DETAILED DESIGN REPORT

DESIGN OF A ROBOCUP RESCUE ROBOT MECHANICAL SUB SYSTEM

MECH 4680: ENGINEERING DESIGN

TEAM 21: RESCUE RANGERS

Sponsoring Company: UMSATS

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Executive Summary

This report outlines the design of the mechanical sub-systems for a rescue robot intending to compete in the Robot Rescue League (RRL) RoboCup competition. After careful consideration of a variety of design concepts, a design with two fixed main drive tracks and four rotating paddle tracks was decided upon. This was the only design that would satisfy the performance and mobility requirements of the competition. The main tracks are fixed along the sides of the robot, and extend the length of the main body section. One paddle track is mounted on each corner of the main drive, and can be rotated 360 degrees about the axis of the input drive shaft. Together, the two main tracks and four paddle tracks provide propulsion to the robot. Following competition requirements, the robot also features a manipulator arm to allow access to shortcuts requiring dexterity tasks.

The proposed design measures 1113 [mm] in length with the paddles extended outward, and 594 [mm] when rotated inward. The overall width is 676 [mm], measured from the outer edges of the paddle tracks. The overall height is 319 [mm] with the manipulator stowed, and 571 [mm] with the manipulator extended to its maximum height. The total vehicle weight is estimated at 27.4 [kg]. The center of gravity (CG) is located 20 [mm] rear of the geometric center of the robot body, at a minimum height of 76 [mm], and maximum of 121 [mm], depending on the orientation of the paddles and manipulator.

The maximum traversable longitudinal incline was determined to be 82 [º], and lateral incline was 78 [º], with the manipulator stowed. The maximum forward speed is estimated at 80 [m/min] on level ground.

The design features two main 250 [W] 24 VDC Maxon 136207 drive motors mated to a 50:1 harmonic drive gear reduction. The harmonic drives are mounted near the front of the frame, with each one driving one side of the robot in a skid-steer configuration. Each paddle track is rotated by a 40 [W] 24 VDC Maxon DCX26L motor mated to a planetary gearbox with a 231:1 reduction. These are mounted inside each paddle assembly. The paddle motors rotate the paddle via a 3:1 ring and pinion drive, with the ring gear attached to the frame.

The selected manipulator arm provides mounting points for a spherical BublCam optical camera and a laser thermal sensor. Due to time constraints, the team was unable to design a manipulator in house, however an off-the-shelf Lynxmotion AL5D 4-axis manipulator was determined to be sufficient for the design, and was chosen for use on the robot.

The entire robot is powered by a 24 [V] 400 Wh LiPo battery pack, mounted in a quick change battery case. The battery will provide adequate power for an entire 30 minute competition round, with the ability to quickly swap in another fully charged battery pack within a few minutes, between rounds.

The overall vehicle cost is estimated at $12,701.47 CAD, which takes into account the cost of off-the-shelf hardware, and raw material cost for manufactured parts. However, since the client specified that parts would be manufactured at AssentWorks by UMSATS, the labour cost of machining was neglected. This total also does not take into account the possibility of sponsorship and donated parts, which could further reduce the cost.

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1 Introduction

The University of Manitoba Space Applications and Technology Society (UMSATS) is a student run organization whose vision is to "Foster a culture for space exploration by making space missions accessible to undergraduate and graduate students at the University of Manitoba" [1]. The organization's main focus is the creation of a triple pico-satellite as a part of the Canadian Satellite Design Challenge (CSDC) [2].

UMSATS has expressed an interest in developing a robot to compete in the Robot Rescue League (RRL) RoboCup competition. The RoboCup Rescue League is a student design competition which consists of navigating an obstacle course to find victims, simulating a partially collapsed building following an earthquake [3].

Students must design a robot which can navigate various obstacles while mapping the terrain and searching for simulated survivors using a thermal sensor, CO_2 sensor and quick response (QR) code scanner [3]. In order to be successful, teams must develop creative designs using a variety of electrical and electronic components, custom software, control systems, and mechanical mobility systems. This project requires interdisciplinary cooperation between mechanical, electrical, and computer engineering students, similar to what would be seen in larger real world engineering projects.

In 2014-15, a team of electrical engineering students developed the electrical and electronic systems for such a robot, as a final year capstone project. However, their design for the mechanical platform was unable to compete because of issues with reliability and mobility. A photo of the previous 2014-15 robot design can be seen in Figure 1.

Figure 1: Initial UMSATS robot design [4].

UMSATS has requested the design of a new mechanical platform for the robot, which will satisfy the reliability and mobility requirements of the competition.

1.1 Project Objectives

The objective of the project is to design the mechanical components and systems of a rescue robot. The design must be capable of successfully competing in the RoboCup Rescue competition and fulfilling the specific needs of the client.

1.1.1 Project Scope

The scope of the project includes:

- The design of the mechanical drive system that provides mobility to the robot, including appropriate motors and drivetrain components.

- The design of a battery mounting system allowing quick and easy battery replacement.
- The design of the frame and body that supports and contains all the electrical and mechanical components.
- The design of mounting point(s) for a manipulator arm, the arm design (**if time permits**), or the adaptation of an appropriate off the shelf arm.
- The design of the mounting points for an optical camera, as well as thermal and CO_2 sensors on the end of the manipulator arm. These components are referred to as the end effector of the arm.

1.1.2 Project Deliverables

As a result of the project, UMSATS has requested several deliverables other than this report, including:

- A complete CAD model (SolidWorks) with FEA and engineering drawings.
- A bill of materials (BOM) for off the shelf and manufactured parts.
- Estimates of the vehicle weight and the center of gravity (CG) location.
- Estimated performance specifications.
- Recommended maintenance and inspection intervals.

1.1.3 Project Exclusions

The scope of this project excludes:

- The design of the manipulator arm end effector containing the vision system and sensors used to detect victims.

- The command modules and data handling necessary to remotely operate the robot.
- The design of the robotic controller used to operate the robot.

1.2 Technical Specifications

The design team developed target specifications to focus the design efforts around the client needs. To start the process, the needs of the client were carefully evaluated and assigned a weight value based upon importance. Performance metrics for the design were then established to quantify the client needs.

1.2.1 Customer Needs

After meeting with the contacts at UMSATS, a list of customer needs was generated in order to define the requirements of the design. The design requirements were used throughout the design process to ensure the competition and client requirements were met. The client needs were given an importance rating on a scale from 1 – 5. A need with an importance of one represents a low importance to meet the need, while an importance of five is a need that is critical to meet. TABLE I identifies the customer needs, along with the importance rating assigned to them by the team.

TABLE I: CUSTOMER NEEDS AND THEIR RELATED IMPORTANCE.

Need #	Customer Needs	Weight / Importance
N1	Ease of Battery Removal/Install.	4
N2	Design is reliable.	3
N3	Design is low cost.	2
N4	Manipulator can grasp and manipulate objects.	3
N5	Can traverse steps.	5
N6	Can traverse step fields.	5
N7	Can traverse crossing ramps.	5
N8	Can climb a steep incline.	5
N9	Mounts micro controller.	5

Need #	Customer Needs	Weight / Importance
N10	Mounts sensors and video camera.	5
N11	Can access all victim locations.	4
N12	Can access the course's shortcuts.	2
N13	Is easy to maneuver through the course.	4
N14	Manipulator can be stowed when not in use.	3
N15	Manufacturable at Assentworks.	4
N16	Can withstand impacts.	3
N17	Is capable of forward motion.	5
N18	Is capable of backward motion.	4
N19	Is capable of navigating sharp corners.	3
N20	Is capable of fitting in tight spaces on course.	3
N21	Can operate for the full competition round duration.	5

The importance values for each need were arrived at by the team through group discussion and careful consideration of the competition rules. Needs N5 – N10, N17 and N21 were ranked as fives because they make up the core functions that the robot has to perform to successfully compete in the competition.

Needs N1, N11, N13, and N18 were ranked fours because they represent large components of the competition scoring, but are not necessary to simply compete. Needs N1, and N15 were ranked fours because the client has requested them, but they are not necessary to successfully compete in the competition.

Needs N2, N4, N14, N16, N19 and N20 were ranked threes because they provide extra functionality to the robot that will allow it to be more competitive.

Needs N2 and N12 were identified by the client as optional performance goals, and as such were ranked as twos.

1.2.2 Performance Metrics

With a final list of project needs, metrics were created to meet each need. Each metric was given an importance value equal to the maximum importance of all the needs it will meet. Using the maximum value ensures that importance of the metric coincides with the needs it will meet. Marginal and ideal values were assigned to each of the metrics to quantify how the team will meet them. The marginal value represents the bare minimum value required to successfully compete in the competition. The ideal value represents the desired value required to contend with other robots in the competition. TABLE II outlines the project metrics and the metric's importance, marginal and ideal values.

TABLE II: METRIC IMPORTANCE, MARGINAL AND IDEAL VALUES.

Metric #	Metric	Importance	Marginal Value	Ideal Value	Unit
M1	Battery Installation/Removal Time	4	<5	<3	$[min]$
M2	Design Lifetime	3	>2	≥5	$[years]$
M3	Total Cost	2	<15000	<10000	$[CAD]$
M4	Manipulator Grasping Force	3	>3	>5	$[lbs]$
M5	Manipulator Pulling Force	3	>3	>5	$[lbs]$
M6	Manipulator Lifting Force	3	>2	>5	$[lbs]$
M7	Ramp Incline Traversable	5	>45	60	$[°]$
M8	Gap Size Crossable	5	>20	>40	$[cm]$
M9	Hurdle Height Traversable	5	>20	>30	$[cm]$
M10	Stair Incline Traversable	5	>40	>45	$[°]$
M11	Continuous Pitch/Roll Ramp Speed	5	>10	>75	$[m/min]$

Metric #	Metric	Importance	Marginal Value	Ideal Value	Unit
M12	Crossing Pitch/Roll Ramp Speed	5	>10	>50	$[m/min]$
M13	Symmetric Step Field Speed	5	>5	>11	$[m/min]$
M14	Sustained Forward Speed	5	>50	>90	$[m/min]$
M15	Sustained Reverse Speed	4	>30	>70	$[m/min]$
M16	Mounts Microcontroller	5	Yes	Yes	$[subj]$
M17	Housing Weight Capacity	5	>12	>20	$[kg]$
M18	Mounts Manipulator End Effector	5	Yes	Yes	$[subj]$
M19	Manipulator Weight Capacity	5	>2	>4	$[kg]$
M20	Vehicle Width	4	<100	<50	$[cm]$
M21	Vehicle Height	4	<100	<40	$[cm]$
M22	Vertical Manipulator Reach	4	>40	>80	$[cm]$
M23	Manipulator Planar Reach Radius	4	>50	>60	$[cm]$
M24	Manipulator End Diameter	4	<15	<10	$[cm]$
M25	Vehicle Length	4	<120	<80	$[cm]$
M26	Turning Radius	4	<100	<50	$[cm]$
M27	Manipulator stows when not in use.	3	Yes	Yes	$[subj]$
M28	Manufacturable at Assentworks	4	Yes	Yes	$[subj]$
M29	Impact Height Withstand able	4	>30	>50	$[cm]$
M30	Battery Life	3	>30	>35	$[min]$

Each metric was then correlated to the needs that it would evaluate. By correlating the metrics to the needs, the team can show how each of the project needs will be met. TABLE III shows the relationships between the needs and metrics.

TABLE III: RELATIONSHIP OF CLIENT NEEDS TO QUANTIFIABLE METRICS.

Needs	Metrics	M1 Battery Installation/Removal Time	M2 Design Lifetime	M3 Total Cost	M4 Manipulator Grasping Force	M5 Manipulator Pulling Force	M6 Manipulator Lifting Force	M7 Ramp Incline Traversable	M8 Gap Size Crossable	M9 Hurdle Height Traversable	M10 Stair Incline Traversable	M11 Continuous Pitch/Roll Ramp Speed	M12 Crossing Pitch/Roll Ramp Speed	M13 Symmetric Step Field Speed	M14 Sustained Forward Speed	M15 Sustained Reverse Speed	M16 Mounts Microcontroller	M17 Housing Weight Capacity	M18 Mounts Manipulator End Effector	M19 Manipulator Weight Capacity	M20 Vehicle Width	M21 Vehicle Height	M22 Vertical Manipulator Reach	M23 Manipulator Planar Reach Radius	M24 Manipulator End Diameter	M25 Vehicle Length	M26 Turning Radius	M27 Manipulator stows when not in use.	M28 Parts use only machines available at Assentworks for manufacture	M29 Impact Height Withstandable	M30 Battery Life
N1	Ease of Battery Removal/Install.	●																													
N2	Design is reliable.		●																												
N3	Design is low cost.																														
N4	Manipulator can grasp and manipulate objects.				●	●	●																								
N5	Can traverse steps.									●	●																				
N6	Can traverse step fields.													●																	
N7	Can traverse crossing ramps.												●																		
N8	Can climb a steep incline.							●																							
N9	Mounts micro controller.																●	●													
N10	Mounts sensors and video camera.																		●	●											
N11	Can access all victim locations.																				●	●	●	●	●	●					
N12	Can access the course's shortcuts.				●	●	●														●	●	●					●			
N13	Is easy to maneuver through the course.							●	●	●	●	●	●	●	●	●					●	●					●				
N14	Manipulator can be stowed when not in use.																					●									
N15	Manufacturable at Assentworks.																												●		
N16	Can withstand impacts.																													●	
N17	Is capable of forward motion.								●	●	●	●	●	●	●																
N18	Is capable of backward motion								●	●	●	●	●	●		●															
N18	Is capable of navigating sharp corners.																				●	●					●				
N19	Is capable of fitting in tight spaces on course.																				●	●			●	●	●	●			
N20	Can operate for the full competition round duration.																														●

1.3 Constraints and Limitations

The team identified the project constraints and limitations while generating technical specifications, meeting with the client, and analyzing the competition rules. The RRL competition rules specify the nature of the course and its obstacles. These rules dictated the majority of the constraints on the design, as this directly related to the client's objective of competing in the competition. TABLE IV contains the project constraints identified by the team, a short description and their source.

TABLE IV: DESCRIPTION AND SOURCE OF PROJECT CONSTRAINTS.

Constraint #	Description	Source
C1	The robot height must be less than 120 [cm] with the manipulator stowed [3].	Competition Rules
C2	The course hallways are 120 [cm] wide [3].	Competition Rules
C3	The robot's manipulator arm must have mounting points on the end of the arm to accommodate the video camera, a thermal and a CO_2 sensor to detect victims in the course.	Client
C4	Victim locations are accessed through holes with a diameter of 15 [cm] [3].	Competition Rules
C5	The holes to access the victim locations can be located up to 120 [cm] above floor level [3].	Competition Rules
C6	The event rounds last 15 minutes (preliminary) and 30 minutes (final), so the robot must have adequate battery power to run for one entire 30 minute round from a full battery [3].	Competition Rules
C7	The robot must traverse stairs with 20 [cm] risers inclined 40 [°] from the horizontal [3].	Competition Rules
C8	The robot must traverse a "pipe step" obstacle with a vertical step of up to 30 [cm] [3].	Competition Rules
C9	The robot must traverse incline ramps up to 45 [°] from the horizontal [3].	Competition Rules

Constraint #	Description	Source
C10	The robot must traverse symmetric stepfields [3].	Competition Rules
C11	The robot must traverse crossing pitch/roll ramps angled at 15 [°] from the horizontal [3].	Competition Rules
C12	The robot must traverse continuous pitch/roll ramps angled at 15 [°] from the horizontal [3].	Competition Rules
C13	The client can only manufacture parts at Assentworks in Winnipeg.	Client
C14	The client has requested the design be limited to common engineering materials such as aluminum and steel.	Client
C15	Any motors used shall be specified from Maxon Motors and be the EC variety	Client
C16	If chain is used, ANSI 40 shall be the size used due to its ease of availability	Client

Each of these constraints was discussed to determine possible effects it may have on the design. C1 and C2 provide the major size constraints on the design. C1 limits the height, while C2 limits the length and width of the robot base. To successfully traverse the hallways the robot must be able to make 90 [°] corners in the 120 [cm] hallways.

C3 – C5 constrain the manipulator design. It must be long enough to reach the highest holes, and the end must be smaller than 15 [cm] in diameter, while still being able to mount the video camera and sensors.

C6 constrains the battery powering the robot. To be able to last for this duration, a larger battery with a higher milli-amp hour rating will have to be used. A larger battery will in turn have an effect on the frame and housing size, as this is where it will mount.

C7 – C12 describe the course obstacles that the robot must face. C13 and C14 are the major material limitations for the design. Being limited to a smaller number of materials makes the design problem simpler, but weight may have to be added in key areas to create the same strength that could have been created with stronger and lighter materials.

C15 and C16 describe specific requests made by the client related to our detailed design. C15 was requested simply because of the client's past experience working with this brand of motor. C16 was requested to ease maintenance of the robot.

2 Design Process and Concept Selection

Although the robot operates as a single machine, its design consists of several main subsystems which must work together for the robot to function. Before beginning the design, our team met with the client to get specific details about the performance requirements for a rescue robot to function competitively. Using this information, the design was broken up into subsystems for ease of design, specifically frame and body, suspension, mobility system, battery mounting system, and manipulator arm.

2.1 Concept Generation and Selection

The concept generation was preceded by research into past competitors, and relevant standards to rescue robot operations. Performing this research provided context in regards to the tasks the robot must perform, how it will be operated, and the environment it will be operated in. The research also provided a starting point for developing functional concepts.

Concept generation was performed first individually, then as a team in a brainstorming session. Due to the large number of concepts, a small sketch of each concept was created and pair with a one or two sentence description. The sketches helped to lend a visual aid to concepts during brainstorming sessions. The initial concepts for each subsystem generated were compared relative to each other using a concept screening matrix. This eliminated some concepts, and the winning concepts were combined and improved upon before moving into concept scoring. The team then used a weighted criteria matrix to score the concepts in a quantifiable manner. The results were discussed with the client before settling on a final design concept for each subsystem. The detailed concept screening and scoring matrices along with all concepts generated can be found in Appendix A.

2.2 Concept Scoring Criteria

The selection criteria were developed by the team during one of the concept brainstorming sessions. The overall criteria were created based upon the client's needs. Relating the selection criteria and client needs allowed the team to see which criteria were most important, and ensured that the criteria encompassed the entire scope of the project. The generated selection criteria were further related to whichever functional subsystems they applied to. Finally, the team looked at determining extra criteria specific to the functional subsystems of the design. Figure 2 shows the results of the first brainstorming session.

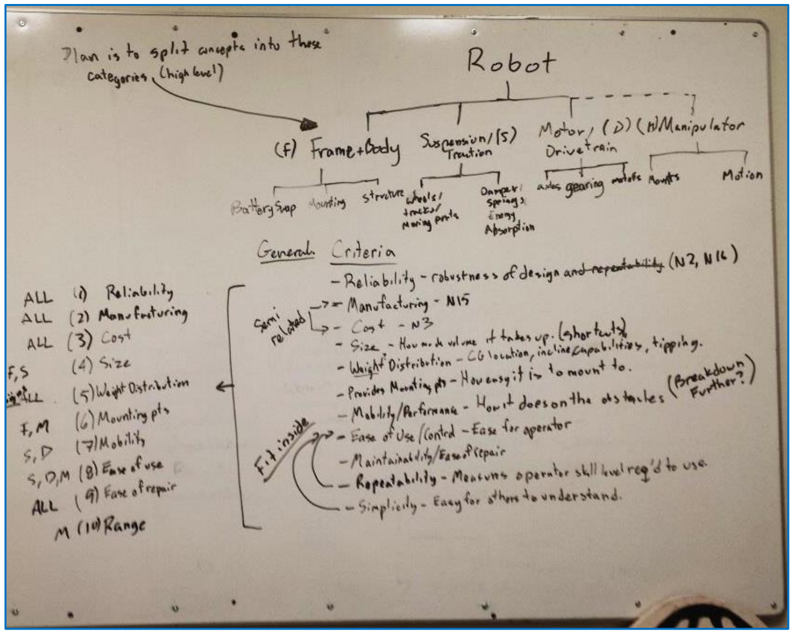


Figure 2: White board generated during selection criteria brainstorming [5].

In Figure 2 the generated criteria are seen in the bottom right, with needs behind a number of them. How each functional subsystem was related to the criteria is shown to the right of the generated criteria. TABLE V shows the shorthand the team used for each functional subsystem.

TABLE V: SHORTHAND NAMES FOR THE FUNCTIONAL SUBSYSTEMS.

Functional Subsystem	Frame	Suspension	Motor and Mobility	Manipulator	Battery Swap
Shorthand	(F)	(S)	(D)	(M)	(B)

During concept screening and scoring, the criteria were re-evaluated to ensure that they completely captured the needs of the project. The final set of selection criteria related to the client needs and functional subsystem is shown in TABLE VI.

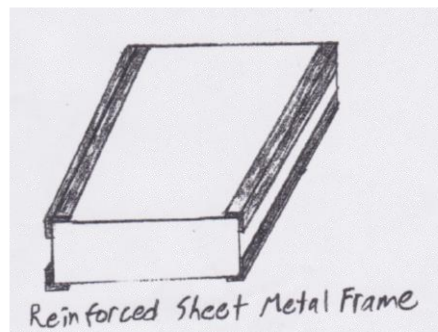
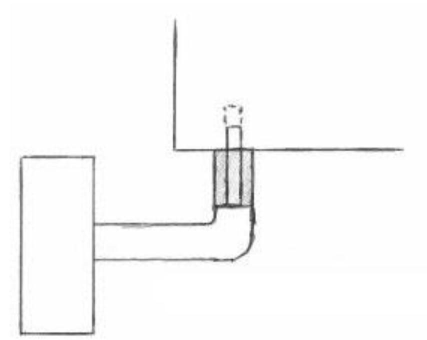
TABLE VI: FINALIZED SELECTION CRITERIA.

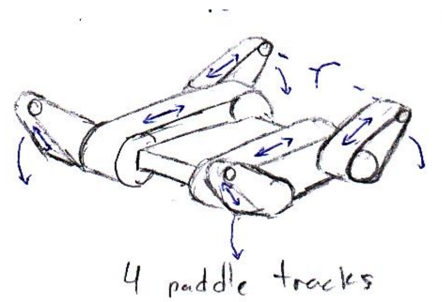
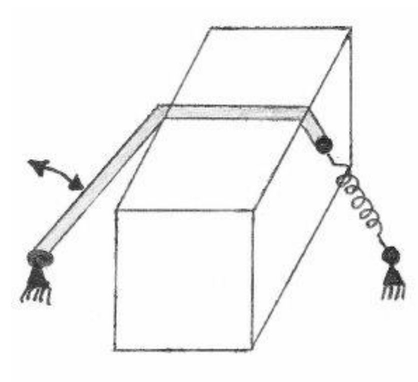
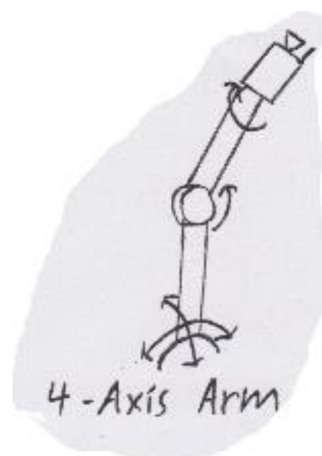
Selection Criteria	Description	Needs Met	Sections Applicable To
Reliability	The ability of the design to endure multiple uses.	N2, N16	ALL
Manufacturability	The ease of the manufacturing process, ie. How simple is it to create the final product.	N15	ALL
Cost	The estimated cost of the design in regards to purchasing materials/parts.	N3	ALL
Size	The compactness of the design in relation to course or internal constraints.	N11 → N14, N20	F, S
Mobility/ Performance	The performance of the design in regards to traversing the course.	N4→N8, N17→N19, N21	D, S
Ease of Use	The ease of operating the design in terms of repeatability and simplicity	N1, N13	D, M, B
Ease of Repair/ Maintenance	The ease of repairing and/or replacing broken or worn out parts.	N2, N15	ALL
Manipulator Range	The range of reach the manipulator has in the vertical and horizontal planes.	N11, N14	M
Ease of Mounting	The ease of adding/designing mounting points to a design.	N9, N10	F, M
Installation Time	The time it takes to install a battery.	N1	B

2.3 Summary of Selected Design

Using the concept screening and scoring process, a final design was chosen for each mechanical subsystem. Once a design concept was chosen for each subsystem, the detailed design of each section could begin. TABLE VII includes a summary of the chosen concepts for each functional section.

TABLE VII: SUMMARY OF SELECTED CONCEPTS FOR DETAILED DESIGN.

Functional Section	Concept Selected	Picture
Frame and Body	Reinforced Sheet Metal	
Suspension (Not Included in Detailed Design)	Rubber Bushing	

Mobility	Four Paddle Track Design	
Battery Mounting System	Modified Latch Design	
Manipulator Arm	4Axis Design	

An initial vehicle weight of 15 kg was assumed for design purposes using comparative data from [6], and initial designs were created. After the first designs were completed, CAD software estimated the vehicle's weight at almost 25 kg, requiring a second design iteration to satisfy the design requirements. The design details of each subsystem are outlined in the Section 3.

3 Detailed Design

Detailed designs were created using the conceptual design ideas as an overview of how each subsystem should operate. The functional subsystems of the robot operation were re-organized and split up in to functional assemblies of the robot. The new subsystems represent the actual assembly process of the robot, such that each system could be made independently and then joined to make the robot. The main design sections include:

- Main Drive Motors and Shafts
- Main Tracks
- Paddle Tracks
- Battery Mounting System
- Manipulator Mounting and End Effector
- Frame and Body

These sections were split equally between the team members to allow the designs to be created in tandem. The team took an iterative design approach to the robot, meeting frequently to ensure that the different sections would interface correctly together.

3.1 Main Drive Motors and Shafts

The drive train design for the main tracks consists of a motor, harmonic drive and two shafts which drive a set of sprockets and a chain. The first step to designing the drive train was to size the motor to provide enough power to drive the robot forward. A gearing system was introduced to the design to increase the torque output of the motor. The gearing ratio was designed to increase the motors torque to the point where it could drive the shaft while still maintaining the desired rotational speed. After the torque and speed output were determined, the shaft was designed to seat all components in the proper spot relative to the frame of the robot. Finally, calculations were performed on the shaft to determine the minimum allowable diameter that would not exceed the material endurance limit.

3.1.1 Motor and Gearing Selection

To select a motor, the torque required to drive the robot was initially estimated using a robot weight of 15 [kg] taken from the NAJI-IV [6]. The final weight of the robot was determined to be 25 [kg], after which the torque calculations were redone for a 25 [kg] robot. The two scenarios considered while calculating the required torque were flat ground driving forward and driving up a 60 [°] ramp. Figure 3 and Figure 4 are free body diagrams for the two scenarios.

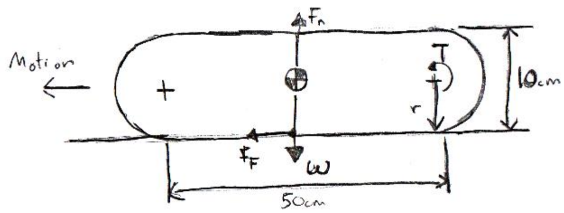


Figure 3: Free body diagram of flat ground motion.

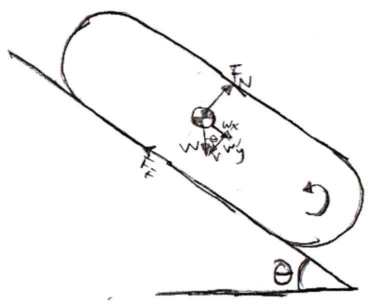


Figure 4: Free body diagram of incline ground motion.

The torque required for each scenario is summarized in TABLE VIII for both the initial robot weight estimate of 15 [kg] and the final 25 [kg] robot.

TABLE VIII: TORQUE REQUIRED FOR DIFFERENT LOADING SCENARIOS.

Scenario	Value Meaning	15 kg Robot Torque (Nm)	25 kg Robot Torque (Nm)
Flat Ground Motion	Max Torque due to friction	16.26	27.1
Uphill Incline Motion	Max Torque due to friction	8.13	13.55
Resist Motion on Incline	Min torque to not slide due to weight.	6.37	10.62

Appendix B contains the details of the torque calculations.

The motor selection was also dependent upon meeting the sustained forward speed marginal metric of 50 [m/min]. Our client requested that our motors be specified from Maxon Motors so that they will integrate into the current electrical systems. The also client recommended the use of a 400 [Wh] battery to power the motors. As a result, the motors were initially selected to be 200 [W], which provided 94.6 [mNm] of torque at 16100 [rpm] for one hour. Moving on to sizing the harmonic drive, the team encountered difficulty finding a drive which could operate at the motor rpm without breaking down. TABLE IX shows the properties of the CSG-17-50-2UH harmonic drive that was selected to gear the motor.

TABLE IX: HARMONIC DRIVE PROPERTIES.

Property	Value
Gearing Ratio	50
Rated Torque @ 2000 rpm	21 Nm
Limited Repeat Torque	44 Nm
Limit for Average Torque	34 Nm
Limit for Momentary Peak Torque	91 Nm
Maximum Input Speed	10000 rpm
Limit for Average Input Speed	6500 rpm
Weight	460g

The maximum rpm the harmonic drive could handle was 10000 [rpm] when properly maintained [7]. Maxon Motors could not supply a 200 [W] motor with a nominal speed lower than 10000 [rpm]. Therefore a 250 [W] motor was selected, which operates at 4300 [rpm] and can provide 331 [mNm] of torque during nominal operation [8]. Operating at the nominal rpm will result in a geared linear speed of 34.3 [m/min]. This speed does not meet the speed metric of 50 [m/min]; however operating the motor at 10000 [rpm] will produce a speed of 78.8 [m/min], which does meet the metric. The final motor properties are detailed in TABLE X.

TABLE X: PROPERTIES OF THE 250W MOTOR.

Property	Motor Value
Nominal Voltage	24V
Nominal Speed	4300rpm
Nominal Torque	331mNm
Nominal Current	7.51A
Max Speed	12000rpm
Stall Torque	2540mNm
Max Axial Load (dynamic)	20N
Max force for press fits	170N
Max radial load (5mm from flange)	180N
Weight	1100g

It was important to consider the maximum loads permissible on the motor shaft while designing the drive train. The main load present on the drive shaft of the motor is due to axial loading of the harmonic drives wave generator that occurs during operation [7]. Eq. 1 shows the formula used to determine the axial force generated by operating the harmonic drive.

$$F = 2 * \frac{T}{D * .00254} * .07 * \tan(30)$$ **Eq. 1**

Where F is the axial force (N), T is the output torque (Nm), and D is the gear size (pitch).

The use of a sprocket differs from a gear because the pitch size relates to the diameter in a different manner. For example, a 25 tooth sprocket does not have the same diameter or pitch as a 25 tooth gear. The bottom of Eq. 1 is converting the diametrical pitch into the module or modulus. In other words the imperial unit of a gear is converted into a similar unit for metric gears. The modulus is described by Eq. 2.

$$m = \frac{p}{\pi} \qquad \text{Eq. 2}$$

Where m is the modulus and p is the circular pitch (distance between teeth) in mm.

The best way to convert this for a chain is to use the chain pitch and convert it into mm. For our chain the pitch is 0.5 [in] or 12.7 [mm], which results in a modulus of 4.045. Substituting this value for D*.00254 and the nominal output torque of 16.55 [Nm] in Eq. 1 results in a force of 0.33 [N]. This is well below the dynamic rating of 20 [N] and thus our motor should be unharmed during operation.

The final design parameters of the harmonic drive and motor combination are presented in TABLE XI.

TABLE XI: FINAL DESIGN PARAMETERS FOR MOTOR

Property	Value
Nominal Motor Speed	4300 rpm
Nominal HD Output Speed	86 rpm
Max Motor Speed	10000 rpm
Max HD Output Speed	200 rpm
Nominal Motor Torque	331 mNm
Nominal Output Torque	16.55 Nm

3.1.2 Drive and Idler Shaft Design

The drive system consists of two different shafts, a drive shaft and idler shaft, both of which interface with the main frame and paddle drives. The shaft designs are shown in Figure 5 and Figure 6.

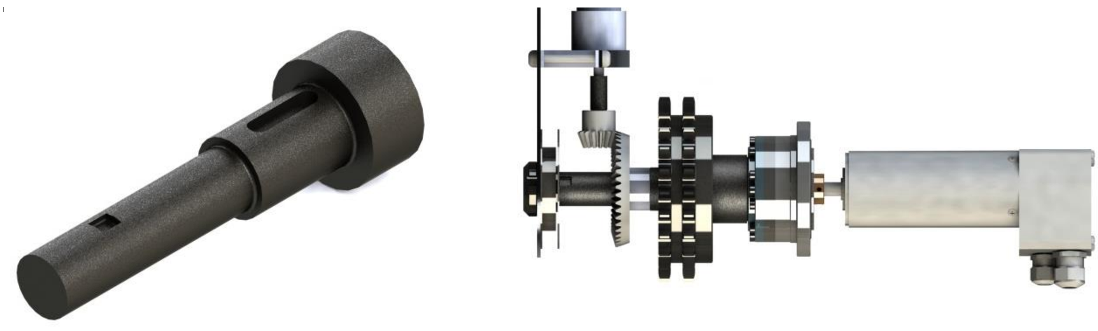


Figure 5: Main drive shaft design.

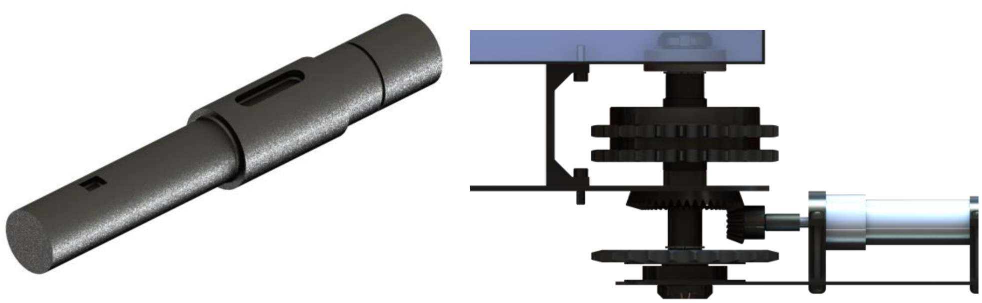


Figure 6: Idler shaft design.

The motor is mounted to the frame using two brackets, one at the rear and one at the shaft face. The motor shaft inserts directly to the harmonic drive and is secured using two set screws. The harmonic drive then mounts the shaft using six M5 bolts. The drive sprocket is secured to the shaft using a keyed taper lock bushing and a shoulder. A needle bearing is then used to locate the cover plate, and ring gear for the paddle actuation. Finally a single sprocket is mounted using a keyway, bearing and shaft collar. Figure 7 details this assembly with an exploded view.

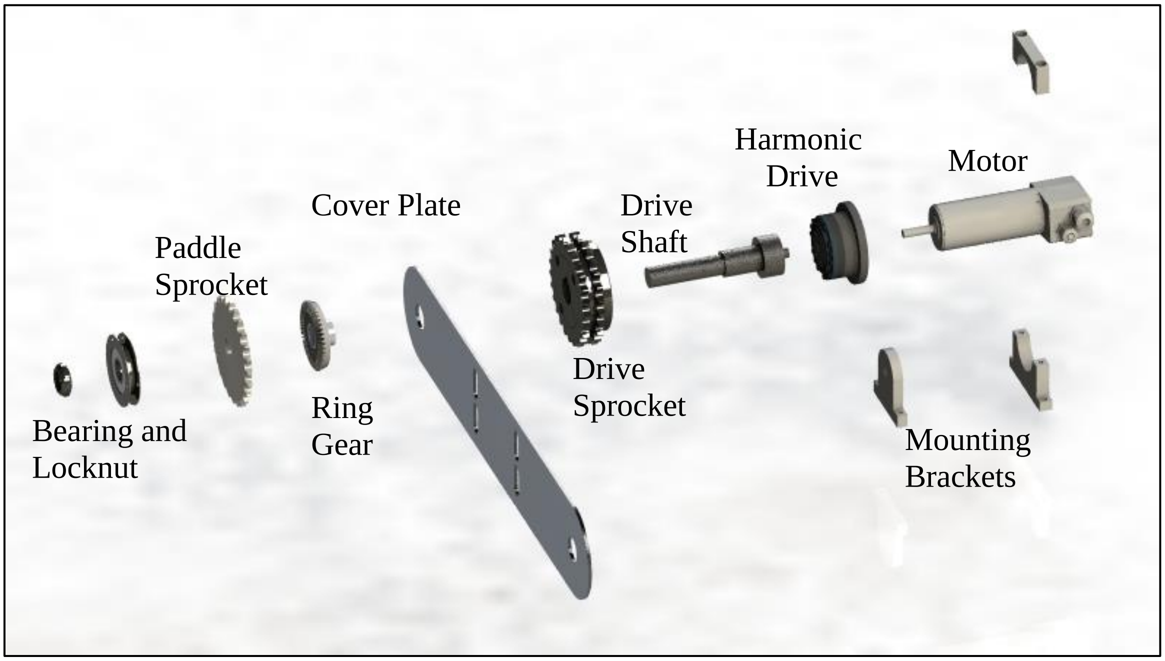


Figure 7: Exploded view of the shaft design.

Both shafts were analyzed as beams in bending with a fully reversed loading scenario. A fully reversed loading scenario is used when a shaft is in constant operation because the bending force acts first on one side of the shaft, then the other through rotation. This loading scenario will result in a more conservatively sized shaft than the actual sporadic loading scenario. Using a fully reversed loading scenario is favorable for the life of the component compared to a more accurate estimate of the starts and stops in a competition round.

Using the methods presenting in Chapter 12 of the [9], the shaft was analyzed to determine the minimum diameters in each section. For the shaft, a 4130 normalized steel rod with material properties determined from the supplier Online Metals will be used. Figure 8 shows the general layout of the drive shaft and idler shaft.

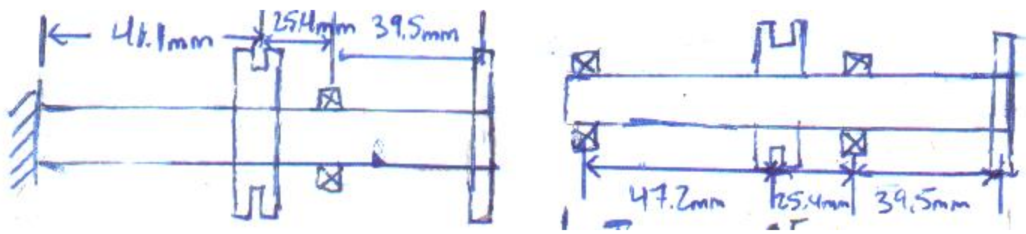


Figure 8: Layout of the drive (left) and idler (right) shafts.

The average torque expected to be output from the harmonic drive is 16.55 [Nm]. This torque occurs when the motor is operating at nominal rpm and torque, which are specified as the maximum continuous operating values for torque and rpm. It is recommended the drive not be operated continuously above this limit. As a result, the nominal output torque of the harmonic drive was used for the torque loading of the drive. This resulting tension force acting on the chain is 163.34 [N]. Figure 9 shows the free body diagram for the two different shafts.

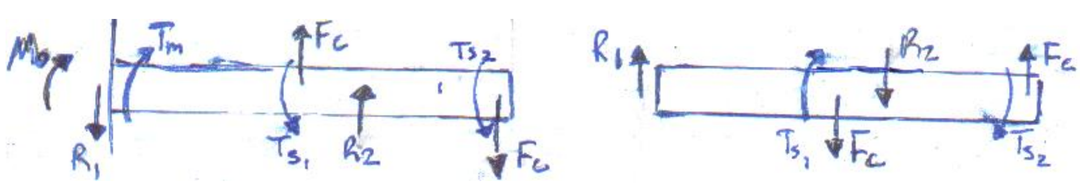


Figure 9: Free body diagram of the drive (left) and idler (right) shafts.

From these diagrams, the shear and bending moment diagrams were produced. Appendix B has the full details of the calculations used to determine the shear and bending moments. Figure 10 shows the shear force diagrams of the drive and idler shafts.

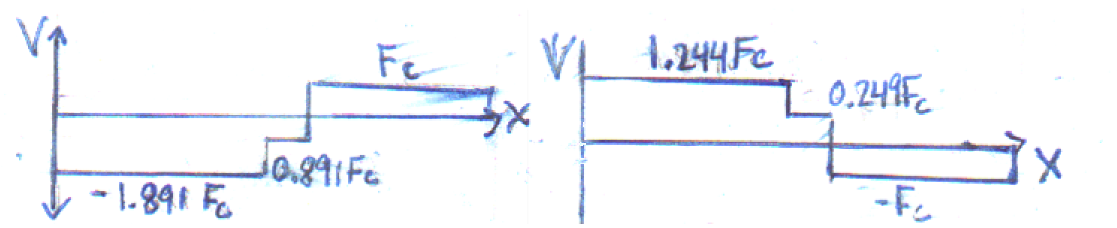


Figure 10: Shear force diagrams for the drive (left) and idler (right) shafts.

Figure 11 shows the shear force diagrams of the drive and idler shafts.

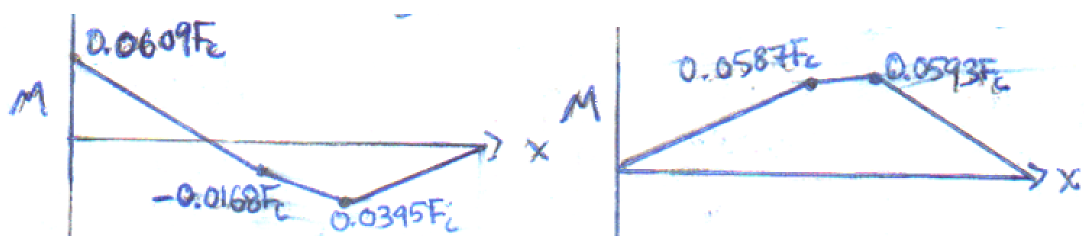


Figure 11: Bending moment diagrams for the drive (left) and idler (right) shafts.

For a shaft in fully reversed bending loads the minimum diameter can be determined using Eq.3.

$$D = \left[\frac{32N}{\pi}\sqrt{\left(\frac{k_t M}{Sn'}\right)^2 + \frac{3}{4} * \left(\frac{T}{S_y}\right)^2}\right]^{\frac{1}{3}} \qquad \textbf{Eq.3}$$

The design factor N was chosen as 2.0 due to this being a predictable loading scenario with minimal uncertainties. The factor k_t is dependent upon the stress concentrations in the separate sections of the shaft. Variables M and T are the bending moment and torque in a section of the shaft. S_n' and S_y are the modified endurance strength and yield strength of the material.

TABLE XII contains the various k_t factors used.

TABLE XII: STRESS CONCENTRATION FACTORS FOR A SHAFT.

Shaft Item	k_t
Retaining Ring Groove	3.0
Sharp Fillet	~2.5 (Dependent upon Diameter)
Well Rounded Fillet	~1.5 (Dependent upon Diameter)
Keyways	2.0

The stress concentration factors for a shaft can be determined using the graph in Figure 12 from [9].

Figure 12: Stress concentration factor (k_t) for a stepped round shaft.

Stress concentration factors for the radius were initially assumed to be the values in TABLE XII for a sharp fillet. Sn' can be calculated by applying modified factors for size, material, loading scenario and reliability to the endurance strength of 4130 normalized steel rod. The ultimate and yield strength of 4130 normalized steel is 97.2 [ksi] and 63.1 [ksi] respectively. The endurance limit was determined using the ultimate strength and Figure 13 taken from [9].

Figure 13: Endurance strength (S_n) vs Tensile strength (S_u) for wrought steel.

Material, size, loading, and reliability factors were applied to the endurance stress to get the adjusted endurance strength for this application. TABLE XIII summarizes the values found.

TABLE XIII: VALUES USED TO DETERMINE THE ENDURANCE LIMIT.

Variable	Value
S_u	97.2 ksi
S_y	67.1 ksi
S_n	37.5 ksi
C_m	1.00
C_s	0.88
C_{st}	1.0
C_r	0.81
S_n'	**26.61 ksi**

Using Eq.3 and the values in TABLE XIII the minimum diameters of the shaft were determined. TABLE XIV shows the minimum diameters useable for the shaft not to fail due to fatigue.

TABLE XIV: MINIMUM SHAFT DIAMETERS.

Section	Min. Drive Shaft Diameter	Min. Idler Shaft Diameter
1	15mm	11mm
2	13mm	15mm
3	13mm	15mm

To mount the proper components to the harmonic drive and to the sprockets, larger diameters were chosen. Choosing a larger diameter will mean the shaft is over designed, but this can also help account for any uncertainties in the loading scenario such as the speed required to machine the shaft. The k_t factors for the fillet radii must also be recalculated. A sharp fillet was chosen between the three diameters with a minimum value of 1mm and the allowable radius can be determined using Figure 12. TABLE XV shows the final shaft diameters and allowable fillet radii.

TABLE XV: CHOSEN SHAFT DIAMETERS.

Section	Min. Drive Shaft Diameter	Min Fillet Radii	Min. Idler Shaft Diameter	Allowable Fillet Radi
1	40mm	--	22.225mm (7/8in)	.5mm
2	25.4mm (1in)	.889mm	25.4mm (1in)	--
3	20mm	0.5mm	20mm	0.5mm

The allowable fillet radii are below the machining minimum of 1 [mm], so setting a fillet radii of 1 [mm] will create a lower stress concentration than already anticipated.

3.2 Main Tracks

The main track design consists of an ANSI 40-2 chain with bent link attachments which is driven by the main drive motor. The bent link attachments allow for traction pads to be mounted to the robot. Figure 14 shows the bent link chain, and how the traction pads will attach to it.

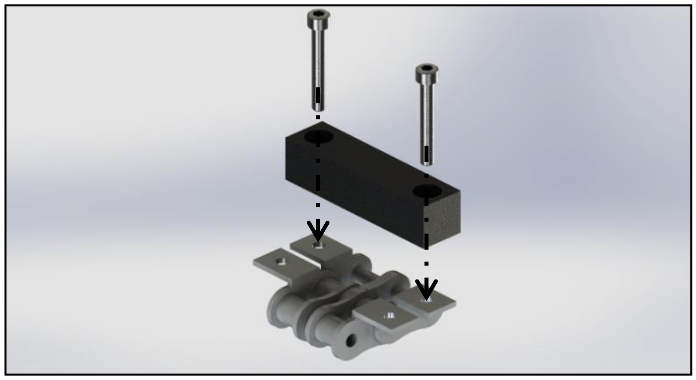


Figure 14: Chain and traction pad assembly.

It will be possible to switch this material in and out, depending on the robot traction needs. The chain is driven by a 25 tooth drive sprocket mounted to the drive shaft using a taper lock bushing and a keyway. There is a second 25 tooth taper lock sprocket mounted on an idler shaft at the front end of the vehicle. The side of the track has a ball bearing attached to a cover plate to prevent debris or parts from getting in to the chain system. A chain tensioner is also integrated in to the design to allow for adjustments of the tension depending on conditions. The main track design can be seen in Figure 15.

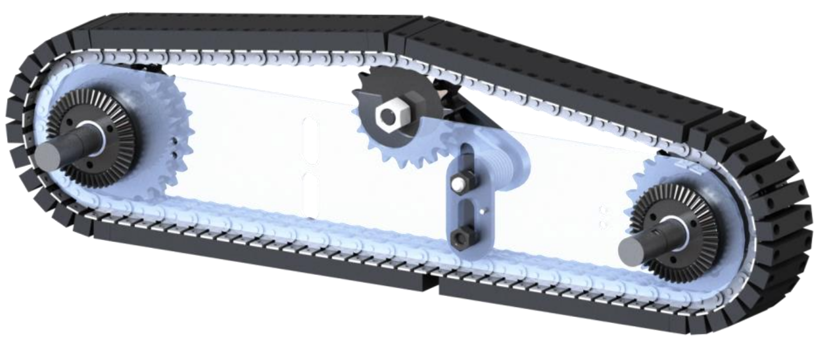


Figure 15: Render of the main track assembly.

Different materials were considered for the tread, based upon providing the maximum amount of friction, while maintaining durability over the lifetime of the robot. TABLE XVI lists the materials considered and their mechanical properties.

TABLE XVI: MECHANICAL PROPERTIES OF RUBBERS FOR TRACTION.

Material	Shore A Hardness	Tensile Strength (psi)	Coefficient of Friction
EPDM Seal	60	3625	0.55
NBR	70	1200	2.21
Polyurethane 1	40	850	0.97
Polyurethane 2	60	3000	0.80
Polyurethane 3	90	5500	0.70
FKM	75	1000	1.30

The Shore A hardness scale can be related to the following reference materials in TABLE XVII.

TABLE XVII: SHORE A HARDNESS SCALE REFERENCE MATERIALS.

Shore A Hardness	Material
25	Rubber Band
55	Door Seal
70	Automotive Tire Tread
78	Soft Wheels of roller skates/skateboards
70 – 90	Hydraulic O – rings
100	Hard Wheels of roller skates/skateboards

The NBR material was chosen for its high coefficient of static friction coupled with a fair Shore A hardness. It will operate similar to a tire tread covering the entire track of the robot. This material has fair abrasion resistance, oil resistance and weather resistance making it a viable choice for tread material. However, the design of the tread is modular such that if UMSATS wishing to experiment with other tread materials and configurations, it is possible to do so.

The chain tensioner was custom designed because off the shelf options proved to be too large and difficult to integrate into the design. The chain tensioner design is seen in Figure 16.

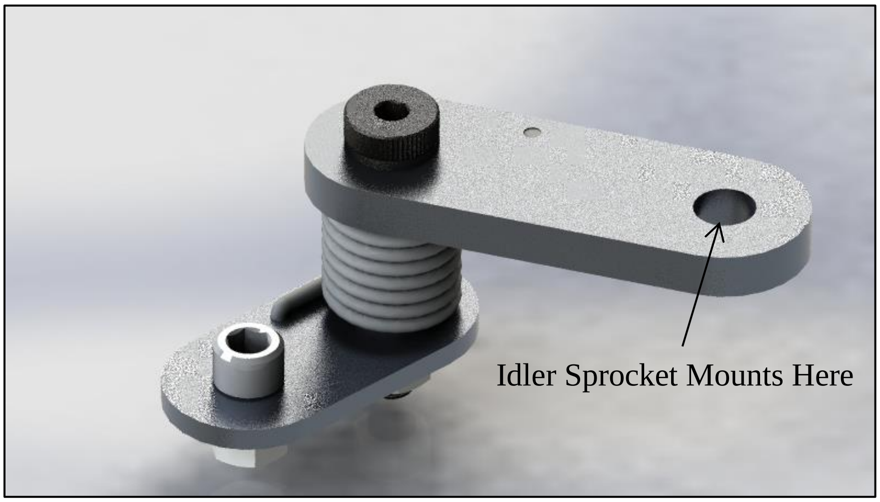


Figure 16: Chain tensioner design.

The tensioner consists of two laser cut aluminum 6061 – T6 arms, a 120 [°] torsion spring made of music wire, wrapped around a dry running plastic bushing and a shoulder bolt. The torsion spring is capable of holding up to 44.36 [lbs-in] of torque before the arms deflect to fully parallel. The determined force in the chain was 163.34 [N] or 36.73 [lbf]. The tensioner arm is at a 60 [°] angle to the chain drive if it is running flat. Figure 17 shows the loading scenario of the chain tensioner at the lowest point it can be mounted vertically.

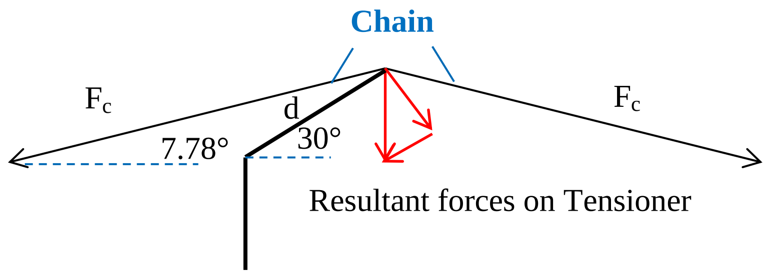


Figure 17: Loading scenario of the chain tensioner.

Where F_c is the chain tension, and the length of the arm is denoted by d. Figure 17 was used to determine the resultant force on the tensioner and was calculated using Eq. 4.

$$F_{tens} = 2 * \sin(7.78) * F_c \qquad \textbf{Eq. 4}$$

The forces acting perpendicular to the tensioner arm and the subsequent moment acting on the spring are determined using Eq. 5.

$$M = F_{\perp} * d = F_{tens} * \cos(30) * d \qquad \textbf{Eq. 5}$$

Where $F_{\perp}$ is the perpendicular force to the arm.

The moment determined cannot exceed the moment the spring is capable of handle, but of more importance was to ensure the spring would not deflect greater than 30 [°]. Eq. 6 for helical torsion springs from Chapter 19 of Machine elements in Mechanical Design is used to determine the angular deflection.

$$\theta = \frac{10.2 * M * D_m * N_a}{E * D_w^4} \qquad \textbf{Eq. 6}$$

Theta is the angle the spring deflects through in [rad], M is the applied moment, D_m is the mean diameter of the coils, N_a is the number of coils, E is Young's Modulus of the material and D_w is the wire diameter.

Using the values presented in TABLE XVIII the angle of deflection was found to be less than 30 [°]. This means the spring will support the chain and add tension to the assembly.

TABLE XVIII: TENSIONER CALCULATED RESULTS

Variable	Calculated Value
$\mathbf{F_c}$	36.73 lbs
d	2.75 in
$\mathbf{F_{tens}}$	9.94 lbs
M	23.68 lbf-in
$\mathbf{D_m}$	0.989 in
$\mathbf{N_a}$	7.17
E	29,000 ksi
$\mathbf{D_w}$	0.135 in
θ	**10.19°**

The tensioner is mounted to the cover plate of the main tracks using two bolts and can be adjusted upwards by 20 [mm] to add tension to the chain as it wears from use.

3.3 Paddle Tracks

The primary purpose of the paddle tracks is to allow the robot to climb and traverse obstacles of a greater height than the main tracks alone would allow. They can also be used to raise the body of the robot, to allow more ground clearance when required.

Each paddle features a track similar to the main tracks, made from a single strand ANSI 40 chain and 25 tooth sprockets. However, the paddles are shorter than the main tracks, with a sprocket center to center distance of approximately 250 [mm]. This distance can be adjusted to tension the chain, through the use of two slots in the frame, where the two frame sections are fastened together. The sprockets are mounted to the two-piece paddle frame with spherical ball bearings pressed into mounting flanges. Drive torque is provided via a driveshaft from the main track drive system, powering the inboard sprocket of each paddle. The paddle drive system is illustrated in Figure 18, Figure 19 and Figure 20.

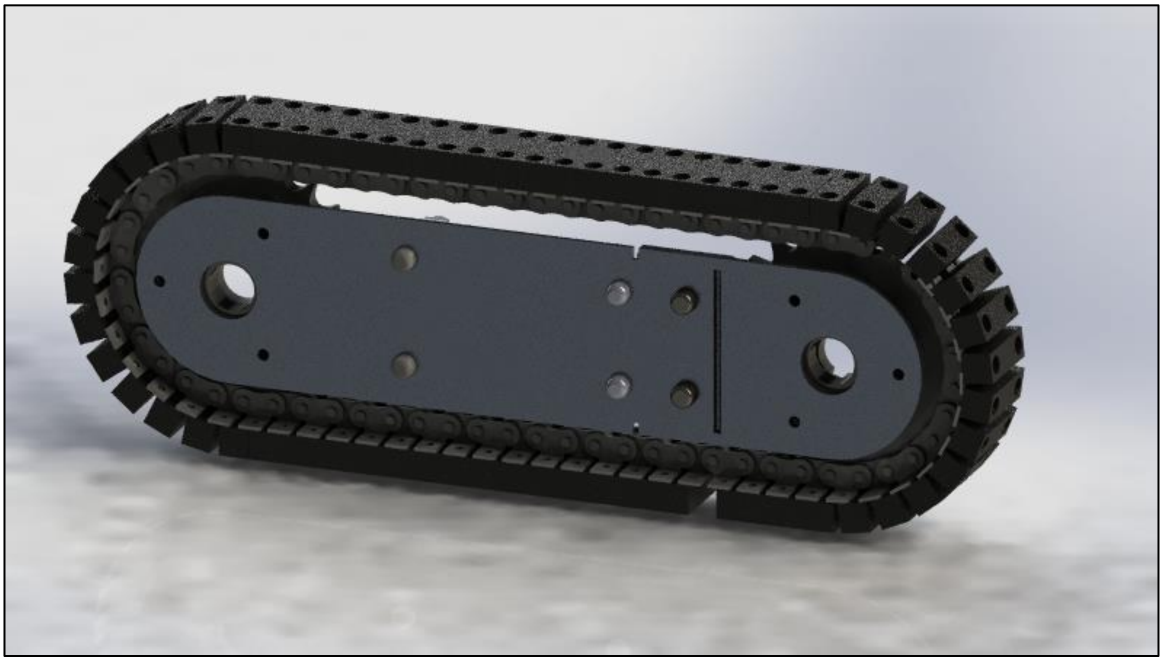


Figure 18: Layout of paddle frame with track installed.

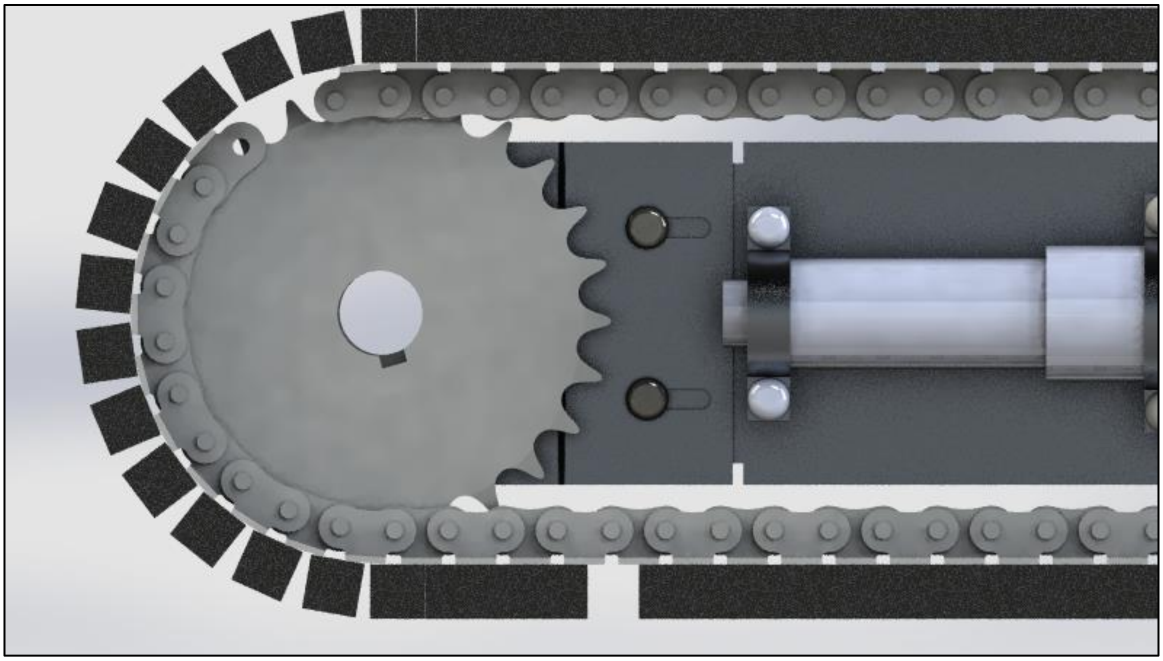


Figure 19: Paddle track chain tensioner.

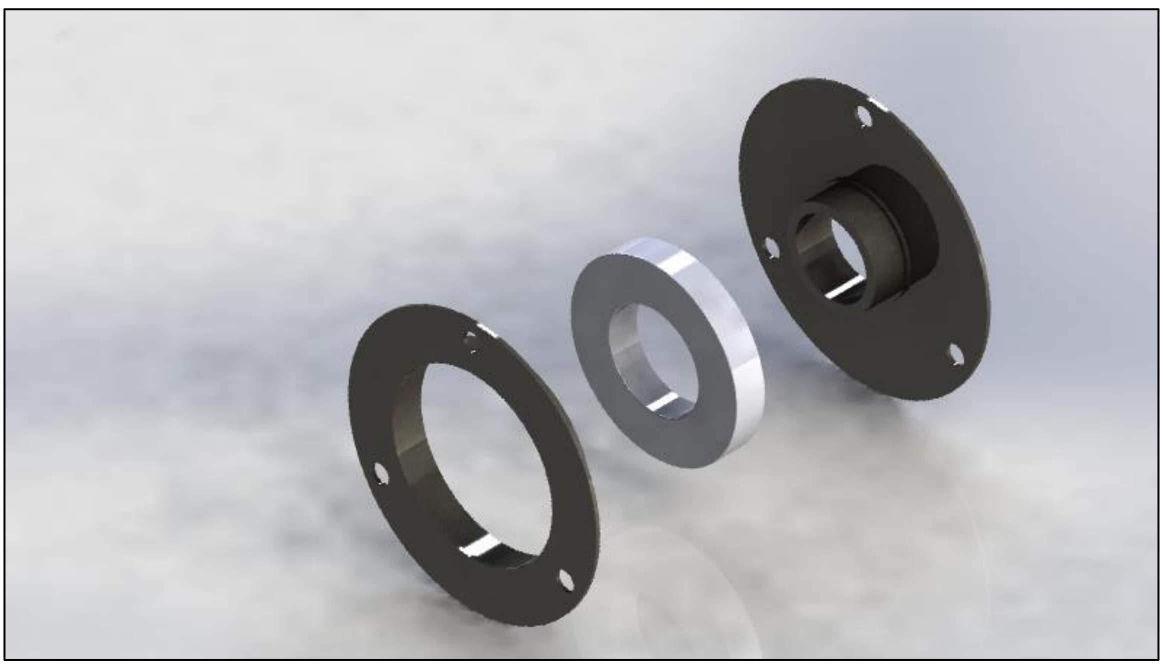


Figure 20: Sprocket bearing and mounting flanges.

The paddle tracks must also include a means to rotate the paddle assembly about the axis of the driveshaft. This design aspect proved to be somewhat challenging, as extra motors would be required to rotate the paddles, operating independently of the main drive motors. Since the paddle must rotate about the axis of the driveshaft, it was not possible to mount another motor directly in the axis of rotation. A beveled ring and pinion gear were chosen due to the compact profile, with the ring gear surrounding the driveshaft, and fixed to the side plate of the main track assembly. An additional bearing would be required in the center of the ring gear, to provide support for the driveshaft. For packaging reasons, a low profile needle roller bearing was selected for this location. As well, extra frame supports were added to support the cover plate from the axial load. The ring gear layout is illustrated in Figure 21.

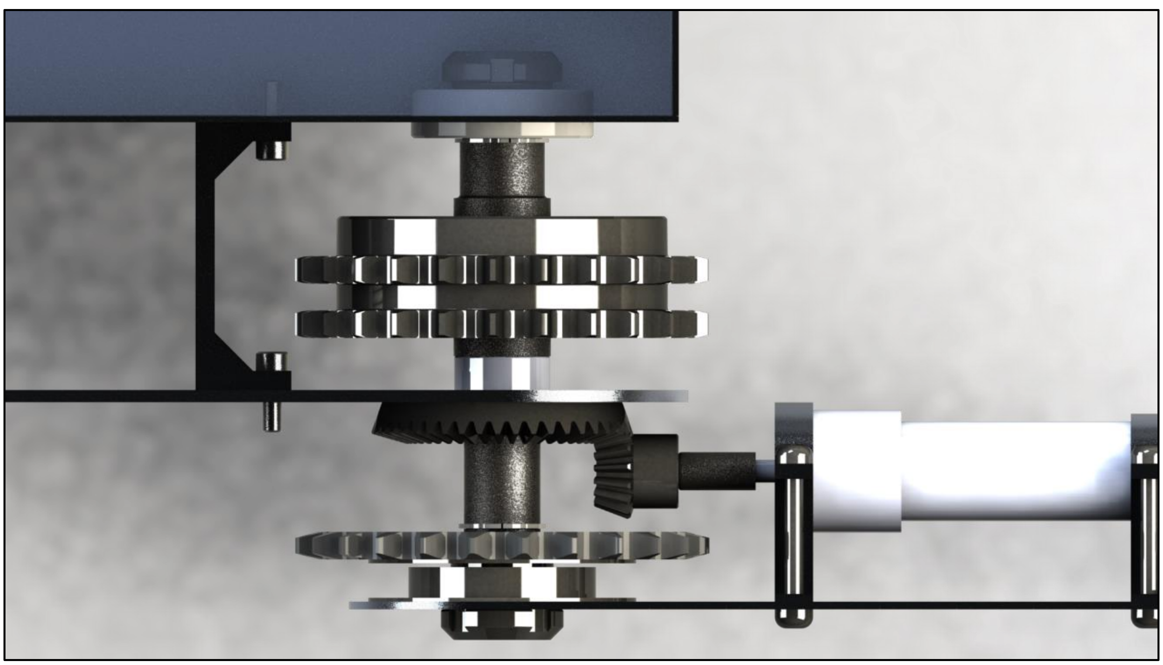


Figure 21: Ring gear mechanism for paddle rotation.

The motor required to rotate the paddle was determined based on the torque required for a ‘worst case’ scenario with all paddles extended fully outward, and one pair of adjacent paddles (front or rear) used to lift the full weight of the robot off the ground. This scenario assumed that the center of gravity (CG) was located in the longitudinal center of the robot, and that the robot was sitting on level ground. This is illustrated in Figure 22.

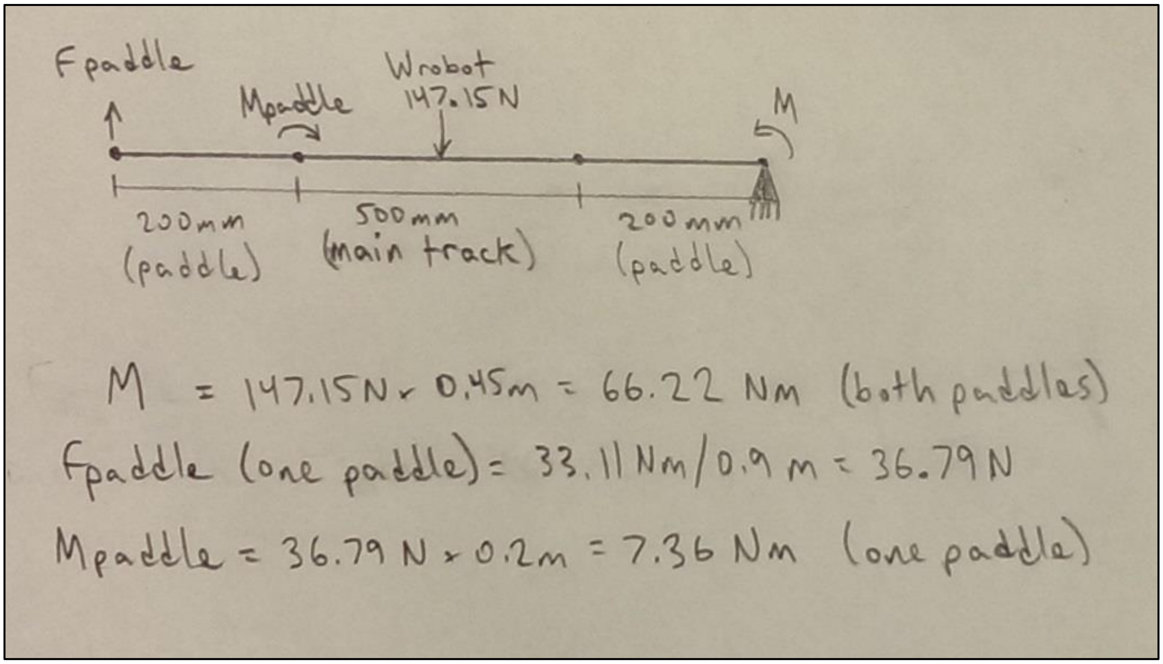


Figure 22: Initial calculations for required paddle rotation motor torque.

For the initial calculations, the robot weight was estimated to be 15 [kg], with center to center track distances of 500 [mm] for the main track, and 200 [mm] for the paddles. Based on initial calculations it was determined that a torque of 14.72 [Nm] would be required between the pair of paddle motors, or 7.36 [Nm] per paddle. The ring and pinion gears provide a 3:1 reduction, requiring a minimum torque output of 2.45 [Nm] from the motor. Since Maxon motors were used for the main drive motors, the paddle motors were also sourced from this supplier. Due to the torque requirements, a 40 [W] motor was selected. With the use of a higher motor gear reduction a 20-25 [W] model could have been used. However, the higher reduction gearbox would increase cost and weight.

Once the initial CAD models were created, the vehicle weight was found to be significantly higher than expected, with a calculated weight of 25 [kg]. The design was also modified slightly, extending the original paddle center to center distance from 200 [mm] to 250 [mm]. This required recalculation of the torque requirements. Using the same procedure as before, the new design would require a minimum torque output of 5.11 [Nm] at the motor output.

One advantage of using Maxon motors is that they offer several gearboxes, which are compatible with a particular motor design. The same 40 [W] motor could still be used in the redesigned configuration, although the higher reduction gearbox would slightly increase the overall size and cost of the motor assembly. The initial design used a 35:1 planetary gearbox. However, the next higher reduction available increased this to a 231:1 ratio. This new gearbox provides well more than the required torque, with a maximum theoretical output of 13.35 [Nm] per motor available at the gearbox output shaft.

The manufacturer specs state that this gearbox is rated for 6.6 [Nm] continuous torque, or 8 [Nm] intermittent torque. Since the paddles are not operated continuously, the intermittent values were used. However, this will still require that the motor’s torque be limited to 60% of its maximum output to avoid gearbox failure. This can be accomplished with the motor controller, by limiting maximum amperage to the motor during operation. Alternately, the supplier might offer a less powerful motor, which could be geared to provide the same torque output at the expense of rotational speed. Due to time constraints, this option was not explored, but could be considered for future design iterations.

3.4 Battery Mounting System

The battery mounting system consists of six metal brackets that are fixed within the frame through the use of fasteners. They are spaced in a rectangular arrangement that fits firmly around the shape of the battery. This prevents the battery from moving around while still allowing it to be easily installed and removed. There are two brackets equally spaced along the long sides of the battery and one centered on each of the short sides. The layout is illustrated in Figure 23.

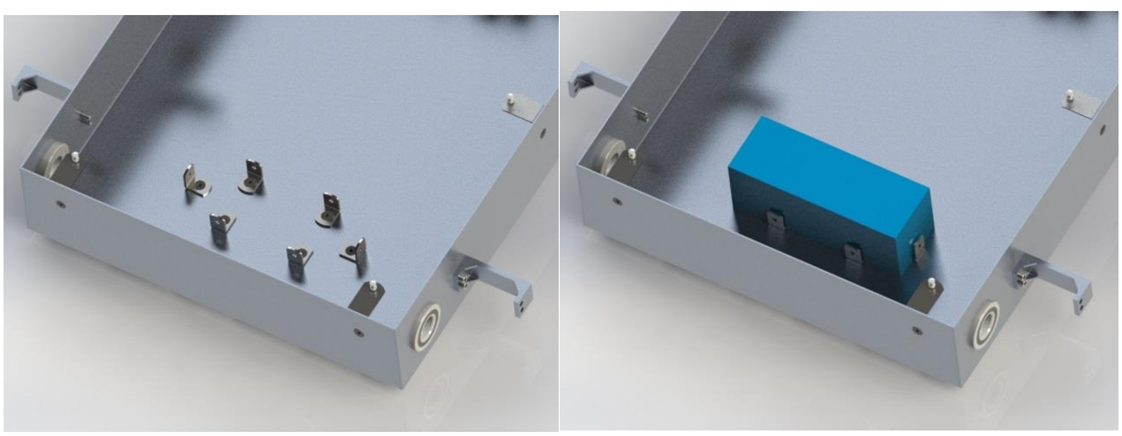


Figure 23: Battery Mounting Brackets without (left) and with battery (right).

As the robot is required to ascend and descend various obstacles, there is a chance the battery could fall out of the brackets. In order to solve this problem two, one inch Velcro strips are placed over top of the battery and secured underneath the brackets along the long side of the battery. This will hold the battery down and prevent it from sliding out of the brackets. Two holes will be made in each Velcro strip, and the bracket fasteners will be placed through these holes before being secured to the frame. This is illustrated in Figure 24.

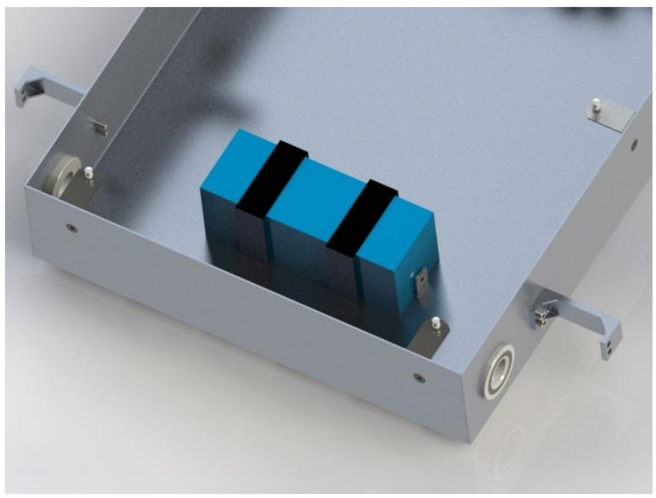


Figure 24: Full Battery Mounting System.

This combined bracket and Velcro mounting system secures the battery in place and prevents it from moving regardless of the situation. The battery is removed by simply tearing apart the Velcro strips. This enables the battery to be easily installed and removed in a matter of seconds. This design effectively meets the client requirement, which was to keep battery installation/removal time under five minutes.

3.5 Manipulator Arm and Mounts

The manipulator design must meet several different functional requirements. It must have a mounting location on the end effector for a 3D fisheye camera. The purpose of this camera is to provide video feedback to the operator, allowing them to navigate the course. As per the client's request, the camera to be used is a Bublcam, which is a 360 spherical camera that weighs 280 [g]. Along with the camera, the end effector must also have a mounting location for a laser temperature sensor, weighing approximately 200 [g].

The end effector must have the ability to access the victim locations and use the temperature sensor to detect the body heat of a victim. The victim locations are accessed through 15 [cm] diameter holes. These access holes range from 0-40 [cm], 40-80 [cm] and 80-120 [cm] elevations.

The end effector must also be capable of grasping and manipulating objects. An example of a grasping task is being able to open a door in the course to access a shortcut to more difficult areas. As many of these shortcuts will be confined spaces with roofs as low as 50 [cm], the manipulator must lie flat to the top of the frame in order to fit.

Due to time constraints, designing a manipulator arm was not feasible. Instead an off the shelf manipulator arm that met all the requirements was selected. The Lynxmotion AL5D 4 Degrees of Freedom Robotic Arm was selected. The selected manipulator is shown in Figure 25.

Figure 25: Lynxmotion AL5D 4 Degrees of Freedom Robotic Arm.

This manipulator was chosen because it meets all the functional requirements and is relatively inexpensive. The arm can reach up to a height of 48.3 [cm], and if the robot stands on its front paddles this will allow the end effector to access victim locations at all three elevations. The end effector can grip objects and rotate, allowing easy access into the course shortcuts. There is also ample room to mount the temperature sensor and Bublcam onto the end effector. This is shown in Figure 26.

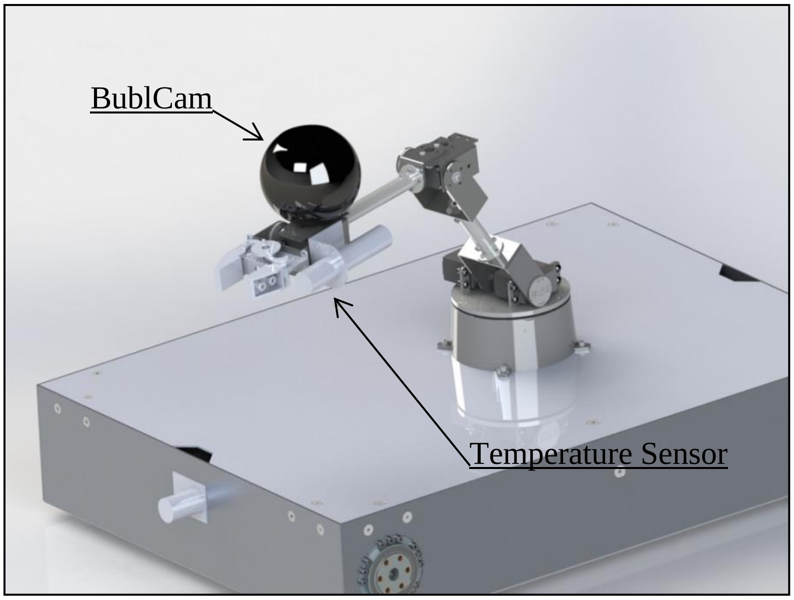


Figure 26: Manipulator with camera and temperature sensor.

The manipulator is also capable of being stowed. This is illustrated in Figure 27.

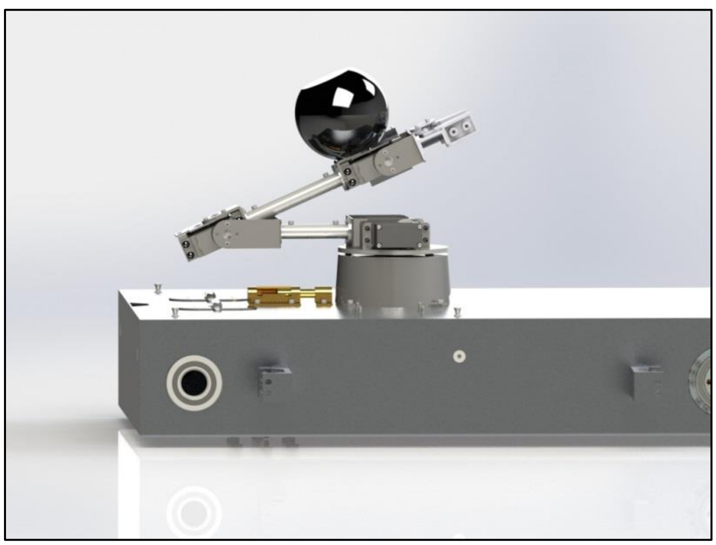


Figure 27: Manipulator Stowed.

As the manipulator must be mounted on top of the frame of the robot, there is a risk that this could cause the robot to tip over. Calculations were carried out to ensure that the location selected prevented this from happening. It was determined that mounting the manipulator three inches behind the robot's CG would provide optimal performance. Two worse case scenarios were considered in the calculations. The first case was to determine the maximum incline the robot could descend with the manipulator fully extended directly in front of it. The weight of the temperature sensor and Bublcam mounted on the end effector, were accounted for in this study. A sketch of this case is shown in Figure 28.

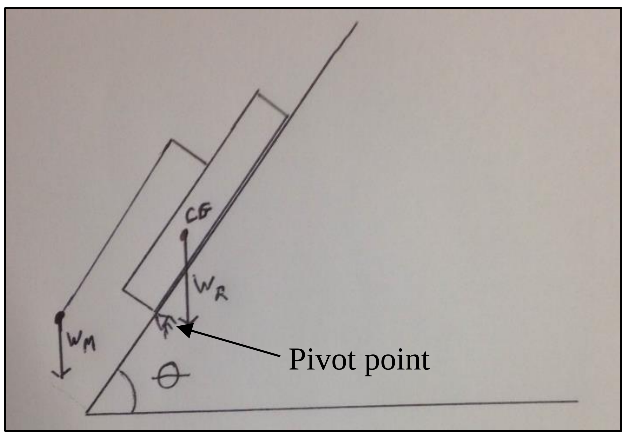


Figure 28: Maximum ramp descent tipping angle calculation.

By calculating the moment about the pivot point, it was determined that the robot could descend up to an incline of 75.4 [°] before there was any risk of tipping over. Using this angle the CG height with the loaded manipulator was calculated to be 137.97 [mm], which was then used to calculate the lateral tipping angle. This calculation is illustrated in Figure 29.

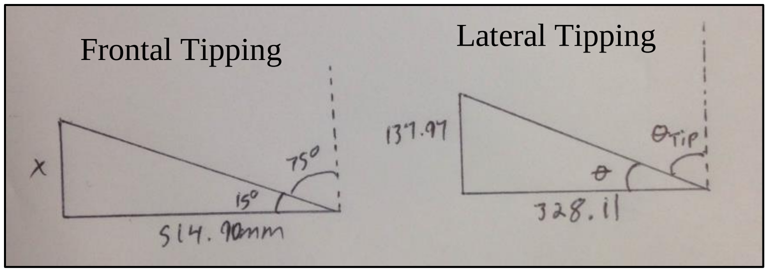


Figure 29: Calculation of Lateral Tipping Angle.

X is the CG height that was calculated using pitch tipping, and is then used in the lateral tipping calculation assuming the cg is centered on the robot frame. From this calculation the lateral tipping angle was determined to be 67.2 [°]. The second case was used to determine the magnitude of force that could be applied on the end effector before the robot would tip over on its side. The worst case scenario considered if the robot had fallen off the side of the tallest step in the course (30cm), with the manipulator fully extended out to the side. A sketch of this case is shown in Figure 30.

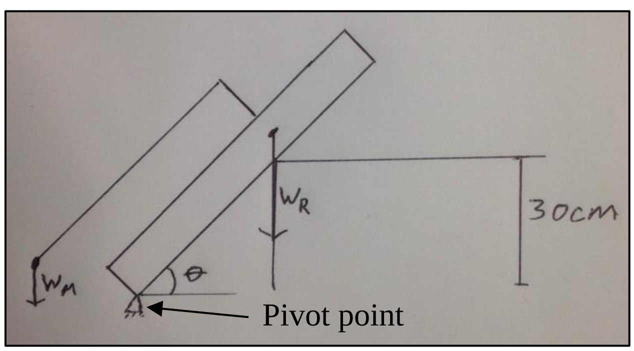


Figure 30: Maximum Lateral Loading Force Calculation.

In this scenario robot is sitting at an angle of 66.1 [°], which is below the lateral tipping angle. By calculating the moment about the pivot point, it was determined that 10 [kg] of force applied to the end effector was necessary to tip the robot over on its side. This is far greater than the total weight of the end effector, which is 0.732 [kg].

3.6 Frame and Body Design

The final frame design is manufactured out of 1/16 [in] aluminum sheet metal. The sheet metal is bent into an open rectangular box shape. This is illustrated in Figure 31.

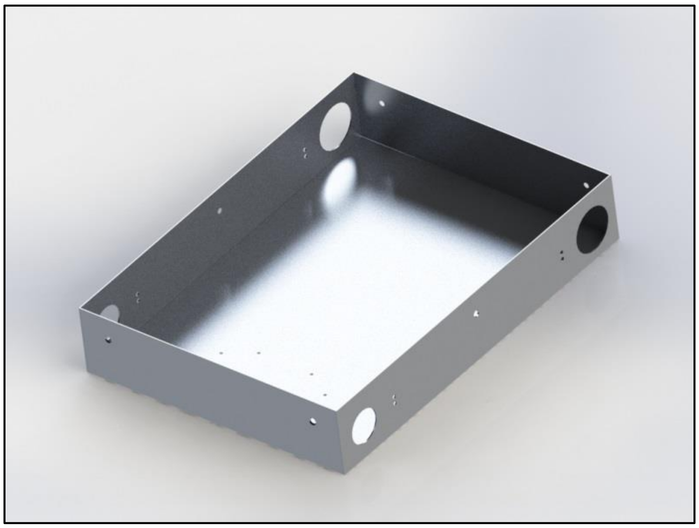


Figure 31: Frame Design.

A removable rectangular lid is placed on top of this box and is also manufactured out of aluminum sheet metal. The lid is supported by six 1.5 [in] long brackets. Two are centered on the long sides of the robot, and one is placed near each corner on the front and back sections of the frame. The lid is fastened to these brackets with the use of six captive panel screws. These panel screws consist of a plunger and a grommet. The grommet is pressed into the mounting hole on the lid and passes through the bracket underneath. The plunger is inserted into the grommet, which expands the grommet effectively fastening the lid to the bracket. This device is illustrated in Figure 32.

[redacted]

Figure 32: Illustration of a captive panel screw [10].

The lid includes a slot at the front and back to allow for easy removal. This is illustrated in Figure 33.

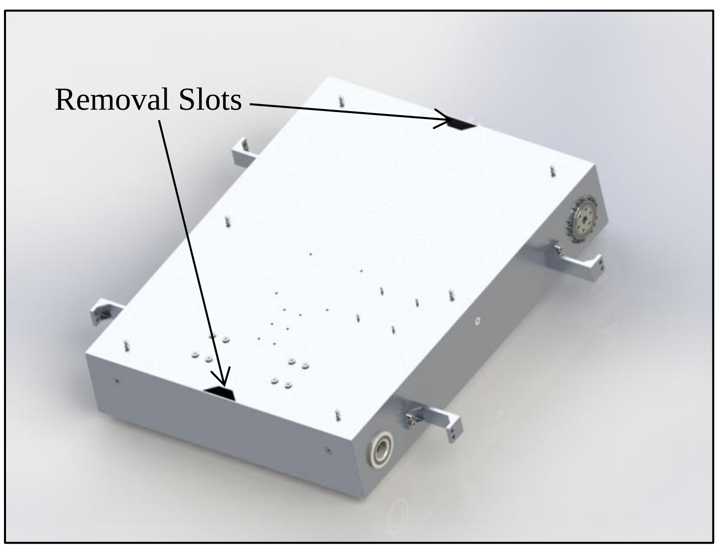


Figure 33: Frame lid with removal slots.

The holes cut into the frame shown in Figure 31 allow the motors, driveshaft and harmonic drives to connect to the main track assembly. Each motor is held in place by two-piece machined aluminum mounts that are fastened to the frame. The harmonic drives sit in the two holes located on the front sides of the frame. The drives are also supported by a machined aluminum bracket fastened within the frame. These mounts are illustrated in Figure 34.

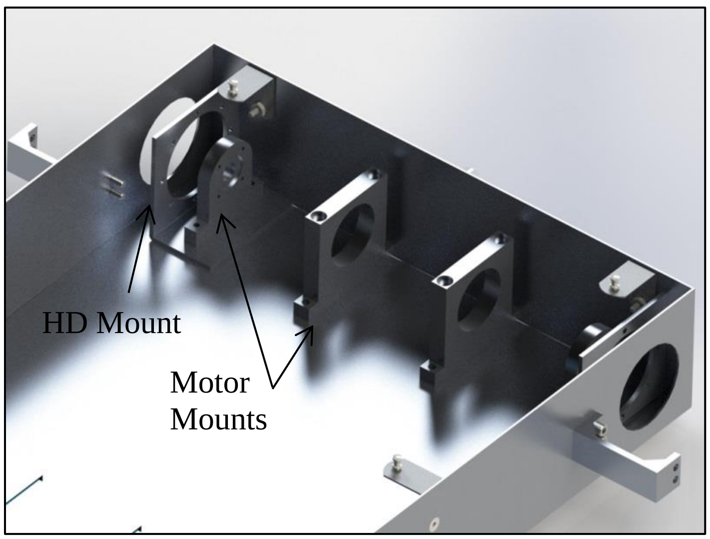


Figure 34: Motor and Harmonic Drive Mounts

There are also several electronic components fastened to the frame, this includes the motor controller, CO_2 sensor and scanning laser rangefinder. The motor controller is centered within the frame and is mounted directly above the battery. The CO_2 sensor is centered and mounted on the outer front side of the frame. The rangefinder is mounted on top of the frame and is located to the right of the manipulator base. This ensures that it will not obstruct the manipulator's movement.

One challenge with this frame design is being able to access the battery for quick installation and removal. Removing all of the fasteners in order take off the lid is will add significant time to the process. There is the issue of having wires running through the lid to the manipulator and rangefinder. In order to overcome these obstacles a battery access door was implemented into the frame. The battery access door is slightly larger than the size of the battery and is placed directly over the battery mounting location within the frame. The bottom side of the door is fastened to the frame by two hinges and the top latches to the frame with the use of a sliding bolt latch. This access door is illustrated in Figure 35.

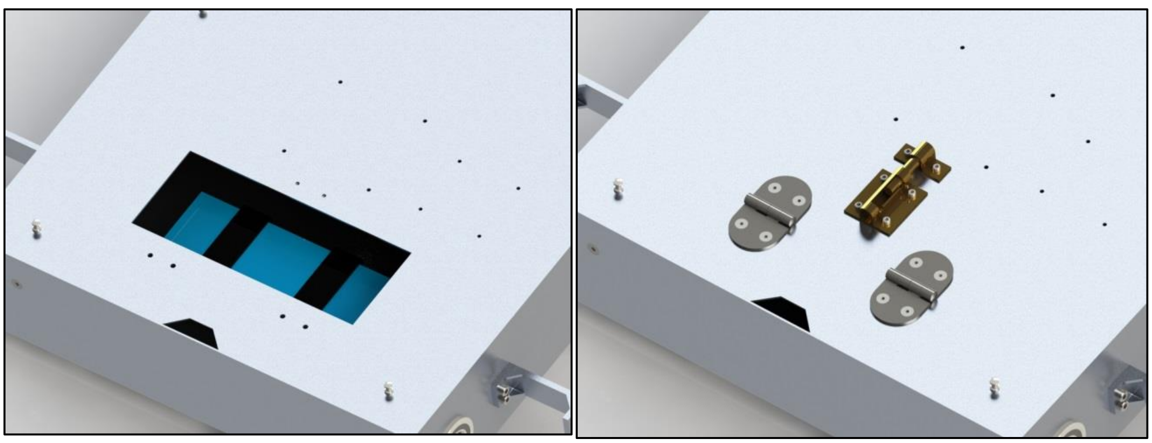


Figure 35: Battery Access Door

One challenge this design could face is excessive vibration. To prevent this, rubber pads can be placed under the two front corners and the female latching component would be elevated at an angle to ensure consistent latching.

3.7 Summary of Design

The final design consists of a five subsystem assembly including the frame, main track, paddle tracks, manipulator and main drive systems. A full Solidworks model was created and will be provided to the client upon completion of the course. A full set of engineering drawings for the manufactured parts can be found in Appendix C.

The design features two main 250 [W] 24 VDC Maxon 136207 drive motors mated to a 50:1 harmonic drive gear reduction. The harmonic drives are mounted near the front of the frame, with each one driving one side of the robot in a skid-steer configuration. Each paddle track is rotated by a 40 [W] 24 VDC Maxon DCX26L motor mated to a planetary gearbox with a 231:1 reduction. These are mounted inside each paddle assembly. The paddle motors rotate the paddle via a 3:1 ring and pinion drive, with the ring gear attached to the frame.

The selected manipulator arm provides mounting points for a spherical BublCam optical camera and a laser thermal sensor. Due to time constraints, the team was unable to design a manipulator in house, however an off-the-shelf Lynxmotion AL5D 4-axis manipulator was determined to be sufficient for the design, and was chosen for use on the robot.

The entire robot is powered by a 24 [V] 400 Wh LiPo battery pack, mounted in a quick change battery case. The battery will provide adequate power for an entire 30 minute competition round, with the ability to quickly swap in another fully charged battery pack within a few minutes, between rounds.

4 Vehicle Performance

The vehicles performance was estimated after the completion of the design. The CG of the robot was determined for a paddle up, paddle down, manipulator stowed and manipulator extended configurations. The vertical location of the CG is measure from the ground plane or bottom of the treads of the robot. The horizontal plane CG location is measured from the geometric center of the vehicle. Figure 36 shows the location of the center of gravity within the robot.

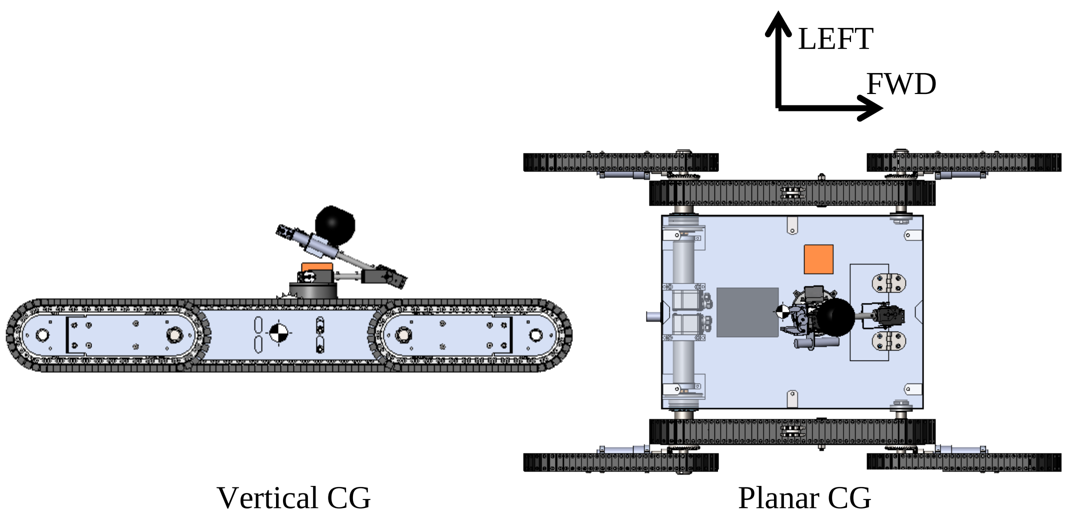


Figure 36: Vertical and Planar CG locations.

The maximum inclines traversable were determined using the CG information. The vehicle length, height, weight, CG location, and maximum inclines traversable for different configurations are presented in TABLE XIX

TABLE XIX: PERFORMANCE VALUE FOR THE FINAL DESIGN.

Metric	Configuration	Value	Units
Vehicle length	Paddles Flat	1113	[mm]
Vehicle length	Paddles Raised	594	[mm]
Vehicle width	All	676	[mm]
Vehicle height	Manipulator Stowed	319	[mm]
Vehicle height	Manipulator Raised	571	[mm]
Vehicle weight	All	25.7	[kg]
Max Vertical CG	Paddles Up, Manipulator Raised	121	[mm]
Min Vertical CG	Paddles Down, Manipulator Stowed	76	[mm]
Planar CG Location	Paddles Down, Manipulator Stowed	20 back 0 left	[mm]
Max traversable incline, longitudinal forward (w/o manipulator)	Paddles Down, Manipulator Stowed	82	[°]
Max traversable incline, lateral (w/o manipulator)	Paddles Down, Manipulator Stowed	78	[°]
Max speed on level ground (est.)	Paddles Down, Manipulator stowed	79.8	[m/min]

4.1 Comparison to Technical Specifications

The actual performance values of the vehicle were compared with the technical specifications set in Section 1.2. TABLE XX shows the relationships between the technical specifications and actual values. A green cell is a met specification, red is unmet, and yellow is the estimated performance for a specification that requires further testing.

TABLE XX: RELATION OF TECHNICAL SPECIFICATIONS TO ACTUALS.

Metric #	Metric	Actual Value	Marginal Value	Ideal Value	Unit
M1	Battery Installation/Removal Time	TBD	<5	<3	$[min]$
M2	Design Lifetime	≥5	>2	≥5	$[years]$
M3	Total Cost	12000	<15000	<10000	$[CAD]$
M4	Manipulator Grasping Force	TBD	>3	>5	$[lbs]$
M5	Manipulator Pulling Force	TBD	>3	>5	$[lbs]$
M6	Manipulator Lifting Force	TBD	>2	>5	$[lbs]$
M7	Ramp Incline Traversable	67	>45	60	[°]
M8	Gap Size Crossable	TBD	>20	>40	$[cm]$
M9	Hurdle Height Traversable	TBD	>20	>30	$[cm]$
M10	Stair Incline Traversable	TBD	>40	>45	[°]
M11	Continuous Pitch/Roll Ramp Speed	TBD	>10	>75	$[m/min]$
M12	Crossing Pitch/Roll Ramp Speed	TBD	>10	>50	$[m/min]$
M13	Symmetric Step Field Speed	TBD	>5	>11	$[m/min]$
M14	Sustained Forward Speed	79.8	>50	>90	$[m/min]$
M15	Sustained Reverse Speed	79.8	>30	>70	$[m/min]$
M16	Mounts Microcontroller	Yes	Yes	Yes	$[subj]$
M17	Housing Weight Capacity	TBD	>12	>20	$[kg]$
M18	Mounts Manipulator End Effector	Yes	Yes	Yes	$[subj]$

Metric #	Metric	Actual Value	Marginal Value	Ideal Value	Unit
M19	Manipulator Weight Capacity	TBD	>2	>4	$[kg]$
M20	Vehicle Width	67	<100	<50	$[cm]$
M21	Vehicle Height	29.7	<100	<40	$[cm]$
M22	Vertical Manipulator Reach	21	>40	>80	$[cm]$
M23	Manipulator Planar Reach Radius	21	>50	>60	$[cm]$
M24	Manipulator End Diameter	9	<15	<10	$[cm]$
M25	Vehicle Length	59.2	<120	<80	$[cm]$
M26	Turning Radius	TBD	<100	<50	$[cm]$
M27	Manipulator stows when not in use.	Yes	Yes	Yes	$[subj]$
M28	Manufacturable at Assentworks	Yes	Yes	Yes	$[subj]$
M29	Impact Height Withstand able	TBD	>30	>50	$[cm]$
M30	Battery Life	48	>30	>35	$[min]$

The specifications that were fully met (highlighted in green) are related to performance values that can be determined at the design stage such as length, width, height and CG.

Some metrics that were missed were the manipulator overall reach targets M22 and M23. Due to time constraints, an off-the-shelf manipulator was purchased. This manipulator did not meet the design requirements while keeping within the budget constraints. A custom manipulator design would be significantly cheaper and fit requirements of the client better. The vehicle width M20 only met the marginal metric due to the unanticipated size of the motor and harmonic drive combination. One possible way to meet this metric in the future would be use a 90° gearing option instead of the harmonic drive. This would allow the frame size to be compressed significantly as the motors could be mounted longitudinally. The sustained forward speed metric M14 only met the marginal value. This occurred due to difficulty sizing a harmonic drive to integrate with a Maxon motor. Sizing a different gearing system, possibly source from Maxon, would allow this system to meet design requirements. Finally the cost of the robot did not meet the ideal metric simply because of the team's inexperience with this type of system. Moving forward a more accurate cost estimate could be made for future design improvements or redesigns.

The specifications highlighted yellow in the table are the estimated performance by the team, but these values will need to be tested on the built robot to ensure their validity. M4 – M6 and M8 – M13 will be tested with the ASTM standards presented in Section 4.2.

4.2 Relevant Standards to Evaluate Metrics

The competition rules provide a link to relevant ASTM standards for urban search and rescue robots. ASTM subcommittee E54.08 on Operational Equipment has jurisdiction over 18 **active** standards and 13 **proposed** standards related to Urban Search and Rescue-Robotic Operations [11]. Eight of the active testing standards and three of the proposed testing standards make up a suite of standard test methods for evaluating mobility of emergency response robots. All of the active mobility testing standards are identified as technical specifications, and the ideal and marginal values for these are taken from the standards. Four of the proposed testing standards make up a suite to evaluate the manipulation of emergency response robots. Both of these testing suites have been created to evaluate the response robots capabilities but may also be used to train operators, ascertain operator proficiencies, and can be used as performance metrics for response robot subsystems. TABLE XXI and TABLE XXII show the active and proposed standards identified as relevant to our project.

TABLE XXI: RELEVANT ACTIVE ASTM STANDARDS.

Standard #	Suite	Sub-Category	Name
E2801-11 [12]	Mobility	Confined Area Obstacles	Gaps
E2802-11 [13]	Mobility	Confined Area Obstacles	Hurdles
E2803-11 [14]	Mobility	Confined Area Obstacles	Inclined Planes
E2804-11 [15]	Mobility	Confined Area Obstacles	Stairs/Landings
E2826-11 [16]	Mobility	Confined Area Terrains	Continuous Pitch/Roll Ramps
E2827-11 [17]	Mobility	Confined Area Terrains	Crossing Pitch/Roll Ramps
E2828-11 [18]	Mobility	Confined Area Terrains	Symmetric Stepfields
E2829-11 [19]	Mobility	Maneuvering Tasks	Sustained Speed

TABLE XXII: RELEVANT PROPOSED ASTM STANDARDS.

Standard #	Suite	Sub-Category	Name
WK21815 [11]	Manipulation	Grasping Dexterity Tasks in Confined Area Shelves	Open Access
WK27851 [11]	Manipulation	Directed Inspection Tasks in Confined Area Shelves	Open Access
WK27852 [11]	Manipulation	Door Opening and Traversal Tasks	N/A
WK44323 [11]	Manipulation	Heavy Lifting	Surrounding Area
WK35213 [11]	Mobility	Confined Area Terrains	Gravel
WK35214 [11]	Mobility	Confined Area Terrains	Sand
WK41553 [11]	Mobility	Confined Space Terrains	Vertical Insertion/ Retrieval Stack with Drops

The mobility suite could be used by UMSATS to validate the designs performance related to M8 – M13, and the manipulation suite could be used by UMSATS to validate the manipulator performance.

5 Bill of Materials

A bill of materials (BOM) was created during the detailed design phase to keep track of part numbers, cost of materials, and which parts were purchased or manufactured. Both BOMs list the cost, quantity and the part number. The part number was assigned using the CAD naming convention in Appendix D. The purchased materials list the supplier as well as the supplier part number, while the manufactured parts list the raw material, stock size and the machining process to be performed. The BOM was split up into the purchased materials and manufactured materials to aid readers in parsing the different information presented.

5.1 Purchased Parts

All parts that are to be purchased include information about the supplier, quantity, cost, supplier part no. and contain notes on any post processing or special ordering instructions. The total cost of all the purchased parts is $12,295.54. TABLE XXIII shows the detailed BOM for purchased parts.

TABLE XXIII: BOM FOR OFF THE SHELF COMPONENTS.

Part No	Supplier Part No	Description	Supplier	Qty.	Unit Cost ($CAD)	Total Cost ($CAD)	Notes
ME16-PAD-P001-PaddleMotorGearboxUnit-R00	DCX26L	EC Motor, 40W, 24V, Graphite Brushes, Ball Bearings	Maxon Motors	4	$285.58	$1,142.32	Motor, gearbox and encoder purchased as set
ME16-PAD-P001-PaddleMotorGearboxUnit-R00	GPX32C	gearbox, 231:1 Reduction	Maxon Motors	4	$285.84	$1,143.36	
ME16-PAD-P001-PaddleMotorGearboxUnit-R00	ENX16	EASY encoder, 1024 Impulse/Revolution	Maxon Motors	4	$108.78	$435.12	
ME16-PAD-P002-PinionGear-R00	A1C 3MYK10015	15 Tooth Pinion Bevel Gear	Stock Drive Products	4	$31.30	$125.20	
ME16-TRC-P008-RingGear-R00	A1C 3MYK10045	45 Tooth Ring Bevel Gear	Stock Drive Products	4	$105.74	$422.96	Requires modifications prior to installation (see drawings)
ME16-PAD-P009-DriveSprocket-R00	2299K33	ANSI 40 drive sprocket 25 tooth	McMaster-Carr	4	$24.34	$97.36	Requires modifications prior to installation (see drawings)
ME16-PAD-P009-DriveSprocket-R00	2299K33	ANSI 40 idler sprocket 25 tooth	McMaster-Carr	4	$24.34	$97.36	Requires modifications prior to installation (see drawings)
ME16-PAD-P003-40-2ChainInner-R00, ME16-PAD-P003-40-2ChainInner-R00	ANSI 40-2	ANSI 40 chain 33 link with B-2 Attachments	Regal	4	$9.08	$36.32	Price Estimate on McMaster Carr (Chain made to order)
ME16-TRC-P010-DriveshaftBearingNSKLM1820-R00	LM1820	20MM ID Needle Roller Bearing	NSK Canada	4	$10.31	$41.24	For driveshaft support
ME16-PAD-P103-SprocketBearingNSK16005-R00	16005	20MM ID Ball Bearing	NSK Canada	8	$10.31	$82.48	For mounting sprockets
ME16-PAD-P104-5x45FastenerSimplified-R00	39050	M5-0.8x45 mm hex cap screw	Fastenal	16	$0.40	$6.40	Motor mount to paddle frame
ME16-PAD-P102-5x14FastenerSimplified-R00	38538	M5-0.8x14 mm hex cap screw	Fastenal	24	$0.25	$5.96	Sprocket to bearing flange
ME16-PAD-P101-5x10FastenerSimplified-R00	38542	M5-0.8x10 mm hex cap screw	Fastenal	32	$0.21	$6.81	Bearing flange to frame, chain tensioner
ME16-PAD-P105-5x38FastenerSimplified-R00	31161714	M5-0.8 low profile nut (5 mm thick)	Fastenal	72	$0.12	$8.93	
ME16-FRM-P013-BatBolt-R00	91253A194	8-32 Alloy Steel Flat-Head Socket Cap Screw (Pack of 100)	McMaster-Carr	1	$12.08	$12.08	Battery access hinge, battery brackets and motor cont bolts
ME16-FRM-P014-BatNut-R00	90480A009	8-32 Low-Strength Steel Hex Nut (Pack of 100)	McMaster-Carr	1	$1.60	$1.60	Battery access hinge, battery brackets and motor cont nuts
ME16-FRM-P011-BatMountBrkt-R00	1556A24	7/8" Bracket	McMaster-Carr	6	$0.43	$2.58	Battery Mount Brackets
ME16-FRM-P008-SideMountBrkt-R00	15705A45	1.5" Bracket	McMaster-Carr	6	$0.83	$4.98	Bracket for lid mounting

ME16-FRM-P015-LidBracketBolt-R00	91263A533	10-24 Zinc-Plated Alloy Steel Flat-Head Cap Screw (Pack of 25)	McMaster-Carr	1	$6.87	$6.87	Side Bracket fasteners
ME16-FRM-P016-LidBracketNut-R00	90480A011	10-24 Low-Strength Steel Hex Nut (Pack of 100)	McMaster-Carr	1	$1.84	$1.84	Nuts for side bracket fasteners
MC16-MAN-A001-Manipulator-R00	AL5DCN-KT-32U	AL5D 4 Degrees of Freedom Robotic Arm Combo Kit	Lynxmotion	1	$414.62	$414.62	Manipulator Kit
MC16-MAN-P001-WristRotate-R00	WRU-MD	Wrist Rotate Upgrade (Medium Duty)	Lynxmotion	1	$48.63	$48.63	Manipulator Wrist Rotate Kit
MC16-MAN-P002-ServoHS422-R00	S422	HS-422 (57 oz. in.) Standard Servo	Lynxmotion	1	$12.97	$12.97	Manipulator Base Servo Motor
CD16-FRM-P004-TempSensor-R00	RAYCMLTJ	Raytek IR Temp. Sensor, 1M	Raytek	1	$402.00	$402.00	Temperature Sensor
ME16-FRM-P002-TempSensorMount-R00	XXXCIACFB	Raytek Stainless Steel Fixed Bracket	Raytek	1	$73.00	$73.00	Temperature Sensor Mounting Bracket
CD16-FRM-P003-Camera-R00	Bublcam	Bublcam	Bublcam	1	$1,069.30	$1,069.30	Bublcam
CD16-FRM-P001-CO2Sensor-R00	RB-Dfr-485	CO2 Sensor Arduino Compatible	Robotshop	1	$75.38	$75.38	CO2 sensor
CD16-FRM-P002-LaserScanner-R00	RB-Hok-06	Hokuyo UTM-30LX Scanning Laser Rangefinder	Robotshop	1	$0.00	$0.00	Hokuyo UTM-30LX Scanning Laser Rangefinder (6378.21 already purchased)
ME16-FRM-P020-ManipBolt-R00	23053	5-40 Black-Oxide Alloy Steel Socket Head Cap Screw	Fastenal	4	$0.17	$0.68	Manipulator Mount and Battery Access Hinge Screws
ME16-FRM-P021-ManipNut-R00	36016	5-40 Low-Strength Carbon Zin Plated Machine Screw Nut	Fastenal	4	$0.05	$0.20	Manipulator Mount and Battery Access Hinge Nuts
ME16-TRC-P001-40-2ChainInner-R00 ME16-TRC-P002-40-2ChainOuter-R00	ANSI 40-2 Chain 96 link with B-2 Attachments	ANSI 40-2 Chain 96 link with B-2 Attachments	Regal	2	$41.56	$83.12	Price Estimate on McMaster Carr (Chain made to order)
ME16-TRC-P006-TaperLockSprocket-R00	D40BTL25	Taper Lock Sprocket	Motion Canada	4	$97.04	$388.16	
ME16-TRC-P005-TaperLockBushing-R00	2012	Taper Lock Bushing	McMaster-Carr	4	$26.19	$104.76	
ME16-TRC-P003-Traction_Pad-R00	9028K43	6" x 36" NBR Sheet	McMaster-Carr	2	$165.38	$330.76	To be cut into 2" x .5" strips for main track tread material
ME16-TRC-P004-Idler-R00	6260K3	Idler Sprocket 1/2" Bore	McMaster-Carr	2	$90.88	$181.76	
ME16-FRM-A001-HarmonicDriveRef-R00	CSG-17-50-2UH	50 Gear Ratio Harmonic Drive	Harmonic Drive	2	$1,670.00	$3,340.00	Quote received from a sales engineer at eletromate.
ME16-TRC-P006-250WMotor-R00	136207	250W EC 45 Brushless Motor with Hall sensors	Maxon Motors	2	$824.07	$1,648.14	
ME16-TRC-P016-RH_TorsionSpring-R00	9271K643	Left Hand 120 Degree Torsion Spring	McMaster-Carr	1	$2.50	$2.50	
ME16-TRC-P016-LH_TorsionSpring-R00	9271K706	Right Hand 120 Degree Torsion Spring	McMaster-Carr	1	$2.50	$2.50	
ME16-TRC-P014-TensionerBushing-R00	6389K117	Light Duty Dry-Running Sleeve Bearing	McMaster-Carr	2	$1.10	$2.20	

ME16-TRC-P015-TensShoulderBolt-R00	91259A720	Alloy Stel Shoulder Screw 1/2" Diameter 2" Length	McMaster-Carr	2	$2.60	$5.20	
ME16-MECH-P001-ShaftCollar-R00	6343K35	M20 x 1.0 Shaft Collar	McMaster-Carr	4	$8.10	$32.40	
ME16-TRC-P017-TensionerBolt-R00	91251A622	3/8" x 1/16 3/4" length (pack of 25)	McMaster-Carr	1	$7.72	$7.72	
ME16-TRC-P018-TensionerNut-R00	94804A320	3/8" x 16 Hex Nut (package of 50)	McMaster-Carr	1	$9.37	$9.37	
ME16-MECH-P002-MainDriveKey-R00	92624A195	18-8 Steel Undersized 1/4" x 1/4" Machine Key (Pack of 10)	McMaster-Carr	1	$11.89	$11.89	
ME16-MECH-P003-PaddleKey-R00	98493A117	18-8 Steel Oversized 3/16" x 3/16" 12" length	McMaster-Carr	1	$3.80	$3.80	
ME16-FRM-P017-BatHinge-R00	1549A570	1-1/2" High, 2-3/4" Wide Surface Mount Hinge	McMaster-Carr	2	$4.62	$9.24	
ME16-FRM-P018-LidPanelScrew-R00	93040A111	0.180" Easy-to-Install Captive Panel Screw (Pack of 10)	McMaster-Carr	1	$14.23	$14.23	
ME16-FRM-P019-BatSlideBolt-R00	1441A32	1-3/4" x 1-1/2" Steel Barrel Slide Bolt	McMaster-Carr	1	$2.44	$2.44	
ME16-MECH-P004-20mm_Ret_Ring-R00	98541A123	20 MM Black-Finish Steel External Retaining Ring (Pack of 50)	McMaster-Carr	1	$10.50	$10.50	
ME16-MECH-P005-.875-Ret-Ring-R00	97633A270	7/8" Black-Finish Steel External Retaining Ring (Pack of 50)	McMaster-Carr	1	$8.58	$8.58	
ME16-TRC-P019-IdlerShaft-R00	IS500	Idler Shaft Should Stud	Brewer Tensioner	2	$8.57	$17.14	
ME16-TRC-P020-IdlerNut-R00	95036A038	1/2-20 Nut (Pack of 10)	McMaster-Carr	1	$9.80	$9.80	
ME16-FRM-P021-RangeFinderScrew-R00	1139503	M3-0.5 x 8mm Black Oxide Finish Alloy Steel Socket Cap Screw	Fastenal	4	$0.19	$0.76	Mounts range finder through frame lid
ME16-FRM-P012-BatVelcro-R00	9273K14	General purpose nylon hook and loop (velcro) (5ft length)	McMaster-Carr	1	$8.18	$8.18	
ME16-PAD-P005-Traction_Pad-R00	9028K43	6" x 36" NBR Sheet	McMaster-Carr	1	$165.38	$165.38	cut into 1 x .5 in strips
	91253A194	8-32 Alloy Steel Flat-Head Socket Cap Screw (Pack of 100)	McMaster-Carr	4	$12.08	$48.32	Mounting Traction Pads
	90480A009	8-32 Low-Strength Steel Hex Nut (Pack of 100)	McMaster-Carr	4	$1.60	$6.40	Mounting Traction Pads
ME16-FRM-P009-ShaftBearing-R00	2342K189		McMaster-Carr	2	$30.87	$61.74	
					Total Cost	**$12,295.54**	

5.2 Manufactured Parts

To determine the cost of the manufactured parts the team looked simply at the material cost and not the machining processes. The client specified that parts would be manufactured at AssentWorks by UMSATS, meaning the labour cost of machining was able to be neglected. The combined cost of all manufactured materials is $405.93. TABLE XXIV shows the BOM for manufactured parts.

TABLE XXIV: BOM CONTAINING THE MANUFACTURED PARTS.

Part No. and Description	Description	Material	Stock Size	Supplier	Mfg process(es) required	Material Quantity	Material Unit Cost	Total Cost	Notes
ME16-FRM-P001-Frame-R02	Frame Material	7075-T6	.063" x 24" x 36" Sheet	Online Metals	Laser Cutting and Bending	1	$74.68	$74.68	
ME16-FRM-P003-FrameLid-R00	Frame Lid	7075-T6	.063" x 12" x 24" Sheet	Online Metals	Laser Cutting	1	$31.69	$31.69	
ME16-TRC-D007-IdleShaft-R00	Idler Shafts	4130 normalized rod	1.625" Dia x 3' length	Online Metals	Lathing	1	$94.09	$94.09	Shares Material with Drive Shaft
ME16-TRC-D011-DriveShaft-R00	Drive Shaft	4130 normalized rod	1.625" Dia x 3' length	Online Metals	Lathing	0	$94.09	$0.00	Shares Material with Idler Shaft
ME16-TRC-D009-CoverPlate-R00	Cover Plate	6061-T6 Sheet	.19" x 12" x 12"	Online Metals	Laser Cutting	1	$23.15	$23.15	
ME16-TRC-D013-TensionerBase-R00	Tensioner Arm	6061-T6 Sheet	.375" x 8" x 8"	Online Metals	Laser Cutting	1	$16.04	$16.04	Shares Material with Tensioner Base
ME16-TRC-D012-TensionerBase-R00	Tensioner Base	6061-T6 Sheet	.375" x 8" x 8"	Online Metals	Laser Cutting	0	$16.04	$0.00	Shares Material with Tensioner Base
ME16-PAD-P010-SprocketBearingFlangeInner-R00	Inner Flange	1018 Flat Bar	.5" x 3" x 12"	Online Metals	CNC	1	$15.91	$15.91	
ME16-PAD-P011-SprocketBearingFlangeOuter-R00	Outer Flange	1018 Flat Bar	.5 x 3" x 12"	Online Metals	CNC	1	$15.91	$15.91	
ME16-PAD-P006-InnerPaddleFrame-R00	Inner Paddle Frame	6061-T6 Sheet	.08" x 12" x 12"	Online Metals	Laser Cutting	4	$10.37	$41.48	
ME16-PAD-P007-OuterPaddleFrame-R00	Outer Paddle Frame	6065 T651 Plate	.25" x 12" x 12"	Online Metals	CNC	1	$30.88	$30.88	
ME16-PAD-P008-MotorPinionAdapter-R00	Motor Pinion Adapter	4130 Normalized rod	0.4375" Dia x Random Length (10"-12")	Online Metals		1	$2.53	$2.53	
ME16-PAD-P012-MotorMountRearUpper-R00	Motor Mount Upper	6061 T651 Plate	0.5" x 0.625" x 2"	Online Metals	CNC	0.25	$21.38	$5.35	Purchase one 8" x 8" sheet for next 3
ME16-PAD-P014-MotorMountFrontUpper-R00	Motor Mount Front Upper	6062 T651 Plate	0.5" x 0.75" x 2.25"	Online Metals	CNC	0.25	$21.38	$5.35	""
ME16-PAD-P015-MotorMountFrontLower-R00	Motor Mount Front Lower	6063 T651 Plate	0.5" x 1.5" x 2.25"	Online Metals	CNC	0.25	$21.38	$5.35	""
ME16-PAD-P013-MotorMountRearLower	Motor Mount Lower	6064 T651 Plate	0.5" x 1.5" x 2.25"	Online Metals	CNC	0.25	$21.38	$5.35	""

ME16-TRC-P008-RingGear-R00	Ring Gear	Purchased	45 Tooth Ring Bevel Gear	Stock Drive Products	Vertical Band Saw	0	$105.74	$0.00	Modified Part from Purchased BOM
ME16-TRC-P003-Traction_Pad-R00	Traction Pad	Purchased	6" x 36" NBR Sheet	McMaster-Carr	Knife, Drill Press	0	$165.38	$0.00	Modified Part from Purchased BOM
ME16-FRM-P004-MotorMountBase-R00	Motor Mount Base	6061-T6 Flat Bar	.5" x 4" x 12"	Online Metals	CNC	1	$12.73	$12.73	
ME16-FRM-P005-MotorMountTop-R00	Motor Mount Top	6061-T6 Flat Bar	.5" x 4" x 12"	Online Metals	CNC	1	$12.73	$12.73	
ME16-FRM-P005-MotorMountFront-R00	Motor Mount Front	6061-T6 Flat Bar	.5" x 4" x 12"	Online Metals	CNC	1	$12.73	$12.73	
							Total Cost	**$405.93**	

5.3 Summary of Costs

Overall the combined cost of the robot came out to $12,701.47. Since the client specified that parts would be manufactured at AssentWorks by UMSATS, the labour cost of machining was neglected. This total also does not take into account the possibility of sponsorship and donated parts, which could further reduce the cost.

6 Maintenance

To ensure the rescue robot design will last the five years required by the client, the team developed a recommended inspection and maintenance schedule. To best determine the inspection and maintenance schedule, the lifetimes of each of the parts were first taken into consideration. Using the determined part lifetimes, we created a recommended schedule to prevent failures and mitigate the risks associated with these types of failures.

6.1 Part Lifetimes

The first step in determining the lifetimes of parts on the design was to consider typical operating conditions of the robot, including time of operation, and tasks being performed. We assumed that the robot is operated for two four-hour sessions a week, over the required five year life. This type of schedule will allow UMSATS to perform testing, operator training, and practice on Saturday and Sunday each week. The calculation of the operating hours is shown in Eq. 7.

$$hours\ of\ operation = \frac{hours}{session} * \frac{sessions}{week} * \frac{week}{year} * years\ operated\ for \qquad \textbf{Eq. 7}$$

$$hours\ of\ operation = 4 * 2 * 52 * 5$$

$$hours\ of\ operation = 2080\ hrs$$

The next step was to determine what components are critical to the operation of the robot and are likely to fail due to a fatigue loading cycle.

6.2 Chain Drive Maintenance

The chain drive components were sized using the Machine Elements in Machine Design textbook. The book contains acceptable power values for multiple strand chain, and relates them to torque and rpm values. Our drive was calculated to have an allowable torque of 94.46 [Nm] on the double chain for the main drive, and 55.57 [Nm] on the single chain for the paddle drives. The expected average torque in operation is 16.55 [Nm], well under our chains limits. The tables used were derived from empirical data, which suggests a service life of 15000 hours of operation if proper maintenance is performed. As a result, we have limited the replacement time of the chain to 15000 hours, if no failures are noticed prior to this time.

The proper maintenance procedures for a chain drive should include lubrication, replacement of links, inspection of sprocket wear, and inspection of the chain elongation. The chain drive components are required to be well lubricated to run properly and extend their lifetime. Our application will use manual lubrication, and the sprocket manufacturer Tsubaki, has recommended it be performed every 8 hours, or as often as needed to keep the bearing areas from becoming dry [20].For chain of pitch 50 or lower, operating at room temperature SAE 20 is the recommended lubricant. Chain tension can increase wear and lead to a decreased lifetime in the chain. Our design includes a tensioner design; however, over tightening the chain can produce adverse effects. The recommended slack in a chain system is 4% of the chain span, which is the distance between contacts on the sprockets. In our case this value should be 0.71 [in]. The slack distance is measure as the low point where the chain is tight on the slack side to the high point where the chain is tight on the slack side as seen in Figure 37.

[redacted]

Figure 37: Figure depicting the slack distance S-S' [20].

Regular inspections should also include a measurement of the chain elongation, which for driving sprockets with less than 60 teeth have a recommended maximum elongation of 1.5% the original length. The wearing present on the chain links and roller should be inspected regularly with the inspection for elongation. Figure 38 shows the normal wearing locations on chain links and where cracks are likely to propagate.

[redacted]

Figure 38: Inspection locations for chain link components [20].

The sprocket teeth should also be inspected for uneven wear patterns as this can indicate misalignment between the shafts or partial engagement of the chain. Figure 39 shows the difference between an acceptable wearing pattern and one that indicates misalignment.

[redacted]

Figure 39: Wearing areas to check on sprocket [20].

If uneven wear is detected within a sprocket it can be indicative of misalignment. There are three steps for the alignment of a chain drive.

1. The shafts must be parallel to the ground. This can be done using a level on each of the shafts and ensuring both beads align at center. The incorrect and correct alignment is shown in Figure 40.

[redacted]

Figure 40: Alignment of the vertical location of each sprocket [20].

2. The shafts must be aligned parallel to each other or the chain tension can be affected. Proper alignment can be performed using a scale on either end of the shaft as shown in Figure 41.

[redacted]

Figure 41: Alignment of shafts in a parallel manner [20].

3. The sprockets must finally be aligned in the axial direction. Sprockets tilted off axis from each other can result in a twisted chain and uneven wear. Figure 42 depicts the proper method using a straight edge to align the sprockets.

[redacted]

Figure 42: Axial alignment of sprockets.

For this application the shaft contains keyways, a shoulder and a taper lock sprocket, which should aid in the axial alignment. However, it is still important to perform these checks on the alignment for optimal performance. TABLE XXV presents the relevant information for maintaining the chain drive and the recommended inspection intervals.

TABLE XXV: SUMMARY OF RELEVANT CHAIN MAINTENANCE.

Maintenance Task	Interval of Inspection	Notes
Chain Lubrication	Every 8 hours of operation or as necessary	Use lubricant SAE 20
Inspect Chain Slack	Start of every operation	Adjust tensioner as needed.
Inspect Chain Elongation	Once every two months or every 60 hours of operation	Max elongation 1.5% of original length
Inspect Sprocket Wear	Once every two months or every 60 hours of operation	Uneven wear indicates misalignment of drive
Inspect Chain Links	Once every two months or every 60 hours of operation	Cracks in linkages can result in catastrophic failure

Appendix E contains the installation and maintenance manual for chain drives provided by Tsubaki for technical reference.

6.3 Bearings

The bearings on the shaft are standard roller or ball bearings. These types of bearings have a basic dynamic load rating, which indicates the load that the bearing will be good for one million revolutions. Eq.8 shows how to convert the lifetime using dynamic load rating and actual loading.

$$L_2 = L_1 * \left(\frac{C_r}{P}\right)^k \quad \textbf{Eq.8}$$

In this equation, C_r is the basic dynamic load rating, L_1 is one million revolutions, and P is the expected radial loading on the bearing.

Bearing lifetime was calculated in hours by dividing L_2 by the average number of revolutions in an hour of steady operation. The idler shaft bearing and drive shaft bearing lifetimes were calculated to be 2.9×10^{10} and 2.38×10^{11} hours respectively. The bearing lifetimes are orders of magnitude greater than the required lifetime of the robot. As a result, these components will most likely not need to be replaced. However, regular inspections are still recommended to check for debris in the bearing as it impedes its performance. All of the selected bearings are shielded, which helps prevent debris from entering them. As a result, we are recommending these only be inspected every third chain inspection, which equates to every 6 months. Simply rotating the shaft and listening to the bearing for smooth turning should be adequate inspection.

6.4 Shaft Maintenance

The shafts were designed such that the stress occurring during normal operations will not exceed the endurance limit of 4130 normalized steel. On top of this, the actual diameter of the shaft is much greater than the computed minimum diameter necessary. This means it is unlikely the shafts will fail in normal operation unless some type of imperfection occurs on the shaft due to impact loading or environmental effects. Regular inspection of the shafts for cracks should still be performed, as crack growth and propagation due to impact loading may still occur. Key areas to check for cracks are near key seats, retaining rings, and near fastener locations. Regular inspections should also check for rusting of the components. TABLE XXVI summarizes the inspection procedure for the shafts.

TABLE XXVI: INSPECTION INFORMATION FOR THE SHAFTS.

Maintenance Task	Interval of Inspection	Notes
Inspect Shaft for visible cracks	Every two months	Shoulders, key seats, retaining ring grooves are important spots to check
Inspect Shaft for Rust	Every two months	Sanding can remove rust, but ensure rotor is still balanced.

6.5 Harmonic Drive

The harmonic drive is one of the most difficult parts to maintain on the robot and has one of the shortest lifetimes. Appendix E contains the product catalog for the harmonic drive, which provides extra detail for maintenance, installation considerations and operating conditions. The lifetime of the harmonic drive was calculated using the formula in Eq. 9.

$$L_h = L_n * \left(\frac{T_r}{T_{avg}}\right)^3 * \left(\frac{n_r}{n_{avg}}\right) \quad \textbf{Eq. 9}$$

L_h is the expected life in hours, L_n is the rated lifetime, T_r and T_{avg} are the rated and average torque, and n_r and n_{avg} are the rated and average operating speeds.

The rated lifetime was given as 10,000 hours. Rated torque and speed of the robot are 21 [Nm] and 2000 [rpm]. The average torque and speed expected were taken as 16.55 [Nm] and 86 [rpm], the same ones used to size the drive and chain. Using these values an expected lifetime of 475 x 10^3 hours was determined for the harmonic drive. As a result, this component will not need to be replaced if it is properly maintained.

To properly maintain the harmonic drive and extend the product lifetime, proper lubrication of the flex spline and internal components is important. There are two types of lubrication that can be used in the harmonic drive, grease or oil. Oil lubricated drives can operate at a max input of 10000 [rpm], while grease drives can only operate at 7300 [rpm]. The maximum rpm of the motor is 12000 [rpm], which led to the choice of using oil lubricant in the drive. There were 11 recommended oils that work well with the harmonic drive. Mobil gear 626 was selected to be used with the drive. Figure 43 shows a diagram of the recommended oil level to maintain for a horizontal installation.

Figure 43: Recommended oil level A for a horizontal installation [7].

The recommended oil level to maintain for the CSG-17 style drives is 12 [mm]. The product catalog recommends the first oil change takes place after 100 hours of operation and then every 1000 hours of operation after this.

6.6 Summary of Maintenance

The components identified to be maintained and their respective lifetime on the robot has been identified in TABLE XXVII.

TABLE XXVII: WEAR ITEMS ON THE DESIGN.

Part No.	Description	Hours Until Replacement
ME16-PAD-P009-DriveSprocket-R00	Paddle Sprockets	>15000
ME16-PAD-P003/4-40-2ChainInner/Outer-R00	Paddle Chain	>15000
ME16-TRC-P001/2-r0-2ChainInner/Outer-R00	Main Track Chain	>15000
ME16-TRC-P006-TaperLockSprocket-R00	Main Track Sprocket	>15000
ME16-TRC-P011-DriveShaft-R00	Drive Shaft	N/A*
ME16-TRC-P007-IdlerShaft-R00	Idler Shaft	N/A*
ME16-FRM-P009-ShaftBearing-R00	Idler Shaft Bearing	2.9×10^{10}
ME16-TRC-P010-DriveShaftBearing-R00	Needle Bearing	2.38×10^{11}
ME16-FRM-A001-HarmonicDriveRef-R00	Harmonic Drive	4.75×10^{3}

*Lifetime is dependent upon non fatigue scenarios

Using this data, the team developed the inspection schedule presented in Table XX.

Maintenance Task	Interval of Inspection	Notes
Chain Lubrication	Every 8 hours of operation or as necessary	Use lubricant SAE 20
Inspect Chain Slack	Start of every operation	Adjust tensioner as needed.
Inspect Chain Elongation	Once every two months or every 60 hours of operation	Max elongation 1.5% of original length

Inspect Sprocket Wear	Once every two months or every 60 hours of operation	Uneven wear indicates misalignment of drive
Inspect Chain Links	Once every two months or every 60 hours of operation	Cracks in linkages can result in catastrophic failure
Maintenance Task	Interval of Inspection	Notes
Inspect Shaft for visible cracks	Every two months	Shoulders, key seats, retaining ring grooves are important spots to check
Inspect Shaft for Rust	Every two months	Sanding can remove rust, but ensure rotor is still balanced.
Inspect Bearing for Dirt or Damage	Every 6 months	Rotate the shaft ,and listen if the bearing is running smooth.
Oil Change for Harmonic Drive	1^{st} after 100 hours, 1000 hours for subsequent.	Maintain an oil level of 12mm.

7 Future Recommendations

As the design was nearing completion, the team identified several areas for possible improvement in future design iterations. Many of these were due to the time limitations imposed by the scope of the project, and would have been explored in more detail, if more time was available. Since the design will benefit from these further improvements, they are outlined in this section.

The most significant area where the design can be improved is to reduce the overall vehicle weight. The weight dictates aspects of the design such as overall power requirements, and mobility of the robot within the course. It is highly recommended that the vehicle weight be reduced for future design iterations, using several methods.

The first recommendation is to perform a detailed FEA analysis of all manufactured components, especially larger and heavier components such as the main robot body, and structural components of the main track and paddle track assemblies. Based on FEA, material could be cut out of lower stress areas, to minimize the weight of these components.

Further weight reduction could be gained by optimizing the chain drive components used to manufacture and deliver power to the track drive systems. Early in the design process, the client suggested that ANSI 40 chain and sprockets be used, due to the ease of obtaining the hardware required. Although these components will perform satisfactorily, they are significantly stronger than what the robot design actually requires to function.

ANSI 40 single row chain (used for paddle tracks) is rated for a working load of 3603 N, and a minimum tensile strength of 13901 N [21]. ANSI 40-2 double row chain (used for main tracks) is rated for a 6094 N working load, with a minimum tensile strength of 27801 N. Due to drive torque, the design will only experience a maximum chain tension of 331 N. This means that the single row chain is 10.9 times stronger than required for the application, and the double row chain 18.4 times stronger. By using a lighter duty chain such as single row ANSI 25, the chain weight can be reduced by about 75%, while still having a safety factor of 2 [21]. Alternately, it might be possible to eliminate the chain altogether, replacing it with a synchronous belt drive system. This could also provide a traction surface without the need to attach tread blocks to the chain links.

Another area which could be optimized is the selection of drive motors and gearboxes. The motor supplier (Maxon) has many options for motors and gearboxes, allowing for a large number of combinations. Motor and gearbox combinations were selected based on the performance requirements. However there may be other combinations which would also satisfy the requirements at a reduced weight and/or cost. In addition to the motor and gearbox selection, it might be possible to also change the location of the drive and paddle rotation motors to allow for a smaller overall design, improving mobility, especially through narrower areas in the course.

Another area which could be further explored is the development of testing methods to evaluate the robot performance. The RoboCup rulebook [3] and ASTM standards for rescue robot mobility developed by Subcommittee E54.08 [11] should be consulted for the design and construction of obstacles similar to the ones which will be encountered in the competition course. Using a mock-up of the event obstacles will greatly aid in determining the actual performance capabilities and requirements of the robot. This data could be used to further refine the design, in areas such as motor power requirements, weight distribution, manipulator design, and battery requirements.

One last area which should be explored is the design of a custom manipulator arm. Due to time constraints, the team did not design the manipulator, but instead specified a suitable off-the-shelf design. Due to the complexity of a manipulator arm, and the variety of design options available, this could prove to be a suitable project for a future design team.

8 Conclusion

After considering a variety of design concepts, it was decided that the ‘four paddle’ design would be the only design which would be able to meet all performance criteria of the RoboCup competition. This design features two main tracks along the sides of the robot, and one paddle track on each corner. Together, the two main tracks and four paddle tracks provide propulsion to the robot.

Motive power will be provided from two main 250 [W], 24 [V], EC Maxon 136207 drive motors mated to CSG-17-50-2UH 50:1 harmonic drives for gear reduction. The motors and harmonic drives are mounted internally, near the front of the frame, with each one driving one side of the robot in a skid-steer configuration. Each paddle track is powered by the same main drive motors via drive shafts from the main track system, and rotated about the driveshaft axis by a 40 [W], 24 [V], DC Maxon DCX26L motor mated to a planetary gearbox with a 231:1 reduction. One of these paddle rotation motors is mounted inside each paddle assembly, allowing independent control of each paddle. The paddle motors rotate the paddle via a 3:1 ring and pinion drive, with the ring gear attached to the frame.

The proposed design measures a maximum of 1113 [mm] in length with the paddles extended outward, with an overall width of 676 [mm], measured from the outer edges of the paddle tracks. The overall height is 319 [mm] with the manipulator stowed, and 571 [mm] with the manipulator extended to its maximum height. The robot is slightly too wide for the 600 mm wide shortcuts but can still access all other areas of the course without difficulty.

The total vehicle weight is estimated at 27.4 [kg], based on the SolidWorks models. This is higher than the team had expected, but is acceptable for a first design iteration. Using FEA analysis, the manufactured components can be optimized to reduce the weight, by cutting out material from low stressed regions. The weight can also be further reduced through the use of smaller chain drive components, and might also benefit from alternate motor/gearbox combinations.

The CAD model shows the center of gravity (CG) is located 20 [mm] rear of the geometric center of the robot body, at a minimum height of 76 [mm], and maximum of 121 [mm], depending on the orientation of the paddles and manipulator. Based on the vehicle dimensions, and the SolidWorks CG estimate, the maximum traversable longitudinal incline was determined to be 82 [º], and lateral incline of 78 [º], with the manipulator stowed. This will ensure that the robot will have no difficulty traversing the 45 [º] inclines present in the course obstacles. The maximum forward speed is estimated at 80 [m/min] on level ground, when running the drive motors at maximum speed.

Due to competition requirements, the robot also features a manipulator arm to allow access to shortcuts requiring dexterity tasks, as well as providing mounting points for a spherical BublCam optical camera and a laser thermal sensor. Due to time constraints, the team was unable to design a manipulator in house, however an off-the-shelf Lynxmotion AL5D 4-axis manipulator was determined to be acceptable for the competition, and was chosen for use on the robot. It would be ideal if an optimized design could be developed by a future design team, however the AL5D arm is sufficient to compete in the competition.

The entire robot is powered by a 24 [V] 400 [Wh] LiPo battery pack, mounted in a quick change battery case. This battery will provide adequate power for one entire competition round, with the ability to quickly swap in another fully charged battery pack within a few minutes, between rounds.

The team estimates the overall vehicle cost at $12,701.47 CAD, which takes into account the cost of off-the-shelf hardware, and raw material cost for manufactured parts. However, since the client specified that parts would be manufactured at AssentWorks by UMSATS members, the labour cost of machining was neglected. This total also does not take into account the possibility of sponsorship and donated parts which could further reduce the cost.

Although the robot has aspects which can be improved upon, the team believes that this design will be acceptable for a first design attempt. It satisfies almost all of the design criteria specified by the client, and provides a good foundation for future design iterations.

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[35] *3 - Concept Generation,* class notes for MECH 4860, Department of Mechanical Engineering, University of Manitoba, Fall 2015.

Appendices

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Introduction

These appendices detail the supplementary design details for the report entitled "The Design of a Mechanical Subsystem for a Rescue Robot". The supplementary content details

- The concept generation, screening and scoring process.
- The analysis used to size components of the design.
- The Engineering Drawings for manufactured parts.
- The naming convention used for the SolidWorks assembly model provided to the client.
- Part Catalogs for the sprocket and harmonic drive detailing the installation and maintenance processes

Appendix A: Concept Generation, Scoring, Screening and Selection

A.1 Internal Concept Generation

Using the information gathered from external research, the team could begin internal concept generation for a rescue robot. To start internal generation, the team first created a methodology to follow while generating and developing concepts. By adhering to the developed methods, the team was able to efficiently generate concepts relevant to the customer needs and project objectives.

A.1.1 Methodology

The generation of concepts started with individual generation of ideas. The team then met, and had a brainstorming session using the Gallery Method [1]. The idea behind using the Gallery Method was to use visuals to stimulate new ideas and conversation in team members. We started the brainstorming session by breaking apart the design into five functional subsystems: Frame, Suspension, Mobility and Motors, Battery Swap and Manipulator. Figure 1 shows the team's breakdown of the mechanical design into functional subsystems.

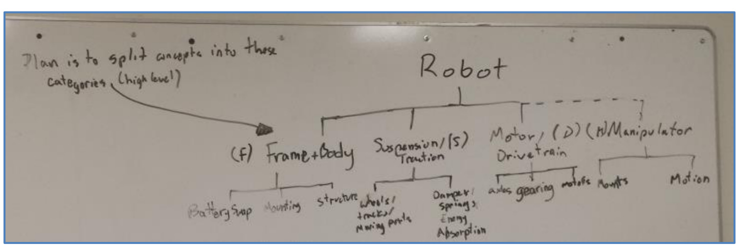


Figure 1: Functional breakdown of the rescue robot mechanical design [2].

For each subsystem, team members drew concept sketches from their individual brainstorming on a whiteboard, and provided a brief explanation to familiarize the team with the concept. While discussing these ideas, team members came up with variations on ideas and new concepts to add to the whiteboard. An example of this for the Mobility and Motors subsystem is shown below in Figure 2.

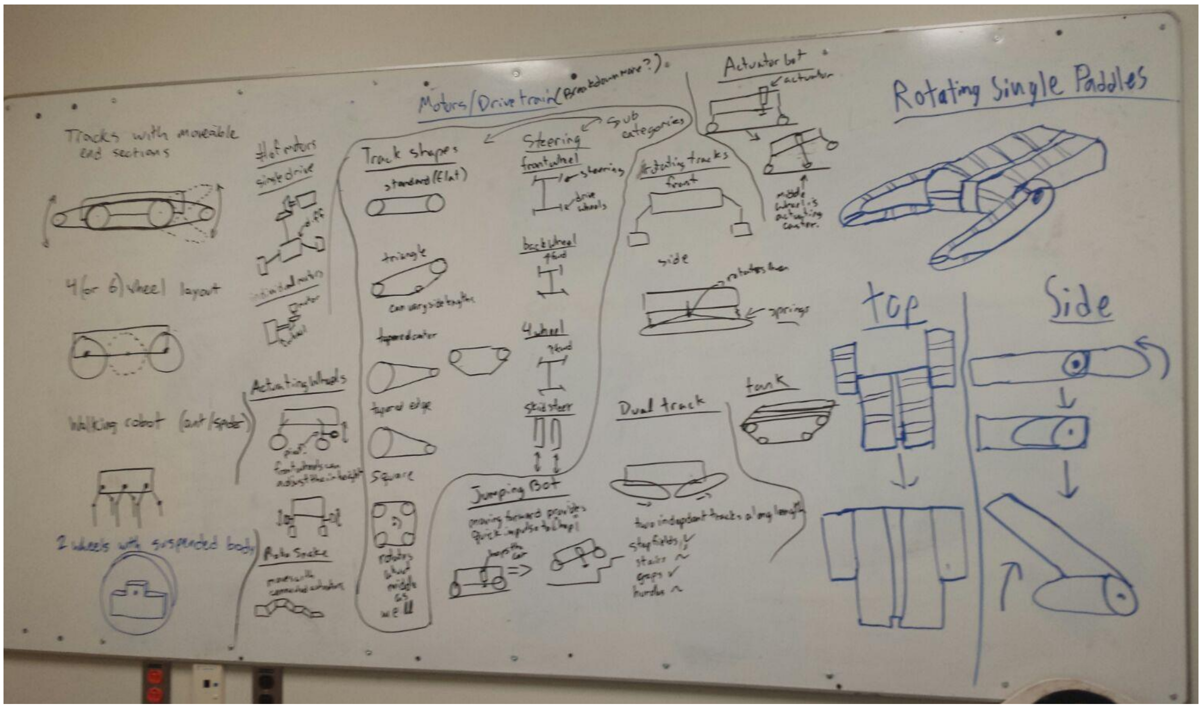


Figure 2: Mobility and motors concept generation [3].

All of the concepts generated in this procedure were documented and transferred to a spreadsheet in preparation for the concept screening procedure.

A.1.2 Concepts

After going through the concept generation process, we were left with concepts for each of the functional subsystems of the design. This section will outline the concepts for the frame, suspension, motors and mobility, battery swap and manipulator subsystems.

A.1.2.1 Frame

The frame provides a structure on which to mount all other components of the robot, while withstanding external loads due to the robot's motion through the course. The frame concepts developed by the team are outlined in this section. The concepts are labelled as FRA-#, numbered sequentially with descriptive names.

FRA-1: Reinforced Sheet Metal Frame

The reinforced sheet metal concept was inspired from designs observed in previous competition designs [4]. The concept consists of a rectangular box made from metal sheets. The sheets are fastened together at the corners with mechanical fasteners such as bolts or rivets. Figure 3 shows a sketch of this concept.

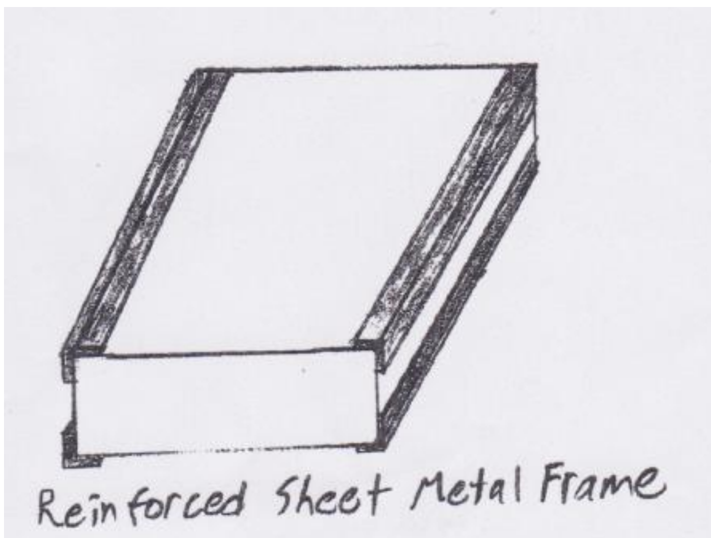


Figure 3: Sketch of the reinforced sheet metal concept [5].

Steel angle brackets are fastened along the longitudinal seams in order to strengthen the design. This design will provide flexibility in mounting components, and ease of repair. However, it provides less structural rigidity than concepts such as the tube frame.

FRA-2: CNC Frame

The CNC concept is similar to the sheet metal design, but it consists of machined wall panels. This concept is shown below in Figure 4.

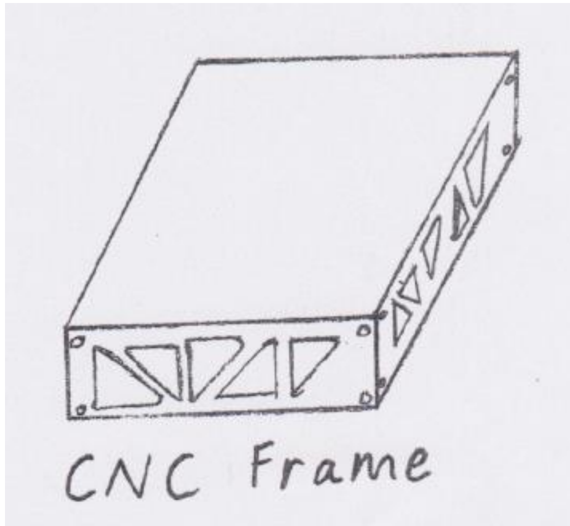


Figure 4: Sketch of the CNC frame concept [5].

By machining strategically placed holes or slots into the wall panels, it is possible to create a lightweight, yet durable frame.

FRA-3: One Piece Frame

The idea behind the one piece frame is using a solid block, or additive manufacturing to create a solid piece of frame. This concept would need no fasteners to come together and could have mounting points design directly into it. Figure 5 is a sketch of the one piece frame concept.

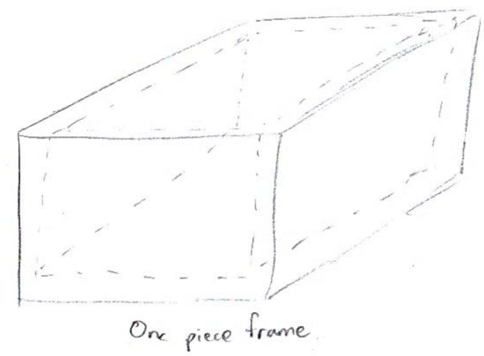


Figure 5: Sketch of the one piece frame [6].

This concept would be difficult to manufacture but would provide very customizable mounting points and an extremely rigid structure.

FRA-4: Ladder Frame

One of the simplest frame designs involves building a two-dimensional rectangular frame with cross members. A sheet metal body is then built up from the frame base to enclose electrical components such as the motors, battery and microcontroller. This design concept is shown in Figure 6.

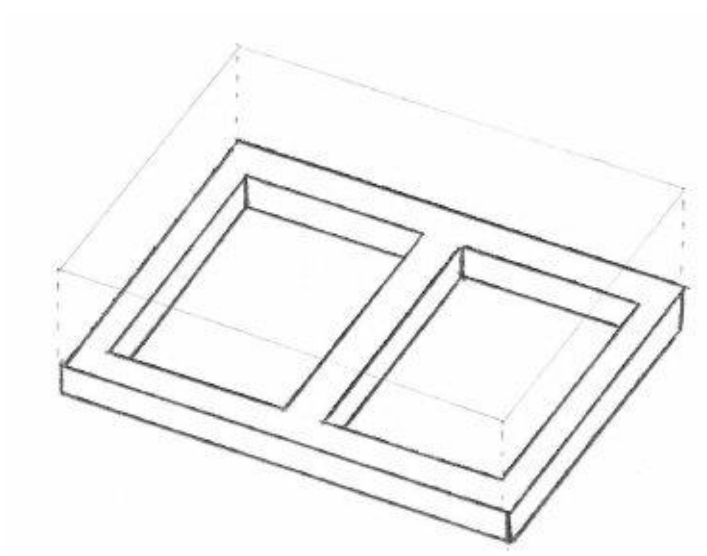


Figure 6: A simple ladder frame construction [7].

This is a concept used in automotive applications, particularly in trucks and older cars. The design is relatively simple to build and repair, although it is not as rigid in torsion as some other possible frame designs, and could also be somewhat heavier.

FRA-5: X-Frame

The X-frame concept is a variation of the ladder frame concept. It also consists of a two-dimensional load bearing structure; however the internal cross members are arranged in an X shape, rather than in rectangular sections. An example of the X-frame concept is shown in Figure 7.

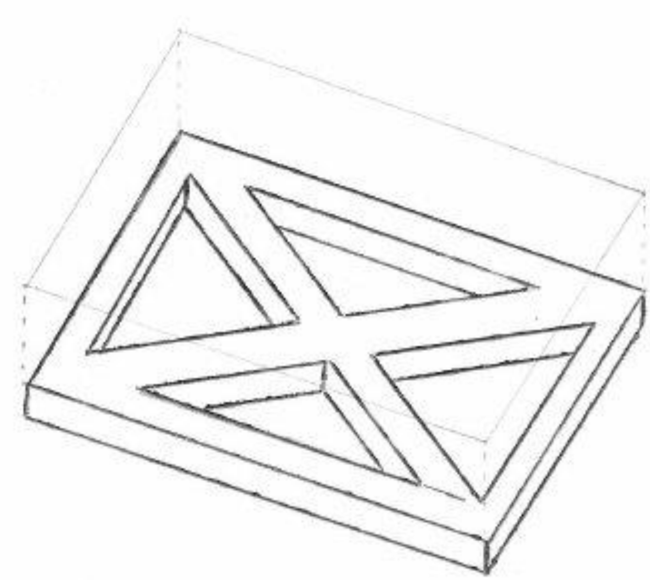


Figure 7: Sketch of the X-frame concept [7].

Depending on the layout, it might yield a slight weight and rigidity advantage over the ladder frame; however this will depend on the final design.

FRA-6: Tube Frame

The tube frame concept was inspired by the Formula Electric and Mini Baja SAE vehicle designs. It consists of hollow rods that are welded together at the corners. Figure 8 shows a sketch of this concept.

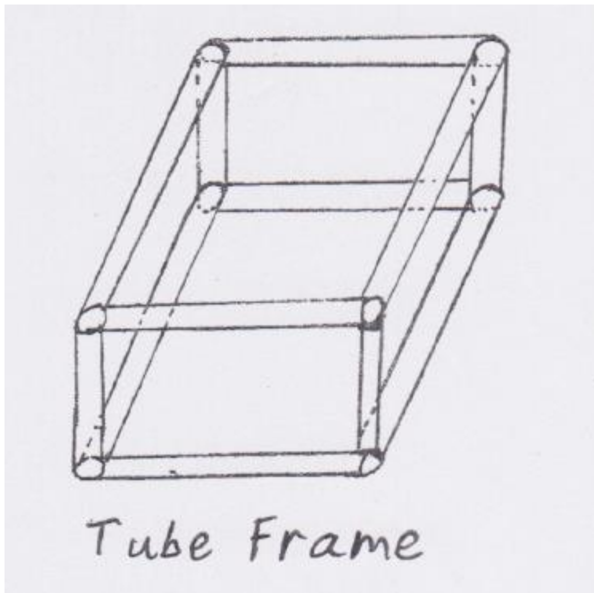


Figure 8: Sketch of the tube frame concept [5].

This design has proven to withstand heavy stresses and impacts in the SAE vehicles. However, design of mounting points to the frame is limited, and repair of this design would be difficult. This design could also incorporate non-load bearing panels to fill in the gaps of the frame, provide more mounting points and protect internal components.

A.1.2.2 Suspension

Suspension provides a means for the robot to absorb impact and vibration caused by its motion through the course, as well as maintaining reliable contact between its propulsion system (wheels, tracks, etc) and the ground surface during operation. There are several different ways to accomplish these functions, and various concepts will be listed sequentially as SUS-#, with a brief description of each.

SUS-1: Double A-Arm

Double A-Arm suspension has two frames extending sideways from the frame to the wheel hub. This allows the wheel to move up and down while maintain the same wheel camber [8]. Figure 9 is a sketch of the Double A-Arm geometry.

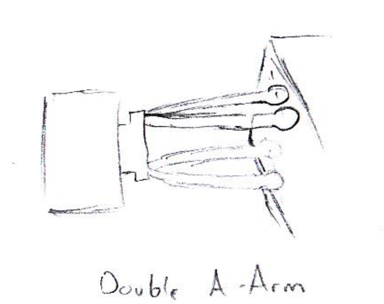


Figure 9: Sketch of the double A-arm concept geometry [6].

This geometry creates easy to control suspension travel and easily controlled wheel camber. The main down fall is that it only has lateral rotation and requires width to create the necessary geometry.

SUS-2: Trailing Arm

The trailing arm concept was introduced to the team from the Baja conceptual design report. It was further researched to gain more understanding of the idea and different ways to implement it. Trailing arm suspension creates an axis parallel to the wheel axis about which the arm rotates [8]. Figure 10 shows a top down sketch of trailing arm geometry.

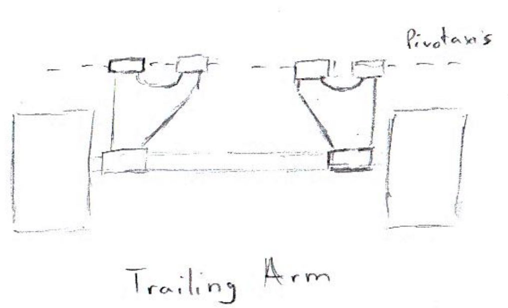


Figure 10: Sketch of the trailing arm suspension concept [6].

The main benefits of this suspension are that it has easy transition over obstacles due to being oriented longitudinally in the vehicle. However, trailing arms would add significant length to the robot and do not handle any lateral loadings very well.

SUS-3: 3-Link Suspension

The concept of 3-Link suspension combines the advantages of a trailing arm while providing more lateral support. One arm is tied longitudinally into the frame, and two lateral supports are added going to the wheel hub [8]. Figure 11 shows a sketch of the geometry from a top view.

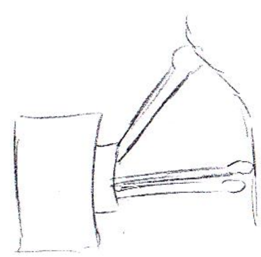


Figure 11: Sketch of 3-link suspension geometry [6].

This geometry has many of the benefits of a semi trailing arm such as including support for lateral loads [8]. However, the disadvantages of this geometry are much the same in that it is hard to control the wheel camber and toe out during the suspension travel.

SUS-4: 5-Link Suspension

The 5-Link suspension geometry is the similar to the 3-link geometry and usually has 3-4 lateral supports and 1-2 trailing supports [8]. This system allows more control of the kinematics of the suspension than other geometries but is the most complex. Figure 12 shows a sketch of the geometry.

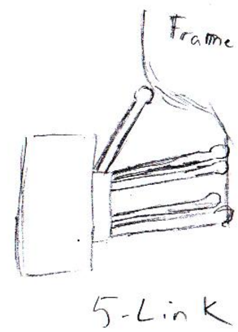


Figure 12: Sketch of the 5-link suspension geometry [6].

SUS-5: Semi-Trailing Arm

The semi-trailing arm suspension concept was also sourced from the Baja conceptual design report and further research. The main idea behind this suspension is to modify the axis of rotation of trailing arm geometry so that it bases through each of the wheel hubs [8]. Figure 13 shows a sketch of the semi-trailing arm geometry.

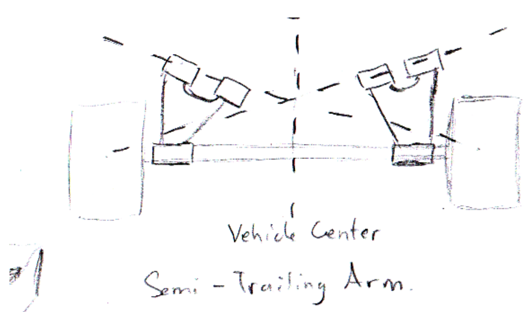


Figure 13: Sketch of the semi-trailing arm geometry [6].

The advantage of orienting your trailing arms in this geometry is that it can take more of the lateral loading on wheels than a straight trailing arm. The problems associated with semi-trailing arms are the changes in wheel camber during rotation of the arm.

SUS-6: Leaf Spring

The leaf spring suspension concept was inspired by older automobile suspension designs. It consists of slender arc-shaped rectangular steel members that are stacked on top of each other and then fixed to the frame of the vehicle. Figure 14 illustrates this concept.

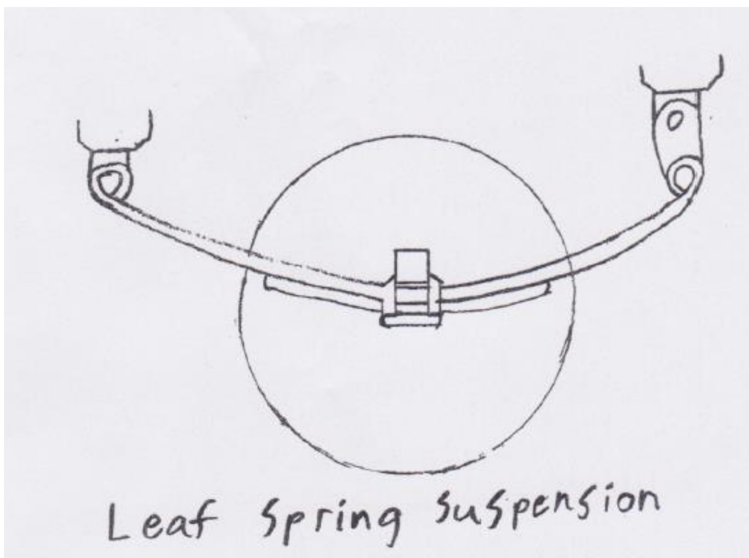


Figure 14: Sketch of the leaf spring concept [5].

Typically the rectangular members rest on top of the axle, and any time the vehicle hits a bump, the force is transferred from the tire to the axle, and then from the axle to the leaf spring. The arc shape of the leaf spring allows it to compress and extend freely.

SUS-7: Torsion Bar

Similar to the leaf spring, this concept was inspired by an automobile suspension design. The concept consists of a “spring steel” bar, which is mounted to the wheels via a suspension arm. This concept is shown in Figure 15.

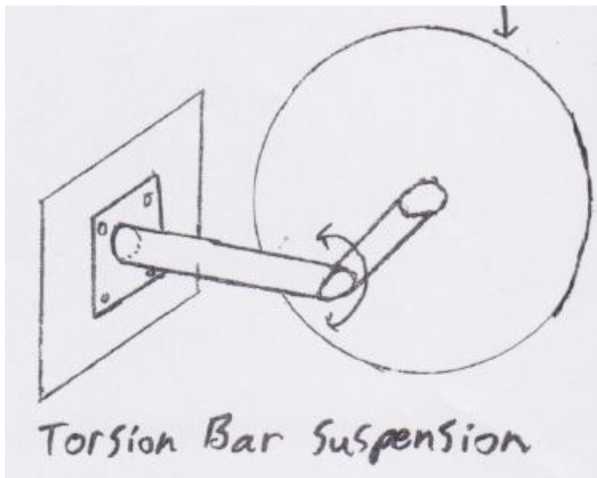


Figure 15: Sketch of the torsion bar concept [5].

Spring steel has a high yield strength, allowing it to experience significant twisting or deflection and still return to its original shape. The forces experienced on the wheel are transferred to the torsion bar in the form of a torsional force (torque). The high torsional resistance of the bar absorbs this torque, while allowing some suspension travel.

SUS-8: Rubber bushings

This design incorporates a guide pin which is attached to the wheel or track, mating into a corresponding hole or slot within the chassis. In between the two is a soft rubber bushing which allows for some motion, as well as absorption of vibration. The design is very simple, however it does not allow for much range of motion (“suspension travel”) in operation. This concept is shown in Figure 16.

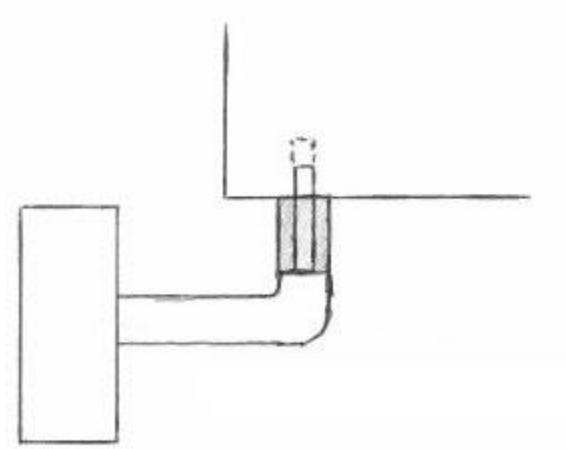


Figure 16: A simple rubber bushing design [7].

A.1.2.3 Motors and Mobility

The mechanical design provides the robot with its locomotion. This is a crucial part of our design, and as such had the most concepts created. Each of the concepts is labelled with MOB-#, the number assigned sequentially and given a descriptive name.

MOB-1: Four Paddle Track Concept

The four paddle track concept is the most popular design seen from competitors, and often one of the best performing designs at past competitions [9]. Figure 17 shows a sketch of the four paddle track concept.

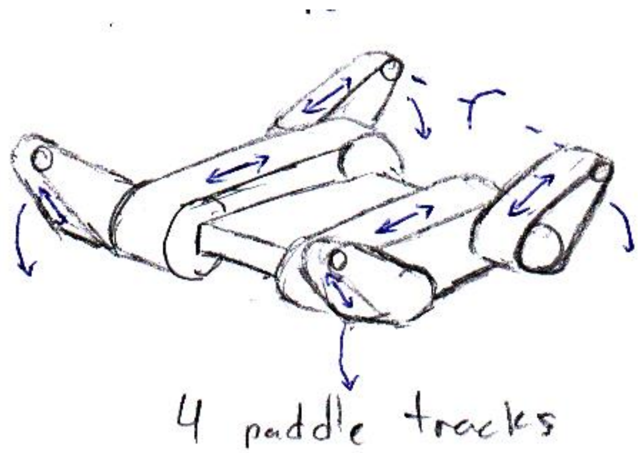


Figure 17: Sketch of the four paddle track concept [6].

This concept contains two main tracks which act as a skid steer to control the robot motion on flat ground. The front and back paddles also have tracks, which can create motion. The paddles in the back and front are then able to actuate about their attachments to the main body. The front paddles actuate in tandem, as do the rear paddles, reducing the number of motors necessary. This design will require at least four motors, and could be increased to 6 motors if each of the paddles was made to actuate independently. This design provides versatility to the operator in traversing obstacles, and should be able to traverse stairs, hurdles. This design will need an integrated frame to keep the center of gravity low.

MOB-2: Walking Robot

The walking robot concept is inspired by the gait of spiders and other animals in nature. Figure 18 shows a sketch of the concept.

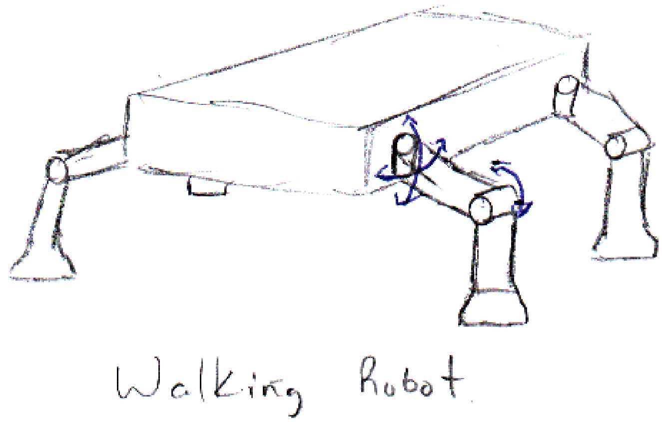


Figure 18: Sketch of the walking robot concept [6].

The walking robot uses four-legged locomotion with a gait similar to a spider. The four legs extend out of the side of the robot, and are hinged in two directions at the frame. There is a third joint further down the leg acting like a knee for the robot. This motion could be accomplished using servo motors, or using actuators if necessary.

MOB-3: Four or six wheel drive system

This design involves using either four or six wheels, mounted to the robot frame via the suspension. The wheels will be driven with a chain or shaft drive system, using a skid-steer system to vary the rotational speed between the left and right sides of the robot to steer it. This design concept is shown in Figure 19.

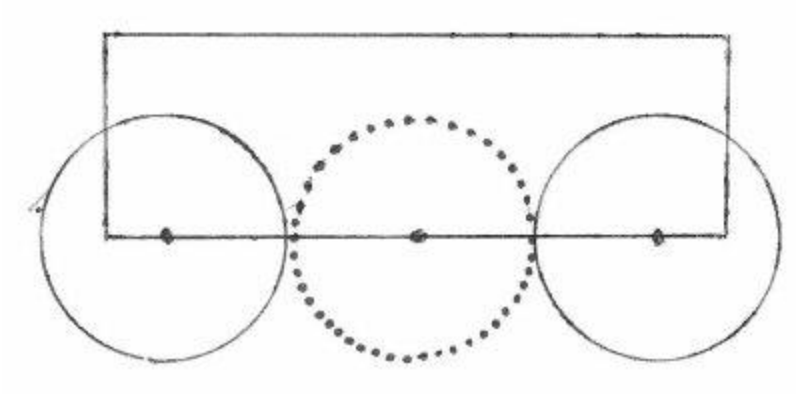


Figure 19: Four or six wheel drive configuration [7].

MOB-4: Two-wheel suspended system

This concept involves using two large parallel wheels, with the entire chassis of the robot suspended between them. This would require consideration of the size and shape of the robot chassis to ensure adequate ground clearance, and could also create problems for controlling the robot, due to a high center of gravity and limited traction. This concept is outlined in Figure 20.

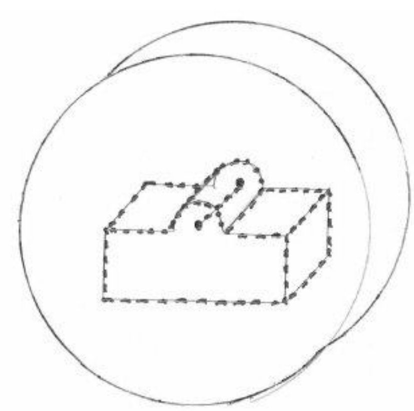


Figure 20: Two-wheel suspended design [7].

MOB-5: Robo-snake

The Robo-snake concept was derived from a youtube video [10]. This design sees multiple actuators linked together forming a chain. The linking of the actuators creates the effect of snake like locomotion in that the robot will drag itself along the ground. Figure 21 is a sketch of the robo-snake concept.

Figure 21: Sketch of the robo-snake concept [7].

This concept would require very complex controls and manufacturing. The video that we watched had to be sped up to show the robot climbing up a step, however other videos have seen similar robots climb up trees or students legs [10].

MOB-6: Vertical Wheeled Car

The vertical wheeled car takes inspiration from a video of a small robot climbing stairs [11]. Figure 22 shows a sketch of the Vertical Wheeled Car.

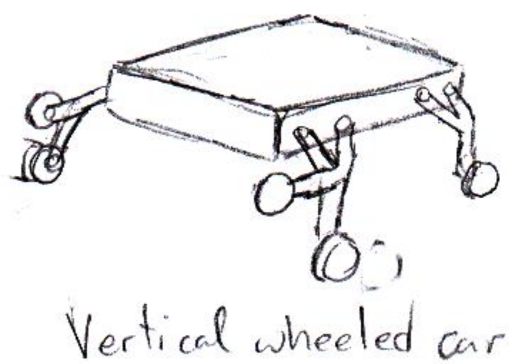


Figure 22: Sketch of the vertical wheeled car concept [6].

The vertical wheeled car uses a suspension design with wheels that allows travel in the vertical direction. A rigid wheel then extends off of the frame in front of the car. The vertical wheels are mainly used for traversing stairs, providing a second point of traction on the vertical face for ease of climbing. The framing of this concept could be relatively low to the ground due to no need for large wheels. The vertical wheel car would require at least four motors, and could use six if each wheel is independently powered.

MOB-7: Suspension Tracks

The Suspension Tracks concept derives from the idea of swapping out wheels in a traditional suspension design such as the Baja car. Figure 23 shows a sketch of the design.

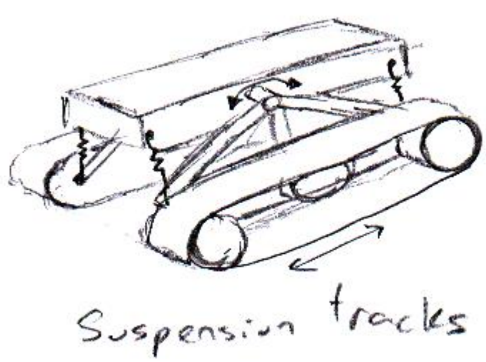


Figure 23: Sketch of the suspension tracks concept [6].

This design attaches a track to a swivel point on the main frame. Shocks or springs would be added to the front and back ends of the track. Therefore, the two tracks can rotate independently in vertical planes, allowing the design to traverse uneven terrain such as crossing roll ramps and symmetric stepfields with ease. This design would require two motors, one powering each track.

MOB-8: Actuating Robot

The actuating robot concept was created based upon MOB-12: Jumping robot, as a more conservative approach to using an actuator. Figure 24 shows a sketch of the concept.

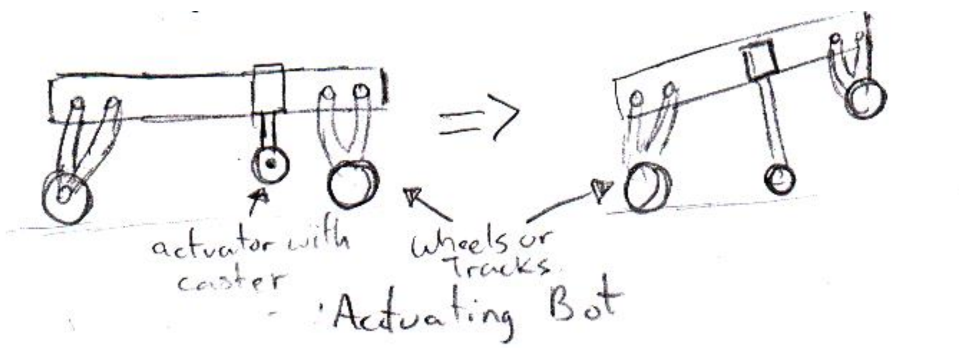


Figure 24: Sketch of the actuating robot concept [6].

This design, similar to the jumping robot, could use wheels or tracks for the main locomotion, and has two actuators forward of the center of gravity. The actuators have caster wheels located on the end, and when actuated, tilt the robot to the operators need. The actuator bot would require two motors for a skid steer, one for a rear or front wheel drive, and four if each wheel was independently operated. Two actuators will be necessary as well. This will allow the robot to traverse stairs and the pipe steps easily as it will allow the track or wheel to get above the obstacle.

MOB-9: Rotating Single Paddles

The Rotating Single Paddles concept was inspired by the Paktho Rescue Robot [12]. This concept consists of two main tracks mounted on the sides of the frame, and a set of front arms with their own set of tracks. This is illustrated in Figure 25.

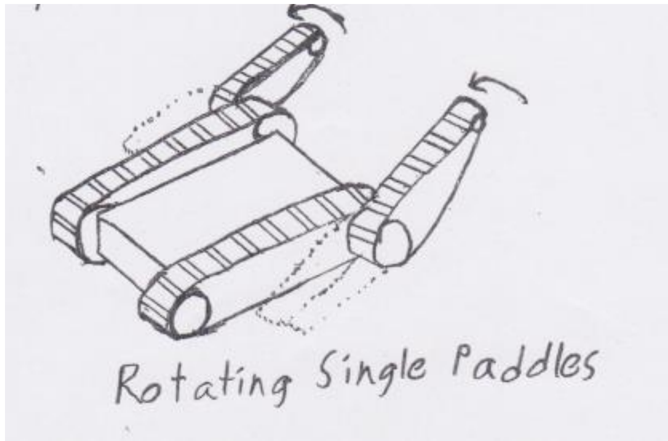


Figure 25: Sketch of the rotating single paddles concept [5].

In this concept the front arms have the ability to rotate 180˚ and “switch places” with the main tracks. This means that the front arms would stabilize the robot on the ground, while the main tracks are lifted upwards. This feature is advantageous when ascending stairs. This design requires at least three motors: one to run the main tracks, one to run the arm tracks, and one to rotate the arms.

MOB-10: Tank Concept

The tank concept is named after the inspiration for the idea, a tank. The tank uses trapezoidal tracks on either side for locomotion. This design could allow for an integrated frame to maintain a low center of gravity with the large track height required to traverse the stair obstacle. Figure 26 shows a sketch of the concept.

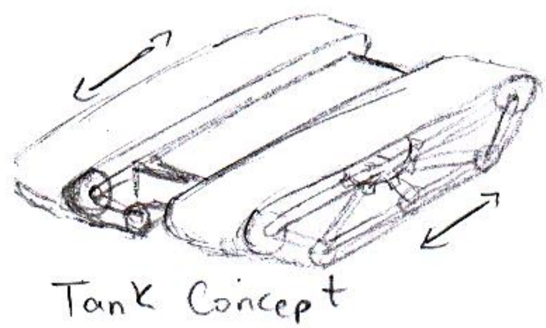


Figure 26: Sketch of the tank concept [6].

The slanted portions of the track allow the design to gain traction on inclines, stairs and stepfields. The tank would utilize skid steer capabilities allowing for easy user control and lower turning radius.

MOB-11: Dual Tracks along Robot Length (DTAL)

The DTAL concept was thought of based upon the pretense of replacing wheels on a regular vehicle with tracks. The main idea is to split the track on each side of the robot into two, which are able to rotate independently. This allows for more flexibility when compared to a single track on each side, and provides more traction due to increased surface contact on uneven surfaces. Figure 27 shows a sketch of the DTAL concept.

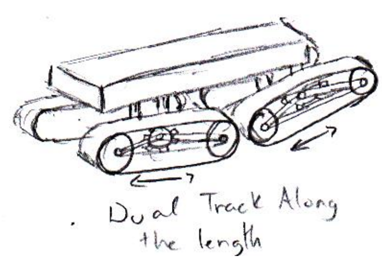


Figure 27: Dual track along robot length concept sketch [6].

The DTAL concept could be used with an integrated body that articulates at the center, or with a raised body shown in Figure 27.

MOB-12: Jumping Robot

The jumping robot concept is inspired by how fleas jump. The main idea behind the concept is it uses either wheels or tracks for locomotion. The Jumping Robot also contains four actuators that contained stored energy of some kind. Figure 28 shows a sketch of the jumping robot.

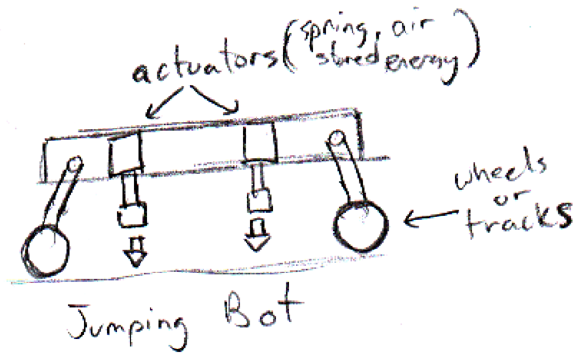


Figure 28: Sketch of the jumping robot [6].

The actuators produce an extremely quick action when triggered, impacting the ground and launching the robot into the air. This will allow the design to jump up stairs, or over obstacles when necessary. The wheels and frame on the jumping robot can be reduced in size because they do not have to reach above a set of stairs, which should allow the center of gravity to be low.

A.1.2.4 Battery Swap System

UMSATS has explicitly requested a battery swap system that provides fast swaps between competition rounds, so that battery performance will be optimal. Therefore, the team generated concepts for this system, even though it does not provide core functionality to the robot to compete. Concepts in this section will be labeled with BAT-#, as well as a descriptive name.

BAT-1: Battery Nest

The battery nest concept can be likened to the creation of shadow board for tools. The frame has a specific spot, which can only fit the battery. Foam or other padding could be used to hold the battery snugly in place. Figure 29 shows a sketch of the concept.

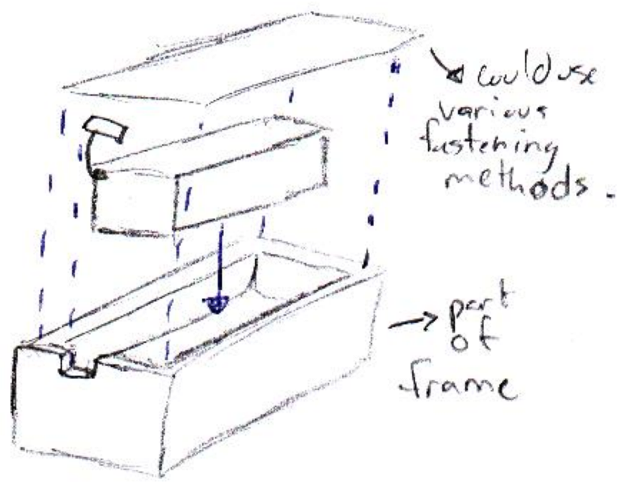


Figure 29: Sketch of the battery nest concept [6].

The top of the battery back is then fastened over top of the battery, isolating the battery from vibrations and protecting it from damage.

BAT-2: Quarter Turn Battery Box

The quarter turn battery box consists of a fully enclosed box housing the battery. This box can then be removed or installed on to the frame and fastened using quarter turn bolts. Figure 30 shows a sketch of the concept.

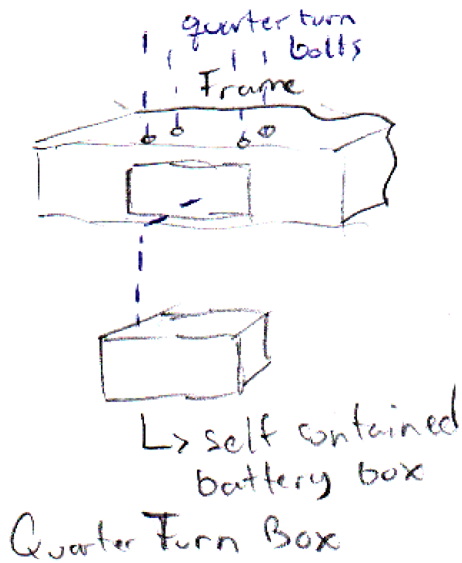


Figure 30: Sketch of the quarter turn battery box concept [6].

It has also been identified for this concept, that the quarter turn bolts can be replaced by alternative fastening methods such as standard bolts, latches or clips.

BAT-3: Magnetic battery mounting system

This concept incorporates a self-contained battery case, which encloses the battery pack(s) required by the robot's electrical systems. The case features several magnets, which connect to corresponding magnets within the robot chassis in the battery mounting location. These magnets provide a means to retain the battery case in the desired location, as well as to provide a power connection between the battery and the chassis, similar to the system used in applications such as MacBook laptop power cables. This system would allow for very fast battery swaps, as it does not require any mechanical power cable connectors to be disconnected and reconnected. The user would only need to grasp a handle on the battery case and lift it out, and then drop a fully charged pack into its place in the robot. This design is illustrated in Figure 31.

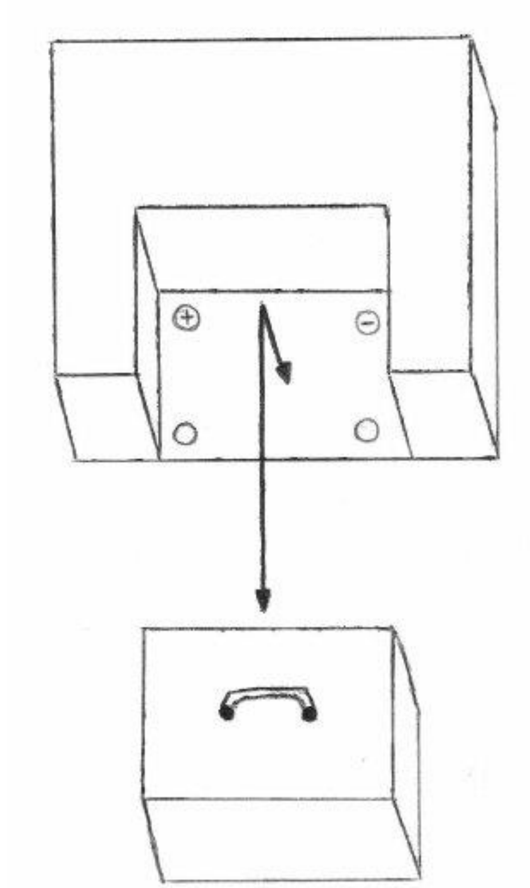


Figure 31: Magnetic battery case system [7].

BAT-4: Spring or Velcro battery retention system

This design consists of a rigid arm, which is mounted at a fixed pivot on one end, and swings over the top of the battery pack. The other end is fixed and tensioned with the help of a detachable spring or Velcro strap, attached to another fixed point on the chassis, on the other side of the battery. This design would also allow for fast battery swaps, while securely mounting the battery within the chassis. The concept is shown in Figure 32.

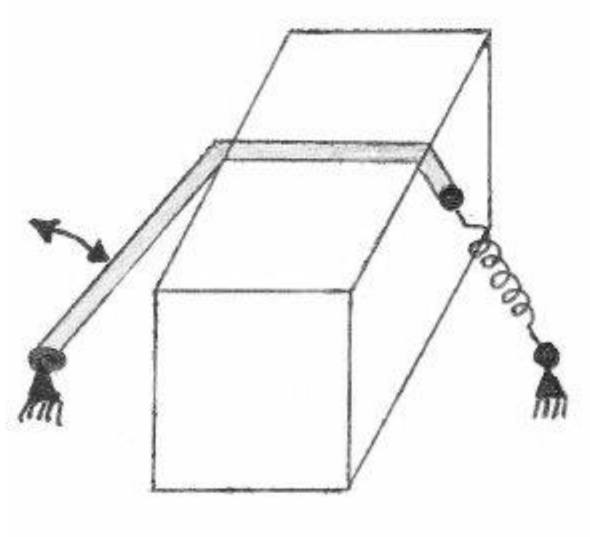


Figure 32: Spring or velcro battery retention system [7].

BAT-5: Battery Latch

The battery latch concept consists of four metal L-brackets, each with a gusset on one side (not shown in sketch). These brackets are placed to fit the contours of the battery, and fixed to the frame of the robot. This prevents the battery from shifting up and down, or side to side in the horizontal plane. There are also two latches fixed to the frame. These latches have a hard padding, and are positioned at a height that fits securely against the top of the battery. The latches have 180˚ of rotation, which gives them the ability to hold down the battery, while being able to rotate out of the way to remove the battery. This concept is shown in Figure 33.

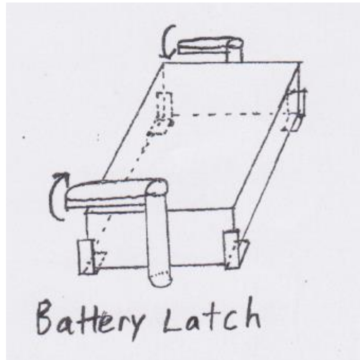


Figure 33: Sketch of the battery latch concept.

The simplicity of the design allows it to be easily combined with other battery swap concepts.

A.1.2.5 Manipulator

The manipulator section of the robot allows the operator to see the course. The video camera and end effector are attached to the end of this component, and it must have a wide range of motion to be able to see and identify victims. Concepts in this section will be labeled sequentially with MAN-#, as well as a descriptive name.

MAN-1: Telescopic Arm

The telescopic arm was inspired by the NuTech-R4 robot design in the 2008 RoboCup Rescue Robot championship held in China [4]. This concept consists of three telescopic sections that extend using a motor. The sections collapse and fold up allowing it to be easily stowed. Figure 34 illustrates this concept.

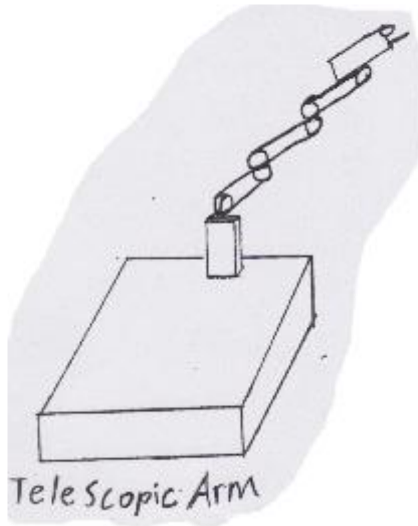


Figure 34: Sketch of the telescopic arm concept [5].

In this concept the arm is mounted to the front of the frame, and is able to rotate 180˚ in the horizontal plane, and roughly 120˚ in the vertical plane. The end effector is mounted on the end of the arm.

MAN-2: Simple Arm

This concept is the simplest possible manipulator design. It consists of an arm fixed to the frame, with the end effector mounted on the end of it. A single motor is used to move the arm up and down in the vertical plane. Figure 35 illustrates this concept.

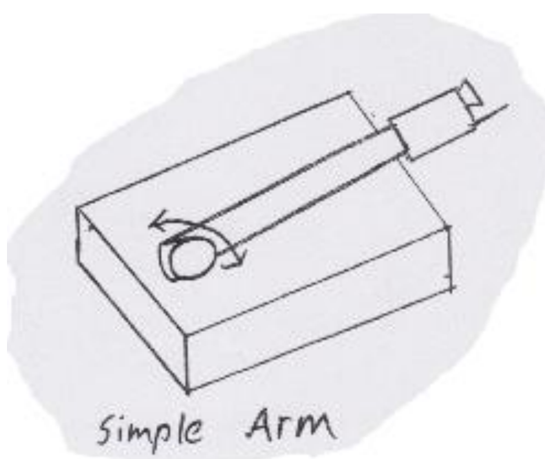


Figure 35: Sketch of the simple arm concept [5].

MAN-3: 4-Axis Arm

The 4-axis arm concept was the most common manipulator design seen in past competition designs as well as the in Couture et al [13]. The 4-axis arm concept consists of a two-section arm fixed to the frame. The end effector is mounted on the end of the arm. Figure 36 illustrates this concept.

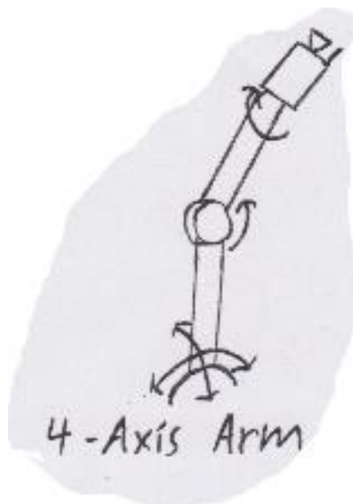


Figure 36: Sketch of the 4-axis arm [5].

This concept has 360˚ range in the horizontal plane and 180˚ in the vertical plane. The middle “elbow” joint contains a motor that allows 180˚ range of motion. This allows the manipulator to fold up and be stowed. The end effector is also given the ability to rotate, allowing for easier sensing of victims. This concept requires a minimum of four motors.

MAN-4: Double Arm

The double arm concept is a fresh idea that came as a result of the team brainstorming session. The idea is that linear rail systems in the frame take care of any forward motion necessary for the manipulator. Then, a set of two arms support the end effector, each with a shoulder joint at the rail, and an elbow joint some distance along the arm. Figure 37 is a sketch of the concept.

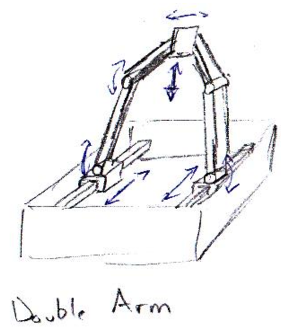


Figure 37: Sketch of the double arm manipulator concept [6].

This concept would require a lot of space within the frame to host the linear rails. It would only require two motors, as the elbow joints on each side could be freely rotating. The combination of the shoulder and elbow joints would allow motion of the end effector up and down as well as side to side in the plane perpendicular to the robot travel.

A.2 Concept Development and Selection

The concepts generated were further developed by the team using a concept screening, integration, and scoring process. A set of criteria was created for each functional subsystem to evaluate and compare concepts. Using these criteria, the concepts for each functional subsystem went through a concept screening process. Concepts were compared relative to a reference concept or benchmark and given a plus (+), minus (-) or same (0) for each of the grading criteria. Screening was done individually by each team member, to prevent bias being introduced from team members' opinions. The team then met, compared their concept screening matrices, and created a final master concept screening matrix. This process helped eliminated bias towards one's own ideas, because the votes of the other two would show the bias.

Concepts that passed concept screening were often augmented, combined, or added to using good ideas from designs that did not pass. The new concepts were then subjected to a concept scoring analysis. The criteria for each functional subsystem were weighted through a criteria weighting matrix. Each criterion was put head to head with the others, assessing which criteria is most important as related to the subsystem section. The criteria weighting was reviewed and approved by the client. The weighted criteria were then used to score each remaining concept on a scale from 1 – 5. This was performed as a team by simply working our way through each criteria and concept, discussing the scores that each other gave, and deciding upon a final score for the concept.

A.2.1 Development of Selection Criteria

The selection criteria were developed by the team during a brainstorming session. The overall criteria were created using the client's needs. This allowed the team to see which criteria were most important, and ensured that the criteria adequately covered the needs of the project. The five functional subsystems were then related to the generated criteria if they were applicable. Finally, the team looked at determining extra criteria for functional subsystems that were more specific. Figure 38 shows the results of the first brainstorming session.

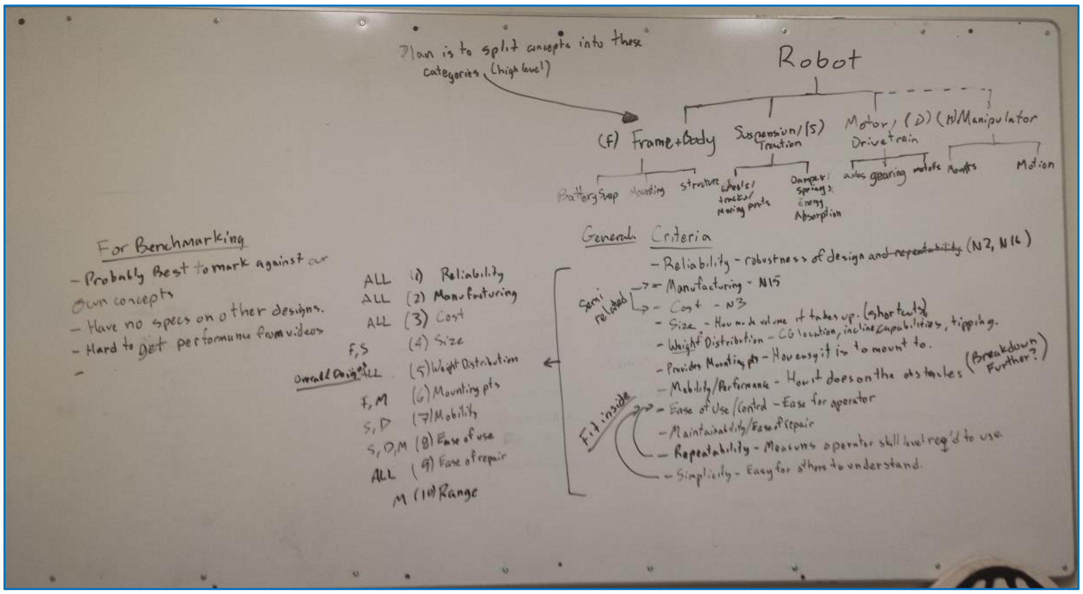


Figure 38: White board generated during selection criteria brainstorming [2].

In Figure 38 the generated criteria are seen in the bottom right, with needs behind a number of them. How each functional subsystem was related to the criteria is shown to the right of the generated criteria. TABLE I shows the shorthand the team used for each functional subsystem.

TABLE I: SHORTHAND NAMES FOR THE FUNCTIONAL SUBSYSTEMS.

Functional Subsystem	Frame	Suspension	Motor and Mobility	Manipulator	Battery Swap
Shorthand	(F)	(S)	(D)	(M)	(B)

During concept screening and scoring, the criteria were re-evaluated to ensure that they completely captured the needs of the project. The final set of selection criteria related to the client needs and functional subsystem is shown in TABLE II.

TABLE II: FINALIZED SELECTION CRITERIA.

Selection Criteria	Description	Needs Met	Sections Applicable To
Reliability	The ability of the design to endure multiple uses.	N2, N16	ALL
Manufacturability	The ease of the manufacturing process, ie. How simple is it to create the final product.	N15	ALL
Cost	The estimated cost of the design in regards to purchasing materials/parts.	N3	ALL
Size	The compactness of the design in relation to course or internal constraints.	N11 → N14, N20	F, S
Mobility/ Performance	The performance of the design in regards to traversing the course.	N4→N8, N17→N19, N21	D, S
Ease of Use	The ease of operating the design in terms of repeatability and simplicity	N1, N13	D, M, B
Ease of Repair/ Maintenance	The ease of repairing and/or replacing broken or worn out parts.	N2, N15	ALL
Manipulator Range	The range of reach the manipulator has in the vertical and horizontal planes.	N11, N14	M
Ease of Mounting	The ease of adding/designing mounting points to a design.	N9, N10	F, M
Installation Time	The time it takes to install a battery.	N1	B

A.2.2 Frame

The selection criteria was used to complete the concept screening, integration and scoring for the frame functional subsystem.

A.2.2.1 Concept Screening

FRA-6 was used as the reference concept while performing the screening. TABLE III shows the final concept screening results for the Frame subsystem.

TABLE III: FRAME CONCEPT SCREENING MATRIX

	Concept Variants					
Selection Criteria	FRA-1	FRA-2	FRA-3	FRA-4	FRA-5	REF (FRA-6)
Reliability	-	0	+	0	0	0
Manufacturability	+	0	-	+	+	0
Cost	+	-	-	0	0	0
Size	0	0	0	0	0	0
Mounting Points	+	+	+	0	0	0
Ease of Repair	+	-	-	0	0	0
Pluses	4	1	2	1	1	0
Sames	1	3	1	5	5	6
Minuses	1	2	3	0	0	0
Net	3	-1	-1	1	1	0
Rank	1	5	5	2	2	4
Continue?	YES	NO	NO	YES	YES	YES

The concepts marked as YES were combined or improved before moving onto the concept scoring stage.

A.2.2.2 Integration of Concepts

Four concepts were selected to move forward to the scoring stage, but it was decided that it would be ideal to have three concepts. As the Ladder Frame (FRA-4) and X-Frame (FRA-5) are very similar concepts that scored the exact same in the screening process, they were combined into a single concept called “2D Base with Wall” for the final scoring process.

A.2.2.3 Criteria Weighting

This sections criteria weighting was reviewed and approved by the client at a later meeting. TABLE IV shows the final criteria weights and how the team arrived at them.

TABLE IV: CRITERIA WEIGHTING FOR FRAME

Criteria		Reliability	Manufacturability	Cost	Size	Mounting Points	Ease of Repair
A	Reliability		A	A	A	A	A
B	Manufacturability			B	B	B	F
C	Cost				D	E	F
D	Size					E	F
E	Mounting Points						E
F	Ease of Repair						
Total		5	3	0	1	3	3
Weightings		0.33	0.20	0.00	0.07	0.20	0.20

After completing the weighting matrix the cost criteria received a zero value. This does not mean that the cost will not be considered during design. It simply means that the difference in cost between the three concepts was considered minimal, resulting in cost being the least important criteria and as thus will not be used during the scoring phase. Although size is an important factor, it was only given 7% weighting. This is because all three concepts have a similar shape and can be built to varying sizes. There was a three-way tie between manufacturability, mounting points and ease of repair, which were all 20%. This is because it is undesirable to have difficult manufacturing, repairing or mounting locations, but this will not prevent us from having a functional design. Reliability was weighted the highest because if a frame design cannot withstand repeated use then it does not meet the client needs.

A.2.2.4 Scoring

The final results of this scoring process for the three concepts are shown below in TABLE V.

TABLE V: FINAL RESULT OF THE SCORING FOR THE FRAME SUBSYSTEM.

Concept Scoring								
			Name of Concept Class					
			2D Base With Wall		Reinforced Sheet Metal		Tube Frame	
Criteria		Weight	Score	Weighted	Score	Weighted	Score	Weighted
A	Reliability	0.33	4	1.33	4	1.33	5	1.67
B	Manufacturability	0.20	3	0.60	4	0.80	2	0.40
D	Size	0.07	4	0.27	4	0.27	4	0.27
E	Mounting Points	0.20	4	0.80	5	1.00	3	0.60
F	Ease of Repair	0.20	3	0.60	4	0.80	2	0.40
		Total	3.6		4.2		3.3	
		Rank	2		1		3	
		YES/NO	NO		YES		NO	

It can be seen in TABLE V that the Reinforced Sheet Metal concept was a clear winner. What made this concept stand out from the rest were its manufacturability, ease of repair and the ability to place mounting points anywhere on the frame.

A.2.2.5 Summary

In summary, the six concepts generated from our internal search methods were put into a screening matrix. From the screening matrix we narrowed it down to four concepts. The X-Frame and Ladder Frame concepts were combined into a 2D Base with Wall concept, this left three concepts to go through the final scoring matrix. Criteria were assigned specific weight values by going through a criteria weight matrix. Final three concepts were scored from 1-5 in all criterions. Reinforced Sheet Metal came out on top as a clear winner.

A.2.3 Suspension

The selection criteria was used to complete the concept screening, integration and scoring for the suspension functional subsystem.

A.2.3.1 Concept Screening

The Rubber Bushing was used as the reference concept while performing the screening. TABLE VI shows the final concept screening results for the Suspension subsystem.

TABLE VI: SUSPENSION CONCEPT SCREENING MATRIX

	Concept Variants							
Selection Criteria	SUS-1	SUS-2	SUS-3	SUS-4	SUS-5	SUS-6	SUS-7	REF (SUS-8)
Reliability	0	0	0	0	0	0	0	0
Manufacturability	-	-	-	-	-	-	-	0

Cost	-	-	-	-	-	-	0	0
Size	-	-	-	-	-	0	0	0
Mobility and Obstacle Performance	+	+	+	+	+	+	+	0
Ease of Repair	-	-	-	-	-	-	0	0
Pluses	1	1	1	1	1	1	1	0
Sames	2	2	2	2	2	3	5	7
Minuses	4	4	4	4	4	3	1	0
Net	-3	-3	-3	-3	-3	-2	0	0
Rank	4	4	4	4	4	3	1	1
Continue?	NO	NO	NO	NO	NO	YES	YES	YES

Three concepts were selected to move onto the final scoring matrix.

A.2.3.2 Integration of Concepts

Combining suspension concepts did not improve the functionality of them, so the three concepts moved onto the final scoring matrix as is.

A.2.3.3 Criteria Weighting

This sections criteria weighting was reviewed and approved by the client at a later meeting. TABLE VII shows the final criteria weights and how the team arrived at them.

TABLE VII: SUSPENSION CRITERIA WEIGHTING MATRIX.

Criteria	Relia bility	factu rabili	Cost	Size	ity / Perfo rman	of Repai

A	Reliability		A	A	A	E	A
B	Manufacturability			B	B	E	B
C	Cost				D	E	F
D	Size					E	F
E	Mobility / Performance						E
F	Ease of Repair						
Total		4	3	0	1	5	2
Weights		0.27	0.20	0.00	0.07	0.33	0.13

The cost criteria received a zero after the weighting was complete. This does not mean that the cost will not be taken into account during design; rather it is simply the least important criteria and as thus will not be used during the scoring phase. Although the relative size of each concept is different, each of them has little impact on the design in terms of the course restraints. For this reason size was given a 7% weighting. Manufacturability and ease of repair were given mid-level importance because these are desirable, but are not mandatory for a functioning design. Manufacturability was weighted higher than ease of repair because the high reliability of these concepts means they likely won’t need to be repaired often. Reliability was weighted second highest because they are many obstacles throughout the competition meaning the concepts will be undergoing repeated use. Mobility and obstacle performance were weighted the highest because being able to traverse the course is connected to the majority of the client needs.

A.2.3.4 Scoring

The final results of this scoring process for the three concepts are shown below in TABLE VIII.

TABLE VIII: RESULTS FROM SUSPENSION SCORING MATRIX.

Concept Scoring								
			Name of Concept Class					
			Leaf Spring		Torsion Spring		Rubber Bushing	
Criteria		Weight	Score	Weighted	Score	Weighted	Score	Weighted
A	Reliability	0.27	4	1.07	3	0.80	5	1.33
B	Manufacturability	0.20	4	0.80	3	0.60	5	1.00
D	Size	0.07	4	0.27	3	0.20	5	0.33
E	Mobility and Obstacle Performance	0.33	5	1.67	4	1.33	3	1.00
F	Ease of Repair	0.13	4	0.53	4	0.53	5	0.67
		Total	4.3		3.5		4.3	
		Rank	1		3		1	
		YES/NO	YES		NO		YES	

It can be seen in TABLE VIII that the Torsion Spring concept was a clear loser. The Leaf Spring and Rubber Bushing concepts tied. We decided to move forward with both concepts and choosing which one to use will be dependent on which mobility concept is selected and the detailed design.

A.2.3.5 Summary

In summary, eight concepts went through the screening process and three were chosen to move onto the scoring process. No concepts were combined, as it added no benefit to the designs functionality. Mobility and Obstacle Performance and Reliability were weighted the highest of the criterion. Through the scoring process it was decided to select both the Leaf Spring and Rubber Bushing concepts for suspension. The choice of which one will be used is dependent on the mobility concept selected.

A.2.4 Motors and Mobility

Using the selection criteria, concept screening, integration and scoring were completed for the motors and mobility functional subsystem.

A.2.4.1 Concept Screening

Concept screening was completed individually by each team member on the various mobility concepts generated. After each performing the screening analysis on our own, the team met and discussed the results, creating an aggregate concept screening. This helped to eliminate bias of evaluating our own designs. MOB-3 was used as the reference concept while performing the screening. TABLE IX shows the final concept screening results for the Mobility and Motors subsystem.

TABLE IX: AGGREGATE OF INDIVIDUAL CONCEPT SCREENING.

	Concept Variants												
Selection Criteria	MOB-1	MOB-2	MOB-3 (4 WHEEL)	MOB-3 (6 WHEEL)	MOB-4	MOB-5	MOB-6	MOB-7	MOB-8	MOB-9	MOB-10	MOB-11	REF (MOB-12)
Reliability	+	0	+	+	0	0	+	+	0	+	+	+	0
Manufacturability	-	-	+	+	0	-	-	0	0	0	0	-	0
Cost	-	-	+	0	0	-	0	0	0	0	0	0	0
Size	0	+	0	-	-	+	0	0	0	0	0	0	0
Mobility/ Performance	+	+	-	-	-	+	0	+	+	+	+	+	0

Ease of Use	+	-	+	+	0	-	+	+	+	+	+	+	0
Ease of Repair	0	-	+	0	-	-	0	+	0	0	0	0	0
Pluses	3	2	5	3	0	2	2	4	2	3	3	3	0
Sames	2	1	1	2	4	1	4	3	5	4	4	3	7
Minuses	2	4	1	2	3	4	1	0	0	0	0	1	0
Net	1	-2	4	1	-3	-2	1	4	2	3	3	2	0
Rank	7	11	1	7	13	11	7	1	5	3	3	5	10
Continue?	YES	NO	YES	YES	NO	NO	YES	YES	YES	YES	YES	YES	NO

The concepts marked as YES were combined or improved before moving onto the concept scoring stage.

A.2.4.2 Integration of Concepts

While nine concepts were picked to move forward due to their positive rankings, each of these concepts contained flaws that were evident even at the screening stage. The team tried to integrate multiple concepts in to a single one, improve concepts with outside ideas and with ideas from the failed concepts.

The four wheeled and six wheeled MOB-9 concepts were combined into a single concept, which would be labeled wheel design. While there are multiple configurations for a wheeled design, the underlying principle in each is the same for traversing the course obstacles. The team also identified that MOB-6 could be integrated on to any wheel design to provide the extra mobility necessary to traverse stairs should a smaller set of wheels be necessary. This concept was renamed as Wheeled Design for the concept scoring.

MOB-10 (Tank) was augmented using MOB-7 (Suspension Tracks) when moving on to scoring. The idea for MOB-7 was simply adding a suspension system onto a set of tracks to allow small amounts of travel around a center point. MOB-10 will remain similar, except the tracks will be attached to the frame of the robot using rubber bushings to add some lateral spring and cushion impacts. This concept was renamed to Tank with Suspension for concept scoring.

MOB-1 (4 Paddle Track Design) will move forward separately without being combined with other concepts. However after talks with the team and the client, it was decided to pair the front flippers rotation, and the back flippers rotation. That is, instead of all four flippers operating independently, the front and back flippers will each work in tandem. This concept was renamed to Tandem 4 Paddle Design.

MOB-9 (Rotating Single Paddles) and MOB-11 (Dual Tracks along Length) will both move forward independently without any changes. It was simply reiterated by the team during screening that MOB-9's paddles do not move independently, and that the paddles are capable of lifting the entire body. As well it was noted that for MOB-11, each of the tracks has slight suspension to allow the front tracks to move independent from the rear tracks, allow for better surface traction on uneven terrain.

A.2.4.3 Criteria Weighting

During the team's meetings to score the concepts, a criteria weighting was performed on the criteria relating to the motors and mobility section. Each criterion was put head to head with the others, assessing which criteria is most important as related to the mobility of the robot. This sections criteria weighting was vetted by the client during a later meeting, which is important because this section consists of the core function meeting the most client needs. TABLE X shows the final criteria weights and how the team arrived at them.

TABLE X: CRITERIA WEIGHTING MATRIX FOR MOBILITY.

Criteria	Reliability	Manufacturability	Cost	Size	Mobility/ Performance	Ease of Use	Ease of Repair
A Reliability		A	A	A	E	G	A
B Manufacturability			B	B	E	G	H
C Cost				D	E	G	H
D Size					E	G	D
E Mobility / Performance						E	E
G Ease of Use							G
H Ease of Repair							
Total	4	2	0	2	6	5	2
Weightings	0.19	0.10	0.00	0.10	0.29	0.24	0.10

The cost criteria received a zero after the weighting was complete. This does not mean that the cost will not be taken into account during design; rather it is simply the least important criteria and as thus will not be used during the scoring phase. The relative weightings of the rest of the criteria show the high importance place on creating a mobile and easy to use design. Manufacturing, Size and Ease of Repair ended up tied with 10% because they are important to the client, but can be worked around if the design performs much better in other areas. For example, we have been asked to try and make our design manufacturable at Assentworks; however our client has noted during meetings that this is not the only option available, if more complex machines are needed.

A.2.4.4 Scoring

The weighted criteria were then used to score each remaining concept on a scale from 1 – 5. This was performed as a team by simply working our way through each criteria and concept, discussing the scores that each other gave, and deciding upon a final score for the concept. To properly evaluate each concept on the mobility criteria, it was split into stairs, inclines, stepfields, and pipe steps sub criteria. Each concept was graded separately on these criteria, and then the average value of these was used as the mobility grade. TABLE XI shows the results of the first concept scoring.

TABLE XI: RESULTS OF THE FIRST CONCEPT SCORING FOR MOBILITY.

Concept Scoring											
		Name of Concept Class									
		Wheeled Design		Tank with Suspension		Tandem 4 Paddles		Rotating Dual Paddles		Dual Tracks along Length	
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
A	0.19	5	0.95	5	0.95	4	0.76	4	0.76	4	0.76
B	0.10	4	0.38	3	0.29	3	0.29	4	0.38	4	0.38
D	0.10	3	0.29	4	0.38	4	0.38	4	0.38	3	0.29
E	0.29	3.25	0.93	3.75	1.07	4.25	1.21	4	1.14	3.88	1.11
G	0.24	4	0.95	4	0.95	3	0.71	4	0.95	4	0.95
H	0.10	4	0.38	2	0.19	2	0.19	3	0.29	3	0.29
	Total	3.88		3.83		3.55		3.90		3.77	
	Rank	2		3		5		1		4	
	YES/NO	NO		NO		NO		YES		NO	

The results of this scoring were extremely close. This required the team to perform sensitivity analyses on the concept scoring to determine if one concept could truly be declared the winner.

A.2.4.5 Sensitivity Analysis

A number of the values were altered on all five of the remaining concepts to see if they would significantly affect the standings. TABLE XII shows the changes tried and how they affected the scoring

TABLE XII: SENSITIVITY ANALYSES PERFORMED ON THE MOBILITY SCORING.

Change Made:	Revised Rotating Dual Paddle's score for Criteria G from 4 to 3 based on difficulties seen by the operator in the video we watched.			
Revised Scores				
Wheeled Design	Tank with Suspension	Tandem 4 Paddles	Rotating Dual Paddles	Dual Tracks Along Length
3.88	3.83	3.55	3.67	3.77
Change Made:	Revised Tandem 4 Paddle's score for Criteria G from 3 to 4 as it will be easier for the operator once he has gotten used to the robot.			
Revised Scores				
Wheeled Design	Tank with Suspension	Tandem 4 Paddles	Rotating Dual Paddles	Dual Tracks Along Length
3.88	3.83	3.79	3.90	3.77
Change Made:	Revised DTAL's score for Criteria D from 3 to 4 because it's size is similar to other concepts.			
Revised Scores				
Wheeled Design	Tank with Suspension	Tandem 4 Paddles	Rotating Dual Paddles	Dual Tracks Along Length
3.88	3.83	3.55	3.90	3.87
Change Made:	Revised Rotating Dual Paddles's Mobility score from 4 to 3.5 because it will operate worse on stairs and stepfields than initially scored.			
Revised Scores				
Wheeled Design	Tank with Suspension	Tandem 4 Paddles	Rotating Dual Paddles	Dual Tracks Along Length
3.88	3.83	3.55	3.76	3.87

TABLE XII shows that even small changes can result in concepts coming closer to winning and can change the result of which concept wins. Due to the closeness of the competition, the team thought it best to discuss these five concepts with our client. In the meeting with our client, we were advised not to score the concepts on the average performance over all of the obstacles, but rather on the single hardest obstacle. The client and the team agreed that this would be the pipe steps/hurdles that have rolling elements. Therefore the mobility criterion was solely weighted on this because if you cannot traverse these obstacles, you cannot get to other areas of the course. The revised scoring matrix is shown in TABLE XIII.

TABLE XIII: REVISED SCORING MATRIX FOR THE MOBILITY CONCEPTS.

Concept Scoring											
		Name of Concept Class									
		Wheeled Design		Tank with Suspension		Tandem 4 Paddles		Rotating Dual Paddles		Dual Tracks along Length	
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
A	0.19	5	0.95	5	0.95	4	0.76	4	0.76	4	0.76
B	0.10	4	0.38	3	0.29	3	0.29	4	0.38	4	0.38
D	0.10	3	0.29	4	0.38	4	0.38	4	0.38	3	0.29
E	0.29	1	0.29	2	0.57	5	1.43	3	0.86	2	0.57
G	0.24	4	0.95	4	0.95	3	0.71	4	0.95	4	0.95
H	0.10	4	0.38	2	0.19	2	0.19	3	0.29	3	0.29
	Total	3.24		3.33		3.76		3.62		3.24	
	Rank	4		3		1		2		4	
	YES/NO	NO		NO		YES		NO		NO	

From this scoring there is a clearer winner than previously. As well, our client expressed that the tandem 4 paddle design is the only one he has ever seen perform reliably on the hurdle step obstacle. Due to this we are going to proceed with this concept for mobility.

A.2.4.6 Summary

Selection of a mobility concept for the rescue robot proved to be a very difficult task. There were 5 very well performing concepts that have all performed at previous RRL competitions and done well. Through performing sensitivity analyses and consulting with the client, the team has selected the Tandem 4 Paddle concept to move forward with to the detailed design.

A.2.5 Battery Mounting System

Using the selection criteria from Section 4.1, concept screening was performed on the various conceptual designs. Some designs were then integrated, before final scoring was completed for the battery case designs.

A.2.5.1 Concept Screening

For this section of the design, the quarter turn battery box (BAT-2) was used as a reference for comparison of the designs. TABLE XIV shows the final screening results for the battery case design.

TABLE XIV: AGGREGATE OF INDIVIDUAL CONCEPT SCREENING.

	Concept Variants					
Selection Criteria	Magnetic mount	Battery latch	Spring retainer	Velcro retainer	Battery nest	Quarter turn fastener REF
Reliability	0	0	0	0	0	0
Manufacturability	0	+	+	+	0	0
Cost	0	0	+	+	0	0
Size	0	0	0	0	0	0
Ease of use/installation	+	+	+	+	+	0
Ease of repair	0	0	+	+	-	0
Time required to install	+	0	+	+	+	0
Pluses	2	2	5	5	2	0
Sames	5	5	2	2	4	7
Minuses	0	0	0	0	1	0
Net	2	2	5	5	1	0
Rank	3	3	1	1	5	6
Continue?	YES	YES	YES	YES	NO	NO

A.2.5.2 Integration of Concepts

Following the concept screening, four designs were selected to move forward with the design. However, we decided that the battery latch, spring retainer, and Velcro retainer designs could be integrated into one concept, labeled as the “modified latch” design. We also decided that the magnetic mounting system could be improved by incorporating elements of the battery nest within a self-contained box, with a hinged lid to enclose it. This design will be labeled as the modified magnetic design.

A.2.5.3 Criteria Weighting

The team determined the relative weight of the design criteria for the battery mounting system, with the use of a criteria selection matrix. The results are shown in TABLE XV.

TABLE XV: CRITERIA WEIGHTING MATRIX FOR THE BATTERY MOUNT.

Criteria	Reliability	Manufacturability	Cost	Size	Ease of use/installation	Ease of repair	Time required to install
A Reliability		A	A	A	E	A	H
B Manufacturability			B	D	E	B	B
C Cost				D	E	G	H
D Size					E	G	H
E Ease of use/installation						E	E
G Ease of repair							G
H Time required to install							
Total	4	3	0	2	6	3	3
Weightings	0.19	0.14	0.00	0.10	0.29	0.14	0.14

As in other sections, the cost received a weighted score of zero; however this does not mean that we will completely disregard the cost of the battery mounting system. The ease of use and installation scored by far the highest, since this is the whole purpose of a quick-change battery system. Reliability also scored high, as this is another important aspect of the design. Manufacturability, ease of repair, and time required to install the components were tied for third place. These are all criteria, which are important to the design. Size scored second to last, due to the relatively small size of the battery case, and the flexibility of the design to locate the battery in various locations within the body of the robot.

A.2.5.4 Concept Scoring

Using these criteria weights, the remaining designs were rated on a scale of 1 to 5. TABLE XVI shows the results of this concept scoring.

TABLE XVI: CONCEPT SCORING FOR THE BATTERY MOUNTING SYSTEM.

		Name of Concept Class			
		Modified magnetic		Modified latch	
Criteria	**Weight**	Score	Weighted	Score	Weighted
Reliability	0.19	4	0.76	5	0.95
Manufacturability	0.14	3	0.43	4	0.57
Cost	0.00		0.00		0.00
Size	0.10	4	0.38	4	0.38
Ease of Use/Installation	0.29	5	1.43	4	1.14
Ease of Repair	0.14	3	0.43	5	0.71
Time Required to Install	0.14	5	0.71	4	0.57
		4.14		4.33	
		2		1	
		NO		YES	

A.2.5.5 Summary

The results of the scoring were very close, however the modified latch design scored slightly higher. After consulting with our client, it was further confirmed that using purely magnets to attach the battery case would not be a good idea, as they felt that a magnetic system would not securely hold the battery in place, when experiencing impacts and vibration during the competition. Therefore the team decided to go with the modified latch design to retain the battery in place within the robot chassis. However, the use of a magnetic power connector was determined to still be a valid design concept, and may be incorporated into the final design.

A.2.6 Manipulator

Using the selection criteria, concept screening, integration and scoring were completed for the manipulator functional subsystem.

A.2.6.1 Concept Screening

The double arm manipulator concept was used as the reference while performing the screening. TABLE XVII shows the final concept screening results for the Manipulator subsystem.

TABLE XVII: MANIPULATOR CONCEPT SCREENING MATRIX

	Concept Variants			
Selection Criteria	MAN-1	MAN-2	MAN-3	REF (MAN-4)
Reliability	0	0	+	0
Manufacturability	0	0	+	0
Cost	0	0	+	0
Size	+	-	-	0
Weight Distribution	+	-	-	0
Mounting Points	0	0	0	0
Ease of Use	0	-	+	0
Ease of Repair	0	0	+	0
Manipulator Range	+	-	-	0
Pluses	3	0	5	0
Sames	6	5	1	9
Minuses	0	4	3	0
Net	3	-4	2	0
Rank	1	4	2	3
Continue?	YES	NO	YES	YES

From the screening process the simple arm concept did not qualify for the scoring process, as it was the only concept to score negatively. The remaining three concepts moved on to the scoring process.

A.2.6.2 Integration of Concepts

All manipulator concepts were significantly different from each other and no method of combining concepts added any benefit, hence all concepts proceeded as is.

A.2.6.3 Criteria Weighting

TABLE XVIII shows the final criteria weights, after performing the criteria weighting.

TABLE XVIII: CRITERIA WEIGHTING MATRIX FOR MANIPULATOR SECTION

Criteria	Simplicity	Manufacturability	Cost	Size	Weight Distribution	Mounting Points	Ease of Use	Ease of Repair	Manipulator Range
Reliability		A	A	A	A	A	G	A	I
Manufacturability			B	B	E	B	G	H	I
Cost				D	E	F	G	H	I
Size					E	D	G	H	I
Weight Distribution						E	G	E	I
Mounting Points							G	H	I
Ease of Use								G	G
Ease of Repair									I
Manipulator Range									
Total	6	3	0	2	5	1	8	4	7
Weightings	0.17	0.08	0.00	0.06	0.14	0.03	0.22	0.11	0.19

After evaluating the criteria for the manipulator, once again the cost scored zero in the rankings. While cost is always a factor for design, it was deemed to be less important than the functionality of the manipulator. Ease of use, manipulator range, and simplicity all scored high, as they are key requirements of the manipulator design. Weight distribution and ease of repair had moderate scores, as these are also important, but not absolutely essential. Manufacturability, size, and mounting points scored relatively low. These are still relevant to the design, but were deemed to be of low priority.

A.2.6.4 Scoring

Based on the criteria weighting, the three competing designs were scored as shown in TABLE XIX.

TABLE XIX: RESULTS OF CONCEPT SCORING FOR THE MANIPULATOR

Concept Weighting							
		Name of Concept Class					
		A (Telescopic)		B (Simple arm)		G (4-axis)	
Criteria	**Weight**	Score	Weighted	Score	Weighted	Score	Weighted
Reliability	0.17	3	0.50	4	0.67	4	0.67
Manufacturability	0.08	3	0.25	3	0.25	3	0.25
Cost	0.00		0.00		0.00		0.00
Size	0.06	5	0.28	2	0.11	3	0.17
Weight Distribution	0.14	5	0.69	3	0.42	4	0.56
Mounting Points	0.03	3	0.08	3	0.08	4	0.11
Ease of Use	0.22	4	0.89	2	0.44	4	0.89
Ease of Repair	0.11	3	0.33	4	0.44	3	0.33
Manipulator Range	0.19	4	0.78	2	0.39	5	0.97
Total		3.81		2.81		3.94	
Rank		2		3		1	
YES/NO		NO		NO		YES	

After the scoring, the 4-axis design came out as the top design, slightly beating out the telescopic arm design.

A.2.6.5 Summary

After screening and scoring the four initial design concepts, the double arm design was eliminated. Since the three remaining designs were functionally different, it was not possible to combine any of these into further concepts. Upon concept scoring, it was determined that the 4-axis arm design would be the best option for the robot design, and therefore this was the final design chosen.

Appendix B: Performance Calculations

B.1 Motor Torque Calculations

To select a motor, the torque required to drive the robot was initially estimated using a robot weight of 15 kg taken from the NAJI-IV [source]. The final weight of the robot was determined to be 25kg, so the torque calculations were redone for a 25 kg robot. The two scenarios considered while calculating the required torque were flat ground driving forward and driving up a 60° ramp. Figure 39 and Figure 40 are free body diagrams for the two scenarios.

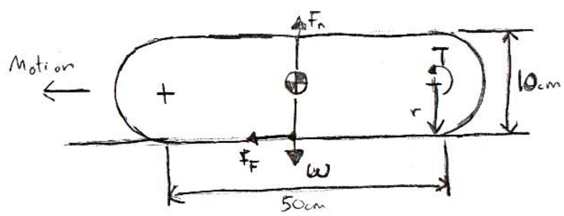


Figure 39: Free body diagram of flat ground motion.

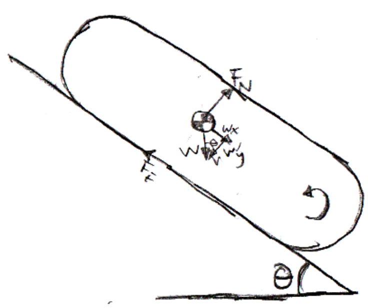


Figure 40: Free body diagram of incline ground motion.

The maximum torque to not exceed ground friction force uses

$$T = F_f r = \mu F_n r = \mu m g r \quad \text{Eq. 1}$$

The friction coefficient (μ) used was for NBR as 2.21 and the radius of the track was taken as 5 cm for both the 25 and 15 kg robots.

Using these values the torque was calculated for the 15 kg robot.

$$T = 2.21 * 15 * 9.81 * .05$$

$$T = 16.26\ Nm$$

The torque was also calculated for the 25 kg robot.

$$T = 2.21 * 25 * 9.81 * .05$$

$$T = 27.1\ Nm$$

For the uphill scenario two different equations were used. Eq. 2 is the torque required to overcome the weight of the robot.

$$T = W_x * r = mgr * sin\theta \qquad \textbf{Eq. 2}$$

Eq. 3 is the maximum torque allowable without the tracks slipping.

$$T = (F_f) * r = F_n * \mu * r = m * g * r * \mu * cos\theta \qquad \textbf{Eq. 3}$$

If we substitute the friction coefficient and radius values for a 15 kg robot on a 60 degree incline, the minimum torque required to overcome the weight can be calculated.

$$T = mgr * sin\theta$$

$$T = 15 * 9.81 * .05 * \sin(60)$$

$$T = 6.37\ Nm$$

Substituting µ and r into Eq. 3 for the 15 kg robot on a 60 degree incline, the maximum torque allowable to not slip was calculated.

$$T = m * g * r * \mu * cos\theta$$

$$T = 15 * 9.81 * .05 * (2.21 * \cos 60)$$

$$T = 8.13\ Nm$$

These calculations were redone for the 25 kg robot.

$$T = mgr * sin\theta$$

$$T = 15 * 9.81 * .05 * \sin(60)$$

$$T = 6.37\ Nm$$

$$T = m * g * r * \mu * cos\theta$$

$$T = 25 * 9.81 * .05 * (2.21 * \cos 60)$$

$$T = 13.55\ Nm$$

The torque required for each scenario is summarized in TABLE XX for both the 15 kg initial robot weight estimate and the final 25 kg robot.

TABLE XX: TORQUE REQUIRED FOR DIFFERENT LOADING SCENARIOS.

Scenario	Value Meaning	15 kg Robot Torque (Nm)	25 kg Robot Torque (Nm)
Flat Ground Motion	Max Torque due to friction	16.26	27.1
Uphill Incline Motion	Max Torque due to friction	8.13	13.55
Resist Motion on Incline	Min torque to not slide due to weight.	6.37	10.62

B.2 Shaft Calculations

Using the methods presenting in Chapter 12 of [14], the shaft was analyzed to determine the minimum diameters in each section. For the shaft, 4130 normalized steel rod with material properties determined from the supplier Online Metals will be used. Figure 41 shows the general layout of the drive shaft and idler shaft.

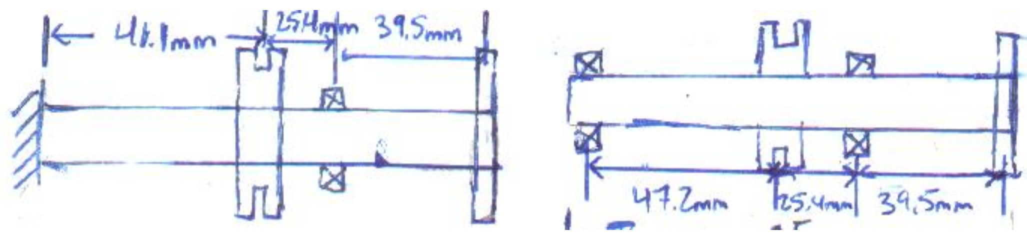


Figure 41: Layout of the drive (left) and idler (right) shafts.

The average torque expected to be output from the harmonic drive is 16.55 Nm. The drive should not be operated continuously above this limit, and thus, this torque was used for the torque loading of the drive. This results in a tension force in the chain (**F_c**) of 163.34N. Figure 42 shows the free body diagram for the two different shafts.

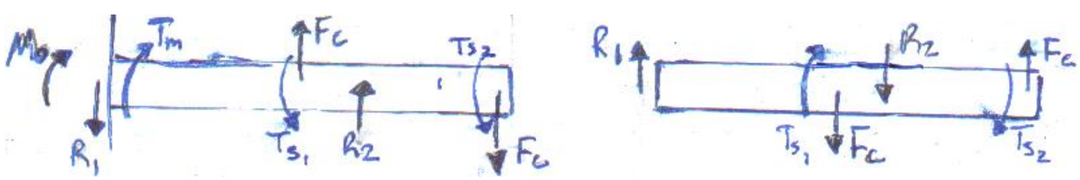


Figure 42: Free body diagram of the drive (left) and idler (right) shafts.

Using the free body diagram, the shear and bending moment equations of each shaft can be determined.

B.2.1 Drive Shaft

The sum of the forces about the fixed end of the drive shaft results in Eq. 4.

$$M_o = F_c * d_1 + R_2 * d_2 - F_C * d_3 \qquad \text{Eq. 4}$$

The sum of the forces in the vertical direction for the drive shaft results in Eq. 5

$$R_1 = R_2 \qquad \text{Eq. 5}$$

The resulting equations cannot be solved for analytically through combining equations. The use of Castigliano's Theorem taken from [15] was used to determine the reaction forces on the shaft and is shown in Eq. 6.

$$y = \frac{1}{EI}\int M(x)\frac{\partial M}{\partial R_2}dx \quad \text{Eq. 6}$$

This equation is used to determine the deflection of a beam. However, it can also be used to determine the reaction forces on a statically indeterminate beam. To do so, the moment in the section of the beam containing R_2 must first be determined. Figure XX depicts the scenario for calculating the moment in section 2 of the beam.

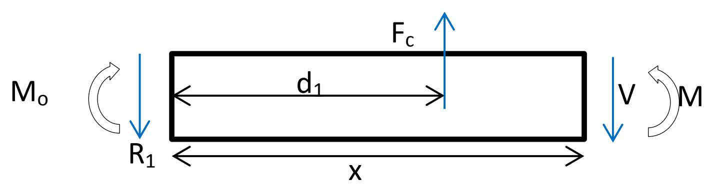


Figure 43: Moment diagram for section two of the drive shaft.

From the diagram, Eq. 7 was developed for the moment and Eq. 8 for the shear in section 2 of the shaft.

$$M_2 = M_o - F_c * d_1 + Vx \quad \text{Eq. 7}$$

$$V_2 = F_c - R_1 \quad \text{Eq. 8}$$

Substituting Eq. 8 and Eq. 4 in to Eq. 7 manipulates the equation into terms of only R_2 and F_c. This equation is shown in Eq. 9.

$$M_2 = R_2 * (d_1 + d_2 - x) + F_c * (x - L) \quad \text{Eq. 9}$$

Differentiating the moment with respect to the reaction force and substituting the result in to Eq. 6 leads to Eq. 10.

$$y = \frac{1}{EI}\int R_2 * (d_1 + d_2 - x) + F_c * (x - L) * (d_1 + d_2 - x)dx \quad \text{Eq. 10}$$

Eq. 10 can be solved at the bearing location by setting y = 0, and by knowing the distances to part locations on the shaft. As the design evolved, the values of d_1 and d_2 changed, but the final values that were used were 41.1mm and 25.4mm. Substituting values of L = 106mm, d_1, d_2 into Eq. 10.

$$0 = \int R_2 * (.0665 - x) + 163.34 * (x - .106) * (.0655 - x)dx$$

$$R_2 = 1.244 * F_c = R_1$$

The reaction forces were then used to generate the bending moment and shear force diagrams.

B.2.2 Idler Shaft

Summing the forces about the simply supported end of the idler shaft shown in Figure 42 results in Eq. 4.

$$F_c * d_1 + R_2 * d_2 = F_C * d_3 \quad \text{Eq. 11}$$

The sum of the forces in the vertical direction for the drive shaft results in Eq. 5

$$R_1 = R_2 \quad \text{Eq. 12}$$

Solving Eq. 11 for the reaction force R_2 results in Eq. 13.

$$R_2 = R_1 = \frac{F_C * (d_3 - d_1)}{d_2} \quad \text{Eq. 13}$$

B.2.3 Shear Force and Bending Moment

Figure 44 shows the shear force diagrams of the drive and idler shafts.

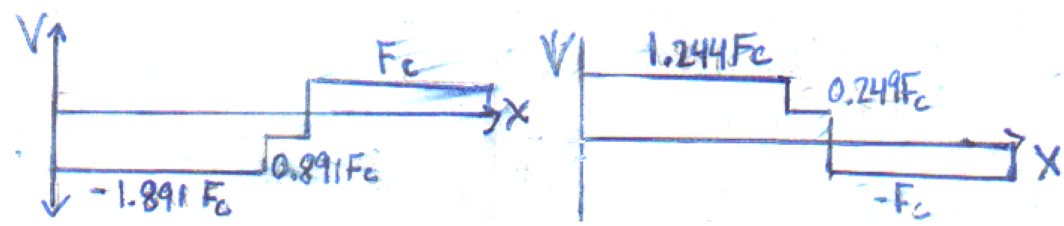


Figure 44: Shear force diagrams for the drive (left) and idler (right) shafts.

Figure 45 shows the shear force diagrams of the drive and idler shafts.

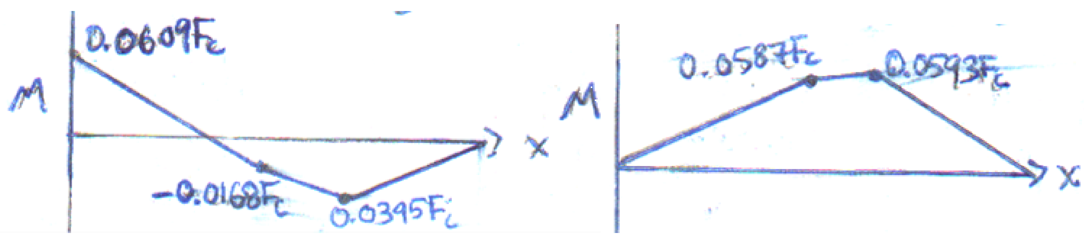


Figure 45: Bending moment diagrams for the drive (left) and idler (right) shafts.

For a shaft in fully reversed bending loads the minimum diameter can be determined using Eq.14.

$$D = \left[\frac{32N}{\pi}\sqrt{\left(\frac{k_t M}{Sn'}\right)^2 + \frac{3}{4} * \left(\frac{T}{S_y}\right)^2}\right]^{\frac{1}{3}} \quad \text{Eq.14}$$

The design factor N was chosen as 2.0 due to a relatively well known loading scenario with good confidence. The factor k_t is dependent upon the stress concentrations in the separate sections of the shaft. Variables M and T are the maximum bending moment and torque in a section of the shaft. S_n' and S_y are the modified endurance strength and yield strength of the material. TABLE XXI contains the various k_t factors used.

TABLE XXI: STRESS CONCENTRATION FACTORS FOR A SHAFT.

Shaft Item	k_t
Retaining Ring Groove	3.0

Sharp Fillet	~2.5 (Dependent upon Diameter)
Well Rounded Fillet	~1.5 (Dependent upon Diameter)
Keyways	2.0

The stress concentration factors for a shaft can be determined using the graph in Figure 46 from [14].

[redacted]

Figure 46: Stress concentration factor (k_t) for a stepped round shaft.

Stress concentration factors for the radius were initially assumed to be the values in TABLE XXI for a sharp fillet. The fillet radius was allowed to be a minimum of 1 mm, and was recalculated once the final diameters were determined to ensure the stress concentration factors were similar.

Sn’ can be calculated by applying modified factors for size, material, loading scenario and reliability to the endurance strength of 4130 normalized steel rod. The ultimate and yield strength of 4130 normalized steel is 97.2 ksi and 63.1 ksi respectively. The endurance limit was determined using the ultimate strength and Figure 47 taken from [14].

Figure 47: Endurance strength (S_n) vs Tensile strength (S_u) for wrought steel.

Material, size, loading, and reliability factors were applied to the endurance stress to get the adjusted endurance strength for this application. TABLE XXII summarizes the values found.

TABLE XXII: VALUES USED TO DETERMINE THE ENDURANCE LIMIT.

Variable	Value
S_u	97.2 ksi
S_y	67.1 ksi
S_n	37.5 ksi
C_m	1.00
C_s	0.88
C_{st}	1.0
C_r	0.81
S_n'	**26.61 ksi**

Using Eq.14 and the values in TABLE XXII the minimum diameters of the shaft were determined. TABLE XXIII shows the minimum diameters useable for the shaft not fail in fatigue loading.

TABLE XXIII: MINIMUM SHAFT DIAMETERS.

Section	Min. Drive Shaft Diameter	Min. Idler Shaft Diameter
1	15mm	11mm
2	13mm	15mm
3	13mm	15mm

To mount the proper components to the harmonic drive and to the sprockets, larger diameters were chosen. Choosing a larger diameter will mean the shaft is over designed, but this can also help account for any uncertainties in the loading scenario such as the speed required to machine the shaft. The k_t factors for the fillet radii must also be recalculated. A sharp fillet was chosen between the three diameters with a minimum value of 1mm and the allowable radius can be determined using Figure 46. TABLE XXIV shows the final shaft diameters and allowable fillet radii.

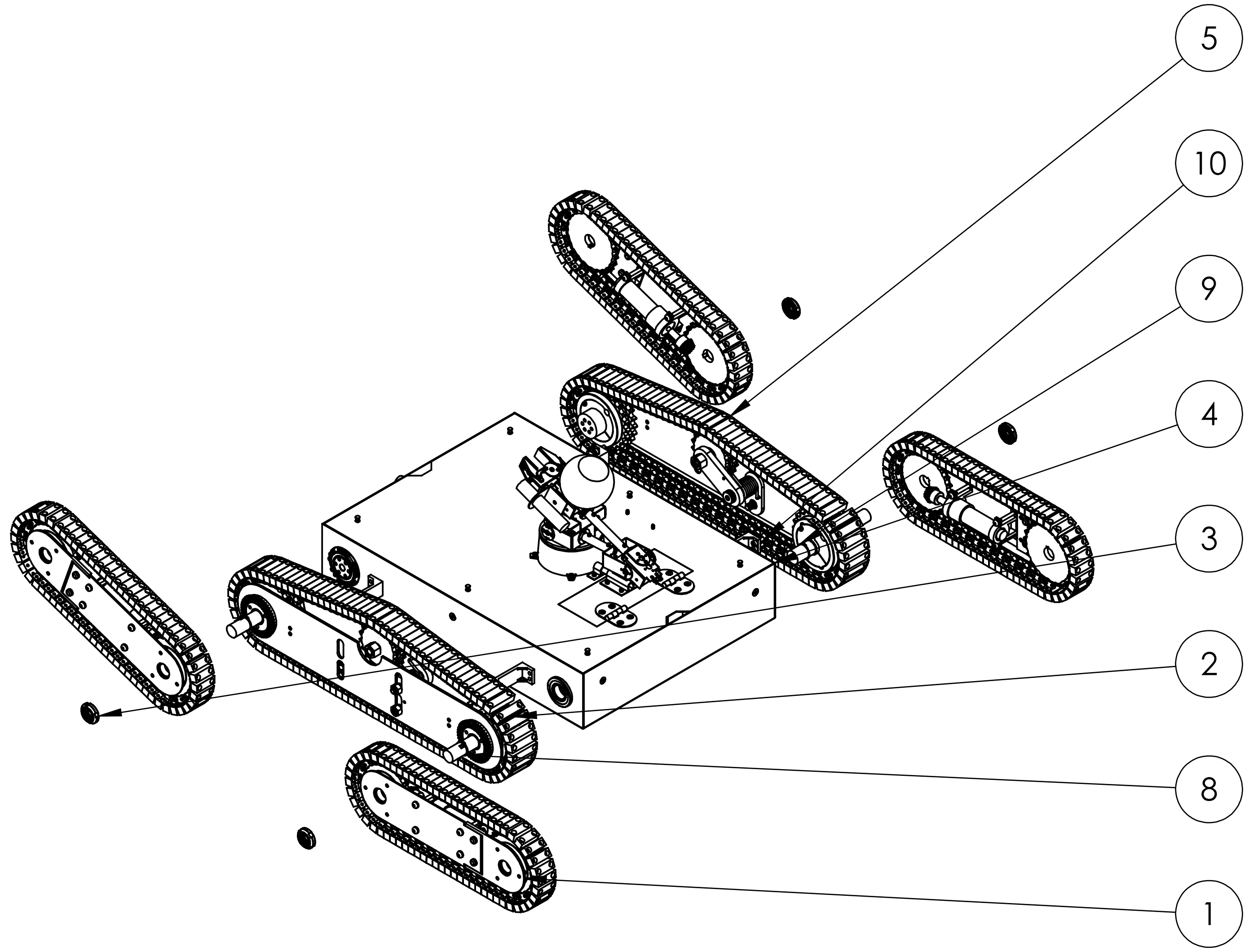
TABLE XXIV: CHOSEN SHAFT DIAMETERS.

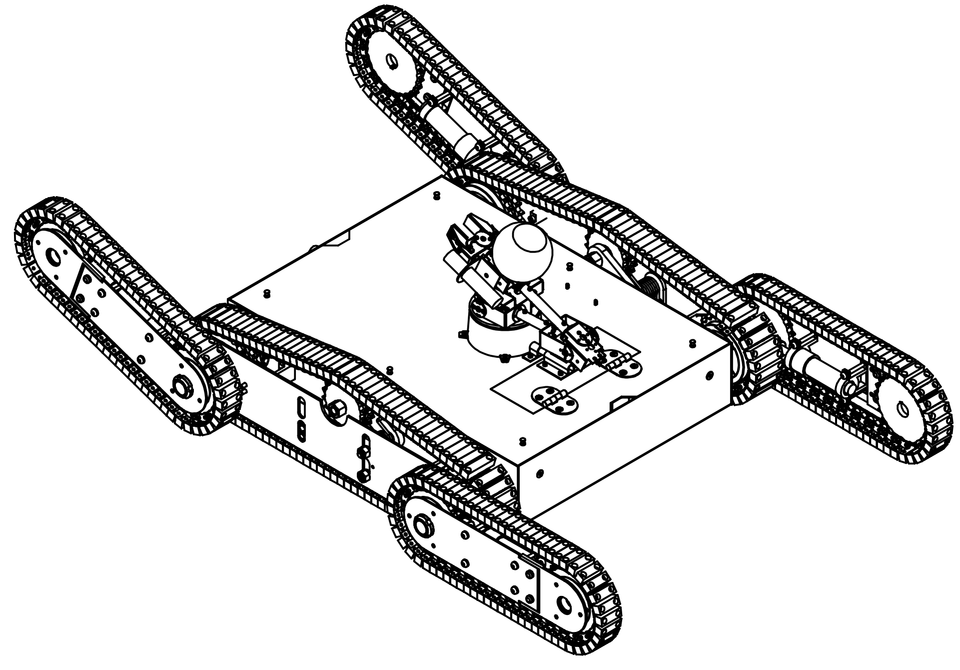
Section	Min. Drive Shaft Diameter	Min Fillet Radii	Min. Idler Shaft Diameter	Allowable Fillet Radi
1	40mm	--	22.225mm (7/8in)	.5mm
2	25.4mm (1in)	.889mm	25.4mm (1in)	--
3	20mm	0.5mm	20mm	0.5mm

The allowable fillet radii are below the machining minimum of 1 [mm], so setting a fillet radii of 1 [mm] will create a lower stress concentration than already anticipated.

Appendix C: Engineering Drawings

This appendix contains the engineering drawings relevant to the design of a mechanical subsystem for a RoboCup Rescue Robot.





ITEM NO.	QTY.	PART NUMBER	DESCRIPTION
10	8	socket head cap screw_am	M5 Fasteners
9	2	ME16-MECH-P005-.875_Ret_Ring-R00	Shaft Retaining Ring
8	4	ME16-MECH-P004-20mm_Ret_Ring-R00	Shaft Retaining Ring
7	1	ME16-MECH-P003-PaddleKey-R00	3/16" x 3/16"D6 Key
6	1	ME16-MECH-P002-MainDriveKey-R00	1/4"x1"4 Key
5	1	ME16-TRC-A001-LH_Main_Track-R00	LH MAIN TARCK ASSEMBLY
4	1	ME16-FRM-A001-FrameAssy-R00	FRAME ASSEMBLY
3	6	ME16-MECH-P001-ShaftCollar-R00	SHAFT COLLAR
2	1	ME16-TRC-A000-RH_Main_Track-R00	RH MAIN TRACK ASSEMBLY
1	4	ME16-PAD-A000-PaddleAssembly-R00	PADDLE ASSEMBLY

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION R00

Team 21: Rescue Rangers

	NAME	SIGNATURE	DATE
DRAWN	Blair Shewfelt		11/27/2015
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

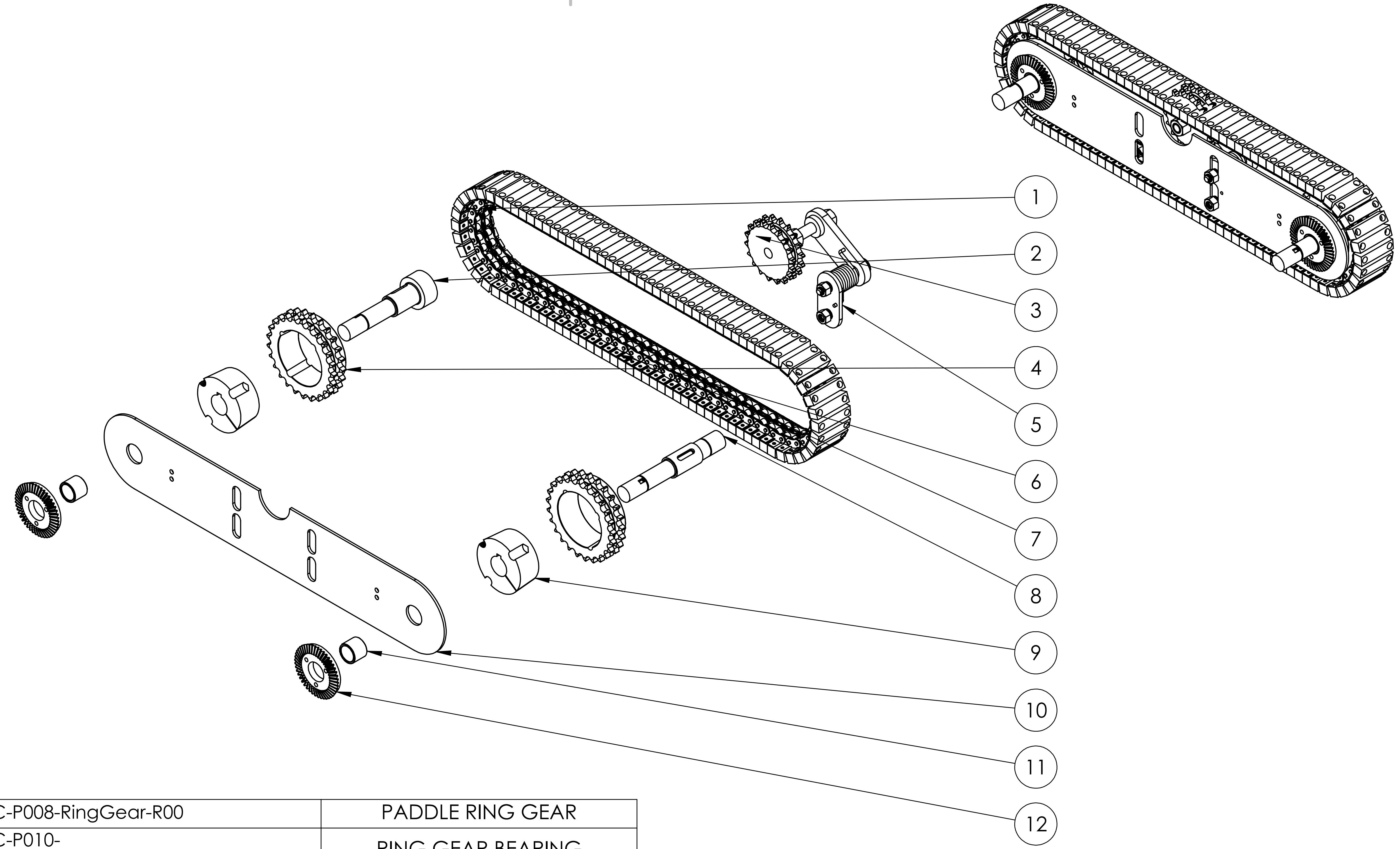
TITLE:
Rescue Robot Full Assembly

DWG NO. ME16-MECH-A000-MainAssy-R00

A3

SCALE:1:10

SHEET 1 OF 1



ITEM NO.	QTY.	PART NUMBER	DESCRIPTION
12	2	ME16-TRC-P008-RingGear-R00	PADDLE RING GEAR
11	2	ME16-TRC-P010-DriveshaftBearingNSKLM1820-R00	RING GEAR BEARING
10	1	ME16-TRC-P009-CoverPlate-R00	PROTECTIVE COVER PLATE
9	2	ME16-TRC-P005-TaperLockBushing-R00	TAPER LOCK BUSHING 1" BORE
8	1	ME16-TRC-P007-IdleShaft-R00	IDLER SHAFT
7	48	ME16-TRC-P002-40-2ChainOuter-R00	ANSI 40-2 CHAIN OUTER LINK
6	96	ME16-TRC-P003-Traction_Pad-R00	NBR RUBBER STRIP
5	1	ME16-TRC-A001-RH_TensionerAssy-R00	TENSIONER ASSEMBLY
4	2	ME16-TRC-P006-TaperLockSprocket-R00	TAPER LOCK SPROCKET 25 TEETH
3	1	ME16-TRC-P004-Idler-R00	18 TOOTH IDLER SPROCKET 1/2" BORE
2	1	ME16-TRC-P011-DriveShaft-R00	DRIVE SHAFT
1	48	ME16-TRC-P00[illegible]-40-2ChainInner-R00	ANSI 40-2 CHAIN INNER LINK

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION R00

Team 21: Rescue Rangers

	NAME	SIGNATURE	DATE
DRAWN	Blair Shewfelt		11/27/2015
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

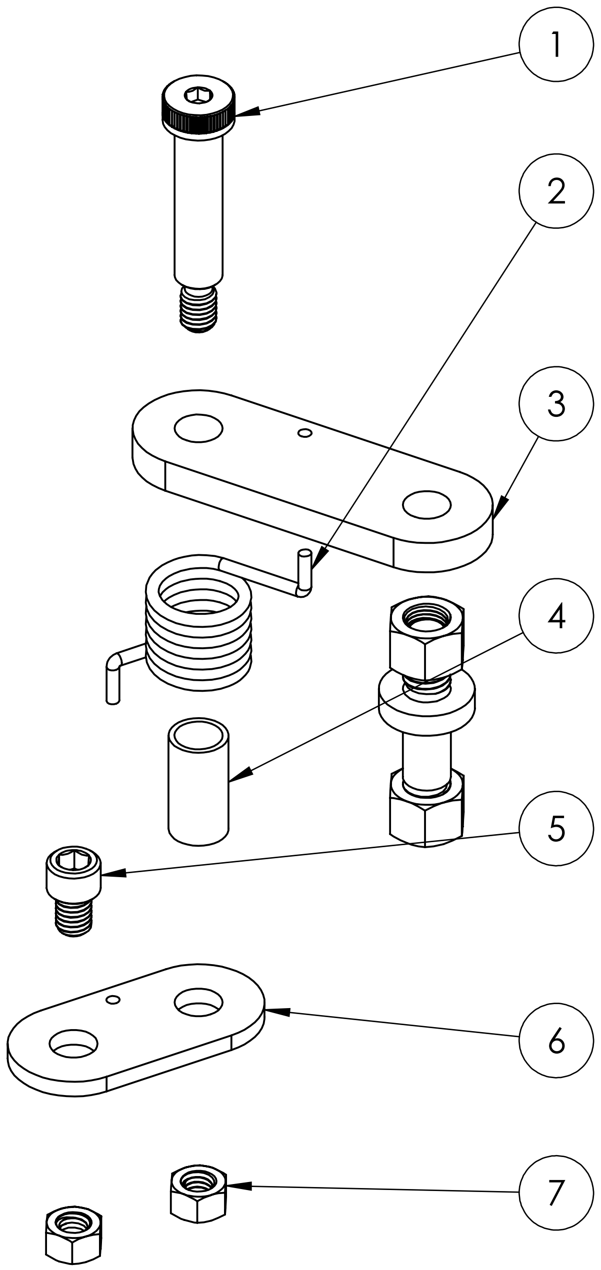
RH MAIN TRACK ASSEMBLY

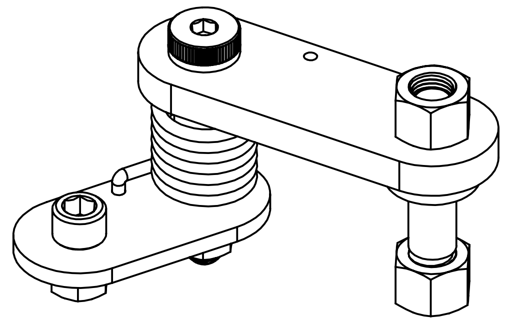
DWG NO. ME16-TRC-A001-Main_Track-R00

A3

SCALE:1:5

SHEET 1 OF 1





ITEM NO.	QTY.	PART NUMBER	DESCRIPTION
9	2	ME16-TRC-P019-IdlerShaft-R00	1/2"-20 Hex Nut
8	1	ME16-TRC-P019-IdlerShaft-R00	Shaft that Holder Idler
7	2	ME16-TRC-P018-TensionerNut-R00	3/8" X 16 NUT
6	1	ME16-TRC-P012-TensionerBase-R00	TENSIONER BASE PLATE
5	1	ME16-TRC-P017-TensionerBolt-R00	3/8" X 16 FASTENER
4	1	ME16-TRC-P014-SleeveBushing-R00	DRY BUSHING
3	1	ME16-TRC-P013-TensionerArm-R00	TENSIONER ACTUATING ARM
2	1	ME16-TRC-P016-RH_TorsionSpring-R00	120 DEGREE TORSION SPRING
1	1	ME16-TRC-P015-TensShoulderBolt-R00	1/2" SHOULDER BOLT 3/8" X 16 THREAD

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

	NAME	SIGNATURE	DATE
DRAWN	Blair Shewfelt		11/27/2015
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

DO NOT SCALE DRAWING

REVISION R00

Team 21: Rescue Rangers

TITLE:

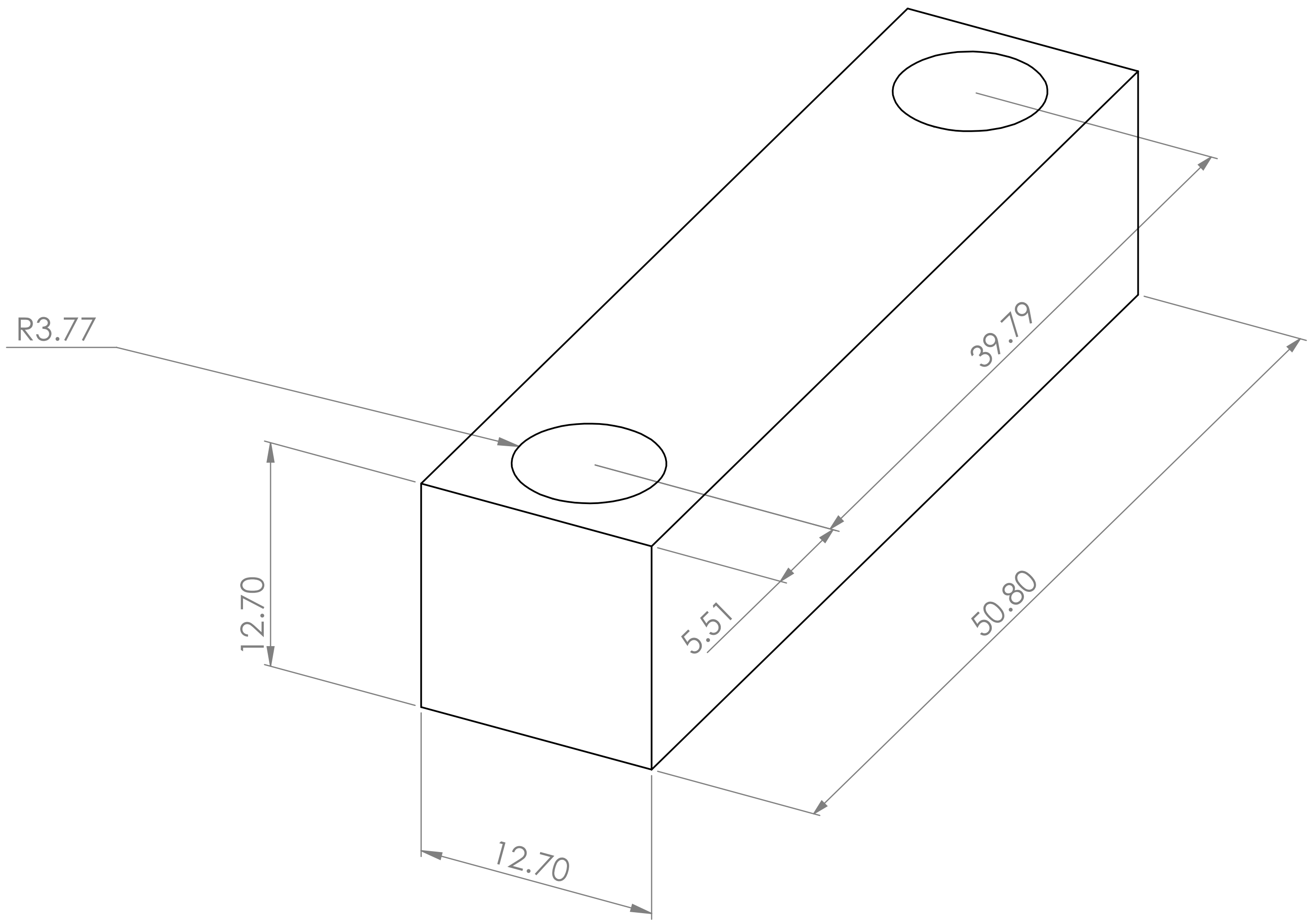
RH TENSIONER ASSY, LH OPP

DWG NO. ME16-TRC-A001-RH_TensionerAssy-R00

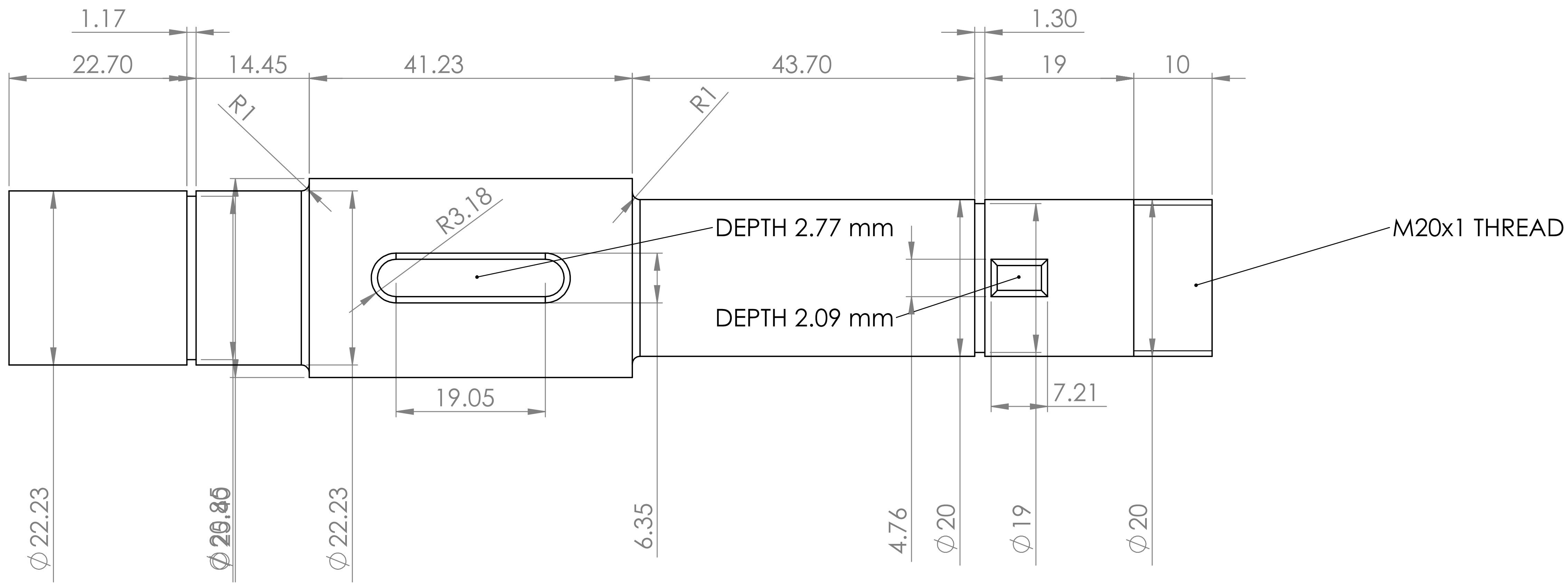
A3

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 1 mm ANGULAR: 1 deg		FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION 00
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN	L. REMPLE		05/12/15			TRACK TRACTION PAD	
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: NBR Rubber		DWG NO. ME16-TRC-D003-Traction_Pad-R00	A3
				WEIGHT:		SCALE:3:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:		DEBURR AND BREAK SHARP EDGES	

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

DO NOT SCALE DRAWING

REVISION 00

TITLE:

IDLE SHAFT

MATERIAL: 4340 Steel

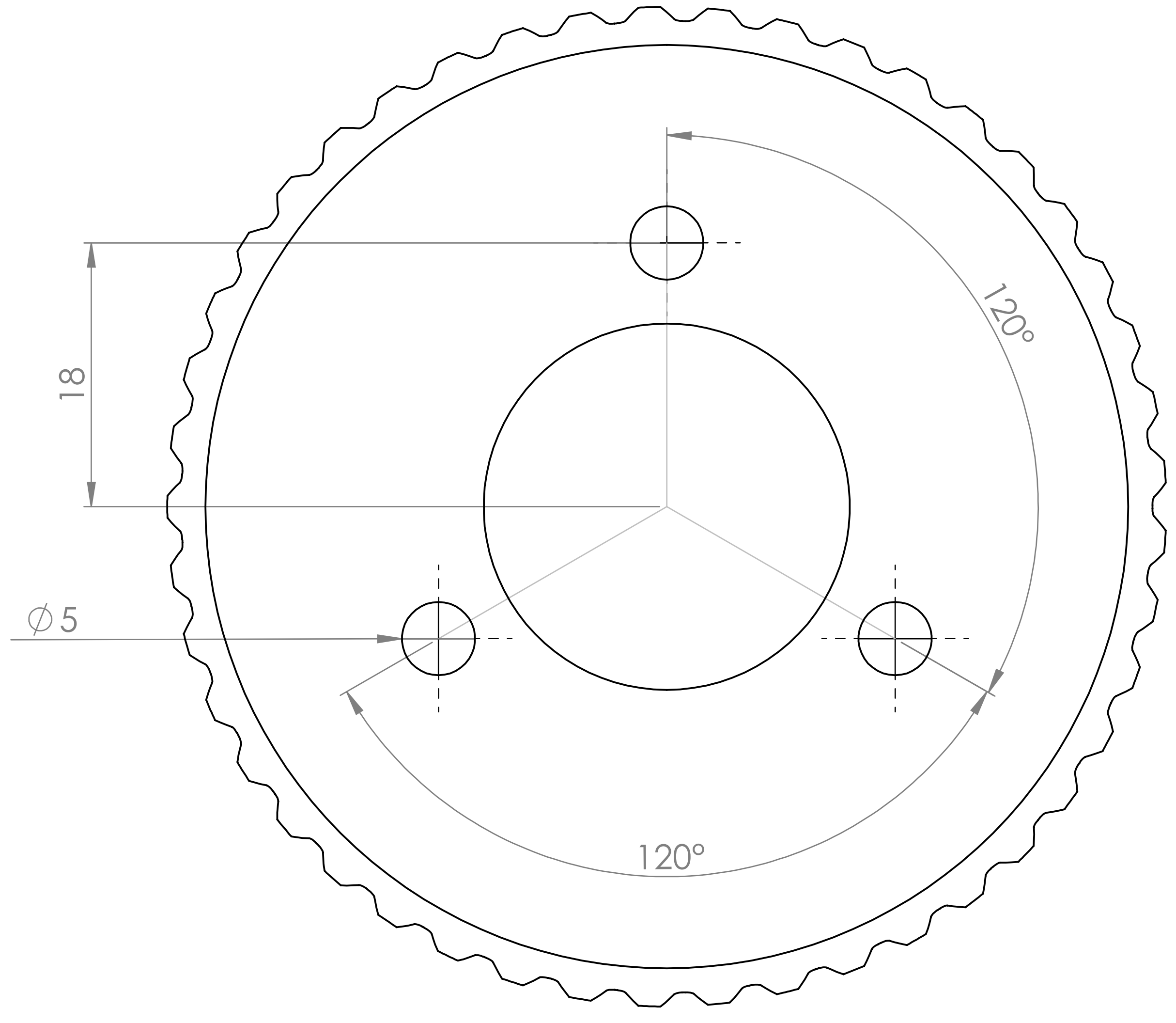
DWG NO. ME16-TRC-D007-IdleShaft-R00

A3

WEIGHT:

SCALE:1.5:1

SHEET 1 OF 1



MODIFIED RING GEAR PN A1C 3MYK10045
REQUIRES BACK FACE OF GEAR MACHINED FLUSH
AND HOLES DRILLED AT SPECIFIED LOCATIONS

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 DEG	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: MODIFIED RING GEAR

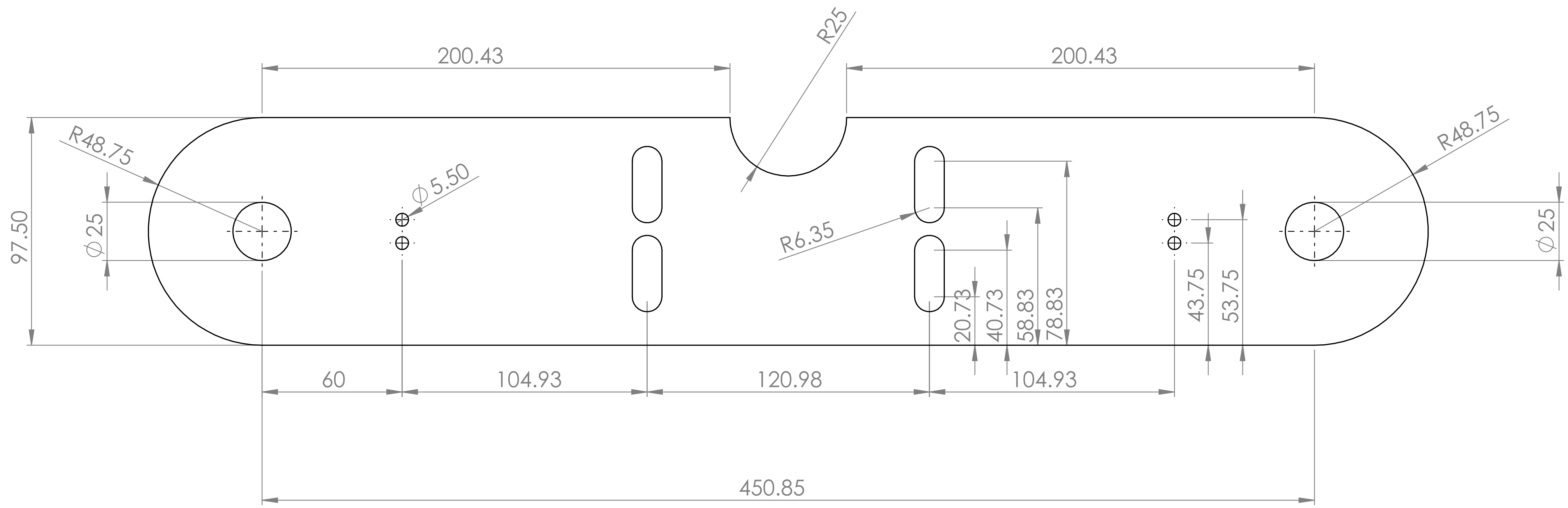
MATERIAL: Steel (alloy unknown)

DWG NO. ME16-TRC-D008-RingGear-R00 — A3

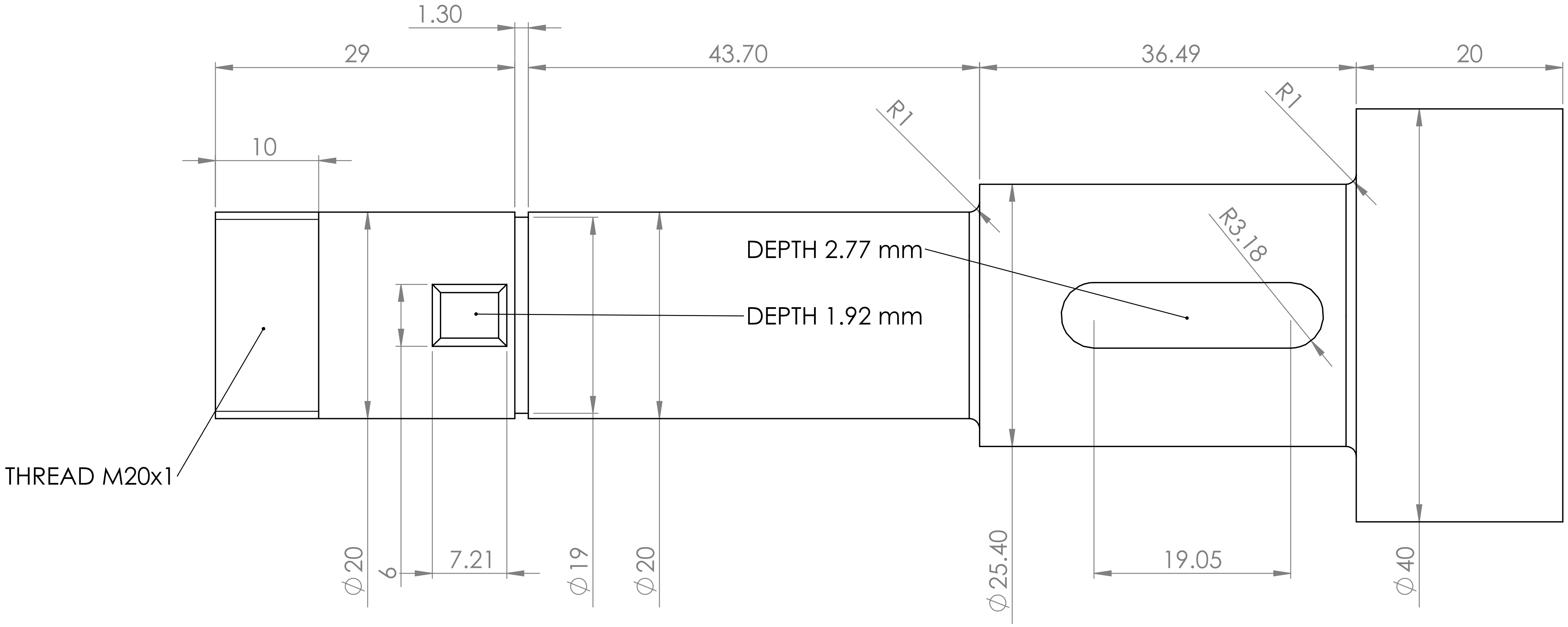
WEIGHT:

SCALE:1.5:1 — SHEET 1 OF 1

MATERIAL THICKNESS 4.826 mm



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00		
	NAME	SIGNATURE	DATE	TITLE: MAIN TRACK COVER PLATE			
DRAWN	L. REMPLE		05/12/15				
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: Al 6061-T6	DWG NO. ME16-TRC-D009-CoverPlate-R00	A3	
				WEIGHT:	SCALE:1:2	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: 0.5 mm
ANGULAR: 1 deg

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

DRIVE SHAFT

MATERIAL: 4340 Steel

DWG NO. ME16-TRC-D011-DriveShaft-R00

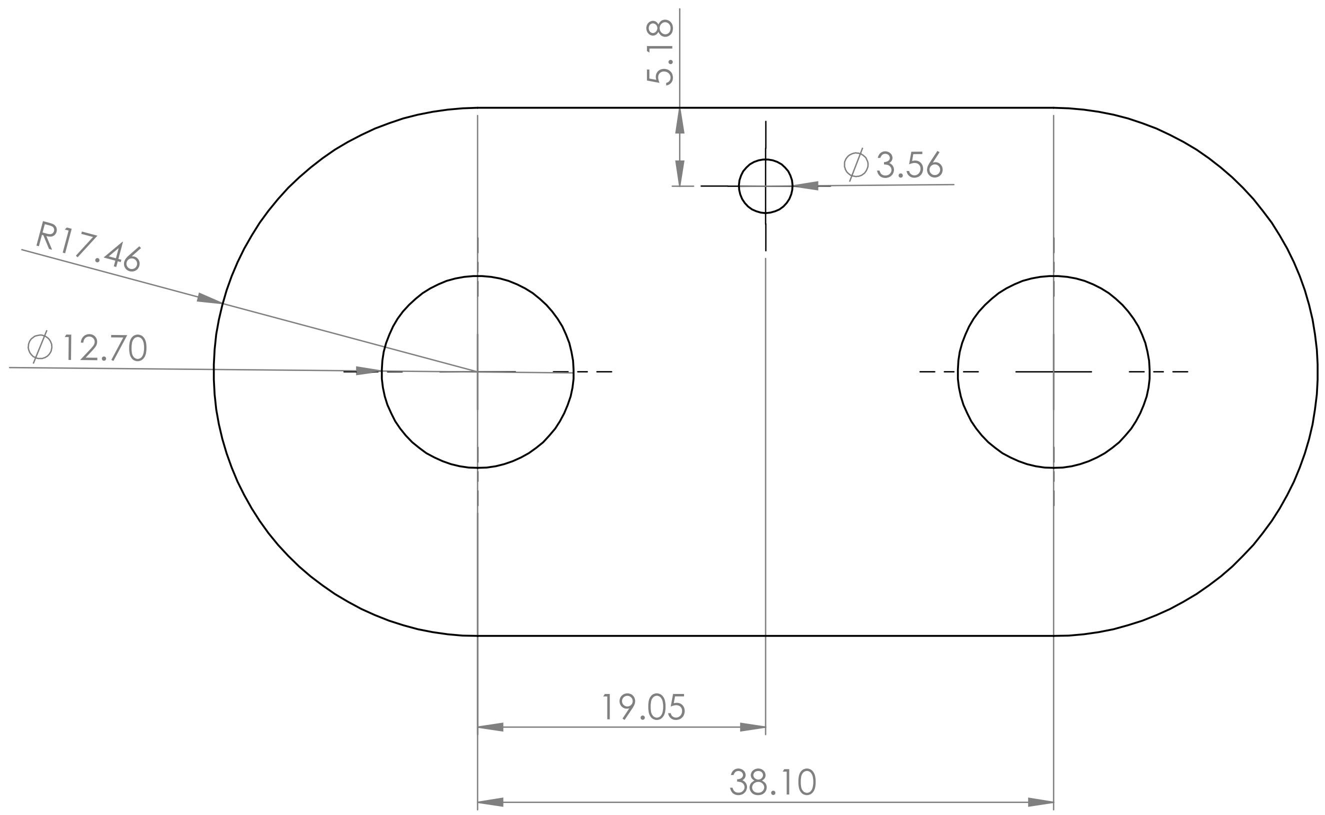
A3

WEIGHT:

SCALE:1:2

SHEET 1 OF 1

MATERIAL THICKNESS 4.76 mm



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: TENSIONER BASE

MATERIAL: 1020 Steel

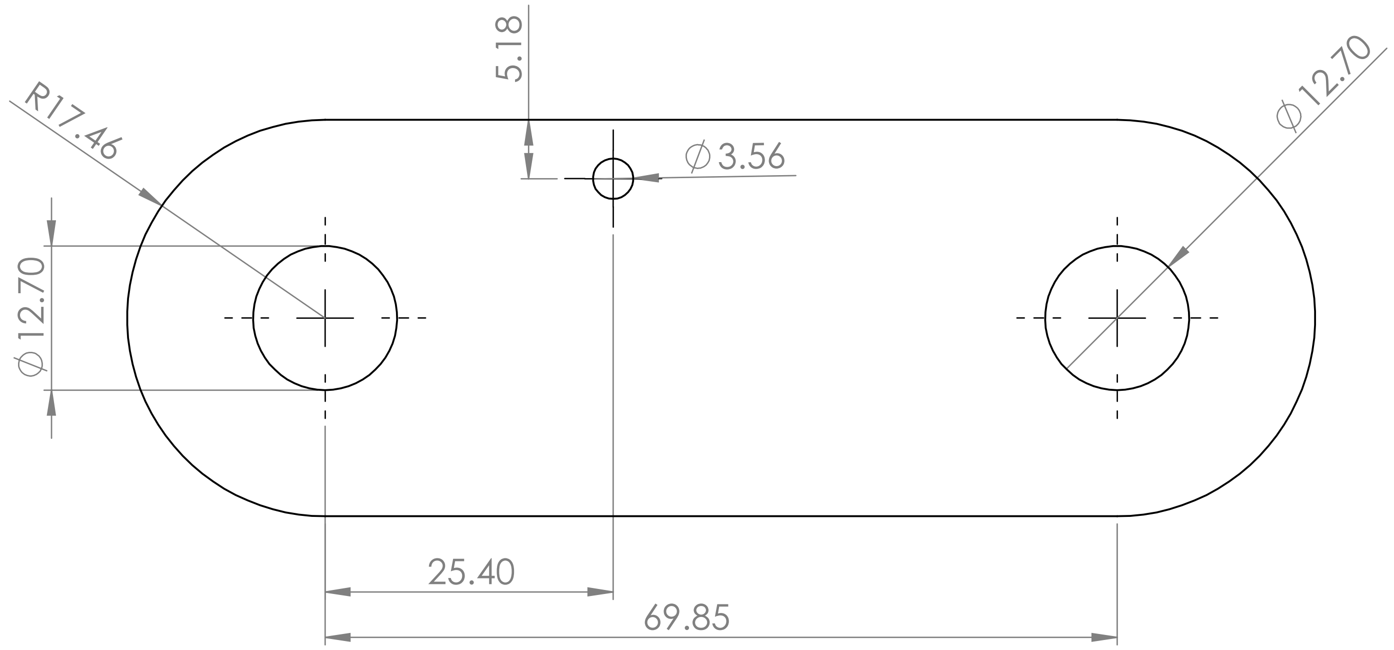
DWG NO. ME16-TRC-d012-TensionerBase-R00 A3

WEIGHT:

SCALE:2:1

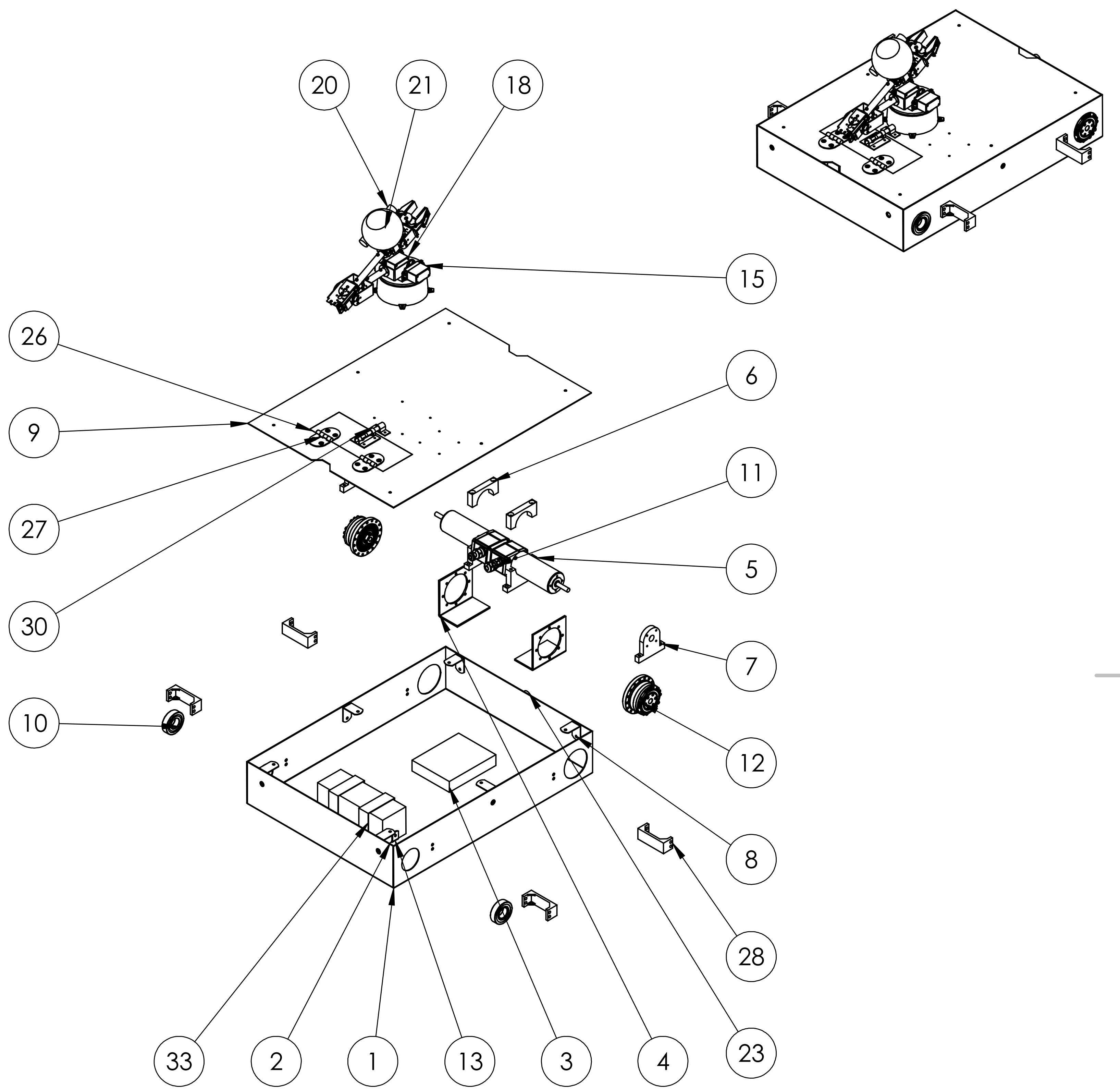
SHEET 1 OF 1

MATERIAL THICKNESS 9.53 mm



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00
	NAME	SIGNATURE	DATE	TITLE: TENSIONER ARM
DRAWN	L. REMPLE		05/12/15	
CHK'D				
APPV'D				
MFG				
Q.A			MATERIAL: 1020 Steel	DWG NO. ME16-TRC-D013-TensionerArm-R00 A3
			WEIGHT:	SCALE:1.5:1 SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
34	ME16-FRM-P021-RangeFinderScrew-R00	M3 x 8MM	4
33	ME16-FRM-P012-BatVelcro-R00	Velcro	2
32	ME16-FRM-P014-BatNut-R00	8-32 Nut	8
31	ME16-FRM-P013-BatBolt-R00	8-32 Flat Head	8
30	ME16-FRM-P019-BatSlideBolt-R00	1-3/4" x 1-1/2" Steel Barrel Slide Bolt	1
29	socket head cap screw_am	M5	8
28	ME16-FRM-P012-SuppBrkt-R00	Support Bracket	4
27	ME16-FRM-P017-BatHinge-R00	Hinge	2
26	ME16-FRM-P004-BatteryAccessLid-R00	Lid for Battery Access	1
25	ME16-FRM-P018-LidPanelScrew-R00	Captive Panel Screw	6
24	ME16-FRM-P016-LidBracketNut-R00	10-24 Nut	12
23	CD16-FRM-P001-CO2Sensor-R00	C02 Sensor	1
22	CD16-FRM-P002-RangeFinder-R00	Laser Range Finder	1
21	CD16-FRM-P003-Camera-R00	BublCam	1
20	CD16-FRM-P004-TempSensor-R00	Temperature Sensor	1
19	ME16-FRM-P002-TempSensorMount-R00	Mounting Bracket	1
18	MC16-MAN-A001-Manipulator-R01	Alum Tube Arm Assembly	1
17	ME16-FRM-P021-ManipNut-R00	5-40 Nut	10
16	ME16-FRM-P020-ManipBolt-R00	Flat Head 5-40 Bolt	10
15	MC16-MAN-A003-BaseAssy-R00	Manipulator Base	1
14	ME16-FRM-P015-LidBracketBolt-R00	10-24 Bolt	12
13	ME16-FRM-P011-BatMountBrkt-R00	7/8" Bracket	6
12	ME16-FRM-A001-HarmonicDriveRef-R00	CSG-17-50-2UH	2
11	ME16-TRC-P006-250WMotor-R00	250W Maxon Motor	2
10	ME16-FRM-P009-ShaftBearing-R00	7/8" Bearing	2
9	ME16-FRM-P003-FrameLid-R01	Aluminum Lid	1
8	ME16-FRM-P008-SideMountBrkt-R00	1.5" Bracket	6
7	ME16-FRA-P005-MotorFrontMount-R00	Motor Mount	2
6	ME16-FRM-P005-MotorMountTop-R00	Two Piece Mount	2
5	ME16-FRM-P004-MotorMountBase-R00	Two Piece Mount	2
4	ME16-FRM-P002-HarmonicDrMount-R00	HD Mount	2
3	MC16-FRM-P001-MotorCont-R00	Motor Controller	1
2	BA16-BOO-P001-Battery-R00	Battery	1
1	ME16-FRM-P001-Frame-R02	Main Frame	1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING · REVISION R00

Team 21: Rescue Rangers

	NAME	SIGNATURE	DATE
DRAWN	Blair Shewfelt		11/27/2015
CHK'D			
APPV'D			
MFG			
Q.A			

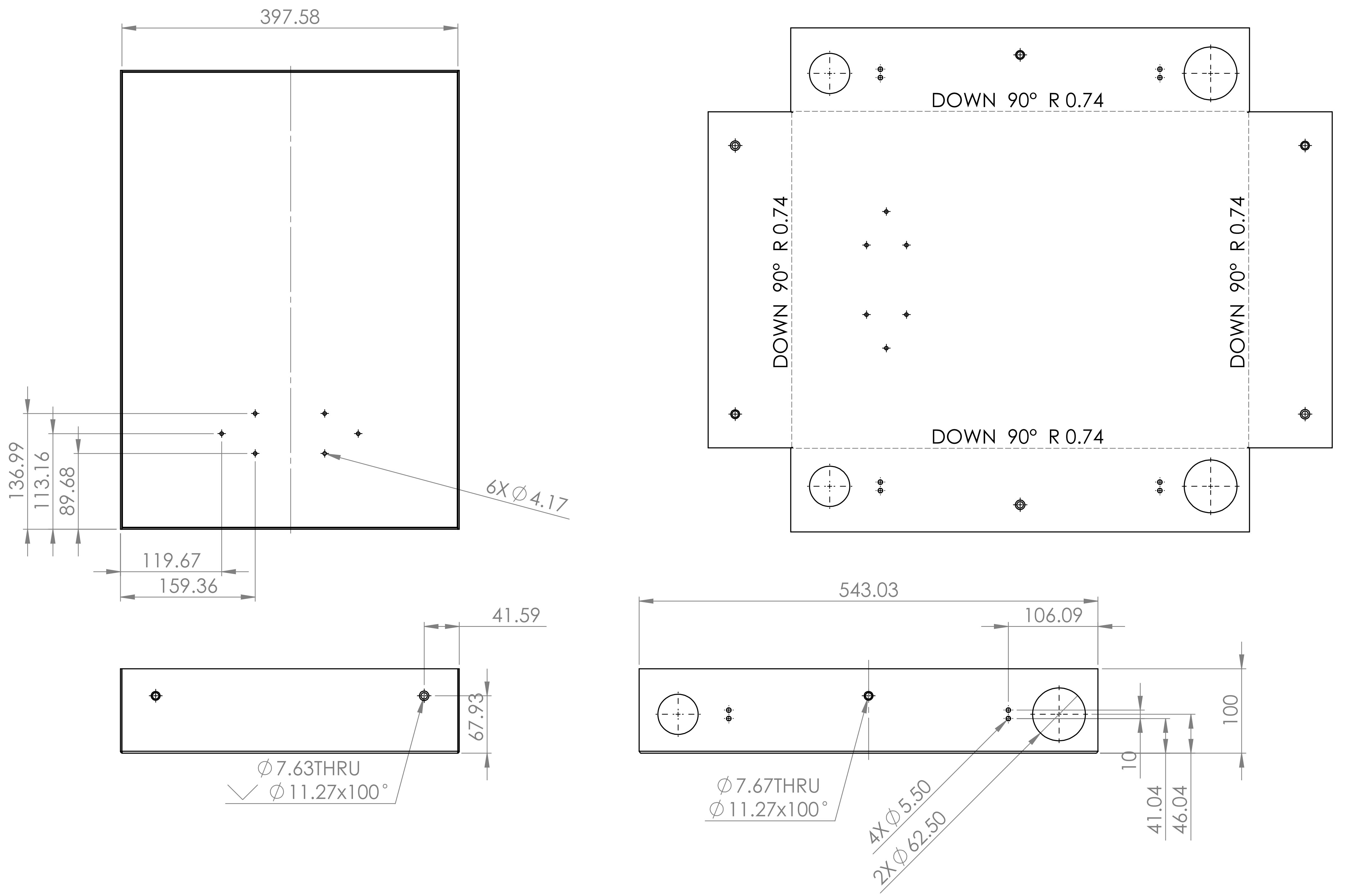
TITLE:

MATERIAL:

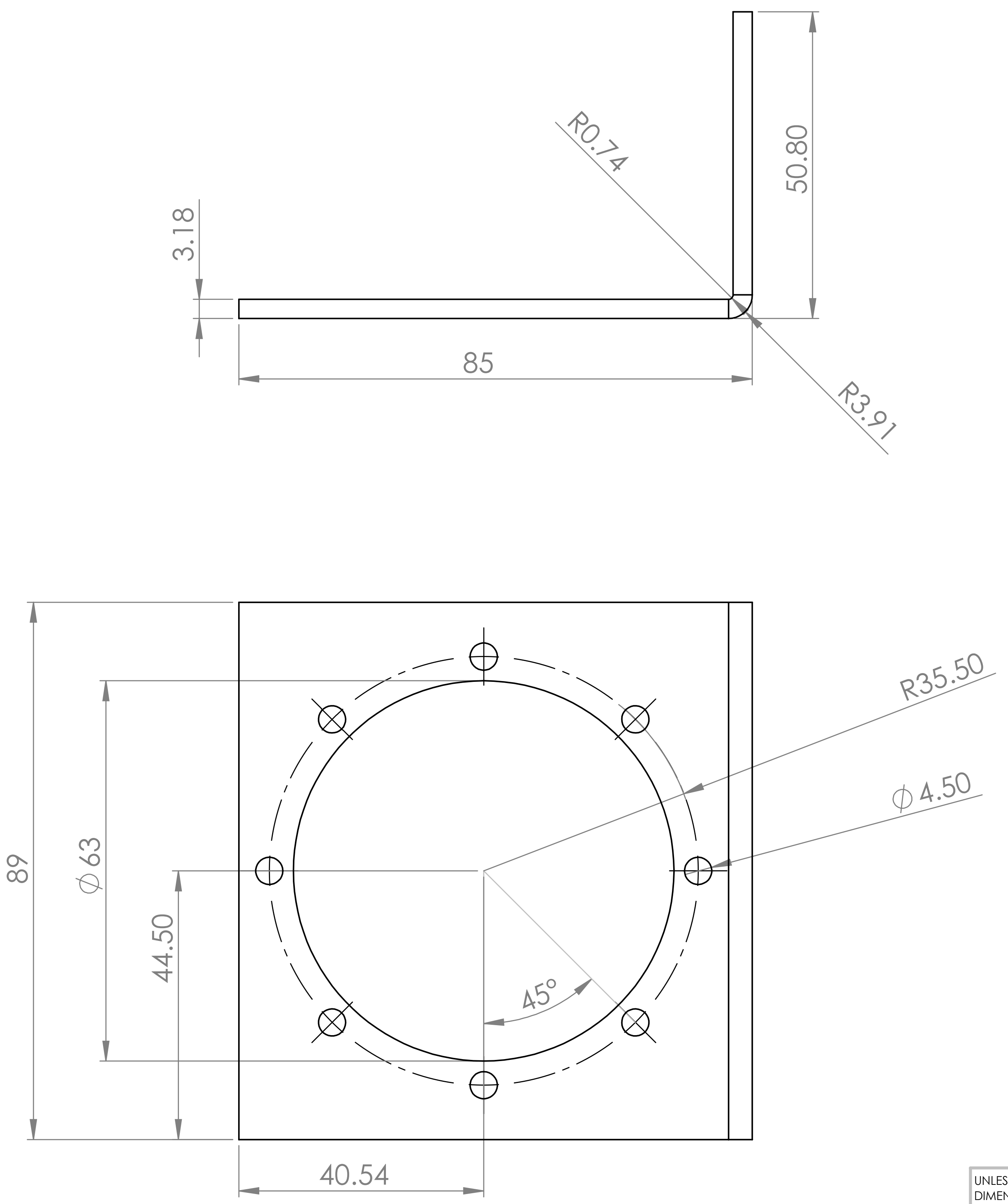
WEIGHT:

DWG NO. ME16-FRM-A001-FrameAssy-R00 · A3

SCALE:1:10 · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +- 0.5 mm ANGULAR: +- 1 deg	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	R00
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN	Blair Shewfelt		11/27/2015			
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL:	DWG NO. ME16-FRM-D001-Frame-R00		A3
			WEIGHT:	SCALE:1:5	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

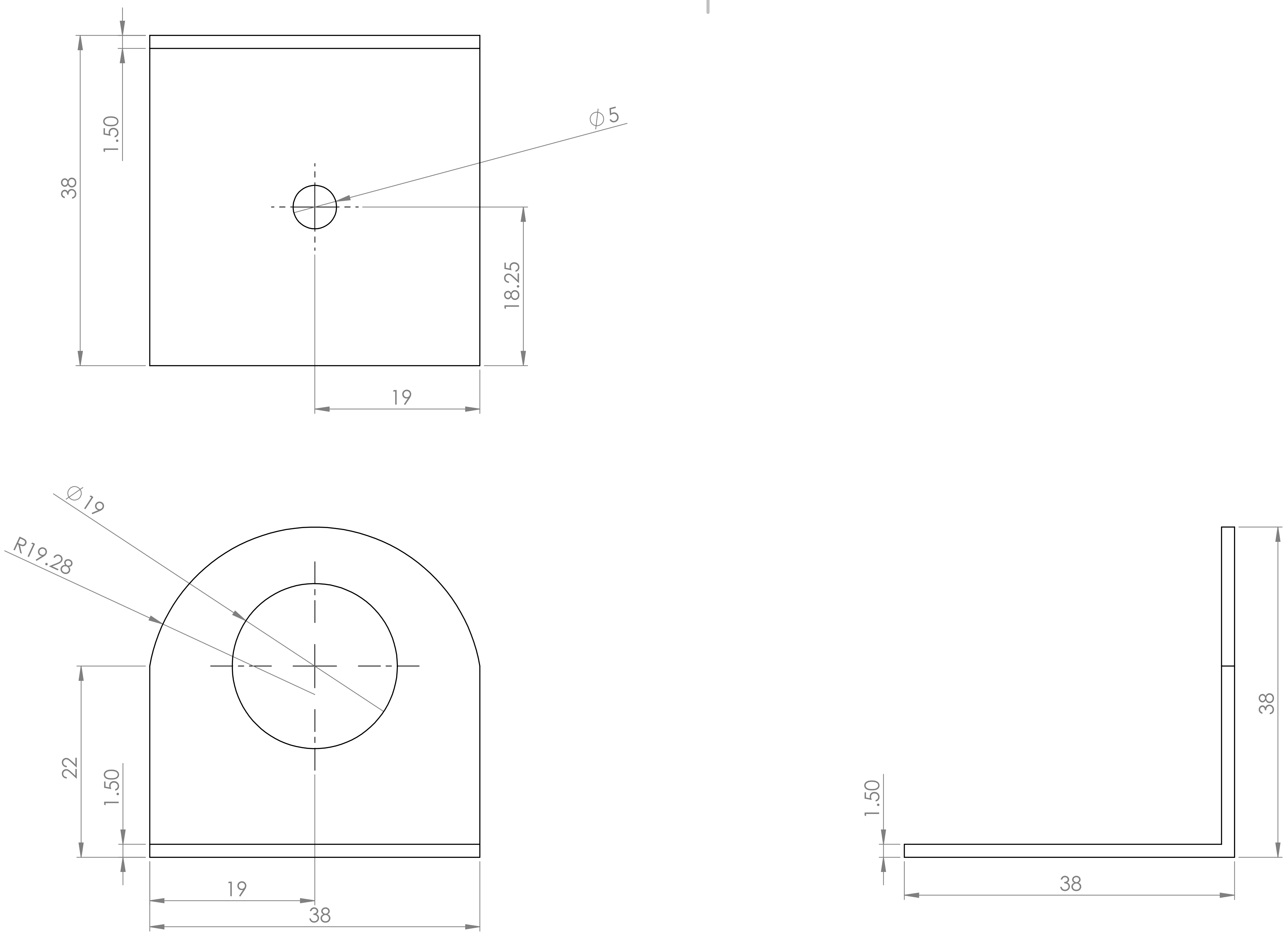
TITLE: HARMONIC DRIVE MOUNT

MATERIAL: 1020 Steel

DWG NO. ME16-FRM-D001-HarmonicDrMount-R00 A3

WEIGHT:

SCALE:1:1 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: 0.5 mm
ANGULAR: 1 deg

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

TEMPERATURE SENSOR MOUNT

MATERIAL: 1020 Steel

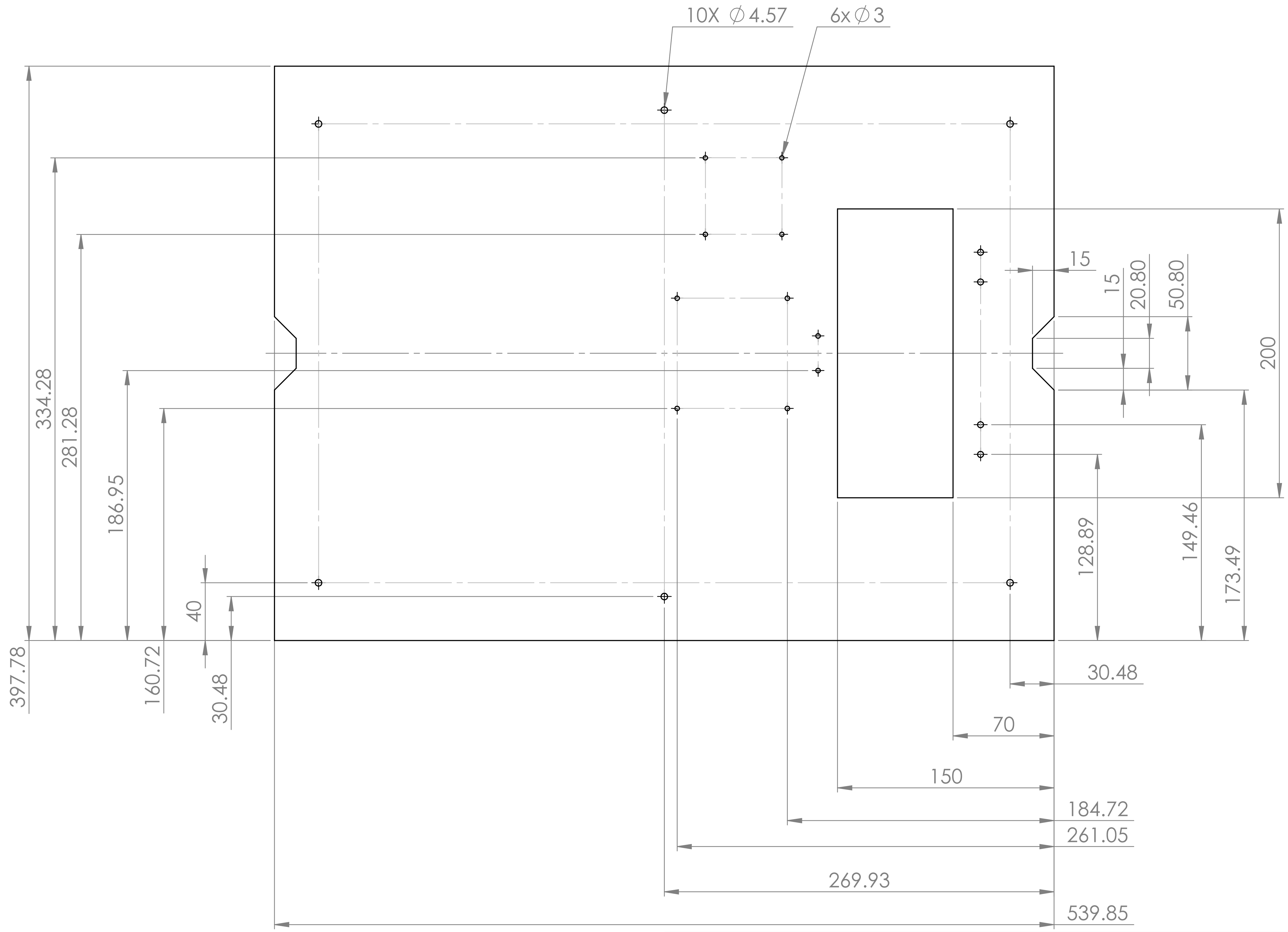
DWG NO. ME16-FRM-D002-TempSensorMount-R00

A3

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: FRAME LID

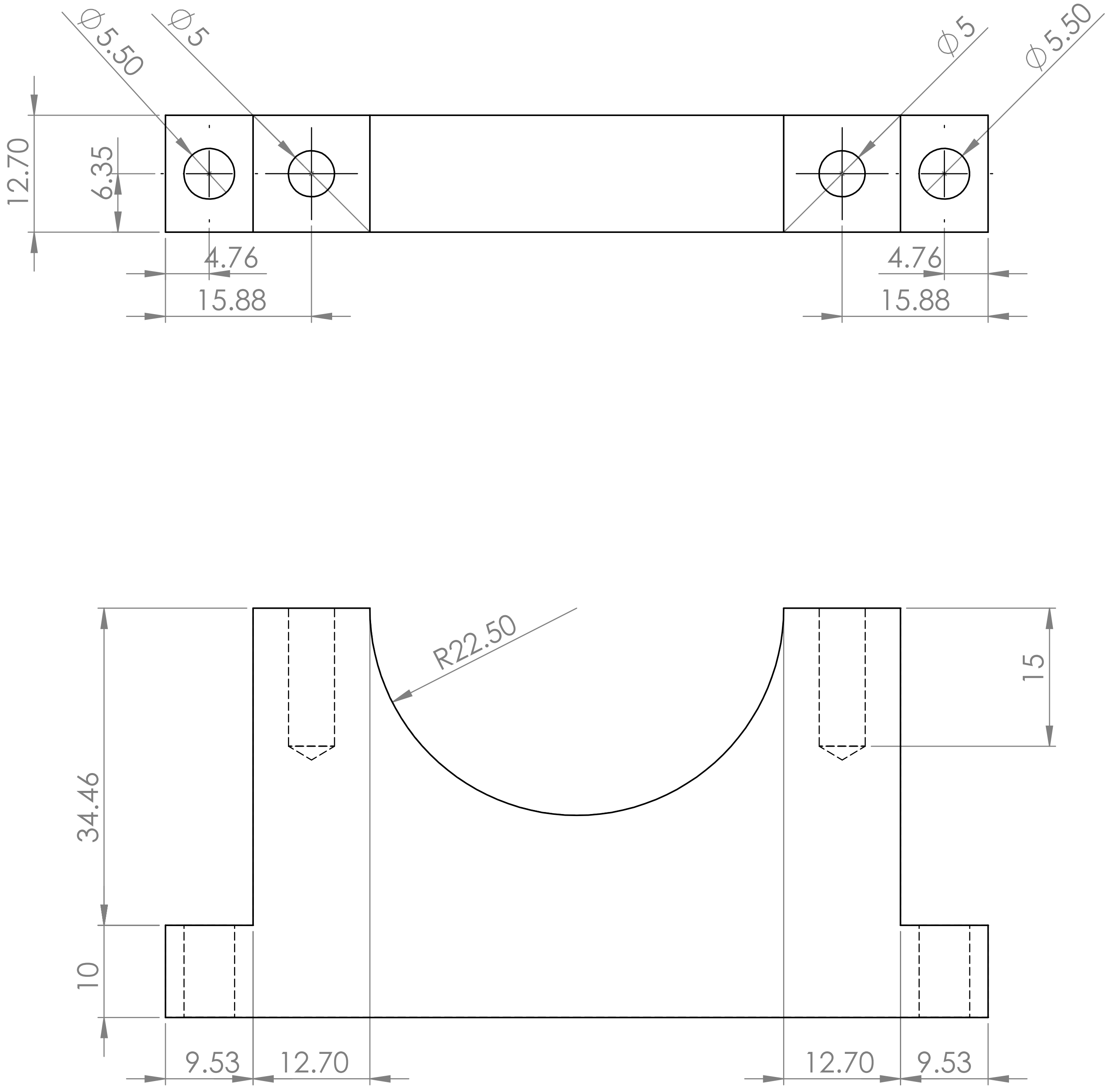
MATERIAL: Al 6061-T6

DWG NO. ME16-FRM-D003-FrameLid-R00 A3

WEIGHT:

SCALE:1:4

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

DRIVE MOTOR MOUNT BASE

MATERIAL: Al 6061-T6

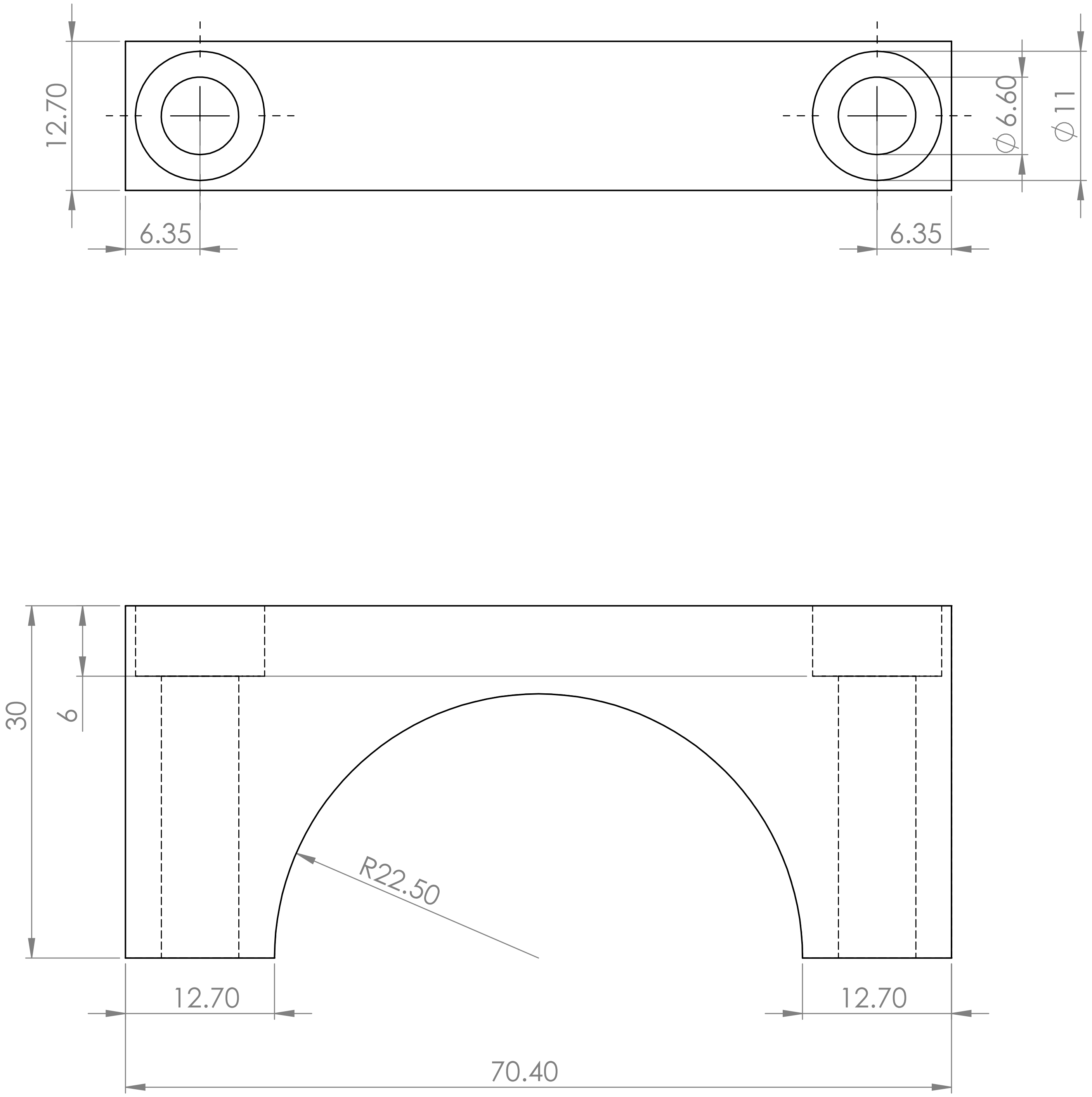
DWG NO. ME16-FRM-D004-MotorMountBase-R00

A3

WEIGHT:

SCALE:1.5:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

DRIVE MOTOR MOUNT TOP

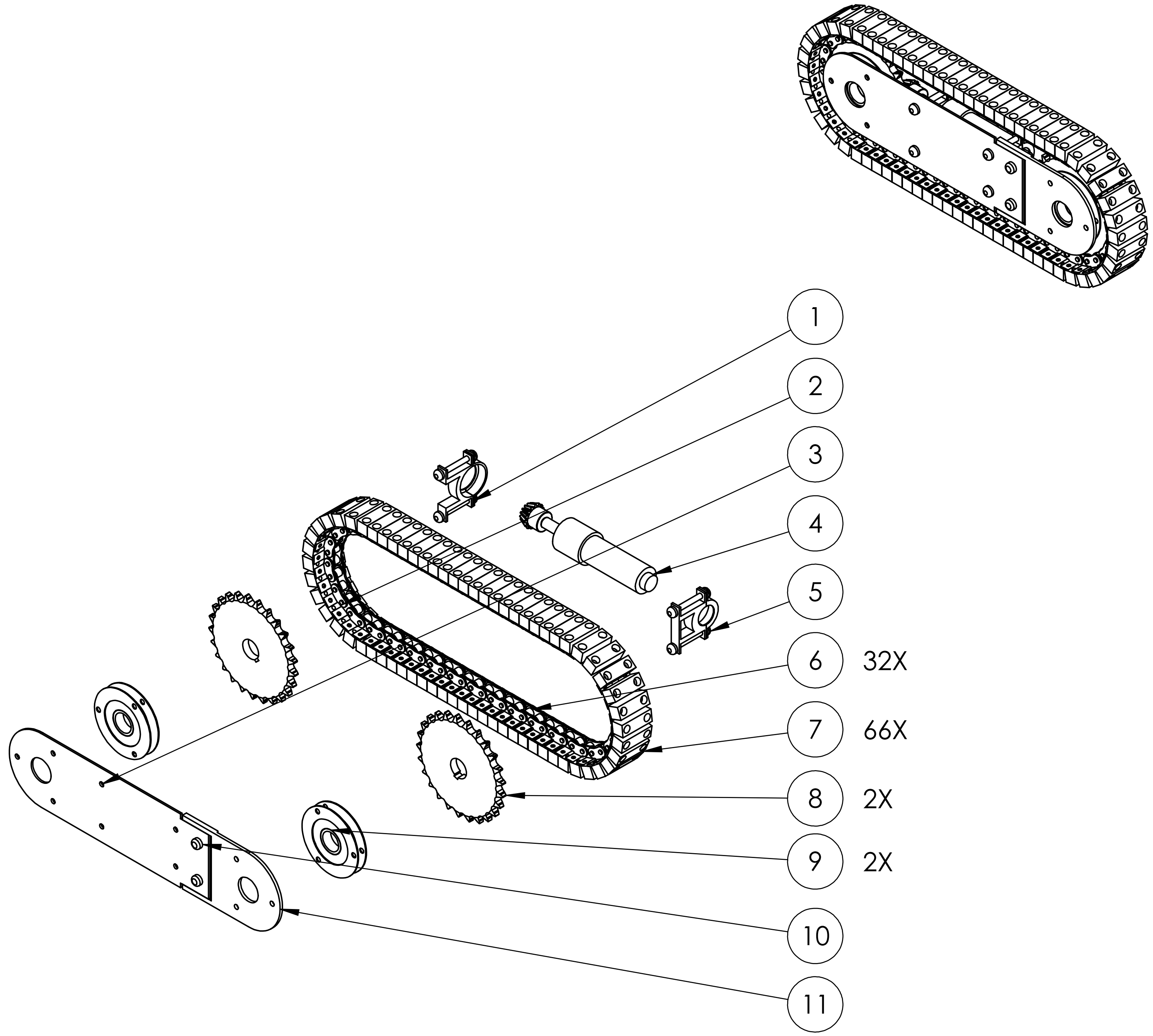
MATERIAL: Al 6061-T6

DWG NO. ME16-FRM-D005-MotorMountTop-R00 — A3

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



ITEM NO.	QTY.	PART NUMBER	DESCRIPTION
11	1	ME16-PAD-P007-OuterPaddleFrame-R00	OUTER PADDLE FRAME
10	2	ME16-PAD-P101-5x10FastenerSimplified-R00	M5 X 10MM FASTENER
9	2	ME16-PAD-A001-SprockerBearingFlangeAssembly-R00	BEARING AND MOUNT FLANGE ASSEMBLY
8	2	ME16-PAD-P009-DriveSprocket-R00	25 TOOTH SPROCKET
7	66	ME16-PAD-P005-Traction_Pad-R00	NBR RUBBER PAD
6	32	ME16-PAD-P004-40-ChainOuter-R00	ANSI 40 CHAIN OUTER LINK
5	1	ME16-PAD-A003-MotorMountAsembly-R00	REAR MOTOR MOUNT ASSEMBLY
4	1	ME16-PAD-A002-MotorGearAssembly-R00	PINION AND MOTOR ASSEMBLY
3	1	ME16-PAD-P006-InnerPaddleFrame-R00	INNER PADDLE FRAME
2	32	ME16-PAD-P003-40_Chain_Inner-R00	ANSI 40 CHAIN INNER LINK
1	1	ME16-PAD-A004-MotorMountAsemblyFront-R00	FRONT MOTOR MOUNT ASSEMLBY

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION R00

Team 21: Rescue Rangers

	NAME	SIGNATURE	DATE
DRAWN	Blair Shewfelt		11/27/2015
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

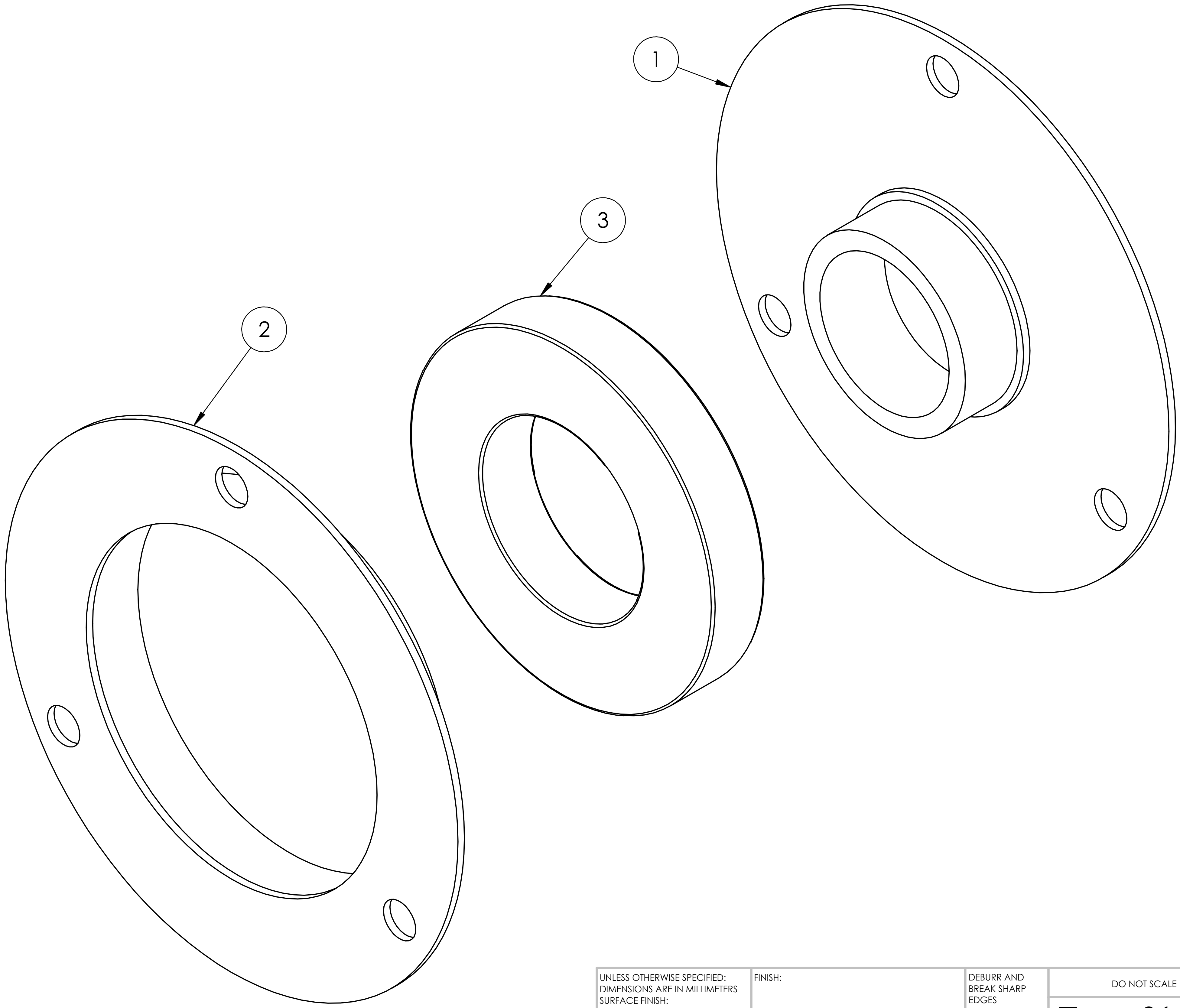
Paddle Assembly

DWG NO. ME16-PAD-A000-PaddleAssembly-R00

A3

SCALE:1:5

SHEET 1 OF 1



ITEM NO.	QTY.	PART NUMBER	DESCRIPTION
3	1	ME16-PAD-P103-SprocketBearingNSK16005-R00	BEARING
2	1	ME16-PAD-P011-SprocketBearingFlangeOuter-R00	OUTER FLANGE
1	1	ME16-PAD-P010-SprocketBearingFlangeInner-R00	INNER FLANGE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION R00

Team 21: Rescue Rangers

	NAME	SIGNATURE	DATE
DRAWN	Blair Shewfelt		11/27/2015
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

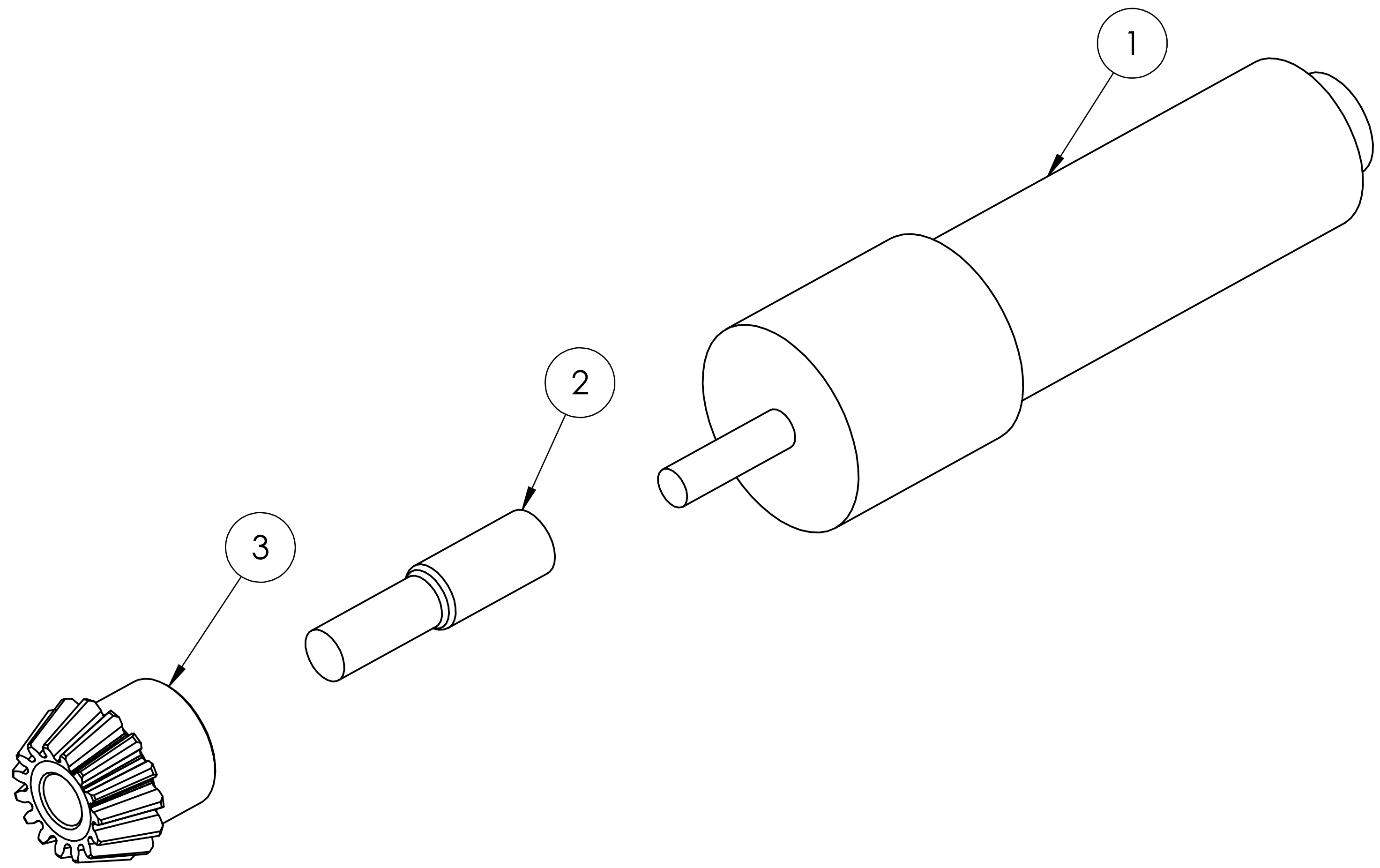
TITLE:
PADDLE BEARING FLANGE ASSEMBLY

DWG NO.
ME16-PAD-A001-SprockerBearingFlangeAssembly-R00

A3

SCALE:2:1

SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
3	ME16-PAD-P002-PinionGear-R00	Pinion Bevel Gear	1
2	ME16-PAD-P008-MotorPinionAdapter-R00	Shaft Adapter	1
1	ME16-PAD-P001-PaddleMotorGearbox Unit-R00	40W Maxon Motor	1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION R00

Team 21: Rescue Rangers

	NAME	SIGNATURE	DATE
DRAWN	Blair Shewfelt		11/27/2015
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO. ME16-PAD-A002-MotorGearAssembly-R00

A3

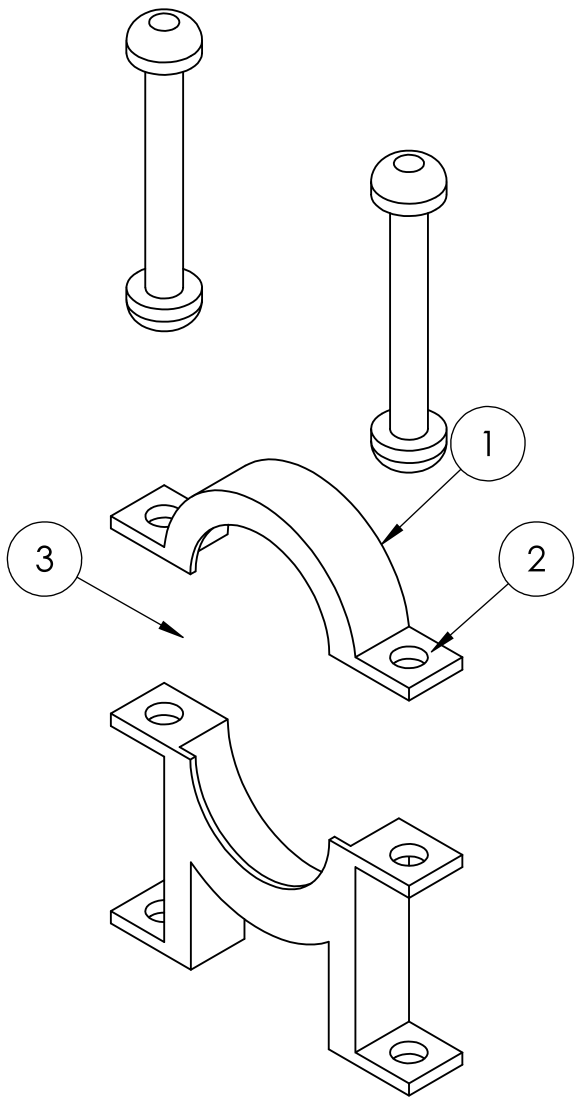
WEIGHT:

SCALE:1:1

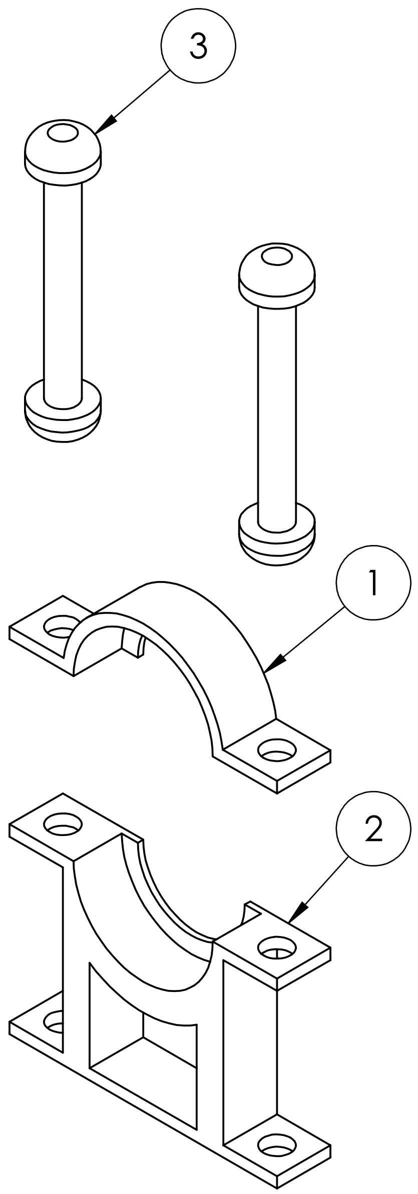
SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	ME16-PAD-P012-MotorMountFrontUpper-R00	Upper Front Motor Mount	1
2	ME16-PAD-P013-MotorMountFrontLower-R00	Lower Front Motor Mount	1
3	MirrorME16-PAD-P104-5x38FastenerSimplified-R00	M5 Fasteners	2

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	ME16-PAD-P012-MotorMountUpper-R00	Rear Upper Motor Mount	1
2	ME16-PAD-P013-MotorMountLower-R00	Rear Lower Motor Mount	1
3	ME16-PAD-P104-5x38FastenerSimplified-R00	M5 Fasteners	2



Front Motor Mount



Rear Motor Mount

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION R00

Team 21: Rescue Rangers

	NAME	SIGNATURE	DATE
DRAWN	Blair Shewfelt		11/27/2015
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

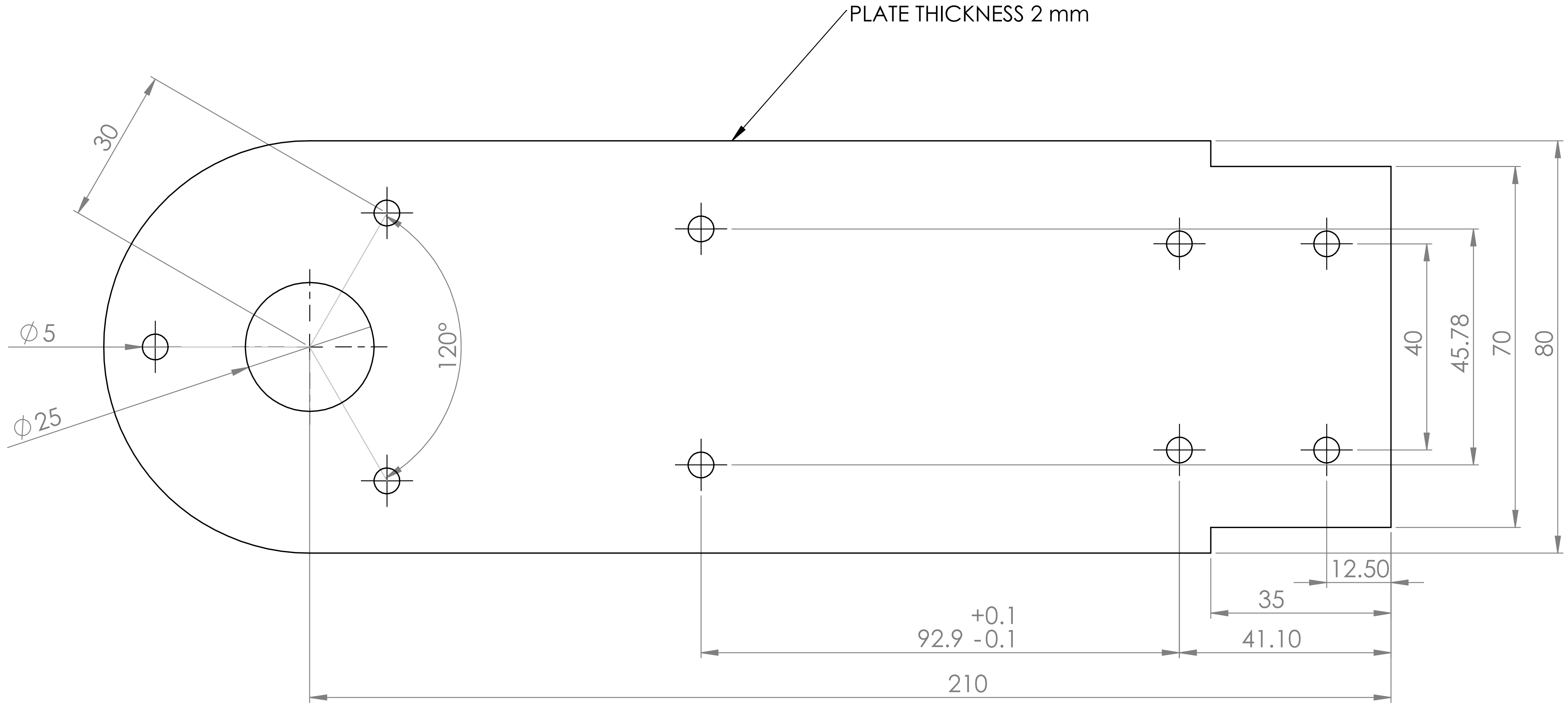
DWG NO. ME16-PAD-A004-MotorMountAsemblyFront-R00

A3

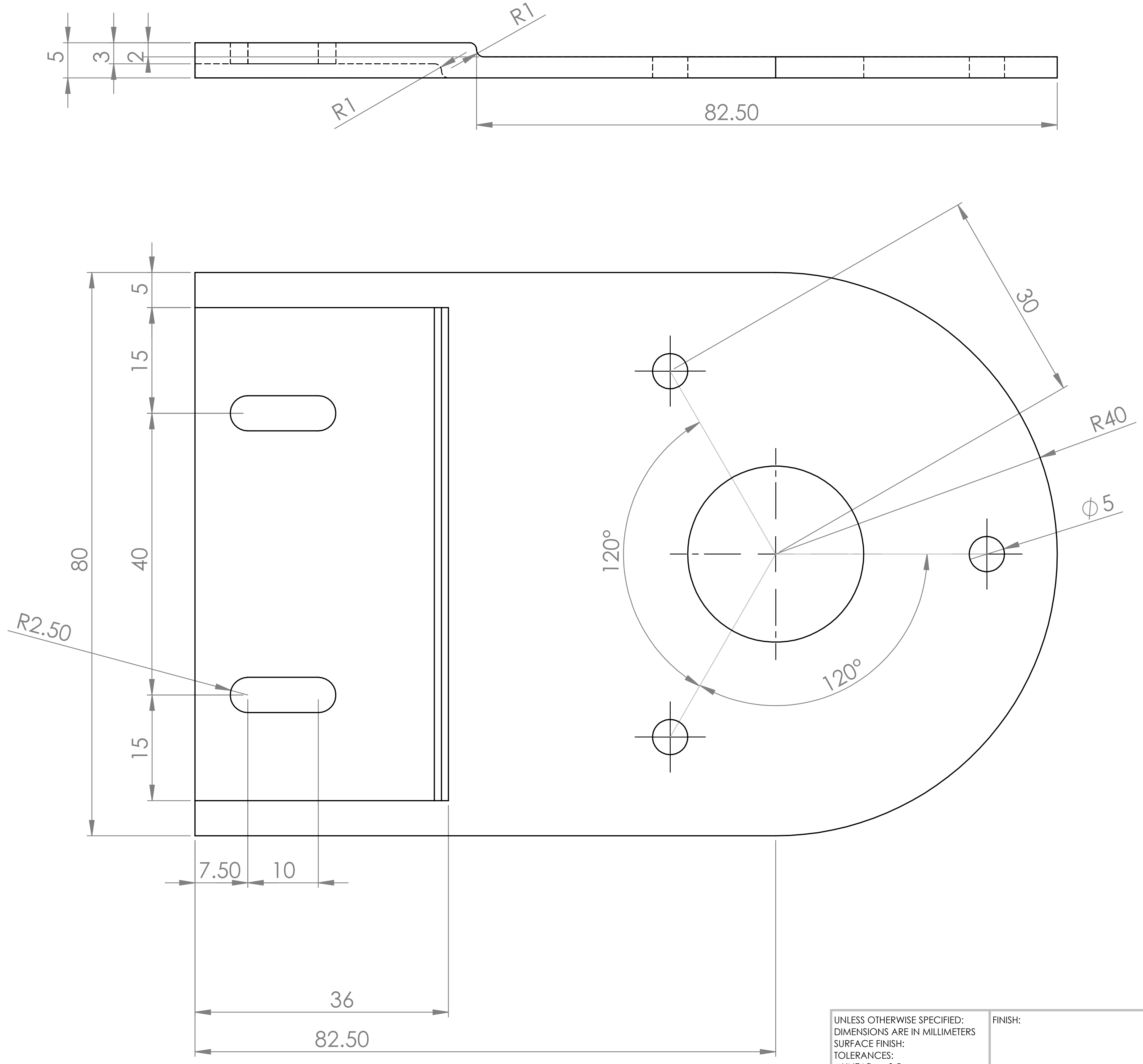
WEIGHT:

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: +- 0.5 mm ANGULAR: +-1 deg		FINISH:				DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00
	NAME	SIGNATURE	DATE				TITLE: INNER PADDLE FRAME	
DRAWN	L. REMPLE		05/12/15					
CHK'D								
APPV'D								
MFG								
Q.A				MATERIAL: Al 6061-T6			DWG NO. ME16-PAD-D006-InnerPaddleFrame-R00	A3
				WEIGHT:			SCALE:1:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: +- 0.5 mm
ANGULAR: +- 1 deg

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

OUTER PADDLE FRAME

MATERIAL: Al 6061-T6

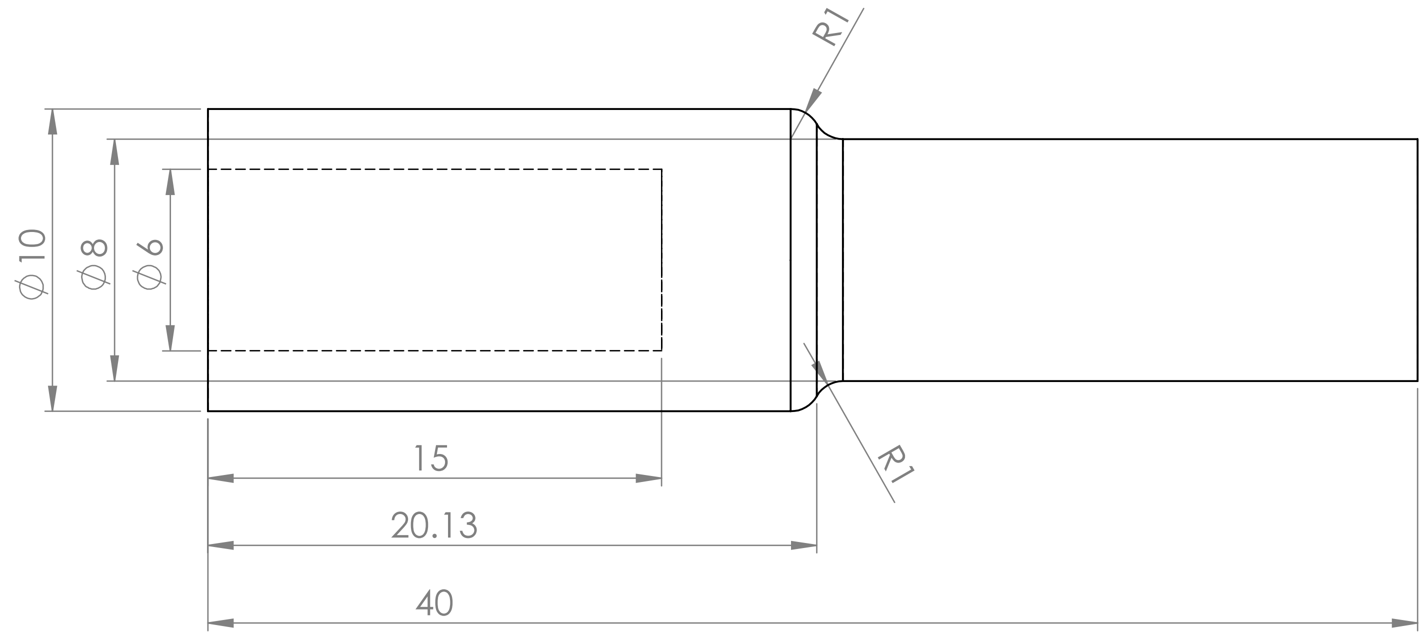
WEIGHT:

DWG NO. ME16-PAD-D007-OuterPaddleFrame-R00

A3

SCALE:1.5:1

SHEET 1 OF 1



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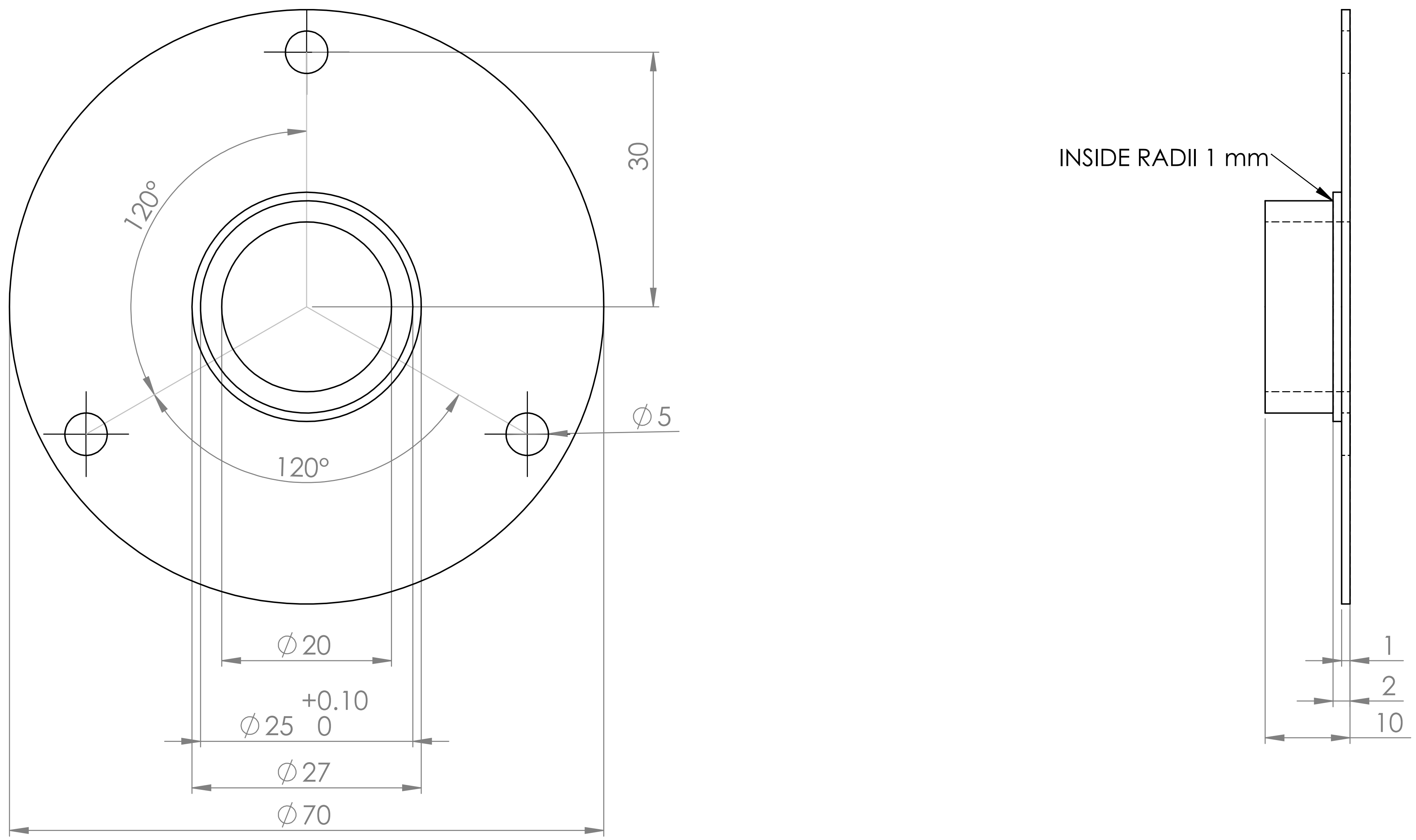
	NAME	SIGNATURE	DATE			TITLE: PADDLE MOTOR TO PINION ADAPTER
DRAWN	L.REMPLE		05/12/15			
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: 4130 Steel		DWG NO. ME16-PAD-D008-MotorPinionAdapter-R00 A3
				WEIGHT:		SCALE:5:1 SHEET 1 OF 1



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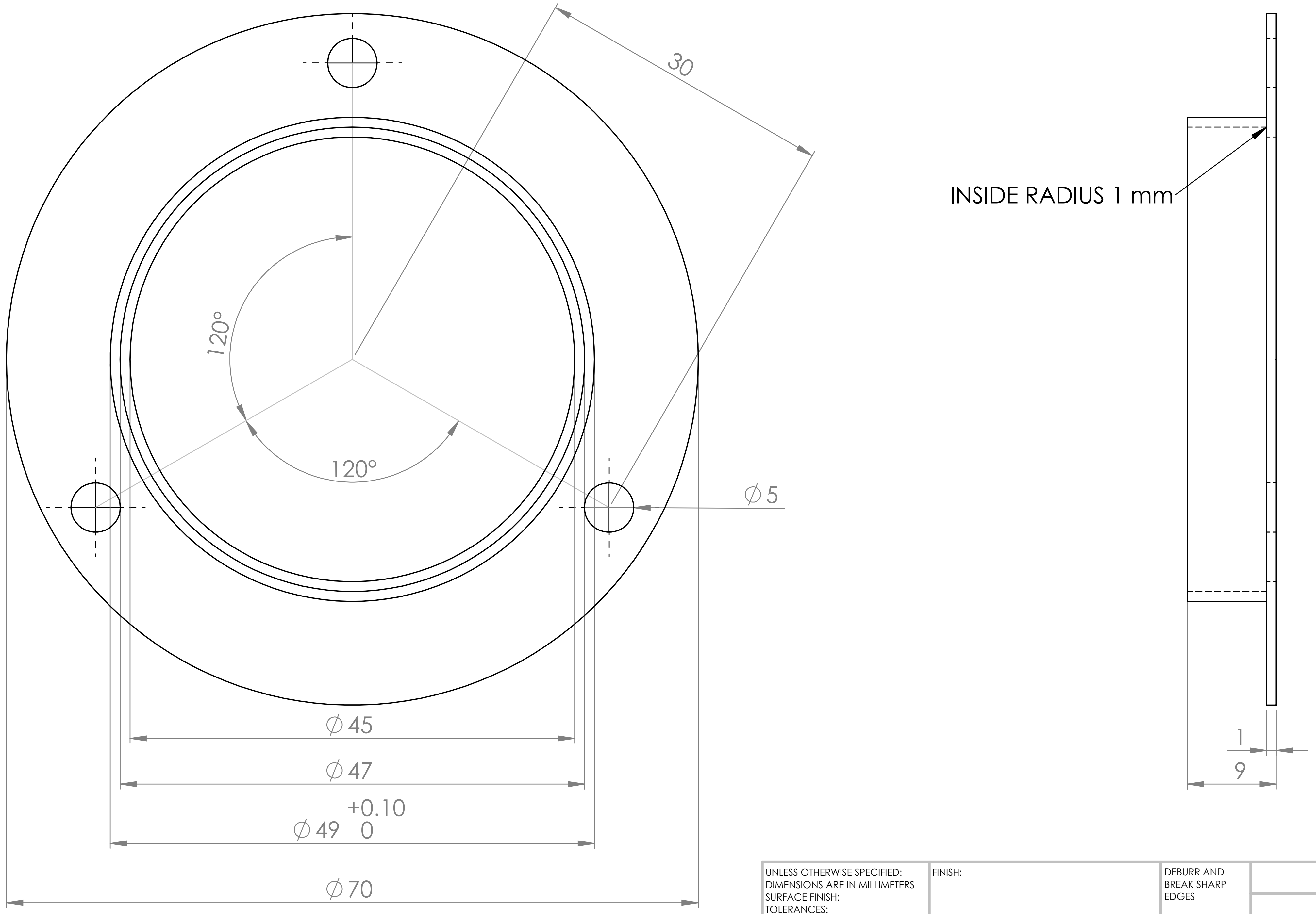
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN	L. REMPLE		05/12/15	INNER SPROCKET BEARING FLANGE		
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: 1020 Steel	DWG NO. ME16-PAD-D010-SprocketBearingFlangeInner-R00	A3	
			WEIGHT:	SCALE:1.5:1	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: 0.5 mm
ANGULAR: 1 deg

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L. REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

OUTER SPROCKET BEARING FLANGE

MATERIAL: 1020 Steel

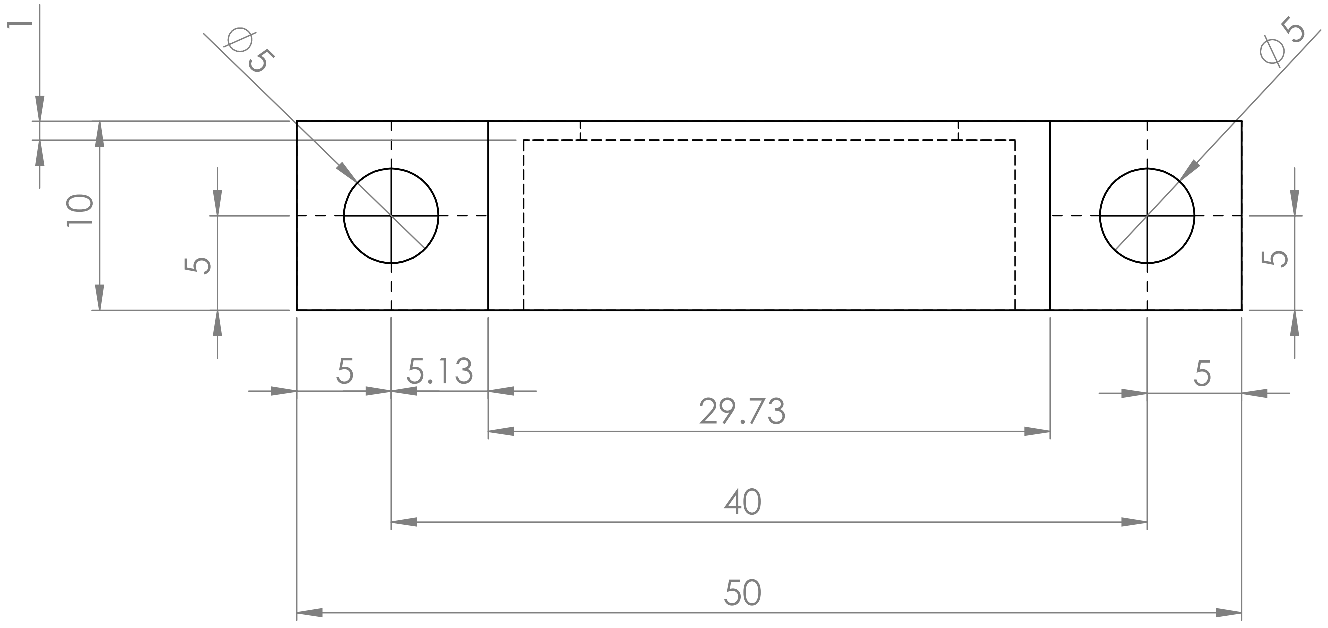
DWG NO. ME16-PAD-D011-SprocketBearingFlangeOuter-R00

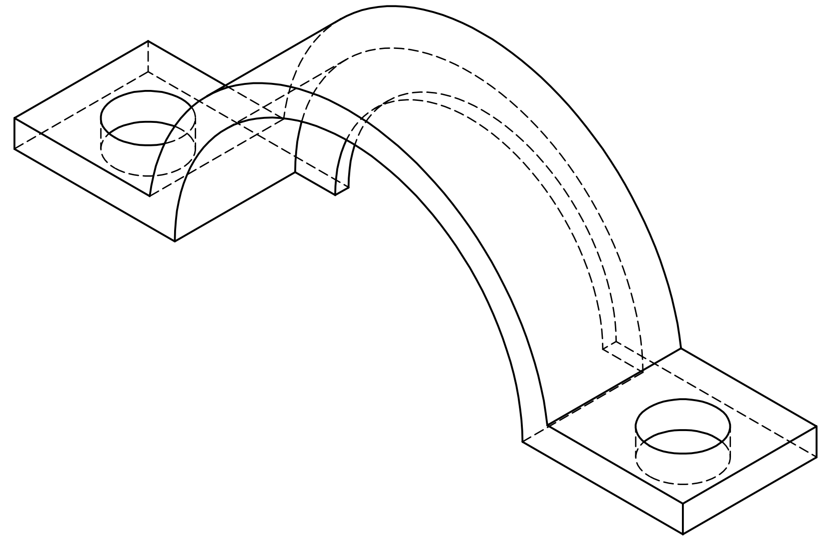
A3

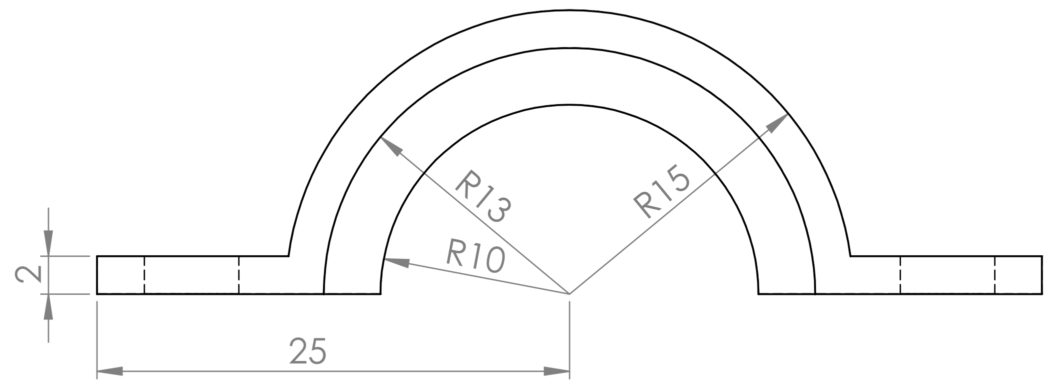
WEIGHT:

SCALE:2:1

SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION 00

	NAME	SIGNATURE	DATE
DRAWN	L.REMPLE		05/12/15
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: Al 6061-T6

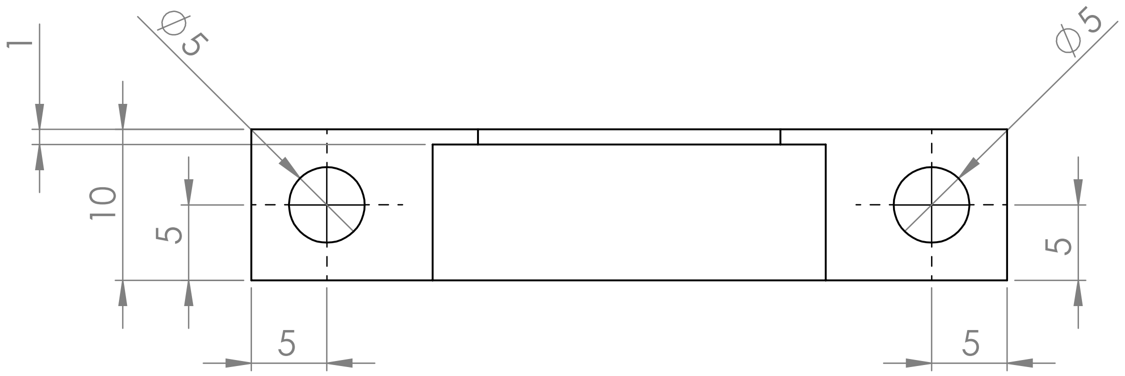
WEIGHT:

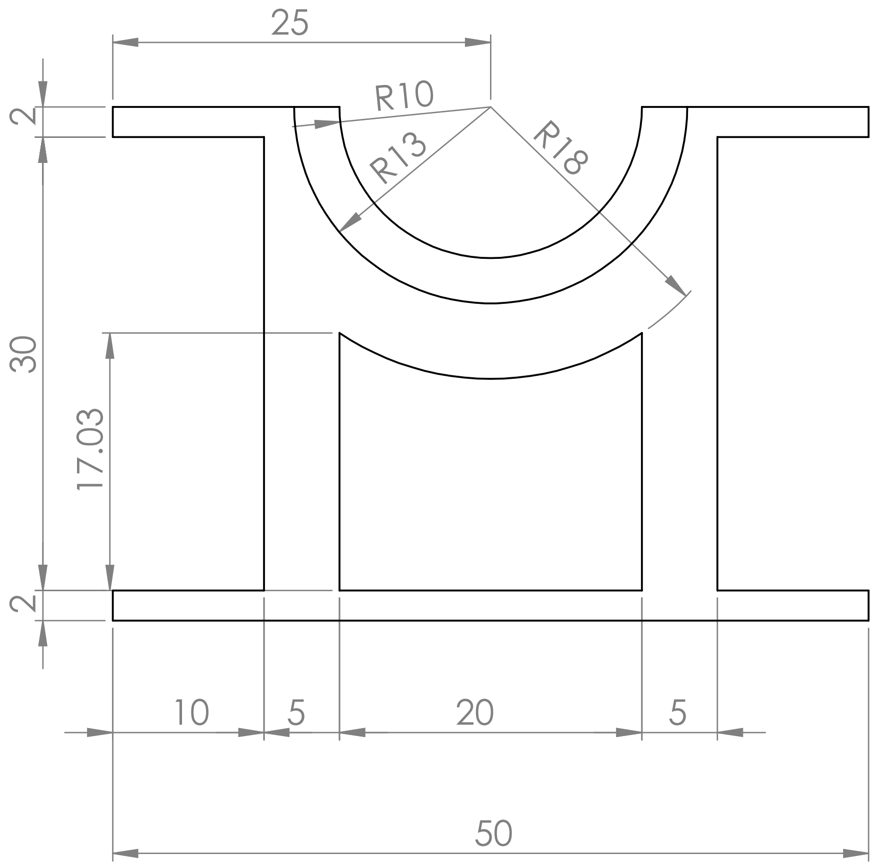
TITLE:

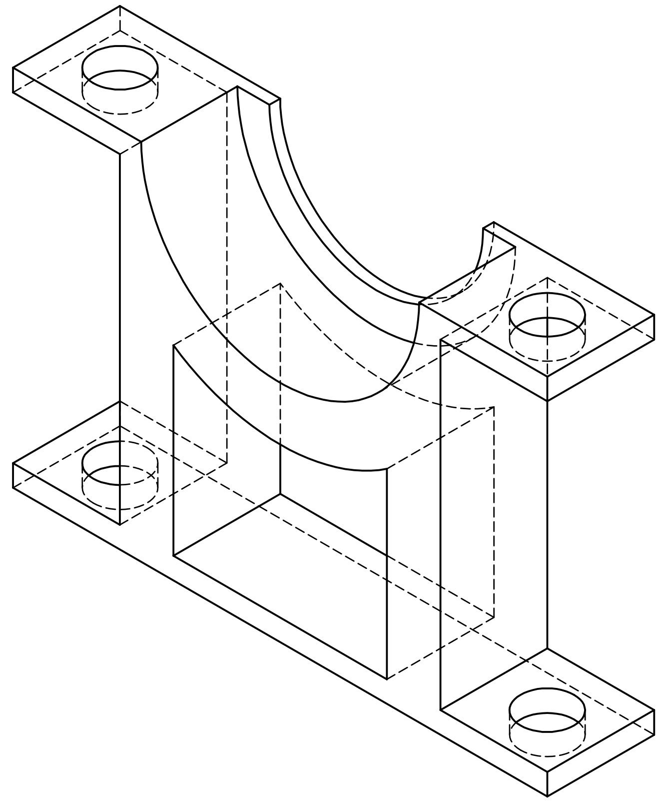
REAR UPPER PADDLE MOTOR MOUNT

DWG NO. ME16-PAD-D012-MotorMountRearUpper-R00 A3

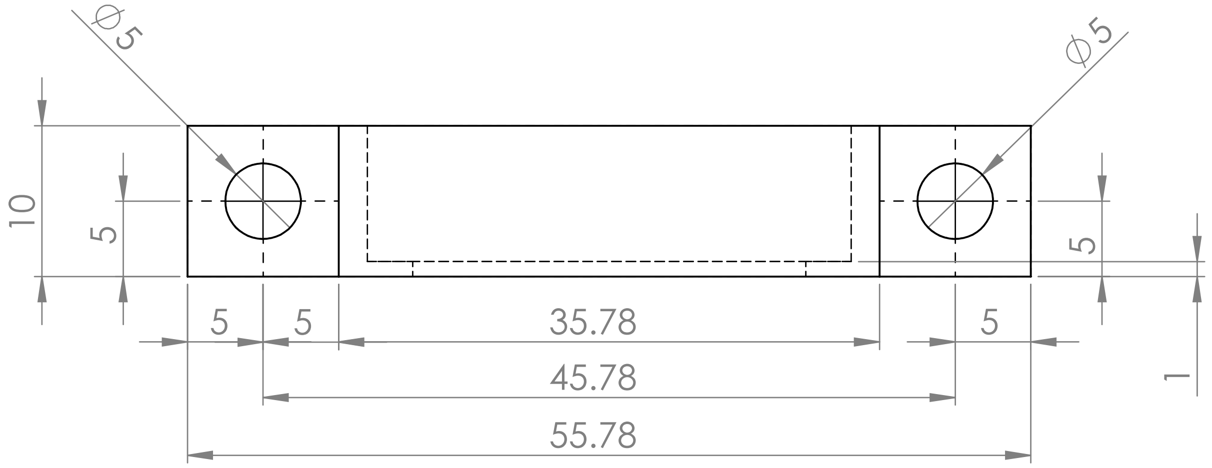
SCALE:2.5:1 SHEET 1 OF 1

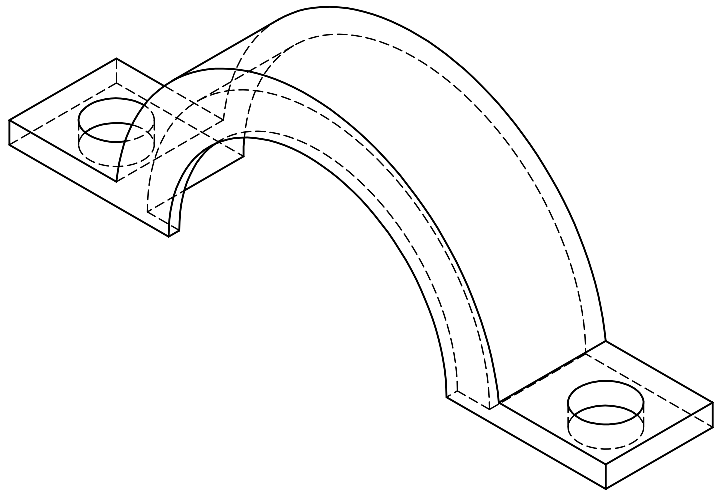


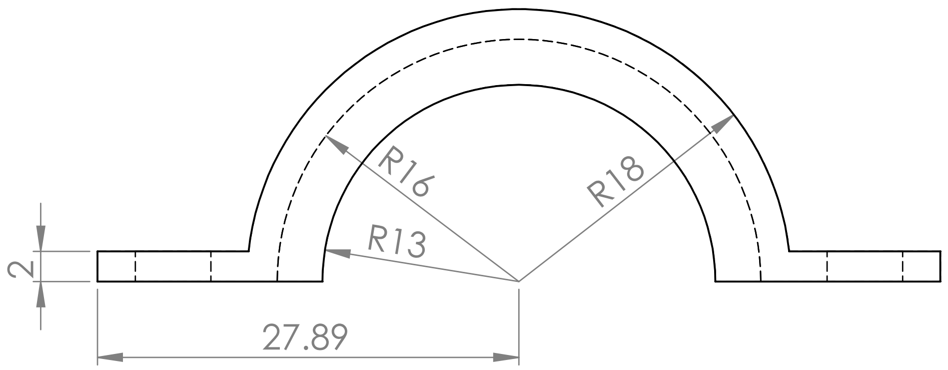




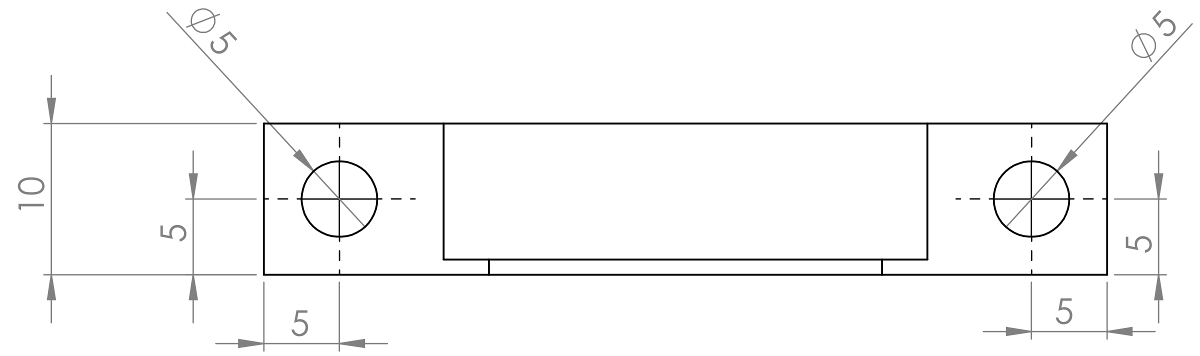
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg		FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00
	NAME	SIGNATURE	DATE		TITLE:	
DRAWN	L. REMPLE		05/12/15		REAR LOWER PADDLE MOTOR MOUNT	
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: Al 6061-T6	DWG NO. ME16-PAD-D013-MotorMountRearLower-R00	A3
				WEIGHT:	SCALE:2:1	SHEET 1 OF 1

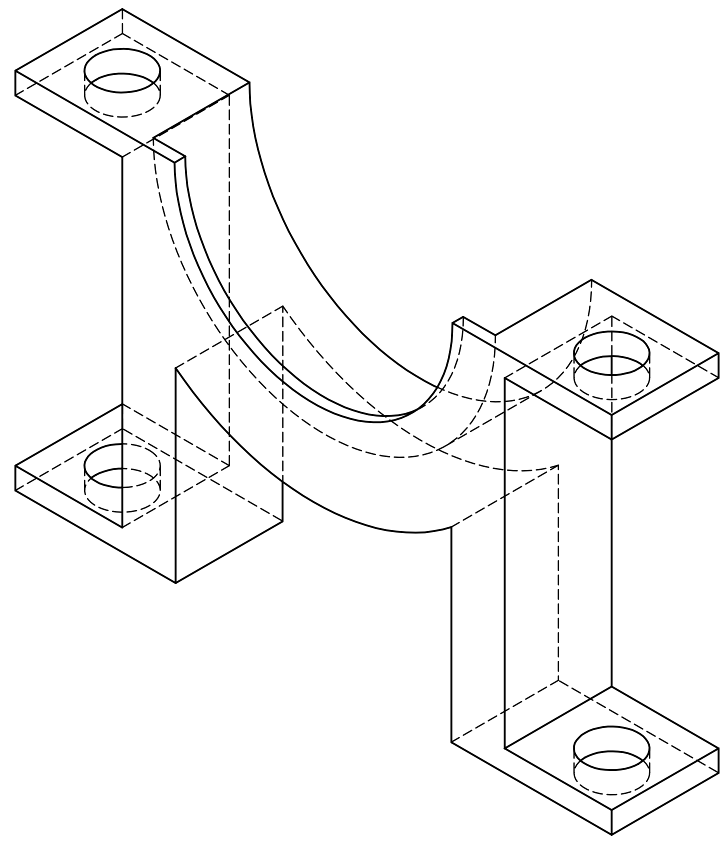


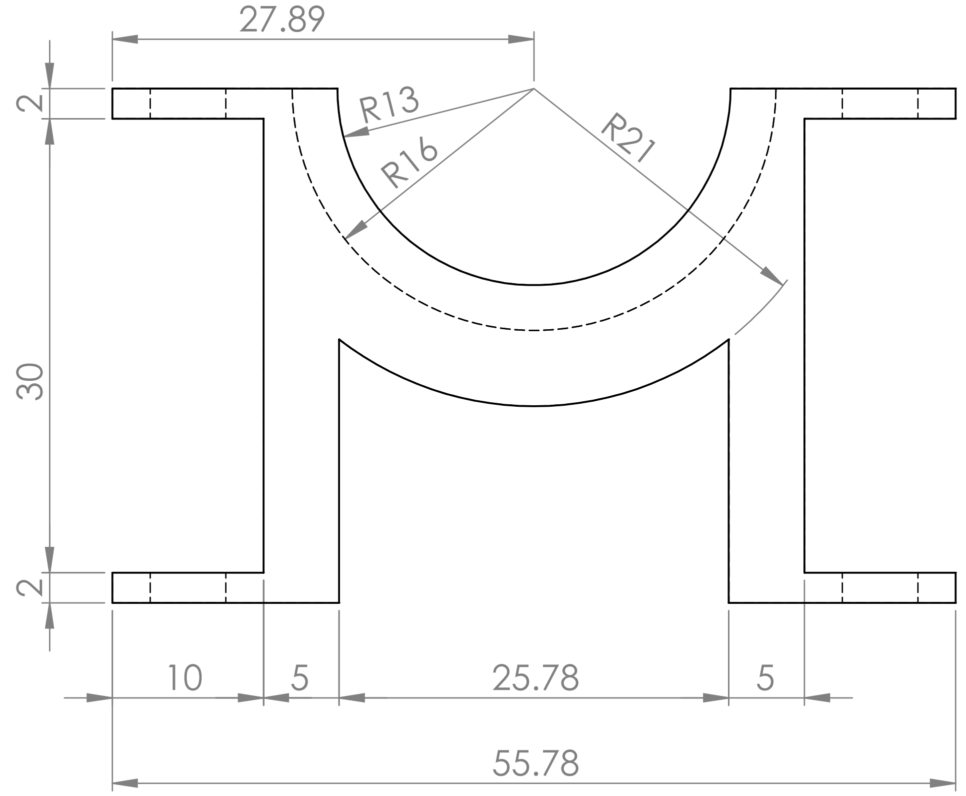




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	L. REMPLE		05/12/15	FRONT UPPER PADDLE MOTOR MOUNT	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: Al 6061-T6	DWG NO. ME16-PAD-D014-MotorMountFrontUpper-R00	A3
			WEIGHT:	SCALE:2:1	SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: 0.5 mm ANGULAR: 1 deg	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION 00
	NAME	SIGNATURE	DATE	TITLE: FRONT LOWER PADDLE MOTOR MOUNT	
DRAWN	L. REMPLE		05/12/15		
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: Al 6061-T6	DWG NO. ME16-PAD-D015-MotorMountFrontLower-R00	A3
			WEIGHT:	SCALE:2:1	SHEET 1 OF 1

Appendix D: CAD Naming Convention

When using SolidWorks, all CAD files must adhere to the following naming convention:

Ayy-SEC-P/Axxx-Name-Rxx

A*yy*:

A: denotes which **sub-system** the part will be used for (Mechanical (ME), Command and Data Handling (CD), Motor and Control (MC), Battery and Supply (BA), Vision (VS), Operator System (OS).

yy*:* are the last two digits of the year in which the competition will be held. This year will be **16**.

SEC:

SEC: is the three letter abbreviation of the section within the sub-systems name. The section abbreviations for the mechanical sub-system are listed in the table below.

Frame	**Suspension**	**Traction**	**Manipulator**	**Battery Quick Change**
FRM	SUS	TRC	MAN	BQC

General parts can be labelled under the sub-system descriptors in the SEC part.

P/A/D:

Stands for Part, Assembly, or Drawing

A Numerical Designation will be assigned to each Part, Assembly, and Drawing and should be the **next unused number** for **Assemblies and Parts.** Drawings shall be name to match the part or assembly number.

Name:

Should be a descriptor of the part such as FwdLeftMotor.

No spaces in part names! E.g. 'HStabRib3', <u>not</u> 'H Stab Rib 3'

Rxx:

Revision history

The first revision is R00

Example: You are modeling a frame piece. There are part numbers already up to P018.

As well, the piece is called rib 3, and it is a brand new part. Therefore the file would be

called: ME16-FRM-P019-Rib3-R00.sldprt

Appendix E: Product Catalogs

This appendix contains the installation and maintenance manual for the sprocket and chain drive as well as the product catalog for the harmonic drive. This appendix will be redacted from the published version.

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