|---|
| Select | Imperial | Metric | | | | |
| Weight of Robot (LB) | | 0.00 | (kg) | Total Mass | 181.41 | (kg) |
| Weight of Cargo (LB) | 400 | 181.41 | (kg) | Static Force | 1258.36 | (N) |
| Drive Train Loss (%) | 25 | 25 | | Accel. Force | 663.48 | (N) |
| Max Grade (Degrees) | 45 | 0.79 | Rad | Total Force | 1921.84 | (N) |
| Max Acceleration (ft/s/s) | 12 | 3.66 | m/s/s | Torque Needed (Nm) | 65.09 | (Nm) |
| Final Wheel Diameter (in) | 12 | 0.30 | m | Torque Needed (Lb-Ft) | 48.01 | Lb-Ft |
| Differential Gear ratio | 6 | 6 | | Torque Needed (oz-in) | 9216.968507 | (oz-in) |
| Transmission gear ratio | 1 | 1 | | Speed at given RPM | 4.487333333 | m/s |
| Motor RPM | 5300 | 5300 | | Speed at given RPM | 10.03789543 | mph |
| | | | | Power output With loss | 4499.919689 | W |

| HALF SCALE | | | | | | |
|---|---|---|---|---|---|---|
| Select | Imperial | Metric | | | | |
| Weight of Robot (LB) | 50 | 22.68 | (kg) | Total Mass | 45.35 | (kg) |
| Weight of Cargo (LB) | 50 | 22.68 | (kg) | Static Force | 314.59 | (N) |
| Drive Train Loss (%) | 25 | 25 | | Accel. Force | 165.87 | (N) |
| Max Grade (Degrees) | 45 | 0.79 | Rad | Total Force | 480.46 | (N) |
| Max Acceleration (ft/s/s) | 12 | 3.66 | m/s/s | Torque Needed (Nm) | 3.81 | (Nm) |
| Final Wheel Diameter (in) | 3.75 | 0.10 | m | Torque Needed (Lb-Ft) | 2.81 | Lb-Ft |
| Differential Gear ratio | 8 | 8 | | Torque Needed (oz-in) | 540.0567485 | (oz-in) |
| Transmission gear ratio | 1 | 1 | | Speed at given RPM | 1.05171875 | m/s |
| Motor RPM | 5300 | 5300 | | Speed at given RPM | 2.352631741 | mph |
| | | | | Power Output with Loss | 749.9834275 | W |

*Figure H.2: Torque Analysis Spreadsheet*

Calculating the required power needs of the drive system was achieved through analyzing the necessary torque. The required torque is dependent on the total weight of the system, the incline being scaled, and the acceleration. A spead-sheet was developed with parameters that can be modified to achieve a balance when taking into consideration battery life, weight, capability, and cost.

The maximum weight of the half scale robot will be 100 lbs when fully loaded. The drive train loss (friction) was estimated at 25%. This was based on the extreme case of a four-wheel-drive vehicle, which is typically 17-25%. The friction in the tracks and one gearbox in the DOG was estimated to be comparable to vehicles that have torque converters, transfer-cases, a transmission, and differentials. The maximum scalable grade while fully loaded is set at forty-five degrees, ten degrees steeper than a standard staircase. With a drive wheel diameter of 3.75", and a gear reduction of 8:1, the required torque was determined to be 540 in-oz, and the power draw will be 750 watts. Two motors will be used (one per track) with a rated rpm of 5300. The max speed with these parameters, when on flat terrain will be about 2.3mph.

### H3. Axle Analysis

The dynamic and static performance requirements of the half scale robot with regards to the drivetrain and axles include a fully loaded weight (robot weight plus carrying weight) of 45kg or 100 lbs and the ability to traverse semi-complex terrain such as very light rubble and curbs.

Taking into consideration these requirements, the static calculations with respect to the axles were calculated. This simply includes the fully loaded weight of the robot divided by the number of load bearing contact points, eight in this case since there are eight wheels touching the ground. In conclusion each axle will have to support 5.62kg or 12.4lbf.

The dynamic calculations are a bit more involved with more variables and are split up into two different scenarios. The first scenario is for impact force on axles from the robot falling. The robot is expected to flex and withstand impacts from minor falls resulting from going over the semi-complex terrain as mentioned before. Therefore it is estimated that the robot will have to withstand, in the absolute worst case, about 2.5cm of a fall with an estimated maximum spring and track compression of 2cm based off of the suspension design. This leads to a each axle enduring a maximum impact force of about 69N or 15.5lbf while fully loaded. The equation used to calculate impact force from falling is F=mgh/d where 'm' is the mass, 'g' is gravity, 'h' is the height of the fall, and 'd' is deflection of the suspension. This equation is also shown in figure H.3.1.

The second dynamic scenario is regular horizontal impact on the robot (running into objects). It is mainly a function of the total loaded weight, horizontal velocity, and the combined net deflection distance of the track and suspension system combined. Assuming a fully loaded weight of 100lbs, 2.2mph (1m/s) of curb climbing speed, a maximum track and suspension displacement of 2.14in (5.44cm), and four contact points, the estimated maximum horizontal impact force experienced by the front of the robot is about 23.3lbf. The maximum track and suspension displacement was calculated by the amount the track would be deformed under tension when hitting a 6in curb (3in for half scale). The assumption of four contact points was made by determining that only the front portion of the track and the first wheel would be in contact with the curb while initially trying to climb it. The equation used to calculate impact force from falling is F=mv^2/(2d) where 'm' is the mass, 'v' is horizontal velocity, and 'd' is the deflection of the suspension and track combined. This equation is also shown in figure H.3.1.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Dynamic Calculations** | | | | | | | | |
| Impact force from falling | | | | | | Impact force from horizontal collision | | |
| F=mgh/d | | | | | | F=mv^2/(2d) | | |
| m | **45** | mass of robot (kg) | | | | m | 45 | mass of robot (kg) |
| g | 9.81 | 9.81 m/s^2 | | | | v | 1 | velocity (m/s) |
| h | 0.025 | height of fall (m) | | | | d | 0.0544 | compression of contact point, flex (m) |
| d | 0.02 | suspension compression (m) | | | | | | |
| | | | | | | | | |
| Force = | 551.8125 | Newtons | | | | Force = | 413.6029 | Newtons |
| per wheel | 68.97656 | | | | | | 92.97794 | lbs |
| | 15.50593 | lbf | | | | per contact point | 23.24449 | lbs |
| Number of load bearing points = | | | 8 | | | | | |
| | | | | | | Max | 23.24449 | |
| **Static Calculations** | | | | | | | | |
| m | 45 | mass of robot (kg) | | | | | | |
| per wheel | 5.625 | kg | | | | | | |
| | 12.40313 | lb | | | | | | |
| | | | | | | | | |
| **Axle Calculations** | | | | | | | | |
| Axle Shear calculations | | | | Bending Moment Analysis | | | | |
| axle diameter = | 0.006 | (m) | | axle length (lengt | 0.036 | m | Input Cell | Output cell |
| Axle area | 2.83E-05 | | | | | | | |
| Tau_max = | 548070.3 | Pa | | Max bnd mmt | 0.209200368 | Nm | | |
| | 79.49088 | psi | | | 0.154297823 | Lb*ft | | |
| | | | | | | | | |
| | | | | I (moment of inertia, pi*r^4/4) | 6.36173E-11 | | | |
| Axial Stress/strain | | | | Yield Strength (mild Steel) | 370000000 | 370 Mpa | | |
| None forseeable | | | | M (bending moment) | 7.846127652 | Nm | | |
| no axial force | | | | Max Force | 217.9479903 | N | | |
| | | | | | 48.99470823 | lbf | | |
| Max Shear strength (mild steel, 0.65% C) | 1.16E+07 | psi | | | | | | |
| **factor of safety** | **145928.7** | | | **factor of safety** | **2.11** | | | |

*Figure H.3.1: Screenshot of excel spreadsheet showing calculations stemming from impact forces*

After completing impact force calculations, it was observed that the force from horizontal collisions would always be greater on the track wheels than the robot simply falling. This makes sense conceptually since the number of contact points experiencing horizontal impacts is only 4 whereas there are 8 points to distribute the force from falling. With this in mind, axle bending moment and shear analysis was conducted for forces resulting from horizontal impacts since it is the larger of the two forces the robot will experience.

The load bearing axles are supported on either side and can be modeled as a simply supported beam as shown in figure H.3.2, therefore the axle will be experiencing a shear stress on two planes and a maximum bending moment near the center of the axle. Using the impact force from horizontal collisions values, the shear stress experienced by a 6mm axle is 548kpa or 79.5 psi. Mild steel has a 0.65% carbon component and has a shear strength of 80 GPa or

1.16e7 psi giving a shear stress factor of safety of 145929. Mild steel also has a yield strength of 370 MPa and using that to calculate the maximum bending moment results in a yield bend force of 48.9lbf per axle which results in a factor of safety of 2.11. It is important to note that this value is the minimum force required to even start bending the axle plastically. Realistically a much larger force is required to permanently bend the axle, which will result in a theoretically higher factor of safety. This is also for absolute worst case scenarios which the robot will unlikely encounter. Furthermore, no axial forces or strains are foreseeable on these axles. The equations used for the shear and bending moment analysis are shown in figure H.3.3.

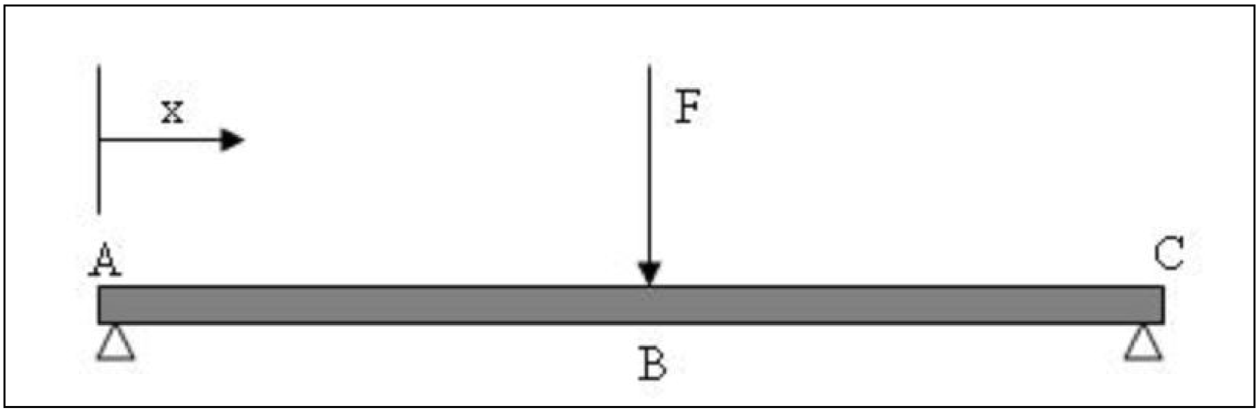



*Figure H.3.2: Representation of load bearing axles for tanks tread system as a simply supported beam*

**Shear Stress Equations:**

$\tau = \frac{4S}{3A} * \frac{1}{2}$ (for circular rods)

$S = shear\ force\ (impact\ force)$
$A = axle\ circular\ area$

**Bending Moment Equations:**

$M = \frac{SI}{y}$

$I = \frac{\pi r^4}{4}$

$M = bending\ moment$
$I = moment\ of\ inertia$
$S = yield\ strength\ (370 Mpa\ for\ mild\ steel)$
$y = distance\ from\ neutral\ axis\ (simply\ the\ radius\ in\ this\ case)$

*Figure H.3.3: Equations for bending moment and shear stress analysis*

In terms of the drive axles specifically, which are non load bearing, the maximum torsion they must be able to withstand is 270 oz-in. This is for instances where the robot is traversing complex terrain such as curbs and requires substantial torque for a limited time under max carrying weight.

Changes/Progression from CDR

Several iterative design changes were made to the tread system since the CDR. These include a change in the order of assembly and spacing of the wheels and tread plate to chassis mounting design. These resulted in a changed shear force and bending moment numbers summarized below.

*Table H.3.1: Summary of shear and bending force changes post CDR*

| | CDR | Post CDR |
|---|---|---|
| Shear Force | 235.88 PSI (49,200 FoS) | 79.49 PSI (145,928 FoS) |
| Bending Force | 44.51 lbf(1.92 Fos) | 48.99 lbf (2.11 FoS) |

As you can see, these design changes resulted in increased factor of safety (FoS) and overall decreased shear force and bending moment values leading to a more robust and safer design of the robot.

## H4. Spring Analysis

As mentioned before, the PESA robot will be required to go over semi-complex terrain such as light rubble and curbs. To achieve this the engineering team decided it was paramount that the continuous track system (otherwise known as tank tread system) would need some sort of suspension.

Existing continuous track designs were used as inspiration and it was decided the best place to add the shock assemblies was by mounting them to the tread plate (Figure F.10) and for all the links that had wheels touching the ground (four on each side). However, suspension designs can be complex and figuring out the exact placements and geometries of the shocks analytically proved to be difficult because there were too many variables to consider.

These variables included:

- Range of motion of shocks
- Force each shock would have to withstand
- Interference with other parts of the track system

To solve this, the team drilled several holes into the tread plate and iteratively figured out where the shocks would mount and the angle at which they would stay as shown in Figure H.4.1. The holes were drilled in a particular diagonal manner where they would not affect the mechanical advantage and interference of the shocks. Then, one side of the track was completely assembled and each mounting hole was tested to see if there was any interference with the spacers, bolts, washers, etc already assembled. After trying all the configurations, the middle hole worked perfectly for our particular assembly.

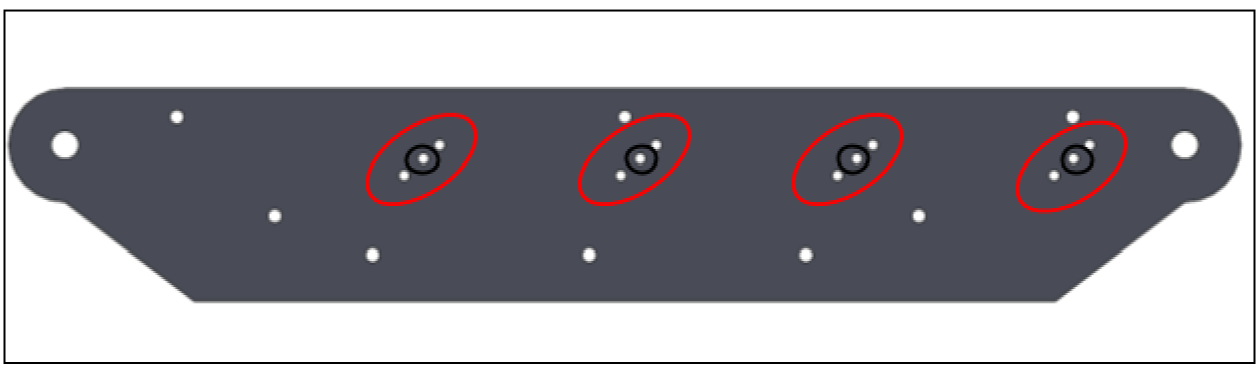


*Figure H.4.1: Image of tread plates highlighting the test mounting holes*

After the geometry of the suspension was finalized, mathematical calculations were carried out to figure out the forces and moments on the individual spring and links. The math is the same as shown in figure H.3.3 and the FBD for these is shown below in figure H.4.2.

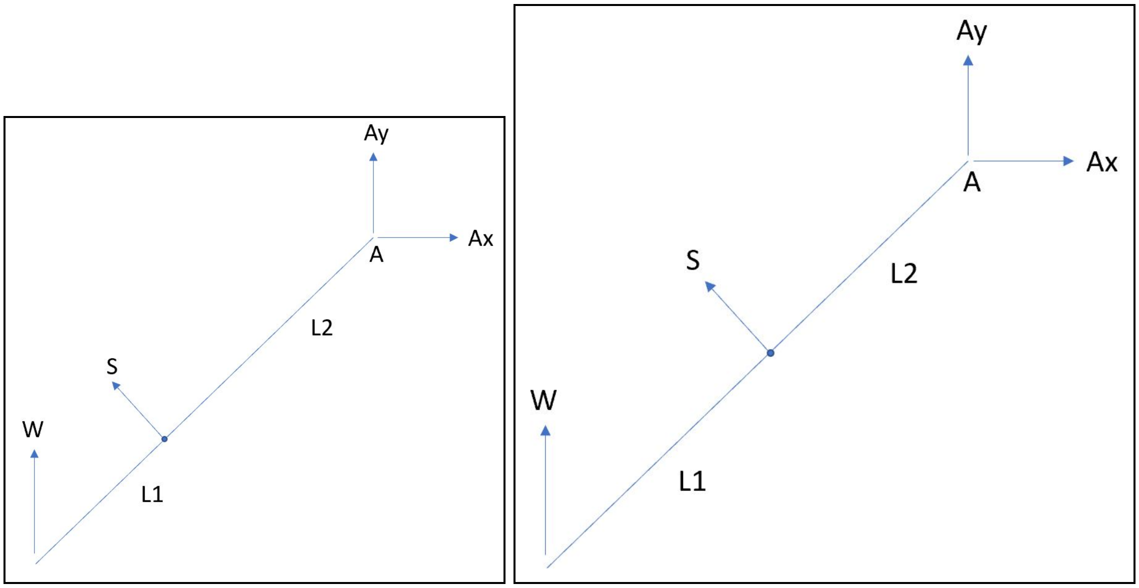
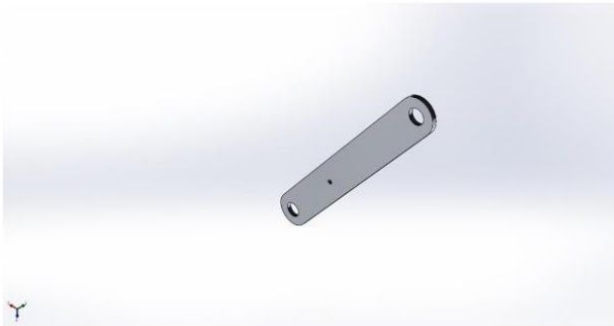



*Figure H.4.2: the FBD for the bottom and front arms that was used for the spring calculations*

Overall, taking the worst case vertical impact forces into account, each spring would have to withstand 17.51lbf (77.84N) and will compress a total of 0.98in (2.5cm). The testing and validation section of this report confirms the functionality of the suspension system.

## H5. Front Arm Link FEA



# Simulation of Front Arm

**Date:** Thursday, November 21, 2019
**Designer:** Solidworks
**Study name:** Dynamic Handling
**Analysis type:** Static

### Description

Forces, stress, strain, and maximum displacement values of PESA robot front arm link for worst case scenarios.

### Study Properties

| | |
|---|---|
| **Study name** | Dynamic Handling |
| **Analysis type** | Static |
| **Mesh type** | Solid Mesh |
| **Thermal Effect:** | On |
| **Thermal option** | Include temperature loads |
| **Zero strain temperature** | 298 Kelvin |
| **Include fluid pressure effects from SOLIDWORKS Flow Simulation** | Off |
| **Solver type** | FFEPlus |
| **Inplane Effect:** | Off |
| **Soft Spring:** | Off |
| **Inertial Relief:** | Off |
| **Incompatible bonding options** | Automatic |
| **Large displacement** | On |
| **Compute free body forces** | On |
| **Friction** | Off |
| **Use Adaptive Method:** | Off |

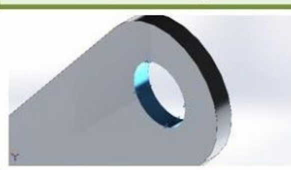
### Units

| | |
|---|---|
| **Unit system:** | SI (MKS) |
| **Length/Displacement** | mm |
| **Temperature** | Kelvin |
| **Angular velocity** | Rad/sec |
| **Pressure/Stress** | N/m^2 |

## Material Properties

| Model Reference | Properties | Components |
|---|---|---|
|  | **Name:** 5052-H32<br>**Model type:** Linear Elastic Isotropic<br>**Default failure criterion:** Max von Mises Stress<br>**Yield strength:** 1.95e+08 N/m^2<br>**Tensile strength:** 2.3e+08 N/m^2<br>**Elastic modulus:** 7e+10 N/m^2<br>**Poisson's ratio:** 0.33<br>**Mass density:** 2680 kg/m^3<br>**Shear modulus:** 2.59e+10 N/m^2<br>**Thermal expansion coefficient:** 2.38e-05 /Kelvin | SolidBody 1(Cut-Extrude2)(FrontArm) |
| Curve Data:N/A | | |

## Loads and Fixtures

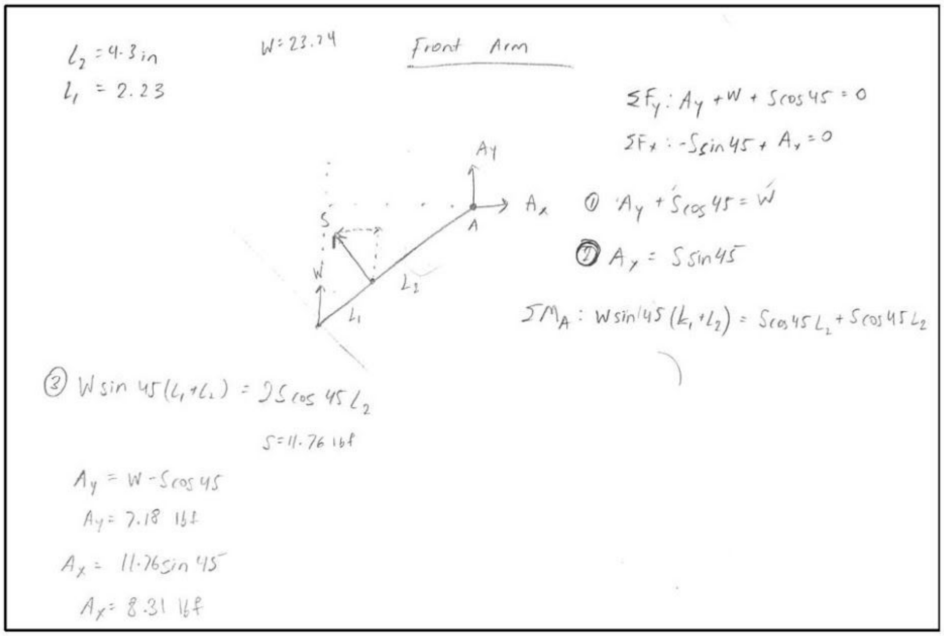
| Fixture name | Fixture Image | Fixture Details |
|---|---|---|
| Fixed-2 |  | **Entities:** 1 face(s)<br>**Type:** Fixed Geometry |

**Resultant Forces**

| Components | X | Y | Z | Resultant |
|---|---|---|---|---|
| Reaction force(N) | -40.0727 | 3.75509e-06 | 102.572 | 110.122 |
| Reaction Moment(N.m) | 0 | 0 | 0 | 0 |

| Load name | Load Image | Load Details |
|---|---|---|
| Force-1 |  | **Entities:** 1 face(s)<br>**Reference:** Face< 1 ><br>**Type:** Apply force<br>**Values:** ---, 15.5, --- lbf |
| Force-2 |  | **Entities:** 1 face(s)<br>**Reference:** Face< 1 ><br>**Type:** Apply force<br>**Values:** ---, ---, -11.76 lbf |

Methodology for calculating forces in each hole shown below.




**Equations used**:

$\Sigma Fy = Ay + W + Scos(45) = 0$ Sum forces in x-direction

$\Sigma Fx = Ax - Ssin(45) = 0$ Sum forces in y-direction

$\Sigma M_A = Wsin(45)(L1 + L2) = 2Scos(45)L2$ Sum moments at A

**Variables defined**:

W = maximum impact force each link will have to withstand (obtained from impact force calculations)

Ay, Ax = reaction forces at A

S = force on link due to spring

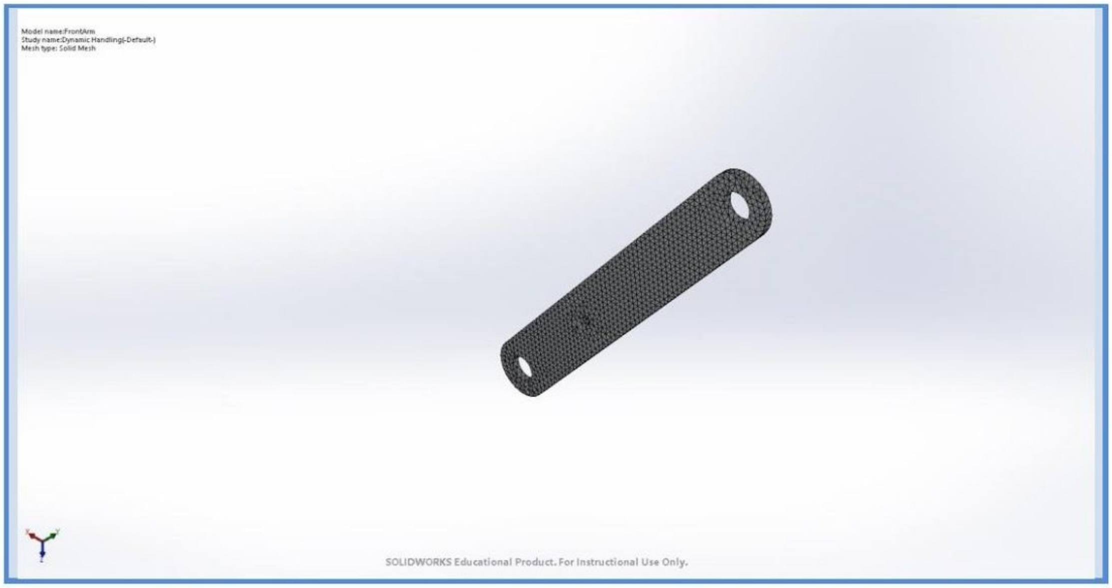
L1, L2 = see diagram shown above

## Mesh information

| | |
|---|---|
| **Mesh type** | Solid Mesh |
| **Mesher Used:** | Standard mesh |
| **Automatic Transition:** | Off |
| **Include Mesh Auto Loops:** | Off |
| **Jacobian points** | 4 Points |
| **Element Size** | 0.0955922 in |
| **Tolerance** | 0.00477961 in |
| **Mesh Quality Plot** | High |

### Mesh information - Details

| | |
|---|---|
| **Total Nodes** | 16090 |
| **Total Elements** | 9162 |
| **Maximum Aspect Ratio** | 3.5677 |
| **% of elements with Aspect Ratio < 3** | 99.9 |
| **% of elements with Aspect Ratio > 10** | 0 |
| **% of distorted elements(Jacobian)** | 0 |
| **Time to complete mesh(hh;mm;ss):** | 00:00:02 |
| **Computer name:** | X-ME2038PC22 |




## Resultant Forces

### Reaction forces

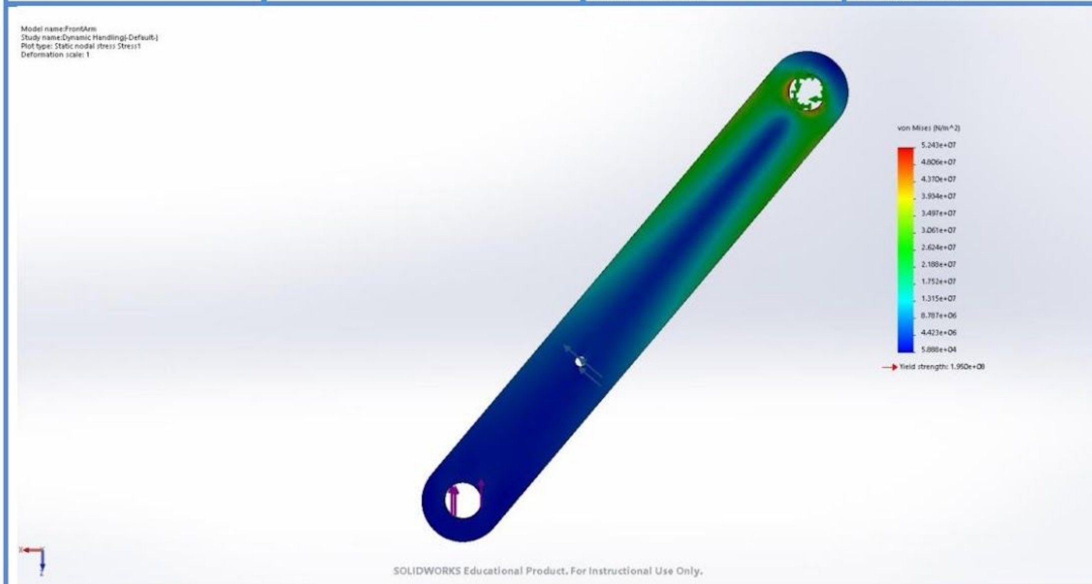
| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N | -40.0727 | 3.75509e-06 | 102.572 | 110.122 |

### Reaction Moments

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N.m | 0 | 0 | 0 | 0 |

## Study Results

| Name | Type | Min | Max |
| --- | --- | --- | --- |
| Stress1 | VON: von Mises Stress | 5.888e+04 N/m^2<br>Node: 15604 | 5.243e+07 N/m^2<br>Node: 13684 |




FrontArm-Dynamic Handling-Stress-Stress1

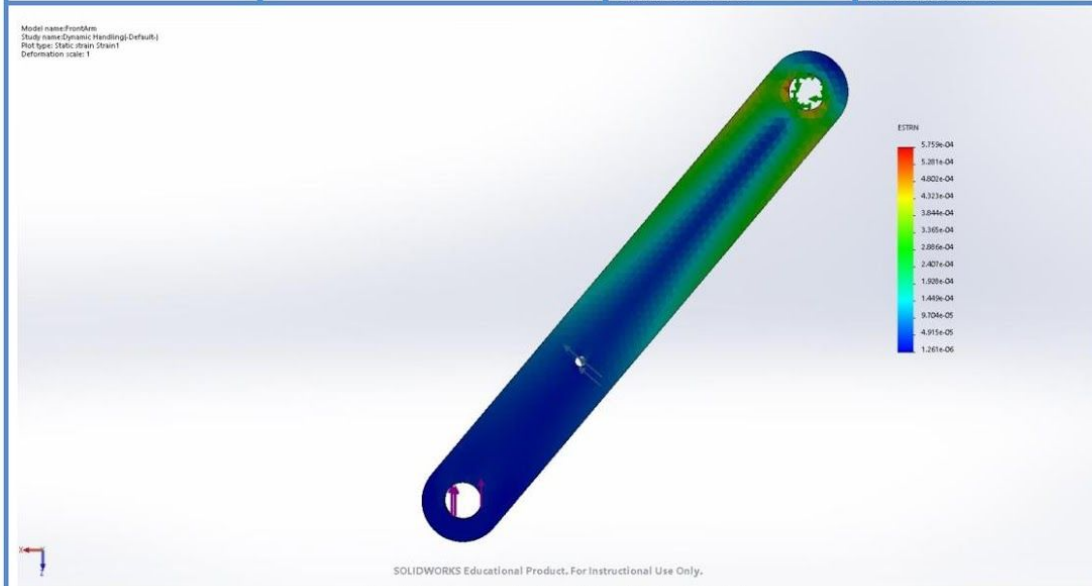
Maximum stress occurs at top bearing hole at a value of 5.24e07 N/m^2. This results in a minimum factor of safety of 3.7 which is in range and acceptable for worst case impact scenarios.

| Name | Type | Min | Max |
| --- | --- | --- | --- |
| Displacement1 | URES: Resultant Displacement | 0.000e+00 mm<br>Node: 1 | 4.330e-01 mm<br>Node: 81 |


FrontArm-Dynamic Handling-Displacement-Displacement1

Maximum displacement occurs at bottom of link for a value of 0.43 mm which is small and negligible.

| Name | Type | Min | Max |
|---|---|---|---|
| Strain1 | ESTRN: Equivalent Strain | 1.261e-06<br>Element: 8454 | 5.759e-04<br>Element: 7761 |




FrontArm-Dynamic Handling-Strain-Strain1

Strain values are small and negligible.

## Conclusion

The front arm link made of 5052 aluminum meets and exceeds the Phoenix Robotics team's expectations for the maximum forces and torques it will be required to withstand.

# H6. Bottom Arm Link FEA

## Simulation of Bottom Arm

**Date**: Thursday, November 21, 2019
**Designer**: Solidworks
**Study name**: Dynamic Handling
**Analysis type**: Static

## Description

Forces, stress, strain, and maximum displacement values of PESA robot bottom arm link for worst case scenarios.

## Assumptions

Top bearing hole assumed to be a fixture to simulate worst case scenario of a stuck bearing and to simplify calculations.

## Model Information

**Model name:** BottomArm
**Current Configuration:** Default

| **Solid Bodies** | | | |
|---|---|---|---|
| **Document Name and Reference** | **Treated As** | **Volumetric Properties** | **Document Path/Date Modified** |
| Cut-Extrude1  | Solid Body | **Mass:0.0244468 kg**<br>**Volume:9.12194e-06 m^3**<br>**Density:2680 kg/m^3**<br>**Weight:0.239579 N** | **\\nas01.itap.purdue.edu\puhome\My Documents\Senior Design\CAD\Tread Assembly\BottomArm.SLDPRT**<br>Nov 21 19:54:07 2019 |

## Study Properties

| | |
|---|---|
| Study name | Dynamic Handling |
| Analysis type | Static |
| Mesh type | Solid Mesh |
| Thermal Effect: | On |
| Thermal option | Include temperature loads |
| Zero strain temperature | 298 Kelvin |
| Include fluid pressure effects from SOLIDWORKS Flow Simulation | Off |
| Solver type | FFEPlus |
| Inplane Effect: | Off |
| Soft Spring: | Off |
| Inertial Relief: | Off |
| Incompatible bonding options | Automatic |
| Large displacement | Off |
| Compute free body forces | On |
| Friction | Off |
| Use Adaptive Method: | Off |

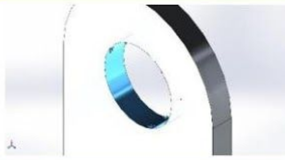
## Units

| | |
|---|---|
| Unit system: | SI (MKS) |
| Length/Displacement | mm |
| Temperature | Kelvin |
| Angular velocity | Rad/sec |
| Pressure/Stress | N/m^2 |

## Material Properties

| Model Reference | Properties | Components |
|---|---|---|
|  | **Name:** 5052-H32<br>**Model type:** Linear Elastic Isotropic<br>**Default failure criterion:** Max von Mises Stress<br>**Yield strength:** 1.95e+08 N/m^2<br>**Tensile strength:** 2.3e+08 N/m^2<br>**Elastic modulus:** 7e+10 N/m^2<br>**Poisson's ratio:** 0.33<br>**Mass density:** 2680 kg/m^3<br>**Shear modulus:** 2.59e+10 N/m^2<br>**Thermal expansion coefficient:** 2.38e-05 /Kelvin | SolidBody 1(Cut-Extrude1)(BottomArm) |
| Curve Data:N/A | | |

## Loads and Fixtures

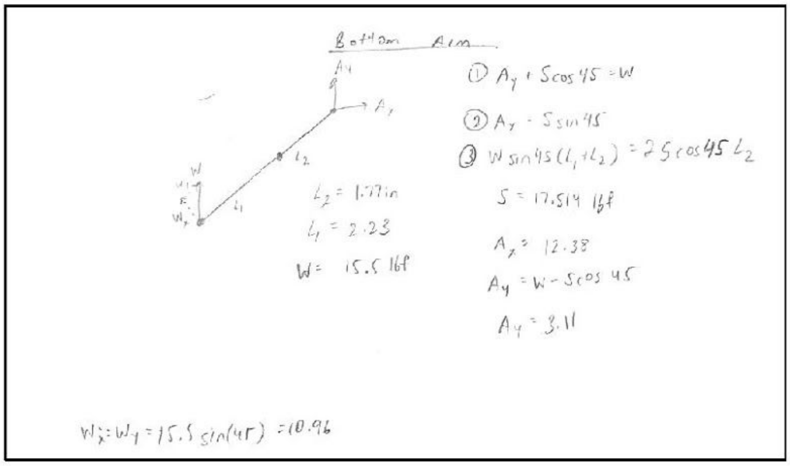
<table>
<tr><th>Fixture name</th><th>Fixture Image</th><th>Fixture Details</th></tr>
<tr><td>Fixed-1</td><td></td><td>Entities: 1 face(s)<br>Type: Fixed Geometry</td></tr>
</table>

**Resultant Forces**

| Components | X | Y | Z | Resultant |
|---|---|---|---|---|
| Reaction force(N) | -48.761 | 0.000809848 | 126.64 | 135.703 |
| Reaction Moment(N.m) | 0 | 0 | 0 | 0 |

<table>
<tr><th>Load name</th><th>Load Image</th><th>Load Details</th></tr>
<tr><td>Force-1</td><td></td><td>Entities: 1 face(s)<br>Reference: Face< 1 ><br>Type: Apply force<br>Values: 10.96, 10.96, --- lbf</td></tr>
<tr><td>Force-2</td><td></td><td>Entities: 1 face(s)<br>Reference: Face< 1 ><br>Type: Apply force<br>Values: ---, 17.514, --- lbf</td></tr>
</table>

Methodology for calculating forces in each hole shown below.




**Equations used: (same as front arm)**

$\Sigma Fy = Ay + W + Scos(45) = 0$ Sum forces in x-direction

$\Sigma Fx = Ax - Ssin(45) = 0$ Sum forces in y-direction

$\Sigma M_A = Wsin(45)(L1 + L2) = 2Scos(45)L2$ Sum moments at A

**Variables defined: (same as front arm, different values for L1 and L2)**

W = maximum impact force each link will have to withstand (obtained from impact force calculations)

Ay, Ax = reaction forces at A

S = force on link due to spring

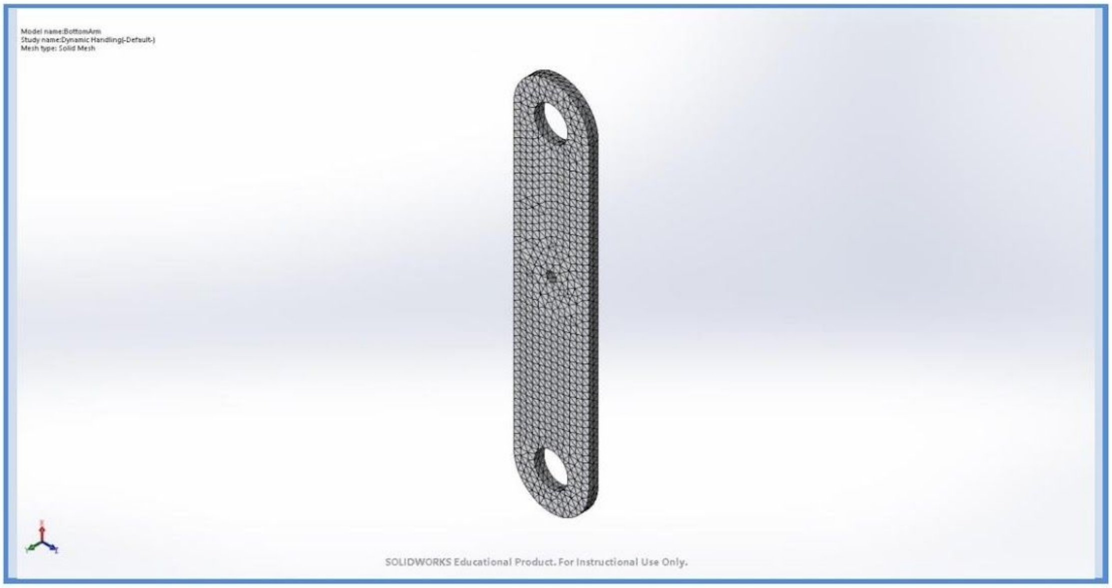
L1, L2 = see diagram shown above

## Mesh information

| | |
|---|---|
| **Mesh type** | Solid Mesh |
| **Mesher Used:** | Standard mesh |
| **Automatic Transition:** | Off |
| **Include Mesh Auto Loops:** | Off |
| **Jacobian points** | 4 Points |
| **Element Size** | 0.0822931 in |
| **Tolerance** | 0.00411465 in |
| **Mesh Quality Plot** | High |

### Mesh information - Details

| | |
|---|---|
| **Total Nodes** | 14421 |
| **Total Elements** | 8155 |
| **Maximum Aspect Ratio** | 3.2047 |
| **% of elements with Aspect Ratio < 3** | 99.9 |
| **% of elements with Aspect Ratio > 10** | 0 |
| **% of distorted elements(Jacobian)** | 0 |
| **Time to complete mesh(hh;mm;ss):** | 00:00:02 |
| **Computer name:** | X-ME2038PC22 |




## Resultant Forces

### Reaction forces

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N | -48.761 | 0.000809848 | 126.64 | 135.703 |

### Reaction Moments

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N.m | 0 | 0 | 0 | 0 |

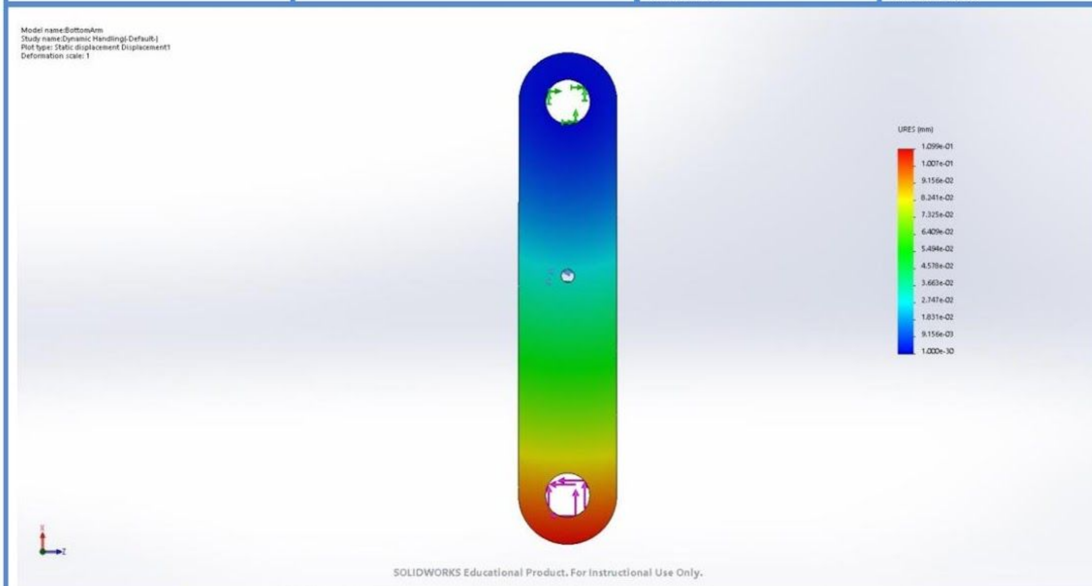
## Study Results

| Name | Type | Min | Max |
|---|---|---|---|
| Stress1 | VON: von Mises Stress | 5.563e+04 N/m^2<br>Node: 13389 | 3.234e+07 N/m^2<br>Node: 3 |


BottomArm-Dynamic Handling-Stress-Stress1

Maximum stress occurs at top bearing hole at a value of 3.23e07 N/m^2. This results in a minimum factor of safety of 6.03 which is in range and acceptable for worst case impact scenarios.

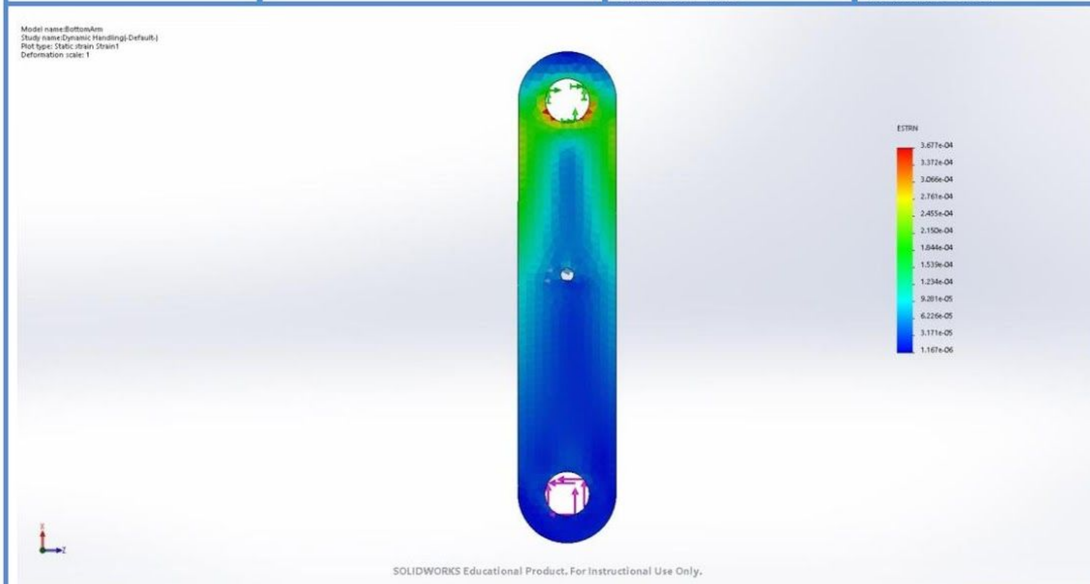
| Name | Type | Min | Max |
|---|---|---|---|
| Displacement1 | URES: Resultant Displacement | 0.000e+00 mm<br>Node: 1 | 1.099e-01 mm<br>Node: 141 |




BottomArm-Dynamic Handling-Displacement-Displacement1

Maximum displacement occurs at bottom of link for a value of 0.109 mm which is small and negligible.

| Name | Type | Min | Max |
|---|---|---|---|
| Strain1 | ESTRN: Equivalent Strain | 1.167e-06<br>Element: 1228 | 3.677e-04<br>Element: 5297 |



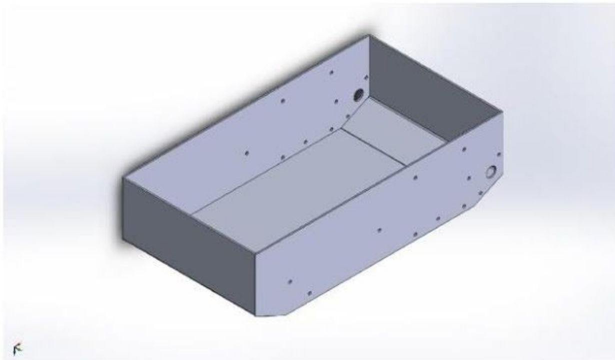

BottomArm-Dynamic Handling-Strain-Strain1

Strain values are small and negligible.

## Conclusion

The front arm link made of 5052 aluminum meets and exceeds the Phoenix Robotics team's expectations for the maximum forces and torques it will be required to withstand.

## H7. Chassis FEA



# Simulation of Chassis FEA

**Date**: Wednesday, November 20, 2019
**Designer**: Solidworks
**Study name**: Static 1
**Analysis type**: Static

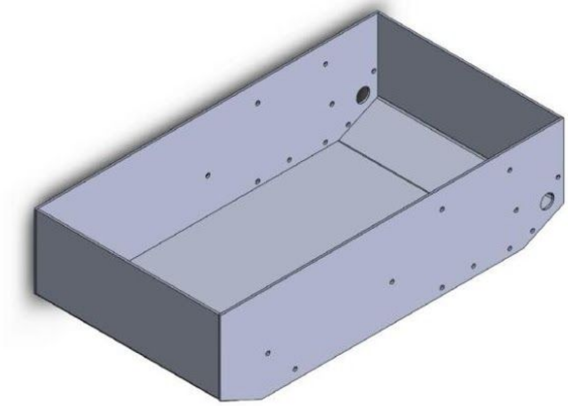
### Description

Forces, stress, strain, and maximum displacement values of PESA robot chassis for worst case scenarios.

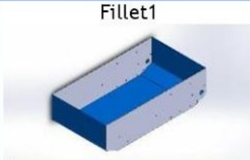
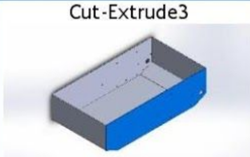
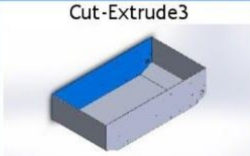
### Assumptions

Two forces were applied for the chassis FEA. The first force was spread across the bottom floor of the chassis to simulate weight of electronics, power train, and battery. The second force was placed along the top edges to simulate the weight of the stokes basket the robot will carry on top.

## Model Information



**Model name:** ChassisFEA
**Current Configuration:** Default

| Solid Bodies | | | |
|---|---|---|---|
| **Document Name and Reference** | **Treated As** | **Volumetric Properties** | **Document Path/Date Modified** |
| Fillet1<br> | Solid Body | **Mass:2.0648 kg**<br>**Volume:0.000770449 m^3**<br>**Density:2680 kg/m^3**<br>**Weight:20.2351 N** | **\\nas01.itap.purdue.edu\puhome\My Documents\Senior Design\CAD\Chassis\Chassis_Bottom.SLDPRT**<br>Nov 20 21:19:21 2019 |
| Cut-Extrude3<br> | Solid Body | **Mass:0.70518 kg**<br>**Volume:0.000263127 m^3**<br>**Density:2680 kg/m^3**<br>**Weight:6.91076 N** | **\\nas01.itap.purdue.edu\puhome\My Documents\Senior Design\CAD\Chassis\Chassis_Side.SLDPRT**<br>Nov 20 21:19:21 2019 |
| Cut-Extrude3<br> | Solid Body | **Mass:0.70518 kg**<br>**Volume:0.000263127 m^3**<br>**Density:2680 kg/m^3**<br>**Weight:6.91076 N** | **\\nas01.itap.purdue.edu\puhome\My Documents\Senior Design\CAD\Chassis\Chassis_Side.SLDPRT**<br>Nov 20 21:19:21 2019 |

## Study Properties

| | |
|---|---|
| Study name | Static 1 |
| Analysis type | Static |
| Mesh type | Solid Mesh |
| Thermal Effect: | On |
| Thermal option | Include temperature loads |
| Zero strain temperature | 298 Kelvin |
| Include fluid pressure effects from SOLIDWORKS Flow Simulation | Off |
| Solver type | FFEPlus |
| Inplane Effect: | Off |
| Soft Spring: | Off |
| Inertial Relief: | Off |
| Incompatible bonding options | Automatic |
| Large displacement | Off |
| Compute free body forces | On |
| Friction | Off |
| Use Adaptive Method: | Off |
| Result folder | SOLIDWORKS document (\\nas01.itap.purdue.edu\puhome\My Documents\Senior Design\CAD\Chassis) |

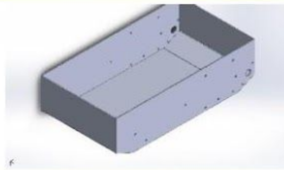
## Units

| | |
|---|---|
| Unit system: | SI (MKS) |
| Length/Displacement | mm |
| Temperature | Kelvin |
| Angular velocity | Rad/sec |
| Pressure/Stress | N/m^2 |

## Material Properties

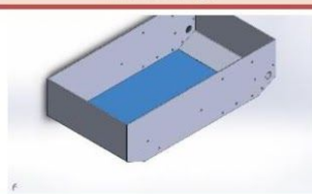
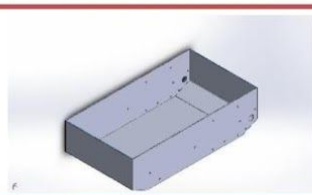
| Model Reference | Properties | Components |
|---|---|---|
|  | **Name:** 5052-H32<br>**Model type:** Linear Elastic Isotropic<br>**Default failure criterion:** Max von Mises Stress<br>**Yield strength:** 1.95e+08 N/m^2<br>**Tensile strength:** 2.3e+08 N/m^2<br>**Elastic modulus:** 7e+10 N/m^2<br>**Poisson's ratio:** 0.33<br>**Mass density:** 2680 kg/m^3<br>**Shear modulus:** 2.59e+10 N/m^2<br>**Thermal expansion coefficient:** 2.38e-05 /Kelvin | SolidBody 1(Fillet1)(Chassis_Bottom-1), SolidBody 1(Cut-Extrude3)(Chassis_Side-1), SolidBody 1(Cut-Extrude3)(Chassis_Side-2) |
| Curve Data:N/A | | |

## Loads and Fixtures

| Fixture name | Fixture Image | Fixture Details |
|---|---|---|
| Fixed-1 |  | **Entities:** 8 face(s)<br>**Type:** Fixed Geometry |

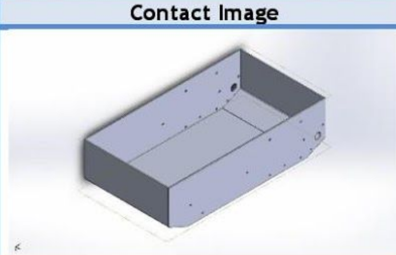
**Resultant Forces**

| Components | X | Y | Z | Resultant |
|---|---|---|---|---|
| Reaction force(N) | 0.111097 | -0.0320324 | -444.805 | 444.805 |
| Reaction Moment(N.m) | 0 | 0 | 0 | 0 |

| Load name | Load Image | Load Details |
|---|---|---|
| Force-1 |  | **Entities:** 1 face(s)<br>**Type:** Apply normal force to simulate electronics, power train, and battery<br>**Value:** 50 lbf |
| Force-2 |  | **Entities:** 2 face(s)<br>**Type:** Apply normal force along edges to simulate carrying of stokes basket and the weight it will carry.<br>**Value:** 50 lbf |

Total force on chassis is 100 lbf.

## Contact Information

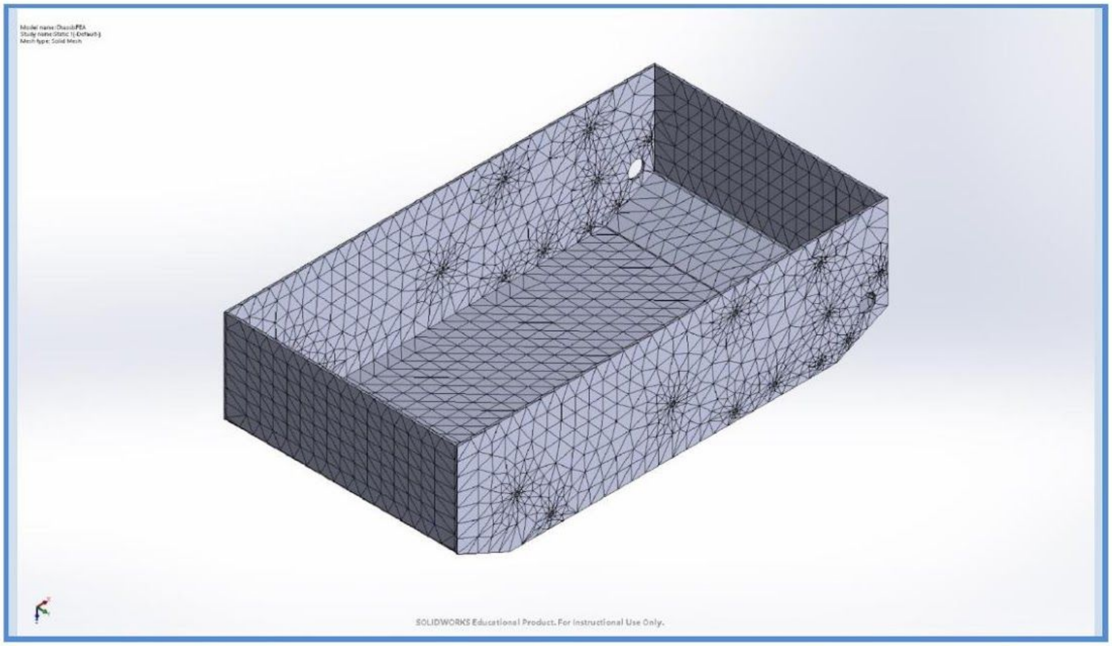
| Contact | Contact Image | Contact Properties |
|---|---|---|
| Global Contact |  | **Type:** Bonded<br>**Components:** 1 component(s)<br>**Options:** Compatible mesh |

## Mesh information

| | |
|---|---|
| **Mesh type** | Solid Mesh |
| **Mesher Used:** | Standard mesh |
| **Automatic Transition:** | Off |
| **Include Mesh Auto Loops:** | Off |
| **Jacobian points** | 4 Points |
| **Element Size** | 0.719061 in |
| **Tolerance** | 0.0359531 in |
| **Mesh Quality Plot** | High |
| **Remesh failed parts with incompatible mesh** | Off |

### Mesh information - Details

| | |
|---|---|
| **Total Nodes** | 24768 |
| **Total Elements** | 12135 |
| **Maximum Aspect Ratio** | 50.954 |
| **% of elements with Aspect Ratio < 3** | 14.4 |
| **% of elements with Aspect Ratio > 10** | 3.54 |
| **% of distorted elements(Jacobian)** | 0 |
| **Time to complete mesh(hh;mm;ss):** | 00:00:03 |
| **Computer name:** | X-ME1030PC09 |




## Resultant Forces

### Reaction forces

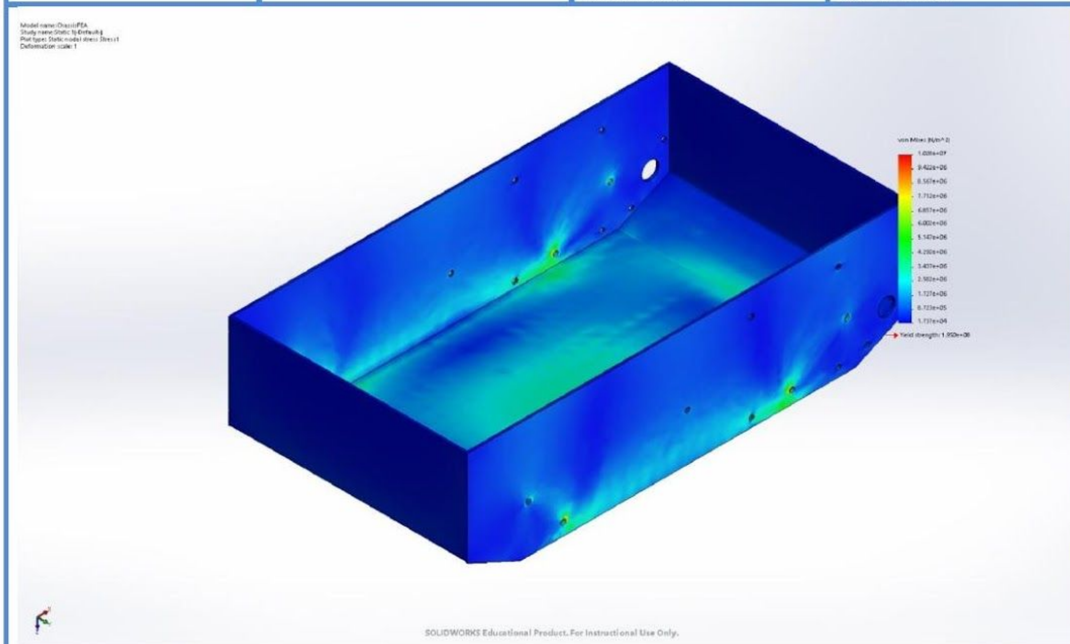
| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N | 0.111097 | -0.0320324 | -444.805 | 444.805 |

### Reaction Moments

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N.m | 0 | 0 | 0 | 0 |

## Study Results

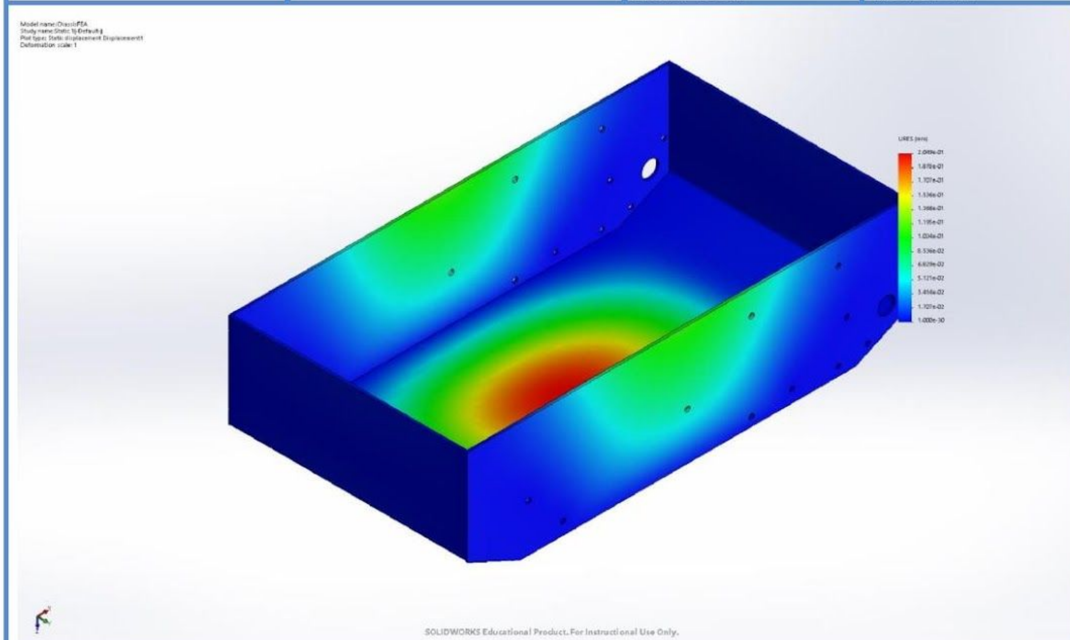
| Name | Type | Min | Max |
|---|---|---|---|
| Stress1 | VON: von Mises Stress | 1.737e+04 N/m^2<br>Node: 14571 | 1.028e+07 N/m^2<br>Node: 10881 |




ChassisFEA-Static 1-Stress-Stress1

Maximum stress occurs at bottom mounting holes for a value of 1.028e07 N/m^2. Taking maximum stress into account, factor of safety for the chassis is 18.96.

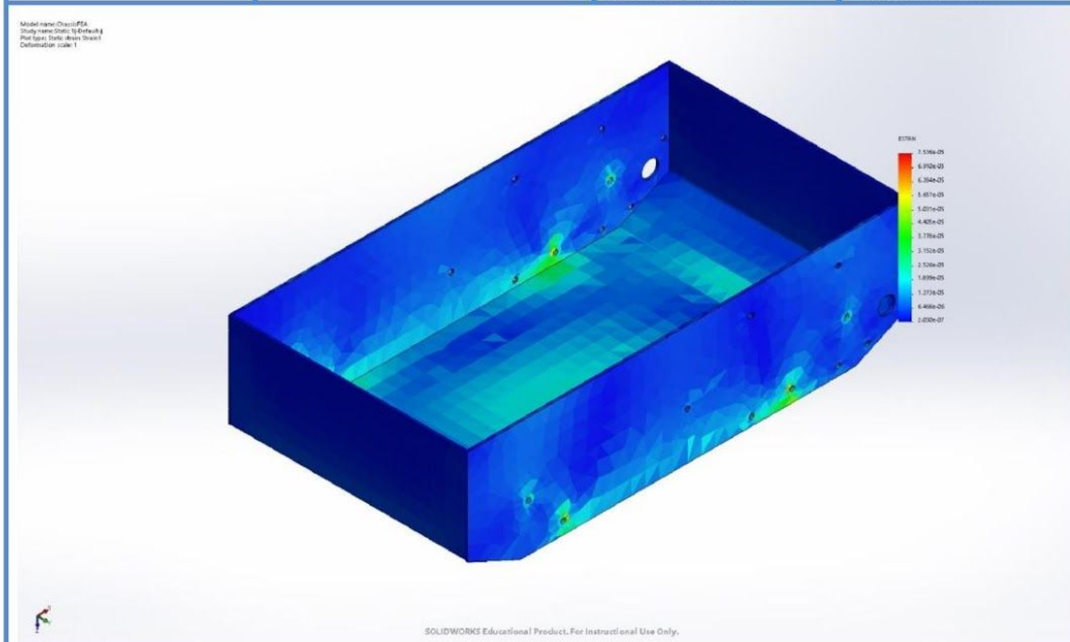
| Name | Type | Min | Max |
|---|---|---|---|
| Displacement1 | URES: Resultant Displacement | 0.000e+00 mm<br>Node: 10377 | 2.049e-01 mm<br>Node: 7820 |




ChassisFEA-Static 1-Displacement-Displacement1

Maximum displacemtn occurs middle of chassis floor and is 0.02mm which is small and negligible.

| Name | Type | Min | Max |
|---|---|---|---|
| Strain1 | ESTRN: Equivalent Strain | 2.030e-07<br>Element: 10524 | 7.536e-05<br>Element: 11042 |



ChassisFEA-Static 1-Strain-Strain1

Strain values are nominal.

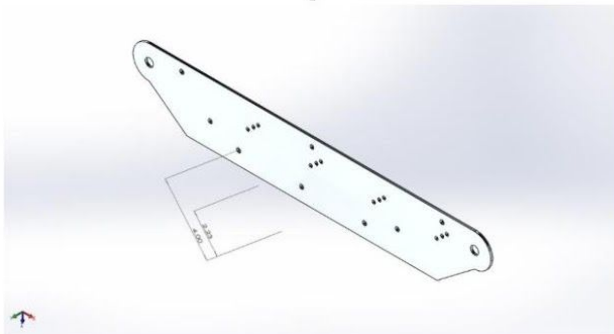
## Conclusion

The chassis made of 5052 aluminum meets and exceeds the Phoenix Robotics team's expectations for the maximum forces and torques it will be required to withstand.

## H8. Tread Plate FEA

**Phoenix Robotics**

S



# Simulation of Tread Plate

**Date**: Wednesday, November 20, 2019
**Designer**: Solidworks
**Study name**: Static 1
**Analysis type**: Static

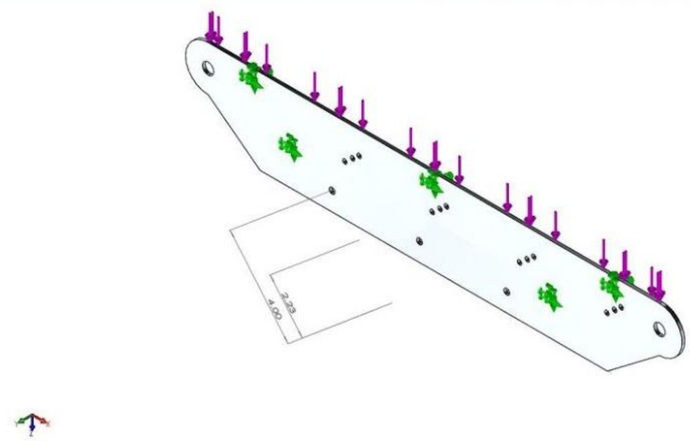
### Description

Forces, stress, strain, and maximum displacement for tread plate of the PESA robot for worst case scenarios.

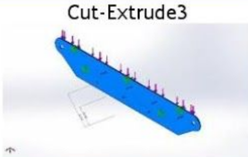
## Assumptions

The five mounting holes where ¼" bolts will be placed through to hole the tread plate to the chassis are considered as fixtures while a normal force is applied on top of the tread plate to simulate the weight force of the robot plus its maximum carrying load.

## Model Information



**Model name:** TreadPlate
**Current Configuration:** Default

| Solid Bodies | | | |
|---|---|---|---|
| **Document Name and Reference** | **Treated As** | **Volumetric Properties** | **Document Path/Date Modified** |
| Cut-Extrude3  | Solid Body | **Mass:0.40047 kg**<br>**Volume:0.000149429 m^3**<br>**Density:2680 kg/m^3**<br>**Weight:3.9246 N** | **\\nas01.itap.purdue.edu\puhome\My Documents\Senior Design\CAD\Tread Assembly\TreadPlate.SLDPRT**<br>Nov 20 22:34:49 2019 |

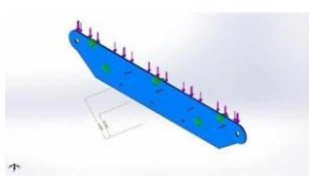
## Study Properties

| | |
|---|---|
| **Study name** | Static 1 |
| **Analysis type** | Static |
| **Mesh type** | Solid Mesh |
| **Thermal Effect:** | On |
| **Thermal option** | Include temperature loads |
| **Zero strain temperature** | 298 Kelvin |
| **Include fluid pressure effects from SOLIDWORKS Flow Simulation** | Off |
| **Solver type** | FFEPlus |
| **Inplane Effect:** | Off |
| **Soft Spring:** | Off |
| **Inertial Relief:** | Off |
| **Incompatible bonding options** | Automatic |
| **Large displacement** | Off |
| **Compute free body forces** | On |
| **Friction** | Off |
| **Use Adaptive Method:** | Off |

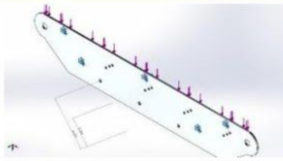
## Units

| | |
|---|---|
| **Unit system:** | SI (MKS) |
| **Length/Displacement** | mm |
| **Temperature** | Kelvin |
| **Angular velocity** | Rad/sec |
| **Pressure/Stress** | N/m^2 |

## Material Properties

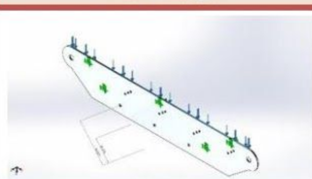
| Model Reference | Properties | Components |
|---|---|---|
|  | **Name:** 5052-H32<br>**Model type:** Linear Elastic Isotropic<br>**Default failure criterion:** Max von Mises Stress<br>**Yield strength:** 1.95e+08 N/m^2<br>**Tensile strength:** 2.3e+08 N/m^2<br>**Elastic modulus:** 7e+10 N/m^2<br>**Poisson's ratio:** 0.33<br>**Mass density:** 2680 kg/m^3<br>**Shear modulus:** 2.59e+10 N/m^2<br>**Thermal expansion coefficient:** 2.38e-05 /Kelvin | SolidBody 1(Cut-Extrude3)(TreadPlate) |
| Curve Data:N/A | | |

## Loads and Fixtures

| Fixture name | Fixture Image | Fixture Details |
|---|---|---|
| Fixed-1 |  | **Entities:** 5 face(s)<br>**Type:** Fixed Geometry |

**Resultant Forces**

| Components | X | Y | Z | Resultant |
|---|---|---|---|---|
| Reaction force(N) | -0.00104005 | 0.000118077 | -222.41 | 222.41 |
| Reaction Moment(N.m) | 0 | 0 | 0 | 0 |

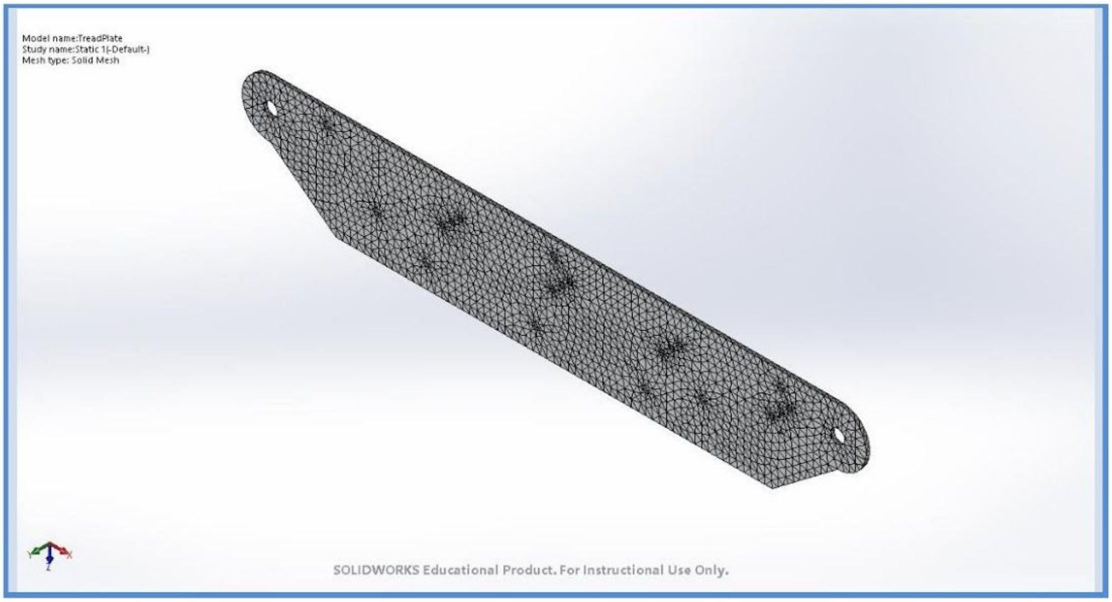
| Load name | Load Image | Load Details |
|---|---|---|
| Force-1 |  | **Entities:** 1 face(s)<br>**Type:** Apply normal force<br>**Value:** 50 lbf |

## Mesh information

| | |
|---|---|
| **Mesh type** | Solid Mesh |
| **Mesher Used:** | Standard mesh |
| **Automatic Transition:** | Off |
| **Include Mesh Auto Loops:** | Off |
| **Jacobian points** | 4 Points |
| **Element Size** | 0.248145 in |
| **Tolerance** | 0.0124072 in |
| **Mesh Quality Plot** | High |

### Mesh information - Details

| | |
|---|---|
| **Total Nodes** | 18355 |
| **Total Elements** | 8738 |
| **Maximum Aspect Ratio** | 6.7602 |
| **% of elements with Aspect Ratio < 3** | 95.3 |
| **% of elements with Aspect Ratio > 10** | 0 |
| **% of distorted elements(Jacobian)** | 0 |
| **Time to complete mesh(hh;mm;ss):** | 00:00:03 |
| **Computer name:** | X-ME2038PC10 |




## Resultant Forces

### Reaction forces

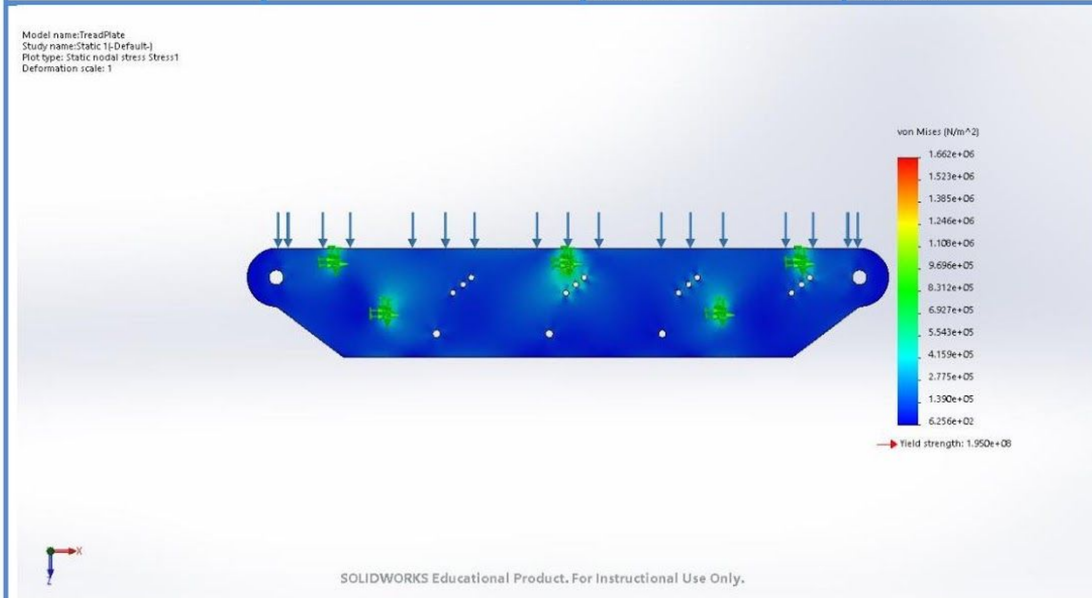
| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N | -0.00104005 | 0.000118077 | -222.41 | 222.41 |

### Reaction Moments

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N.m | 0 | 0 | 0 | 0 |

## Study Results

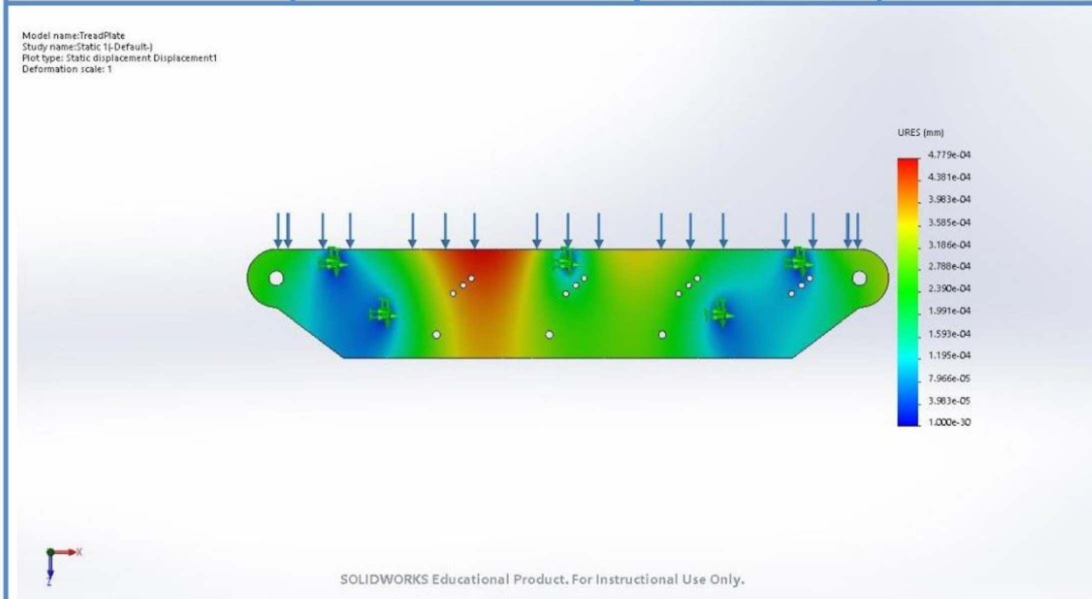
| Name | Type | Min | Max |
|---|---|---|---|
| Stress1 | VON: von Mises Stress | 6.256e+02 N/m^2<br>Node: 535 | 1.662e+06 N/m^2<br>Node: 202 |




TreadPlate-Static 1-Stress-Stress1

The maximum stress occurs at the mounting holes at a value of 1.662e+06 N/m^2 accounting for the robot weight plus the weight it is expected to carry for a total value of 100lbs. Taking the yield strength into account, the factor of safety (FoS) is 117.

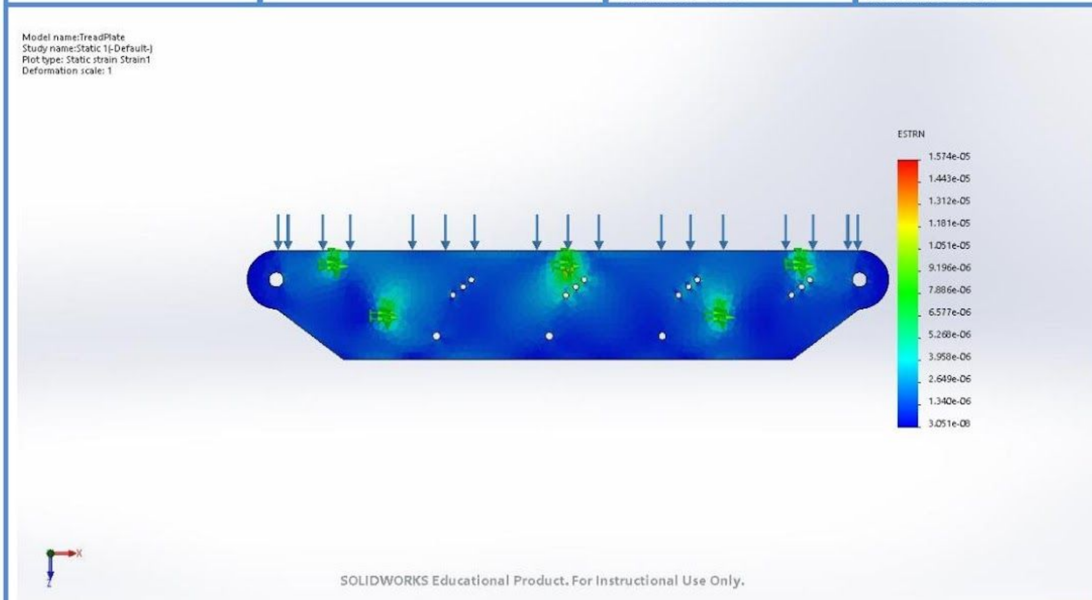
| Name | Type | Min | Max |
|---|---|---|---|
| Displacement1 | URES: Resultant Displacement | 0.000e+00 mm<br>Node: 1 | 4.779e-04 mm<br>Node: 14908 |




TreadPlate-Static 1-Displacement-Displacement1

The maximum displacement value for the tread plate is 0.00047mm and will not impact robot performance and can be considered extremely negligible.

| Name | Type | Min | Max |
|---|---|---|---|
| Strain1 | ESTRN: Equivalent Strain | 3.051e-08<br>Element: 5653 | 1.574e-05<br>Element: 6376 |




TreadPlate-Static 1-Strain-Strain1

Strain values are nominal.

## Conclusion

The tread plate made of 5052 aluminum meets and exceeds the Phoenix Robotics team's engineering expectations for the max forces and torques it will be required to withstand.

## H9. Drive Shaft FEA

# Simulation of Drive Shaft

**Date**: Wednesday, November 20, 2019
**Designer**: Solidworks
**Study name**: Static 1
**Analysis type**: Static

### Description

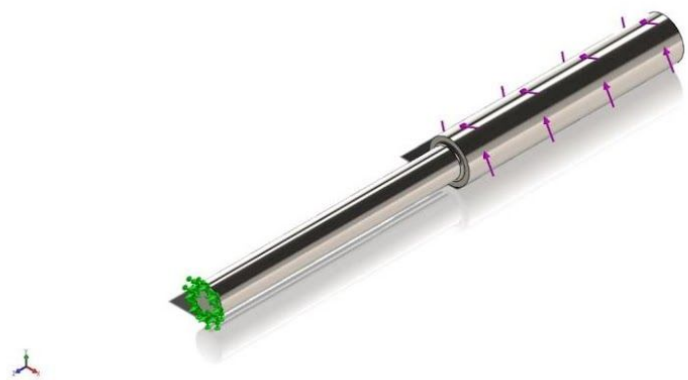
Forces, stress, strain, and maximum displacement values of PESA robot drive shaft for worst case scenarios.

## Assumptions

Smaller diameter end of the drive shaft was considered a fixture and a torque was applied to simulate drive chain acting on the shaft. This was done to simulate the drive train and track friction the drive shaft would have to overcome and to simplify calculations.

Drive shaft was made from scrap steel found in machine shop and assumed to be made of mild alloy steel for FEA purposes.

## Model Information



**Model name:** DriveShaft_Output
**Current Configuration:** Default

**Solid Bodies**

| Document Name and Reference | Treated As | Volumetric Properties | Document Path/Date Modified |
|---|---|---|---|
| Fillet1  | Solid Body | **Mass:0.0418174 kg**<br>**Volume:5.43083e-06 m^3**<br>**Density:7700 kg/m^3**<br>**Weight:0.409811 N** | **\\nas01.itap.purdue.edu\puhome\My Documents\Senior Design\CAD\Chassis\DriveShaft_Output.SLDPRT**<br>Nov 20 23:11:13 2019 |

## Study Properties

| | |
|---|---|
| **Study name** | Static 1 |
| **Analysis type** | Static |
| **Mesh type** | Solid Mesh |
| **Thermal Effect:** | On |
| **Thermal option** | Include temperature loads |
| **Zero strain temperature** | 298 Kelvin |
| **Include fluid pressure effects from SOLIDWORKS Flow Simulation** | Off |
| **Solver type** | FFEPlus |
| **Inplane Effect:** | Off |
| **Soft Spring:** | Off |
| **Inertial Relief:** | Off |
| **Incompatible bonding options** | Automatic |
| **Large displacement** | Off |
| **Compute free body forces** | On |
| **Friction** | Off |
| **Use Adaptive Method:** | Off |

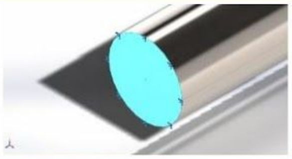
## Units

| | |
|---|---|
| **Unit system:** | SI (MKS) |
| **Length/Displacement** | mm |
| **Temperature** | Kelvin |
| **Angular velocity** | Rad/sec |
| **Pressure/Stress** | N/m^2 |

## Material Properties

| Model Reference | Properties | Components |
|---|---|---|
|  | **Name:** Alloy Steel<br>**Model type:** Linear Elastic Isotropic<br>**Default failure criterion:** Max von Mises Stress<br>**Yield strength:** 6.20422e+08 N/m^2<br>**Tensile strength:** 7.23826e+08 N/m^2<br>**Elastic modulus:** 2.1e+11 N/m^2<br>**Poisson's ratio:** 0.28<br>**Mass density:** 7700 kg/m^3<br>**Shear modulus:** 7.9e+10 N/m^2<br>**Thermal expansion coefficient:** 1.3e-05 /Kelvin | SolidBody 1(Fillet1)(DriveShaft_Output) |
| Curve Data:N/A | | |

## Loads and Fixtures

| Fixture name | Fixture Image | Fixture Details |
|---|---|---|
| Fixed-1 |  | **Entities:** 1 face(s)<br>**Type:** Fixed Geometry |

**Resultant Forces**

| Components | X | Y | Z | Resultant |
|---|---|---|---|---|
| Reaction force(N) | 0.00989151 | -0.00175571 | -0.00786488 | 0.0127586 |
| Reaction Moment(N.m) | 0 | 0 | 0 | 0 |

| Load name | Load Image | Load Details |
|---|---|---|
| Torque-1 |  | **Reference:** Face< 1 ><br>**Type:** Apply torque<br>**Value:** 2.05 N.m |

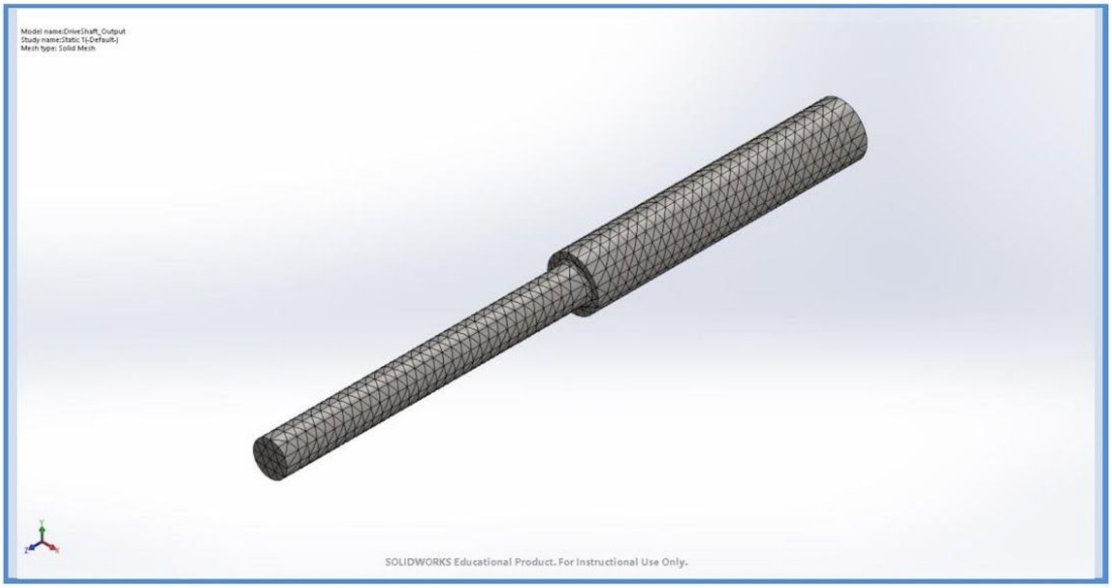
Torque values obtained from torque analysis formulas that take into account CIM motor power output, gearing, and drive train loss.

## Mesh information

| | |
|---|---|
| **Mesh type** | Solid Mesh |
| **Mesher Used:** | Standard mesh |
| **Automatic Transition:** | Off |
| **Include Mesh Auto Loops:** | Off |
| **Jacobian points** | 4 Points |
| **Element Size** | 0.0692268 in |
| **Tolerance** | 0.00346134 in |
| **Mesh Quality Plot** | High |

### Mesh information - Details

| | |
|---|---|
| **Total Nodes** | 12162 |
| **Total Elements** | 7584 |
| **Maximum Aspect Ratio** | 4.7233 |
| **% of elements with Aspect Ratio < 3** | 99.4 |
| **% of elements with Aspect Ratio > 10** | 0 |
| **% of distorted elements(Jacobian)** | 0 |
| **Time to complete mesh(hh;mm;ss):** | 00:00:03 |
| **Computer name:** | X-ME2038PC10 |




## Resultant Forces

### Reaction forces

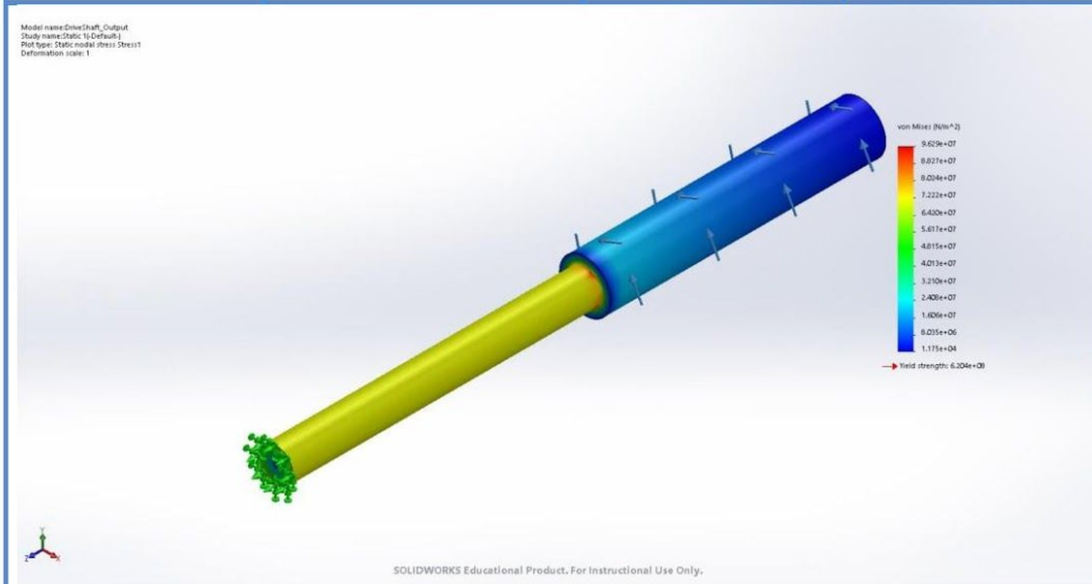
| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N | 0.00989151 | -0.00175571 | -0.00786488 | 0.0127586 |

### Reaction Moments

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N.m | 0 | 0 | 0 | 0 |

## Study Results

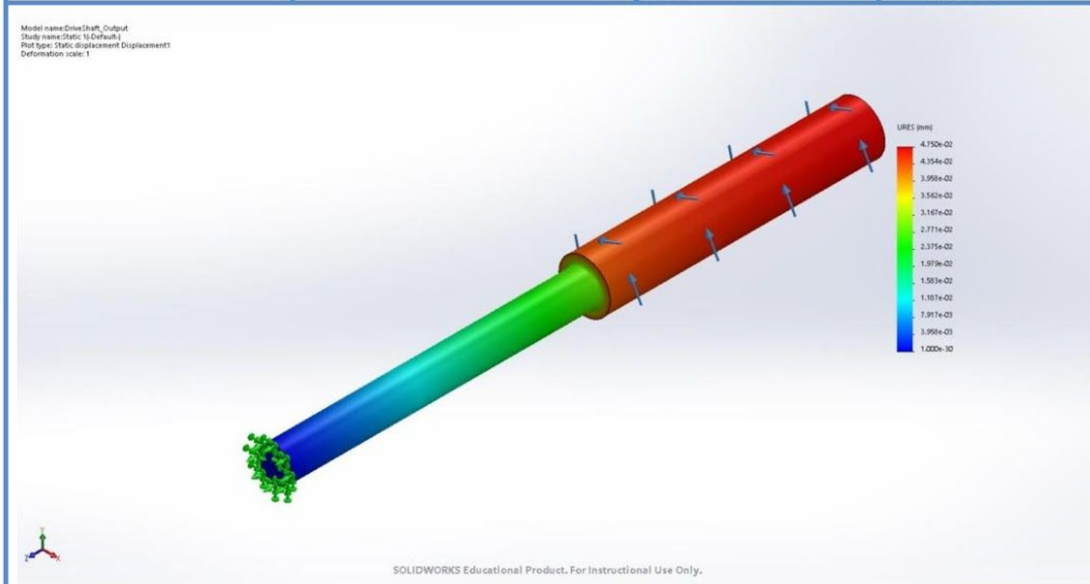
| Name | Type | Min | Max |
|---|---|---|---|
| Stress1 | VON: von Mises Stress | 1.175e+04 N/m^2<br>Node: 6079 | 9.629e+07 N/m^2<br>Node: 12107 |




DriveShaft_Output-Static 1-Stress-Stress1

Maximum stress values occur at point where drive shaft changes diameter for a value of 9.63e07 N/m^2. The minimum factor of safety is 6.44 and occurs at the maximum stress point.

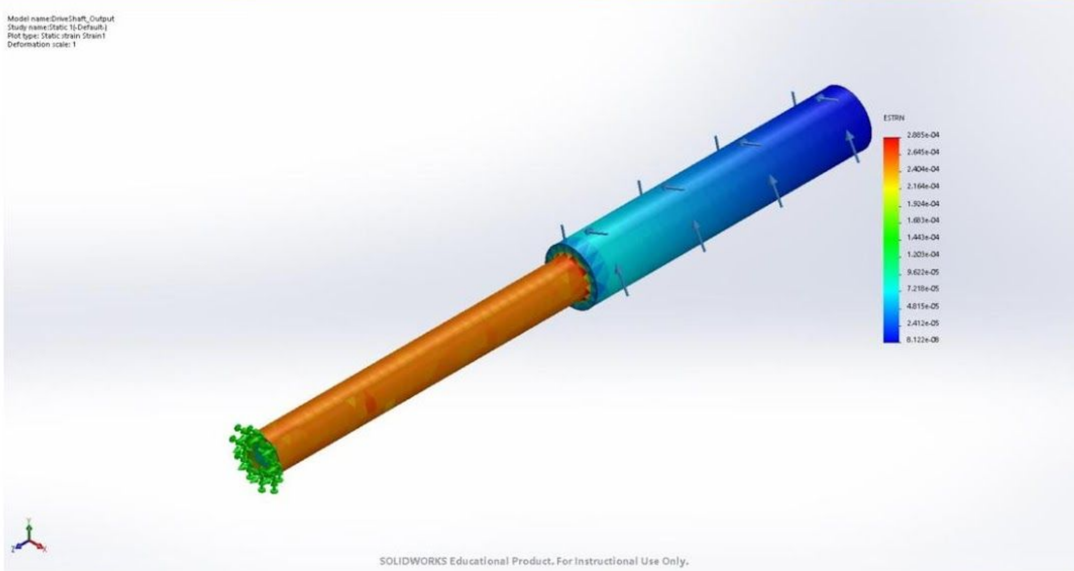
| Name | Type | Min | Max |
| --- | --- | --- | --- |
| Displacement1 | URES: Resultant Displacement | 0.000e+00 mm<br>Node: 404 | 4.750e-02 mm<br>Node: 10548 |




DriveShaft_Output-Static 1-Displacement-Displacement1

Maximum displacement of the shaft occurs for the entire thicker section shown in red for a value of 0.04mm. This max displacement is small and negligible and does not affect performance.

| Name | Type | Min | Max |
|---|---|---|---|
| Strain1 | ESTRN: Equivalent Strain | 8.122e-08<br>Element: 6344 | 2.885e-04<br>Element: 4287 |

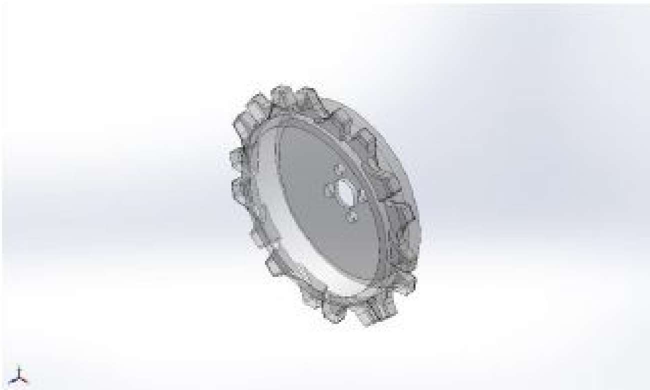



DriveShaft_Output-Static 1-Strain-Strain1

Strain values are small and negligible.

## Conclusion

The drive shaft made of mild alloy steel meets and exceeds the Phoenix Robotics team's expectations for the maximum forces and torques it will be required to withstand.



# Simulation of 9_tooth_sprocket-hub

**Date:** Monday, December 2, 2019
**Designer:** Solidworks
**Study name:** Static 3
**Analysis type:** Static

## Table of Contents

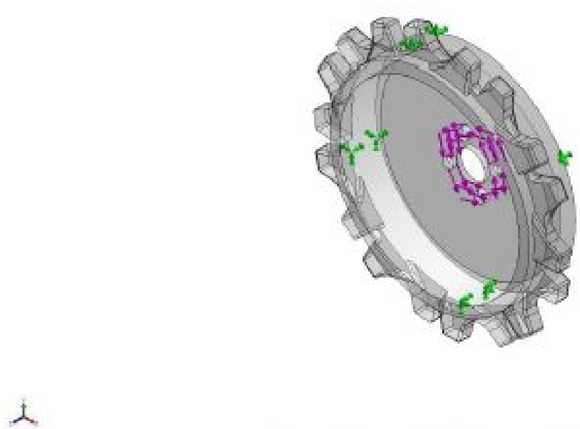


## Description

Force on drive sprocket if the tread locks up and motor doesn't shut off

## Assumptions

## Model Information



**Model name: 9_tooth_sprocket-hub**
**Current Configuration: Default**

**Solid Bodies**

| Document Name and Reference | Treated As | Volumetric Properties | Document Path/Date Modified |
|---|---|---|---|
| Mirror1  | Solid Body | **Mass:0.0211225 kg**<br>**Volume:2.74318e-06 m^3**<br>**Density:7700 kg/m^3**<br>**Weight:0.207001 N** | **W:\2019\Senior Design\Old\Nov.21.19\Sprocket Hub.SLDPRT**<br>Nov 24 13:26:03 2019 |

| | | | |
|---|---|---|---|
| Cut-Extrude2  | Solid Body | Mass:0.0196064 kg<br>Volume:1.83237e-05 m^3<br>Density:1070 kg/m^3<br>Weight:0.192142 N | W:\2019\Senior Design\Old\Nov.21.19\Track Sprocket - 9 Link.SLDPRT<br>Nov 23 16:14:06 2019 |

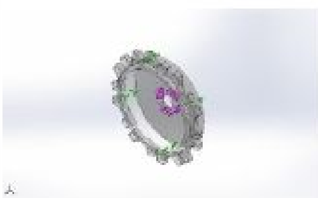
## Study Properties

| | |
|---|---|
| Study name | Static 3 |
| Analysis type | Static |
| Mesh type | Solid Mesh |
| Thermal Effect: | On |
| Thermal option | Include temperature loads |
| Zero strain temperature | 298 Kelvin |
| Include fluid pressure effects from SOLIDWORKS Flow Simulation | Off |
| Solver type | FFEPlus |
| Inplane Effect: | Off |
| Soft Spring: | Off |
| Inertial Relief: | Off |
| Incompatible bonding options | Automatic |
| Large displacement | Off |
| Compute free body forces | On |
| Friction | Off |
| Use Adaptive Method: | Off |
| Result folder | SOLIDWORKS document (W:\2019\Senior Design\Old\Nov.21.19) |

## Units

| | |
|---|---|
| Unit system: | SI (MKS) |
| Length/Displacement | mm |
| Temperature | Kelvin |
| Angular velocity | Rad/sec |
| Pressure/Stress | N/m^2 |

## Material Properties

| Model Reference | Properties | Components |
|---|---|---|
|  | **Name:** Alloy Steel<br>**Model type:** Linear Elastic Isotropic<br>**Default failure criterion:** Max von Mises Stress<br>**Yield strength:** 6.20422e+08 N/m^2<br>**Tensile strength:** 7.23826e+08 N/m^2<br>**Elastic modulus:** 2.1e+11 N/m^2<br>**Poisson's ratio:** 0.28<br>**Mass density:** 7700 kg/m^3<br>**Shear modulus:** 7.9e+10 N/m^2<br>**Thermal expansion coefficient:** 1.3e-05 /Kelvin | SolidBody 1(Mirror1)(Sprocket Hub-1) |
| Curve Data:N/A | | |
|  | **Name:** ABS PC<br>**Model type:** Linear Elastic Isotropic<br>**Default failure criterion:** Unknown<br>**Tensile strength:** 4e+07 N/m^2<br>**Elastic modulus:** 2.41e+09 N/m^2<br>**Poisson's ratio:** 0.3897<br>**Mass density:** 1070 kg/m^3<br>**Shear modulus:** 8.622e+08 N/m^2 | SolidBody 1(Cut-Extrude2)(Track Sprocket - 9 Link-1) |
| Curve Data:N/A | | |

## Loads and Fixtures

| Fixture name | Fixture Image | Fixture Details |
|---|---|---|
| Fixed-1 |  | Entities: 1 face(s)<br>Type: Fixed Geometry |

Resultant Forces

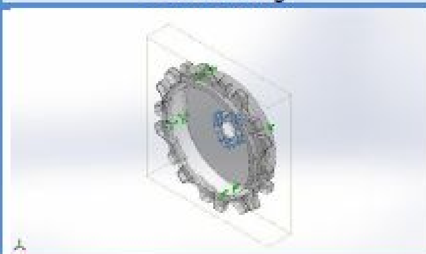
| Components | X | Y | Z | Resultant |
|---|---|---|---|---|
| Reaction force(N) | -0.000142533 | -0.000366516 | -6.43204e-05 | 0.000398481 |
| Reaction Moment(N.m) | 0 | 0 | 0 | 0 |

| Load name | Load Image | Load Details |
|---|---|---|
| Torque-1 |  | Entities: 4 face(s)<br>Reference: Face< 1 ><br>Type: Apply torque<br>Value: 1.9 N.m |

## Connector Definitions

External surface of sprocket is grounded to represent locked tread and the torque is applied to the connecting screws

## Contact Information

| Contact | Contact Image | Contact Properties |
|---|---|---|
| Global Contact |  | Type: Bonded<br>Components: 1 component(s)<br>Options: Compatible mesh |

## Mesh information

| | |
|---|---|
| Mesh type | Solid Mesh |
| Mesher Used: | Standard mesh |
| Automatic Transition: | Off |
| Include Mesh Auto Loops: | Off |
| Jacobian points | 4 Points |
| Element Size | 1.38142 mm |
| Tolerance | 0.0690712 mm |
| Mesh Quality Plot | High |
| Remesh failed parts with incompatible mesh | Off |

### Mesh information - Details

| | |
|---|---|
| Total Nodes | 111626 |
| Total Elements | 69284 |
| Maximum Aspect Ratio | 9.2489 |
| % of elements with Aspect Ratio < 3 | 99.2 |
| % of elements with Aspect Ratio > 10 | 0 |
| % of distorted elements(Jacobian) | 0 |
| Time to complete mesh(hh;mm;ss): | 00:00:08 |
| Computer name: | X-ME2028PC11 |

## Sensor Details
No Data

## Resultant Forces

### Reaction forces

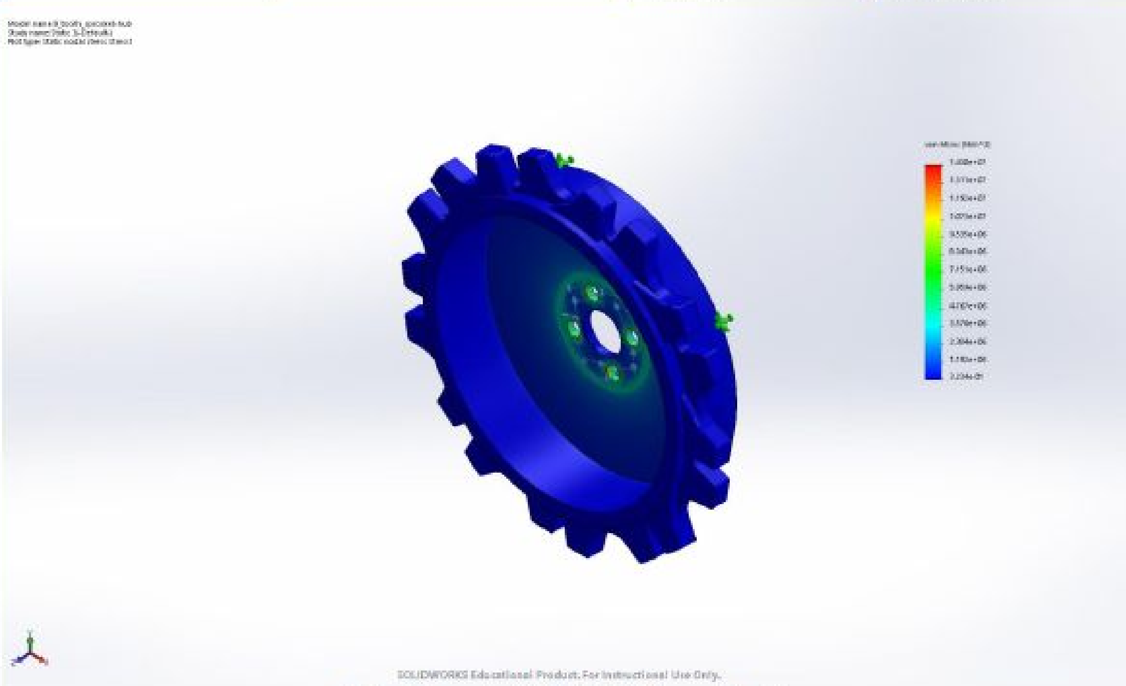
| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N | -0.000142533 | -0.000366516 | -6.43204e-05 | 0.000398481 |

### Reaction Moments

| Selection set | Units | Sum X | Sum Y | Sum Z | Resultant |
|---|---|---|---|---|---|
| Entire Model | N.m | 0 | 0 | 0 | 0 |

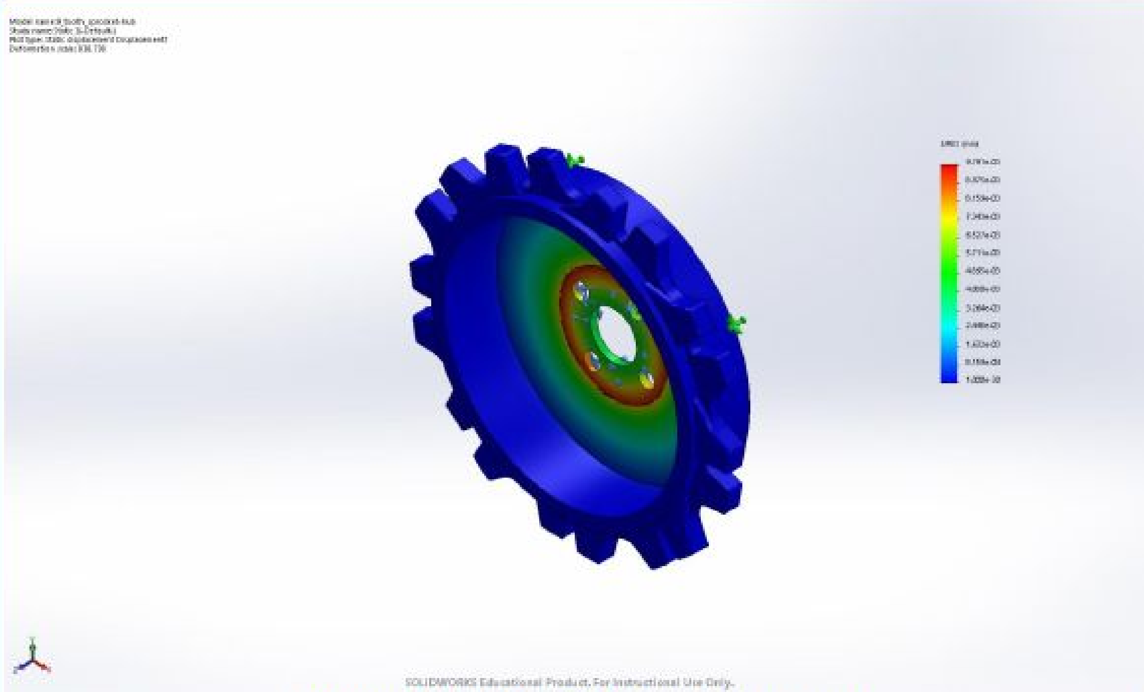
## Study Results

| Name | Type | Min | Max |
|---|---|---|---|
| Stress1 | VON: von Mises Stress | 3.234e-01 N/m^2<br>Node: 56618 | 1.430e+07 N/m^2<br>Node: 13488 |



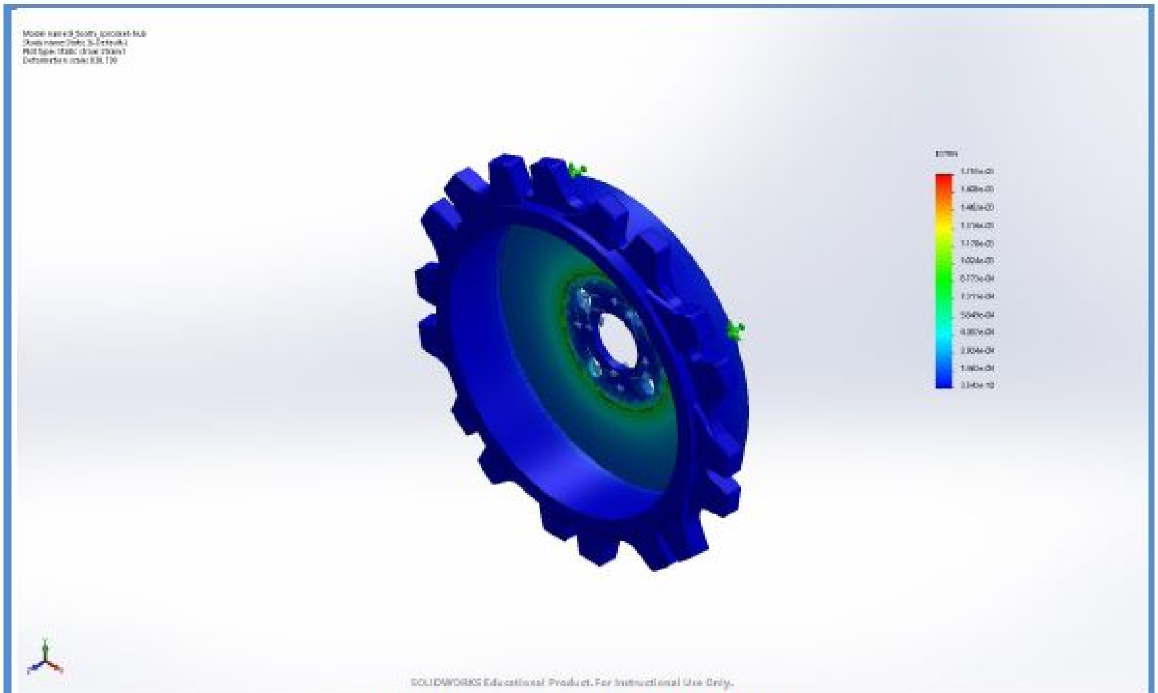

9_tooth_sprocket-hub-Static 3-Stress-Stress1

| Name | Type | Min | Max |
|---|---|---|---|
| Displacement1 | URES: Resultant Displacement | 0.000e+00 mm<br>Node: 16815 | 9.791e-03 mm<br>Node: 711 |




9_tooth_sprocket-hub-Static 3-Displacement-Displacement1

| Name | Type | Min | Max |
|---|---|---|---|
| Strain1 | ESTRN: Equivalent Strain | 3.542e-10<br>Element: 16447 | 1.755e-03<br>Element: 44913 |

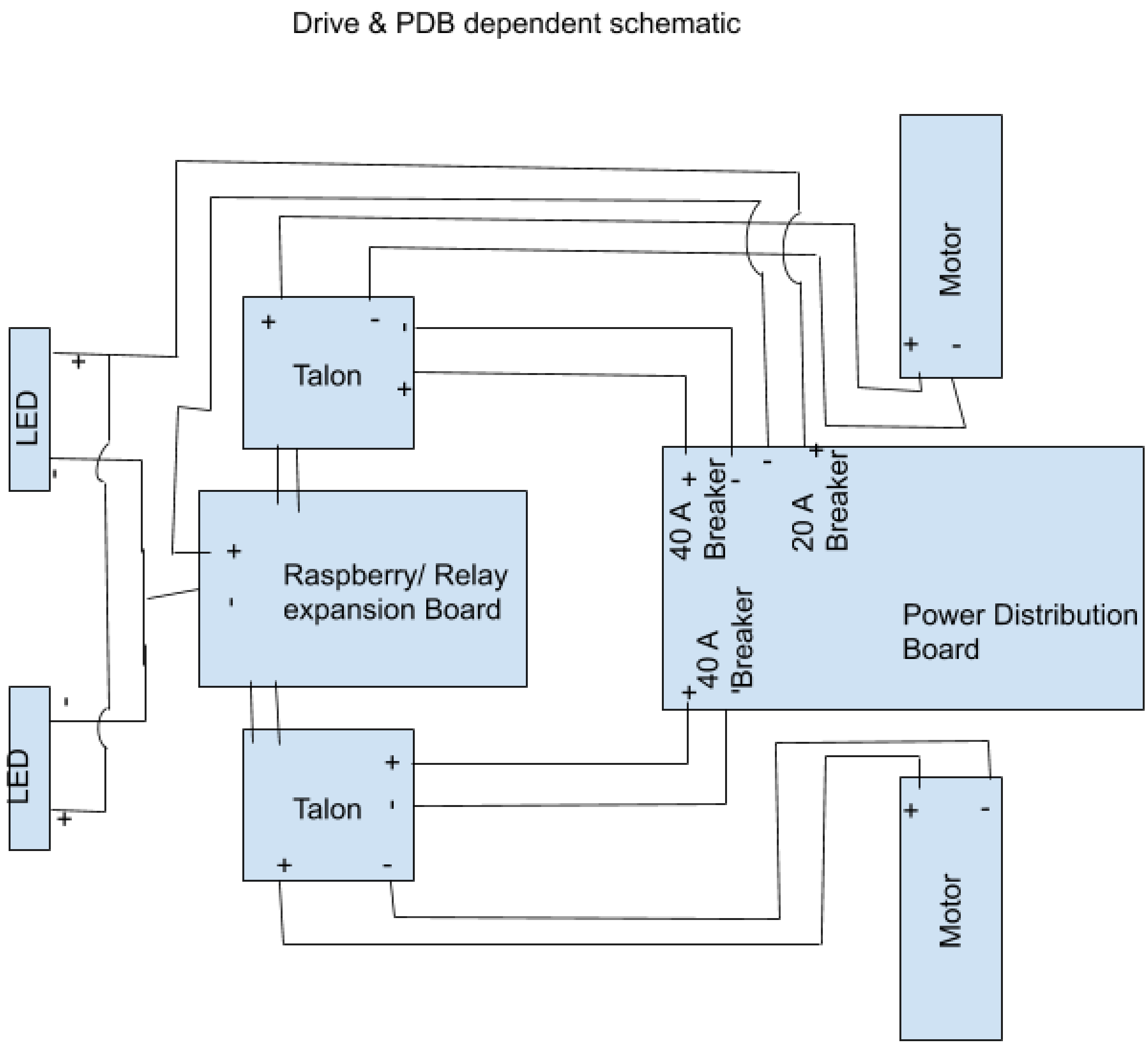



9_tooth_sprocket-hub-Static 3-Strain-Strain1

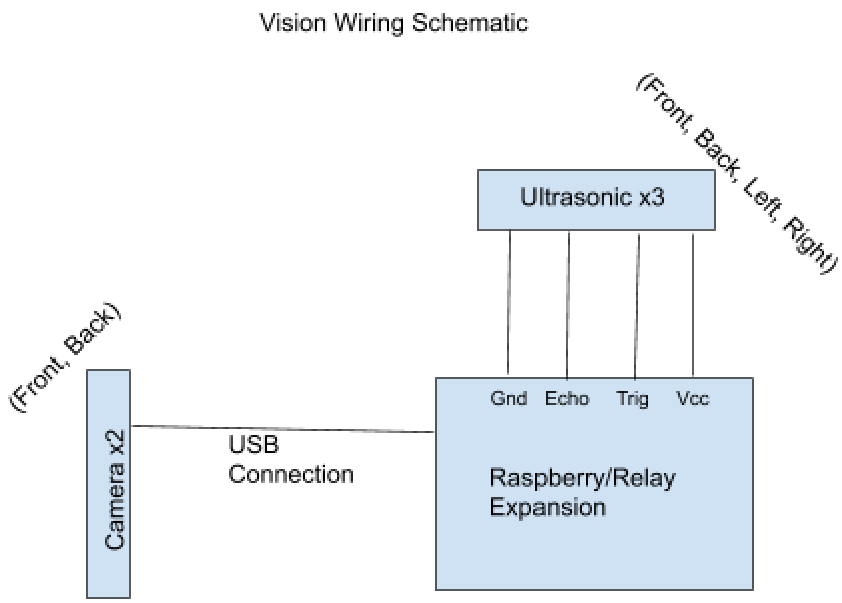
## Conclusion

Based on the FEA the sprocket deforms a negligible amount due to the torque from the motor. While negligible the deformation could cause small cracks to occur that would compromise the integrity of the sprocket. Using a less brittle material would be recommended.

## I: Electronic Schematics

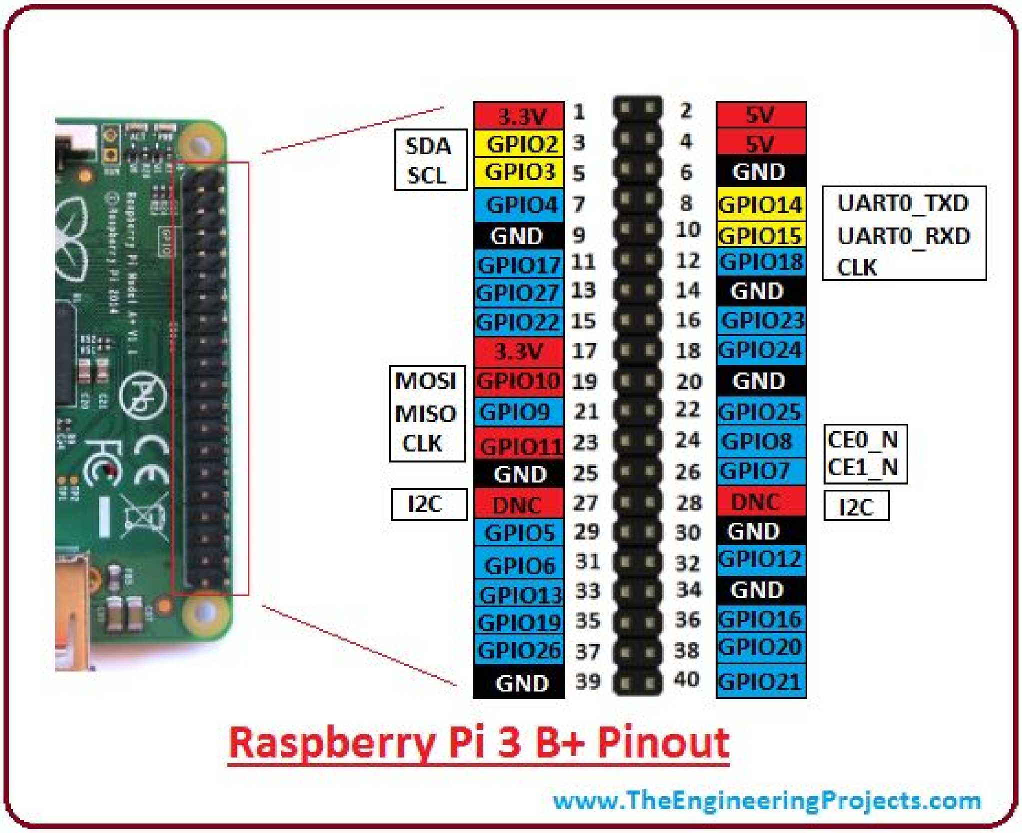



*Wiring schematic detailing components that utilize the power distribution board.*




*Wiring schematic detailing the vision based components, note that the parenthetical notes refer to physical location of components with respect to the chassis; adding to this, all 4 ultrasonics share a common ground and Vcc pins.*

**J: Electronic Circuit Diagram/Wiring Diagram (if ready)**




<u>Pin Layouts</u>

Talon Sr:
PWM1 - GPIO 4
PWM2 - GPIO 17

Relay:
Relay 1 - Use GPIO26 in Python (labeled P25 on board)
Relay 2 - Use GPIO20 in Python (labeled P28 on board)
Relay 3 - Use GPIO21 in Python (labeled P29 on board)

Ultrasonic:
TRIG1 = 23
ECHO1 = 24
TRIG2 = 5
ECHO2 = 6
TRIG3 = 13
ECHO3 = 19

## K: Electronic CAE

*Power draw of electrical components to be used in calculations*

| Component Power draw | | |
|---|---|---|
| Component | Power draw | total |
| LED | 50W | 100W |
| microcontroller | 10W | 10W |
| Camera | 2.5W | 10W |
| Ultrasonics | .1W | 1W |
| Alarm becon | 12W | 12W |
| microphones | .1W | .5W |
| receiver | .15W | .15W |
| | | 135 |

*Power calculations impact on Battery decision (for lead-acid)*

| Designed Scale Run time at max climb | | | | | | |
|---|---|---|---|---|---|---|
| Battery type | Spec | kJ | secs | bat for 1 hr | $/hr | weight(lbs) |
| 12V, 18Ah | 75% discharge | 583.2 | 777.6171828 | 5 | 250 | 12.5 |
| 12V. 85Ah | 75% discharge | 2754 | 3672.081141 | 1 | 200 | 45 |
| | | | | | | |
| | | | | | | |
| Designed Scale Run time at stationary | | | | | | |
| Battery type | Spec | kJ | secs | bat for 1 hr | $/hr | weight(lbs) |
| 12V, 18Ah | 75% discharge | 583.2 | 4320 | 1 | 50 | 12.5 |
| 12V. 85Ah | 75% discharge | 2754 | 20400 | 1 | 200 | 45 |

Assuming at worst, only three-quarters of the battery is able to discharge, the Amp-hour of each battery is converted to kJ by the following expression:

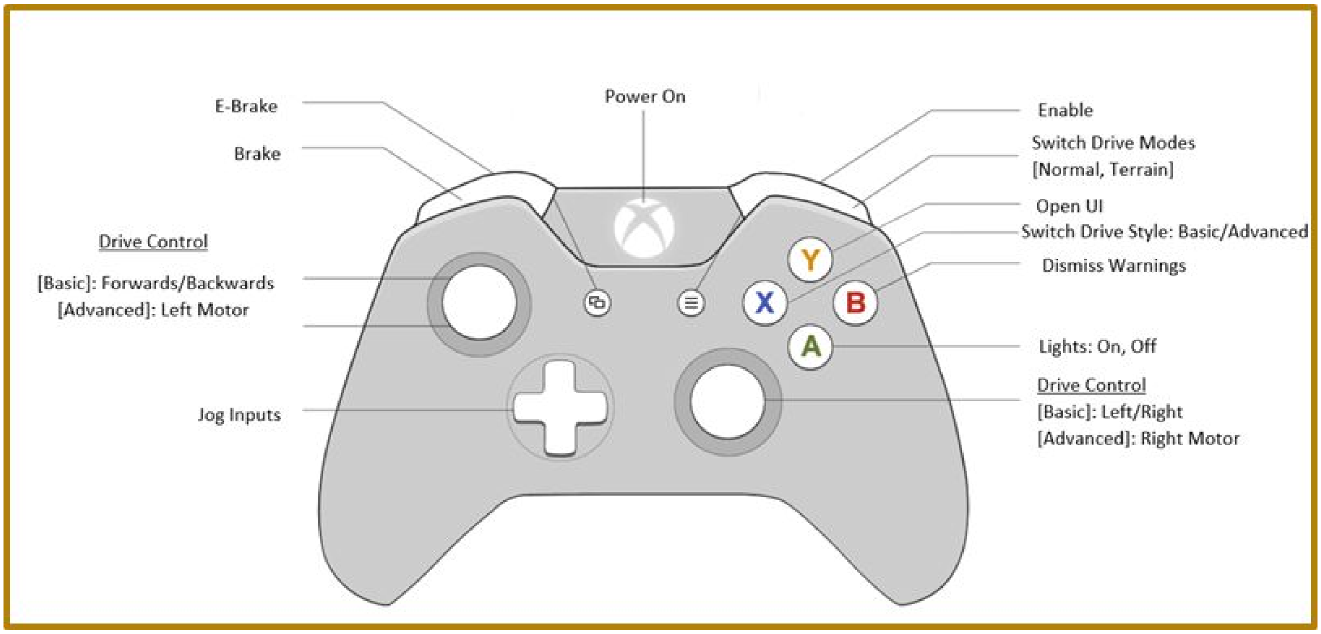
$$kJ = V * Ah * .75 * 3600/1000$$

Where, V is the voltage and Ah is the Amp hour. The Joule capacities of the batteries are then converted to run time (in seconds) by dividing it by the wattage for each use case. Meaning, the wattage of max climb worst case (750W based off the prior torque analysis, Appendix H) and for the stationary power draw condition (135W based on the individual component draw aforementioned). For both cases, the batteries were then assessed to see how many of them would be required to run the system under the conditions for an hour. Then a cost assessment was done to determine the cost of batteries per hour.

The goal for the project is to balance battery life with ease of hot-swapping batteries. It was discovered that, with the max climb scenario, the 18Ah battery will only last 12 minutes; and about an hour on the 85Ah battery. From the table for a stationary system, that only demands 135 W, both batteries are well equipped to supply power to these systems. Keeping in mind that the analysis done is under a high drive train loss ratio, a medium battery discharge rate, and various extreme environmental conditions (i.e. steep angle at a fast speed) it was decided that the most cost efficient system would run off of  2 of the 12V-18Ah batteries in parallel; this system will cut down on weight, cost, and an efficient battery life cycle.

**L: Flow Chart of Control/HMI Software/Operation and/or Skeleton Code (pseudo code)**

Controller Layout




Where:
(X logo) Power On: activates controller and connects to raspberry pi.

(Right Trigger) Enable: Acts as a key ignition, the robot will only respond to drive commands while this is held down.

(Left Trigger) Brake: Slows the robot down by ramping the motors down to a stand still.

(Right Button) Switch Drive Modes: Switch between the two drive modes Normal and Terrain, where normal limits the amount of current draw allotted to the motor, and terrain uncaps the motors for more complex environments.

(Left Button) E-Brake: A hard break that cuts the motors off and is meant only as a last resort to avoid an obstacle.

(A) Lights Switch: Turn the lights on and off.

(B) Dismiss Warnings: false positives read from the ultrasonic causing the system to be put in safety mode.

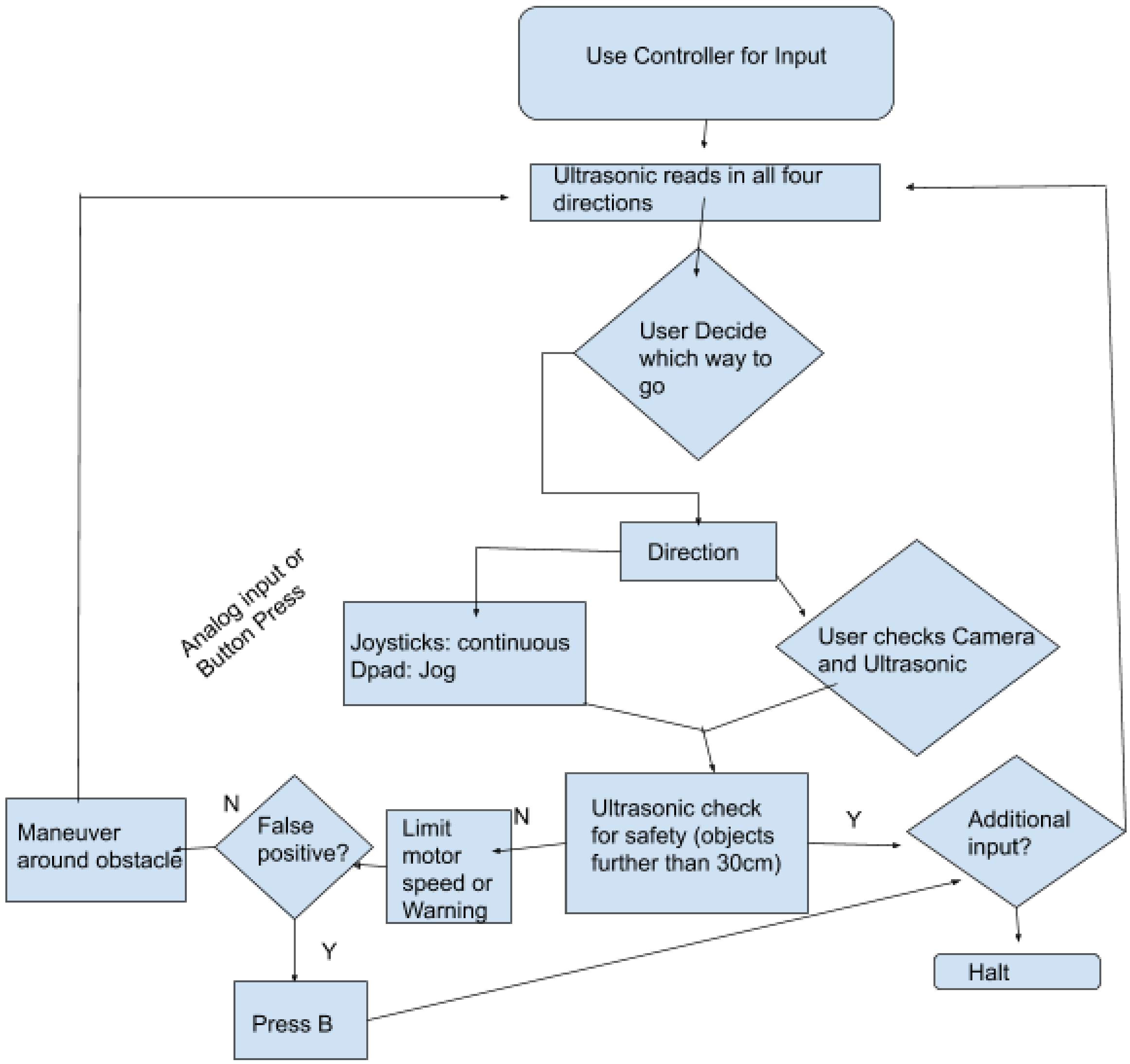
(X) Switch between drive styles: basic and advanced, where basic has a lower learning curve (up and down on the left stick controls front and back, while left and right on the right stick controls turning). Advanced is based on skid steer scheme and has more control over how the robot moves (front back on each stick controls the respective motor).

(Y) Open the UI: for troubleshooting the controller and see the input mapping of each control as read by the code.

(Joysticks) Analog based inputs: takes how far the stick is pushed in either direction (depending on the driving style) and sets it as a speed. For example, using the basic drive mode, pushing the left stick forward slowly will drive the robot forwards; specifically, the robot will ramp up to the speed set by the analog stick (a ratio based off of max allowed speed to max position of joystick).

(Dpad) Jog Inputs: 4 cardinal directions that will jog the robot forwards, backwards, left, or right. Used mostly for small incremental changes to traverse environment.

Flowchart of Safety Mode




While the operator drives the robot, they will use the camera feed to give a sense of the environment the robot is traversing in; the ultrasonics will actively read out the obstacles around the robot as the user drives the system around. If the ultrasonics read an obstacle within 30cm on the left, right, or back it will display a warning indicating the user should look (through cameras) and be aware of these obstacles (press B to dismiss). If the obstacle (again detected within 30cm) is in the front however, the system will cap the motor speed down to 20% asking for the user to maneuver around the obstacle. By doing so, the ultrasonic warning will be cleared and the motor speed will return to the uncapped value. If the user uses the camera and can see there are no obstructions in front of the robot, they can flag the result as a false positive and press B to return to normal operation mode; aka non-safety mode.

## Code

*Combined drive code shown below as it implements all functions, comments are bolded for convenience*

```
import pygame
import RPi.GPIO as GPIO
import time
import random


"""
DEFAULT (Always check the correct mapping on controllertest.py)
#mapping the values for the controller using pygame
NOTES - pygame events and values
JOYAXISMOTION
event.axis              event.value
0 - x axis left thumb   (+1 is right, -1 is left)
1 - y axis left thumb   (+1 is down, -1 is up)
2 - x axis right thumb  (+1 is right, -1 is left)
3 - y axis right thumb  (+1 is down, -1 is up)
4 - right trigger
5 - left trigger
JOYBUTTONDOWN | JOYBUTTONUP
event.button
A = 0
B = 1
X = 2
Y = 3
LB = 4
RB = 5
CL = 6
CR = 7
JOYHATMOTION
event.value
"""

# Define some colors
BLACK = (0, 0, 0)
WHITE = (255, 255, 255)
RED = (255, 0, 0)




# This is a simple class that will help us print to the screen
# It has nothing to do with the joysticks, just output the
# information. The UI Setup.
class TextPrint:
```

```
    def __init__(self):
        self.reset()
        self.font = pygame.font.Font(None, 20)

    def print(self, screen, textString):
        textBitmap = self.font.render(textString, True, BLACK)
        screen.blit(textBitmap, [self.x, self.y])
        self.y += self.line_height

    def printwithcolor(self, screen, textString, color):
        textBitmap = self.font.render(textString, True, color)
        screen.blit(textBitmap, [self.x, self.y])
        self.y += self.line_height

    def reset(self):
        self.x = 10
        self.y = 10
        self.line_height = 15

    def indent(self):
        self.x += 10

    def unindent(self):
        self.x -= 10

def sensordistance(TRIG, ECHO):
    #Sensor needs 10us pulse to trigger
    GPIO.output(TRIG, True)
    time.sleep(0.00001)
    GPIO.output(TRIG, False)

    #Calculating the duration of pulse
    while GPIO.input(ECHO)==0:
        pulse_start = time.time()

    while GPIO.input(ECHO)==1:
        pulse_end = time.time()

    pulse_duration = pulse_end - pulse_start

    #in cm
    distance = pulse_duration * 17150

    #2 decimal places
    distance = round(distance, 2)

    return distance


def toggle(button):
```

```
    if button == 0:
        return 1
    elif button == 1:
        return 0

#instantiating the safety slow system
def printsensorreadout(position, distance):
    if distance<30 and position=="FRONT":
        textPrint.printwithcolor(screen, "{}: {} cm (Obstruction
Ahead!!!)".format(position, distance), RED)
    else:
        textPrint.print(screen, "{}: {} cm".format(position, distance))

#initial values for controller to find neutral position
mode = 0 #0 - Normal, 1 - Sports
display = 0 #0 - Normal 1 - Debugging mode
drive = 0 #0 - Advanced 1 - Basic
light = 0
readout = 0
maxspeed = 0.6 #0.6 Normal 0.8 Sports
ongas = 0
onbreak = 0
dc1 = 7.5
dc2 = 7.5
ljtactive = 0

#GPIO Pins
GPIO.setmode(GPIO.BCM)

#Pins

PWM1 = 4 #Right
PWM2 = 17 #Left

RELAY = 26

#Setup

GPIO.setup(PWM1,GPIO.OUT)
GPIO.setup(PWM2,GPIO.OUT)
GPIO.setup(RELAY, GPIO.OUT)

GPIO.output(RELAY, False)

time.sleep(2)

#50hz -> 20ms period
p1 = GPIO.PWM(PWM1, 50)
p2 = GPIO.PWM(PWM2, 50)
```

```
p1.start(0)
p2.start(0)

pygame.init()


# Set the width and height of the screen [width,height]
size = [500, 700]
screen = pygame.display.set_mode(size)

pygame.display.set_caption("Controller")

# Loop until the user clicks the close button.
done = False

# Used to manage how fast the screen updates
clock = pygame.time.Clock()

# Initialize the joysticks
pygame.joystick.init()

# Get ready to print
textPrint = TextPrint()

while done == False:
    # EVENT PROCESSING STEP
    for event in pygame.event.get():  # User did something
        if event.type == pygame.QUIT:  # If user clicked close
            done = True  # Flag that we are done so we exit this loop

        # Possible joystick actions: JOYAXISMOTION JOYBALLMOTION
JOYBUTTONDOWN JOYBUTTONUP JOYHATMOTION
        if event.type == pygame.JOYBUTTONDOWN:
            if event.button == 0:
                #print("A")
                light = toggle(light)
                if light == 0:
                    GPIO.output(RELAY, False)
                else:
                    GPIO.output(RELAY, True)
            if event.button == 1:
                #print("B")
                readout = toggle(readout)
            if event.button == 3:
                #print("X")
                drive = toggle(drive)
            if event.button == 4:

                #print("Y")
                display = toggle(display)
```

```
        if event.button == 6:
            #print("LB")
            dc1 = 7.5
            dc2 = 7.5
            p1.ChangeDutyCycle(0)
            p2.ChangeDutyCycle(0)
        if event.button == 7:
            #print("RB")
            mode = toggle(mode)
            if mode == 0:
                maxspeed = 0.6
            else:
                maxspeed = 0.8

    if event.type == pygame.JOYAXISMOTION:
        if event.axis == 1:
            #print("LJT UD value: {:>6.3f}".format(-1*event.value))
             # control the noise filter
            ljtactive = 0
            if ongas == 1:
                if drive == 0:
                    if event.value>0:
                        dc2 = 7.5+(event.value*maxspeed*7.5)
                    else:
                        dc2 = 7.5+(event.value*maxspeed*2.5)
                elif drive == 1:
                    if event.value>0:
                        ljtactive = 1
                        dc1 = 7.5+event.value*maxspeed*7.5
                        dc2 = 7.5+event.value*maxspeed*7.5
                    else:
                        ljtactive = 1
                        dc1 = 7.5+event.value*maxspeed*2.5
                        dc2 = 7.5+event.value*maxspeed*2.5
                    if 7.4<dc1<7.6 and 7.4<dc2<7.6:
                        ljtactive = 0
        if event.axis == 2:
            if ongas == 1:
                if drive == 1:
                    if ljtactive == 0:
                        if event.value > 0:
                            dc1 = 7.5-event.value*maxspeed*2.5
                            dc2 = 7.5+event.value*maxspeed*7.5
                        else:
                            dc1 = 7.5-event.value*maxspeed*7.5
                            dc2 = 7.5+event.value*maxspeed*2.5
        if event.axis == 3:
            #print("RJT UD value: {:>6.3f}".format(-1*event.value))
            if ongas == 1:
                if drive == 0:
```

```
                    if event.value>0:
                        dc1 = 7.5+(event.value*maxspeed*7.5)
                    else:
                        dc1 = 7.5+(event.value*maxspeed*2.5)
            if event.axis == 4:
                #print("GAS")
                if event.value>0.2:
                    ongas = 1
                else:
                    ongas = 0
            if event.axis == 5:
                #print("BREAK")
                if event.value>0.2:
                    onbreak = 1
                else:
                    onbreak = 0

        if event.type == pygame.JOYHATMOTION: #jog system
            hat = event.value
            if hat[0] == 1 and hat[1] == 0:
                #print("DPAD: RIGHT")
                p1.ChangeDutyCycle(6.0)
                p2.ChangeDutyCycle(10.0)
                time.sleep(1)
                p1.ChangeDutyCycle(0)
                p2.ChangeDutyCycle(0)
            elif hat[0] == -1 and hat[1] == 0:
                #print("DPAD: LEFT")
                p1.ChangeDutyCycle(10.0)
                p2.ChangeDutyCycle(6.0)
                time.sleep(1)
                p1.ChangeDutyCycle(0)
                p2.ChangeDutyCycle(0)
            elif hat[0] == 0 and hat[1] == 1:
                #print("DPAD: UP")
                p1.ChangeDutyCycle(6.0)
                p2.ChangeDutyCycle(6.0)
                time.sleep(1)
                p1.ChangeDutyCycle(0)
                p2.ChangeDutyCycle(0)
            elif hat[0] == 0 and hat[1] == -1:
                #print("DPAD: DOWN")
                p1.ChangeDutyCycle(10.0)
                p2.ChangeDutyCycle(10.0)
                time.sleep(1)
                p1.ChangeDutyCycle(0)
                p2.ChangeDutyCycle(0)

    if onbreak == 1:
        #Coasting break system
```

```
        diff1 = dc1 - 7.5
        diff2 = dc2 - 7.5
        dc1 -= diff1/10
        dc2 -= diff2/10
        if abs(diff1) < 0.2:
            dc1 = 7.5
        if abs(diff2) < 0.2:
            dc2 = 7.5
    elif ongas == 0:
        dc1 = 7.5
        dc2 = 7.5

    if 7.4<dc1<7.6:
        p1.ChangeDutyCycle(0)
    else:
        p1.ChangeDutyCycle(dc1)

    if 7.4<dc2<7.6:
        p2.ChangeDutyCycle(0)
    else:
        p2.ChangeDutyCycle(dc2)

    # DRAWING STEP
    # First, clear the screen to white. Don't put other drawing commands
    # above this, or they will be erased with this command.
    screen.fill(WHITE)
    textPrint.reset()

    joystick = pygame.joystick.Joystick(0)
    joystick.init()

    if display == 1:
        # Get the name from the OS for the controller/joystick (UI)
        name = joystick.get_name()
        textPrint.print(screen, "Controller: {}".format(name))

        textPrint.print(screen, "")
        textPrint.indent()

        textPrint.print(screen, "LJT RL value:
{:>6.3f}".format(joystick.get_axis(0)))
        textPrint.print(screen, "LJT UD value:
{:>6.3f}".format(-1*joystick.get_axis(1)))
        textPrint.print(screen, "RJT RL value:
{:>6.3f}".format(joystick.get_axis(2)))
        textPrint.print(screen, "RJT UD value:
{:>6.3f}".format(-1*joystick.get_axis(3)))
        textPrint.print(screen, "")

        gas = joystick.get_axis(4)
```

```
        brake = joystick.get_axis(5)

        if gas>0.2:
            textPrint.print(screen, "GAS: ON")
        else:
            textPrint.print(screen, "GAS: OFF")

        if brake>0.2:
            textPrint.print(screen, "BRAKE: ON")
        else:
            textPrint.print(screen, "BRAKE: OFF")

        textPrint.print(screen, "")

        textPrint.print(screen, "A: {}".format(joystick.get_button(0)))
        textPrint.print(screen, "B: {}".format(joystick.get_button(1)))
        textPrint.print(screen, "X: {}".format(joystick.get_button(3)))
        textPrint.print(screen, "Y: {}".format(joystick.get_button(4)))
        textPrint.print(screen, "LB: {}".format(joystick.get_button(6)))
        textPrint.print(screen, "RB: {}".format(joystick.get_button(7)))

        textPrint.print(screen, "")

        hat = joystick.get_hat(0)

        if hat[0] == 0 and hat[1] == 0:
            textPrint.print(screen, "DPAD: NEUTRAL")
        elif hat[0] == 1 and hat[1] == 0:
            textPrint.print(screen, "DPAD: RIGHT")
        elif hat[0] == -1 and hat[1] == 0:
            textPrint.print(screen, "DPAD: LEFT")
        elif hat[0] == 0 and hat[1] == 1:
            textPrint.print(screen, "DPAD: UP")
        elif hat[0] == 0 and hat[1] == -1:
            textPrint.print(screen, "DPAD: DOWN")

        textPrint.print(screen, "")

        textPrint.print(screen, "ljtactive: {}".format(ljtactive))

        textPrint.print(screen, "DC1: {}".format(dc1))
        textPrint.print(screen, "DC2: {}".format(dc2))

    elif display == 0:

        textPrint.print(screen, "DRIVE SCHEME")
        textPrint.print(screen, "")
        if mode == 0:
            textPrint.print(screen, "MODE: NORMAL")
        else:
```

```
            textPrint.print(screen, "MODE: TERRAIN")

        textPrint.print(screen, "DRIVE: BASIC")

        textPrint.print(screen, "")
        textPrint.print(screen, "")


        if readout == 0:
            textPrint.print(screen, "IGNORING ULTRASONIC SENSORS READOUT")
        else:
            textPrint.print(screen, "ULTRASONIC SENSORS READOUT")
            textPrint.print(screen, "")
            printsensorreadout("FRONT",sensordistance(TRIG1,ECHO1))
            printsensorreadout("BACK",sensordistance(TRIG2,ECHO2))
            printsensorreadout("LEFT",47+3*random.random())
            printsensorreadout("RIGHT",43+3*random.random())

    # ALL CODE TO DRAW SHOULD GO ABOVE THIS COMMENT

    # Go ahead and update the screen with what we've drawn.
    pygame.display.flip()

    # Limit to 20 frames per second
    clock.tick(10)


# Close the window and quit.
# If you forget this line, the program will 'hang'
# on exit if running from IDLE.


p1.stop()

p2.stop()

GPIO.cleanup()

pygame.quit()
```

**M: What was learned from final prototype/ improvements**

Mechanical

Mechanically from the final prototype we learned two main lessons. First, we realized that press fitting bearing into sheet metal isn't the best manufacturing process. With the cheaper bearings we used a few of them were broken when press fitting them into the sheet metal. Iif higher quality bearings were used and more accurate manufacturing was used this problem potentially wouldn't have occured. However, looking back on the PESA prototype, the bearing integration is definitely a process we would change based on what we learned.

The second thing we learned was about spring compression and damping. From the PESA prototype testing it was apparent while our suspension system worked, it could use much improvement. It was determined after discussion that the tread arms and therefore springs, were limited to such a small travel range that they weren't compressing enough to properly grip curbs and travel up them effectively. From this lesson, in a future prototype build the travel distance of the tread arms would be increased and the springs would be changed to allow for more compression. To account for this a tensioner would also need to be added to the prototype to account for extra tread slack.

Electrical/Software

When coding around the motors, a few system noise filtering systems had to be implemented. Specifically, a ramp up and down (cyclical electric load) was applied to the motors allowing for a dead band to be found; a band of input voltages where the motors would stay idle. Mapping this point to the idle position of the controller allowed for the creation of a drive code frame around the analog inputs. Adding to this, using the pygame code to write control loops for the different inputs (i.e. jogs, analog ramp ups for the drive) was also a large aspect of the subsystem that was learned by the team to program the system.

Another major learning point for the team was the fact that a queue based drive scheme (py.game) has a limited bus size for inputs; meaning rapid inputs would cause system instability changing the perceived inputs by the system (i.e. causing the jitters referred to in testing and validation). Adding to this, the team learned that the ultrasonics cause a major delay within a queue based system. Delay consideration like these would be applied to future iterations of the project and similar scopes.

To improve the system overall, a multithreaded system would most likely be introduced to code. Specifically the system would have a specific thread to run each command (vision/drive) separately to address the system hang times. A state machine representation of the drive scheme can be used to map every single iteration of the inputs; while a migration from pygame to a non-queue based style code scheme will prevent hang time errors and a more dynamic response. A more robust drive controller that isn't as sensitive to noise will be used (like a dual stick joystick). The ultrasonics can be paired with their own arduino nanos that will compile and report the distances to the raspberry pi to offload delays; this would be implemented only if multithreading does not address the delay issues with ultrasonics. Lastly, the electronics could be integrated onto a custom board that would mitigate any potential connection issues.

## N: Validation Plan, Results, Conclusions

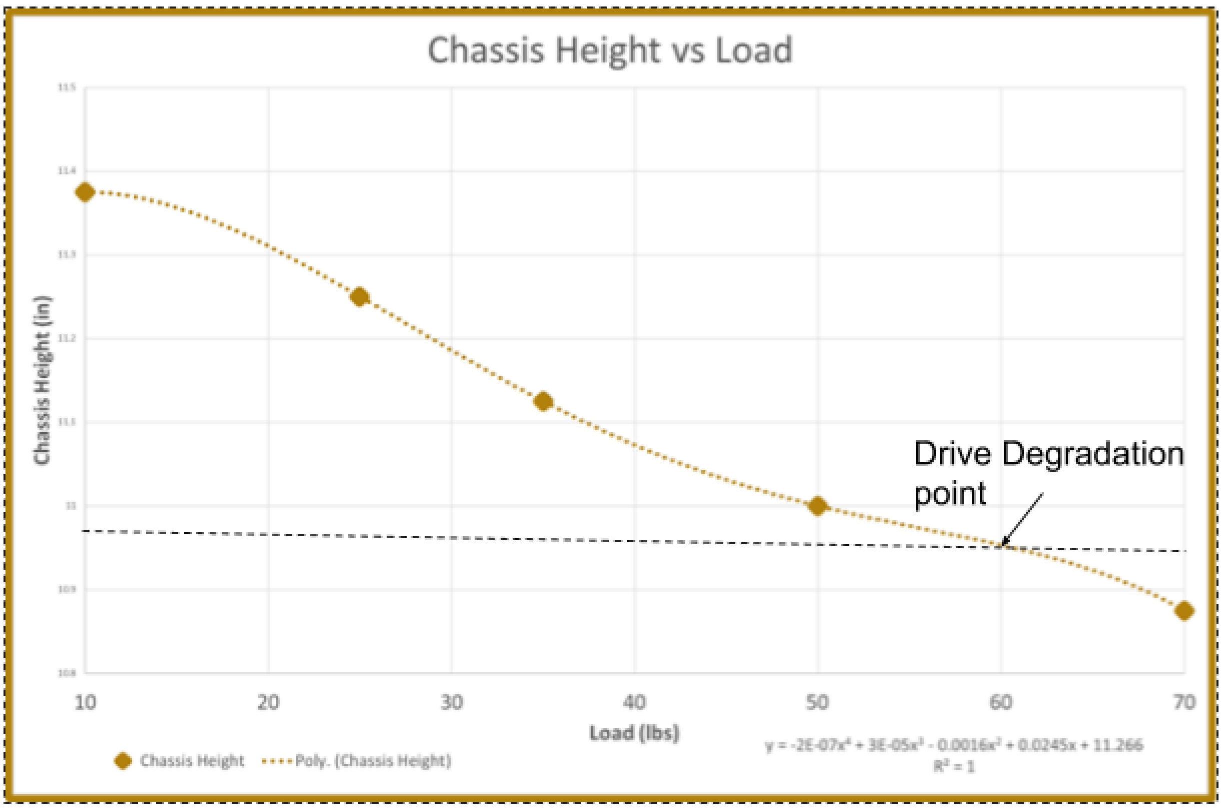
To validate our final prototype the team proposed the following tests:

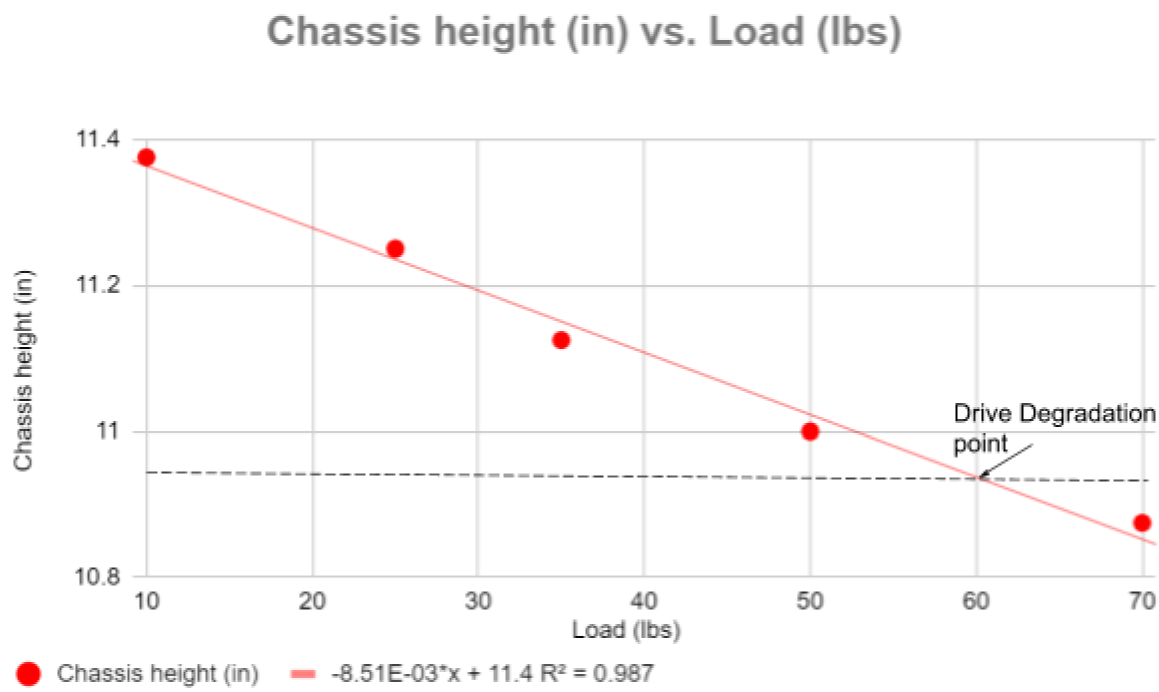
<u>Mechanical</u>

Spring vs Physical Load:

Load the robot on an even surface (robot powered off), measure the height of the chassis from the ground, then add weights incrementing from 10 to 70 lbs. Remeasure after every weight. The point where the tread slack begins to impact drive, is considered the stopping point, or a point when the springs cant hold the weight.

From the teams testing, the following data was collected:



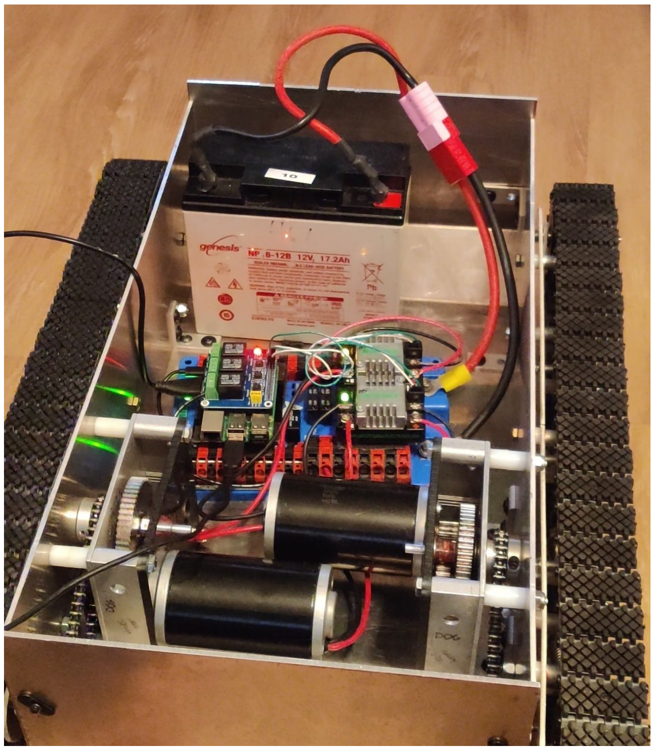



From this, it can be determined that the system responds closely to a linear response with an R squared value of .987, with variance from the expected linear response due to non-perfect loading. A polynomial response was used to map the response with a higher fidelity approximation of the spring deflection. From the test (marked in the polynomial graph), it was determined that the robot only starts spring deflection at weights over 10lbs, and can safely hold up to 60lbs, which is above the goal of this half scale product. When loads over 60 where applied the springs were not the failing point, but the physical treads which slacked too much.

Electrical

Wiring test:

Ensure that the wiring works for all subsystems and connections are being made, FRC standards are used for the expected loads. LED indicators will show that the system is performing correctly, and that no relays are clicking.



As per FRC regulations all 16 gauge connections require a 30A or below breaker fuse, while all 12 gauge connections require a 40A breaker fuse. Specifically the motors and speed controllers used 12 gauge and the other components used 16 gauge. Only the signal wires (from components to raspberry pi) utilised 22 gauge. All lights were on and system was working safely.

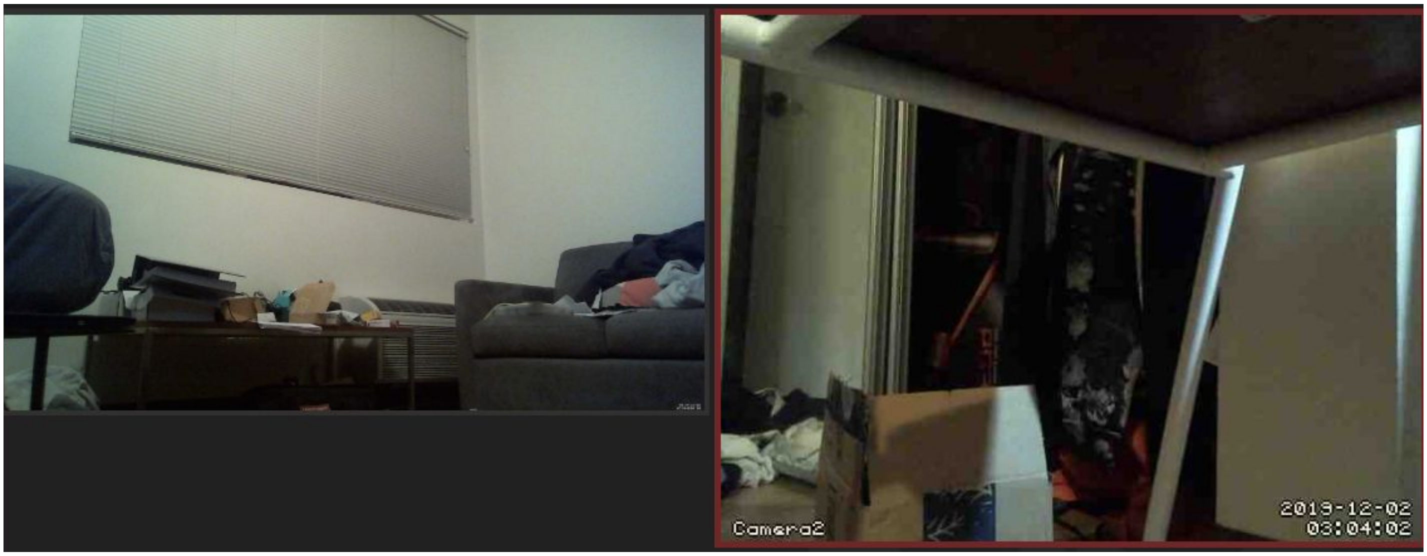
Input test:

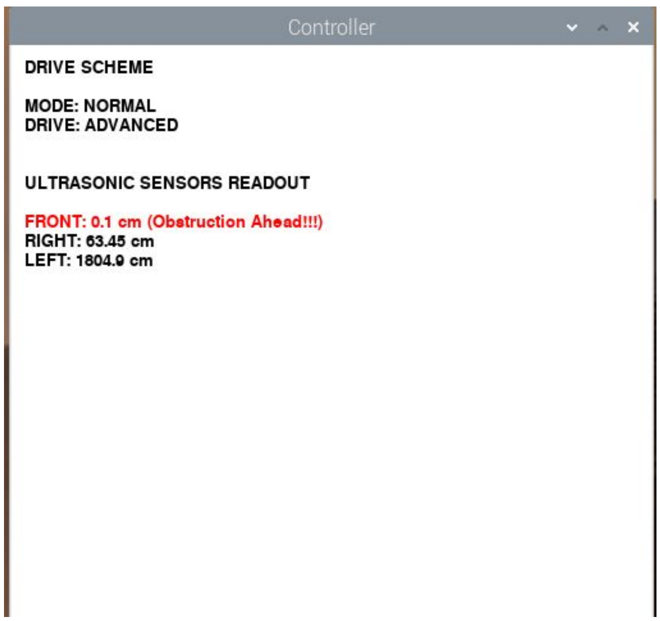
A simple test that tests each input on the controller (refer to HMI appendix) to see if the robot and UI visually responds to each input with minimal delay. The robot will be put up on a block to ensure complete control of a disconnected robot is achievable, and the estop is located safely outside of the chassis.

From the idle tests, the system responded well to inputs from the controller, with delays only due to the fact that the robot is connected over a wifi hotspot, and only noticeable within the camera updates; specifically the camera delays were within an acceptable (within scope of project) 10 second margin. These delays are expected as a wifi hotspot was used within the scope of this project. Overall, the goals of creating an easy to use control scheme that responds quickly were met. However there are present jitter in the controller present where, if too many commands are pressed concurrently, the system “hangs” and overflows the queue and causes random (uninstantiated) motions. This is a limitation of the pygame code used, and required for the separation of the code (see appendix code) into two separate codes;  one for the advanced system (skid steer) and basic. The lights were also changed to be hard wired on to ensure they would not be turned off due to jitters.

UI/Camera/Ultrasonic and Warnings:

Make sure the UI responds clearly to inputs, the camera shows the environment, and the ultrasonics read clearly with minimal delays. Check the ultrasonics give a warning when object detected and slows motor speed. Again robot will be on a block for this test.




From the tests, the ultrasonics respond quickly and constantly update, clearly reports warnings, and slows the motors down if the safety limit of 30cm is reached; and by pressing B it turns off the ultrasonics. The cameras are easily brought up in a browser and clearly show a view of what is in front of the robot clearly. The view is wide enough to drive comfortably, but has some blind spots. The goals are met to be able to drive the robot remotely; with the limitations of a bluetooth controller connection. However, the aforementioned jitters worsen with the integration of the tested system into the main drive code. This is due to the stacking hang times of the ultrasonic arrays working in line with the input controls. As py.game works as a queue based system, its not running systems simultaneously and has to wait for a response; as new inputs are added the system overloads trying to update. Because of this, the ultrasonics were phased out of the drive code with a note of its potential.

Drive test/Curb test:

When inputs and UI checks satisfied, robot will be placed on the ground to see if the system can execute turns and curb climbs. Motors can use the analog input to run up to max speed (terrain mode) on a ramp.

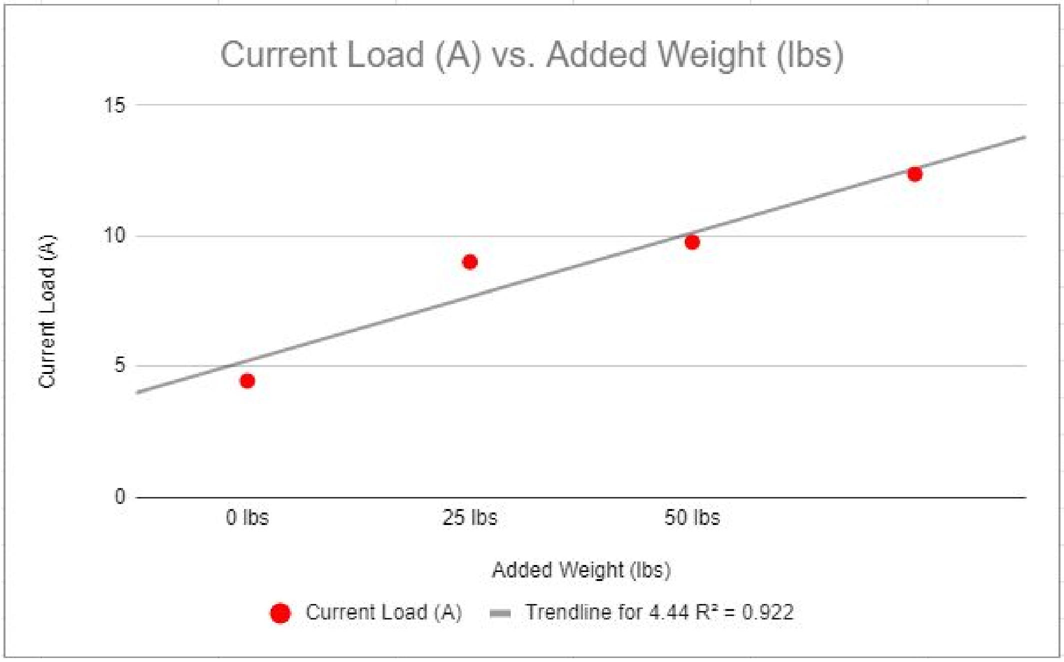
The handling was tested over various terrain including curbs, stairs, stone, and dirt. The robot was operated at speeds deemed reasonable for the terrain at hand. 100% speed over smooth to moderate terrain such as grass, dirt, sticks/stones, and leaves. The robot was slowed to approximately 50% of max speed over aggressive terrain such as stairs and curbs. During the testing the suspension characteristics were analyzed.

Unloaded, the suspension handled most terrain, but struggled scaling steep obstacles.  As the robot overcame an obstacle, the suspension would preload and immediately extend. This would cause an abrupt shift in weight onto the rear wheels, compromising stability. Unloaded, the uneven terrain transferred much of the harsh motion into the chassis.

Implementing an active suspension that could account for weight transfer through changing damping and preload characteristics would ultimately be an ideal solution, but increasing damping and reducing the spring constant slightly would be a valid place to start, but would require more testing and analyzing to perfect.

Motor Load vs Physical Load:

By implementing a voltage to current bridge from the motor to power distribution board, the robot was loaded with various weights ranging from 0lbs to 50lbs to see if the motors would be able to draw enough amps to traverse an environment. This test was done on the ground within a contained areas with a 60% of max speed (Normal) drive mode. Peak voltage for each motor was recorded for test of the drive path, and was converted to current utilizing the bridge.




The response is fairly linear with an Rsq value of .922 allowing for easier predictions within the range of weights. Most importantly the max current draw is within 15 amps during the heaviest (what the robot's max was designed for) load. As the system runs on FRC components (guidelines detail 40 A breaker fuse for these motors), the system is well within the safety measures and wont reach a failure point: where the current draw is too great and the breaker flips, shutting off the robot. Adding to this, the robot has the ability to carry these weights over more complex terrains as the robot has headroom for current draw.

**O: Market Analysis**

After Research Phoenix Robotics came up with the following competitors: Starship, PostMates, Kiwi, Stryker, Aethon, and FMC Technologies.

Starship, PostMates, and Kiwi were considered to be a potential competitor due to their autonomous robot's focus on delivery in Urban environments. These companies Phoenix believe have the potential to adapt their current models to meet similar customer requirements and become a competitor. Through research the technical specifications and cost of their robots can be found in the following chart

| | *Starship* | PostMates Serve | *Kiwi* |
|---|---|---|---|
| Range: | 3.7 mi (2hrs) | 30 mi | 300 m |
| Carry Capacity: | 20 lbs | 50 lbs | <10 lbs |
| Cost: | $8,000-$16,000 | - | - |

Range, carrying capacity and cost were looked at because the team determined those specifications to be the most important and comparable between the delivery robots and PESA.

Stryker, Aethon, and FMC Technologies were considered because they are already established in the medical field. Stryker sells a variety of products including motor assisted gurneys. The team believe that these gurneys would require significantly more engineering to adapt to meet customer requirements while compared to the delivery service robots. However, due to Stryker already being well established in the field the team believes that they have the potential and resources to become a direct competitor in the future.

TUG and FMC Technologies both produce supply robots designed for hospitals. Both of these robots are meant for inside use specifically and are fully autonomous. Since these companies, especially Aethon, focus on autonomous medical delivery, the team considers them our strongest potential competitors. Below a specifications of Stryker, FMC, and Aethon products can be seen.

| | *Stryker Gurney* | FMC Technologies | TUG by Aethon |
|---|---|---|---|
| Range: | - | * | 10 hours |
| Carry Capacity: | 700 lbs | 600 lbs | 750 lbs |
| Cost: | $18,000 | - | $140,000<br>$2,000 per month** |
| Weight: | | 1000 lbs *** | 220 lbs*** |

***Multiple operate in hospitals at once allowing for intermediate charging and 24 hour coverage**
****Tug have an initial estimated cost of $140,000 however 24/7 monitoring and support costs an additional $1,500-2,000 a month**
*****Weights are included in specs so an idea of how much competitor weigh**

Looking at all the potential competitors, the team believes Aethon is our biggest competitor. Aethon already has specs that are closest to our customer requirements. With their 24/7 support infrastructure already in place switching to a remote control system to help EMTs when a mass casualty incident occurs would be an easy adaptation.

# P: Bill of Materials

Final bill of materials for PESA Prototype

**ME 463 Senior Design**

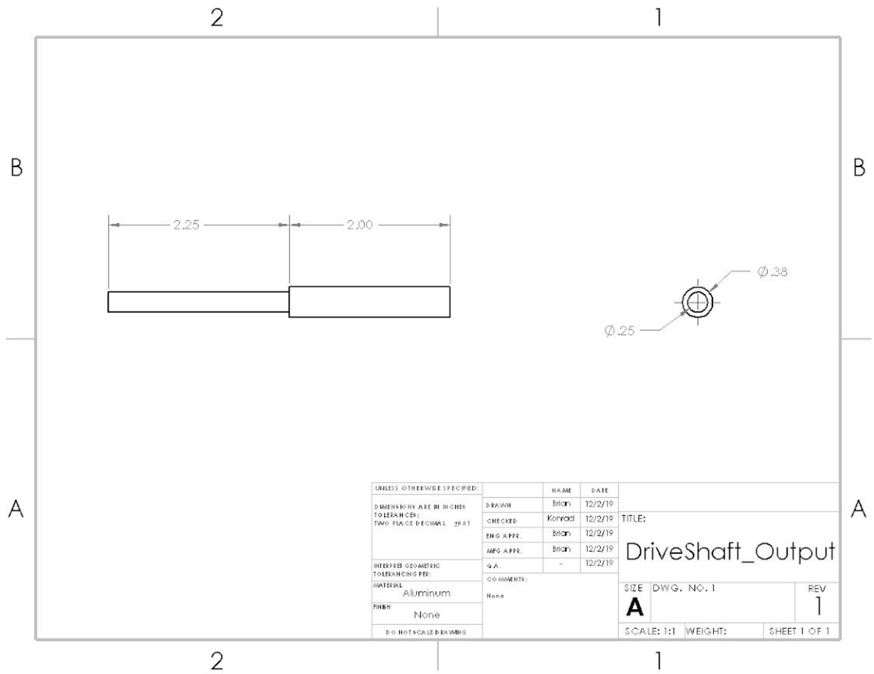
**Team Name: Purdue Emergency Supply Assistant**

| Item ID Number | Item | Description | Source | Unit Cost | Quantity | Total Cost |
|---|---|---|---|---|---|---|
| **Subsystem 1:** | **Drivetrain** | | | | | |
| D1 | Lynxmotion Track | 2" Wide Tank Tread Links | RobotShop | $1.20 | 102 | $ 122.40 |
| D2 | Lynxmotion Track Sprocket | 6 Tooth Tank Tread Sprocket | RobotShop | $7.71 | 8 | $ 61.68 |
| D3 | Lynxmotion Track Sprocket | 9 Tooth Tank Tread Sprocket | RobotShop | $9.65 | 4 | $ 38.60 |
| D4 | Lynmxotion Hub | 1/4" ID Sprocket Hubs | RobotShop | $7.65 | 12 | $ 91.80 |
| D5 | Tank Tread Plate | 5052 Aluminum 1/8" Sheet Metal Plate 72.95 in ^ 2 | Purdue RMS | $5.24 | 4 | $ 20.96 |
| D6 | Front Suspension Link | 5052 Aluminum 1/8" Sheet Metal Plate 6.98 in ^2 | Purdue RMS | $0.50 | 4 | $ 2.00 |
| D7 | Short Suspension Link | 5052 Aluminum 1/8" Sheet Metal Plate 4.45 in^2 | Purdue RMS | $0.32 | 12 | $ 3.84 |
| D8 | Shock | 130 mm RC Shock | Amazon | $6.50 | 8 | $ 52.00 |
| D9 | Spring | 3.5" Long, 0.75" OD, 0.568" ID Compression Spring | McMaster-Carr | $1.73 | 8 | $ 13.84 |
| D10 | Bealngs FR188-2Z | 1/4" ID x 1/2" OD Flanged Bearings | Amazon | $1.60 | 40 | $ 64.00 |
| D11 | Shims | 1/4" ID x 3/8" OD Washers | McMaster-Carr | $0.39 | 76 | $ 15.60 |
| D12 | Spacer | 1/4" ID x 1/2" OD x 0.62" Zinc-Plated Steel Spacer | McMaster-Carr | $1.62 | 12 | $ 19.44 |
| D13 | Spacer | 1/4" ID x 1/2" OD x 1.2" Zinc-Plated Steel Spacer | McMaster-Carr | $3.13 | 10 | $ 31.32 |
| D14 | Spacer | 1/4" ID x 1/2" OD x 1" Zinc-Plated Steel Spacer | McMaster-Carr | $2.61 | 6 | $ 15.66 |
| D15 | Spacer | 1/4" ID x 1/2" OD x 0.33" Zinc-Plated Steel Spacer | McMaster-Carr | $0.86 | 8 | $ 6.89 |
| D16 | Spacer | 1/4" ID x 1/2" OD x 0.72" Zinc-Plated Steel Spacer | McMaster-Carr | $1.88 | 8 | $ 15.03 |
| D17 | Spacer | 3 mm ID x 4 mm OD x 0.47" 18-8 Stainless Steel Spacer | McMaster-Carr | $1.47 | 16 | $ 23.52 |
| D18 | Nut | Medium-Strength Steel Nylon-Insert Locknut, Grade 5, Zinc-Plated, 1/4"-20 Thread Size | McMaster-Carr | $0.04 | 28 | $ 1.23 |
| D19 | Nut | Low-Strength Steel Nylon-Insert Locknut, Zinc-Plated, 10-32 Thread Size | McMaster-Carr | $0.03 | 8 | $ 0.27 |
| D20 | Nut | Medium-Strength Steel Nylon-Insert Locknut, Class 8, Zinc-Plated, M3 x 0.5 mm Thread | McMaster-Carr | $ 0.04 | 8 | $ 0.28 |
| D21 | Bolt | Medium-Strength Grade 5 Steel Hex Head Screw, Zinc-Plated, 1/4" -20 Thread Size, 2-1/2" Long, Fully Threaded | McMaster-Carr | $ 0.23 | 28 | $ 6.32 |
| D22 | Bolt | Steel Pan Head Phillips Screws, 10-32 Thread, 2-1/2" Long | McMaster-Carr | $ 0.16 | 8 | $ 1.25 |
| D23 | Bolt | Steel Pan Head Phillips Screw, M3 x 0.5 mm Thread, 40 mm Long | McMaster-Carr | $ 0.09 | 8 | $ 0.75 |
| | | | **Subtotal** | | | **$ 608.67** |
| **Subsystem 2:** | **Chassis** | | | | | |
| **Item ID Number** | **Item** | **Description** | **Source** | **Unit Cost** | **Quantity** | **Total Cost** |
| C1 | Base Plate | 5052 Aluminum 1/8" Sheet Metal Plate 408 in^2 | Purdue RMS | $29.31 | 1 | $ 29.31 |
| C2 | Side Plate | 5052 Aluminum 1/8" Sheet Metal Plate 127.66 in^2 | Purdue RMS | $9.17 | 2 | $ 18.34 |
| C3 | ToughBox | Gearbox | AndyMark | $80.00 | 2 | $ 160.00 |
| C4 | Motor | CIM Motor | AndyMark | $32.75 | 2 | $ 65.50 |
| C4 | Sprocket | 16 Teeth Chain Sprocket for ANSI 25 Chain, 3/8" Shaft | McMaster-Carr | $11.94 | 2 | $ 23.88 |
| C5 | Sprocket | 16 Teeth Chain Sprocket for ANSI 25 Chain, 1/2" Hex Shaft | AndyMark | $11.00 | 2 | $ 22.00 |
| C6 | Bearings | 3/8" ID 7/8" OD Flanged Bearing - FR6ZZ | AndyMark | $3.00 | 4 | $ 12.00 |
| C7 | Shaft Collar | 1/2" Hex Shaft Collar | AndyMark | $5.00 | 2 | $ 10.00 |
| C8 | Output Shaft | 316 Steel 3/8" OD x 4.25" Shaft | Purdue RMS | $12.77 | 2 | $ 25.54 |
| C9 | Bearing Block | 5052 Aluminum 1/4" Plate 4.2 in^2 | Purdue RMS | $0.63 | 2 | $ 1.26 |
| C10 | Spacer | 1/4" ID x 1/2" OD x 1" Zinc-Plated Steel Spacer | McMaster-Carr | $2.61 | 12 | $ 31.32 |
| C11 | Angle Bracket | Strut Channel Bracket, 90 Degree, Zinc-Plated Steel, 4-1/8" Length | McMaster-Carr | $2.64 | 2 | $ 5.28 |
| C12 | Chassis Cross Brace | 1/16" x 1/2" 6061 Aluminum Angle Stock 11.75" Length | McMaster-Carr | $1.04 | 1 | $ 1.04 |
| C13 | 1/4"-20 Bolt, 1/2" long | Button Head Hex Drive Screw, Black-Oxide Alloy Steel, 1/4"-20 Thread, 1/2" Long | McMaster-Carr | $0.14 | 12 | $ 1.70 |
| C14 | Bolt | Low-Strength Zinc-Plated Steel Hex Head Screw, 1/4"-20 Thread Size, 2-3/4" Long, Fully Threaded | McMaster-Carr | $0.22 | 8 | $ 1.76 |
| C15 | Nut | Medium-Strength Steel Nylon-Insert Locknut, Grade 5, Zinc-Plated, 1/4"-20 Thread Size | McMaster-Carr | $0.04 | 28 | $ 1.23 |
| C16 | Bolt | 10 | McMaster-Carr | $0.37 | 4 | $ 1.48 |
| C17 | PVC elbow | 1/2" PVC 3-way elbow | Home Depot | $1.78 | 8 | $ 14.24 |
| C18 | PVC Chassis Length Pipe | 1/2" PVC pipe 22.5" length | Home Depot | $0.32 | 4 | $ 1.28 |
| C19 | PVC Chassis Width Pipe | 1/2" PVC pipe 10.5" length | Home Depot | $0.15 | 4 | $ 0.60 |
| C20 | PVC Riser Pipe | 1/2" PVC pipe 2" length | Home Depot | $0.03 | 4 | $ 0.12 |
| C21 | Basket Bottom | 1/8" 5052 aluminum sheet 12" x 24" | Purdue RMS | $28.13 | 1 | $ 28.13 |
| C22 | Chassis Cover | .08" OPTIX 24" x 12" Clear Acrylic Sheet | Lowes | $8.37 | 1 | $ 8.37 |
| C23 | #6 1/2" Screws | #6-1/2" long flat head type A phillips screws | Amazon | $0.08 | 12 | $ 0.96 |
| C24 | Basket mount | 3/4" EMT conduit one-hole strap | Home Depot | $0.08 | 4 | $ 0.32 |
| C25 | Chain | #25 chain 68 links | Home Depot | $5.64 | 2 | $ 11.28 |
| | | | **Subtotal** | | | **$ 476.94** |
| **Subsystem 3:** | **Electrical** | | | | | |
| **Item ID Number** | **Item** | **Description** | **Source** | **Unit Cost** | **Quantity** | **Total Cost** |
| E1 | LED | Miniature Light Bulb Bayonet Base, Tubular, 0.33W, 0.02A | McMaster-Carr | $13.91 | 2 | $ 27.82 |
| E2 | Computer Case | Pi Case with Cooling | Amazon | $15.59 | 1 | $ 15.59 |
| E3 | Power Relay Expansion Board | Raspberry Pi Expansion Board Power Relay | Amazon | $23.99 | 1 | $ 23.99 |
| E4 | Power Distribution Board | Power Distribution Panel | AndyMark | $205.00 | 1 | $ 205.00 |
| E5 | Computer | Raspberry Pi 3 Model B Board | Amazon | $38.36 | 1 | $ 38.36 |
| E6 | Speed Controller | Talon SR | AndyMark | $39.99 | 2 | $ 79.98 |
| E7 | Operating Controller | Xbox One Remote | Microsoft | $65.00 | 1 | $ 65.00 |
| E8 | Ultrasonic Sensor | Ultrasonic Distance Sensor - HC-SR04 | Amazon | $3.95 | 4 | $ 15.80 |
| E9 | Camera | Logitech HD Webcam C525 | Logitech | $59.99 | 2 | $ 119.98 |
| E10 | Fuses | 40 Amp Breaker | AndyMark | $7.00 | 2 | $ 14.00 |
| E11 | Fuses | 20 Amp Breaker | AndyMark | $6.00 | 1 | $ 6.00 |
| E12 | 12 Gauge Wire | 2' of 12 Guage Wire | AndyMark | $1.67 | 1 | $ 1.67 |
| E13 | 14 Gauge Wire | 2' of 14 Guage Wire | AndyMark | $1.40 | 1 | $ 1.40 |
| E14 | Ribbon Cable | 15' of 10 Wire Ribbon Cable | AndyMark | $6.98 | 1 | $ 6.98 |
| E15 | Terminal Pins | Terminal Housing Pins | AndyMark | $3.00 | 1 | $ 3.00 |
| E16 | Wire Connectors | 12 Gauge Ring Terminals | AndyMark | $2.50 | 1 | $ 2.50 |
| E17 | E-Stop | 120 Amp Circuit Breaker | AndyMark | $32.00 | 1 | $ 32.00 |
| | | | **Subtotal** | | | **$ 659.07** |
| | | | **Grand Total** | | | **$ 1,744.68** |

## Q. Manufacturing Plans

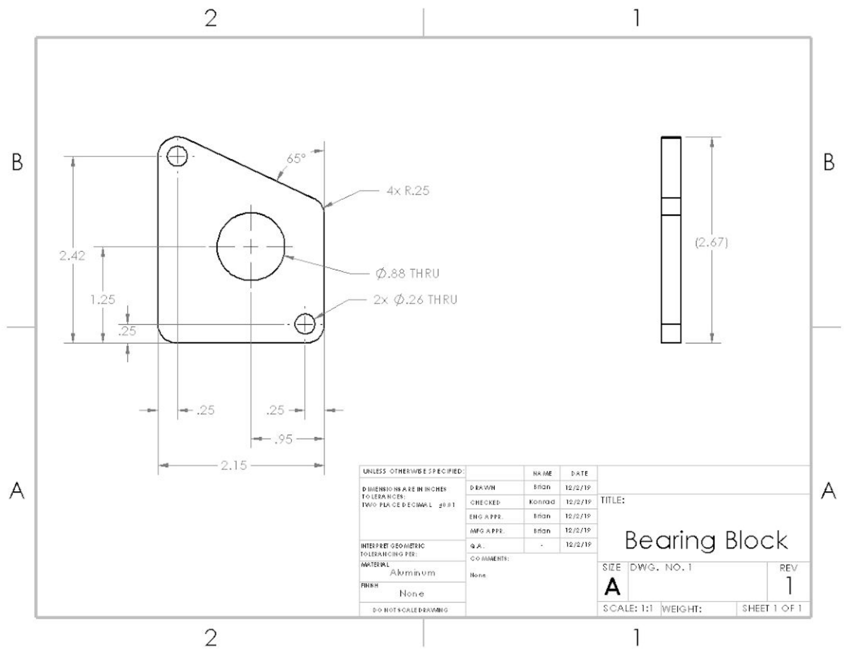
### Q1. Manufacturing and Tooling Operations (MTO)

1) Drive Shaft



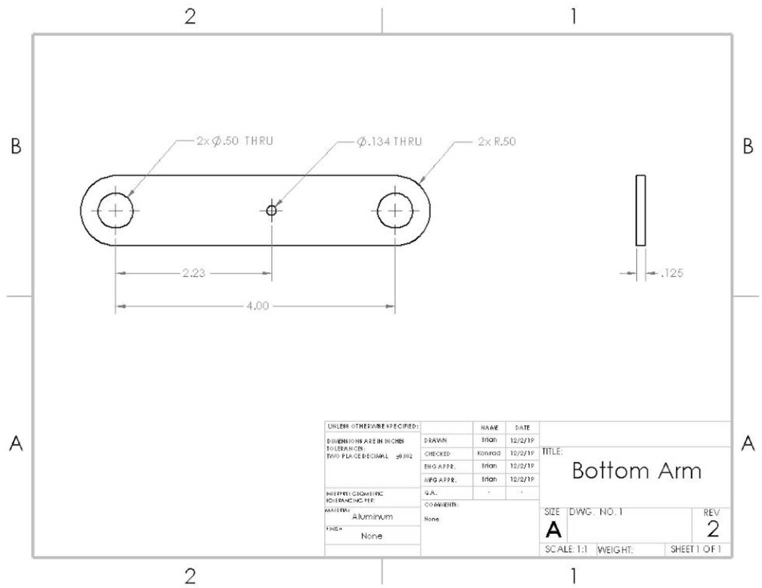

| Step | Operation | Description | Equipment | Notes |
|---|---|---|---|---|
| 1 | Raw Stock | 4.25" x 0.375" OD 316 Steel Shaft | Bandsaw | 250 FPM |
| 2 | Face Ends | Face ends to exact length | Lathe | S = 5806 RPM; F = hand |
| 3 | Turn | 0.25" OD x 2.25" | Lathe | S = 5806 RPM; F = .94 in/s |
| 4 | File | File all sharp edges | Hand Tool | |
| 5 | Inspection | Check Dimensions | Caliper, Micrometer | |

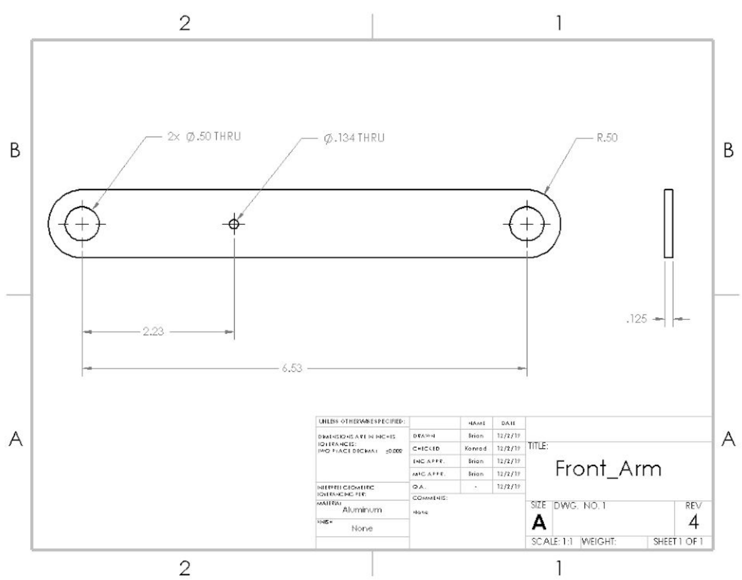
2) Bearing Block

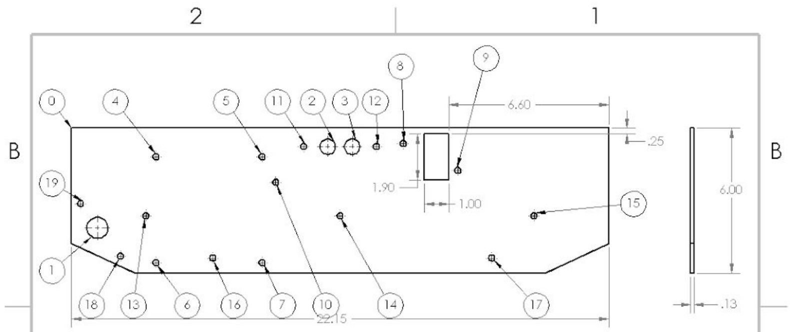



| Step | Operation | Description | Equipment | Notes |
|---|---|---|---|---|
| 1 | Raw Stock | 2.7" x 2.2" x 1/4" 5052 Aluminum Stock | Bandsaw | 300 FPM |
| 2 | Face Ends | 2.67" x 2.15" x 1/4" 5052 Aluminum Stock | Mill | S = 800; F = 3 |
| 3 | Center Drill | #0 Drill, .03 Deep | Mill | S= 1000; F = hand |
| 4 | Drill | 1/4" Drill, Through | Mill | S = 800; F = hand |
| 5 | Drill | 27/32" Drill, Through | Mill | S = 800; F = hand |
| 6 | Ream | 7/8" Reamer Drill Bit, Through | Mill | S = 200; F = .014 |
| 7 | Cut | 245° Cut | Bandsaw | 300 FPM |
| 8 | Sand | Smooth cut edges | Belt Sander | |
| 9 | Debur | Removes sharp edges of holes | Hand Tool | |
| 10 | Inspection | Check Dimensions | Caliper | |

3) Suspension Arms, Tread Plates, Chassis Side Plates, Basket Plate






| Number | Size(D) | X | Y |
|---|---|---|---|
| 0 | - | 0 | 0 |
| 1 | 0.875 | 1.07 | -4.125 |
| 2 | 0.642 | 10.57 | -0.77 |
| 3 | 0.642 | 11.57 | -0.77 |
| 4 | 0.257 | 3.485 | -1.188 |
| 5 | 0.257 | 7.86 | -1.188 |
| 6 | 0.257 | 3.485 | -5.56 |
| 7 | 0.257 | 7.86 | -5.56 |
| 8 | 0.257 | 13.67 | -0.65 |
| 9 | 0.257 | 15.92 | -1.75 |
| 10 | 0.25 | 8.42 | -2.245 |
| 11 | 0.25 | 9.57 | -0.77 |
| 12 | 0.25 | 12.57 | -0.77 |
| 13 | 0.25 | 3.07 | -3.625 |
| 14 | 0.25 | 11.07 | -3.625 |
| 15 | 0.25 | 19.07 | -3.625 |
| 16 | 0.25 | 5.82 | -5.375 |
| 17 | 0.25 | 17.32 | -5.375 |
| 18 | 0.25 | 2.02 | -5.3 |
| 19 | 0.25 | 0.375 | -3.125 |

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.002
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL Aluminum
FINISH None
DO NOT SCALE DRAWING

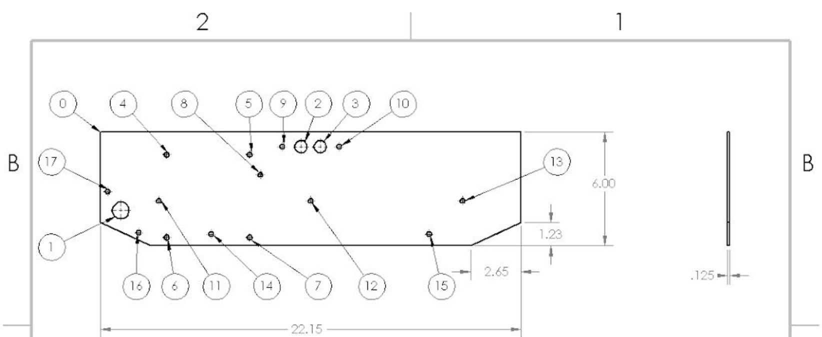
| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | - | 12/2/19 |

COMMENTS: None

TITLE: Chassis_Left_Side

SIZE A DWG. NO. 1 REV 1

SCALE: 1:3 WEIGHT: SHEET 1 OF 1




| Number | Size(D) | X | Y |
|---|---|---|---|
| 0 | - | 0 | 0 |
| 1 | 0.875 | 1.07 | -4.125 |
| 2 | 0.642 | 10.57 | -0.77 |
| 3 | 0.642 | 11.57 | -0.77 |
| 4 | 0.257 | 3.485 | -1.188 |
| 5 | 0.257 | 7.86 | -1.188 |
| 6 | 0.257 | 3.485 | -5.56 |
| 7 | 0.257 | 7.86 | -5.56 |
| 8 | 0.25 | 8.42 | -2.245 |
| 9 | 0.25 | 9.57 | -0.77 |
| 10 | 0.25 | 12.57 | -0.77 |
| 11 | 0.25 | 3.07 | -3.625 |
| 12 | 0.25 | 11.07 | -3.625 |
| 13 | 0.25 | 19.07 | -3.625 |
| 14 | 0.25 | 5.82 | -5.375 |
| 15 | 0.25 | 17.32 | -5.375 |
| 16 | 0.25 | 2.02 | -5.3 |
| 17 | 0.25 | 0.375 | -3.125 |

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.002
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL Aluminum
FINISH None
DO NOT SCALE DRAWING

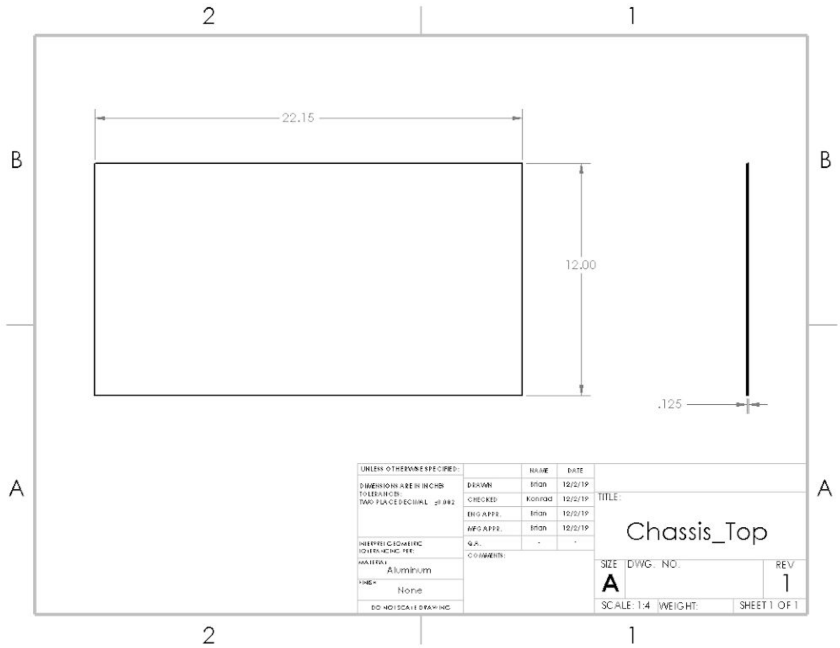
| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | - | 12/2/19 |

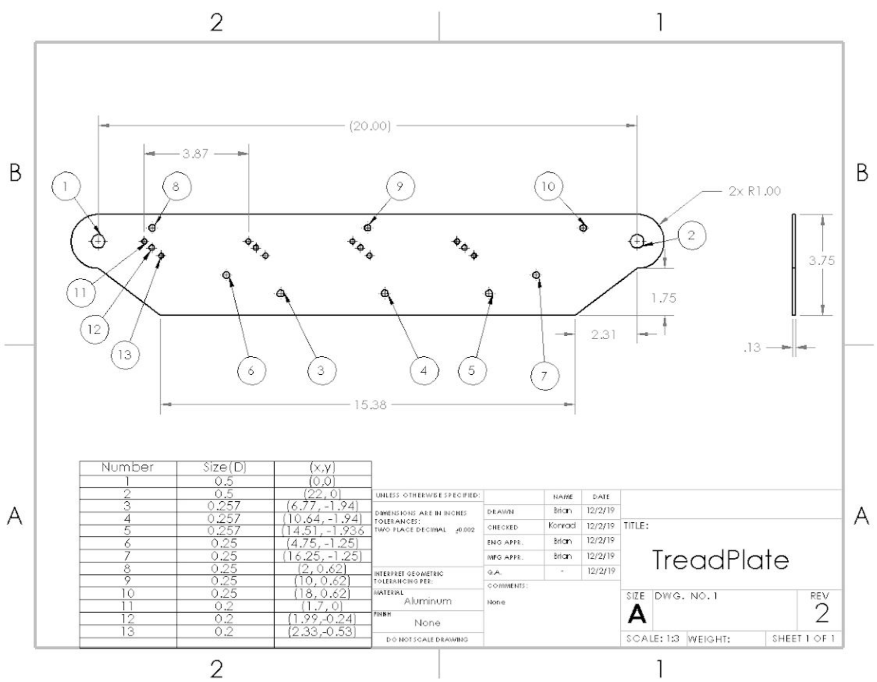
COMMENTS: None

TITLE: Chassis_Right_Side

SIZE A DWG. NO. 1 REV 5

SCALE: 1:3 WEIGHT: SHEET 1 OF 1

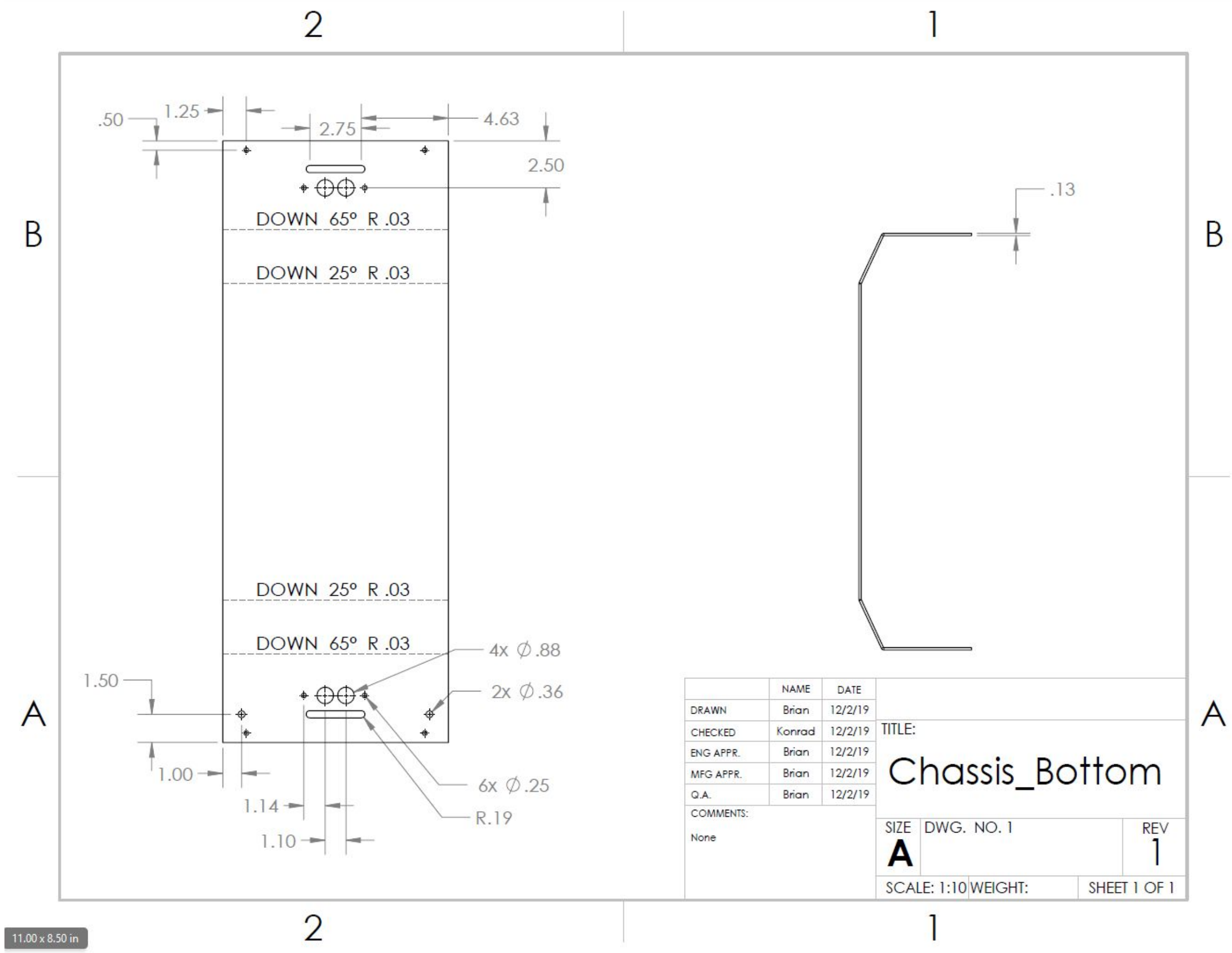



| Number | Size(D) | (x,y) |
|---|---|---|
| 1 | 0.5 | (0,0) |
| 2 | 0.5 | (22,0) |
| 3 | 0.257 | (6.77, -1.94) |
| 4 | 0.257 | (10.64, -1.94) |
| 5 | 0.257 | (14.51, -1.936 |
| 6 | 0.25 | (4.75, -1.25) |
| 7 | 0.25 | (16.25, -1.25) |
| 8 | 0.25 | (2, 0.62) |
| 9 | 0.25 | (10, 0.62) |
| 10 | 0.25 | (18, 0.62) |
| 11 | 0.2 | (1.7, 0) |
| 12 | 0.2 | (1.99,-0.24) |
| 13 | 0.2 | (2.33,-0.53) |

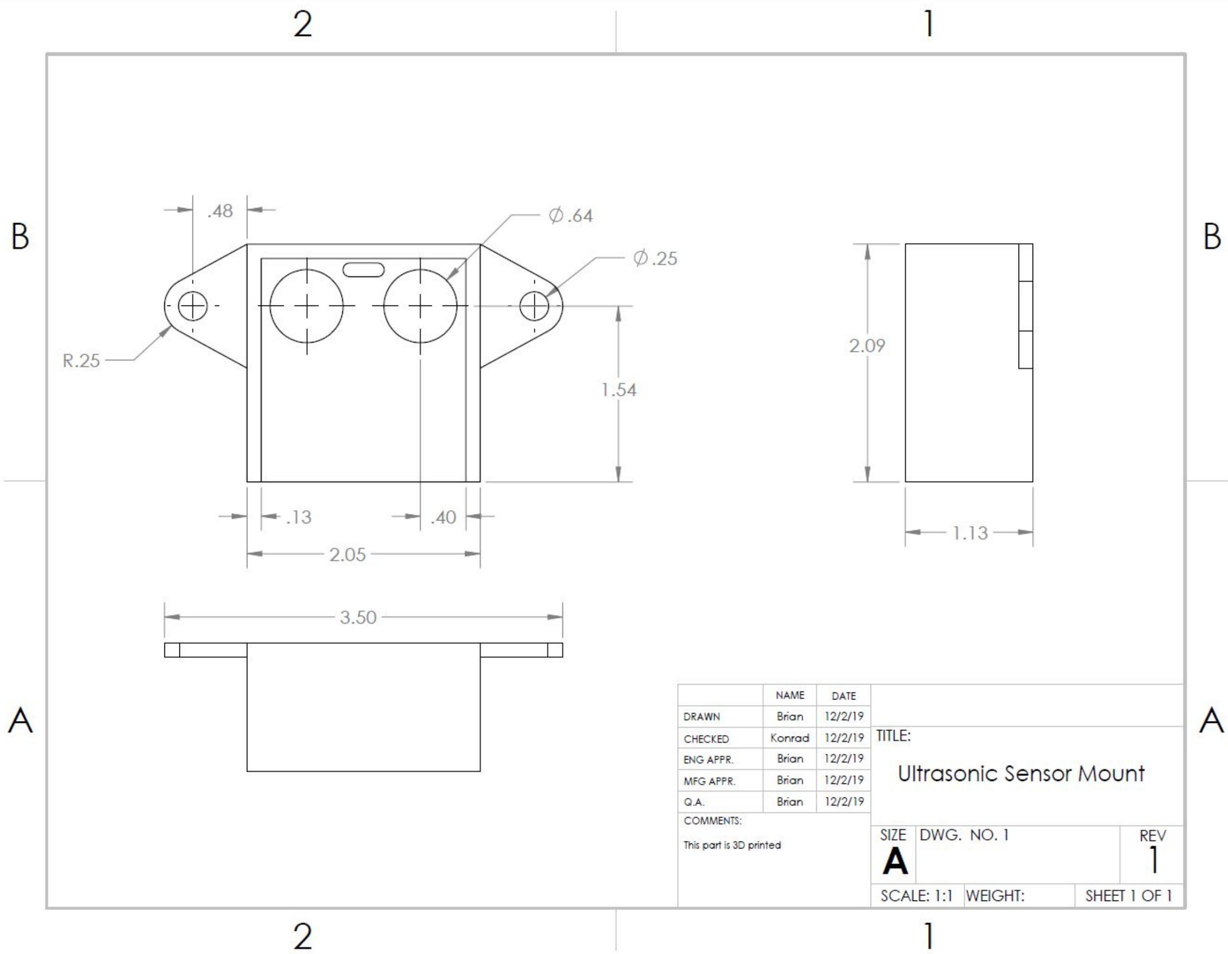
| Step | Operation | Description | Equipment | Notes |
|---|---|---|---|---|
| 1 | Raw Stock | 4’x4’x 1/8” 5052 Aluminum | | |
| 2 | Drawing | Draw parts in CAD file | Solidworks 2018 | |
| 3 | DXF File | Convert CAD file to DXF format | FlowPath | |
| 4 | Cut | Waterjet cuts following DXF | Waterjet | |
| 5 | Cut | Cut tabs from waterjet cuts | Hand Tool | |
| 6 | Sand | Smooth cut edges | Belt Sander | |
| 7 | Debur | Remove sharp edges inside the holes | Hand Tool | |
| 8 | Inspection | Check Dimensions | Caliper | |

4) Chassis Base




| Step | Operation | Description | Equipment | Notes |
|---|---|---|---|---|
| 1 | Raw Stock | 4'x4'x 1/8" 5052 Aluminum | | |
| 2 | Drawing | Draw parts in CAD file | Solidworks 2018 | |
| 3 | DXF File | Convert CAD file to DXF format | FlowPath | |
| 4 | Cut | Waterjet cuts following DXF | Waterjet | |
| 5 | Cut | Cut tabs from waterjet cuts | Hand Tool | |
| 6 | Sand | Smooth cut edges | Belt Sander | |
| 7 | Debur | Remove sharp edges inside the holes | Hand Tool | |
| 8 | Bend | 2 115°, 2 155° bends | Metal Break | |
| 9 | Inspection | Check Dimensions | Caliper | |

5) Ultrasonic Mount




| Step | Operation | Description | Equipment | Notes |
|---|---|---|---|---|
| 1 | Drawing | Draw parts in CAD file | Solidworks 2018 | |
| 2 | STP File | Convert CAD file to STP format | Solidworks 2018 | |
| 3 | GCode | Create print file from STP | CURA | |
| 4 | Print | Print part on Taz 6 | Lulzbot TAZ 6 | |
| 5 | Inspection | Check Dimensions | Caliper | |

**R. Assembly Procedure**

Table Of Contents:



Component List:

| **Subsystem 1:** | **Drivetrain** | |
|---|---|---|
| **Item ID Number** | **Item** | **Description** |
| D1 | Lynxmotion Track | 2" Wide Tank Tread Links |
| D2 | Lynxmotion Track Sprocket | 6 Tooth Tank Tread Sprocket |
| D3 | Lynxmotion Track Sprocket | 9 Tooth Tank Tread Sprocket |
| D4 | Lynxmotion Hub | 1/4" ID Sprocket Hubs |
| D5 | Tank Tread Plate | Sheet Metal Plate |
| D6 | Front Suspension Link | Sheet Metal Plate |
| D7 | Short Suspension Link | Sheet Metal Plate |
| D8 | Shock | 130 mm RC Shock |
| D9 | Spring | 3.5" Long, 0.75" OD, 0.568" ID Compression Spring |
| D10 | Bearings FR188-2Z | 1/4" ID x 1/2" OD Flanged Bearings |
| D11 | Shims | 1/4" ID x 3/8" OD Washers |
| D12 | Spacer | 1/4" ID x 1/2" OD x 0.62" Steel Spacer (between wheels lower, and front wheels) |
| D13 | Spacer | 1/4" ID x 1/2" OD x 1.2" Steel Spacer (Between plates mounting) |
| D14 | Spacer | 1/4" ID x 1/2" OD x 1" Steel Spacer (Between short Arms top) |
| D15 | Spacer | 1/4" ID x 1/2" OD x 0.33" Steel Spacer (Spring tom outer side) |
| D16 | Spacer | 1/4" ID x 1/2" OD x 0.72" Steel Spacer (Spring top chassis side) |
| D17 | Spacer | 3 mm ID x 4 mm OD x 0.47" Steel Spacer |
| D18 | Nut | Medium-Strength Steel Nylon-Insert Locknut, Grade 5, Zinc-Plated, 1/4"-20 Thread Size |
| D19 | Nut | Low-Strength Steel Nylon-Insert Locknut, Zinc-Plated, 10-32 Thread Size |
| D20 | Nut | Medium-Strength Steel Nylon-Insert Locknut, Class 8, Zinc-Plated, M3 x 0.5 mm Thread |
| D21 | Bolt | Medium-Strength Grade 5 Steel Hex Head Screw, |

| | | |
|---|---|---|
| | | Zinc-Plated, 1/4"-20 Thread Size, 2-1/2" Long, Fully Threaded |
| D22 | Bolt | Steel Pan Head Phillips Screws, 10-32 Thread, 2-1/2" Long |
| D23 | Bolt | Steel Pan Head Phillips Screw, M3 x 0.5 mm Thread, 40 mm Long |

| **Subsystem 2:** | **Chassis** | |
|---|---|---|
| **Item ID Number** | **Item** | **Description** |
| C1 | Base Plate | Sheet Metal Plate |
| C2 | Side Plate | Sheet Metal Plate |
| C3 | ToughBox | Gearbox |
| C4 | Motor | CIM Motor |
| C4 | Sprocket | 16 Teeth Chain Sprocket for ANSI 25 Chain, 3/8" Shaft |
| C5 | Sprocket | 16 Teeth Chain Sprocket for ANSI 25 Chain, 1/2" Hex Shaft |
| C6 | Bearings | 3/8" ID 7/8" OD Flanged Bearing - FR6ZZ |
| C7 | Shaft Collar | 1/2" Hex Shaft Collar |
| C8 | Output Shaft | Low-Strength Zinc-Plated Steel Hex Head Screw, 1/4"-20 Thread Size, 2-3/4" Long, Fully Threaded |
| C9 | Bearing Block | Custom 1/4" Aluminum Plate |
| C10 | Spacer | 1/4" ID x 1/2" OD x 1" Steel Spacer |
| C11 | Angle Bracket | Strut Channel Bracket, 90 Degree, Zinc-Plated Steel, 4-1/8" Length |
| C12 | Angle Stock | 1/2" x 1/2" x 11.75" Angle Stock |
| C13 | 1/4"-20 Bolt, 1/2" long | Button Head Hex Drive Screw, Black-Oxide Alloy Steel, 1/4"-20 Thread, 1/2" Long |
| C14 | Bolt | Low-Strength Zinc-Plated Steel Hex Head Screw, 1/4"-20 Thread Size, 2-3/4" Long, Fully Threaded |
| C15 | Nut | Medium-Strength Steel Nylon-Insert Locknut, Grade 5, Zinc-Plated, 1/4"-20 Thread Size |
| C16 | Bolt | Super-Corrosion-Resistant 316 Stainless Steel Hex Head Screw<br>1/4"-20 Thread Size, 1-3/4" Long, Partially Threaded |
| C17 | PVC elbow | 1/2" PVC 3-way elbow |
| C18 | PVC Chassis Length Pipe | 1/2" PVC pipe 22.5" length |
| C19 | PVC Chassis Width Pipe | 1/2" PVC pipe 10.5" length |
| C20 | PVC Riser Pipe | 1/2" PVC pipe 2" length |
| C21 | Basket Bottom | 1/8" 5052 aluminum sheet 12" x 24" |
| C22 | Chassis Cover | .08" OPTIX 24" x 12" Clear Acrylic Sheet |
| C23 | #6 1/2" Screws | #6-1/2" long flat head type A Phillips screws |
| C24 | Basket mount | 3/4" EMT conduit one-hole strap |
| C25 | Chain | #25 chain 68 links |

| Subsystem 1: | Electrical | |
|---|---|---|
| **Item ID Number** | **Item** | **Description** |
| E1 | LED | Miniature Light Bulb Bayonet Base, Tubular, 0.33W, 0.02A |
| E2 | Computer Case | Pi Case with Cooling |
| E3 | Power Relay Expansion Board | Raspberry Pi Expansion Board Power Relay |
| E4 | Power Distribution Board | Power Distribution Panel |
| E5 | Computer | Raspberry PI 3 Model B Board |
| E6 | Speed Controller | Talon SR |
| E7 | Operating Controller | Xbox One Remote |
| E8 | Ultrasonic Sensor | Ultrasonic Distance Sensor - HC-SR04 |
| E9 | Camera | Logitech HD Webcam C525 |
| E10 | Fuses | 40 Amp Breaker |
| E11 | Fuses | 20 Amp Breaker |
| E12 | 12 Gauge Wire | 2' of 12 Gauge Wire |
| E13 | 14 Gauge Wire | 2' of 14 Gauge Wire |
| E14 | Ribbon Cable | 15' of 10 Wire Ribbon Cable |
| E15 | Terminal Pins | Terminal Housing Pins |
| E16 | Wire Connectors | 12 Gauge Ring Terminals |
| E17 | E-Stop | 120 Amp Circuit Breaker |
| E18 | Ultrasonic Housing | Rapid Prototyped sensor housing |
| E19 | Mounting Tape | Gorilla Heavy Duty Double Sided mounting Tape |

# Sub Assembly 1: Drivetrain

## Right Tread Assembly

1. Orient the tread plate D5 according to the image below. Ensure the flare on the bearings (In holes A and M) face toward you.

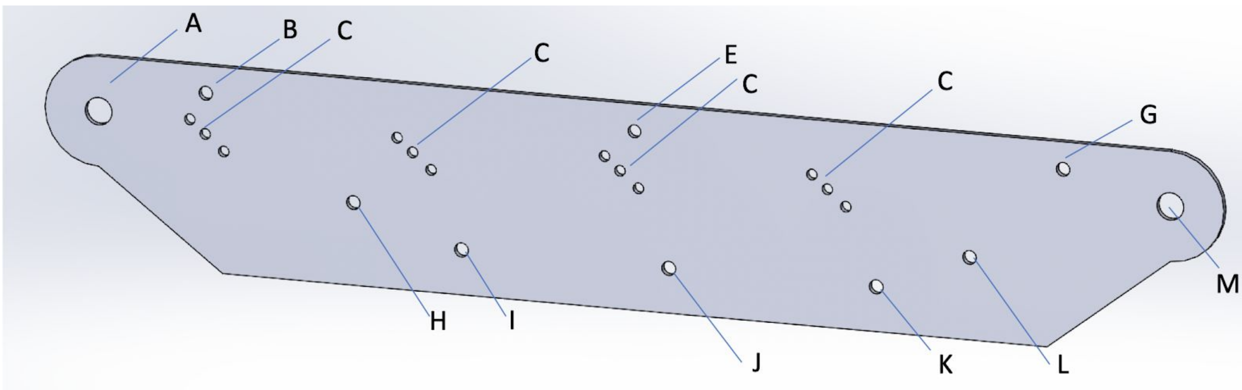



*Figure A1: Tread Plate D5*

2. Slide Shim D11 over bolt D21 and slide the bolt into the back side of the bearing at location “M” shown, so the thread of the bolt is facing outward.
3. Place bolts D21 through the back of the plate in locations I, J, and K. Bolts should be oriented in the same fashion as step 3.
4. Place shim D11 on bolts located at I, J, K, and M.
5. Place links D7 over bolts at locations I, J, and K, ensuring bearing flares are facing up, and shock mounting holes are oriented furthest away from the chassis bolts.
6. Place links D6 over bolts at location M, ensuring bearing flares are facing up, and shock mounting holes are oriented furthest away from the chassis bolts.
7. Place Shims D11 over links at locations I, J, K, and M.
8. Slide Shims D11 over four D21 bolts, and slide them into the four link ends opposite of the tread plate.
9. Place shims D11 over the D21 bolts positioned in step 8.
10. Place one D14 spacer over each bolt located at I, J, and K.
11. Position smaller sprockets D2 over bolts on all four suspension links, at the link ends opposite of the tread plate.

12. Place spacers D12 in the same locations as referenced in step 11, with shims D11 following.
13. Place sprocket D3 on bolt at location M, followed by spacer D12 and shim D11, respectively.
14. Place tread plate D5 over fasteners, with the plate oriented in the same fashion as the plate in step d5
15. Place shim D11 over each of the four bolts protruding from the tread plate placed in step 14.
16. Locate links D7 on the bolts at locations I, J, and K. Oriented in a manner that coincides with the links placed in step 5, ensuring bearing flares are facing up, and shock mounting holes are oriented furthest away from the chassis bolts.
17. Place link D6 over location M, coinciding with the existing link ensuring bearing flares are facing up, and shock mounting holes are oriented furthest away from the chassis bolts.
18. Place sprockets D2 over bolts on the links opposite of points I, J, K, and M.
19. Place sprocket D3 over point M.
20. Thread eight D20 nuts on each of the protruding studs, finger tight.

Shocks and Springs

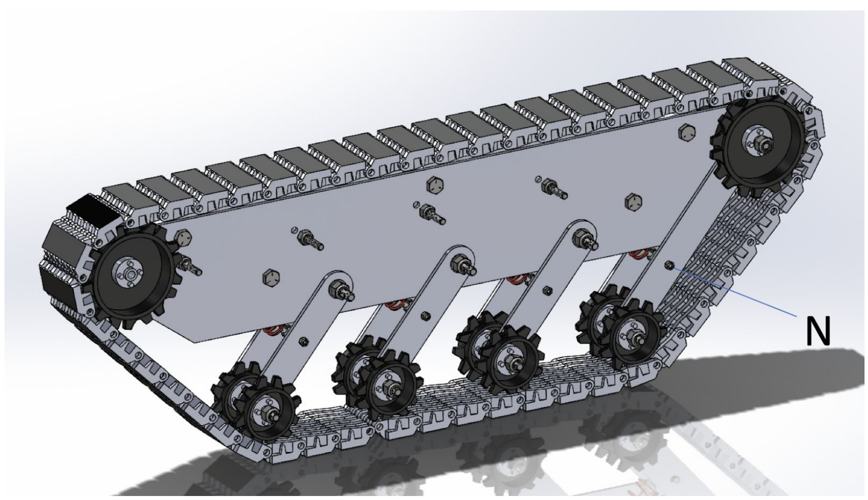


Figure A2: Tread Assembly

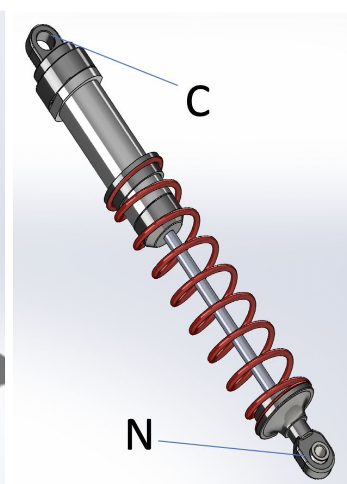


Figure A3: Shock

For Each link:

21. Use 3mm bolt D23 to feed into location N in the suspension links, oriented from inside out.

22. Before fully feeding the bolt through both links, place spacer D12, spring end N, and another spacer D12 in between both links.
    Finger tighten nut D20 on the bolt once located through the suspension link, spacer, spring, spacer, and outer suspension link, respectively.
23. Use a 10-32 bolt D22 to feed through location C on the plate, corresponding to the link location being worked on.
24. Before fully feeding the bolt through both links, place spacer D16, spring end C, and another spacer D15 in between both plates.
25. Tighten #10 hardware by hand.

*Repeat steps 21 through 25 for each of the four suspension arms*

26. Using spacers D13 and bolts D21, place the spacers to coincide with each of the holes in the plates at locations B, E, G, H, and L. Push bolts through the holes, from the outside of the tread plate inward (opposite direction of all other hardware). Leave nuts off as these will be installed at a later time.

## Left Tread Assembly

*Repeat steps 1-26, mirroring the assembly process about the centerline of the chassis*

# Sub Assembly 2: Chassis

## Left Chassis side assembly

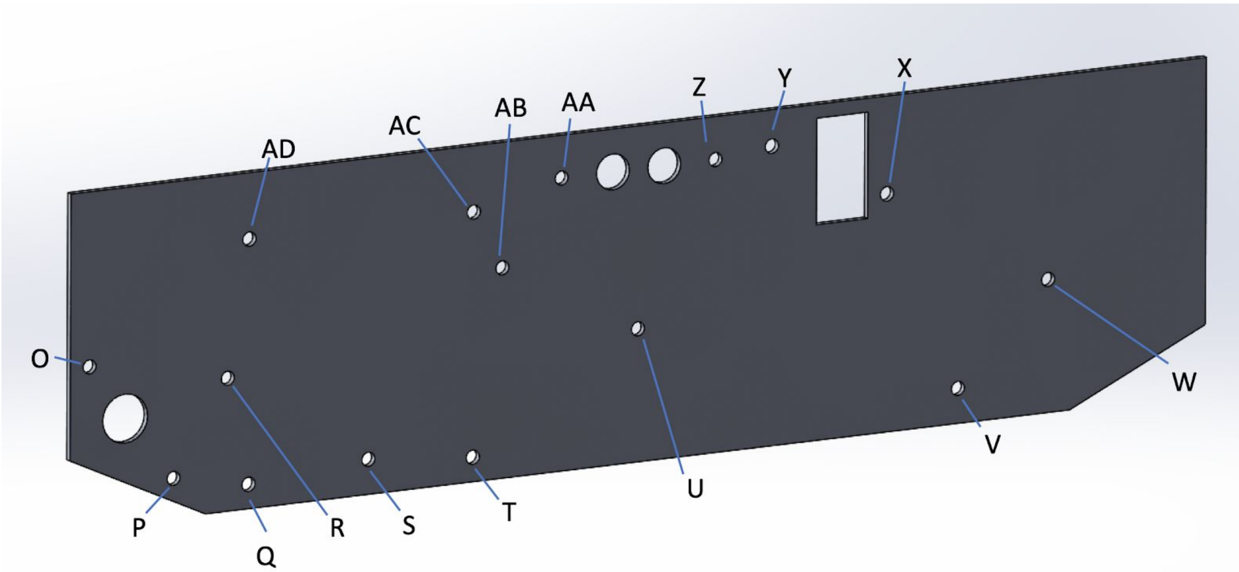



*Figure A4: Stripped Left Hand Chassis Side Plate, Interior view*

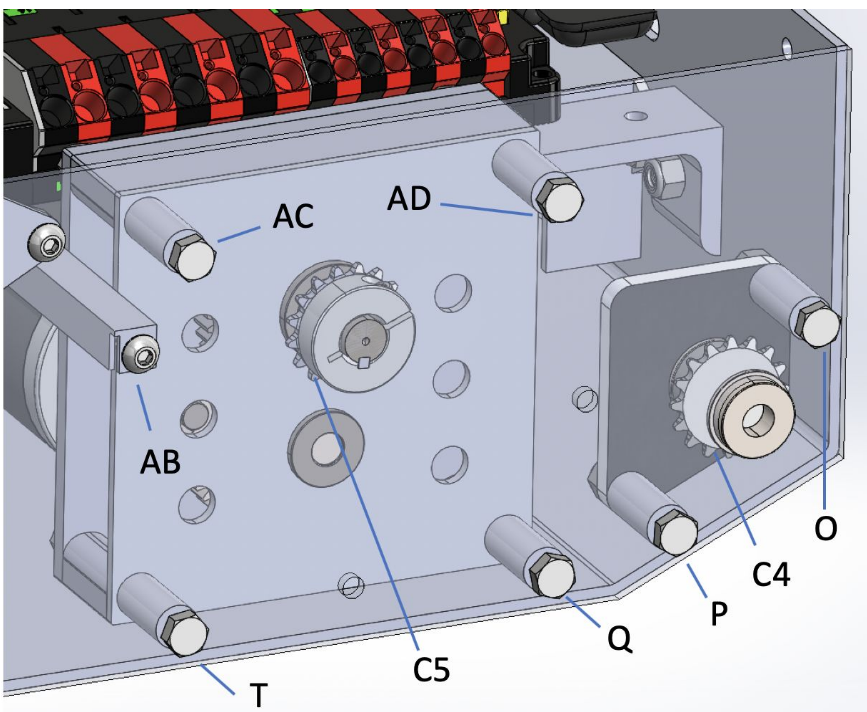



*Figure A5: Left hand gearbox and bearing block view through transparent chassis side*

1. Slide sprocket C5 over the gearbox hex shaft, Orient the sprocket to be offset further away from the gearbox housing. Position the shaft collar over the remaining section of shaft. Tighten the shaft collar clamp bolt to 75lb-in, ensuring the clamp is tight against the sprocket.
2. Position the gearbox in the chassis, feed four C14 bolts through fastener locations T, Q, AC, and AD, from the outside in.
3. Place four C10 spacers over the bolts facing inward through the chassis.
4. Orient the gearbox over the four bolts, positioning the sprocket in the highest orientation.
5. Position the Chain loop C25 over the C5 sprocket.
6. Using C15 nuts, tighten the gear box to the chassis. Torque to 75lb-in.
7. Use two C14 bolts, feel them through locations P and O, into the chassis.
8. Place C10 spacers over the bolts.
9. Orient the bearing block C9 to contour the rear of the chassis, with the flance facing toward the chassis wall. Slide the bolts through the bearing block.
10. Hand tighten two C10 nuts on the bolts.
11. Loop the chain over sprocket C4 in the chassis, orienting the sprocket to be offset away from the bearing block.
12. Slide the ⅜” section of the C8 output shaft into the chassis, feeding through sprocket C4, into the bearing block. Allow the shaft to protrude ⅛ from the back of the bearing block. Space sprocket C4 ⅛” from the bearing block, tighten the set screw on the sprocket to 38 lb-in.
13. Tighten all remaining hardware to 75 lb-in.

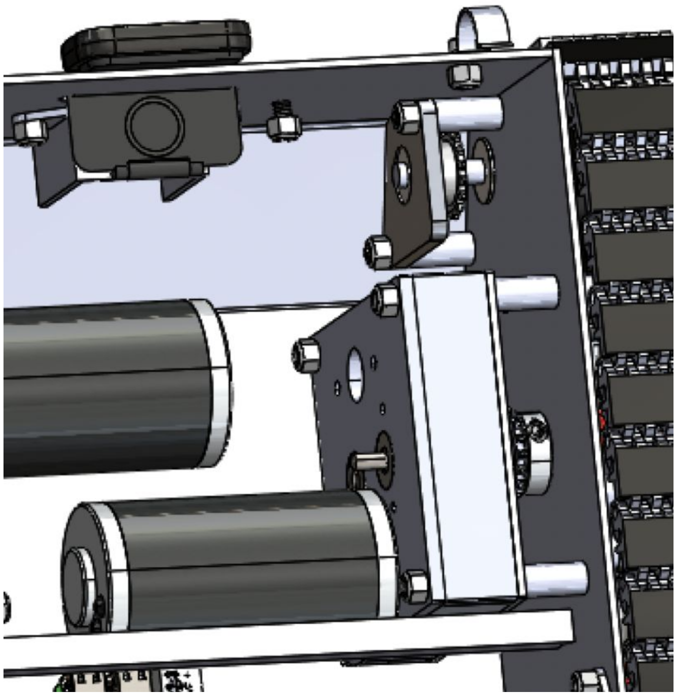


*Figure A6: Left hand gearbox and bearing block assembled, without chain.*

## Right Chassis Side Assembly

*Repeat steps 1- 12 for right side of chassis, mirroring all components*

## Chassis Cross Brace:

1. Orient Chassis Cross Brace across the chassis, with the mounting holes positioned in a coinciding fashion with location AB depicted in figure A5. Orient the outer flats of the angle iron toward the front of the chassis and upward.
2. Feed two C13 bolts through the outside of the chassis inward, on both left and right sides.
3. Use two C15 nuts threaded from the inside of the chassis to the C13 bolts. Torque to 76 lb-in.

## Front and Rear Basket Clips:

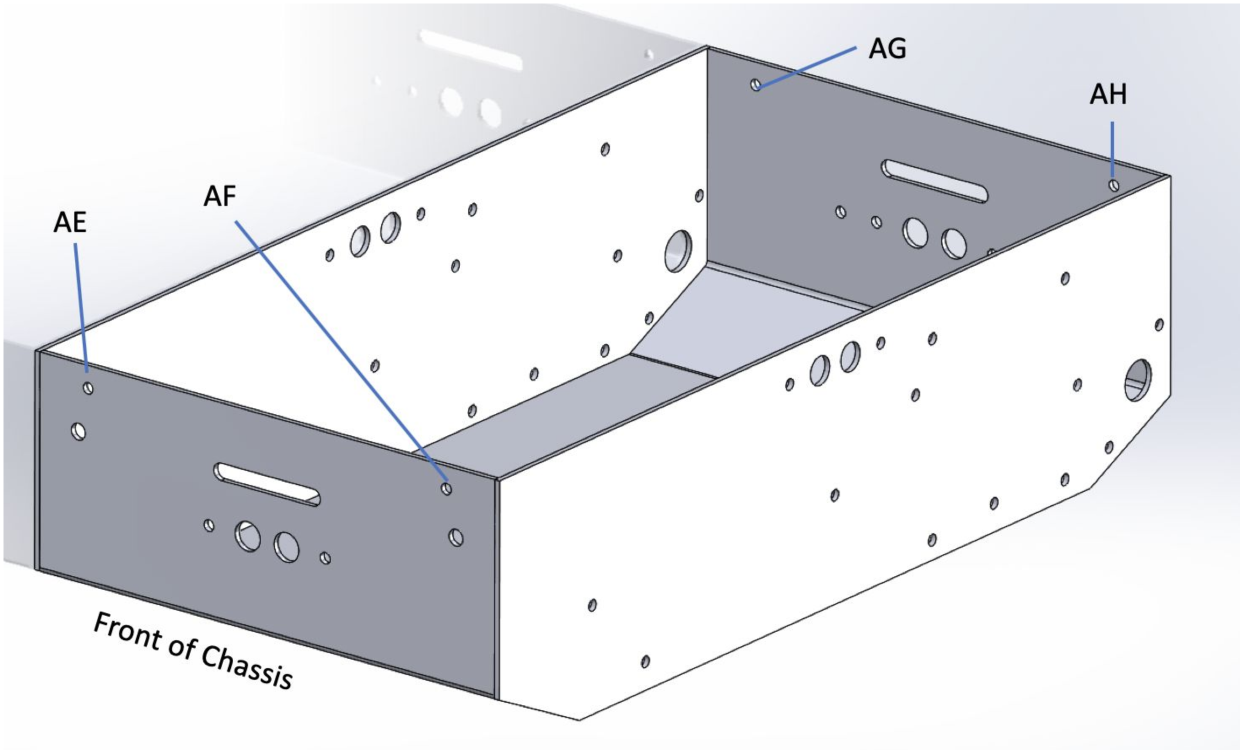



*Figure A7: Chassis with basket mount mounting locations highlighted*

1. Place C24 mount on outside of chassis,  facing inward at location AE.
2. Use bolt C13, fed from the outside in through hole AE.
3. Use nut C15 threaded on bolt C13, torque to 75 lb-in.

*Repeat steps 1-3 for brackets at locations AF, AG, and AH*

## Power Distribution Board (PDB) Mounting Brackets

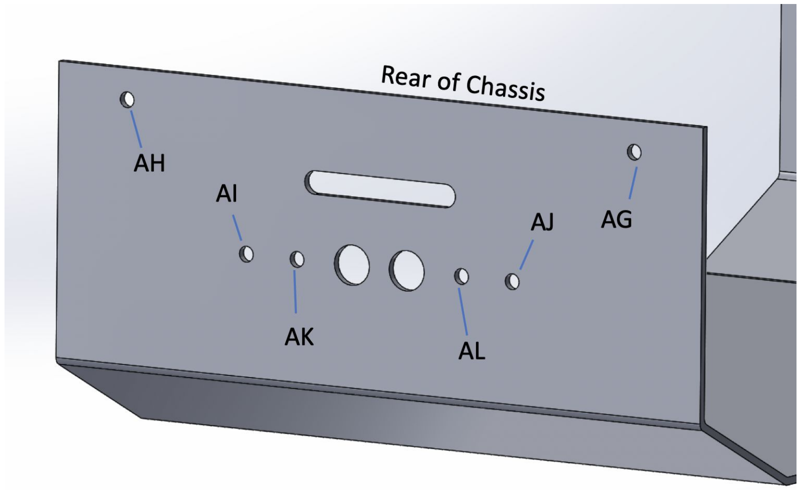



*Figure A8: Chassis with basket mount and PDB mounting locations highlighted*

1. Orient the mounting hole on the shorter side of angle bracket C11 to coincide with the mounting hole at location AI, from the inside of the chassis (refer to figure A9).
2. Feed bolt C13 through the outside of the chassis in through hole AI.
3. Use nut C15 threaded on bolt C13, torque to 75 lb-in.

*Repeat steps 1-3 for bracket at locations AJ*

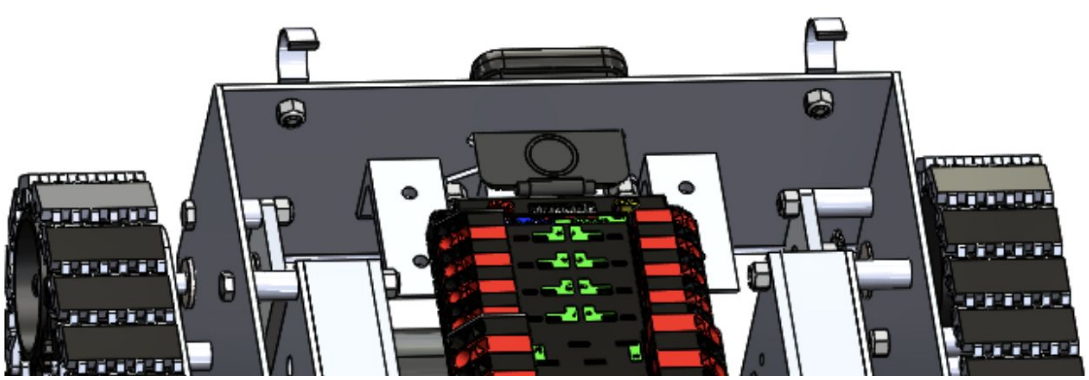


*Figure A9: Rear of chassis depicting location of basket mounting and PDB mounting brackets*

# Sub Assembly 3: Electrical

## Breaker

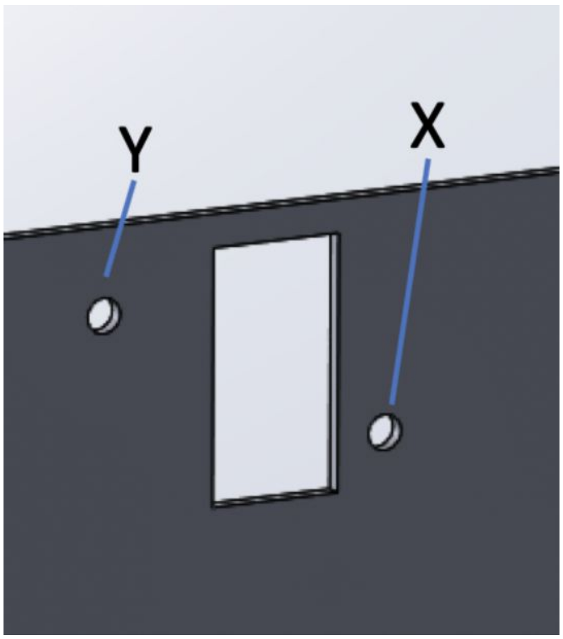



*Figure A10: Provision for breaker depicted in left chassis wall*

1. Orient the emergency stop E17 in a position so the red shut-off is protruding through the side of the robot, and the red shut-off button is on top.
2. Use two D12 spacers between the emergency stop and the chassis wall.
3. Use two D21 bolts entering from outside the chassis, through the spacer and breaker.
4. Thread two D18 nuts onto the D21 bolts.
5. Torque hardware to 36 lb-in.

## Ultrasonic sensors

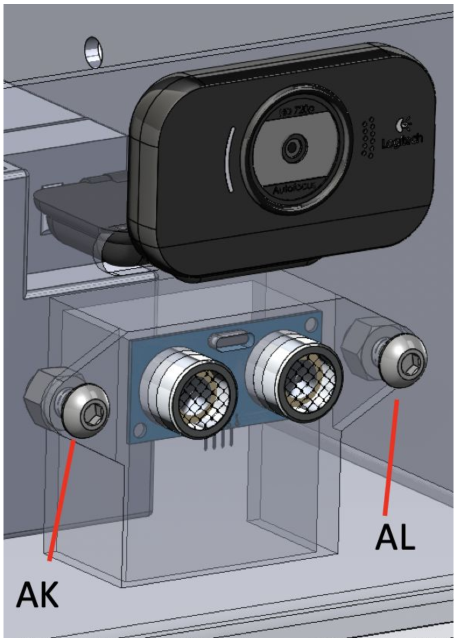



*Figure A11: Mounting of camera and ultrasonic sensor depicted*

1. Press ultrasonic sensor E8 into housing, using light pressure from thumbs evenly across the back of the sensor.
2. Place sensor and housing inside of chassis, coinciding holes wirth mounting locations AK and AL.
3. Feed bolts C13 through the outside of the chassis in through holes located at AK and AL.
4. Use nuts C15 threaded on bolt C13, torque to 75 lb-in.

*Repeat steps 1-4 on the remaining three chassis walls*

## Camera

1. Press the camera E9 in the slot shown in figure A10. use two thumbs to lightly apply pressure at the base of the camera, in line with the slot.

*Repeat for camera on the opposite side of chassis*

## PDB, Speed Controllers, Raspberry PI

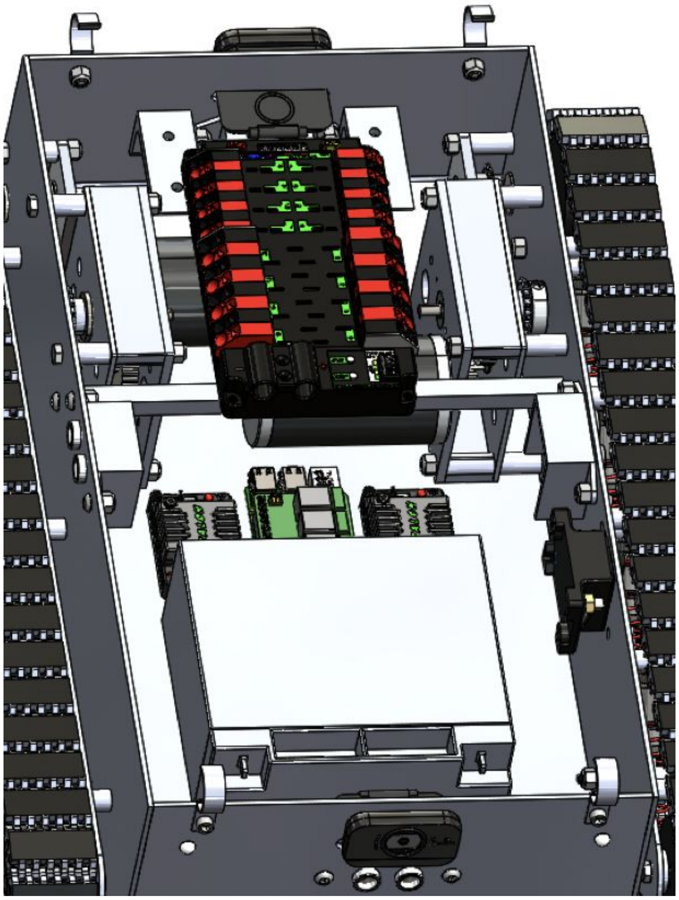


*Figure A12: Mounting of PDB, Speed Controllers, and Raspberry PI depicted*

1. Center the PDB board E4 between gearboxes, 1.5” from the rear of the chassis. Apply mounting tape between any contact areas with the cross brace and rear PDB mounting brackets.
2. Place the speed controllers E6 on either side of the Raspberry Pi E5 on the chassis floor, evenly spaced between the gear boxes, in line with the back side of the chassis cross member above.
3. Use 1” squares of mounting tape for each module. Reference figure A11 for approximate positioning.

# Final Assembly: Marriage of Sub Assemblies

## Tread Assemblies onto Chassis

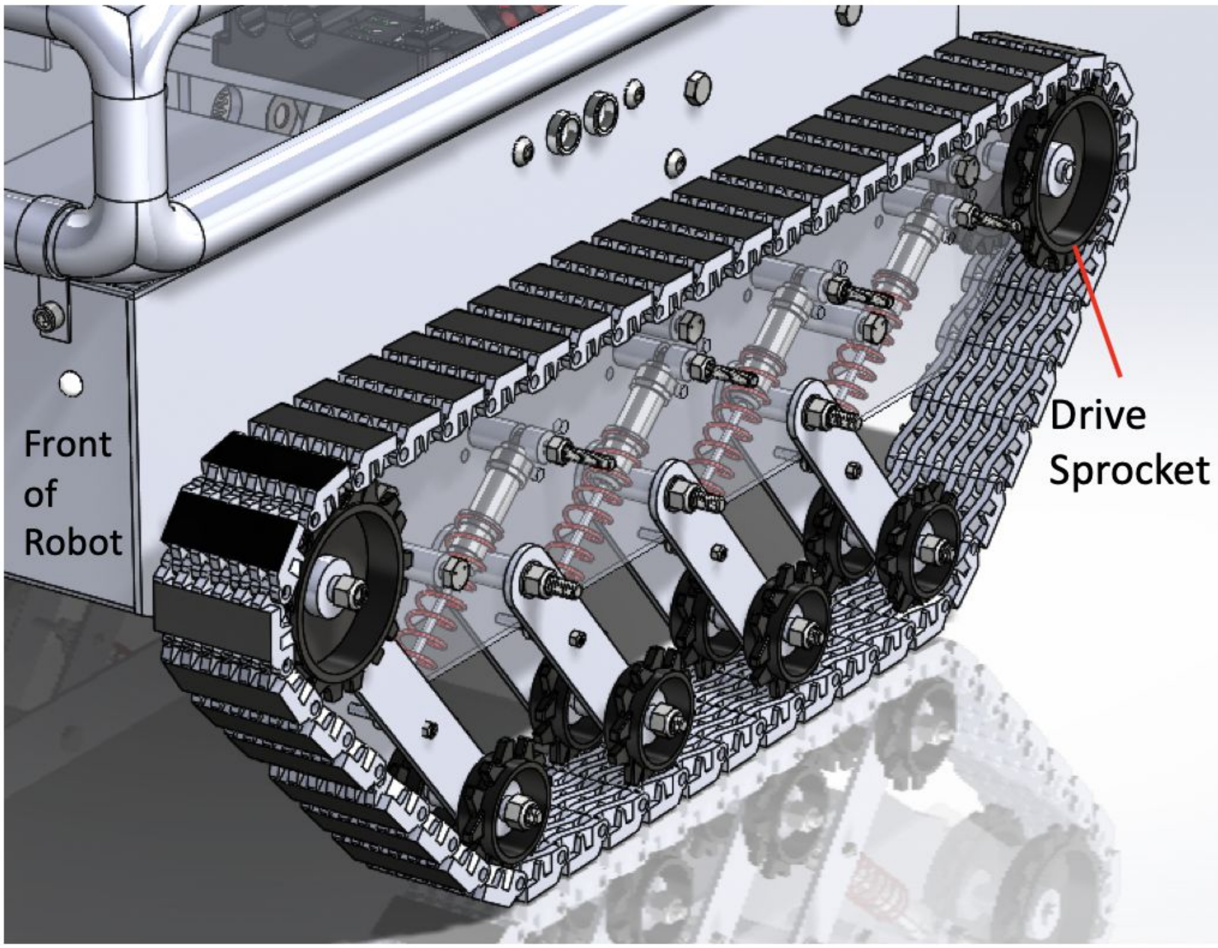
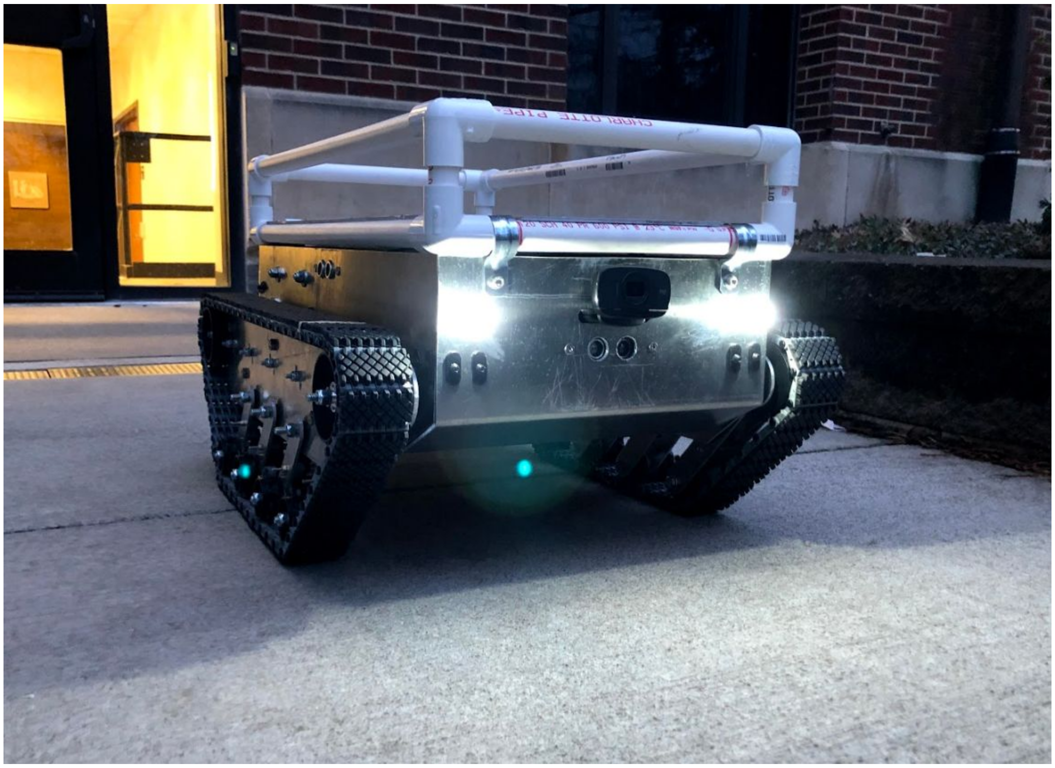


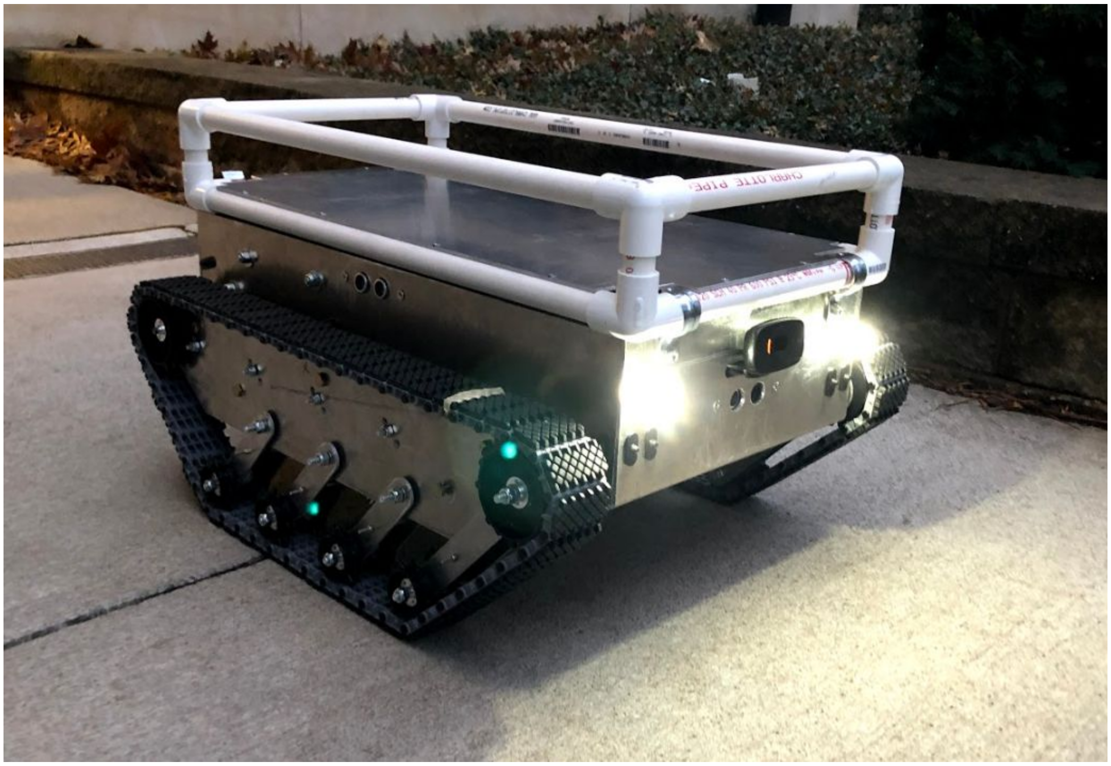

*Figure A13: Left tread sub-assembly fastened to chassis*

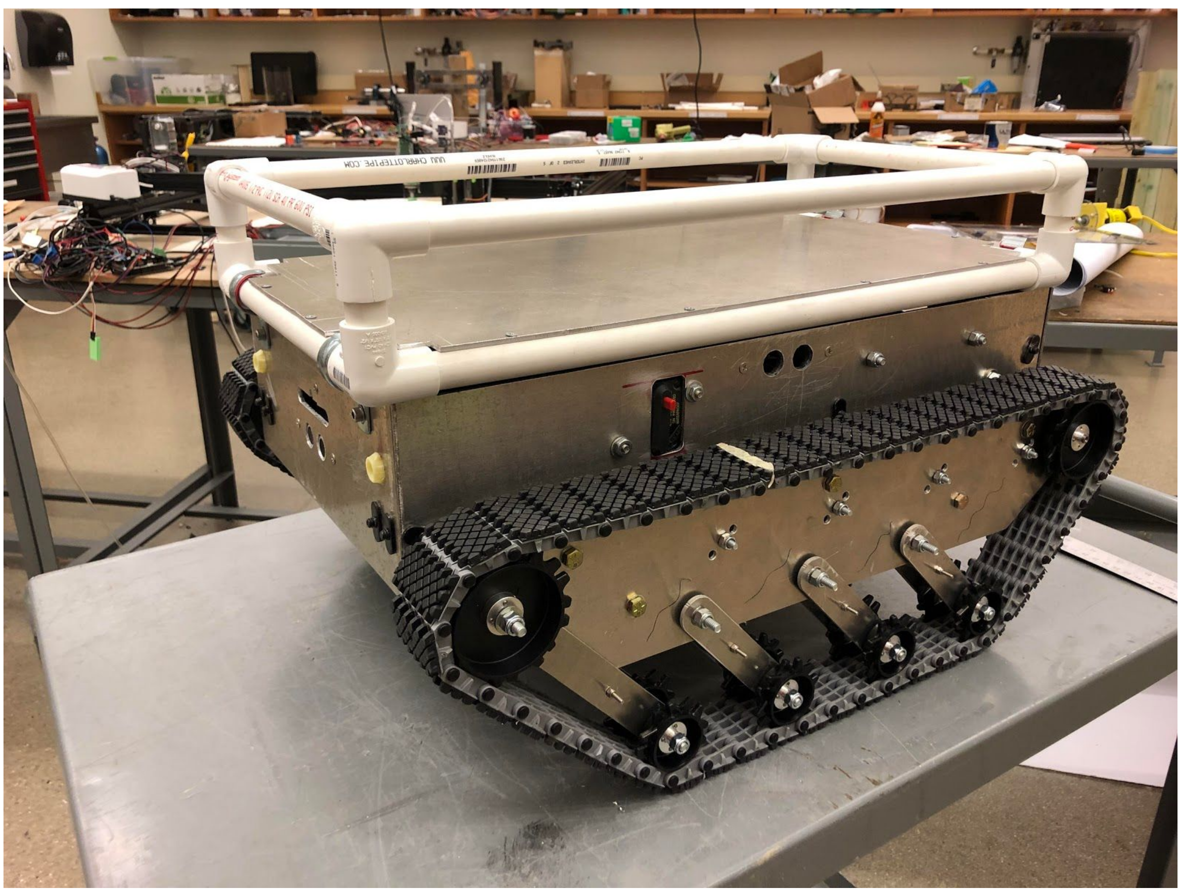
1. Coincide left tread assembly location A (refer to figure A1) on the drive shaft protruding from the rear left side of the chassis.
2. As the tread plate is slid onto the shaft, in between the tread plates, include shim D11, tread sprocket D3, spacer D12, and another shim D11, respectively.
3. Pivot the tread assembly so the mounting bolts in the tread plates coincide with the mounting holes in the chassis.

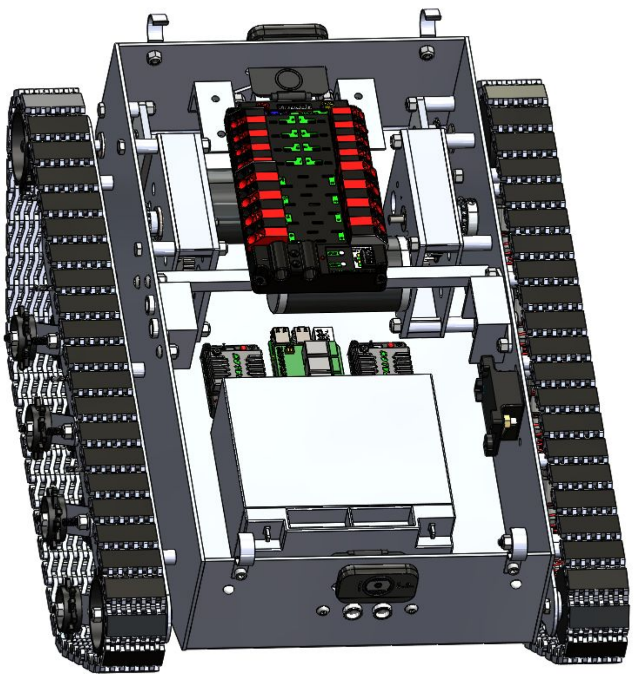
4. Place spacers D12 on each of the five mounting hardware bolts, to space the inner tread plate from the chassis.
5. Push each of the five mounting bolts D21 into the chassis.
6. Thread nuts D18 onto each of the D21 bolts.
7. Torque all ¼” hardware to 75 lb-in.
8. Torque all #10 hardware to 30 lb-in
9. Tighten 3mm hardware one turn beyond when the head and nut of the hardware contact the suspension arms.
10. Slide shim D11 and sprocket D3 onto the drive shaft, respectively.
11. Torque drive sprocket set screws to 26 lb-in.

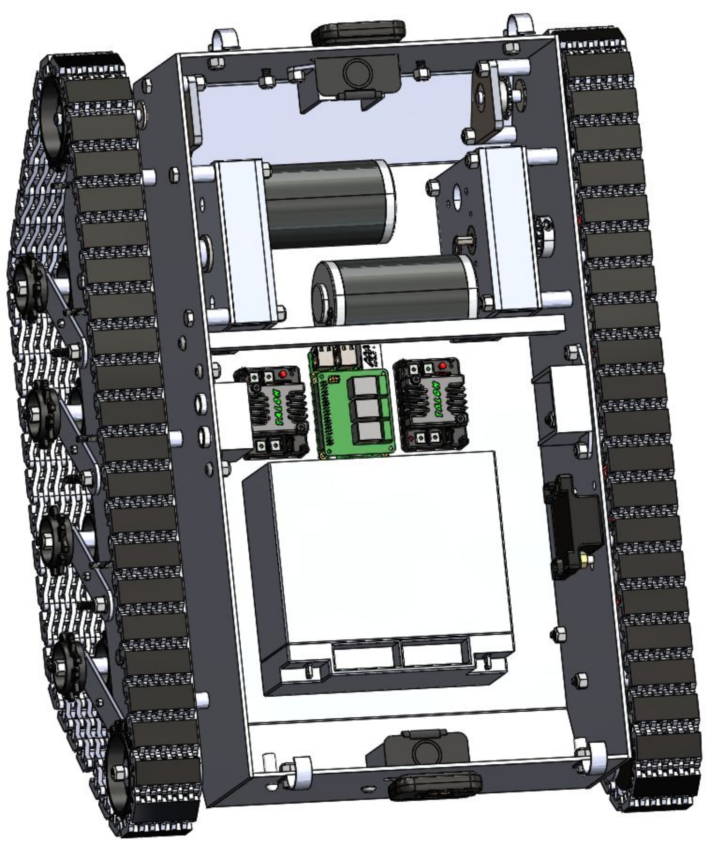
## S. Final Prototype Photos







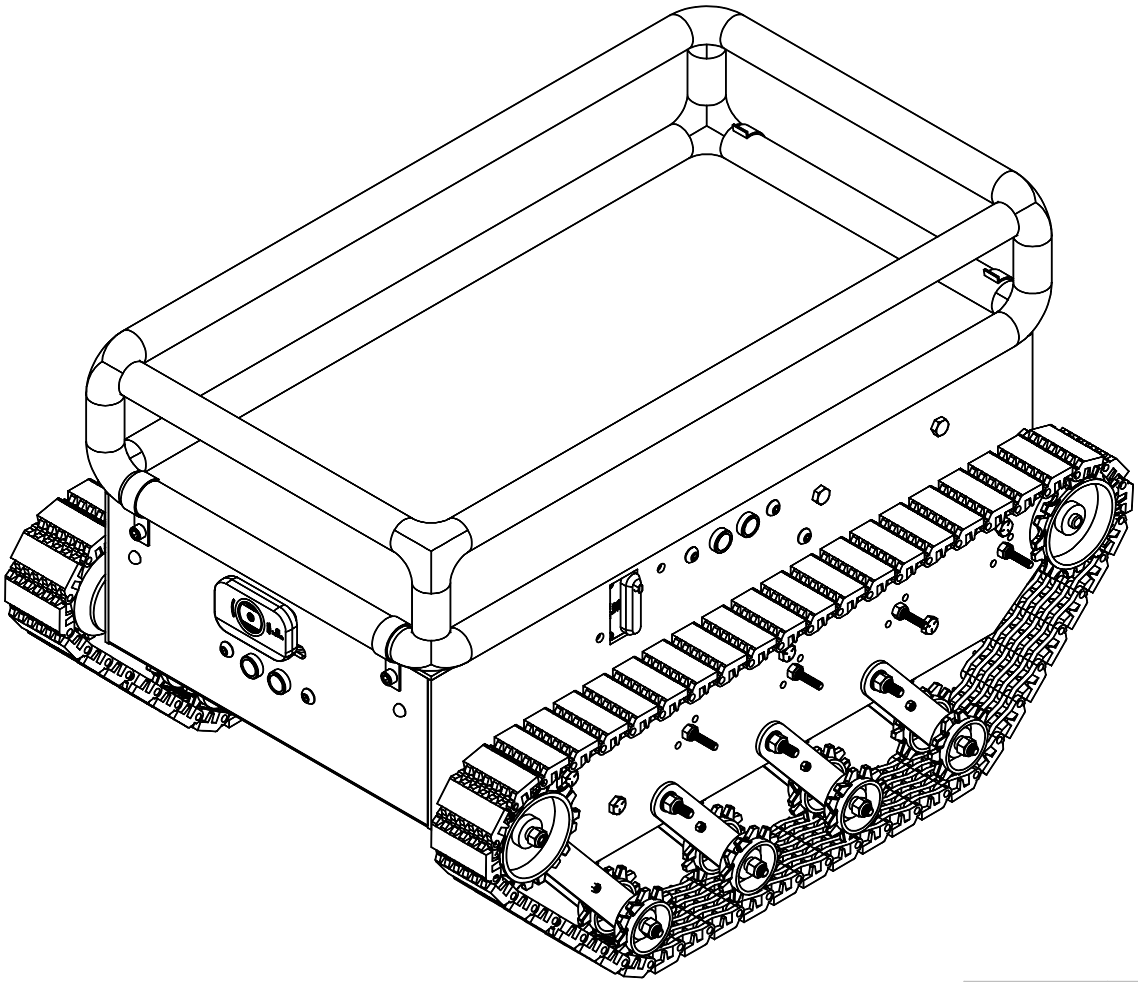




# T: Assembly, Manufacturing, and Part Drawings

2 | 1

B | B



A | A

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| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# PESA

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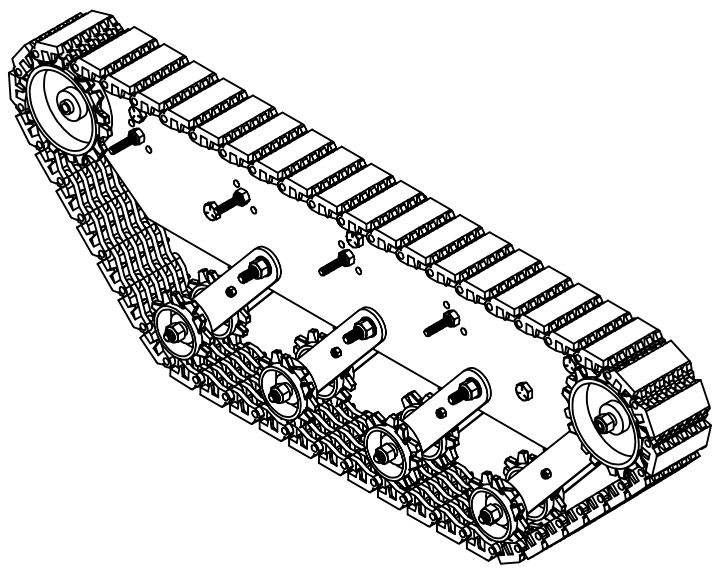
2 | 1

2 1

B



A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# Tread Assembly

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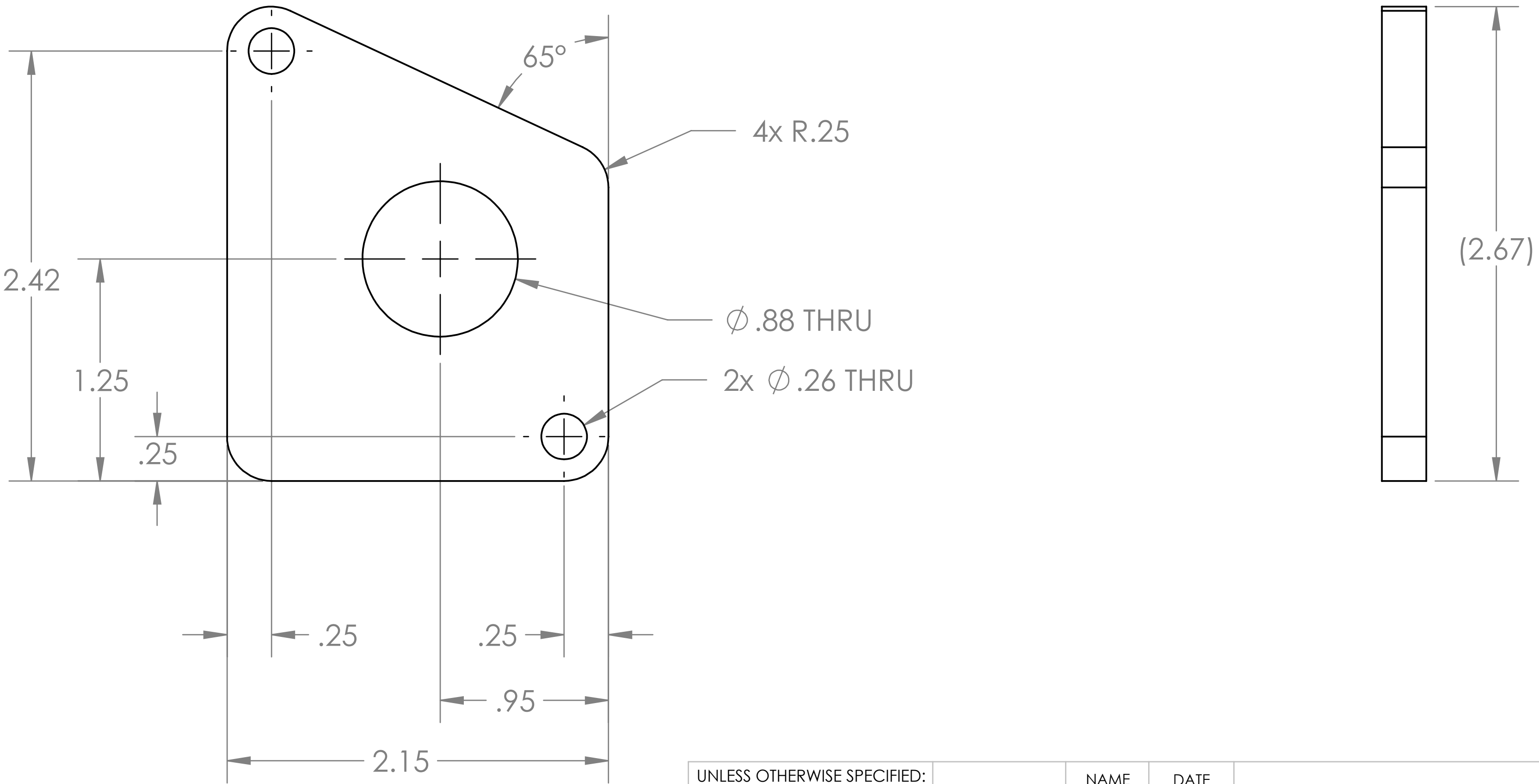
|---|---|---|

2 1

2 1

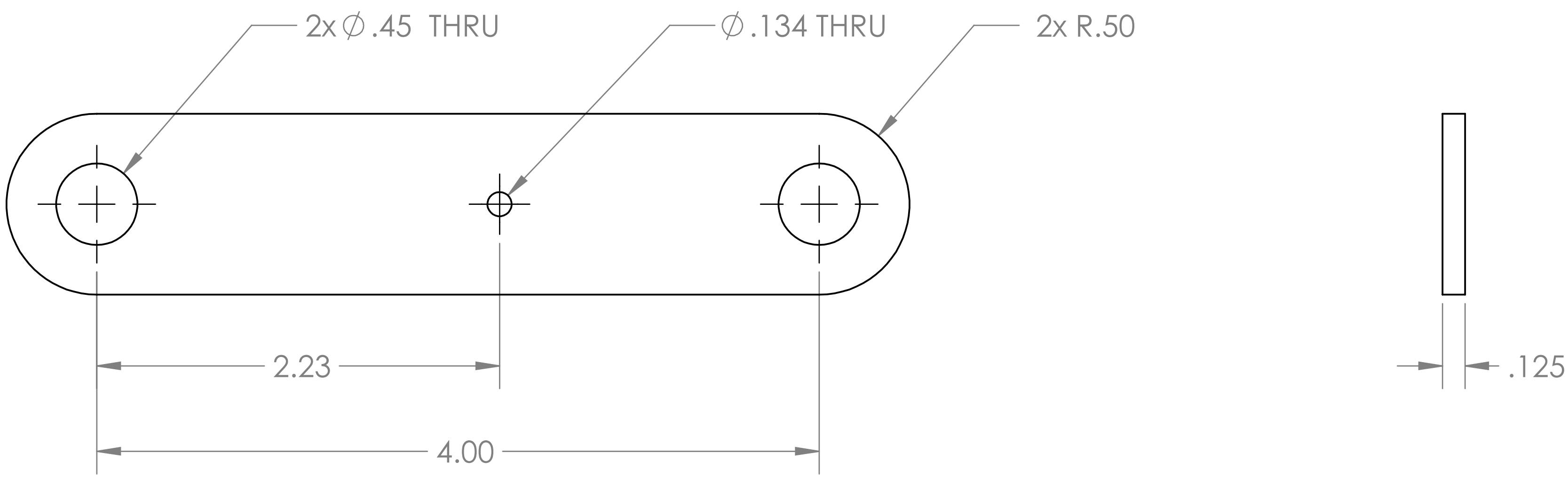
B B




A A

| | | | | |
|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE | |
| DIMENSIONS ARE IN INCHES<br>TOLERANCES:<br>TWO PLACE DECIMAL ±0.01 | DRAWN | Brian | 12/2/19 | |
| | CHECKED | Konrad | 12/2/19 | TITLE: |
| | ENG APPR. | Brian | 12/2/19 | |
| | MFG APPR. | Brian | 12/2/19 | Bearing Block |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | - | 12/2/19 | |
| MATERIAL<br>Aluminum | COMMENTS:<br>None | | | SIZE A · DWG. NO. 1 · REV 1 |
| FINISH<br>None | | | | |
| DO NOT SCALE DRAWING | | | | SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1 |

2 1




| | | | |
|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE |
| DIMENSIONS ARE IN INCHES<br>TOLERANCES:<br>TWO PLACE DECIMAL ±0.002 | DRAWN | Brian | 12/2/19 |
| | CHECKED | Konrad | 12/2/19 |
| | ENG APPR. | Brian | 12/2/19 |
| | MFG APPR. | Brian | 12/2/19 |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | - | - |
| MATERIAL Aluminum | COMMENTS: None | | |
| FINISH None | | | |

TITLE:

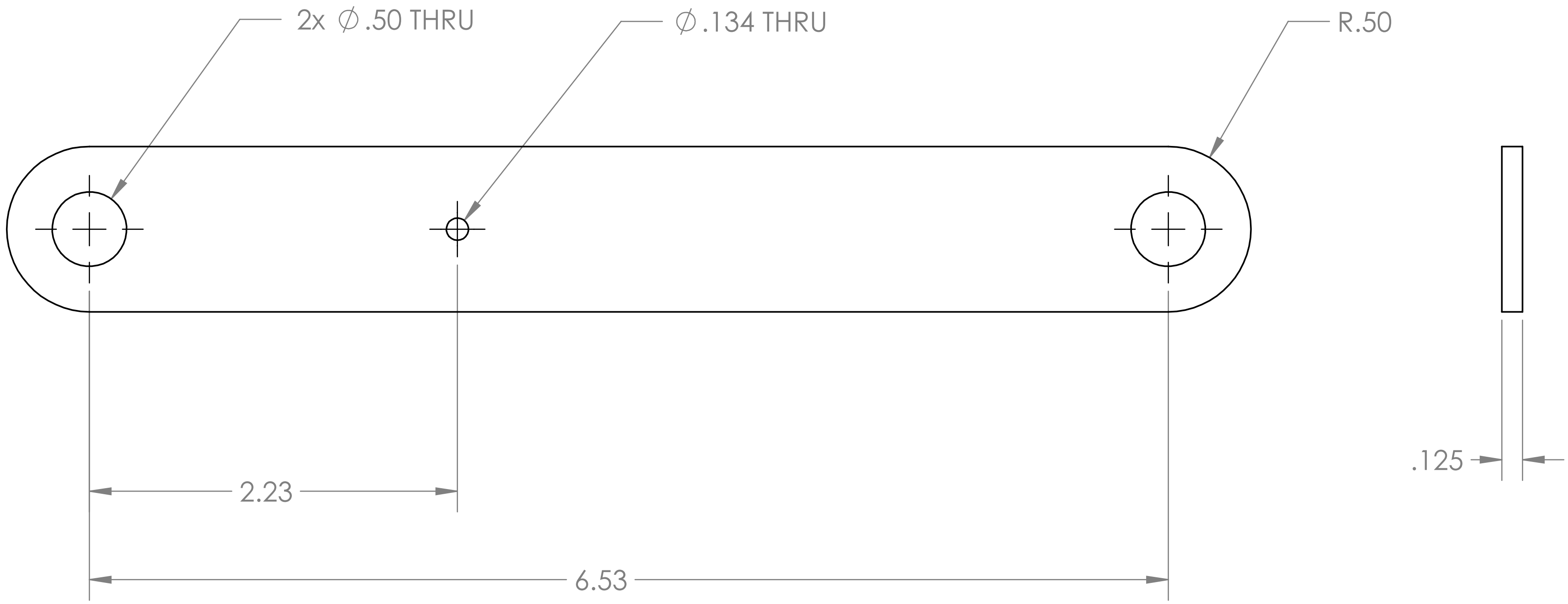
# Bottom Arm

| SIZE | DWG. NO. | REV |
|---|---|---|
| A | 1 | 2 |

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

2 1

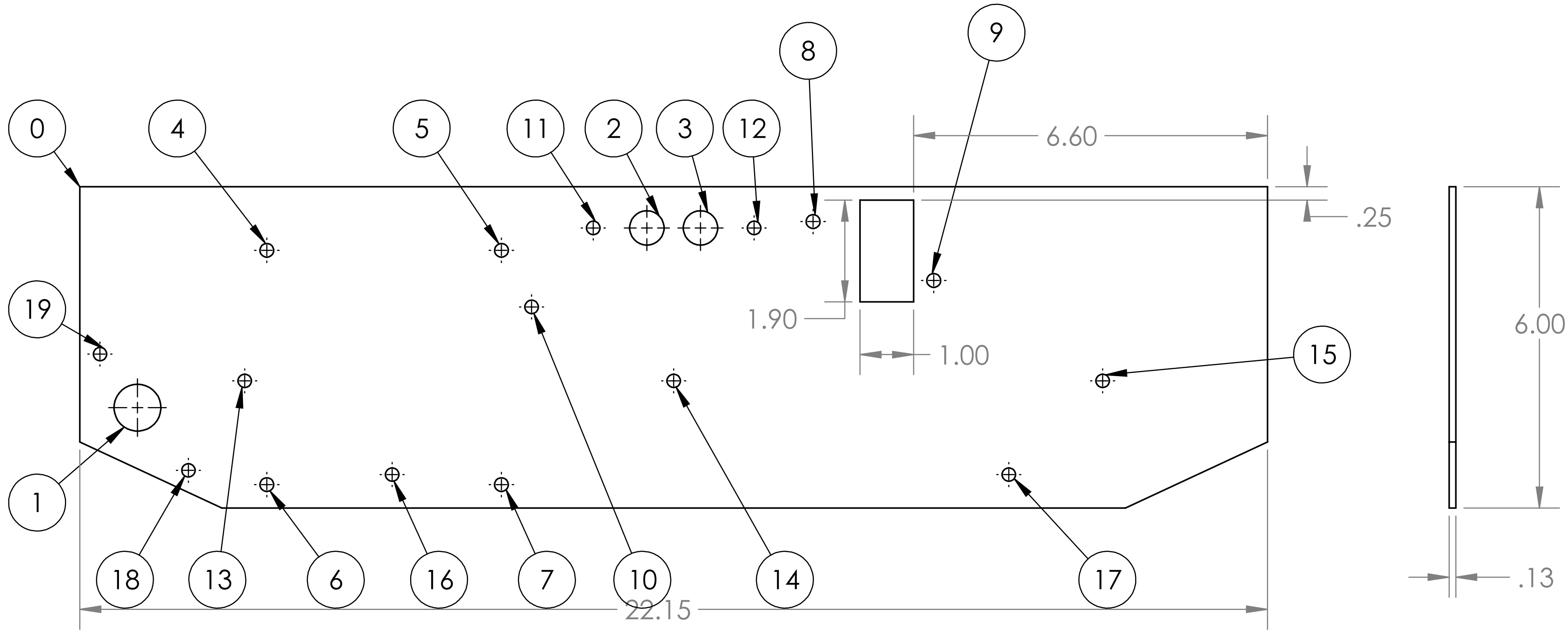
B B




A A

| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE | |
|---|---|---|---|---|
| DIMENSIONS ARE IN INCHES<br>TOLERANCES:<br>TWO PLACE DECIMAL ±0.002 | DRAWN | Brian | 12/2/19 | TITLE: |
| | CHECKED | Konrad | 12/2/19 | Front_Arm |
| | ENG APPR. | Brian | 12/2/19 | |
| | MFG APPR. | Brian | 12/2/19 | |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | - | 12/2/19 | |
| MATERIAL Aluminum | COMMENTS: None | | | SIZE A · DWG. NO. 1 · REV 4 |
| FINISH None | | | | SCALE: 1:1 · WEIGHT: · SHEET 1 OF 1 |

2 1




| Number | Size(D) | X | Y |
|---|---|---|---|
| 0 | - | 0 | 0 |
| 1 | 0.875 | 1.07 | -4.125 |
| 2 | 0.642 | 10.57 | -0.77 |
| 3 | 0.642 | 11.57 | -0.77 |
| 4 | 0.257 | 3.485 | -1.188 |
| 5 | 0.257 | 7.86 | -1.188 |
| 6 | 0.257 | 3.485 | -5.56 |
| 7 | 0.257 | 7.86 | -5.56 |
| 8 | 0.257 | 13.67 | -0.65 |
| 9 | 0.257 | 15.92 | -1.75 |
| 10 | 0.25 | 8.42 | -2.245 |
| 11 | 0.25 | 9.57 | -0.77 |
| 12 | 0.25 | 12.57 | -0.77 |
| 13 | 0.25 | 3.07 | -3.625 |
| 14 | 0.25 | 11.07 | -3.625 |
| 15 | 0.25 | 19.07 | -3.625 |
| 16 | 0.25 | 5.82 | -5.375 |
| 17 | 0.25 | 17.32 | -5.375 |
| 18 | 0.25 | 2.02 | -5.3 |
| 19 | 0.25 | 0.375 | -3.125 |

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Aluminum

FINISH
None

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | - | 12/2/19 |

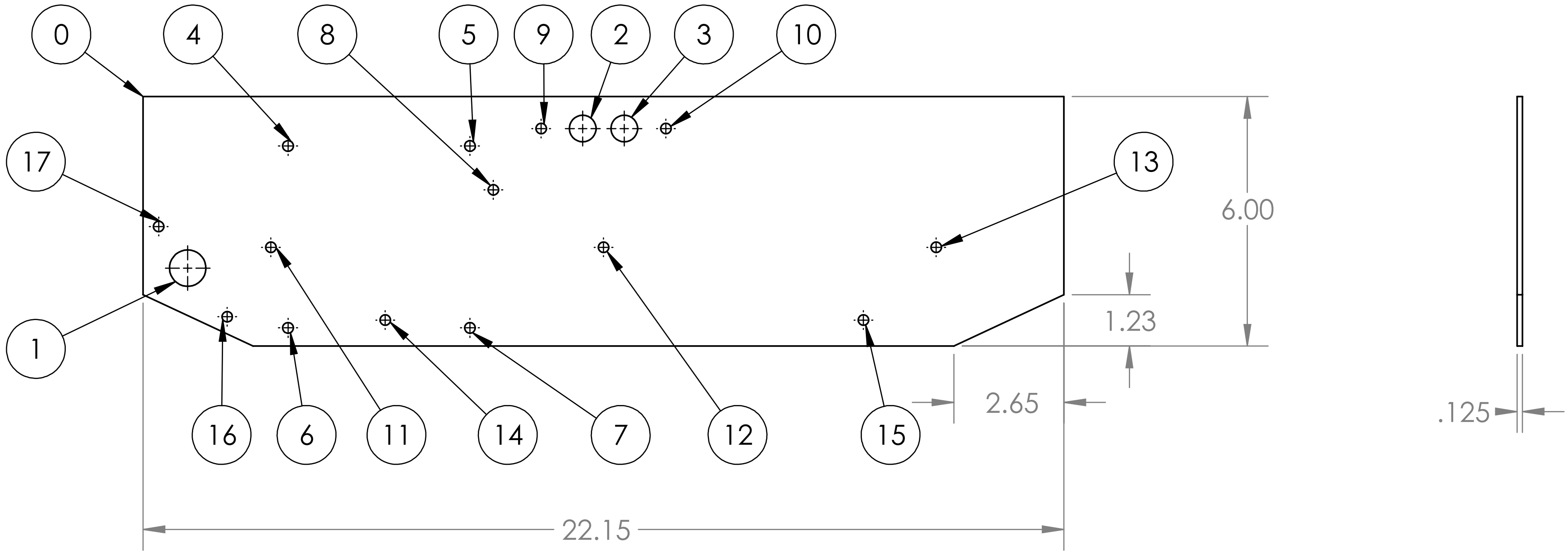
COMMENTS:
None

TITLE:

# Chassis_Left_Side

SIZE A | DWG. NO. 1 | REV 1

SCALE: 1:3 | WEIGHT: | SHEET 1 OF 1




| Number | Size(D) | X | Y |
|---|---|---|---|
| 0 | - | 0 | 0 |
| 1 | 0.875 | 1.07 | -4.125 |
| 2 | 0.642 | 10.57 | -0.77 |
| 3 | 0.642 | 11.57 | -0.77 |
| 4 | 0.257 | 3.485 | -1.188 |
| 5 | 0.257 | 7.86 | -1.188 |
| 6 | 0.257 | 3.485 | -5.56 |
| 7 | 0.257 | 7.86 | -5.56 |
| 8 | 0.25 | 8.42 | -2.245 |
| 9 | 0.25 | 9.57 | -0.77 |
| 10 | 0.25 | 12.57 | -0.77 |
| 11 | 0.25 | 3.07 | -3.625 |
| 12 | 0.25 | 11.07 | -3.625 |
| 13 | 0.25 | 19.07 | -3.625 |
| 14 | 0.25 | 5.82 | -5.375 |
| 15 | 0.25 | 17.32 | -5.375 |
| 16 | 0.25 | 2.02 | -5.3 |
| 17 | 0.25 | 0.375 | -3.125 |

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: Aluminum

FINISH: None

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | - | 12/2/19 |

COMMENTS:

None

TITLE:

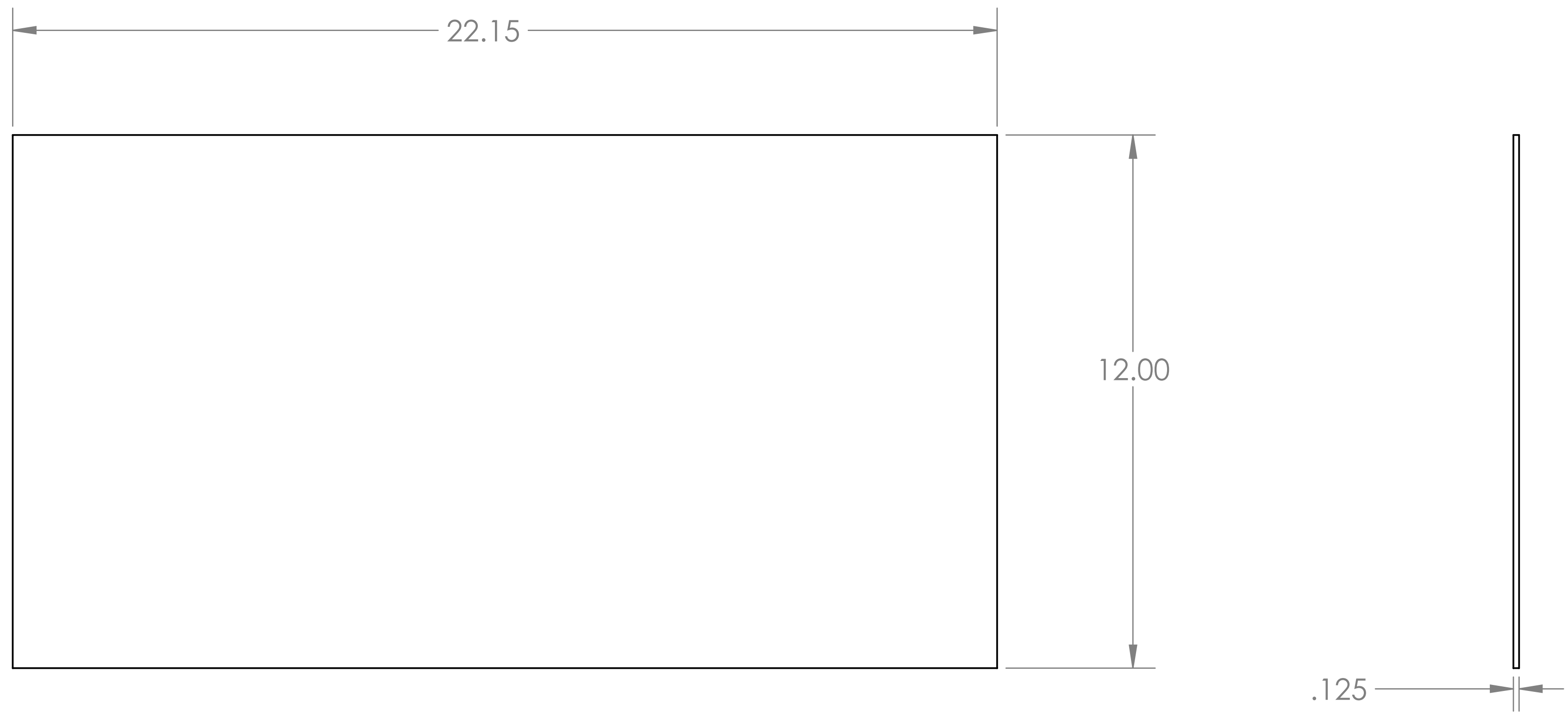
Chassis_Right_Side

SIZE A | DWG. NO. 1 | REV 5

SCALE: 1:3 | WEIGHT: | SHEET 1 OF 1

2 1

B B



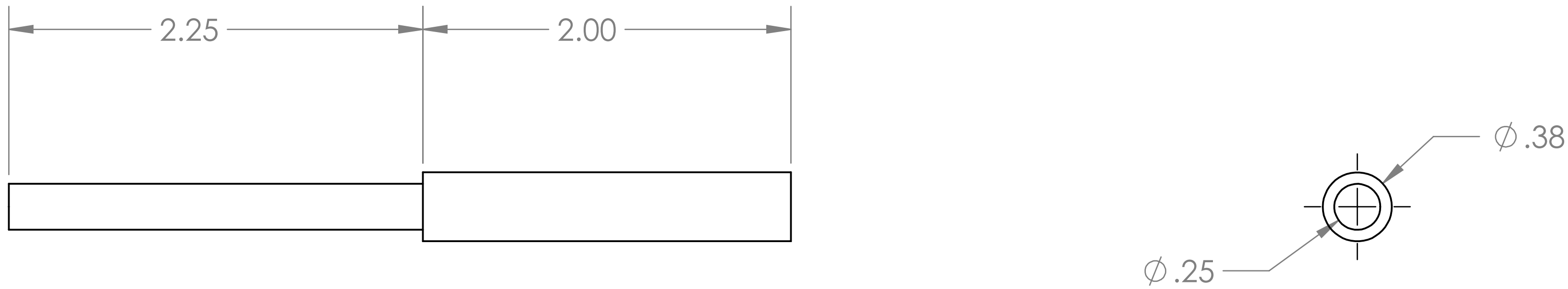

A A

| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE | |
|---|---|---|---|---|
| DIMENSIONS ARE IN INCHES<br>TOLERANCES:<br>TWO PLACE DECIMAL ±0.002 | DRAWN | Brian | 12/2/19 | TITLE: |
| | CHECKED | Konrad | 12/2/19 | Chassis_Top |
| | ENG APPR. | Brian | 12/2/19 | |
| | MFG APPR. | Brian | 12/2/19 | |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | - | - | |
| MATERIAL<br>Aluminum | COMMENTS: | | | SIZE A | DWG. NO. | REV 1 |
| FINISH<br>None | | | | |
| DO NOT SCALE DRAWING | | | | SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1 |

2 1

2 1

B B




A A

| | | | | |
|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE | |
| DIMENSIONS ARE IN INCHES<br>TOLERANCES:<br>TWO PLACE DECIMAL ±0.01 | DRAWN | Brian | 12/2/19 | |
| | CHECKED | Konrad | 12/2/19 | TITLE: |
| | ENG APPR. | Brian | 12/2/19 | DriveShaft_Output |
| | MFG APPR. | Brian | 12/2/19 | |
| INTERPRET GEOMETRIC TOLERANCING PER: | Q.A. | - | 12/2/19 | |
| MATERIAL<br>Aluminum | COMMENTS:<br>None | | | SIZE A — DWG. NO. 1 — REV 1 |
| FINISH<br>None | | | | |
| DO NOT SCALE DRAWING | | | | SCALE: 1:1 — WEIGHT: — SHEET 1 OF 1 |

2 1


| Name | L (in) | OD (in) | ID (in) |
|---|---|---|---|
| 0.33 in Spacer | 0.33 | 0.5 | 0.25 |
| 0.6 in Spacer | 0.6 | 0.5 | 0.25 |
| 0.72 in Spacer | 0.72 | 0.5 | 0.25 |
| 1.2 in Spacer | 1.2 | 0.5 | 0.25 |
| 0.47 in - 3mm Spacer | 0.47 | 0.16 | 0.12 |

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | - | 12/2/19 |

COMMENTS:
Spacers were hand cut from stock

TITLE:

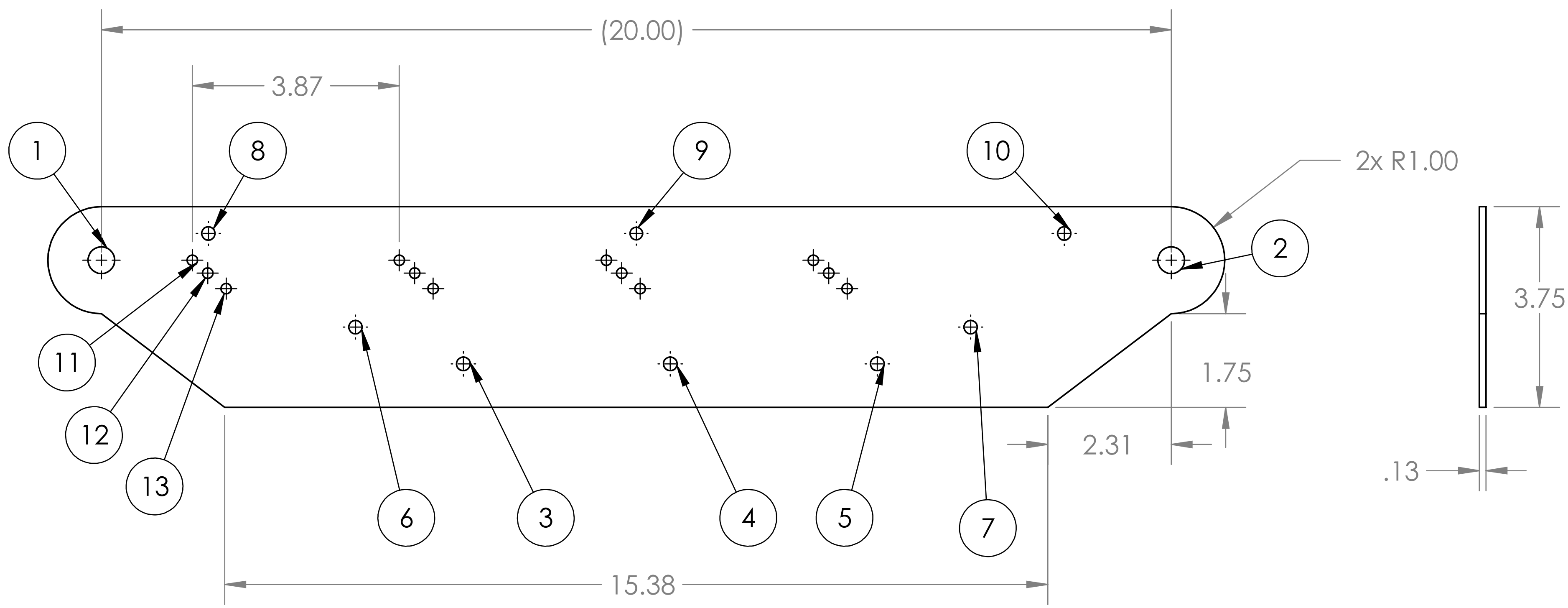
# Spacers

| SIZE | DWG. NO. | REV |
|---|---|---|
| A | | 1 |

SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

2 1

B B




A A

| Number | Size(D) | (x,y) |
|---|---|---|
| 1 | 0.5 | (0,0) |
| 2 | 0.5 | (22, 0) |
| 3 | 0.257 | (6.77, -1.94) |
| 4 | 0.257 | (10.64, -1.94) |
| 5 | 0.257 | (14.51, -1.936 |
| 6 | 0.25 | (4.75, -1.25) |
| 7 | 0.25 | (16.25, -1.25) |
| 8 | 0.25 | (2, 0.62) |
| 9 | 0.25 | (10, 0.62) |
| 10 | 0.25 | (18, 0.62) |
| 11 | 0.2 | (1.7, 0) |
| 12 | 0.2 | (1.99,-0.24) |
| 13 | 0.2 | (2.33,-0.53) |
| | | |

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.002

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL
Aluminum

FINISH
None

DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | - | 12/2/19 |

COMMENTS:

None

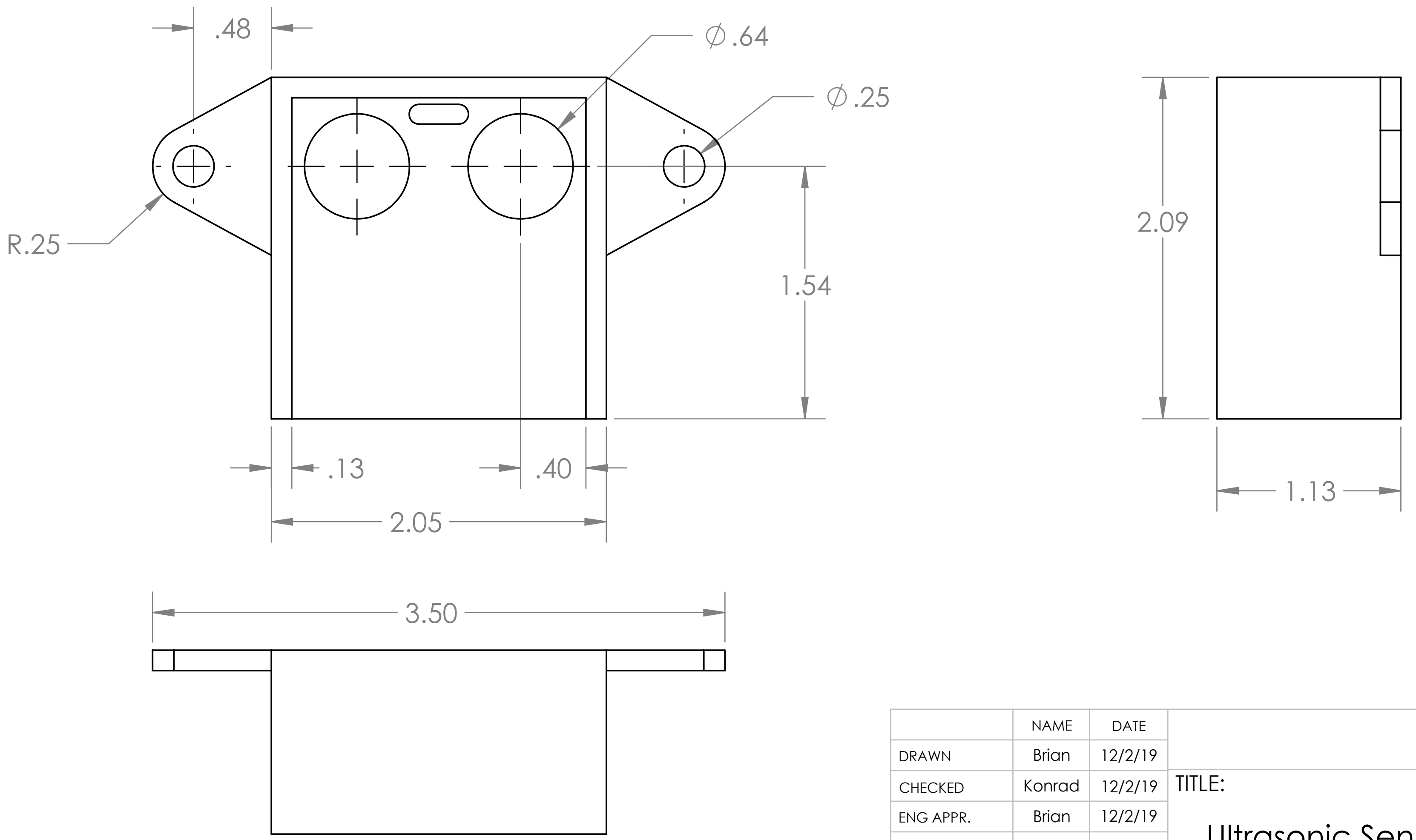
TITLE:

TreadPlate

SIZE A DWG. NO. 1 REV 2

SCALE: 1:3 WEIGHT: SHEET 1 OF 1

2 1




| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

This part is 3D printed

TITLE:

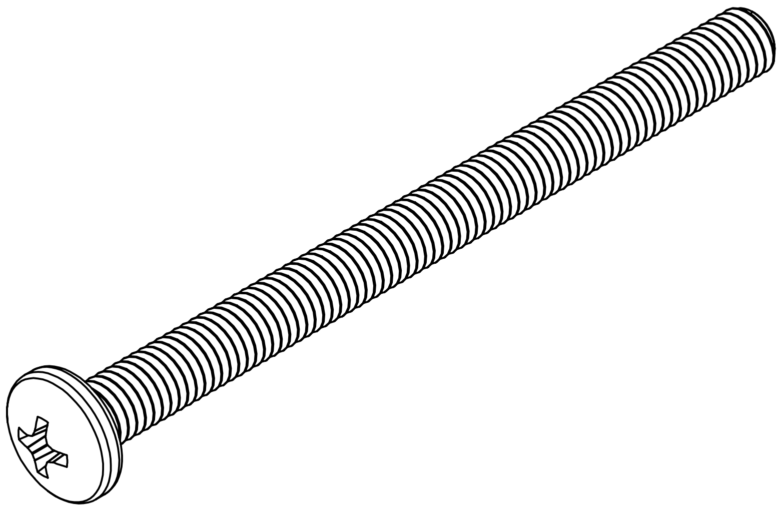
Ultrasonic Sensor Mount

| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| A | | 1 |

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

2 1

B B



A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# 1032 bolts

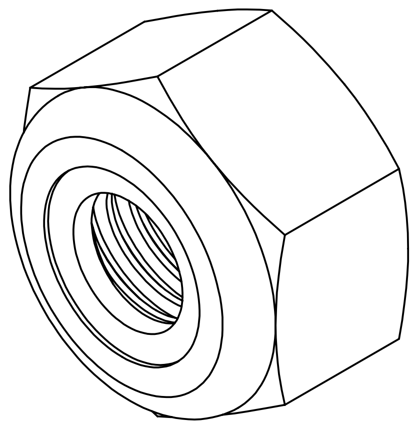
| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| **A** | | 1 |

| SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|

2 1

2 1

B B



A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# 1032 nuts

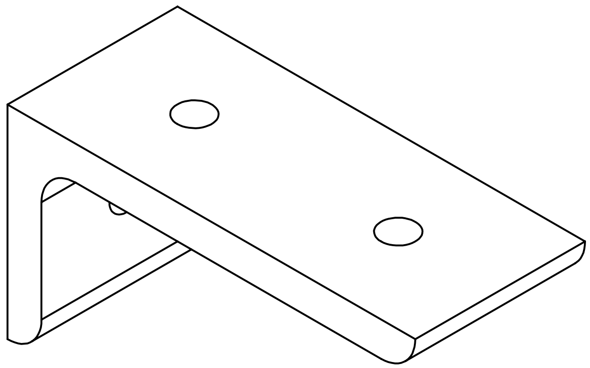
| SIZE | DWG. NO. | REV |
|---|---|---|
| A | 1 | 1 |

| SCALE: 5:1 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|

2 1

2 1

B B



A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

Angle Bracket_PDB Mount

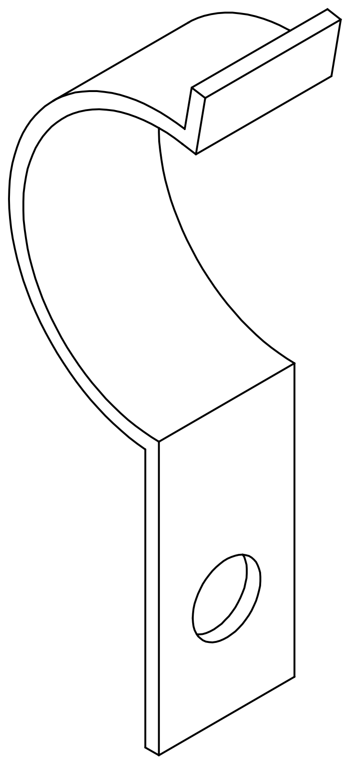
| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| A | | 1 |

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

2 1

2 1

B B



A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

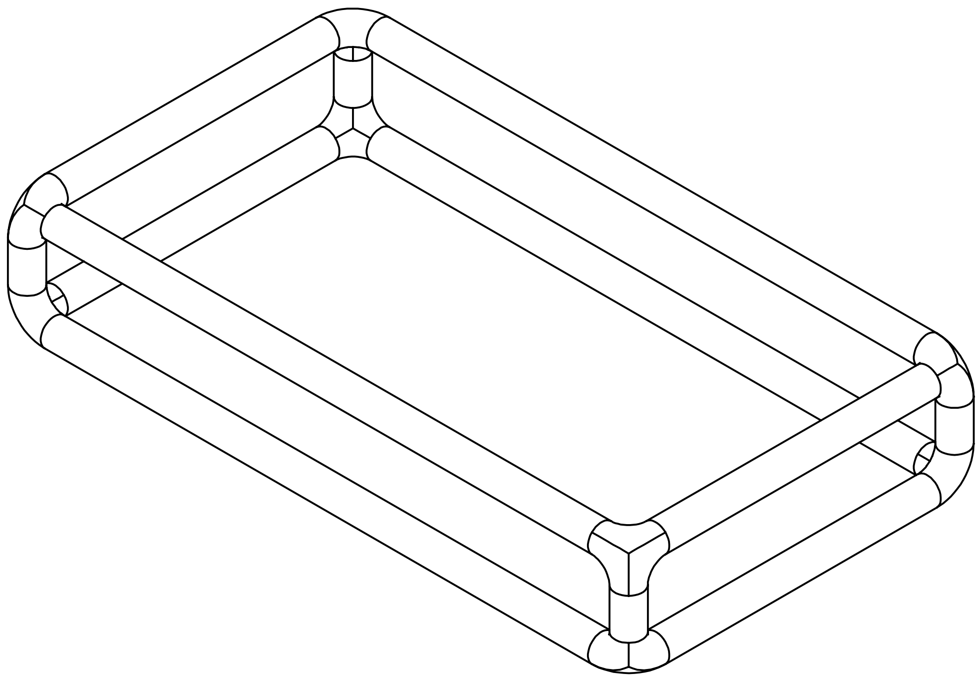
# Back Clip

| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| **A** | | 1 |
| SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1 |

2 1

2 1

B B



A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

Basket is a simple PVC wire frame

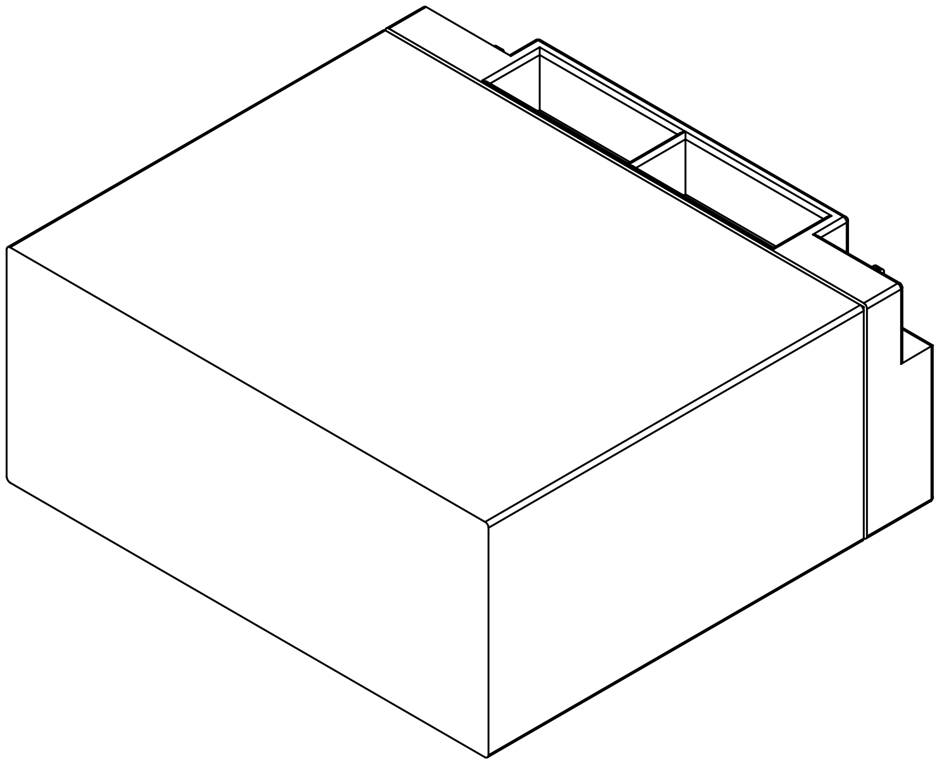
TITLE:

# Basket

| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| **A** | | 1 |

| SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|

2 1



| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

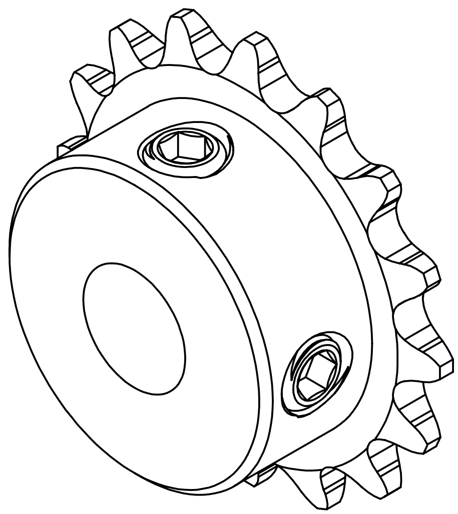
TITLE:

# Battery

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

2 | 1

B



A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# Bore Sprocket

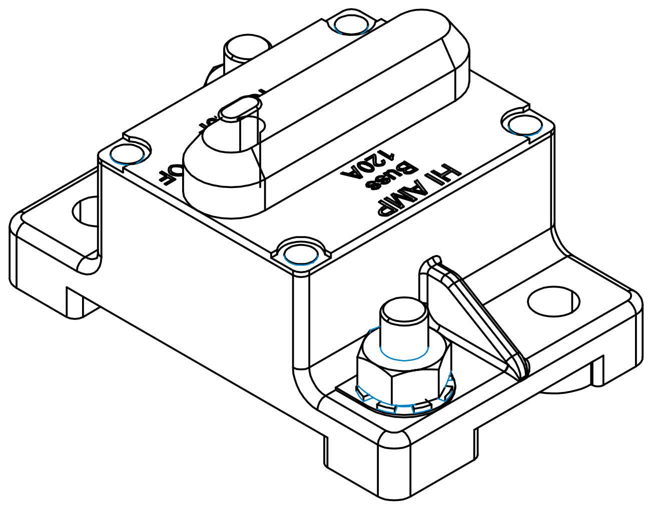
| SIZE | DWG. NO. | REV |
|---|---|---|
| A | 1 | 1 |

| SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|

2 | 1

2 1

B B




A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# Circuit Breaker

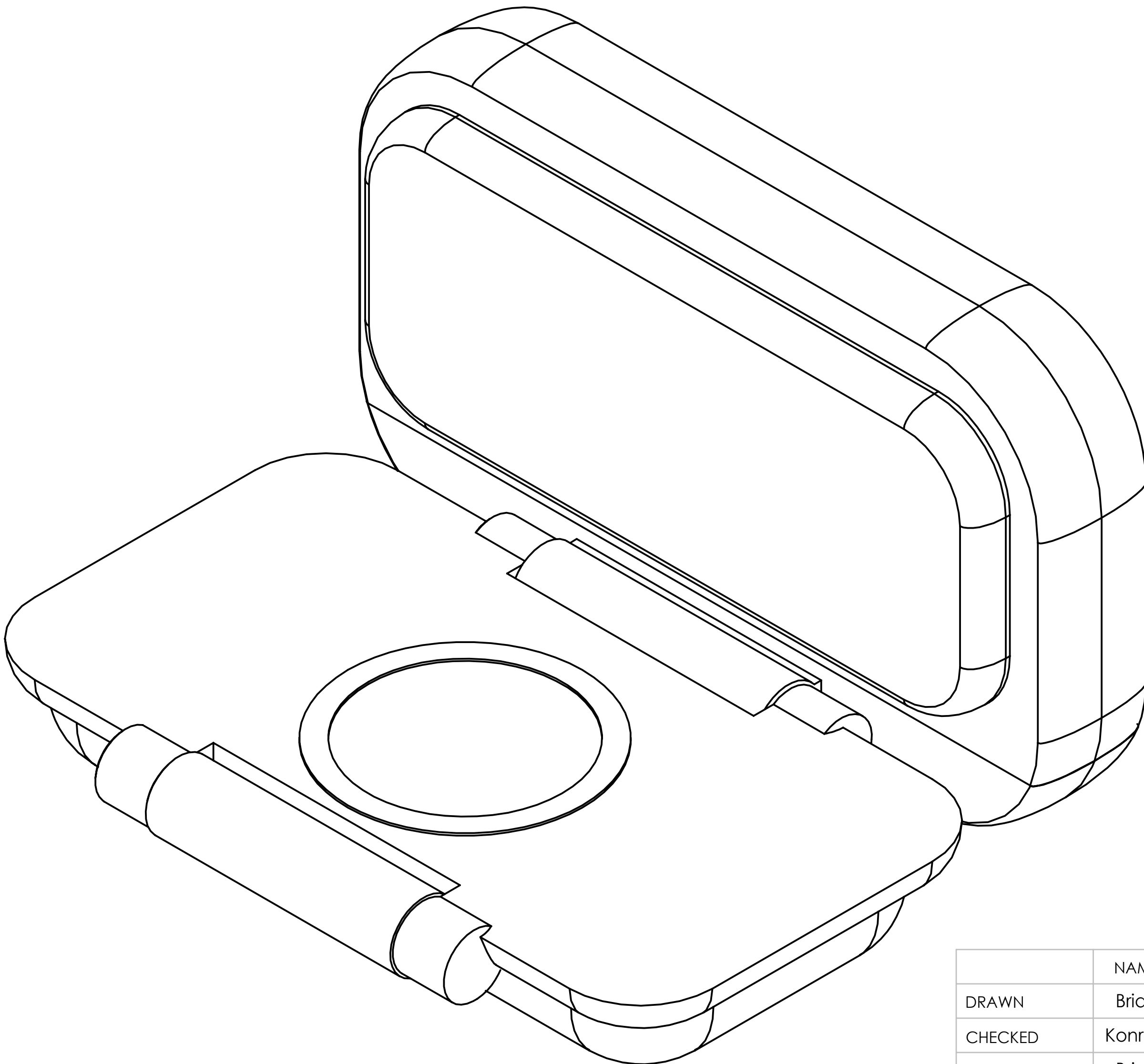
| SIZE | DWG. NO. | REV |
|---|---|---|
| A | 1 | 1 |

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

2 1

2 1

B B



A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# Logitech_C525

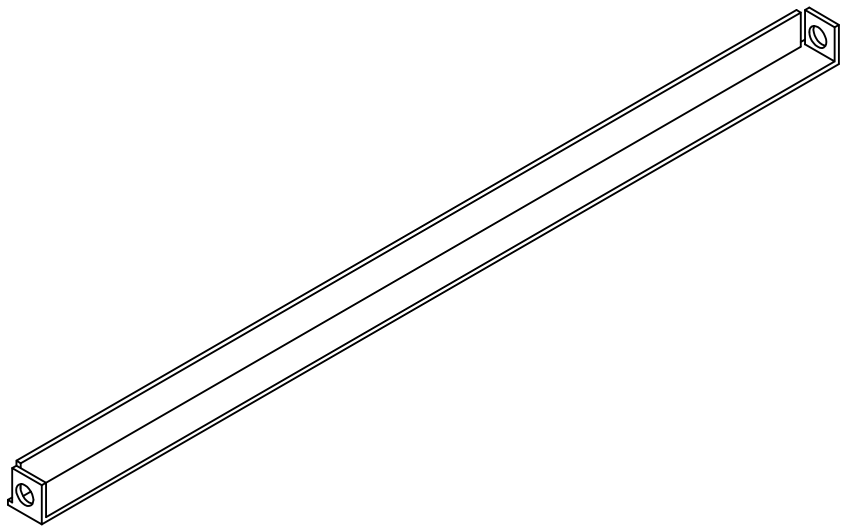
| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| A | | 1 |

| SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|

2 1

2 1

B B



A A

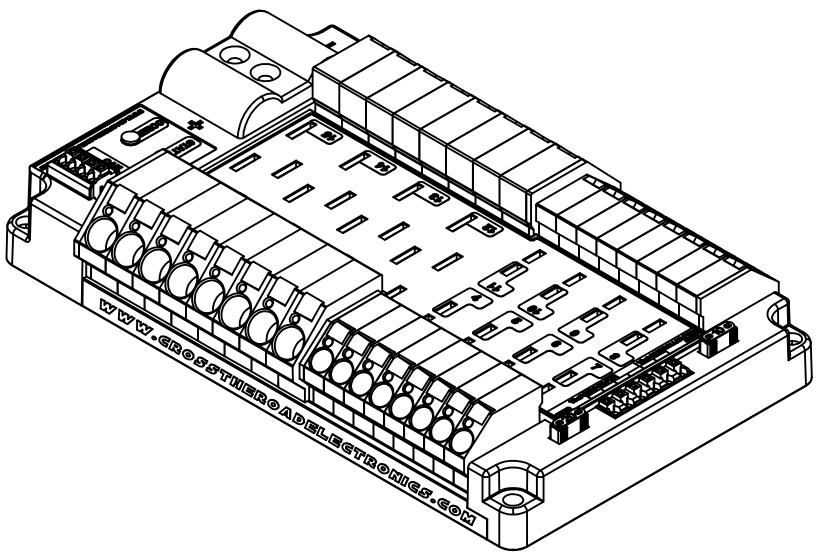
| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |
| COMMENTS: | | |
| None | | |

TITLE:

# PDB Crossbar

| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| **A** | | 1 |
| SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1 |

2 1




| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

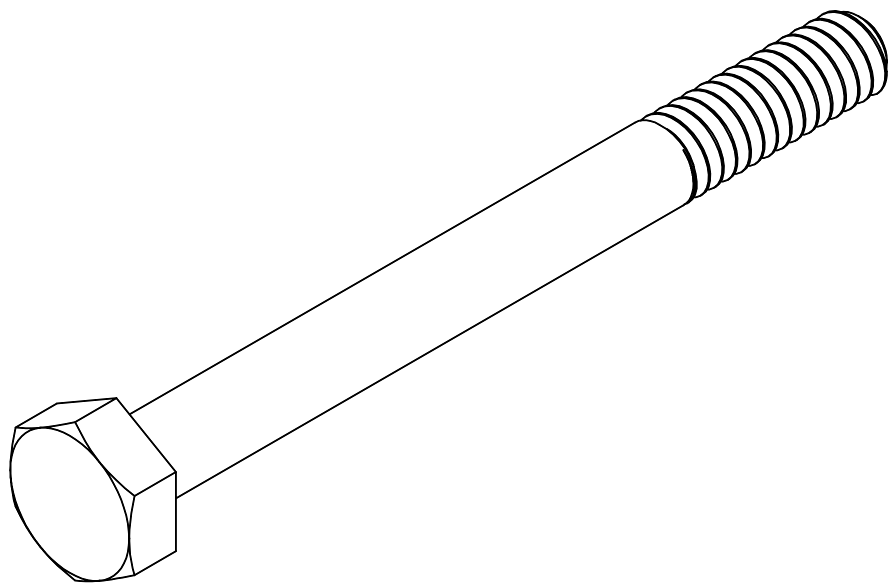
None

TITLE:

Power Distribution Board

| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| A | | 1 |

| SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|



| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

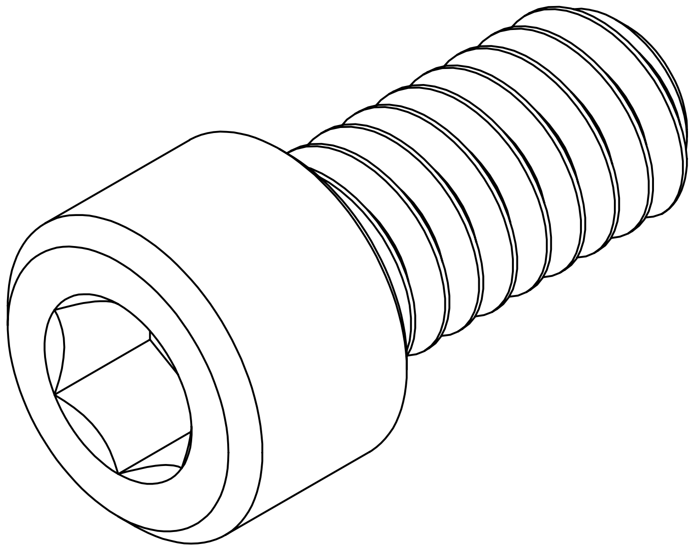
1/4 20 Bolts

| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| **A** | | 1 |

| | | |
|---|---|---|
| SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1 |

2 1

B B



A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

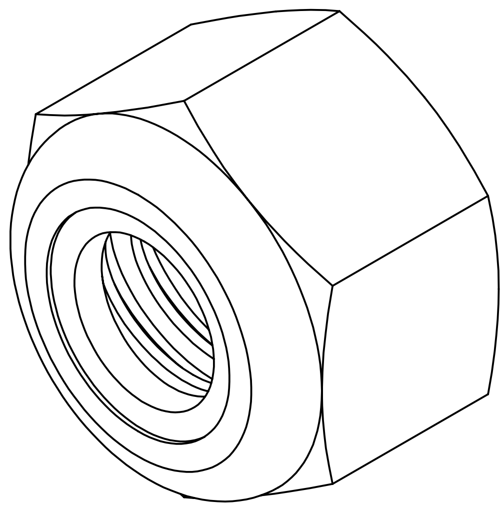
TITLE:

# 1/4-20 Clip Bolts

| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| **A** | | 1 |

| SCALE: 5:1 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|

2 1



| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

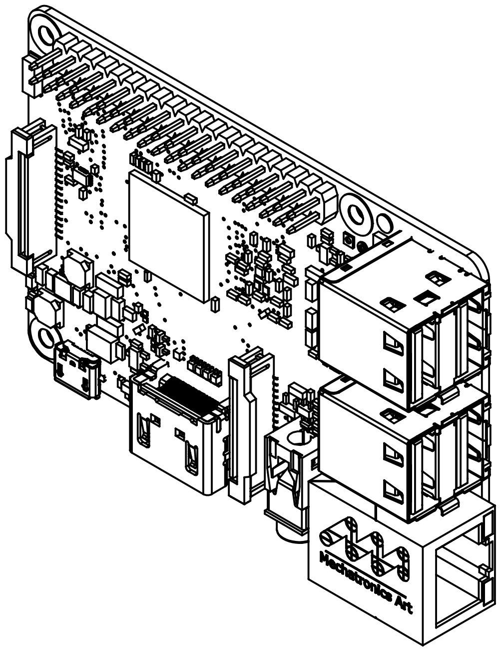
# 1/4-20 Nut

| SIZE | DWG. NO. 1 | REV |
|---|---|---|
| A | | 1 |

| SCALE: 5:1 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|

2 1

B B




A A

| | NAME | DATE |
|---|---|---|
| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# Raspberry Pi 3

| SIZE | DWG. NO. | REV |
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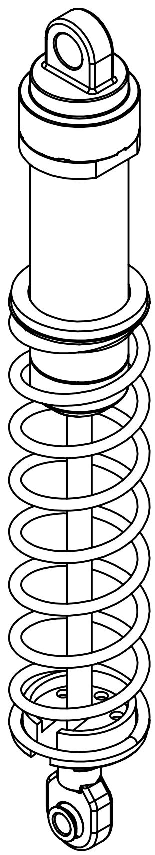
2 1

B B



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| DRAWN | Brian | 12/2/19 |
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| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# Shock

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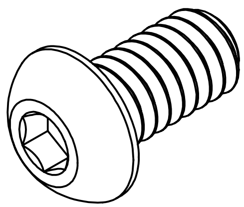
2 1

B B



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| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# Socket Cap Screw

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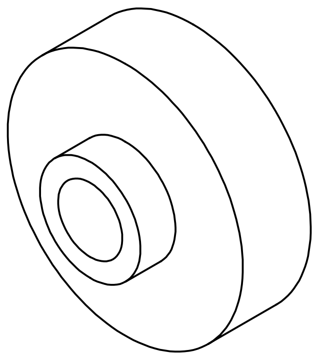
2 1

2 1

B B



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| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

Sprocket Hub

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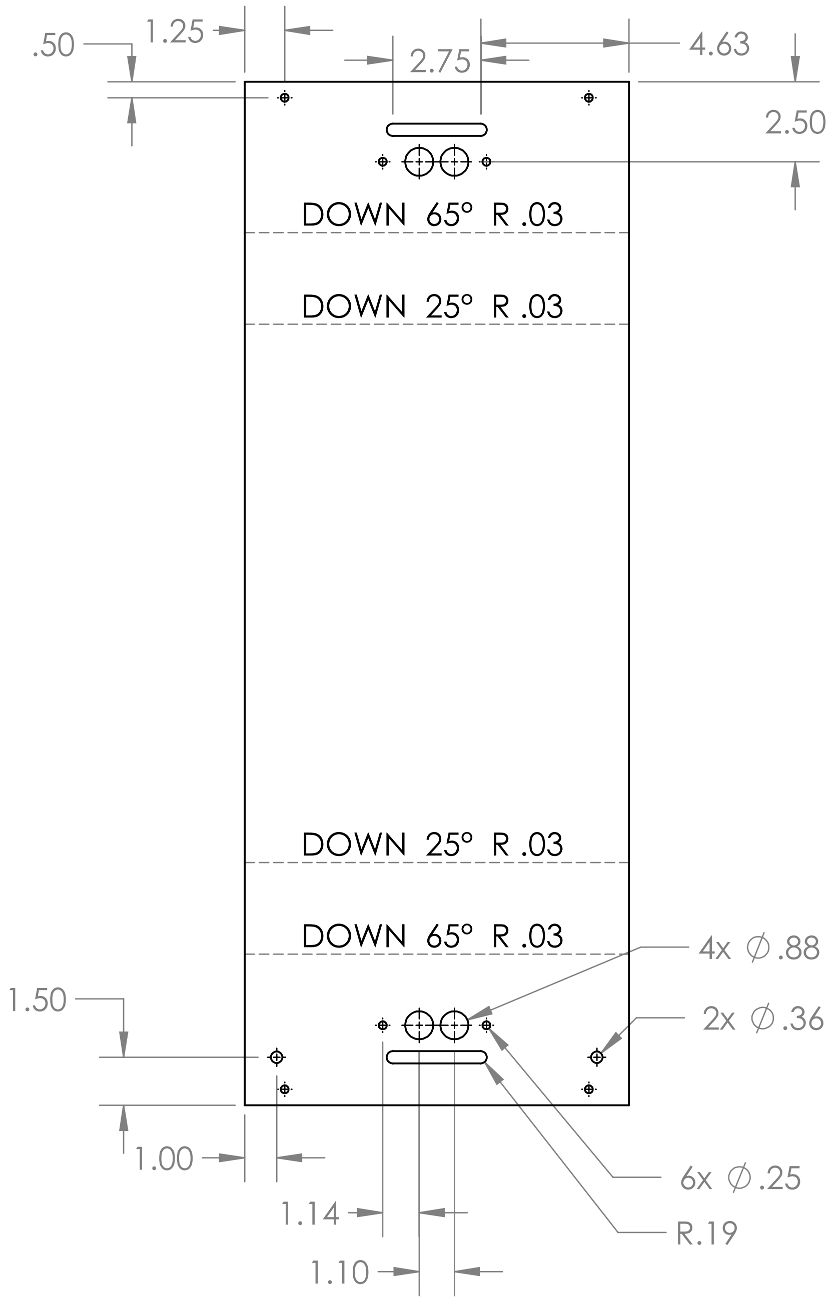
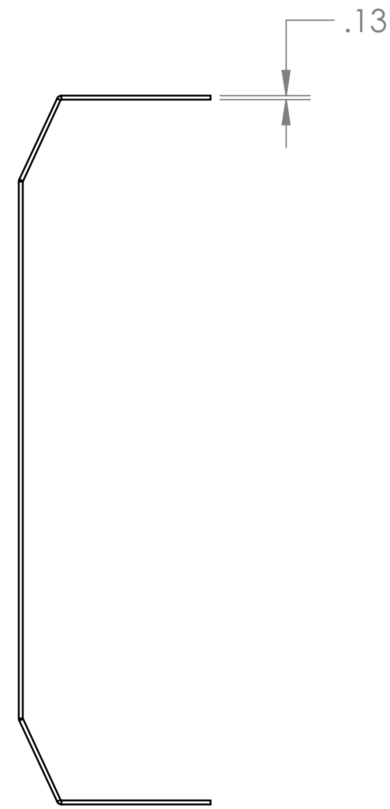
2 1

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| DRAWN | Brian | 12/2/19 |
| CHECKED | Konrad | 12/2/19 |
| ENG APPR. | Brian | 12/2/19 |
| MFG APPR. | Brian | 12/2/19 |
| Q.A. | Brian | 12/2/19 |

COMMENTS:

None

TITLE:

# Chassis_Bottom

| SIZE | DWG. NO. 1 | REV |
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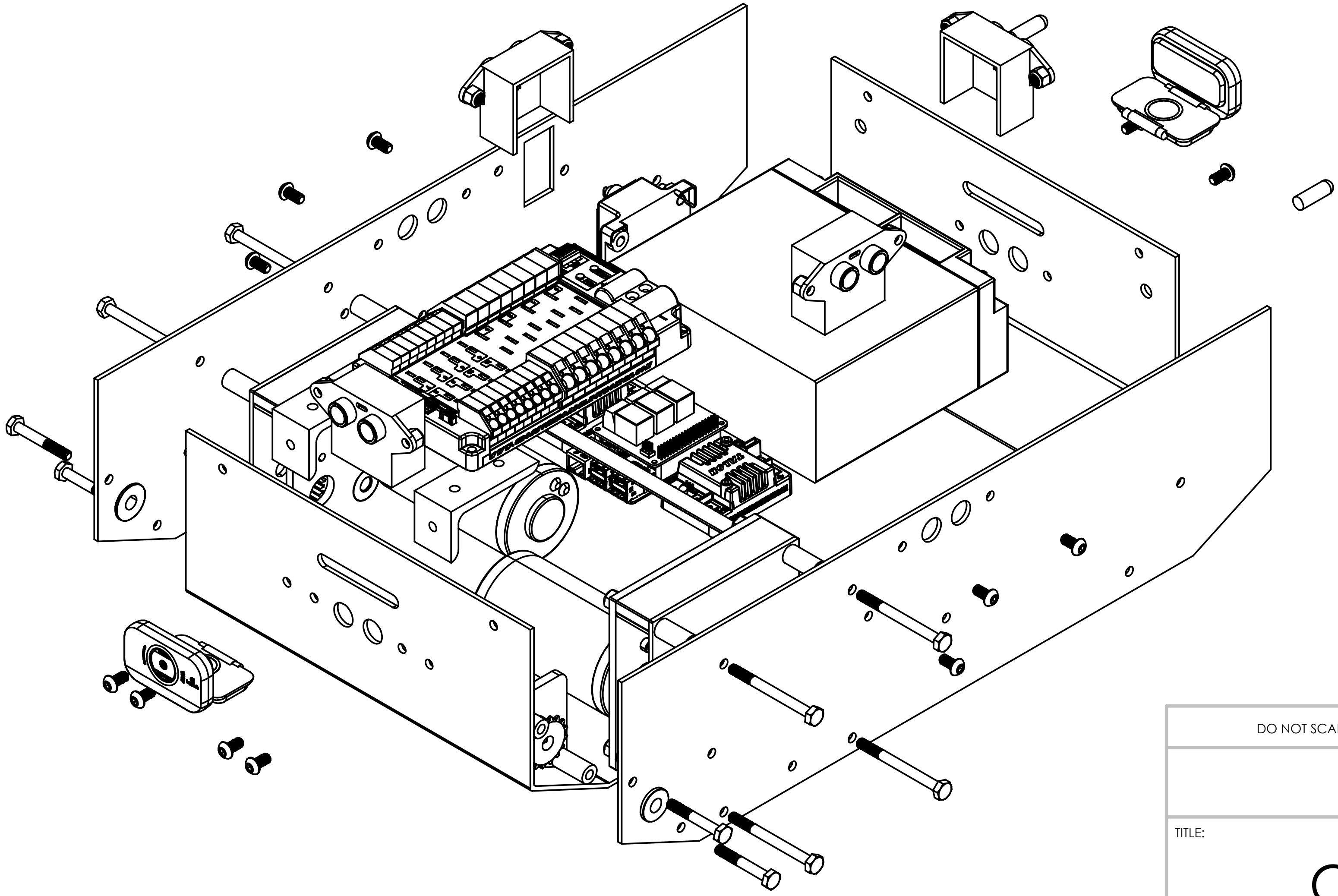
| SCALE: 1:10 | WEIGHT: | SHEET 1 OF 1 |
|---|---|---|



| DO NOT SCALE DRAWING | REVISION |
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TITLE:

# Chassis

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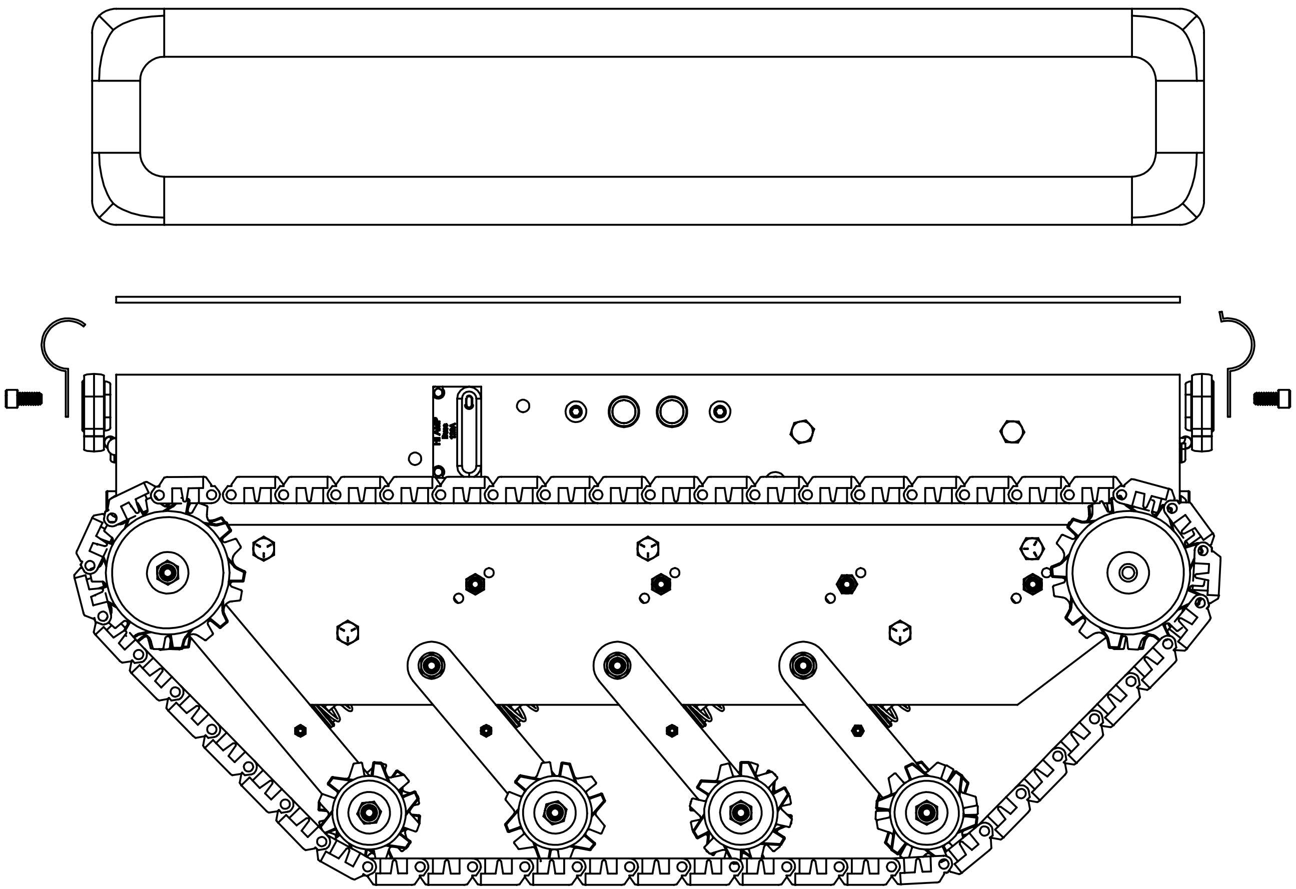

| DO NOT SCALE DRAWING | REVISION |
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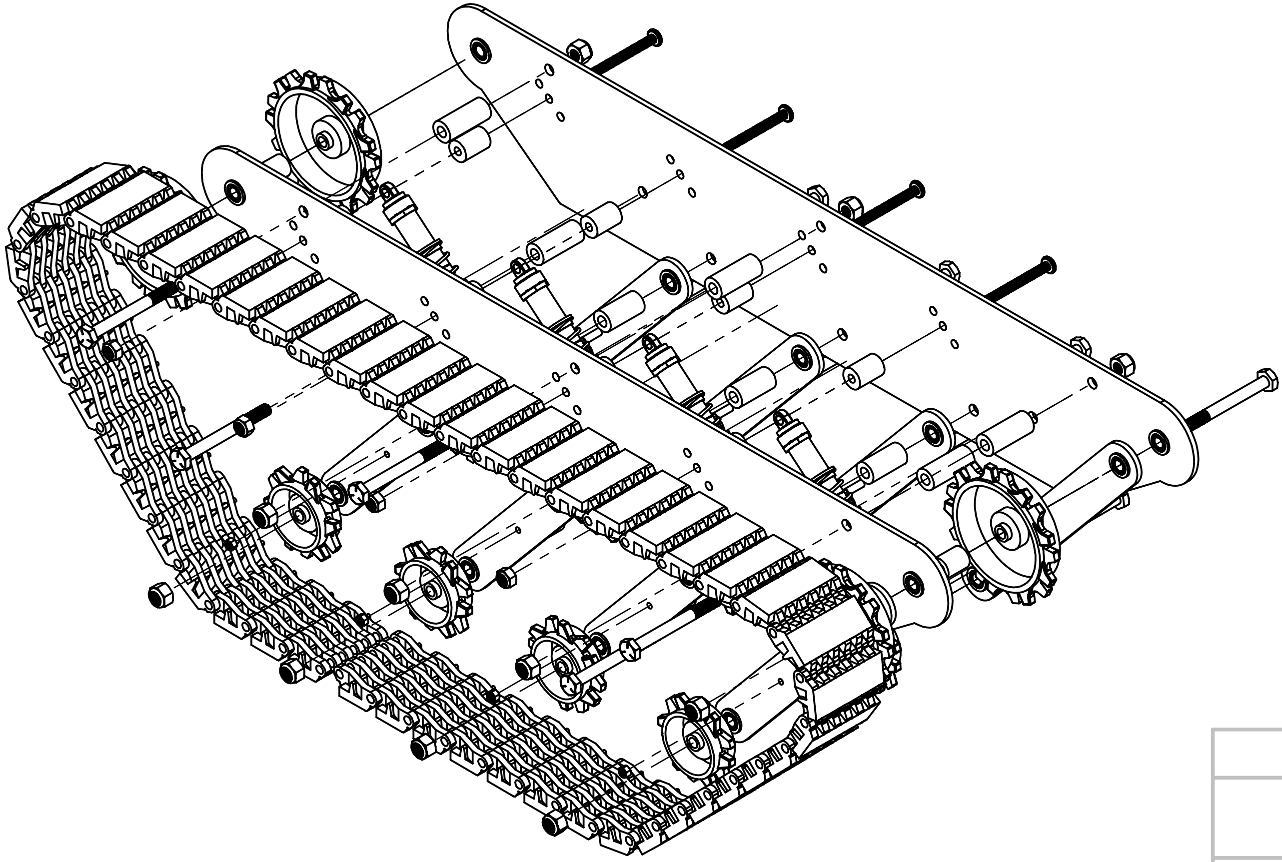
| TITLE: Robot | |
| DWG NO. | A4 |
| SCALE: 1:4 | SHEET 1 OF 1 |

| 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|

D

C



B

A

| | |
|---|---|
| DO NOT SCALE DRAWING | REVISION |
| | |
| TITLE: Tread Assembly | |
| DWG NO. | A4 |
| SCALE: 1:4 | SHEET 1 OF 1 |

| 6 | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|