Master's of Engineering Project Report – Cornell Mars Rover

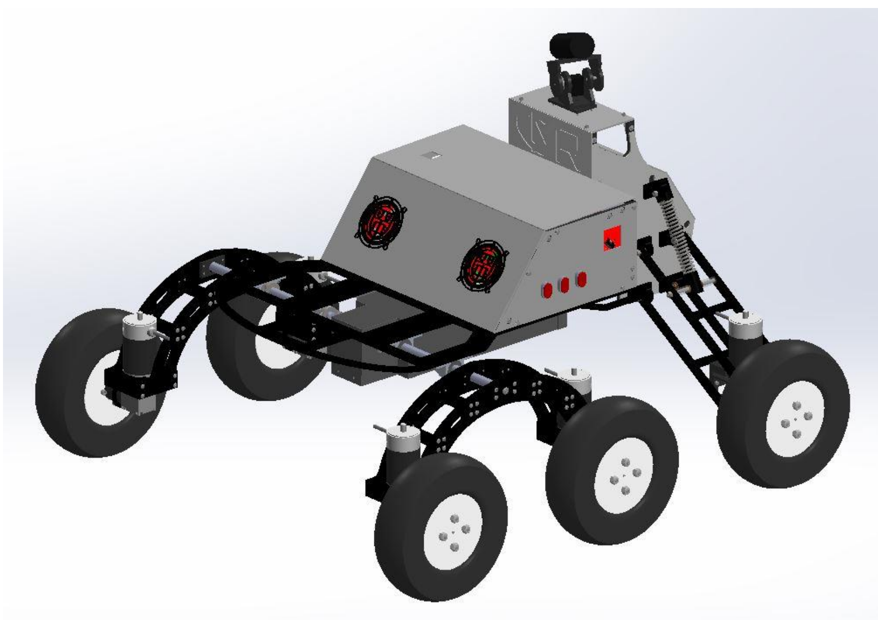

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Table of Contents

1 – Abstract

Masters of Engineering Degree (Mechanical)

Project Title:

Cornell Mars Rover

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Abstract:

With the increase in difficulty of the University Rover Challenge guidelines concerning the terrain traversal requirements, the Cornell Mars Rover project team needed to modify its existing suspension design to satisfy these stricter requirements. The new guidelines included the necessity to be able to traverse a half-meter shear face, as well as the necessity to have a greater amount of clearance for traversing obstacles. These changes placed greatly increased strength and geometric demands on the suspension systems of rovers that needed to be met if success was to be achieved in the competition.

In order to implement a solution to these issues, the suspension system was redesigned to use 90° vertical motors to power the wheels in place of the previously-used horizontal motors. Further, strength was strategically added to the suspension system in order to provide maximum resistance to the impulse force that would be experienced by the suspension when traversing the half-meter shear face. This was done while minimizing the increase in mass of the system.

Specifically, the rocker portion of the suspension underwent a significant redesign, having essentially everything except its general geometric properties modified. The distance between the rocker plates was increased, plates were used to encase the motors, and strengthening elements were added. All of these changes were necessary, however, in order to adapt the system to the 90° vertical motors and to ensure structural integrity would be maintained even under the most extreme loading conditions.

In addition to the rocker redesign that occurred, the battery enclosure also required modifications. The previous design left space for the drive batteries to move in, causing vibrations and the potential for power loss to the drive motors. Further, it did not allow for the housing of the CPU battery, which was a desired trait of the new design. Additionally, this redesign allowed for the attachment of an undercarriage camera, which could be used to observe the operation of the drill underneath the rover.

Finally, significant amounts of remachining were required after initial assembly and throughout the testing stages as additional issues arose. The main issues arising in this area were the interactions of crucial parts with the pivot D-shaft of the rockers and the internal coupling in the motors. Both of these issues posed serious complications for the functionality of the drive system. The former was addressed via the implementation of more precise tolerancing and the replacement of aluminum with steel, while the latter was addressed via modifications made directly to the inner mechanisms of the motors to allow for the addition of a set screw system that would increase the effectiveness of the coupling.

2 – Introduction

My main tasks for the Cornell Mars Rover project team were the redesign of the rocker portion of the suspension system, the redesign of the battery enclosure, general design consulting for the rest of the Drive Systems team, and machining both parts and part modifications for both the Drive Systems and Task Systems sub-teams. Additionally, I gained experience both in the interpersonal skills and the documentation skills required by systems engineering.

The rockers needed to be redesigned in order to enable the rover to be able to compete in the University Rover Challenge under its set of stricter terrain traversal guidelines. These guideline changes included the necessity to be able to traverse a half-meter shear face and more difficult obstacles than in previous competitions. The direct consequences of these new requirements were that the suspension system of the rover had to be stronger, in order to resist the impulse force experienced when traversing the half-meter shear face, and had to provide more clearance, in order to allow the rover to pass over more difficult obstacles. These issues were addressed by replacing the previous horizontal motors with 90° vertical ones, which provided more clearance, and adding strengthening elements to the rockers.

The battery enclosure needed to be redesigned in order to increase the tightness of the fit of the drive batteries in the enclosure, as well as to reduce vibrations and the potential for power loss. Further, the new battery enclosure allowed for the addition of a camera to be mounted to it so that the drill could be observed at an angle while in operation. Additionally, the new battery enclosure allowed for the transfer of the CPU battery from the electronics core to the enclosure.

In terms of the production and assembly of the drive system, there was a large amount of machining that was required. This was compounded by the necessity to remachine certain parts that were either out of tolerance or experienced significant levels of wear after being extensively tested, as well as the necessity to machine modifications to parts. The most notable issue that arose with the production and assembly of the drive system was an internal coupling issue with the motors. This was addressed via modifications to the motors and the addition of a set screw.

With regards to the systems engineering aspects of my work for this project team, my main experiences were with interacting and communicating with other team members in order to achieve successful design integration, providing guidance and motivation to the other team members of my sub-team, and creating systems engineering documentation for the team to utilize in the future.

3 – Design Elements

3.1 – Design Contribution Overview

My primary design focus was to redesign the rocker portion of the suspension system. This needed to be done in order to allow the suspension to perform more effectively with the stricter competition guidelines for terrain traversal. Additionally, I redesigned the battery enclosure. This redesign allowed the enclosure to fit the drive batteries better, allowed for the addition of the CPU battery to the enclosure, and allowed for the undercarriage camera to be mounted at an appropriate angle. Besides these explicit design contributions, I was also involved with helping the design of the rear suspension, as I helped design it for last year's rover. In general, there was also a good deal of design decisions that needed to be shared between the two portions of the suspension system, as the geometry and functioning of one system directly affected the other system. Further, I helped contribute design advice to other components of the drive system, including the limiters, the electronics core, and the wheel assembly. However, my design contributions in these areas will not be documented in this report, as separate reports will be submitted discussing these designs.

3.2 – Design Objectives

Rockers

The main objectives of the suspension design were to refine its ability to traverse obstacles and to increase its strength. These two objectives were of special interest this semester, as the competition guidelines for the University Rover Challenge increased the difficulty of the competition, especially with regards to the demands on the suspension system. The main guideline change that was of chief concern to the suspension's design was the increase in the difficulty of the terrain that would need to be traversed. The terrain changes added the necessity to be able to traverse a half-meter shear face, as well as to traverse obstacles requiring greater clearance. Therefore, in order to meet these new requirements, the focus of the suspension design was aimed at creating as much additional clearance as possible and increasing its strength so that it would be able to withstand the half-meter drop.

Battery Enclosure

The original objective of redesigning the battery enclosure was to create a tighter fit for the drive batteries and to prevent vibrations and the potential loss of power to the drive motors. Subsequently, further objectives were added, including the addition of space in the enclosure to house the CPU battery in order to free up space in the electronics core and the addition of a connection for an undercarriage camera to be mounted to so that drill operations could be observed at an angle.

3.3 – Design Decisions

Rockers

The first major design decision that needed to be made was how best to create additional clearance in the suspension system. After reviewing the designs from previous rovers, it was determined that the area with the most potential for increased clearance was the orientation of the motors. In previous rovers' designs, the six wheels of the rockers and the independent, spring-loaded rear suspension were each powered by a motor that was oriented perpendicularly from the wheel. While in this orientation, the motors stuck out horizontally from the wheels by approximately nine inches into the area under the frame of the rover. To further compound this issue, the motors had to be mounted to the center of the wheels, causing them to be only approximately five inches from the ground. This meant that the effective level of clearance for the rover was approximately five inches. This amount of clearance had been deemed sufficient for the competition guidelines in the past but, due to the newly imposed stricter rules, it was decided that the orientation of the motors should be changed to create more clearance.

To this end, motors were selected that included a 90° gear box that would allow for the motor rotation to be transferred to a secondary output shaft oriented 90° from the motor output shaft. Due to the 90° gear box, these motors could essentially be oriented parallel to the wheel. Further, the motors only stuck out horizontally from the wheels by approximately four inches. This decreased distance from the wheel allowed for much greater clearance; when traversing an obstacle previously, if the object had even a relatively steep slope to any part of it and if the wheel did not pass over the highest point, it was possible for the higher portions of the object to come into contact with the motor, effectively hindering the movement of the rover. However, with the newer motors, the chances of an object being traversed and coming into contact with the motors was drastically decreased, as obstacles were need to have a much steeper grade in order to hit the motors in this decreased distance. By implementing this solution, the effective clearance of the rover became the distance from the ground to the bottom of the rover's frame, which was an effective increase from approximately five inches to a foot.

In order to accommodate this design decision to use vertical motors, both the rocker and independent, spring-loaded suspension components needed to be changed. My primary concern was the implementation of this design decision into the rockers; however, I also consulted with the two team members working on the independent, spring-loaded rear suspension, providing general design input, as I was one of its designers last year.

In order to secure the newly selected 90° motors and resist the predicted worst-case impulse force, the rocker plates needed to be modified. The outer rocker plate was designed with circular sections at the end of either branch that would allow for the motors to be passed through. This would help secure the motors in place and would ensure that the motor final output shaft would be perpendicular to the rockers. Furthermore, both the inner and outer rocker plates had rectangular sections that allowed for the motor plates to connect to, as well as places for the I-beam connectors to attach to.

Additionally, both the inner and outer rocker plates had cutouts placed in them that were used to reduce mass. These cutouts went through several design iterations, starting as large triangles and evolving into smaller slots, in order to find the best shape and orientation. However, due to the relatively large predicted worst-case impulse force that the rockers needed to resist, these cutouts had to be limited in size. Although these cutouts were relatively small, the amount of mass that they eliminated was maximized by testing many different shapes and orientations. The final cutouts were chosen to be slots and were oriented on a path running in parallel to the semi-circular outlines of the rocker plates. This was found to be the optimal shape and placement of the cutouts, as it allowed the most material to remain in the major axis of bending that would be stressed in the worst-case impulse force scenario.

To house these new 90° motors, the distance between the rocker plates was increased so that the motors could fit vertically between them. To secure the motors to the rockers, motor plates were created that fit around the top and bottom of the square portions of the motors. The top motor plate was designed with a circular cutout in the center that would allow it to pass over the cylindrical, vertical portion of the motor and fit onto the top of the square portion. These plates also had a slot cut into the back of the circular region to allow for the wires of the motor to pass through during assembly. The bottom motor plate was designed with a rectangular slat cut into it that would allow for the gearbox to fit into so that the plate could be fitted against the bottom of the square portion. The combination of these top and bottom plates encasing the motor created complete restriction in all degrees of freedom via relatively simple parts. Further, these plates were designed so that the motors could be extracted from the rockers by only removing one plate, thereby saving time in disassembly and reassembly.

These motor plates then attached to the inner and outer rocker plates via screw holes located in both the motor and rocker plates. However, these top and bottom motor plates did not provide enough bending resistance for the rockers, as the rocker plates were relatively large and, thus, had relatively large lever arms from their pivot shafts. In order to provide additional strength to the rocker assemblies, I-beam connectors were added between the inner and outer rocker plates. I-beams were selected as the geometry of these connectors because of their excellent resistance to bending while using minimal mass. In order to make the rocker system able to withstand the predicted worst-case impulse force that might be experienced when traversing the half-meter shear face, it was necessary to use four of these connectors with each rocker assembly. Further, in order to maximize the effectiveness of these connectors, it was chosen that they be oriented with their major axis of bending resistance in the horizontal plane, so as to best resist a sideways impulse force on the rockers. Additionally, to minimize the mass of these connectors, a cutout was made in the center of the web portion, which did not significantly decrease the bending resistance that they provided.

The final components of the rocker design were the reinforcing plates that were attached to each of the rocker plates. They initially had circular cutouts that allowed for the pivot shaft to pass through, but these were later modified to aid the rocker design. This will be discussed in the Design Evaluation section below. The purpose of these reinforcing plates was to alleviate the high amounts of stress occurring around the pivot shafts.

Additionally, it should be noted that the bearings attached to the frame through which the rocker pivot shafts were positioned were also changed. In previous rovers' designs, these bearings were hard plastic, and this was deemed sufficient in strength for the terrain traversal required in the previous competitions. However, with the additional of the necessity to traverse a half-meter shear face, these bearings would be experiencing much greater forces. Therefore, it was decided that the plastic bearings should be replaced with aluminum bearing. These new bearings provided much more strength than their plastic counterparts. Further, they had a self-contained lubrication system, which was an advantage, as it provided protection from contaminants such as dust or sand from interfering with the bearings. Another advantage of using these new bearings was that there were nuts and bolts that were sized to exactly fit the holes connecting the bearings to the frame. This was important because in the previous rover's design, washers had to be used to secure the bearings to the frame, and these washers began to deform due to the stresses that they experienced.

As an additional design consideration, it should be noted that the rocker design was created with reduction of complexity in mind. The variety of fasteners was reduced to only two different lengths of 8-32 screws. Further, each part was designed to require minimal machining, both to facilitate rapid production of the parts and to reduce the potential for the occurrence of machining errors that could be costly, both in time and resources.

Battery Enclosure

In addition to the rocker design, the battery enclosure also needed to be redesigned, as last year's battery enclosure left too much space for the batteries to move around in. Also, it was decided that the CPU battery should be moved from the electronics core to the battery enclosure with the drive batteries. Additionally, a camera needed to be mounted under the frame of the rover that would be pointed at the ground where the drill would be deployed, and the battery case was an ideal position for this purpose. In order to make these accommodations, it was necessary to redesign all elements of the battery enclosure.

The redesign called for three components, each to be cut and bent from sheet metal. The first was the main component, which would attach to the frame and would be the sides and floor of the enclosure. The second component was the back cover, which would attach to the main component and prevent the batteries from falling out of the enclosure when the rover traveled over inclines. The third component was the front cover, which would encompass the CPU battery and would attach to the main component, prevent the batteries from falling out of the enclosure when the rover traveled down inclines. Additionally, there was another component that could be attached to the front cover. This component allowed for the attachment of the camera to the battery enclosure at the appropriate angle to have a view of the desired area.

In order to ensure that the batteries would be contained adequately, foam was placed along the floor and sides of the battery enclosure. This foam not only helped increase the tightness of the fit of the batteries into the enclosure, but it also reduced the vibrations that were experienced.

3.4 – Design Analysis

In order to analyze the stresses and masses associated with the modified rocker design, extensive ANSYS models were run, each with different setups of forces and supports simulating different loading scenarios. Further, several ANSYS iterations were conducted to find the maximum size of the cutouts that could be taken in the rocker plates and the connectors to minimize mass.

In order to ensure that the final modified rocker design would have sufficient strength to withstand the predicted worst-case impulse force experienced when traversing the half-meter shear face, ANSYS was used to model this scenario on multiple design iterations. After iterating on the design multiple times, the final design was selected. This design provided a factor of safety of two against the worst-case scenario. It was determined that this was a sufficient factor of safety, as the worst-case scenario was very unlikely to occur and, even if it did, the rockers should still be able to withstand it with this modest factor of safety. The ANSYS results for equivalent stress, equivalent elastic strain, and total deformation are shown below. Please note the scales accompanying the images, especially in the equivalent stress results, as the image seems to suggest very low levels of stress but the scale indicates otherwise.

Image I.1: Final Rocker Design ANSYS Results – Equivalent Stress

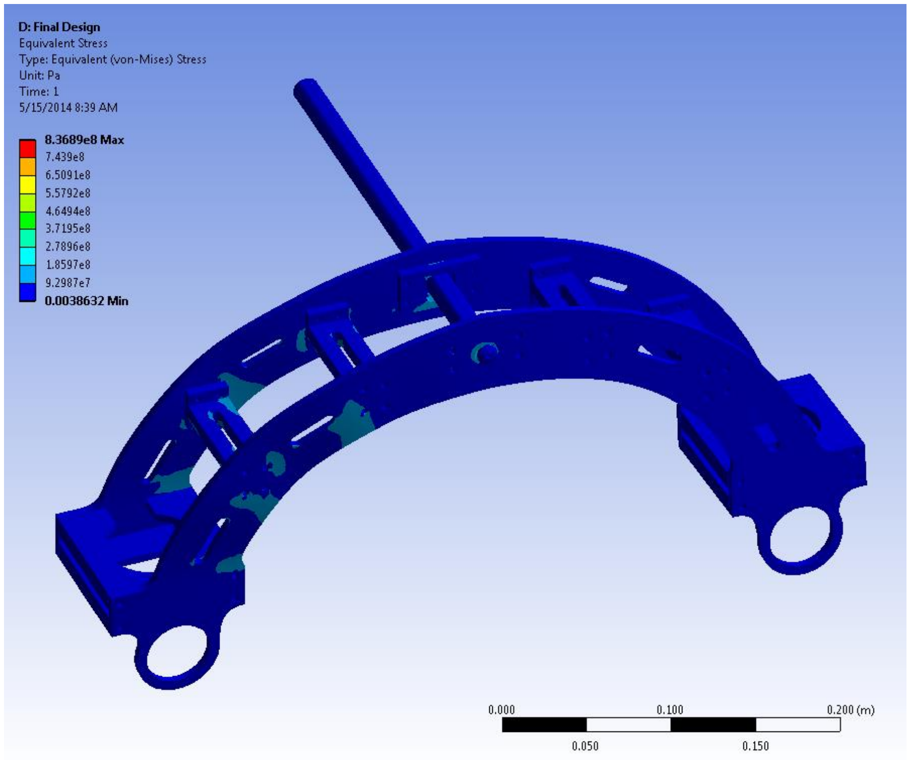


Image I.2: Final Rocker Design ANSYS Results – Equivalent Strain

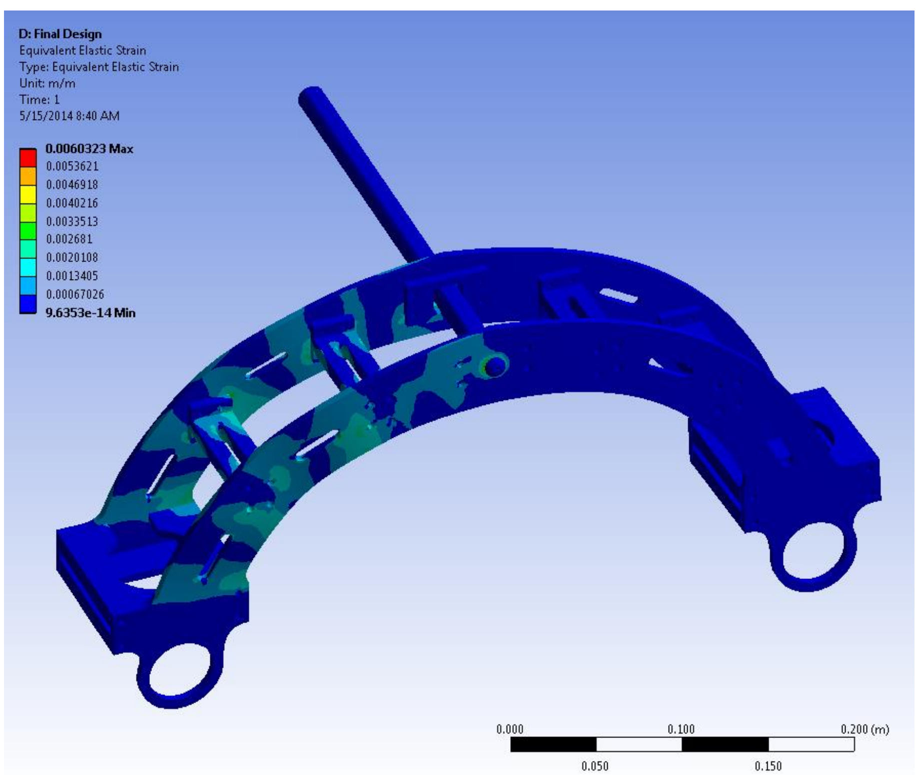
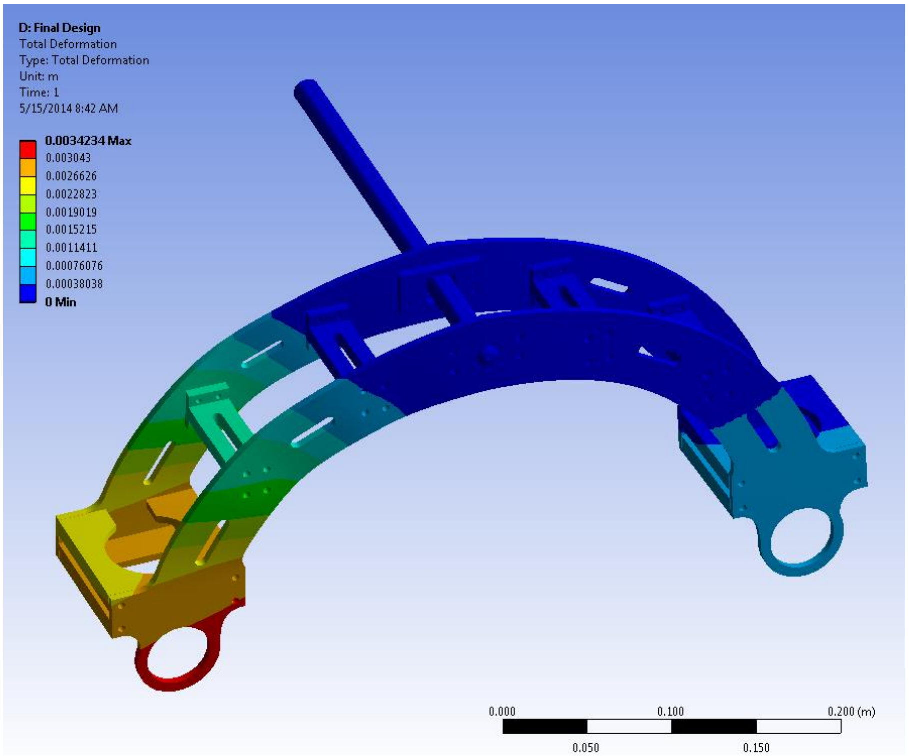


Image I.3: Final Rocker Design ANSYS Results – Total Deformation



After conducting a mass analysis of the final design, the following results were obtained.

Table T.1: Final Rocker Design – Mass Analysis

Final Rocker Modified Design - Mass Analysis			
Part	**Mass (lbs)**	**Mass Individual (kg)**	**Mass Total (kg)**
Front Rocker Plate	0.800	0.363	0.363
Back Rocker Plate	0.736	0.334	0.334
Motor Top Plate	0.183	0.083	0.166
Motor Bottom Plate	0.202	0.092	0.184
Connector	0.126	0.057	0.228
Reinforcing Plate	0.042	0.019	0.019
Pivot Shaft	0.754	0.342	0.342
Bearing	0.202	0.091	0.183
	Total (kg)		
	1.818		
Last Year's Design (Comparable Elements Included)			**% Increase**
1.529	kg		0.189

From this table, it is clear that there was a significant mass increase in the rockers. However, even though the mass of the rockers increased by approximately 19%, this was only equivalent to approximately 0.3kg. This was deemed to be a small enough increase to be acceptable, especially when compared to the additional clearance and strength that the design provided.

3.5 – Design Evaluation

Rockers

The overall design of the rocker system was effective, as it allowed for the incorporation of the vertical motors, thus creating more clearance, and was able to resist the predicted worst-case impulse force when traversing a half-meter shear face. Furthermore, it was able to do this with only an approximate increase in mass of 19% from last year's rocker design. This was relatively minimal when considering the advantages that this design provided and when considering that this 19% mass increase only amounted to approximately 0.3kg. Additionally, the rocker design was able to reduce complexity of the drive system, as it only utilized 8-32 screws with only two different lengths.

Further, the rocker design, when tested in the field, was effective at traversing both normal and extreme terrain. Not only was it able to climb inclines and pass over small obstacles, but it was able to withstand drops from heights exceeding the half-meter competition requirement and climb and go over shear faces.

However, there were some issues with the design that arose during the assembly and testing of the system. The issues associated with assembly were chiefly caused by machining errors and, therefore, will be discussed in the Production and Assembly sections. The issues that arose from testing, however, were more due to the lack of steel-on-steel interactions between the pivot shaft and the rocker system.

The major issue with the rockers only arose after significant testing had occurred. This issue was that the square cutout in the inner rocker plate that was designed to allow for a tight fit against the flat face of the pivot D-shaft began to be worn away by the shaft. The cause of this issue was primarily due to the water jet cuts that made the inner rocker plates. These cuts were not as exact as the design called for and, thus, did not meet the tolerance required for a tight fit between the square cutout and the flat face of the D-shaft. This meant that, when the rockers traversed obstacles, the inner rocker plates would rotate slightly about the pivot shaft. This, in turn, caused the steel of the shaft to wear away at the aluminum of the inner rocker plate. At first, this did not cause enough wear to allow for the potential of slipping between the rockers and the pivot shafts but, after more and more testing was conducted, the wear became too significant to go unaddressed.

In order to remedy this issue, the reinforcing plates were modified; their circular cutouts were replaced with cutouts that matched the D-shaft so that they could provide rotation resistance between the rockers and the pivot shafts. Further, these parts were changed from aluminum to steel in order to further limit the wear that might occur between the two parts. This solution is also discussed in the Production and Assembly sections.

Battery Enclosure

The design of the battery enclosure was effective at addressing the space issues and was successfully implemented. Further, as it created more space in the electronics core by housing the CPU battery and provided an attachment point for the undercarriage camera for monitoring the drill operations, the design was successful in more ways than simply housing the drive batteries. It was also quite easy to produce and assemble, which added to the design's success.

4 – Production and Assembly

4.1 – Production and Assembly Contribution Overview

My contributions to the machining and assembly of the rover this year were manifold. First, I completed all of my specifically assigned parts before the deadline. In order to accomplish this, I needed to return approximately two weeks early from winter break, as I had eight parts to complete. Second, after I completed machining my specifically assigned parts, I began helping Task Systems machine many of their parts. Third, after Drive Systems began its preliminary assembly and found machining errors causing design elements to be out of tolerance, I was the primary machinist who completed touch-up machining on these parts to make them functional again. Finally, I was the primary machinist who performed modifications to the motors after we found a critical problem inherent in their design. After tallying all of the time that I spent in the machine shop making and adjusting parts this semester, I would estimate that I totaled approximately 70 hours of machine time.

4.2 – Production and Assembly Objectives

This year, Drive Systems set a machining deadline that was much more strict than those imposed in the past. The purpose of this was to allow the team to have the drive system assembled much earlier, thus allowing the controls team to have a greater amount of time to test. Drive Systems was able to meet this deadline, despite having to perform some adjustments to parts that had machining issues. However, after significant testing caused issues to arise that required either remachining or modification of parts, production objectives were updated and machining solutions were undertaken.

4.3 – Production and Assembly Issues and Solutions

One of the issues that arose with the production and assembly of the suspension system was the tolerances of certain parts associated with the rocker system. Some of the holes created by the water jet cuts were not placed exactly where they were supposed to be, nor were they the size that they were supposed to be. In fact, they were actually shaped like hexagons instead of circles and needed to be drilled out to be made into circles. In addition, the top and bottom plates that held the motors in place in the rockers were machined slightly out of tolerance, causing thicknesses to be off and, thus, hole placement to be misaligned.

In order to address these issues, remachining had to be done. First, the top and bottom motor plates had to be thinned in order to bring the holes closer to tolerance. However, doing this alone was not sufficient to allow the rockers to be fully assembled. Some of the rocker plate holes needed to be shifted slightly to line up with the holes in the top and bottom motor plates. Once these steps were taken, the rockers fell back within the design specifications and could readily be assembled.

Additionally, the motors that were selected were not the same as the CAD model that the company sent us to base our designs off of. The difference between the CAD model and the actual motors was that the motors had two small plastic knobs protruding from the sides of the vertical portions of the motors. These allowed for access to the inner portion of the motors, but they prevented the top motor plates from fitting over the motors. In order to solve this problem, slots needed to be machined into the sides of the circular cutouts in the top motor plates to allow the plastic knobs to pass through. This was a relatively complex machining process, as it could not be done on the CNC or the NC and instead had to be done on a standard mill. In order to make the slots at the appropriate angles, a special vice had to be used that could rotate the part being machined to a given angle.

Another production-related issue that arose was the tolerancing associated with the parts interacting with the pivot shaft of the rockers, which was a D-shaft. These parts were designed to fit tightly against the flat face of the D-shaft, thus moving with it or impeding its movement, depending on the part. However, due to machining issues, none of these parts fit as tightly as required against the D-shaft. As these parts were made from aluminum and the D-shaft was made from steel, when the D-shaft rotated and the aluminum parts were pressed against it, the steel began to wear the aluminum away. After this happened multiple times, the aluminum parts were worn away to such an extent that they began to slip about the D-shaft, thus negating their effectiveness.

In order to solve this problem, these aluminum parts were remachined out of steel. These parts included the limiters on each rocker assembly and the reinforcing plates on each of the rocker plates. By remachining these parts out of steel in place of aluminum, any slight movement that might occur between them and the D-shaft due to tolerancing would take a much longer time to cause even slight wearing in the parts, thus effectively eliminating the possibility for slipping. Additionally, the limiters were also made 50% wider to further increase their resistance to wear caused when they came into contact with the frame and prevented the rockers from rotating further.

Another of the major issues that arose occurred much later, after the drive system had been assembled and tested. This issue was the coupling of the internal shafts in the new, 90°

motors that had been selected. In order to achieve this 90° orientation, the motors incorporated the use of a gearbox. This gearbox translated the rotation of the vertical output shaft from the motor to a secondary horizontal output shaft, which was the final output shaft of the whole motor system. However, in order to achieve this rotational translation, the vertical output shaft needed to be coupled to the system of gears in the gearbox. The way that the motor system did this was to have the vertical output shaft fit into a sleeve system in the gearbox. This sleeve system consisted of a spacer sleeve that could be fit snuggly around the vertical output shaft and an outer sleeve that fit around the inner sleeve and connected directly to the gear system. However, these sleeves were not directly fastened to the vertical output shaft and, instead, were only coupled through the use of a shaft collar. This shaft collar was fitted around the sleeve-shaft system and was then tightened, which was supposed to hold the system together through the use of high friction. This design was particularly ineffective, as it did not take advantage of the fact that the vertical output shaft was D-shaped, thus providing a flat face against which the coupling system could be secured.

At first, testing the drive system did not produce any issues but, after a significant amount of tested had occurred, the motors began to lose torque and could easily be stopped from rotating by even a light amount of pressure. It was determined that the problem with the drive system was not a controls or electrical issue, but rather an issue with the internal mechanical system of the motors. After the motors were taken apart in search of the issue, it was observed that the shaft collars had loosened, causing the vertical output shaft and sleeve system to slip around each other. This rendered the motors effectively useless, as no rotation from the vertical motor was being translated through the gearbox.

In order to fix this problem, it was determined that machining would have to be done in order to modify the coupling system to prevent this slipping. However, since the motors were such a costly resource, it was decided that only green aprons should perform these modifications, in order to avoid mistakes that would necessitate the purchase of additional motors. The consequence of this decision was that I was the primary machinist who could work on these motor modifications, as I was the only green apron machinist on Drive Systems.

Several solutions were proposed for modifying this internal coupling system. The first, and simplest, solution that was proposed was to use a metal-bonding adhesive to secure the vertical output shaft to the sleeves. This idea was rejected, however, for a few reasons. First, implementing this solution would have made taking the motors apart much more difficult if any internal systems needed further modifications. Second, the gear system was filled with a special grease, and there was no way to prevent the metal-boding adhesive from leaking into the gearbox and mixing with the grease. It was judged that this could cause serious problems for the gear system and, thus, should not be implemented. Another solution that was proposed was to run a metal pin through a hole placed in the sleeves and the vertical output shaft. This solution would have ensured that the two components would never have become decoupled. However, this solution was discounted for two reasons. First, it was decided that drilling a hole through the vertical output shaft would have seriously undermined its strength, which could lead to other, more serious, issues if it was subjected to large amounts of stress. Second, inserting a pin through the sleeves and the vertical output shaft would have required an access hole to be drilled in the square component of the motor system which, in itself, would not have been an issue; however, this hole would have necessarily been in line with the pin, which would provide the potential for the pin to become stuck in this hole when the coupling system was rotating. Even with a screw inserted as a plug, there would have still been a danger of the pin getting stuck, and this would have caused damaged to the motor.

The design modification that was finally selected was to use a set screw to connect the sleeves to the vertical output shaft. A hole would be drilled in the sleeves and a relatively shallow hole would also be drilled in the vertical output shaft. Also, custom shaft collars would need to be machined. These were made by ordering standard shaft collars from McMaster, machining a flat face on one side, and drilling and tapping a hole in that face for the set screw to go through. Additionally, an access hole would also need to be drilled in the square portion of the motor system to allow for the insertion of the set screw.

It should be noted that, in order to machine these modifications, several jigs were needed. The first jig that was made allowed the access holes to be drilled in the square portions of the motor systems. This was necessary because the square part already had four holes drilled in the centers of the sides and four holes drilled in the corners of the square, and drilling an access hole that passed through one of these preexisting holes would create further issues. Therefore, the access hole would need to be drilled at an angle in between the preexisting holes in the sides and in the corners. To further complicate this, the access hole needed to be perpendicular to the tangent of the circular center of the square piece, meaning that it needed to be in the centerline of the circular center. Therefore, the jig needed to allow for the square part to be screwed into it at an appropriately a rotated orientation. After the geometric considerations were made and the jig was completed, the holes were started with an end mill to create a flat surface to drill into and were then finished with the appropriate drill.

The second set of jigs that was made was intended to allow the holes to be drilled in the sleeves attached to the gearbox. The problem that these jigs needed to address was the rotation of the sleeves while the drill was starting to move into them. The first of these jigs had a cutout made in it that allowed for the final output shaft with the key in it to fit into and prevented its rotation. The idea behind this was that the sleeves could be prevented from rotating by preventing the final output shaft from rotating. The second jig was used to hold the rest of the gearbox in place to keep the final output shaft from sliding out of the other jig. However, due to the gear ratio of the gearbox, the sleeve rotated far faster than the final output shaft. This meant that securing the final output shaft as tightly as tolerancing would allow for still allowed significant rotation in the sleeves. Further compounding this problem was a large amount of vibration in the sleeves when the drill came into contact with them. Therefore, these jigs had to be replaced with different jigs that could directly secure the sleeve from rotating.

This new set of jigs was a set of custom V-blocks. Their geometry was designed such that it would grip the outer sleeve between its preexisting slots. By gripping the outer sleeve in the V-blocks and the V-blocks in the vice, the sleeves were effectively stopped from rotating and vibrating and, thus, could be drilled effectively.

Once all of the modifications had been machined, the coupling assembly was put together by placing the shaft collar over the outer sleeve and matching up the set screw holes, screwing the square part onto the vertical motor portion, placing the vertical output shaft into the sleeves and matching up the set screws holes, and screwing the gear box onto the square part. Once the assembly was completed, the shaft collar could be tightened using the preexisting hole in the square part. Finally, the set screw was inserted using the newly machined access hole in the square part and screwed into the shaft collar. The set screw could then be tightened so that it pressed against the hole made in the vertical output shaft.

Another, smaller issue that arose was found when the wheels were assembled. The wheel hubs, when pressed together, were too thick for the screws to effectively hold them together. In order to address this issue, the wheel hubs were counterbored so that their thickness was reduced and the screws could be more easily be run through the hubs and connected with nuts.

4.4 – Production and Assembly Evaluation

After the preliminary assembly of the drive system, there were some issue that arose. Most of these issues were solvable and, after remachining was undertaken to correct them, they were eliminated when the drive system was reassembled.

However, the modifications to the motor that were machined in order to fix the internal coupling issue causing slipping in the motor were not fully successful. After the modified motors were assembled and tested, the slipping issue was temporarily resoled but, after more extensive testing, it arose again. I suspect that the issue with the modifications arose because the set screws were not fastened firmly enough due to the extremely small lever arm on the Allen wrench that fit the set screws. With this very small Allen wrench, it was not possible to turn the set screws far enough into the vertical motor output shaft to firmly secure them. However, due to the serious time constraints arising at the end of the semester and the need for greater amounts of testing, there was not an opportunity to attempt to investigate and remedy this issue further.

5 – Systems Engineering Elements

While working with the Cornell Mars Rover project team, I was able to gain significant experience with systems engineering. This experience manifested itself both in interpersonal interactions and written documentation. Being a project team involving the integration of multiple sub-systems based in different engineering disciplines (primarily mechanical, electrical, and computer science), the necessity of organized and effective communication between sub-teams was crucial. In both the rocker and battery enclosure designs that I worked on, I needed to interact with both members working on different aspects of the drive system and members working on the controls and electrical systems.

With regard to rocker design, I first needed to consult with the team members working on the independent, spring-loaded rear suspension. We needed to communicate with each other in order to ensure that the overall geometry of the drive system would be appropriate for effective skid steering. Specifically, we needed to make sure that our ride heights and wheelbase dimensions were equal. This proved to be more difficult than we had initially expected, as dynamic requirements placed on the rocker system caused several small geometry changes that needed to be reflected in rear suspension geometry changes in order to maintain the overall drive system geometry. Additionally, I needed to communicate with the team member designing the limiters for the rockers. These limiters needed to be based on the geometry of the rockers in order to limit their rotation at the proper angle relative to the frame. Therefore, as the geometry of the rockers changed, I needed to communicate these changes to the designer of the limiters so that they could also be modified accordingly. Finally, when designing the rockers, I needed to consider how the wires from the motors should be placed in order to most effectively connect to the electronics core. For this, I needed to consult with the team members designing the electronics core.

The battery enclosure also required extensive communication with other team members. First, I needed to meet with the controls, electrical, and electronics core designers in order to determine which batteries would need to be housed in the battery enclosure and which would remain in the electronics core. I also needed to discuss wiring from the batteries to the electronics core with its designers. Finally, I had to work with the team member in charge of determining camera placement in order to decide how best to attach the undercarriage camera to the battery enclosure to allow observation of the drill operations.

In addition to these interactions with various team members related to design aspects, I also gained valuable experience with the more personal and managerial side of systems engineering. I often found it interesting how many applications I had learned in my project management course applied directly to situations that arose in my project team work. Issues of dealing with different personalities, different skill and motivation levels, and different areas of expertise were prominent in my work for this project team. As one of the most senior members of the team, I was looked to for guidance throughout the design and production processes. I worked with all members of my sub-team in some manner or other, ranging from freshman to seniors. The experience levels associated with each team member were varied, and I needed to tailor my approach to helping them with their questions to fit their different levels of understanding.

Closely related to this point, I was faced with the difficulty of how best to utilize and increase my teammates skills appropriately. For the newest members of the team, I closely helped them with developing their most basic design and analysis skills, and for the more senior members, I took a more relaxed approach, instead waiting for them to come to me with issues. Further, I was in a position where I sometimes had to direct the work of my teammates; I tailored the work to the level of difficulty involved with the request. For example, I had the freshman members of the sub-team help me with sheet metal operations and the machining of simple parts.

For the more advanced members, I asked them to machine more advanced parts that fit their skill levels and provided assistance only if asked.

Doing this was also a helpful way to provide motivation for increased effort, enthusiasm, and productivity. By acting as a mentor and helping the newest members acquire the necessary basic skills and offering them guidance with the basics of machining, I helped give them a reason to strive for greater levels of involvement. Further, by providing assistance as a colleague to the more advanced team members, I helped them gain confidence and expertise in designing and machining.

In addition to these more interpersonal systems engineering skills, I also utilized skills in documentation that I learned in my model based systems engineering course. To this end, through the guidance of this course, I created many systems engineering documents that can be used by the team in future years. The use of these documents will surely increase the level of organization and interaction of the different sub-teams, providing for smoother design integration and communication between team members. The documents that I created for my project team to use in the future are submitted in addition to this report, some in Excel and some in PowerPoint.

6 – Conclusion

After completing the design, production, assembly, and testing of the new rockers, it was determined that the design effectively addressed the new issues that had arisen this year as a result of the stricter guidelines set forth by the University Rover Challenge. Not only did they successfully withstand drops from heights exceeding those required by the competition, but they also provided a much greater level of clearance for the rover. These results were achieved despite some machining complications that arose, as they were ameliorated by remachining and modifying parts as necessary.

The battery enclosure also achieved a similar level of success, meeting all of the requirements set out for it, including housing the additional CPU battery and providing a connection point for the undercarriage camera.

In terms of the production and assembly, certain levels of success were also achieved. The initial production deadline was met, but the preliminary assembly revealed issues that needed to be addressed via additional machining. However, after the remachining was completed, the assembly fit together as designed.

The single area that was met with only limited success was the modifications made to the internal coupling systems of the motors. A viable solution was decided upon and implemented, but due to limitations on machining and in assembly, this solution was met with only marginal success. In the future, it would be best to avoid this issue by selecting motors from a different vendor.

Finally, working for a project team that required such a high level of integration between different sub-teams involving many areas of engineering expertise provided a significant amount of experience with systems engineering interpersonal skills. Additionally, this high level of integration also provided an excellent opportunity to create and gain experience with a myriad of essential systems engineering documents.

7 – Appendix

Image I.4: Rocker Outer Plate

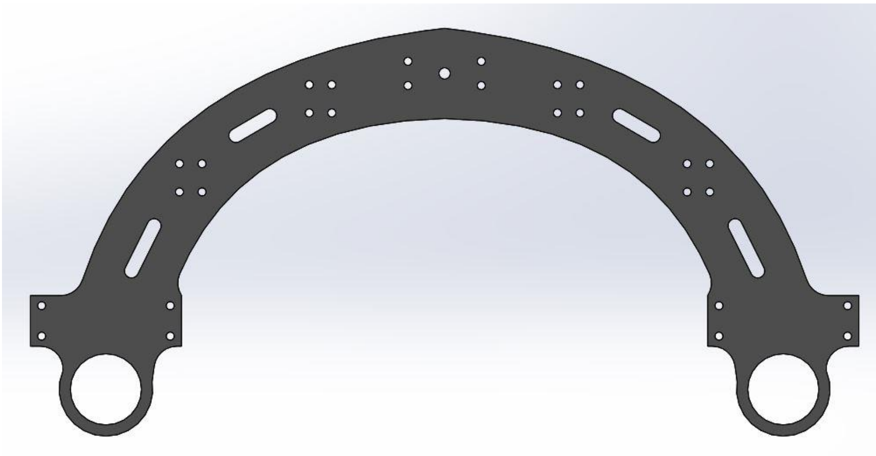


Image I.5: Rocker Inner Plate

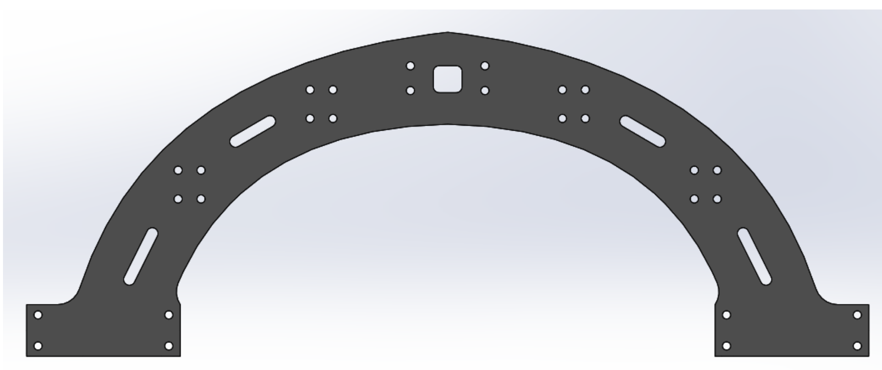


Image I.6: Rocker Top Motor Plate

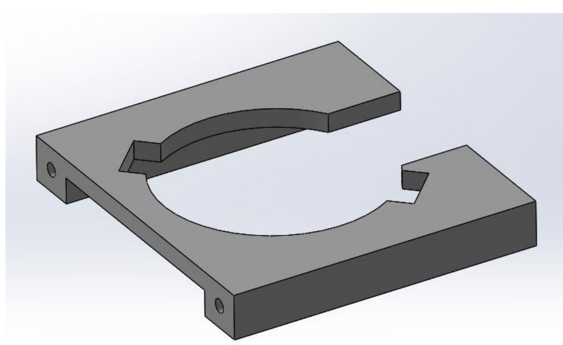


Image I.7: Rocker Bottom Motor Plate

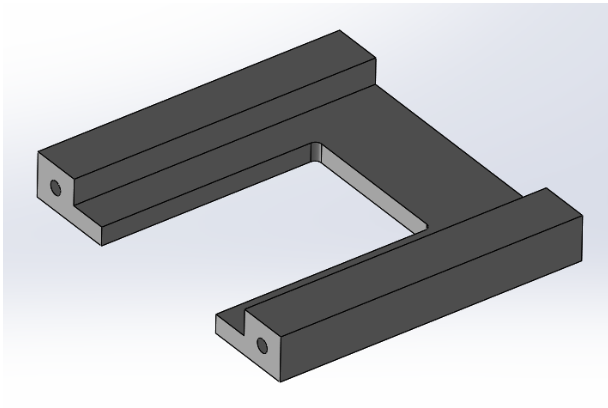


Image I.8: Rocker I-Beam Connector

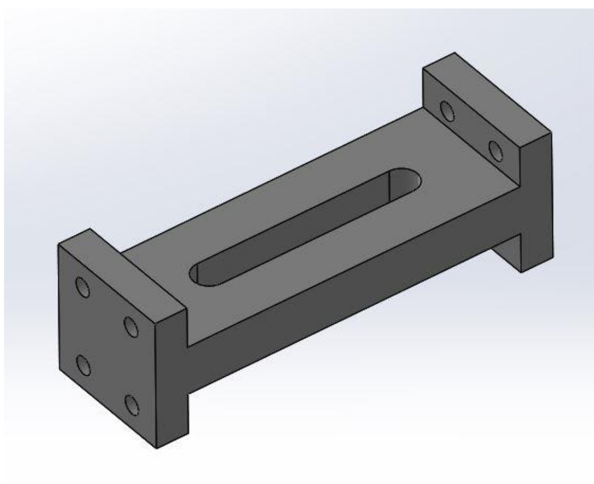


Image I.9: Rocker Metal Bearing

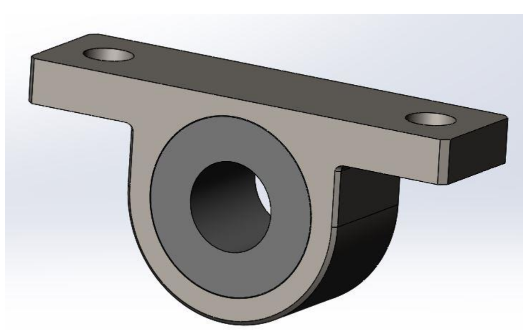


Image I.10: Rocker Pivot D-Shaft

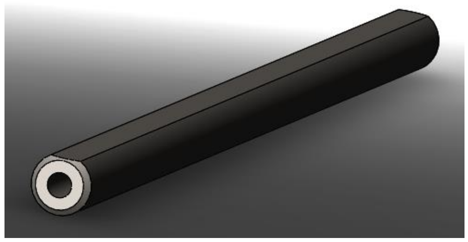


Image I.11: Rocker Shaft Collar

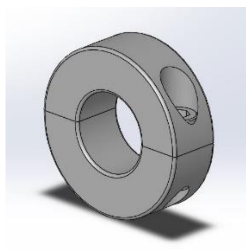


Image I.12: Rocker Assembly – Front view

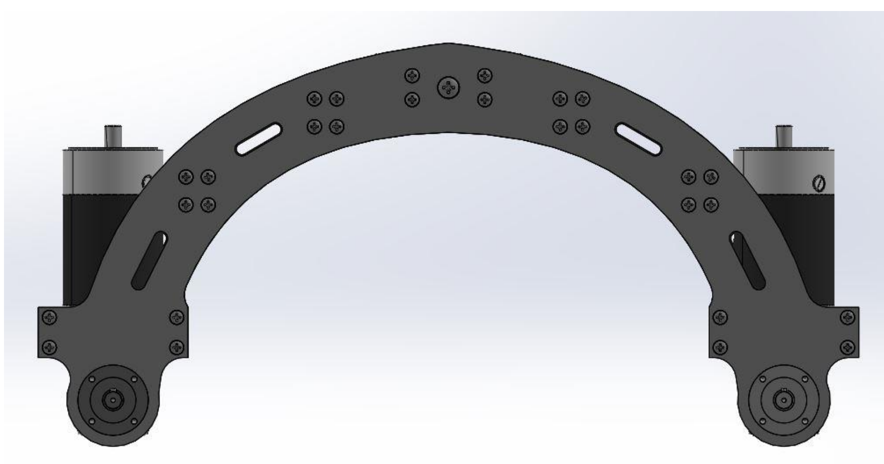


Image I.13: Rocker Assembly – Top View

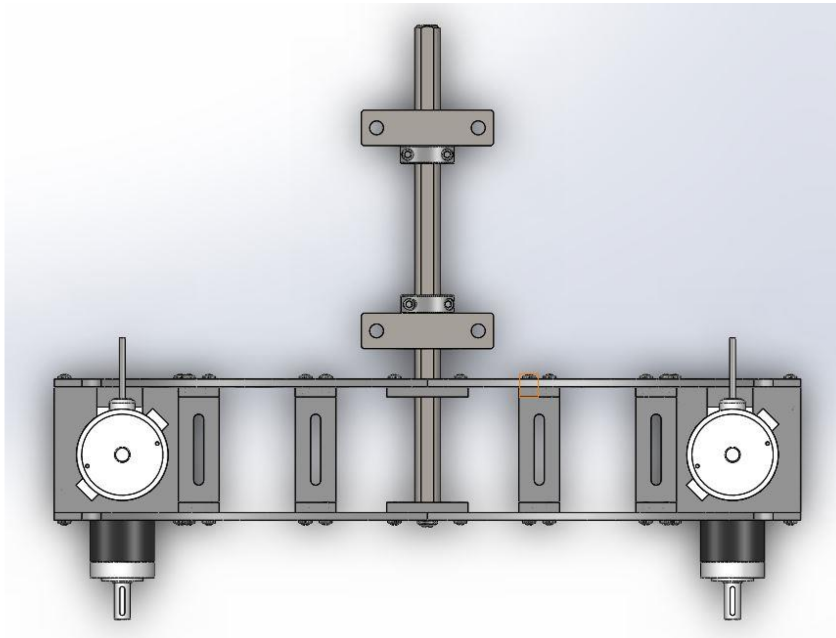


Image I.14: Rocker Assembly – Side View

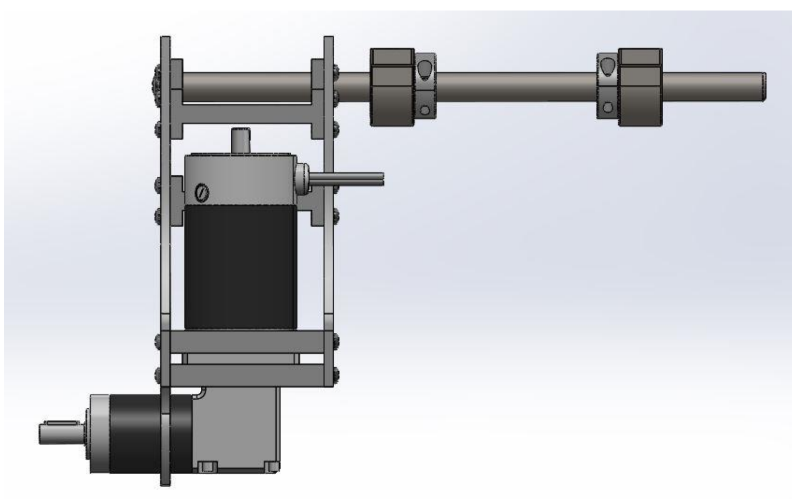


Image I.15: Rocker Assembly – Angled View

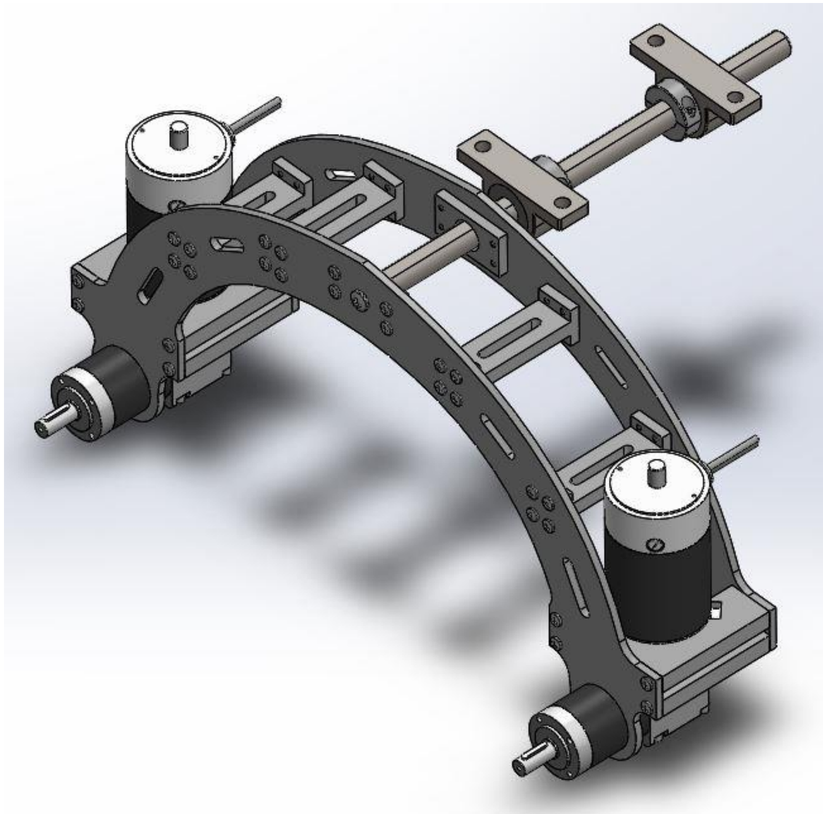


Image I.16: Battery Enclosure – Main Component

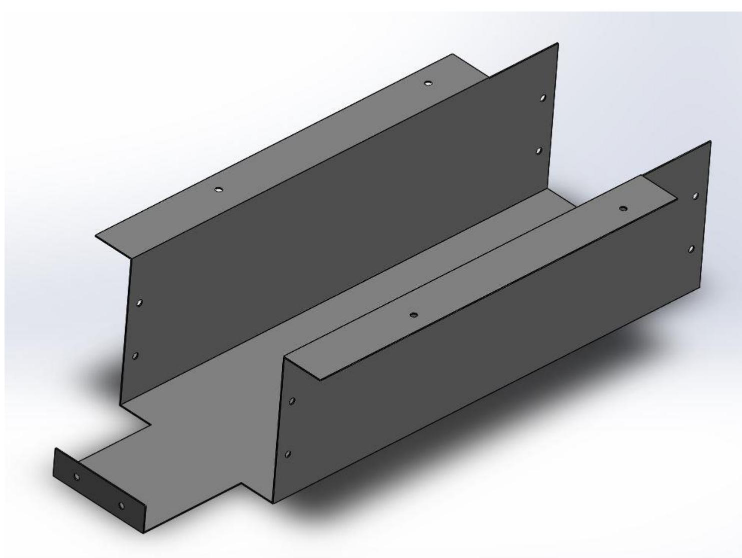


Image I.17: Battery Enclosure – Front Cover Component

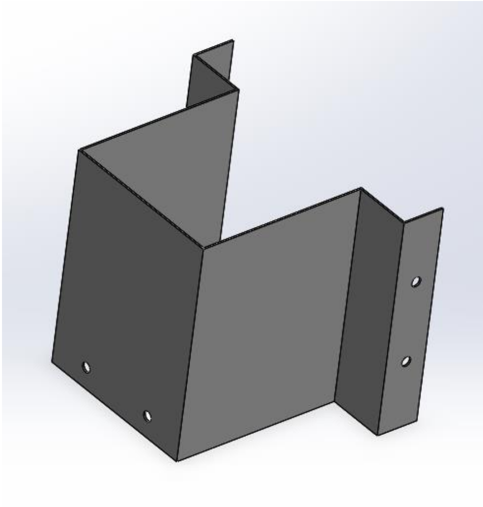


Image I.18: Battery Enclosure – Back Cover Component

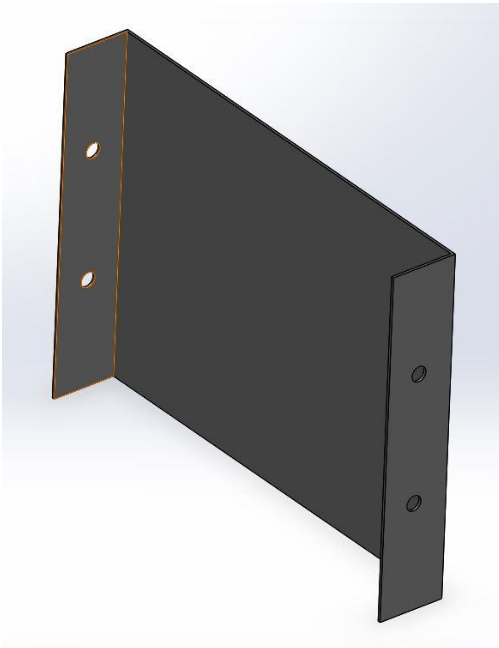


Image I.19: Battery Enclosure Assembly – Top View

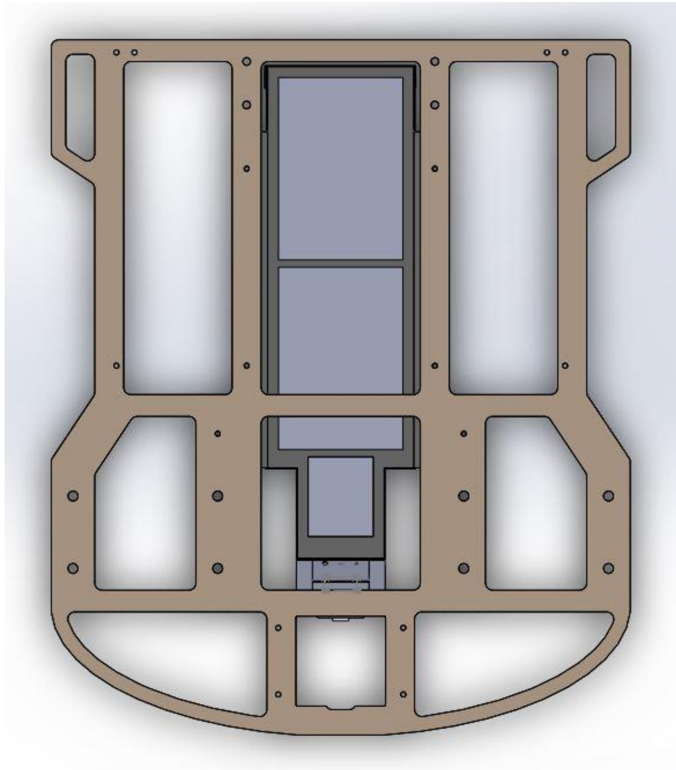


Image I.20: Battery Enclosure Assembly – Angled View 1

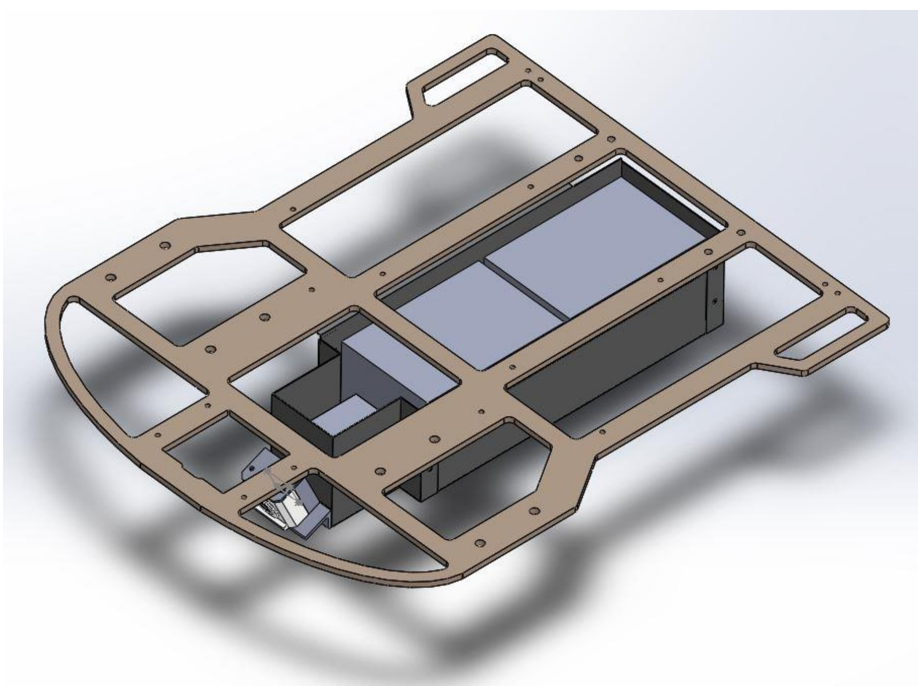


Image I.21: Battery Enclosure Assembly – Angled View 2

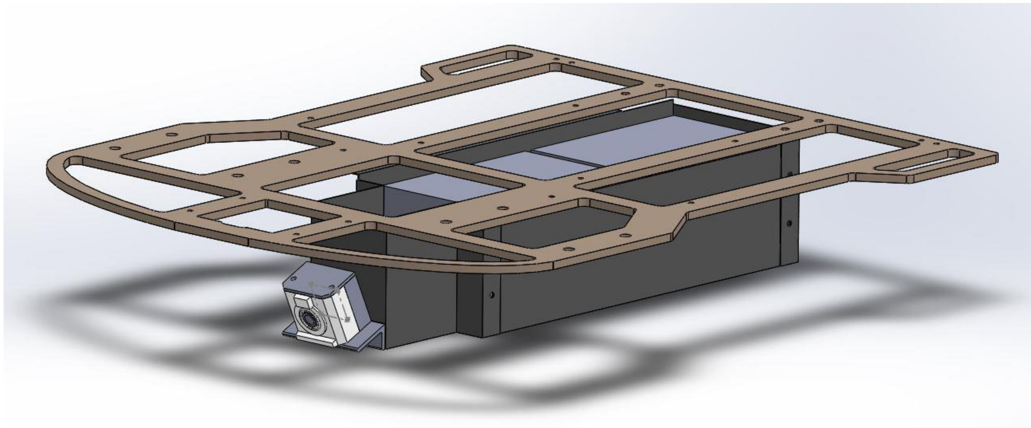


Image I.22: Full Drive Systems Rendered Assembly