Project Deliverable 4

MEMS 1029

Due Date: 7/29/2021

Team Members:

Raúl Casas, Frank Czura, Hannah Lillis, Leanne Boody, Rachel Fry, Jack Rossow

Responsibilities:

Task	Person Responsible	Expected Time (min)	Actual Time (min)
Preliminary Tasks	--	--	--
Update torque requirement	Frank	45	40
Revise current requirement	Frank	30	30
Review suspension spring stresses	Frank	30	20
Review nominal ground clearance	Frank	45	60
New Tasks	--	--	--
Evaluate component masses	Rachel	120	150
Complete drawings of custom parts	--	--	--
Chassis	Hannah	30	30
Front suspension frames & brackets	Rachel	30	90
Front Axle	Rachel	30	15
Stepper Motor Bracket	Rachel	30	15
Front links	Rachel	30	30
Suspension mounting brackets	Leanne	30	30
Bearing blocks in rear	Frank	30	30
Wheels	Leanne	30	40
Rear Suspension Frame	Leanne	30	60
Rear suspension linkages & Frame	Frank	60	45
Shock Assembly Components	Frank	60	60
Motor housings	Hannah	60	60
Motor shafts	Hannah	30	40
Differential housing	Raul	120	120
Differential gears	Raul	90	120
Create subassembly for suspension	Frank	15	10
Constrain stroke length for suspension & adjust for manufacturing	Frank	30	60
Adjust mounting heights on rear frame: 0.115 m	Frank	15	10
Adjust mounting heights on front frame: 0.096 m	Rachel	10	5
Adjust rear axles to fit new differential	Raul	30	45

Assembly Instructions	--	--	--
Create bills of materials for assy/subassy and Exploded view of subassembly and Record names, part #s, and prices of commercial components			
Rear Suspension & subcomponents	Leanne	60	90
Front Suspension & subcomponents	Rachel	120	120
Steering	Rachel	120	120
Gearbox	Frank	100	90
Differential	Raul, Jack	180	180
Overall assembly (with previous assemblies unexploded)	Jack	60	60
Detailed instructions to assemble			
Front suspension and steering & subcomponents	Rachel	120	150
Rear suspension & subcomponents	Frank	60	60
Gearbox	Hannah, Frank	60	60
Differential	Raul, Jack	60	90
Front Wheels	Rachel	60	45
Rear wheels	Frank, Leanne	30	30
Gearbox	Hannah, Frank	30	30
Differential	Raul, Jack	30	90
Presentation	--	--	--
Develop claims for assertion-evidence model	Hannah & Frank	60	60
Organize presentation format, images	Hannah & Frank	60	60
Use feedback from initial rehearsal to improve presentation	All	60	75
Report	--	--	--
Theory of operation	Hannah	30	15
Model explanation	Hannah	30	30
Review of revised items	All	120	120
Suspension updates	Frank	45	45
Differential manufacturability	Raul	30	30
Ground clearance	Frank	30	20
Review of operating parameters	Frank	30	20
BOM and total mass	Leanne	45	30
Assembly instruction combination	Leanne	60	120
Instruction fluidity review/edit	Leanne	90	120
Peer review of assembly instructions	All	200	200
Front suspension	Frank	30	30
Gearbox	Hannah	30	15
Differential	Rachel	60	180
Rear suspension	Leanne	20	20
Shocks	Rachel	15	20
Overall	Jack/Raul	60	20

1. Theory of Operation

The final design is built off the preliminary design outlined in the first deliverable. In summary, the design is a rear-wheel-drive lawnmower with a motor, housed in a chassis consisting of sheet metal. Our design contains 208 individual components. With the design fully developed, the cost of commercial parts is $1640, and the final mass is found to be 28 lbs. The overall final model can be seen in Figure 1 with its updated dimensions.

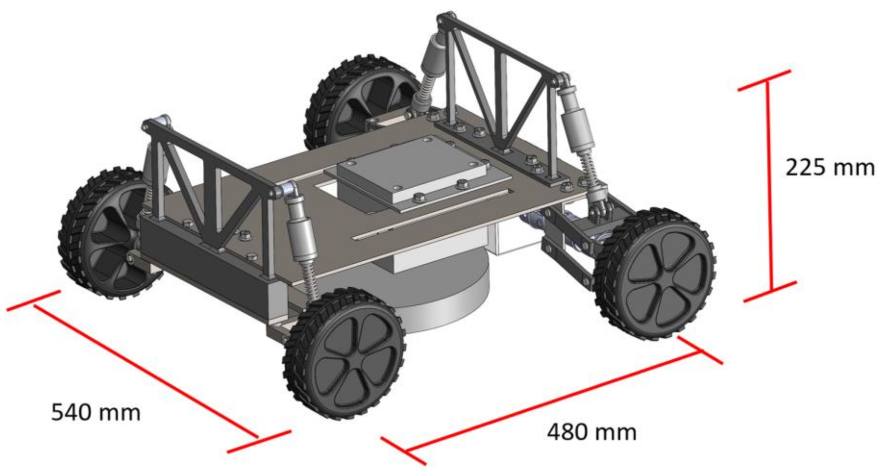


Figure 1: Isometric Overall Assembly with Dimensions

The final design for the mower can be broken into three subsections: Gearbox, Differential, and Front/Rear Suspension. The rack and pinion front wheel steering associated with the Front/Rear Suspension subassembly, as well as the belt drive and blade integrated with the gearbox subassembly can be seen from below in Figure 2.

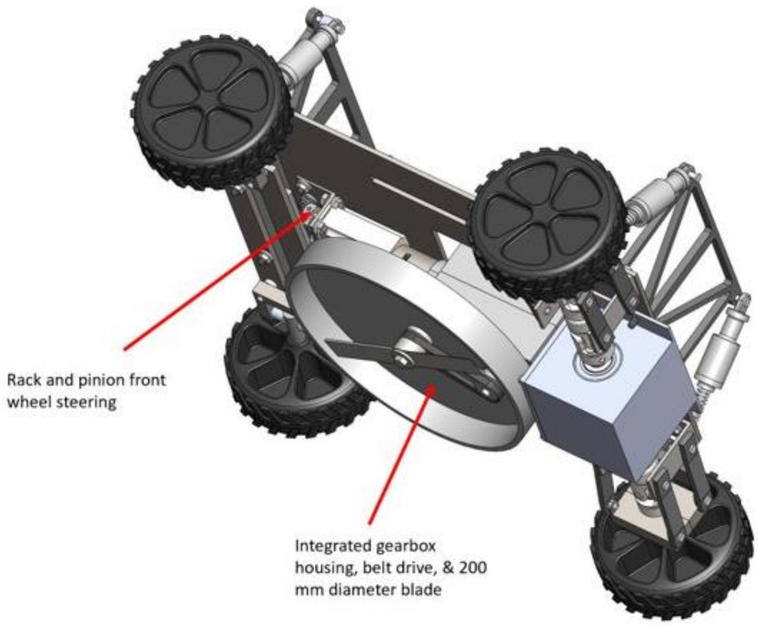


Figure 2: Overall Assembly from Bottom with Detail Callouts

The indepent front/rear suspensions, differential subassembly, custom gearbox, and a top view of the RS-550 motor are shown below in Figure 3.

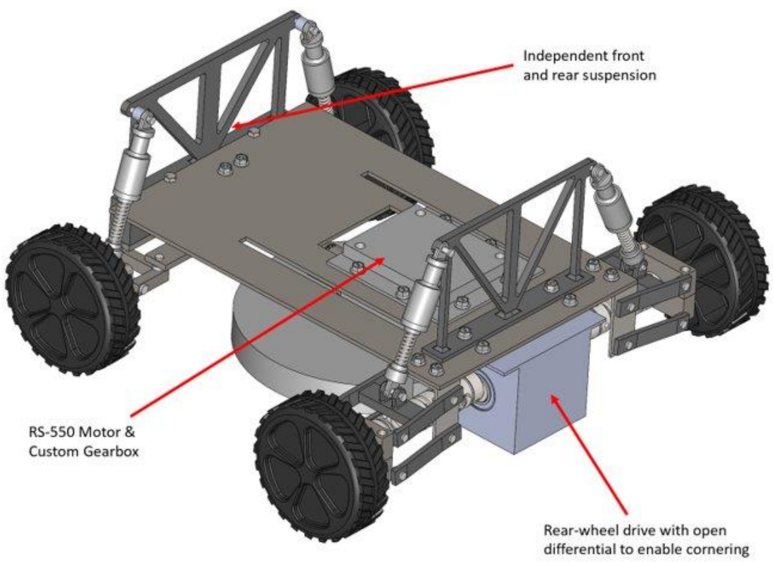


Figure 3: Overall Assembly from Top with Detail Callouts

Separate from the three subsystems is the chassis, shafts and frames, the most significant design choice of which is the inclusion of u-joints along the rear shafts. To accommodate the suspension, each half of the rear axle will have two u-joints which will transmit motion and power between the rotating shafts. Using a combination of two u-joints allows for a uniform velocity along the shafts by canceling the velocity errors that would occur from using only one u-joint. Putting the joints on either rear shaft allows for the suspension to be accommodated and used independently for uneven terrain.

1.1 Gearbox Subsystem

The gearbox subsystem includes the transmission, motor housing, blade, and the belt drive which drives the blade. The transmission remains unchanged from previous deliverables, providing a gear ratio of 27:1 through three 3:1 speed reduction using commercially available spur gears. Additionally, there are two bevel gears implemented to transfer torque to the blade via the belt drive. The transmission is driven by the 12V RS-550 motor that powers the entire device and is mounted to a two-part injection molded housing to accommodate the transmission components, as shown in Figure 4.

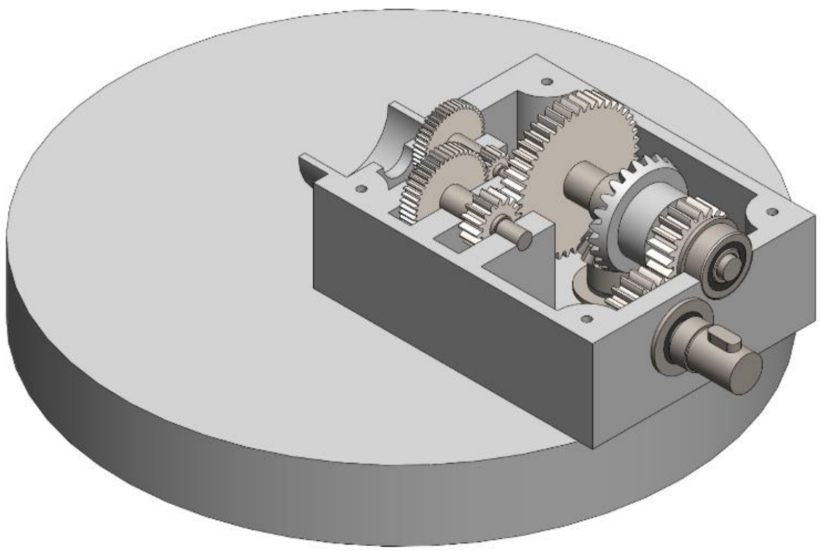


Figure 4: Lower Gearbox Housing with Transmission Components

The gearbox contains four short shafts, as well as the shaft connected to the motor. The gears are positioned along the shaft lengths using shaft steps. The entirely internal shafts support only spur gears and are supported by journal surfaces, the other three shafts are mounted to sealed flanged bearings to support the nominal axial loads from their attached bevel gears. Finally, the output shaft feeds directly into the differential unit and connects to the entry gear via keyway.

The belt drive is in the blade housing which has been attached to the bottom half of the gearbox housing for the updated bottom motor housing design. The new housing allows for the 200 mm diameter blade that will rotate to cut grass as seen in Figure 5. Torque is provided via the bevel gears from the transmission, which rotate the vertical blade shaft that drives the belt drive. This allows the belt to turn and rotate the center shaft, thereby turning the blade and cutting grass.

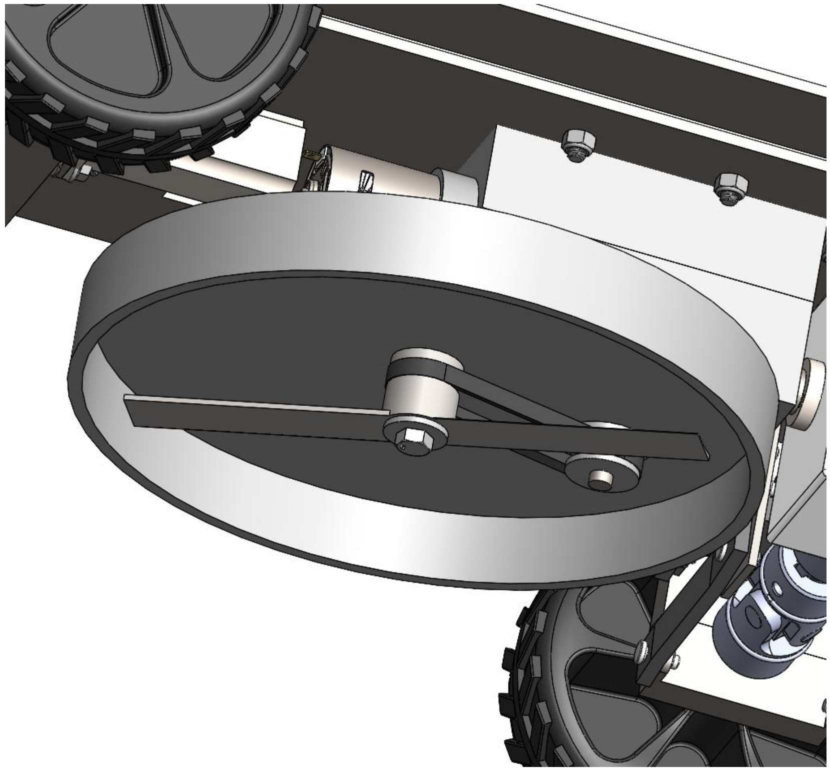


Figure 5: Gearbox Subassembly Blade and Belt Drive

The gearbox subsystem is self-contained with top and bottom motor housings that bolt together and can be attached to the chassis for integration to the overall model.

1.2 Differential

The differential again is consistent with previous deliverables, except for the differential housing, which has been updated to consist of two parts that can be bolted together to allow manufacturability and assembly of the differential. The differential itself consists of a pinion, ring gear, two spider gears that rotate around the axis of the ring gear, and two side gears attached to the shafts connecting to the wheels as seen in Figure 6. All gears in this subsystem are bevel gears which allow motion to be transferred between intersecting shafts. The torque ratio for the differential is 1:1. The subsystem relies on the use of lubrication, with the selected lubrication being cSt 5000 oil to decrease wheelspin without compromising traction while cornering.

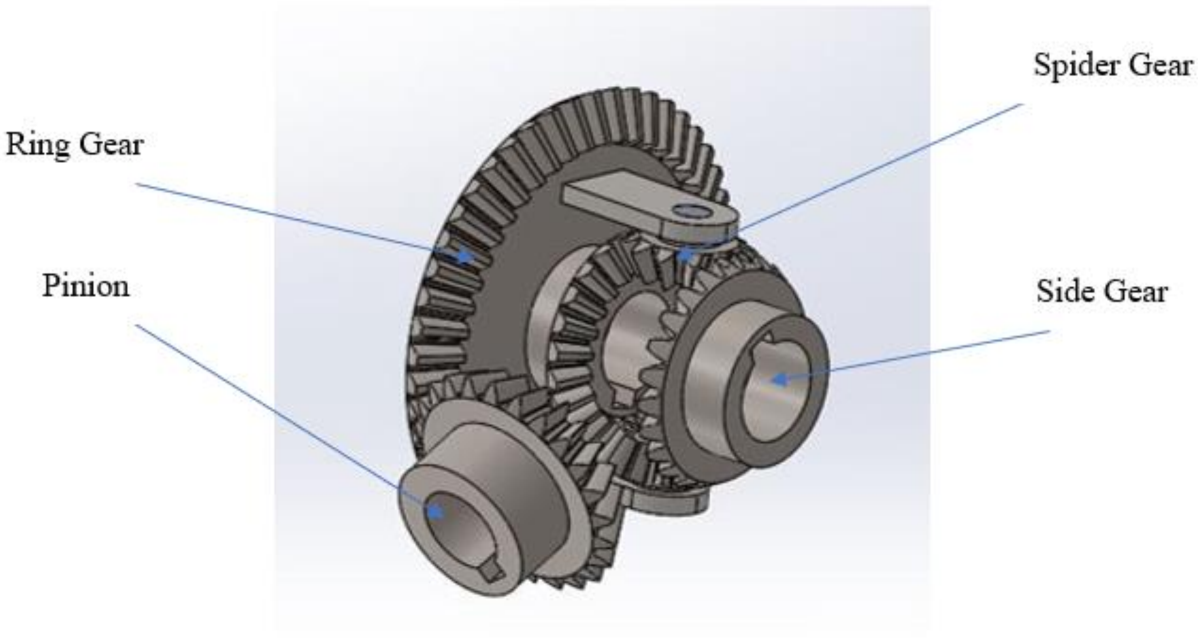


Figure 6: Final Differential with Callouts

When both wheels are rotating at the same speed, the spider gears do not rotate and act as a single solid shaft rigidly attached to the ring gear. When the spider gear rotate, they allow the rear wheels to rotate at different speeds. Their speed depends on the difference in rotational velocity between the two side gears as well as the speed of the ring gear. This allows more power to be transmitted to the outer wheel, which is rotating faster than the inner wheel.

As previously stated, the entire assembly is placed in the differential housing which has been updated to allow for manufacturability and assembly as seen in Figure 7. The housing has spaces for the input and output gears to exit, and once assembled, the enclosure can be bolted to the chassis.

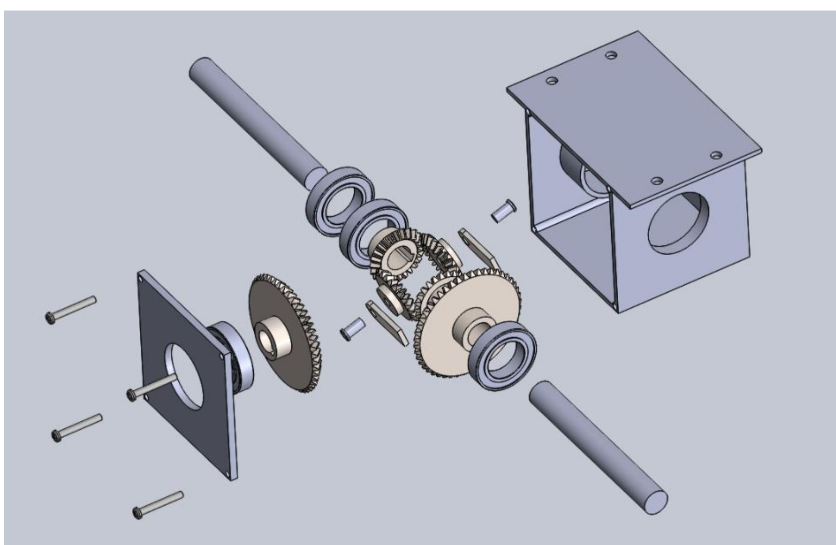


Figure 7: Exploded Differential Assembly

1.3 Front/Rear Suspension

The front and rear suspension subsystem contains not only the front and rear suspension, but also includes the steering system incorporated at the front of the model.

Steering of the vehicle will be handled by a rack and pinion system, consisting of two long links and two short "C' shaped links pinned together. A stepper motor and gear will mesh with a linear gear attached to the back link. As the motor turns the gear, the back link will move side to side. With the front link fixed to the chassis and the back link offset, the links will form a parallelogram, rotating the front wheels relative to the rear wheels, thus turning the vehicle (Figure 8).

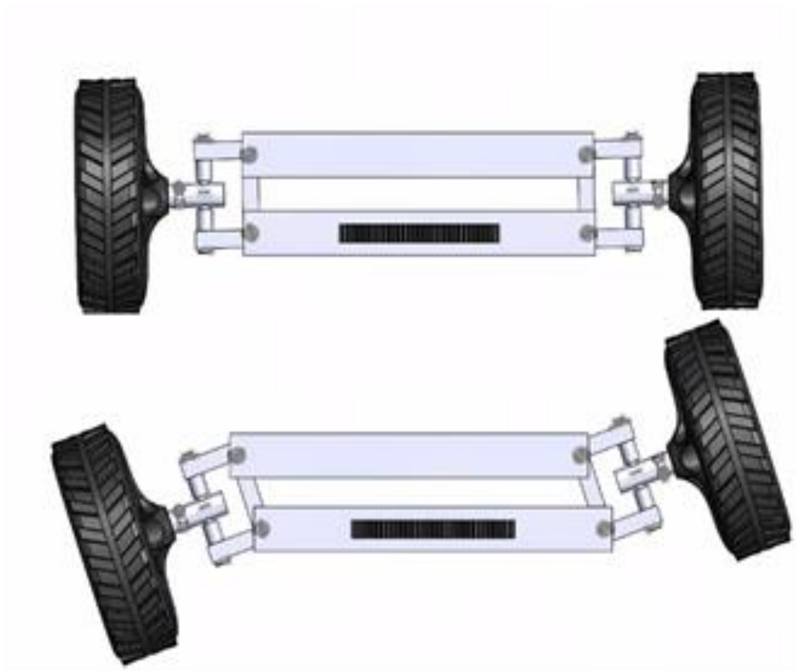


Figure 8: Top View of Steering System

The suspension system is designed to allow independent vertical motion of the wheels over a variety of terrain that may be present in yards. The shock has been updated to withstand stresses it previously could not, and to allow for ease of assembly. The previous housing design was solid and therefore could not be manufactured. The updated design uses threaded components to facilitate manufacturability. With the new design, stress is approximately 40% of the ultimate strength, which limits the worst-case ground clearance of the blade.

The shock has a lower rod that is pinned to a wheel attachment (linkage/axle) and an upper housing that is pinned to an aluminum frame attached to the chassis. Inside the upper housing, a slider constrains the motion of the suspension by limiting the stroke length.

In the rear, the wheels are press fit onto a short shaft that is secured in a four-point contact ball bearing that can support radial, axial, and moment loads to eliminate the need for multiple bearings. This housing is custom designed in two parts that will be bolted together around the bearing (Figure 9).

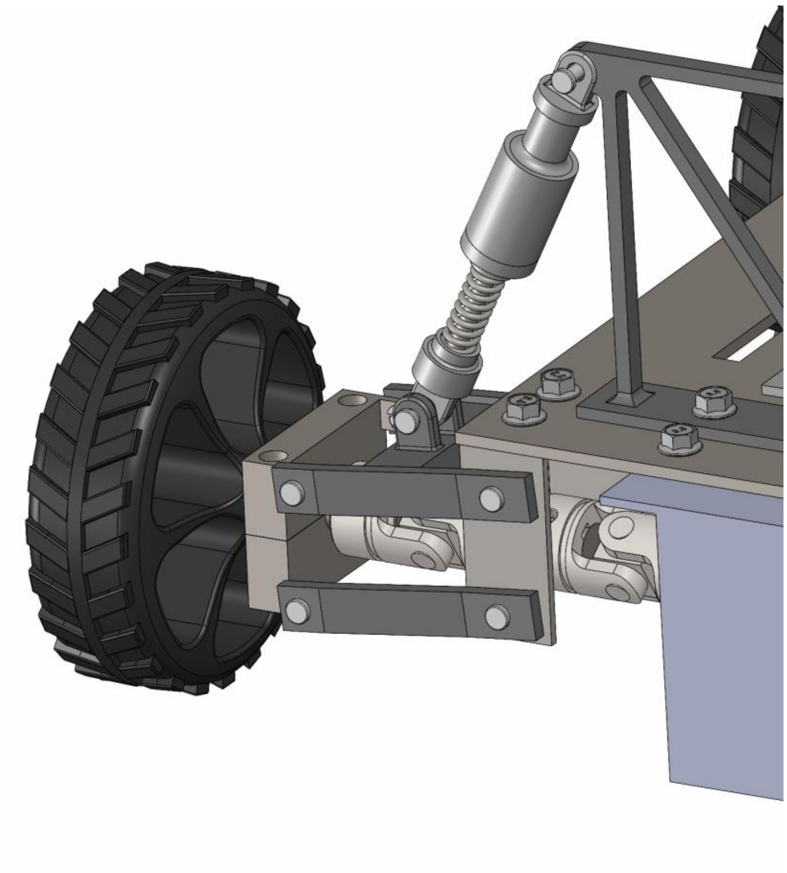


Figure 9: Rear Suspension System

In the front, the wheels are attached via bearing to an axle to which the shock attaches. The axle has a hole through it to allow for rotation about a pin. The pin fits through holes in the ‘C’ shaped links in the front linkage system. The upper end of the shock attaches to the chassis via an aluminum mounting tower (Figure 10). The pins used in the front are the same as the pins used in the rear, but experience lesser loading, thus not requiring further analysis.

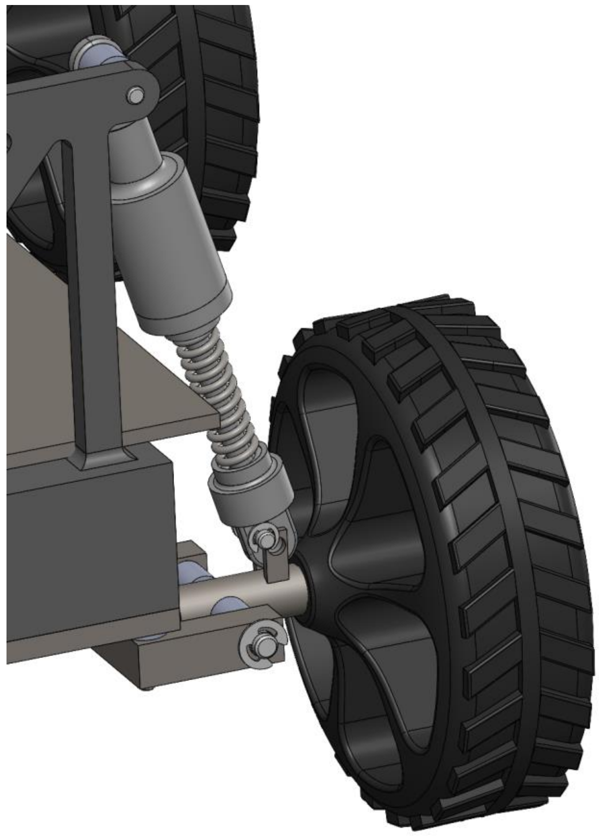


Figure 10: Front Suspension System

2. Elimination of Outstanding Items

2.1. Global Forces & Free Body Diagram, Stress Calculations

After establishing the final weight of the device, the specifications and requirements of the design were updated and the analysis in Appendix A was repeated to ensure proper function. Previously, our device required 6.4 Nm of torque output from the gearbox, with 3.8 Nm being sent to the wheels and approximately 2.6 Nm being sent to the blade. From the updated weight, the required torque to drive the device was reduced from 3.8 to 2.7 Nm, and the torque to the blade was reduced to approximately 0.3 Nm. (The design of the belt drive is mostly conceptual and would theoretically be developed further to understand appropriate gear/belt ratios to provide sufficient torque and speed to run the mower.)

Embodied in this change in torque is a relaxed acceleration requirement for the device; the device is permitted to accelerate to top speed in three seconds as opposed to the two seconds previously required.

Due to the reduced torque and weight, all stresses from previous deliverables would be reduced, and based on our achieved factors of safety we presume that the changes will improve the longevity of our device.

2.2. Spring Stress & Suspension Manufacturability

When the shocks were designed for the second deliverable, they achieved our desired function in large part; however, the system could not be physically assembled as it was, and the spring in the shock experienced shear stresses approaching the yield stress. Therefore, prior to creating instructions for this week, both the manufacturability of the shocks and the stresses experienced by the springs were reassessed.

The updated shock design is not a "shock" per se, in that it does not contain damping. It does, however, contain a sliding contact that limits the travel of the spring. The shock is now divided into five parts: a lower rod, the spring, an upper chamber, a lower chamber, and a sliding contact. Instructions for assembly are detailed in the assembly instructions section; the basic premise for assembly is that the sliding contact threads onto the lower rod around the lower chamber, and the chambers are screwed together. The internal dimensions of the sliding contact were adjusted to limit the spring travel to 15 mm.

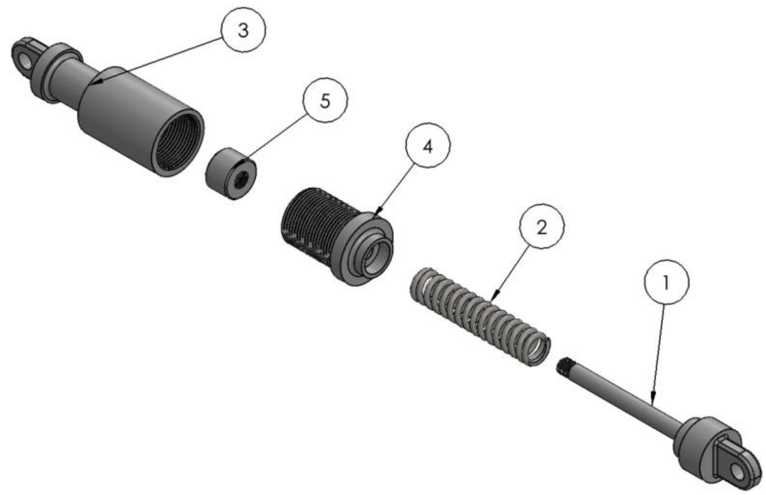


Figure 11: Updated Shock Assembly

The procedure in Appendix B was repeated with updated spring forces under normal and worst-case loading conditions, considering the modified mass of the vehicle and the altered spring travel (taken to be 85.2 N and 197 N, respectively). The resulting maximum shear stress in the spring is 351 MPa under normal load and 810 MPa under the drop condition, representing factors of safety of 2.85 and 1.23 with respect to yield, an improvement over the previous design.

2.3. Ground Clearance & Suspension Geometry

The updated vehicle weight and shock assemblies also affected the calculated ground clearance. This must be considered both to ensure overall function of the mower and to ensure that the quality of the cut is acceptable.

“Ride height”, as described in Appendix B, describes the vertical distance from the top of the chassis to the axis of rotation of the wheels. “ground clearance”, for this purpose, shall describe the vertical distance from the ground to the lowest point on the mower, namely the face of the hex bolt that holds the blade onto the blade housing. “Cut height” shall refer to the vertical distance from the ground to of the bottom of the blade.

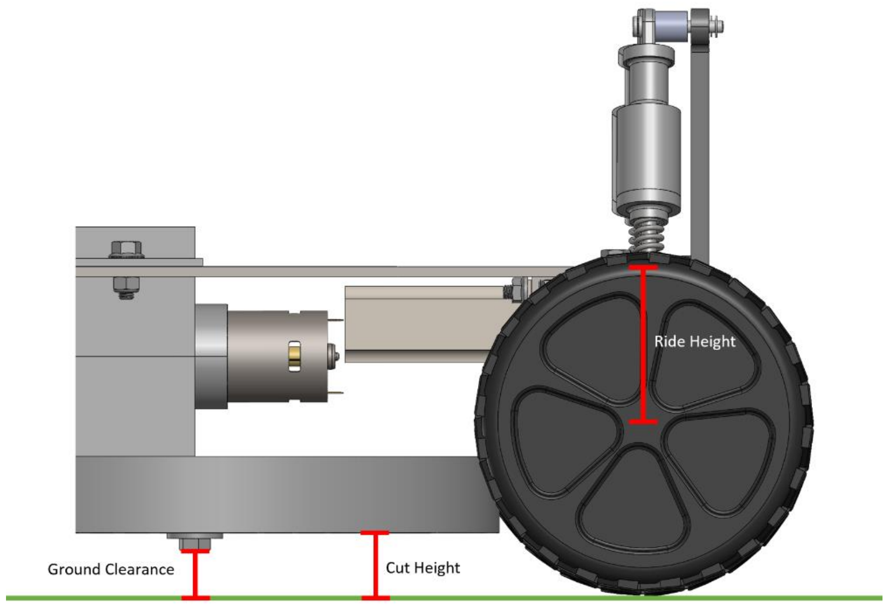


Figure 12: Ride Height Diagram

The analysis in Appendix B was repeated for normal and worst-case loading conditions. The height of attachment for the shocks to the frames in the front and rear was adjusted to maintain a nominal ride height of 60 mm with the updated vehicle weight. As such, the height of attachment of the spring increased by 2 mm in the rear and 6 mm in the front. Under worst-case loading, the ride height is constrained by the travel of the suspension.

The final design has a cut height of 20 mm and a ground clearance of 13 mm under normal loading conditions. When the mower is dropped or encounters a substantial bump in the terrain, the cut height is reduced to 4 mm and the ground clearance goes to zero. This would correspond to a “scalped” section of lawn, and provided the loads are applied only momentarily this should not affect large portions of the cut area.

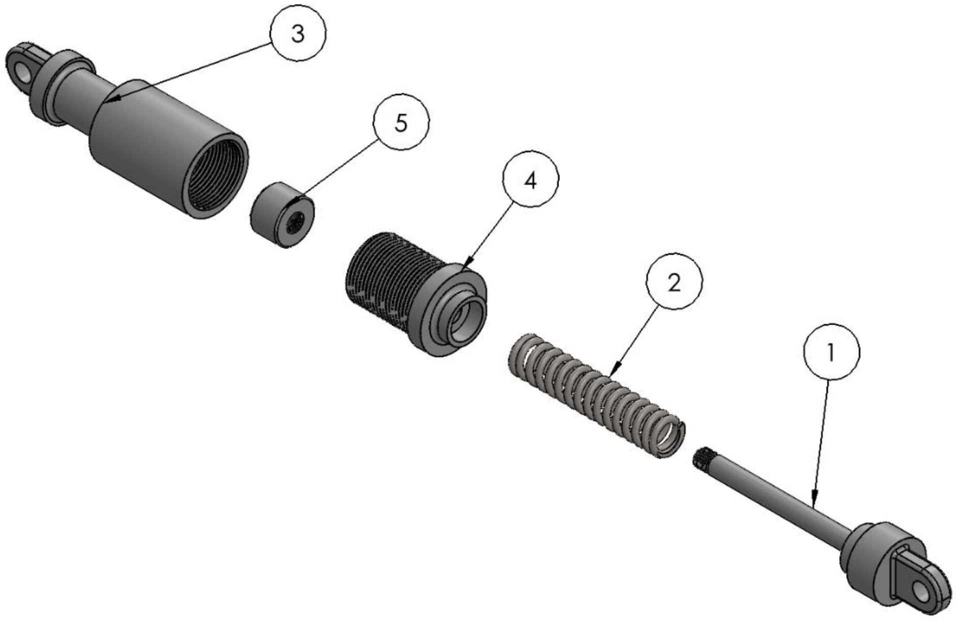
2.4. Differential Manufacturability

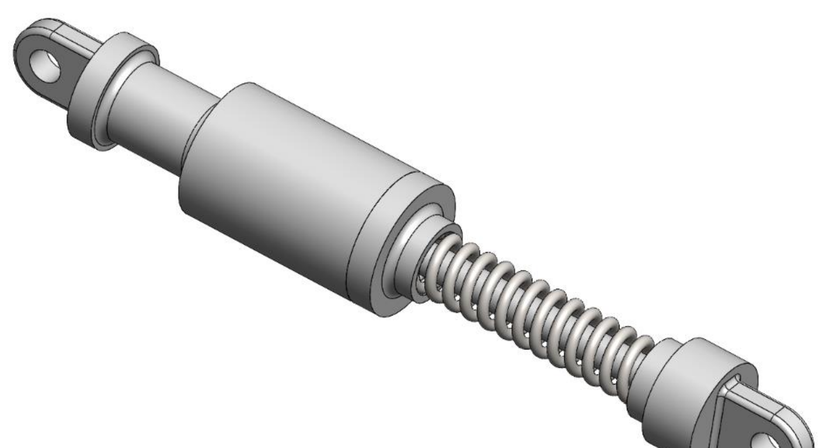
Since the last iteration of the project a few changes have been made to the differential. Bearings have been added to the ring gear, pinion gear, and side gears. These bearings are in the differential housing and allow for a smooth and stable rotation of the rear shafts and the drive shaft. Double shielded bearings were chosen to help prevent debris from interfering with bearing operation. The differential housing has been updated as well. The housing now consists of two parts fastened together with machine screws. This allows the differential to be assembled and disassembled. The differential is then bolted to the chassis.

Additionally, the CAD model of the gear assembly has been finalized to meet the specified dimensions in our calculations. The pinion gear and ring gear each have 48 teeth, a module of 1.5, and a pressure angle of 20 degrees. The spider gears and side gears each have 24 teeth, a module of 1.5, and a pressure angle of 20 degrees. Another change to the gears in how the spider gears are mounted to the ring gear brackets. We have specified that the spider gears will be glued to their own individual shafts which go through the brackets. With the application of lubricant, the ring/spider gear shafts should rotate freely and allow the spider gears to work correctly. These modifications resulted in slight dimension changes for the overall subassembly which required alterations to the dimensions of the rear shafts. Regarding the manufacturing of the differential housing, we intend on injection molding the two halves out of PET.

Assembly Instructions

Shock Assembly

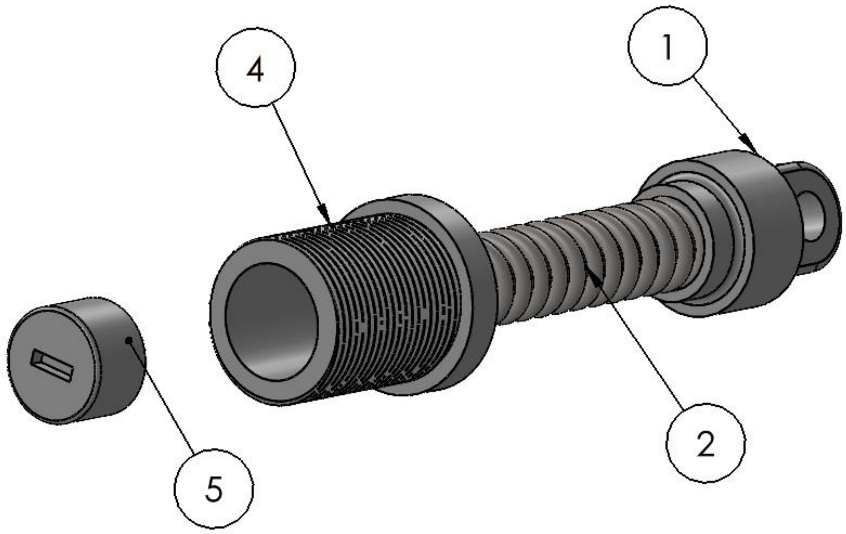




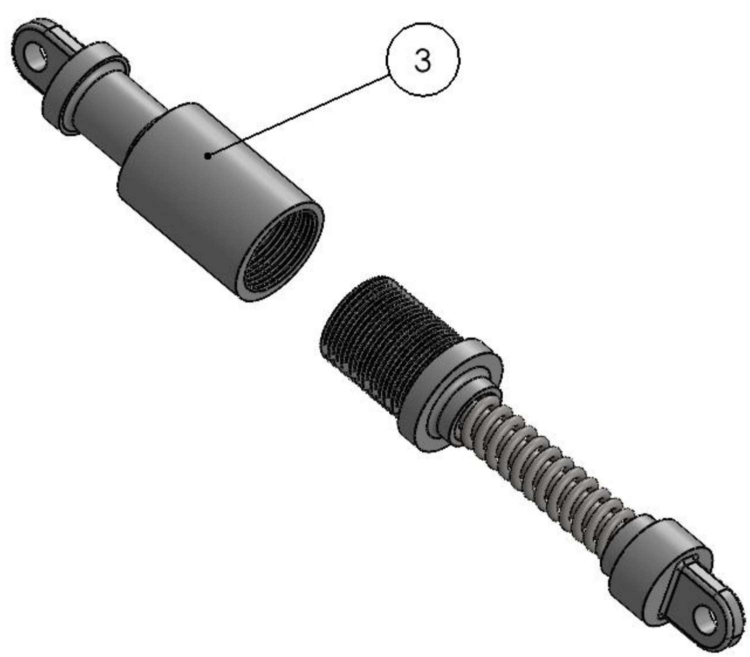
Materials					
[No.]	Description	Supplier (Part Number) Or Drawing Number (Mat'l)	Number Required	Price ($)	Mass (g)
[1]	Lower Rod	Shock-1 (PET)	1	-	8.86
[2]	Compression Spring, 55 mm Long, 12 mm OD	McMaster-Carr (94125K210)	1	11.89	12.57
[3]	Upper Chamber	Shock-2 (PET)	1	-	21.3
[4]	Lower Chamber	Shock-3 (PET)	1	-	8.56
[5]	Slider	Shock-4 (PET)	1	-	2.24
Total for Assembly			**5**	**11.89**	**53.53**

Assembly Instructions

Step 1.) Slide the center of [1] through the center of [2] and the opening on [4]. Then, insert the slider [5] into the chamber of [4] and thread onto [1]. Use a flat-head screwdriver to hold [5] in place while [1] is rotated.



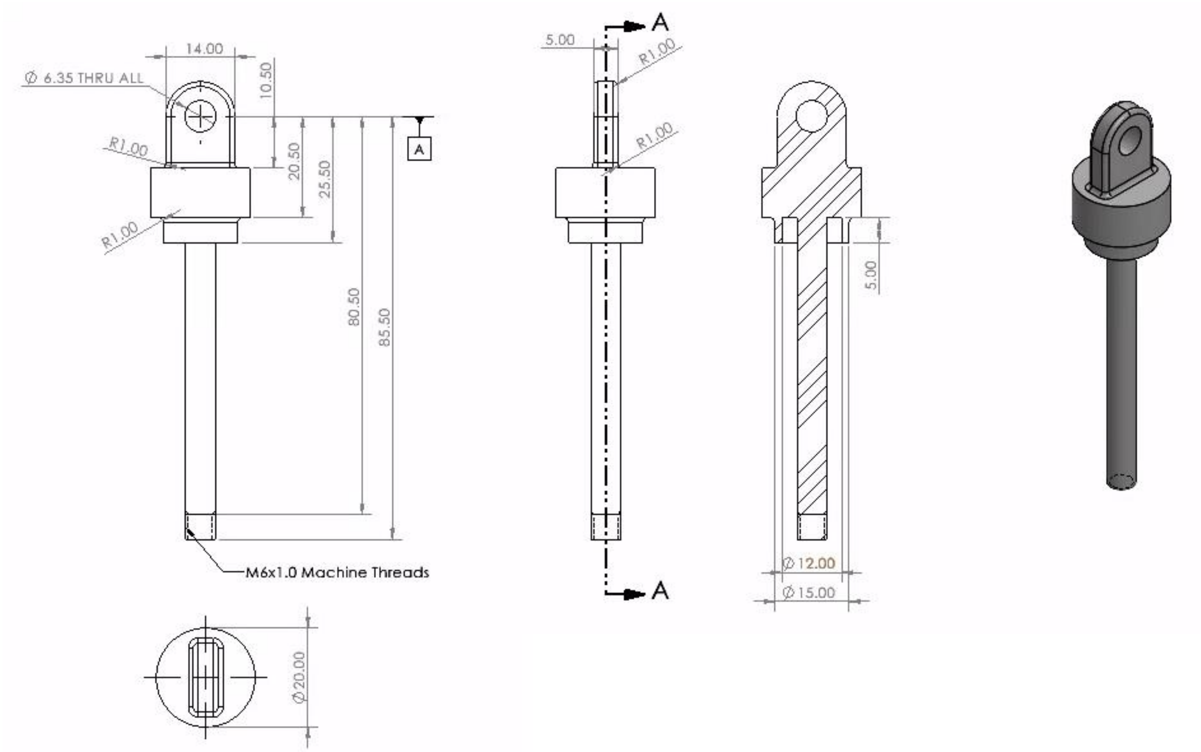
Step 2.) Thread [4] into [3] until snug. For extra strength, apply a plastic threadlocker before threading. Repeat for a total of four assemblies. The suspension is now ready to be assembled to the front and rear suspension assemblies.



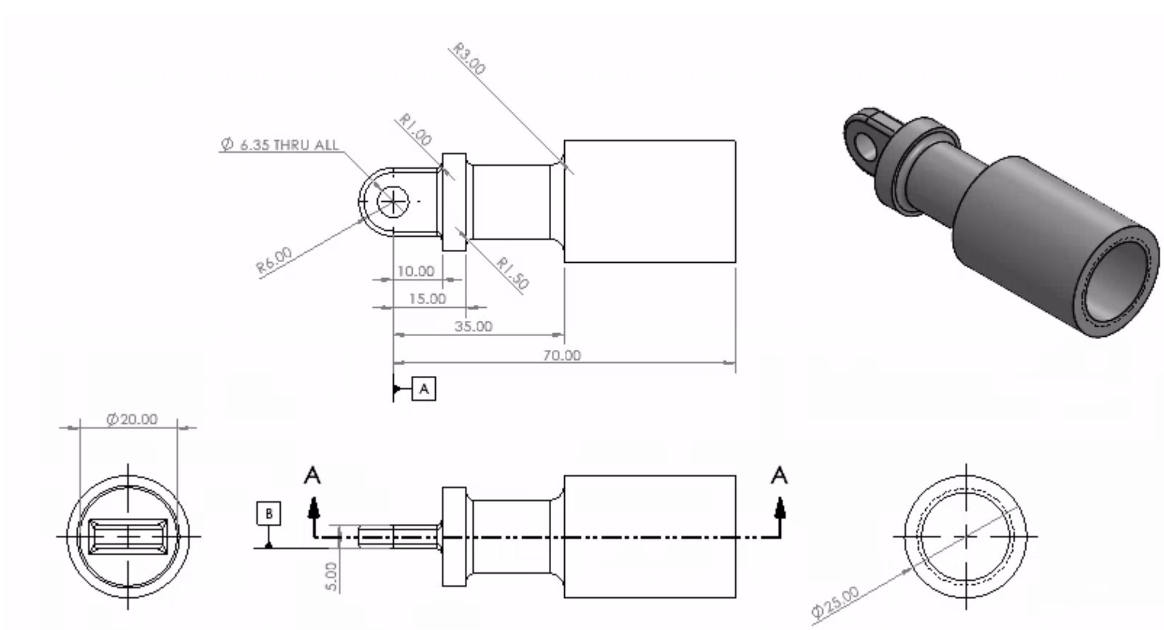
Part Drawings

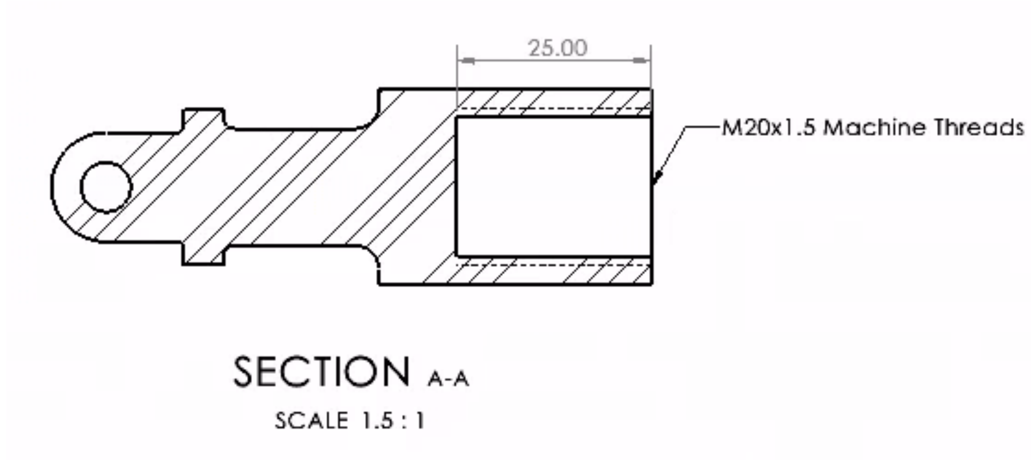
Dimensions in mm, tolerances ± 0.13 unless otherwise specified

Shock-1: Lower Rod

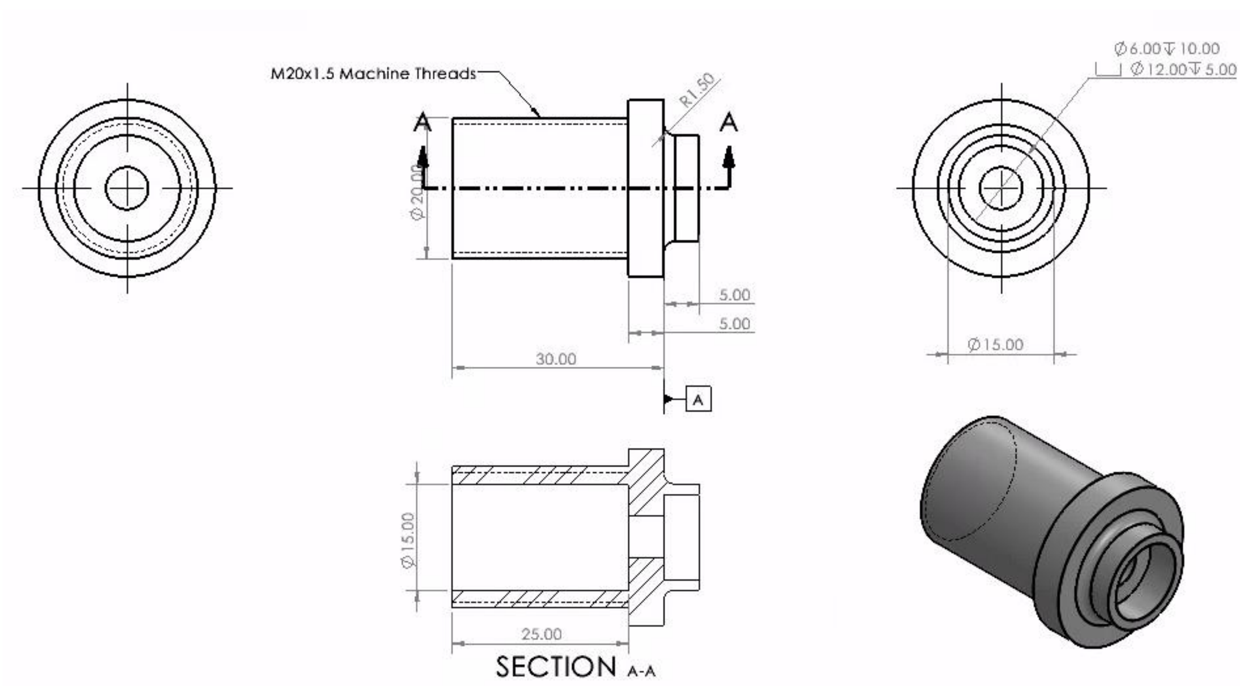


Shock-2: Upper Chamber

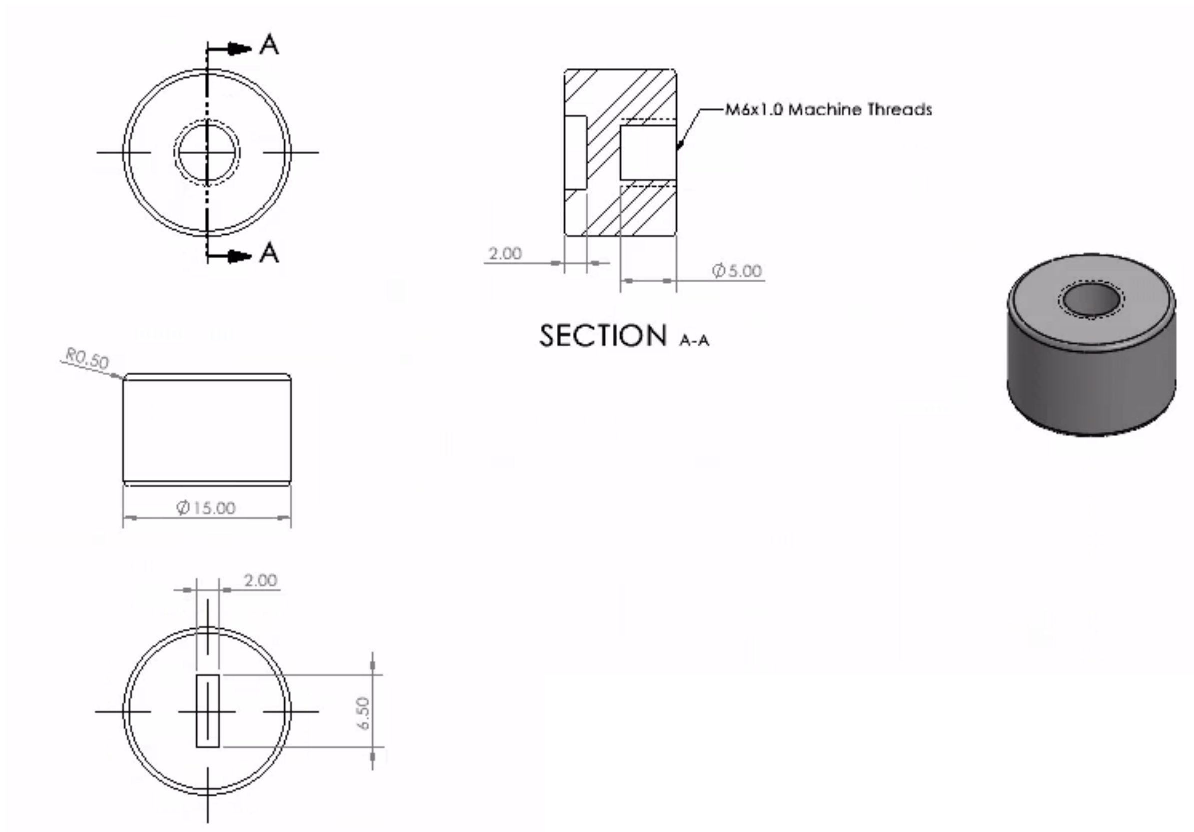




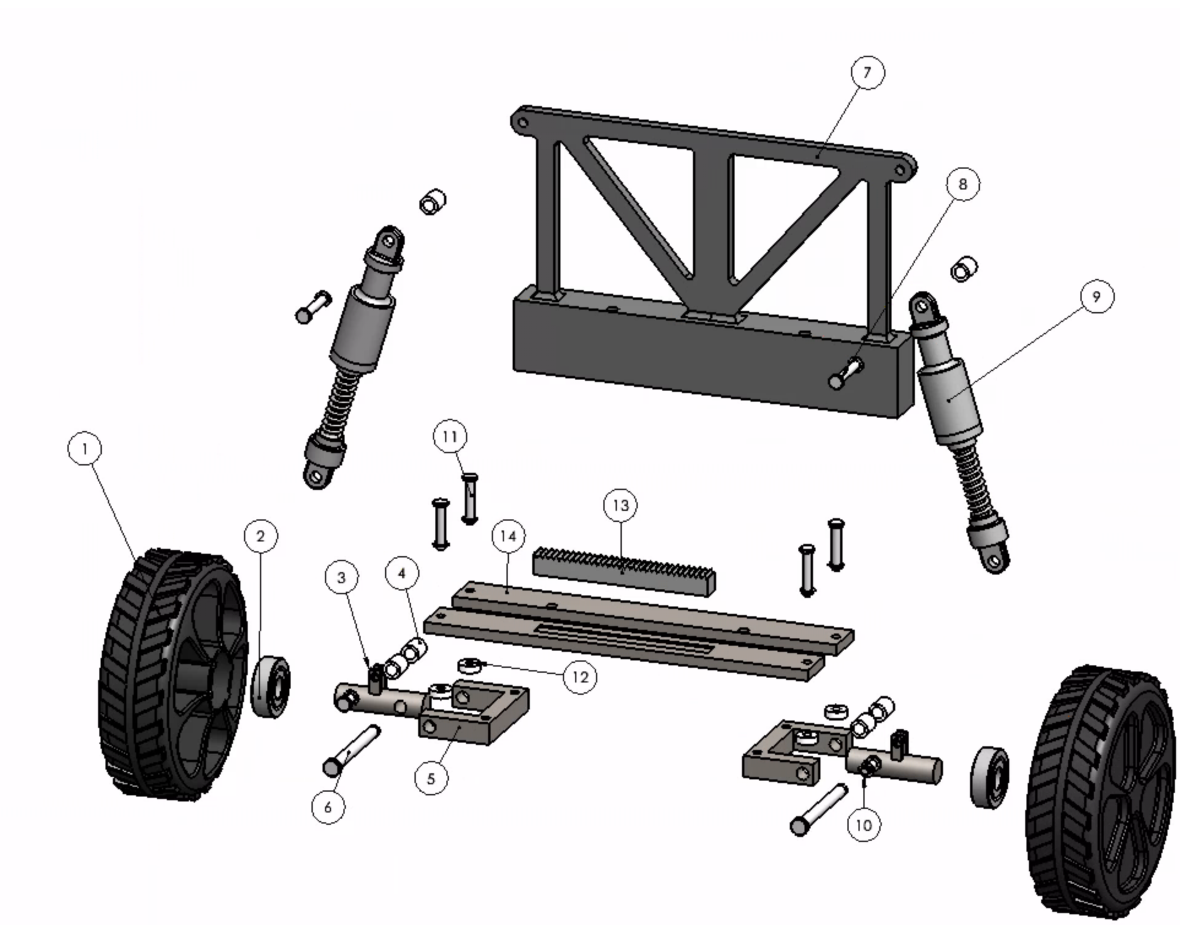
Shock-3: Lower Chamber

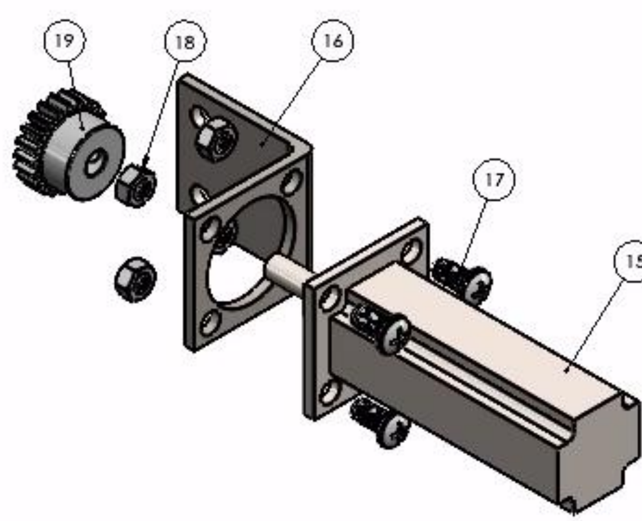


Shock-4: Slider



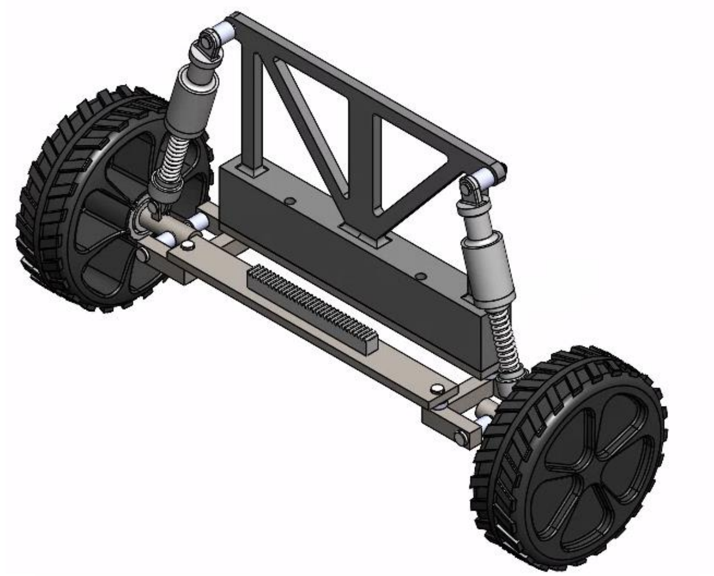
Front Wheel Assembly

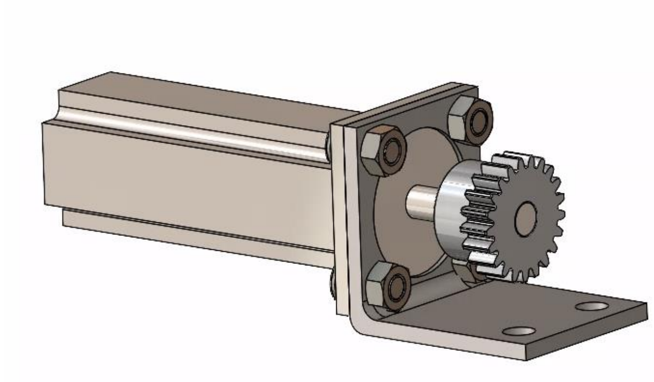




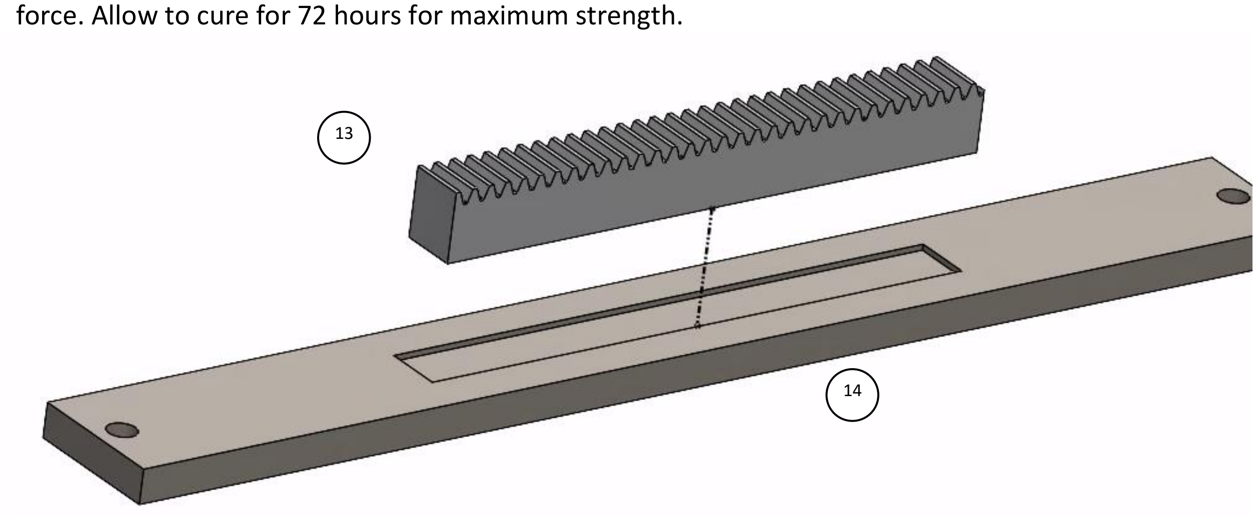
Materials				
[No.] Description	**Supplier (Part Number) Or Drawing Number (Mat'l)**	**Number Required**	**Price Per Part ($)**	**Total Mass Per Part (g)**
[1] Front Wheel	Front- 1 (PET)	2		295.95
[2] Front Wheel Bearings	McMaster (6153K55)	2	27.29	44.89
[3] Front Wheel Shaft	Front- 2 (AISI 1020)	2		53.11
[4] Half Inch Spacer	McMaster (94639A694)	6	0.48	0.71
[5] C-Link	McMaster (8910K943) Front- 3 (AISI 1020)	2	4.41	103.56
[6] Clevis Pin with Retaining Ring 1/4" Dia. x 2 3/8" Lg.	McMaster (92735A705)	2	1.88	17.84
[7] Front Mount Tower	Front- 4 (PET)	1		390.83
[8] Clevis Pin with Retaining Ring 1/4" Dia. x 1 1/8" Lg.	McMaster (92735A685)	2	1.83	5.34
[9] Suspension Assembly	Assembled Component	2 (10)	11.89	42.66
[10] Clevis Pin with Retaining Ring 1/4" Dia. x 3/8" Lg.	McMaster (92735A670)	2	1.79	2.59
[11] Clevis Pin with Retaining Ring 1/4" Dia. x 7/8" Lg.	McMaster (92735A680)	4	1.82	4.44
[12] Short Spacer	McMaster (94639A254)	4	0.18	0.5
[13] Rack	McMaster (2485N217)	1	16.12	85.88
[14] -1 Front Link [14] - 2 Rear Link	McMaster (6775T67) Front- 5 Front- 6 (Low Carbon Steel)	2	12.71	257.86
[15] Stepper Motor	Moons Industries (AM17SS2DGA-N)	1	275	390
[16] Motor Bracket	Front- 7 (AISI 1020)	1		44.37
[17] M5 Screws	McMaster (94102A119)	4	2.58	2.38
[18] M5 Nut	McMaster (90592A095)	4	0.02	1.25
[19] Metal Gear	McMaster (2664N474)	1	24.15	28.35
	Total for Assembly	45 (53)	460	2625.65

Assembly Instructions

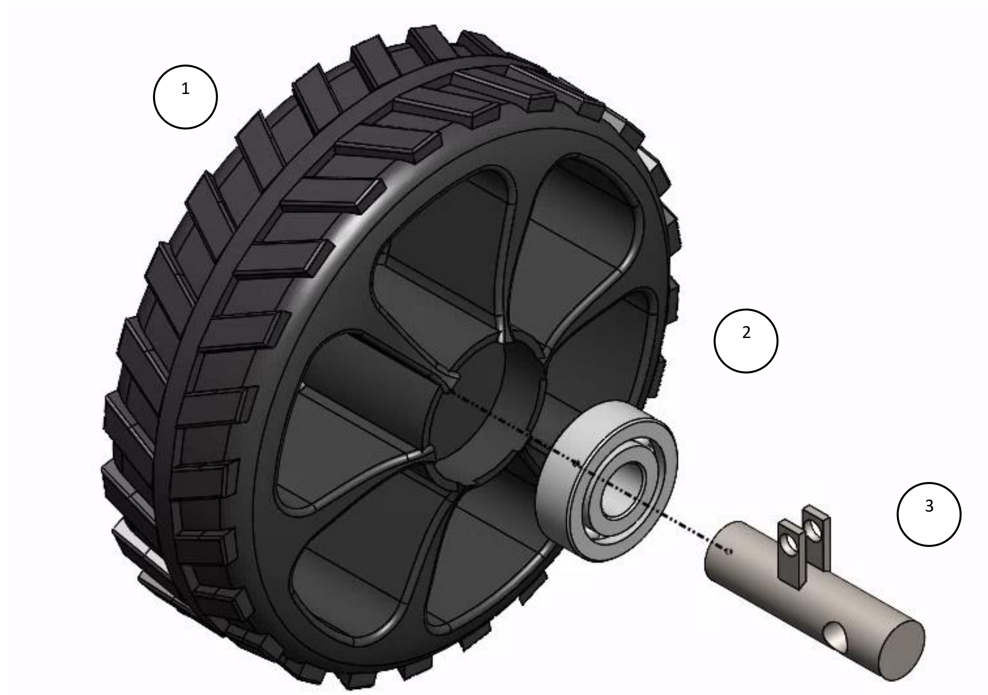




Step 1.) Using Loctite 638, adhere the linear gear [13] to the rear link [14]. Clean the contacting surfaces of [13] and [14]. Then, apply a thin layer of the adhesive to the surfaces and apply a clamping force. Allow to cure for 72 hours for maximum strength.

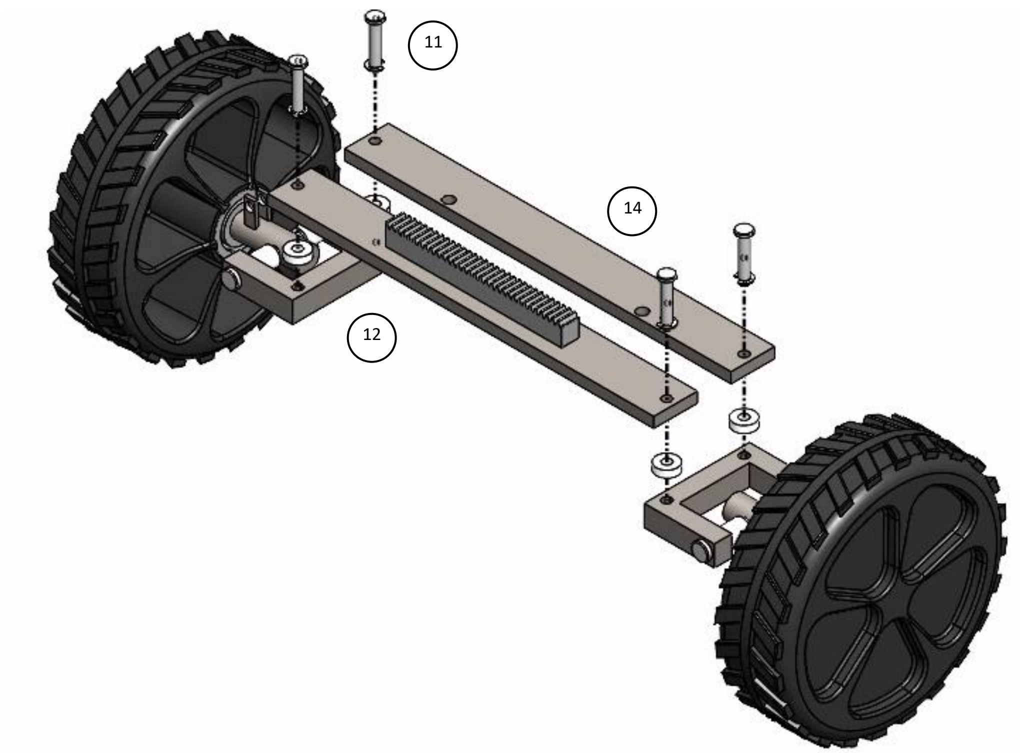


Step 2.) Press fit [2] into [1] and [3] into [2]. Repeat with the other front wheel.

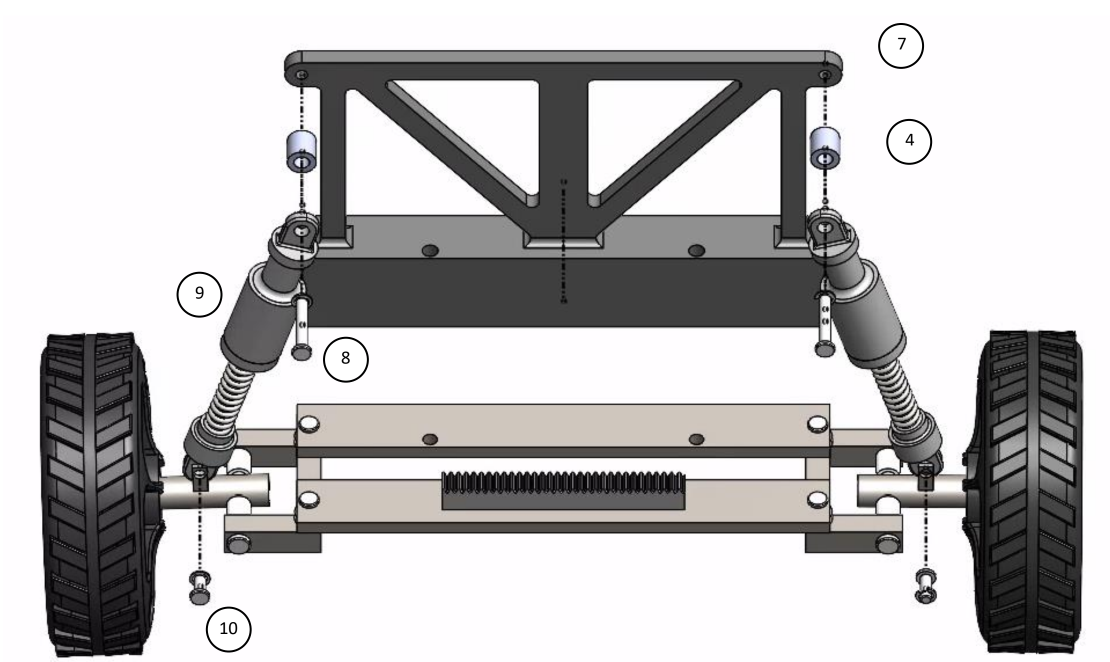


Step 3.) Using the 2 3/8" clevis pin [6], attach the C-link [5] to the wheel assembly with two half inch spacers [4] inside the 'C'. Secure by using pliers to fasten the retaining ring in the clevis pin groove.

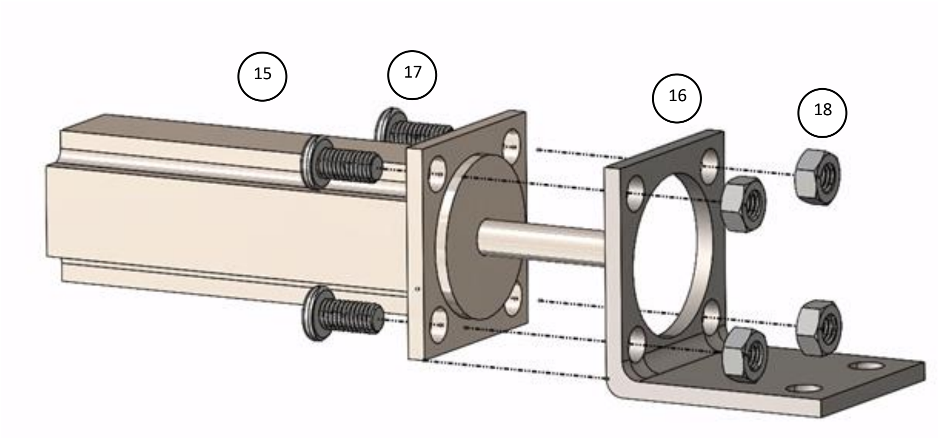
Step 4.) Using [11], pin together the wheel assemblies and bar links [14] with the short spacers between them [12]. Secure by using pliers to fasten the retaining ring in the clevis pin groove.



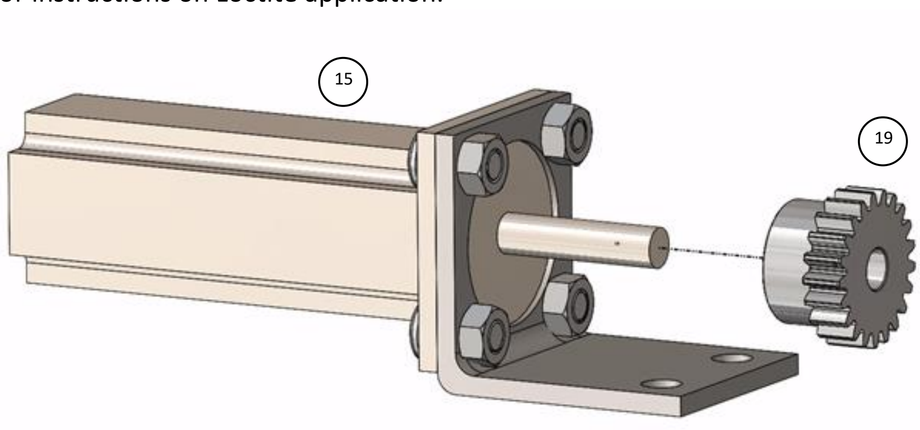
Step 5.) Using the 1 1/8 inch pins [8], attach the shock assemblies [9] to the front mounting tower [7] with a half inch spacer [4] between them. Then attach the lower suspension to the axles using a 3/8 inch pin [10]. Secure by using pliers to fasten the retaining ring in the clevis pin groove.



Step 6.) Using M5 screws [17] and M5 bolts [18], attach the motor bracket [16] to the stepper motor [15].



Step 7.) Attach [19] to the shaft protruding from the stepper motor [15] using Loctite 638 adhesive. See Step 1.) for instructions on Loctite application.

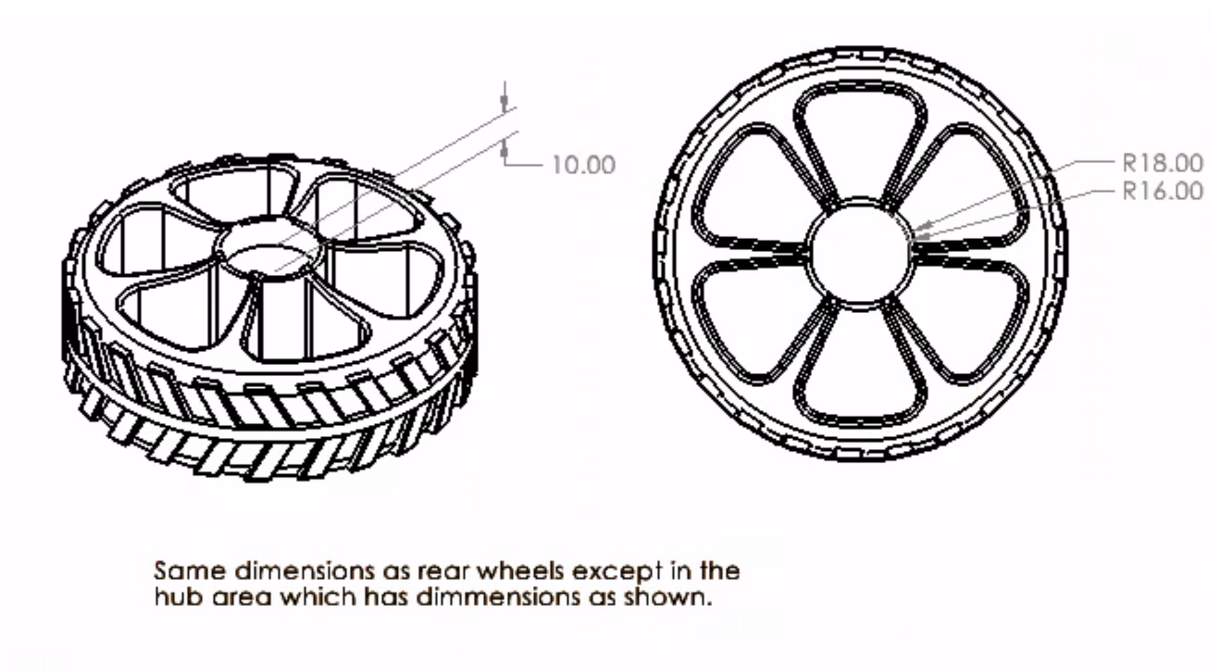


Components are now ready to be attached to the chassis.

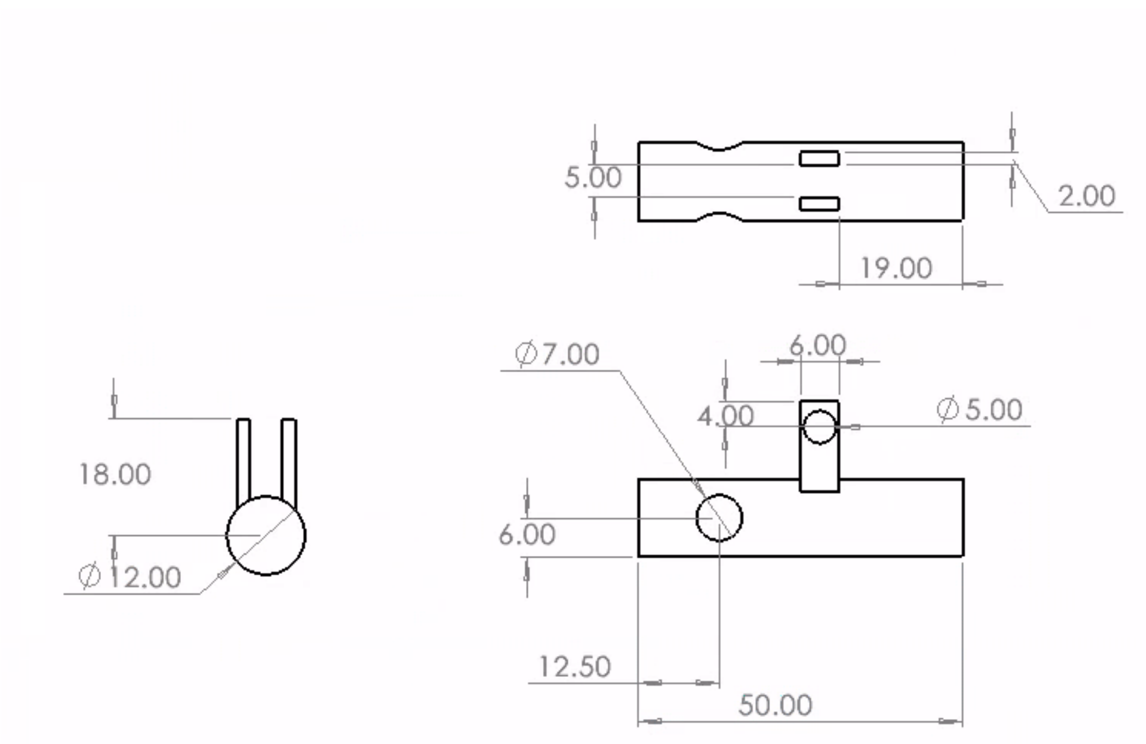
Custom Part Drawings

Dimensions in mm, tolerances ±0.13 unless otherwise specified

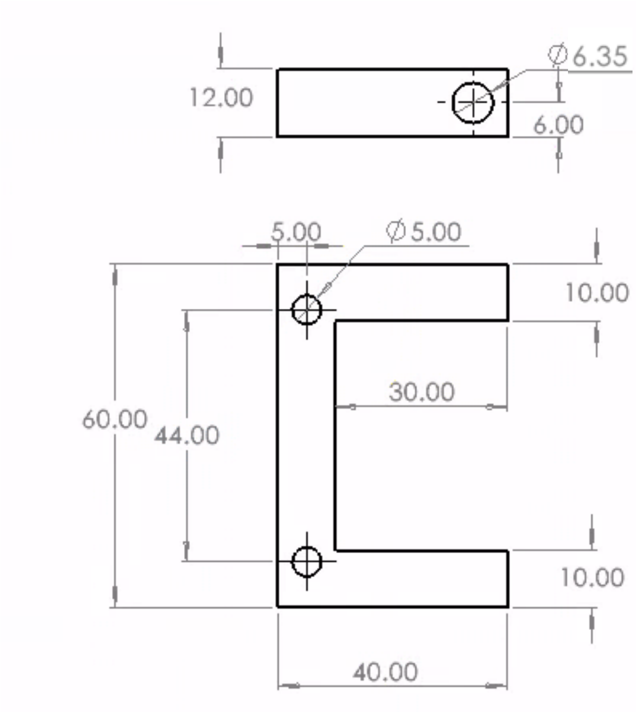
Front-1: Wheel



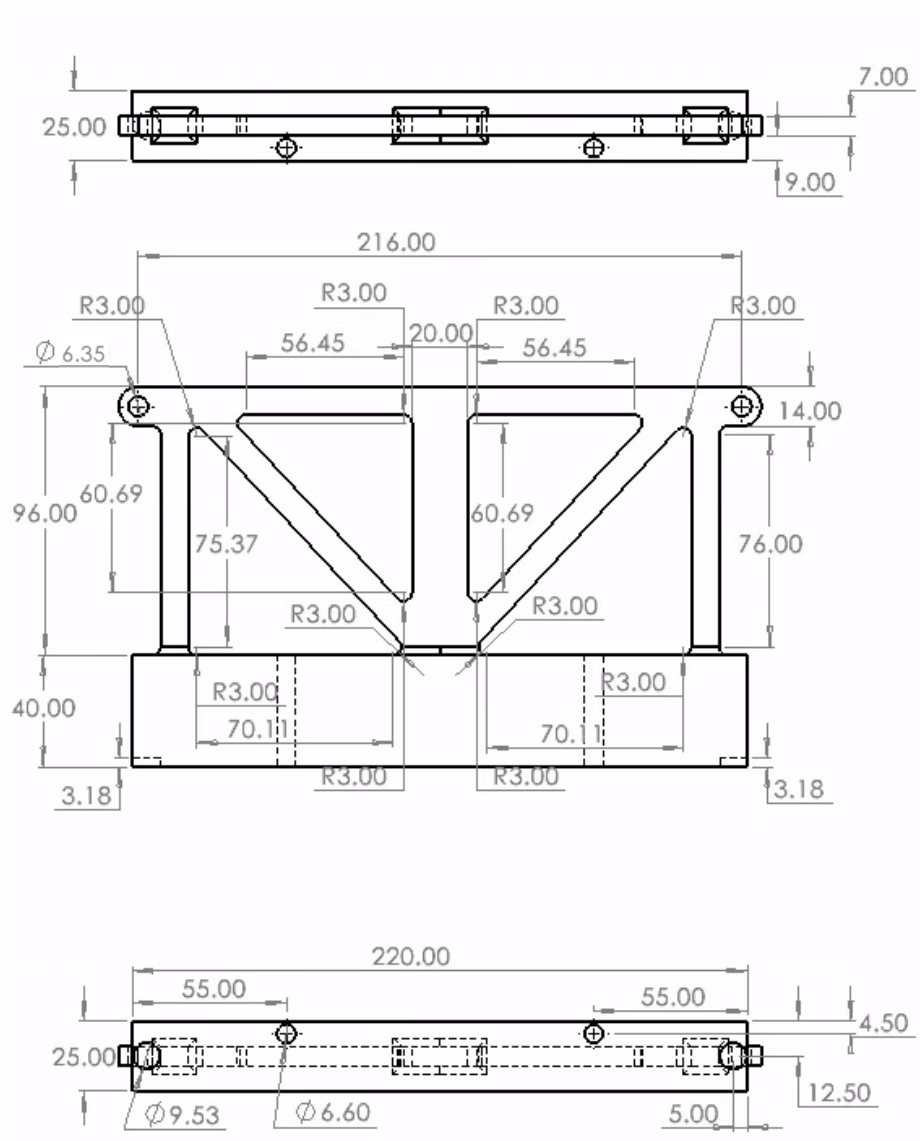
Front-2: Front Wheel Shaft



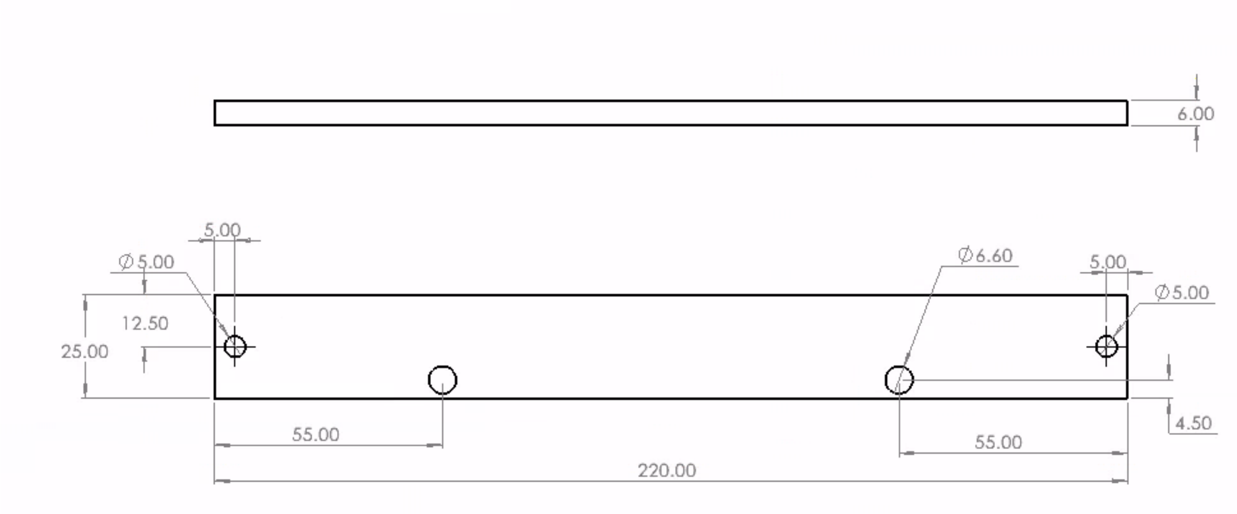
Front-3: 'C' Links



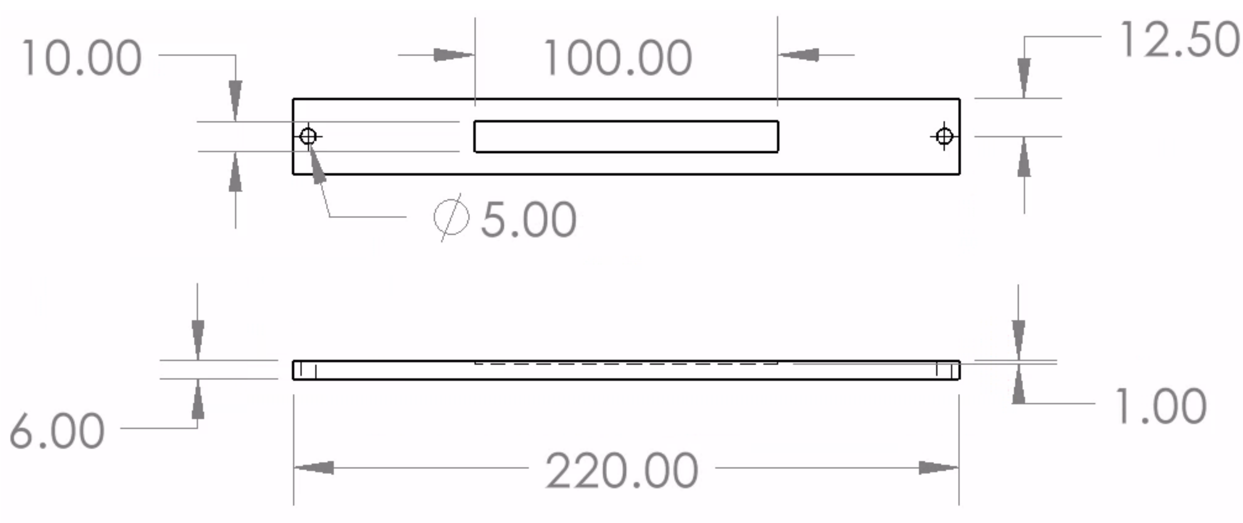
Front-4: Front Mount Tower



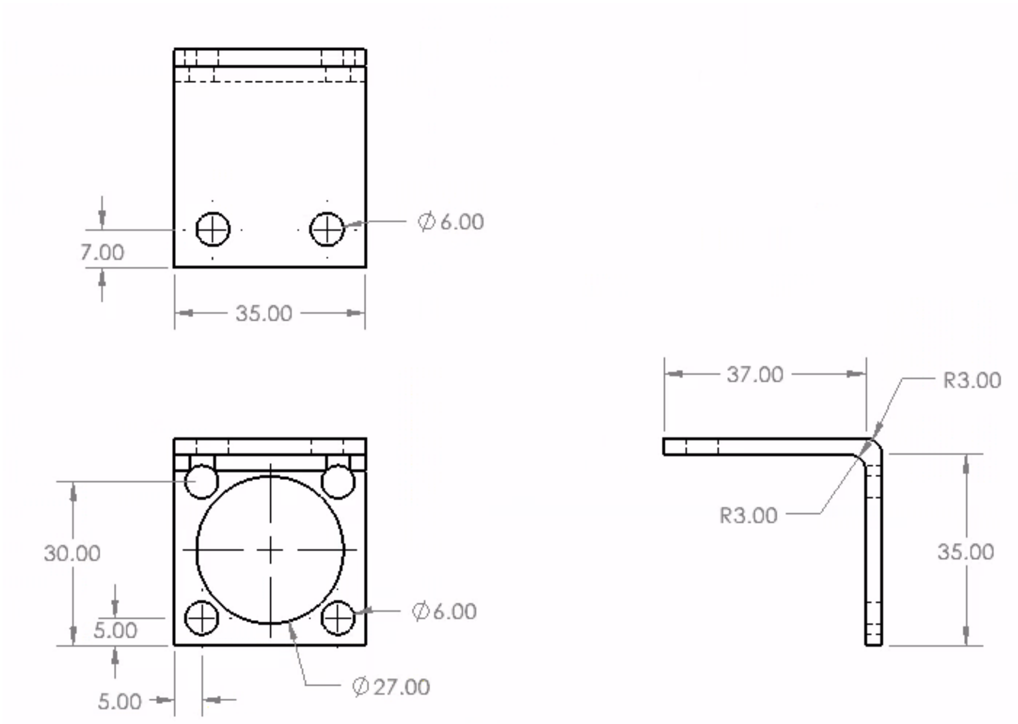
Front-5: Front Link



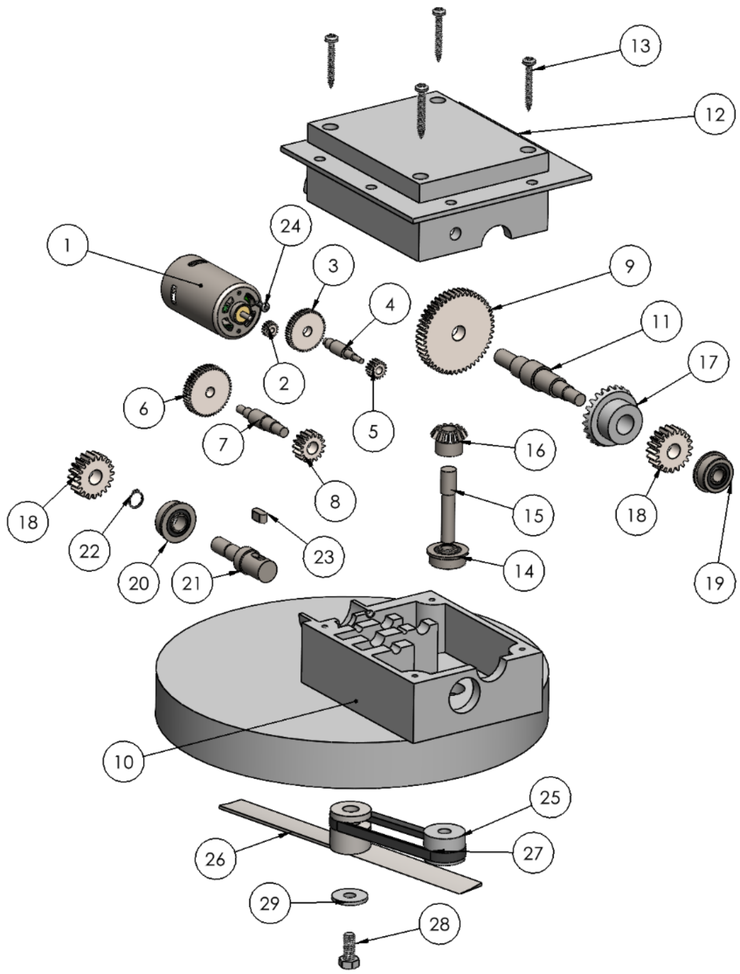
Front-6: Rear Link

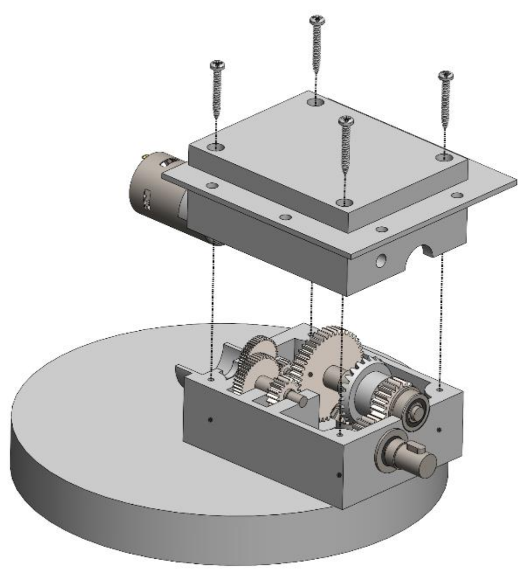


Front-7: Stepper Motor Bracket



Gearbox Assembly

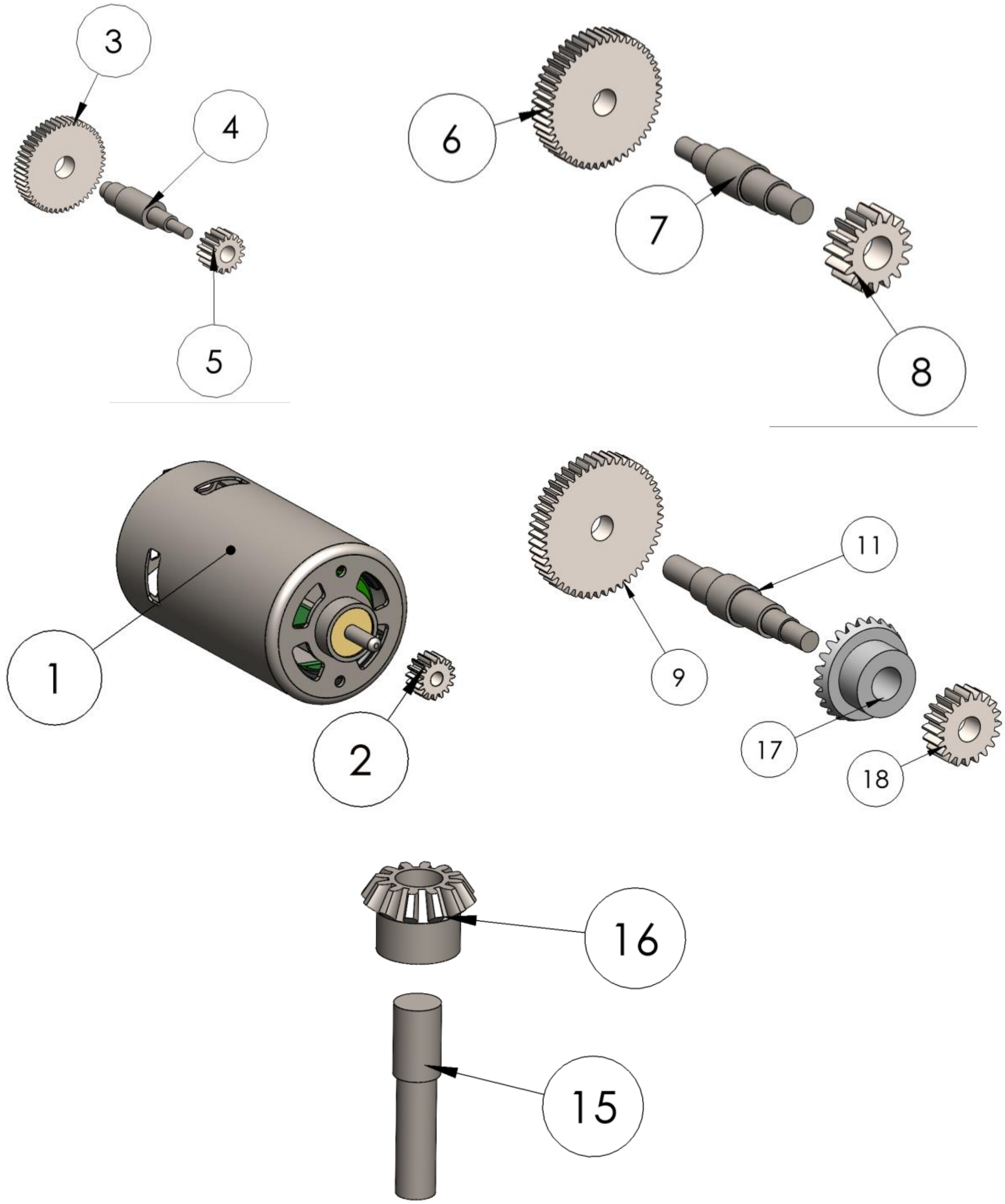




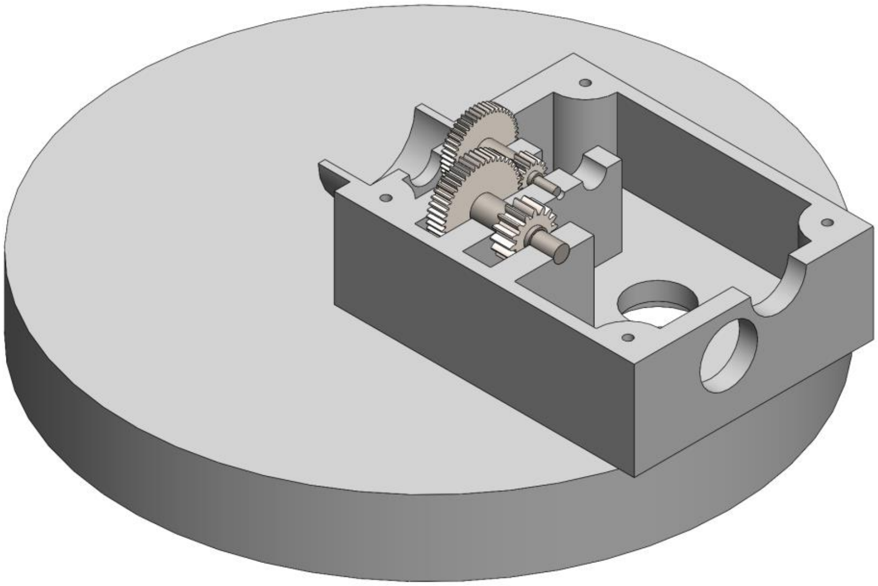
Materials				
[No.] Description	Supplier (Part Number) Or Drawing Number	Number Required	Price Per Part ($)	Total Mass Per Part (g)
[1] RS550 DC Motor	Trossen Robotics (MOT-550)	1	11.95	214
[2] 48-16 Spur Gear	HPCGears (G48-16PG)	1	12.59	1.70
[3] 48-48 Spur Gear	HPCGears (G48-48PG)	1	16.75	17.5
[4] Motor Shaft 1	Gearbox-1 (AISI 1020)	1	-	8.56
[5] 40-16 Spur Gear	HPCGears (G40-16PG)	1	12.30	2.95
[6] 40-48 Spur Gear	HPCGears (G40-48PG)	1	34.30	2.95
[7] Motor Shaft 2	Gearbox-2 (AISI 1020)	1	-	16.3
[8] 24-16 Spur Gear	HPCGears (G24-16PG)	1	14.60	10.3
[9] 24-48 Spur Gear	HPCGears (G24-48PG)	1	19.88	120
[10] Motor Housing Base	Gearbox-3 (PET)	1	-	300
[11] Motor Shaft 3	Gearbox-4 (AISI 1020)	1	-	70.9
[12] Motor Housing Top	Gearbox-5 (PET)	1	-	373
[14] Ball Bearing for 5/16" Shaft Diameter	McMaster-Carr (6384K343)	1	11.27	23.7
[15] Blade Shaft	Gearbox-6 (AISI 1020)	1	-	18.4
[16] Bevel Pinion	McMaster-Carr (2515N12)	1	35.50	18.9
[17] Bevel Gear	McMaster-Carr (2515N11)	1	59.06	69.8
[18] 20-20 Spur Gear	HPCGears (G20-20PG)	2	17.60	31.2
[19] Ball Bearing for 5/16" Shaft Diameter	McMaster-Carr (6384K343)	1	11.27	23.7
[20] Ball Bearing for 3/8" Shaft Diameter	McMaster-Carr (6384K346)	1	13.40	23.2
[21] Output Shaft	Gearbox-7 (AISI 1020)	1	-	47.2
[22] External Retaining Ring for 3/8" OD	McMaster-Carr (97633A170)	1	0.10	0.17
[23] Shaft Key	Gearbox-8 (AISI 1020)	1	-	2.48
[24] M3 x 0.5mm Thread, 8mm Long	McMaster-Carr (92000A118)	1	0.05	0.71
[25] 2L V-Belt Pulley	McMaster-Carr (3060K110)	1	11.24	7.23
[26] Blade	Gearbox-9 (AISI 1020)	1	-	91.7
[27] Belt	Gearbox-10 (Polyurethane)	1	-	5.94
[28] M7 x 1mm Hex Bolt, 16mm Length	McMaster-Carr (91280A412)	1	0.31	7.90
[29] M7 Oversized Washer, 22mm Diameter	McMaster-Carr (91116A250)	1	0.32	5.81
Total for Assembly		**29**	**300.09**	**1547.4**

Assembly Instructions

Step 1.) Assemble gear shafts by combining [3], [4], and [5] as shown below using Loctite 638 adhesive. Clean the surfaces of the shaft and gear hubs. Then, apply a thin layer of the adhesive to the leading edge of the appropriate shaft step and inside the hub of the gear. Slide the gears onto the shaft and apply slight pressure to ensure gear faces are flush with shaft steps. Allow to cure for 72 hours for maximum strength.

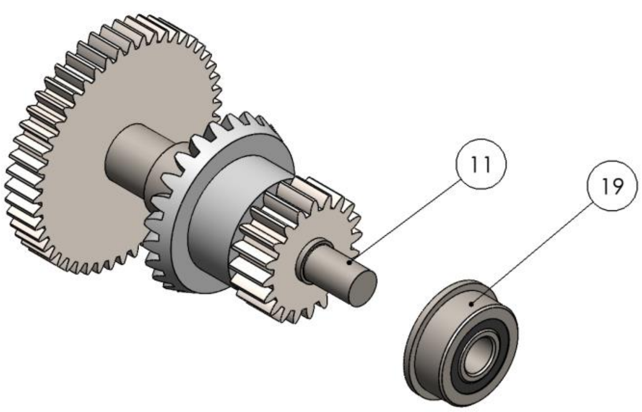


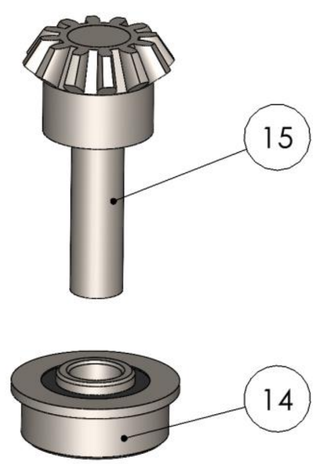
Wipe any excess away carefully. Repeat for [1] and [2] (motor shaft), [6], [7], and [8] (the second internal shaft), [9], [11], [17], and [18] (third internal shaft), and [15] and [16] (blade pinion and blade shaft). Locate the appropriate journal surfaces for [4] and [7], lubricate generously, and locate shafts within the gearbox.

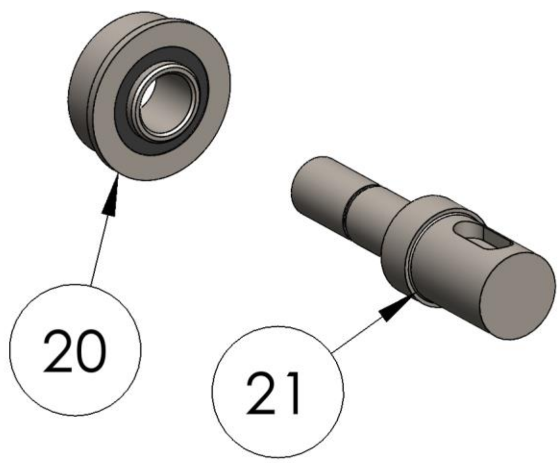


Step 2.) Press fit bearings [14], [19], and [20] onto their corresponding shafts [15], [11], and [21] respectively. See the following for tips for how to accomplish this without the use of a hydraulic press. Ensure that the bearing inner ring is in contact with the appropriate shaft step.

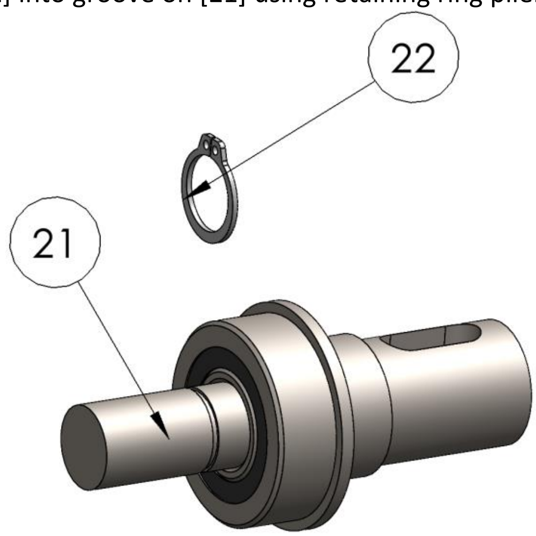
https://www.youtube.com/watch?v=s1pYIBriiP0



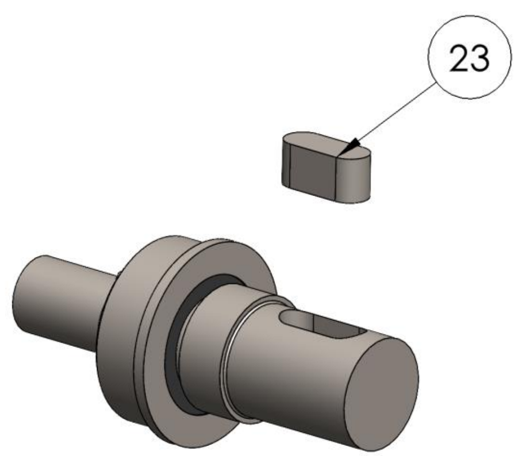


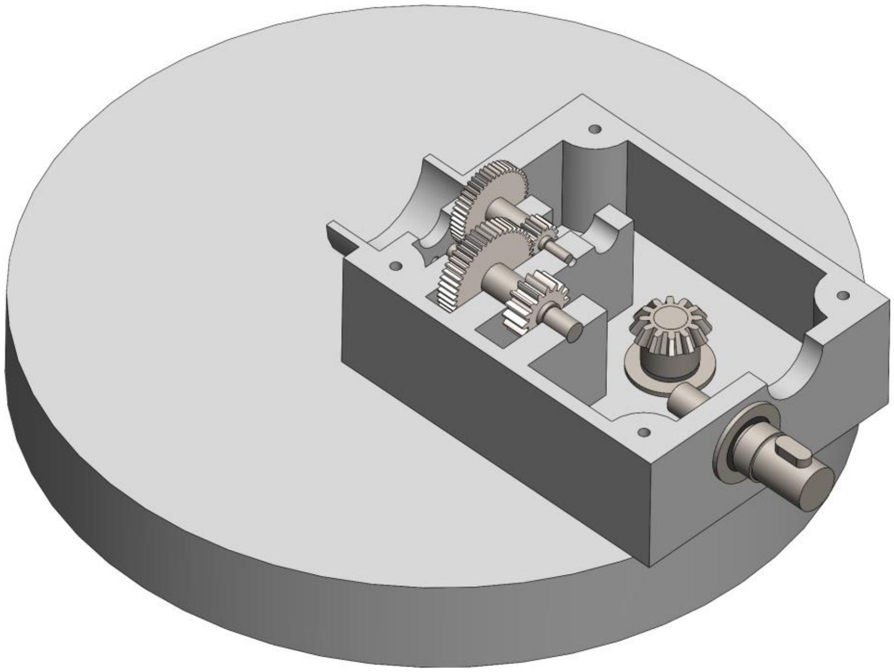


Step 3.) Install snap ring [22] into groove on [21] using retaining ring pliers.

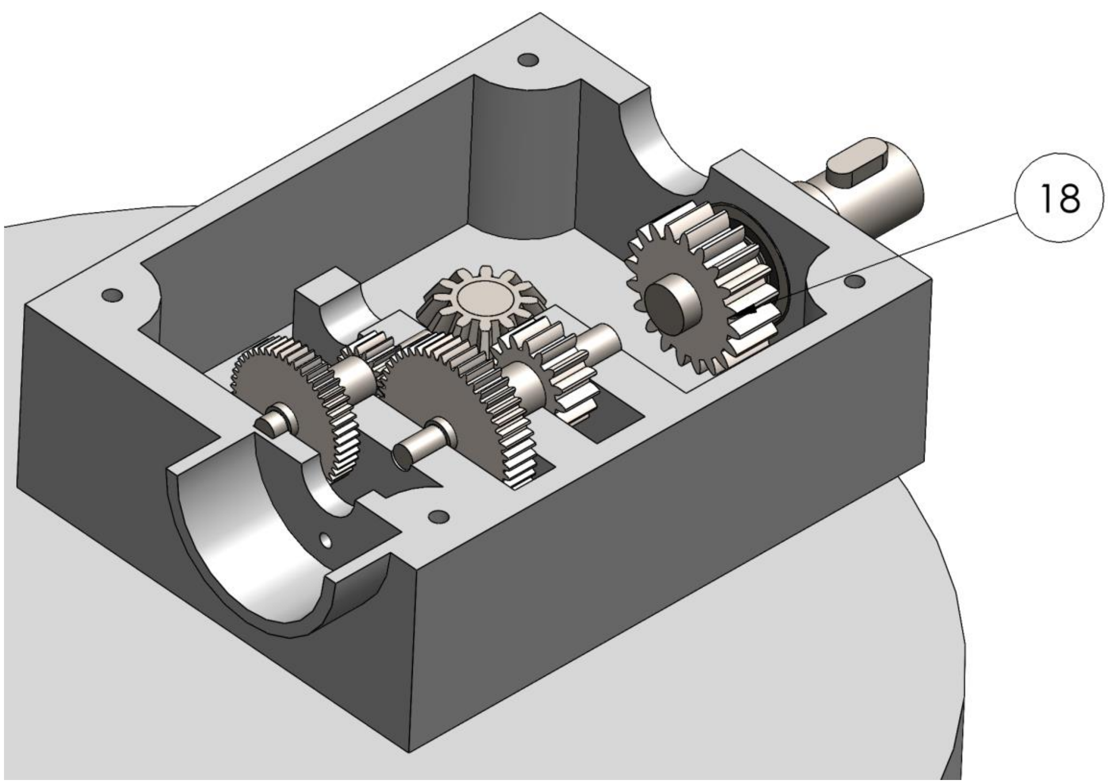


Step 4.) Install [15] and [21] into their corresponding locations in the gearbox, as shown below. Insert [23] into the corresponding slot on [21]. Note that the flange on [20] should contact the exterior of the gearbox, where [14] should contact the interior.

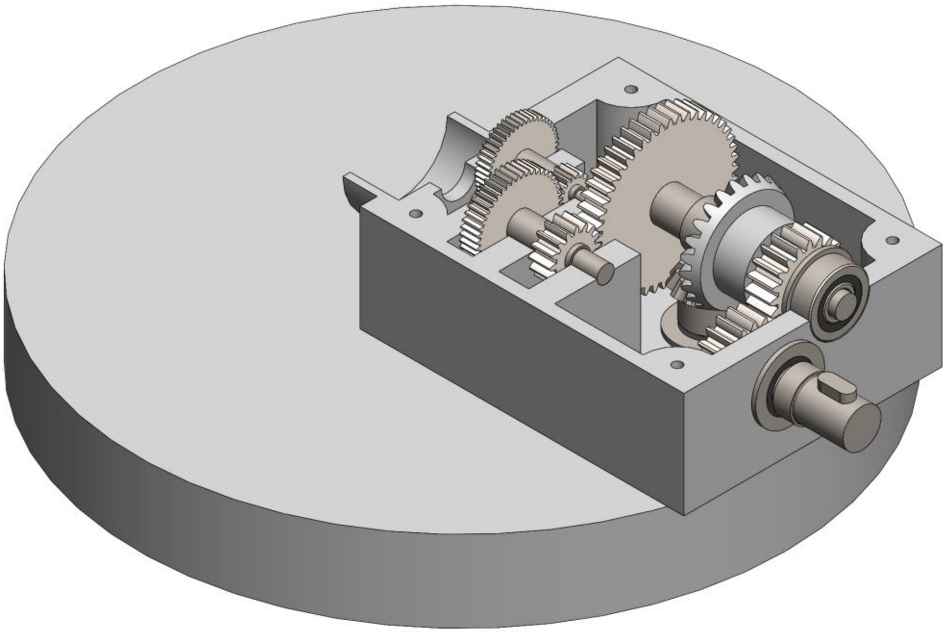




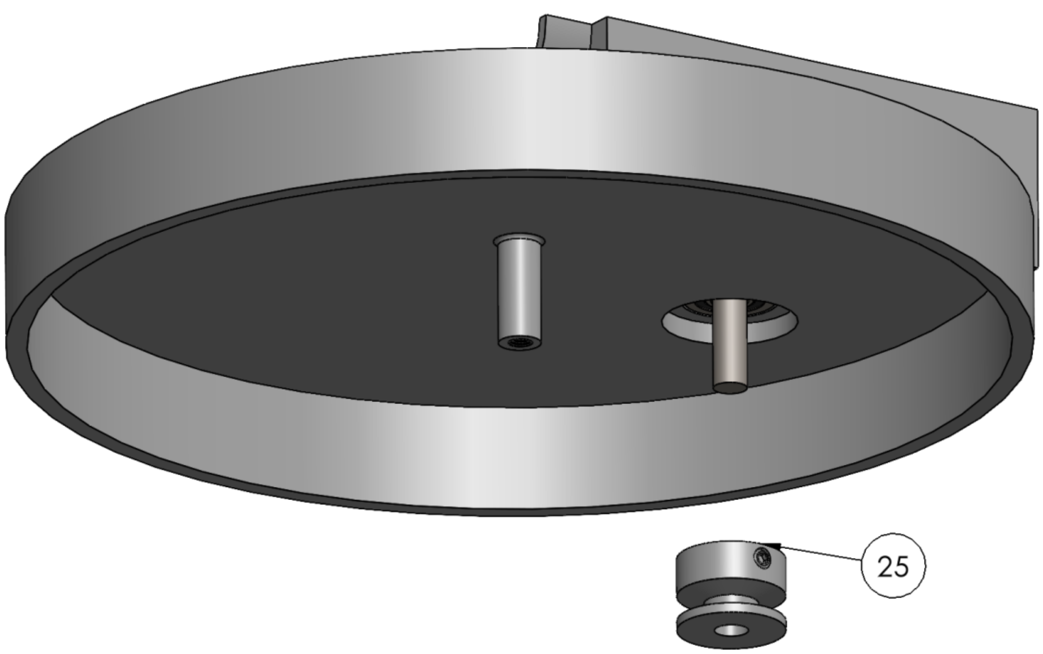
Step 5.) Apply Loctite to [18] and install on [21], following the instructions from step 1.) Slide [18] onto the shaft until it contacts the retaining ring.



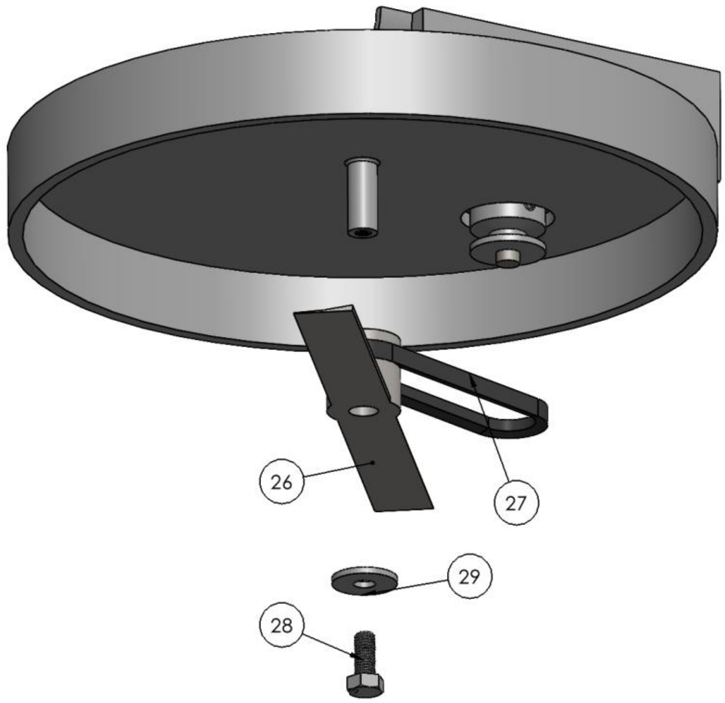
Step 6.) Install [11] and its mounted components, ensuring the journal surface for [11] is well-lubricated.



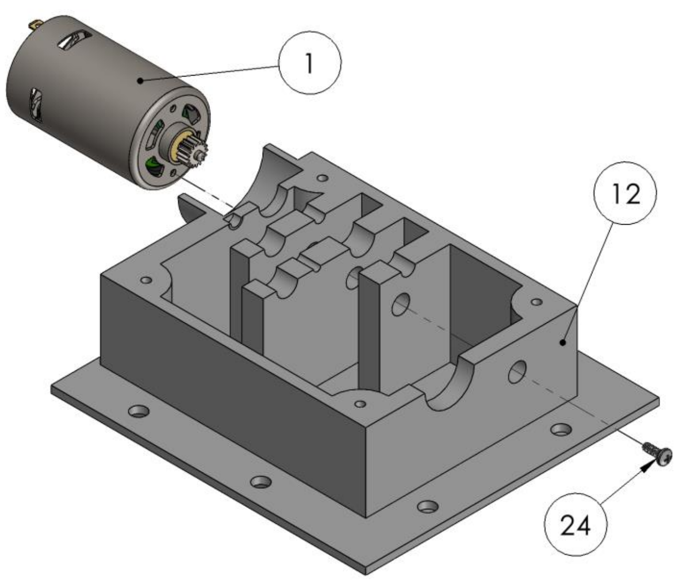
Step 7.) Secure [25] to [15] using 3M Scotch-Weld Metal Bonder Acrylic Adhesive DP8407NS. Follow adhesive instructions. The top surface of the pulley should be in contact with the ball bearing. Allow to cure for sufficient time.



Step 8.) Install [26]-[29] to the assembly. Loop the belt around the groove on the pulley and blade, and slide the blade over the protruding axle on the base. Once the blade slides on to the axle completely, assemble the bolt and washer to retain it. Avoid the sharp edges of the blade.



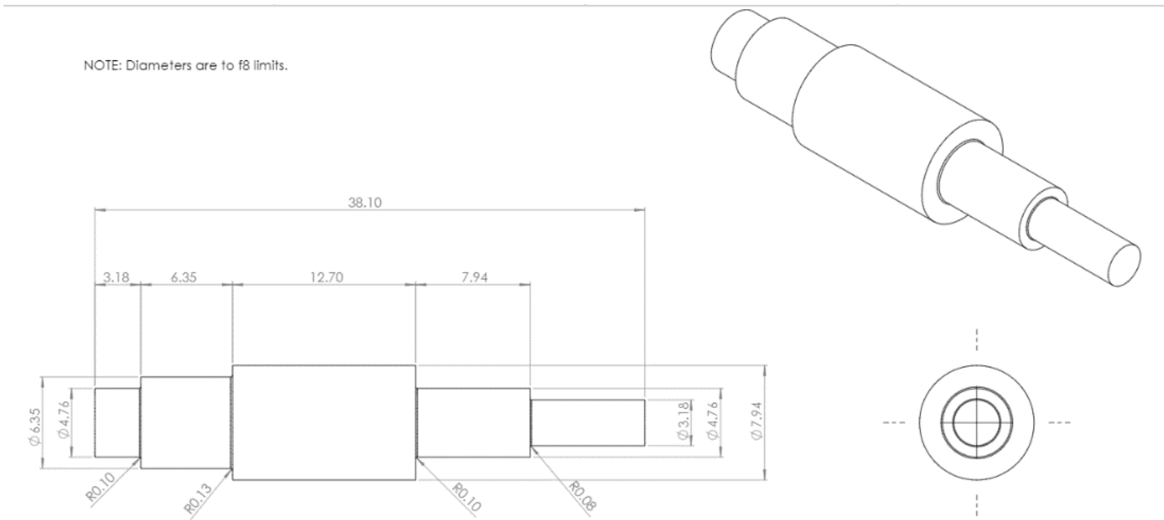
Step 9.) Use the through holes to fasten 24 to 1 and 12. This will combine with the cylindrical profile to constrain rotational motion of the motor.



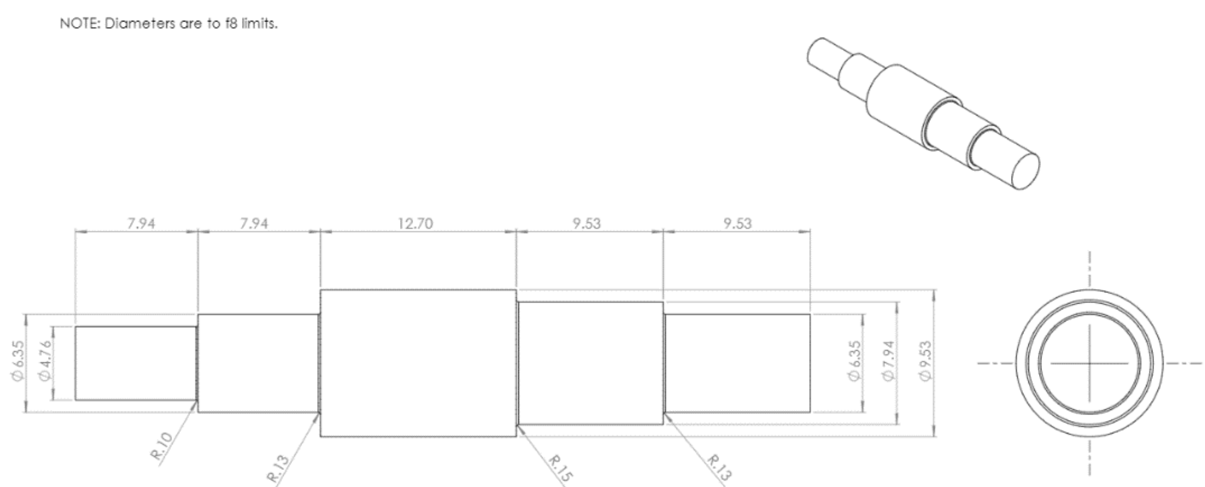
Step 10.) Lubricate journal surfaces in the top cover. The top and bottom of the gearbox are now ready for assembly to the chassis.

Custom Part Drawings

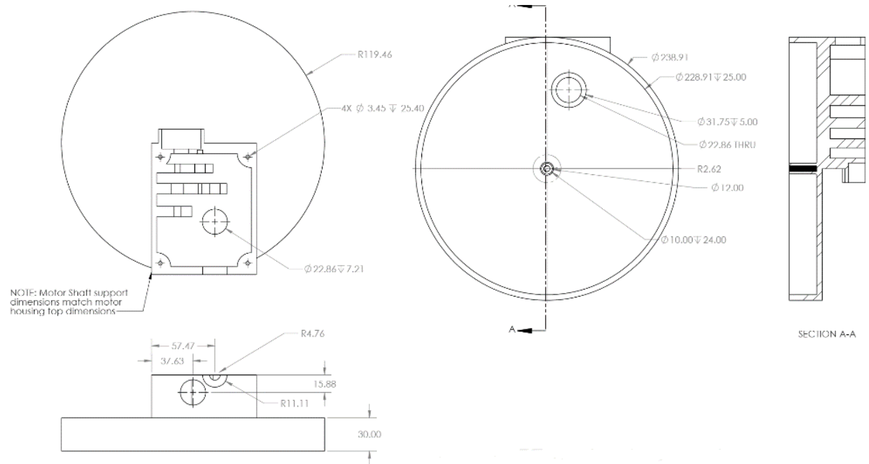
Gearbox-1: Motor Shaft 1 (all dimension in mm)



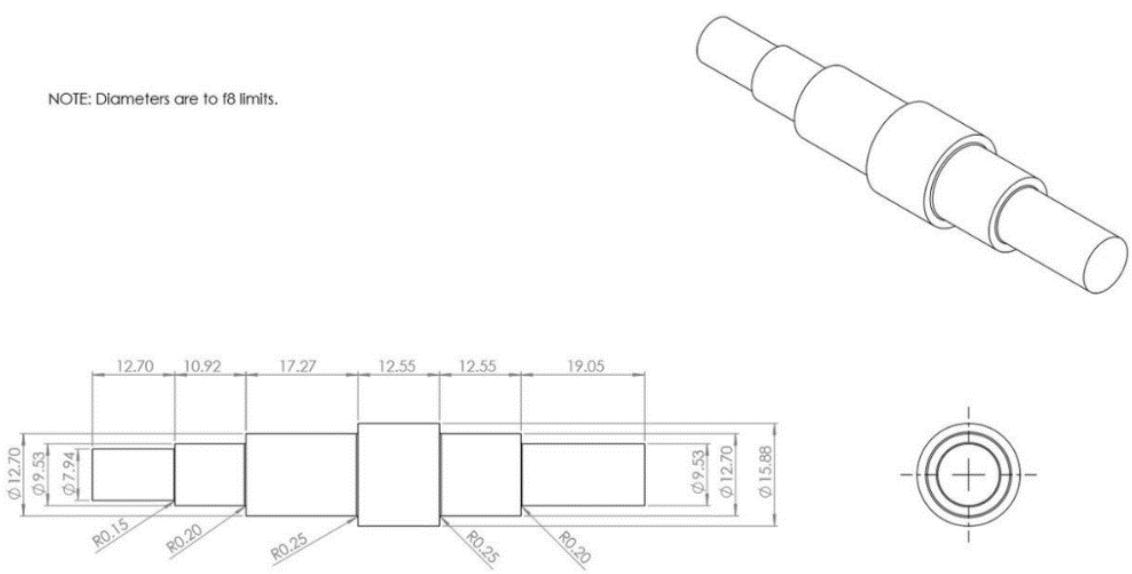
Gearbox-2: Motor Shaft 2



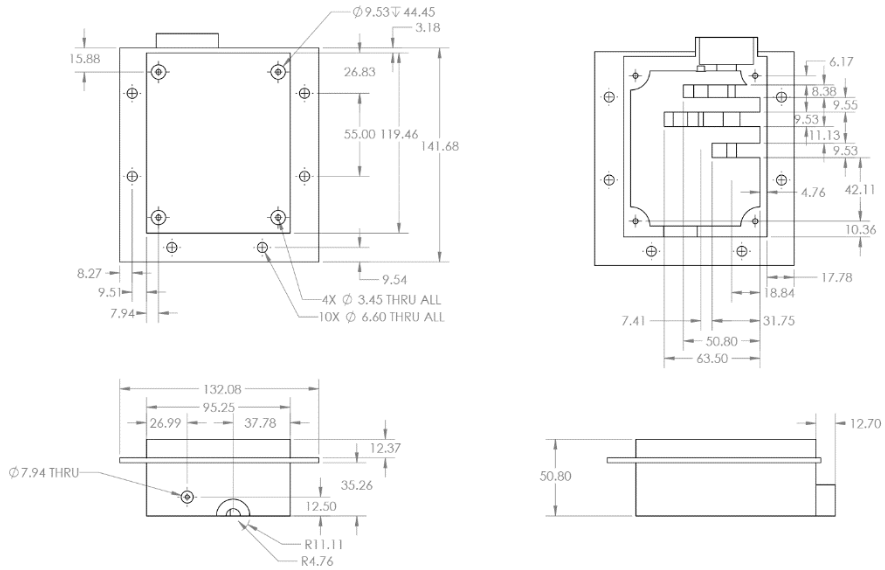
Gearbox-3: Motor Housing Base



Gearbox-4: Motor Shaft 3

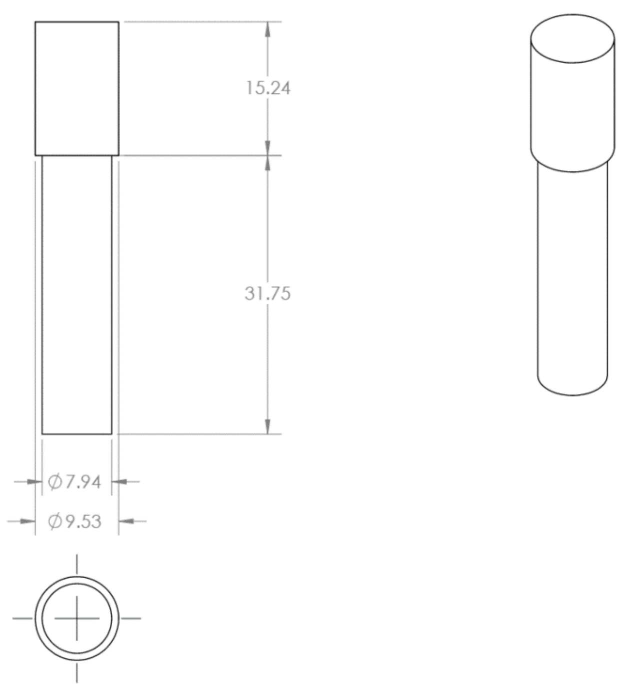


Gearbox-5: Motor Housing Top

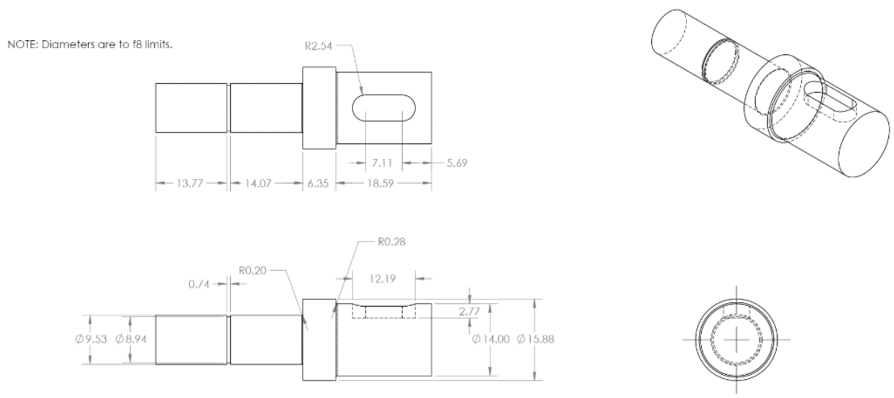


Gearbox-6: Blade Shaft

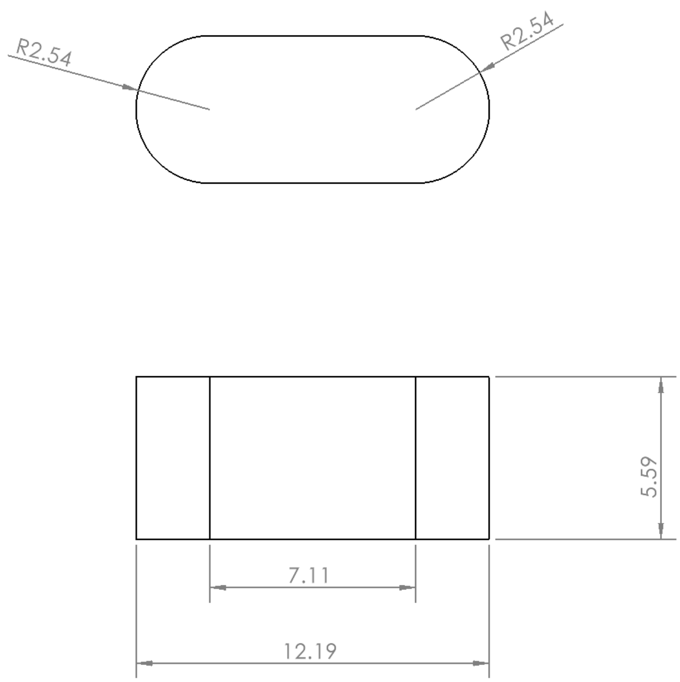
NOTE: Diameters are to f8 limits.



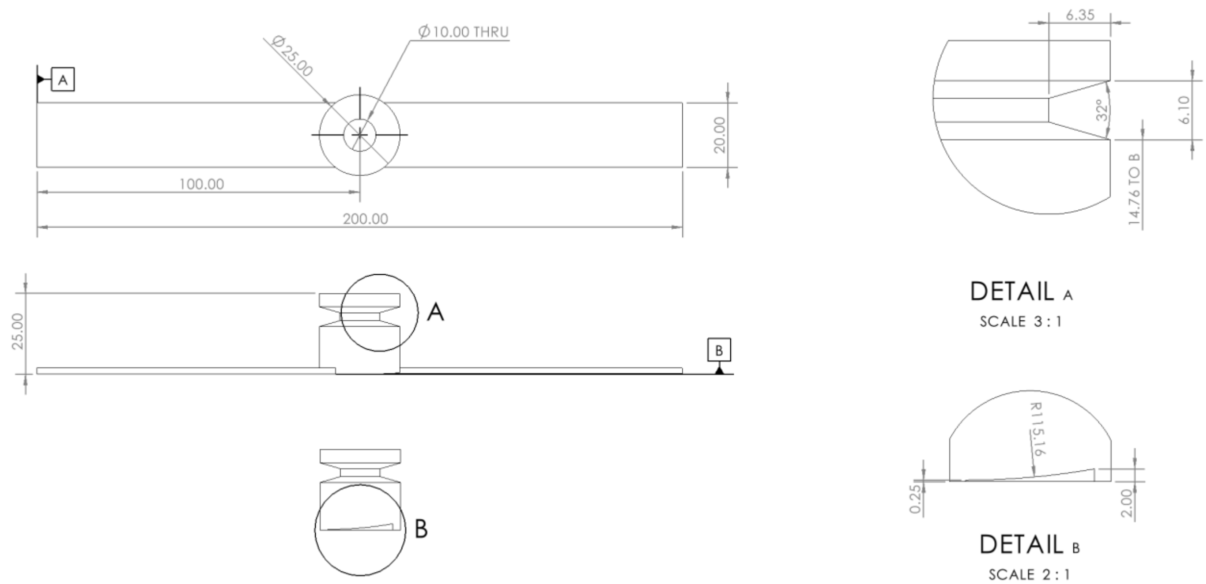
Gearbox-7: Output Shaft



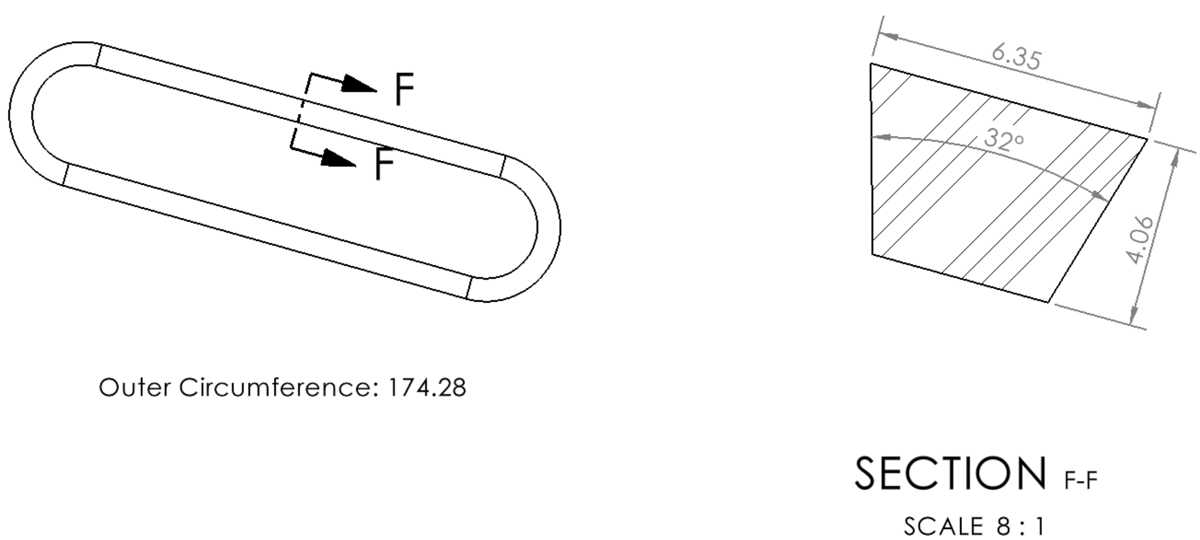
Gearbox-8: Shaft Key



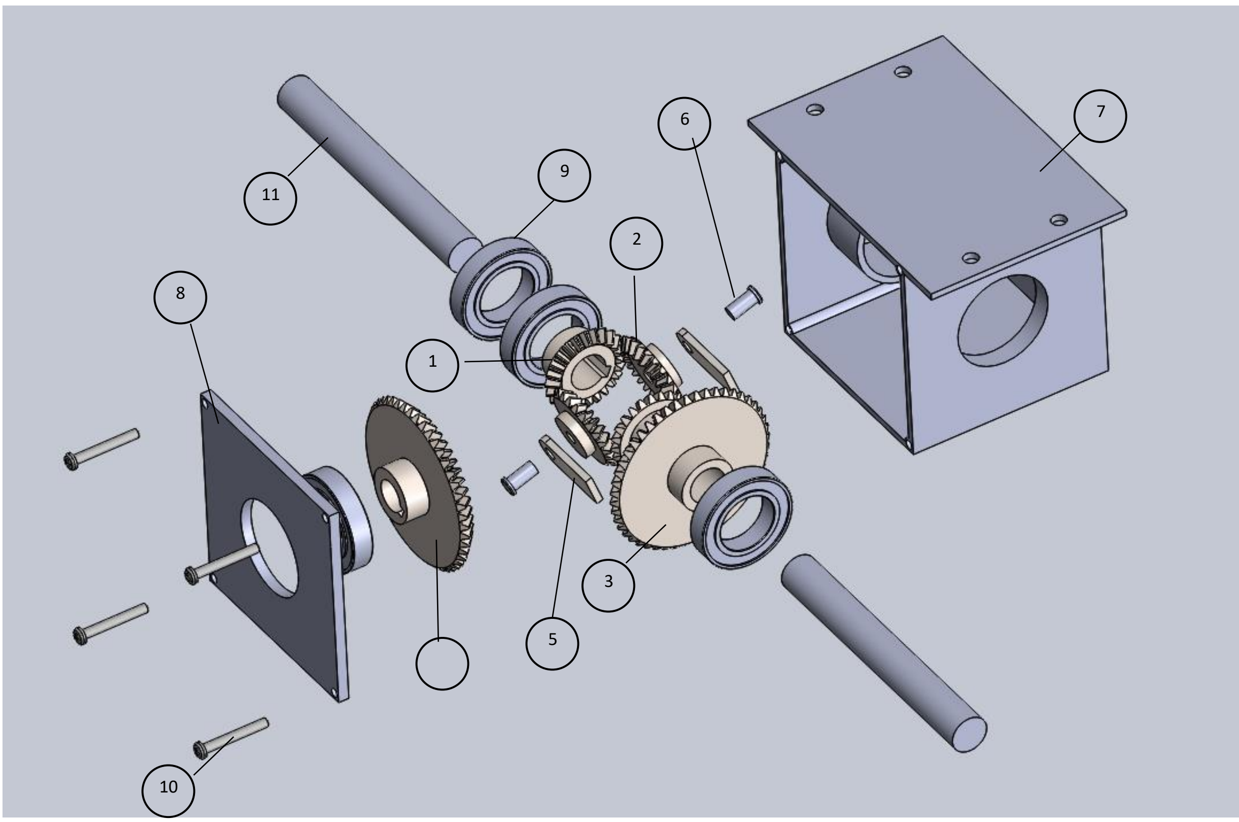
Gearbox-9: Blade



Gearbox-10: Belt

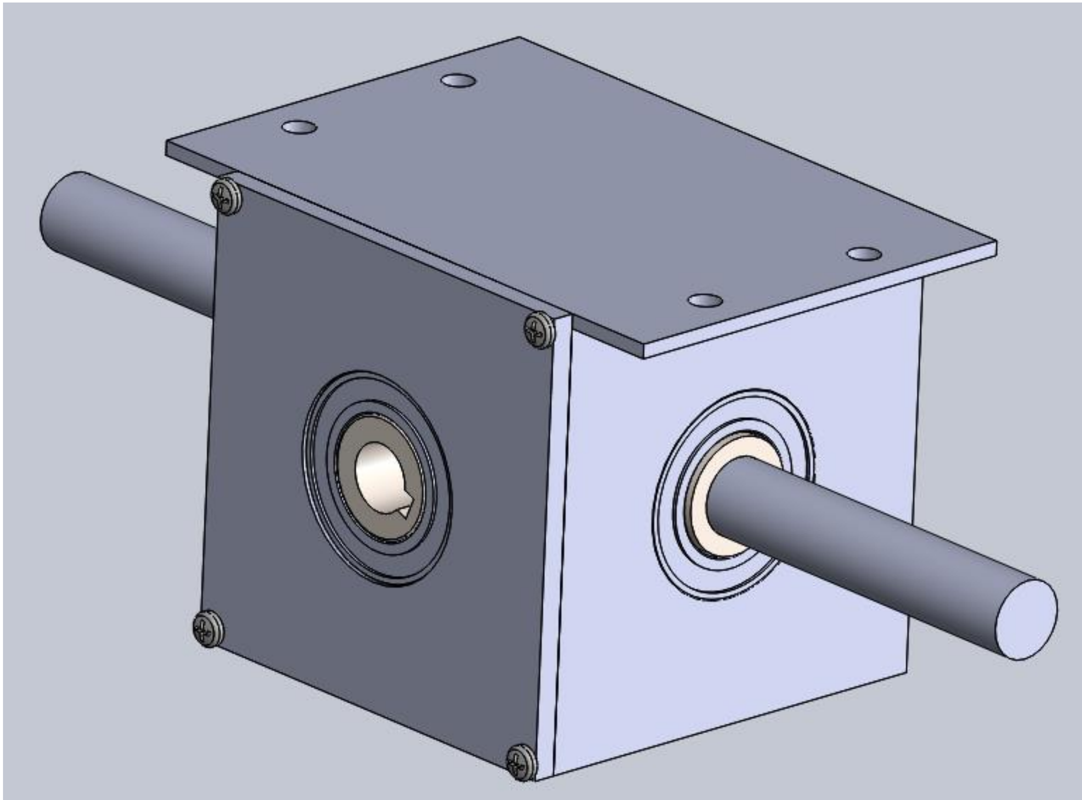


Differential Assembly

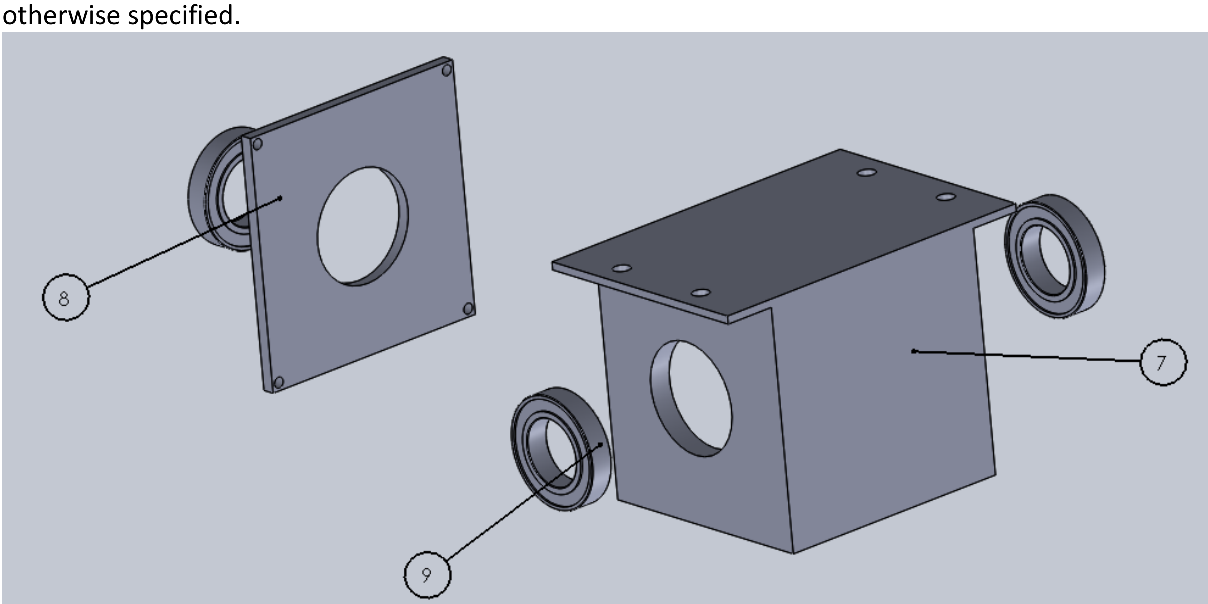


Materials				
[No.] Description	Supplier (Part Number) Or Drawing Number (Mat'l)	Number Required	Price ($)	Mass (g)
[1] Side Gears	McMaster (6529K55)	2	124.6	242.57
[2] Spider Gears	McMaster (6529K55)	2	124.6	242.57
[3] Ring Gear	McMaster (2515N15)	1	94.54	369
[4] Pinion Gear	McMaster (2515N15)	1	94.54	369
[5] Connecting bar for the Ring Gear and the Spider Gears	Differential-1 (1144 Carbon Steel)	2	-	2.2
[6] Pins for the Spider Gears	McMaster (95648A709)	2	0.39	1.63
[7] Larger housing piece that faces to the wheels	Differential-2 (PET)	1	-	195.29
[8] Smaller housing piece that faces the gearbox	Differential-3 (PET)	1	-	49.1
[9] Bearings	Misumi (B6905ZZ)	4	12.76	6.09
[10] Pan Head Machine Screws	Misumi (CSPPN-ST-M4-30)	4	0.03	9.92
[11] Differential Output Shafts	DIfferential-4 (AISI 1020)	2	-	90.2
	Total for Component	22	739.41	2175

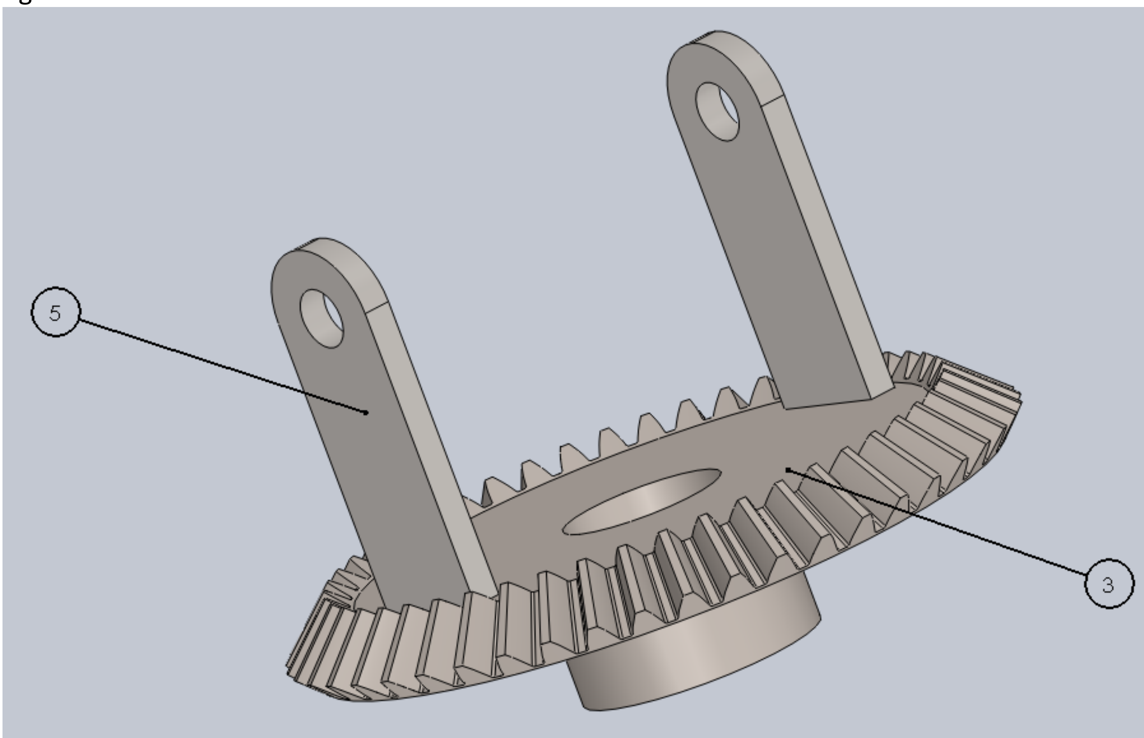
Assembly Instructions



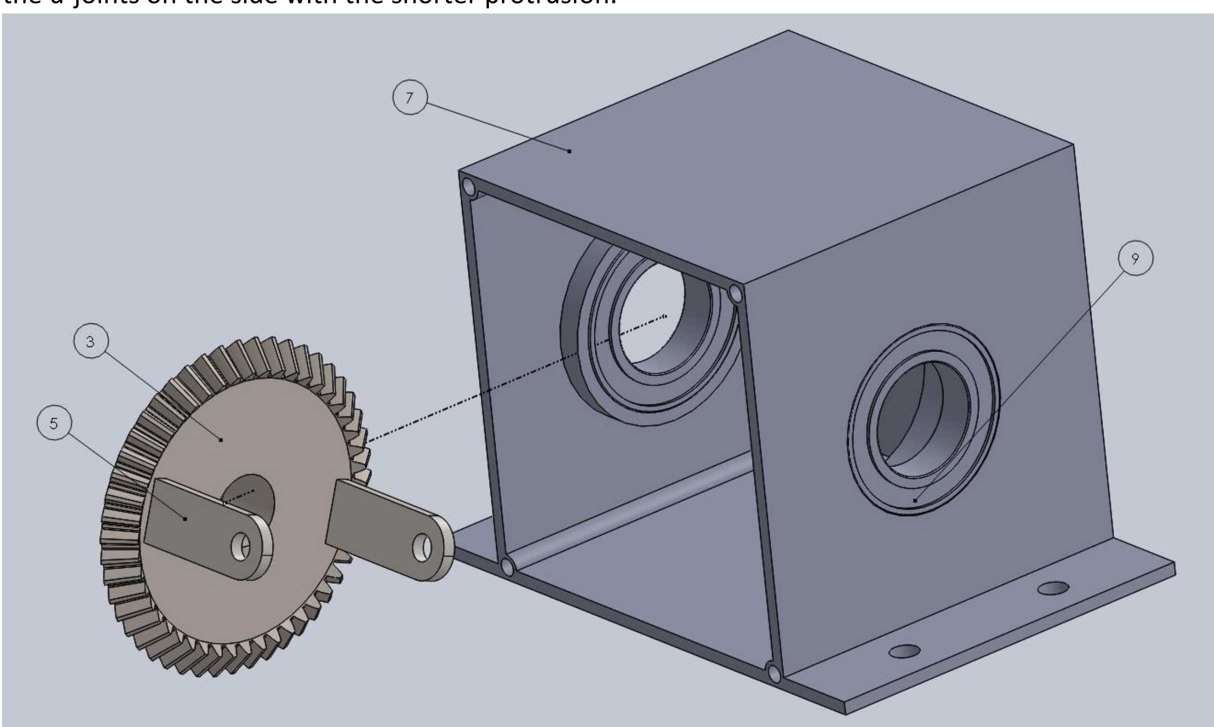
Step 1.) Ensure all 4 bearings [9] are well lubricated. Apply Loctite 638 to the exterior circumference of three of the bearings. Press fit those three of the bearings into the circular openings in the housings ([7] and [8]). Clamp the parts together for 4 minutes to ensure they are fixed. Allow to cure for 72 hours for maximum strength. Loctite guidance in this step applies to all further steps, unless otherwise specified.



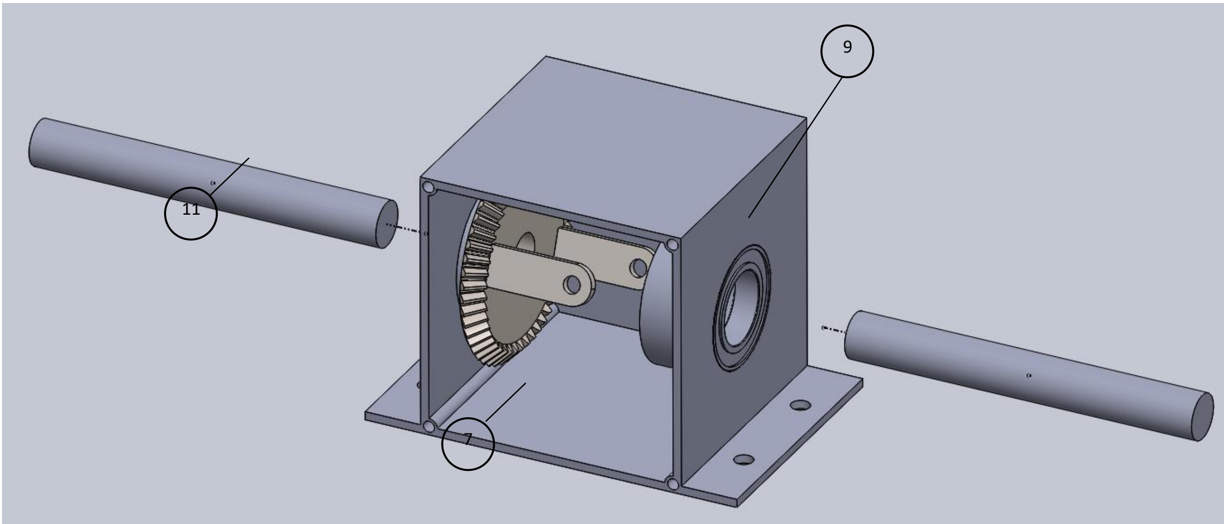
Step 2.) Before attaching any of the gears, the connecting bar for the spider gears [5] must be put into place. To do this, the connecting bars [5] must be fixed to the ring gear [3] opposite of one another using Loctite 638 in the orientation shown below.



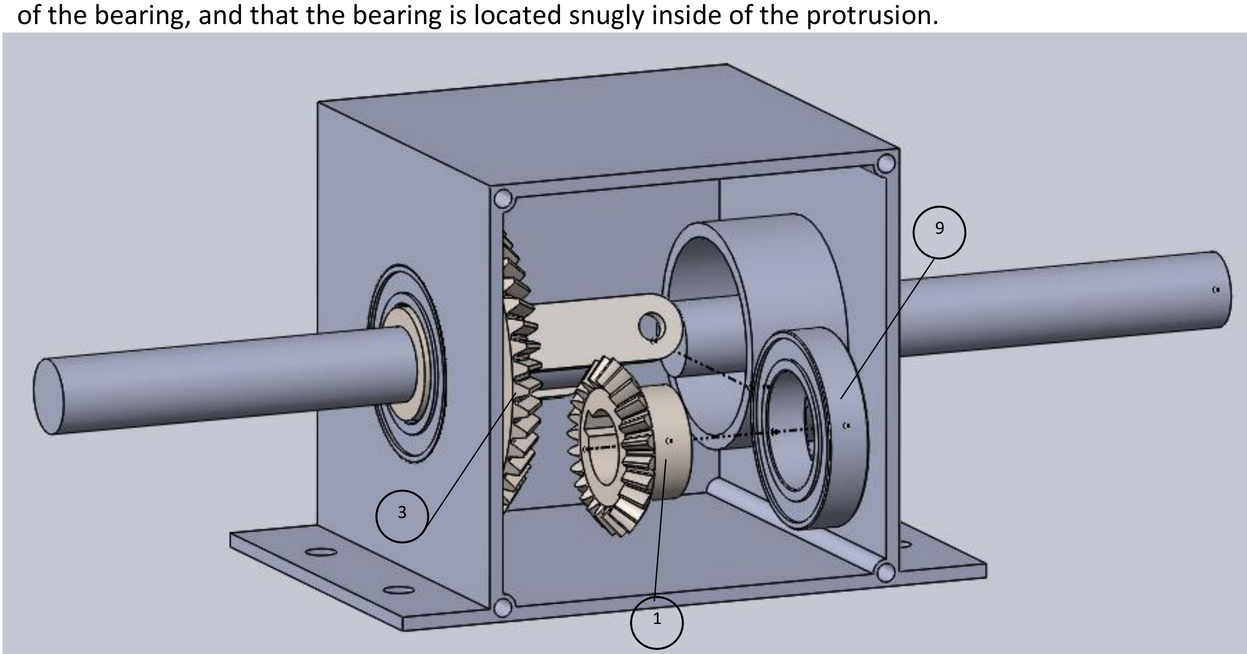
Step 3.) Place the ring gear [3] with the attached connecting bars [5] in the housing [7] on the side with the shorter protrusion into the housing. The gear should also be fit around the shaft that leads to the u-joints on the side with the shorter protrusion.



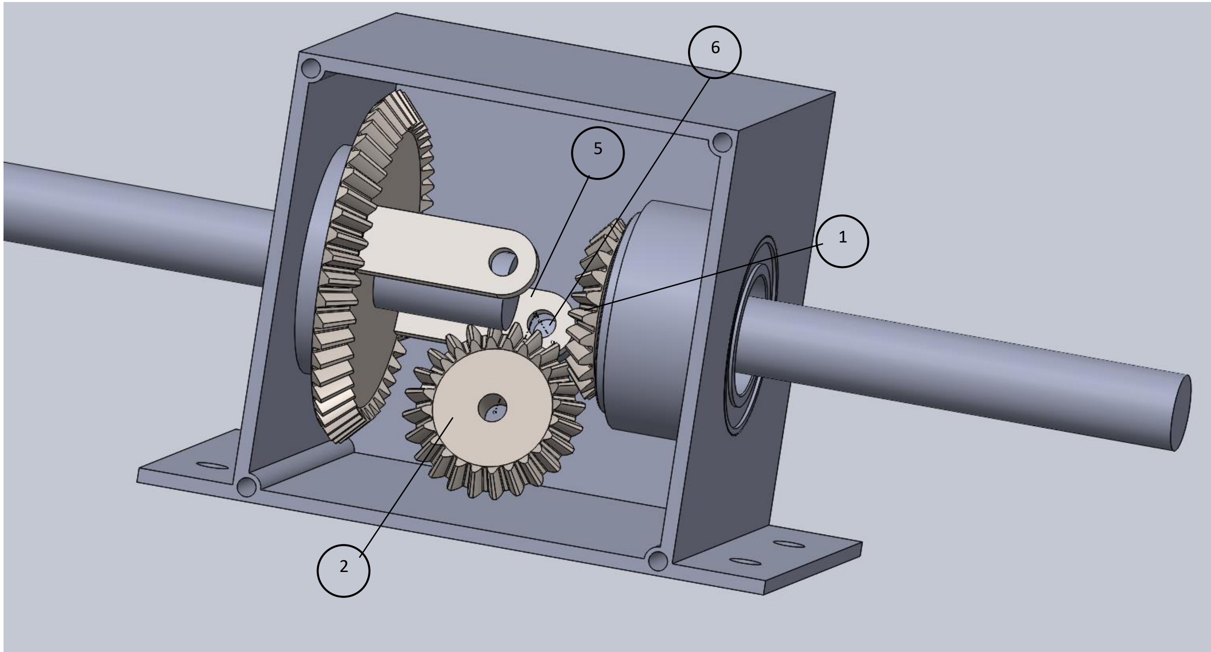
Step 4.) Insert the differential output shafts [11] into the bearings [9] in the differential housing [7].



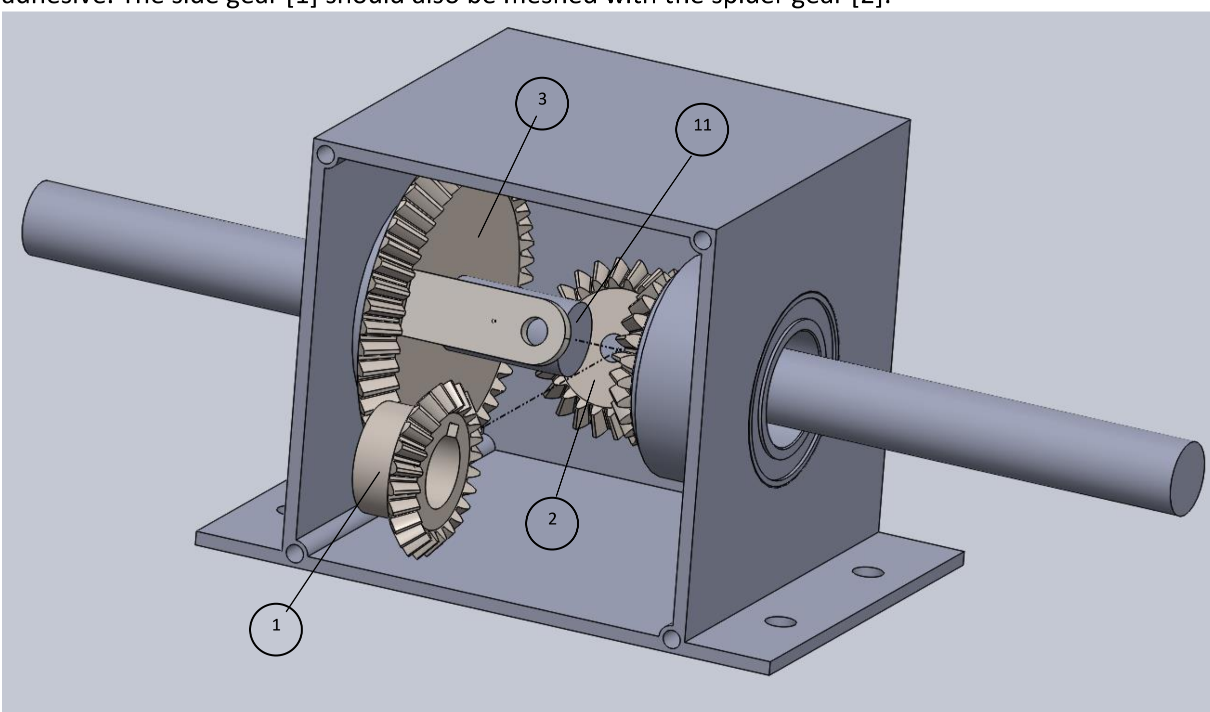
Step 5.) Insert one side gear [1] in the remaining bearing [9] and fix using Loctite 638, and then fix that to both the longer cylindrical protrusion opposite the ring gear [3]. Adhere this using Loctite 638 on the newly placed bearing. Make sure that this is fixed to the shaft. The final location of all other gears in the differential is determined by the placement of this gear. Ensure it is located snugly inside of the bearing, and that the bearing is located snugly inside of the protrusion.



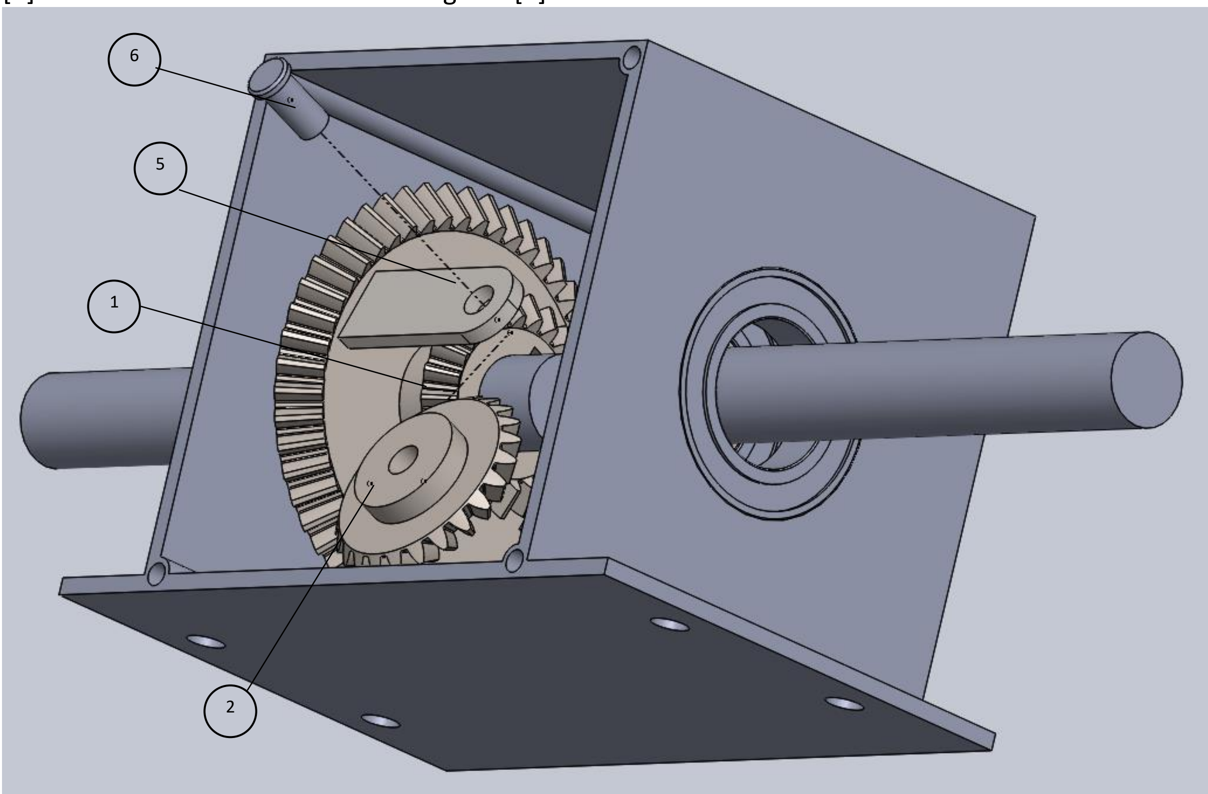
Step 6.) Apply Loctite to the interior hub of one spider gear [2], align it with the hole on the end of the rigid bar [5] furthest from the opening and insert pin [6] through the hole. The spider gear [2] should be meshed with the side gear [1] installed in the step 5.



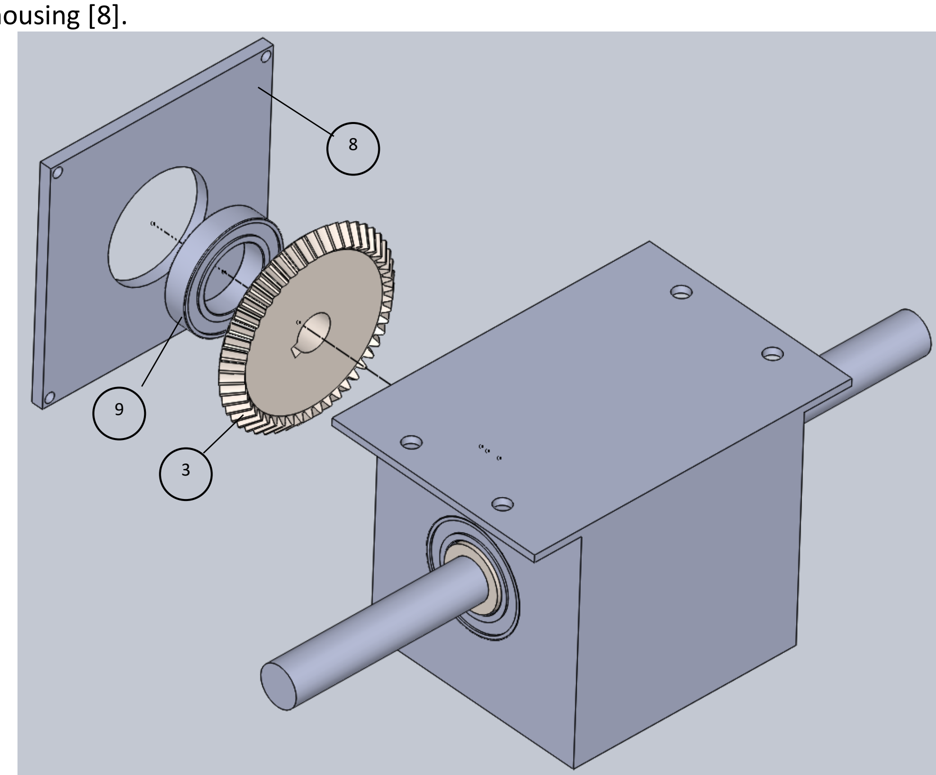
Step 7.) Using Loctite 638 on the interior circumference of the remaining side gear [1], place it so it is concentric with ring gear [3]. Fix this side gear [1] to the end of the shaft [11] leading to the wheel using Loctite 638. Make sure that the ring gear [3] and side gear [1] are not fixed together using the adhesive. The side gear [1] should also be meshed with the spider gear [2].



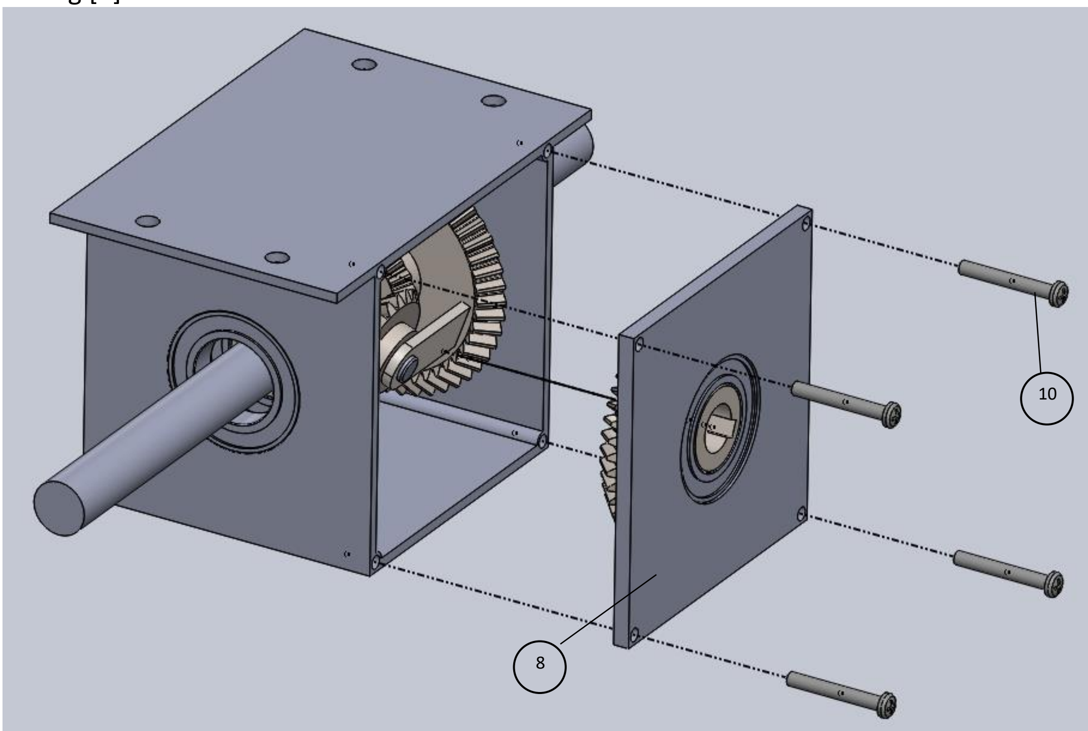
Step 8.) Apply Loctite 638 to the interior hub of the remaining spider gear [2], align it with the hole on the end of the rigid bar [5] closest to the opening, and insert pin [6] through the hole. The spider gear [2] should be meshed with both side gears [1].



Step 9.) Apply Loctite to the exterior hub circumference of the pinion [4] and fit into the bearing [9] in the small housing [8].



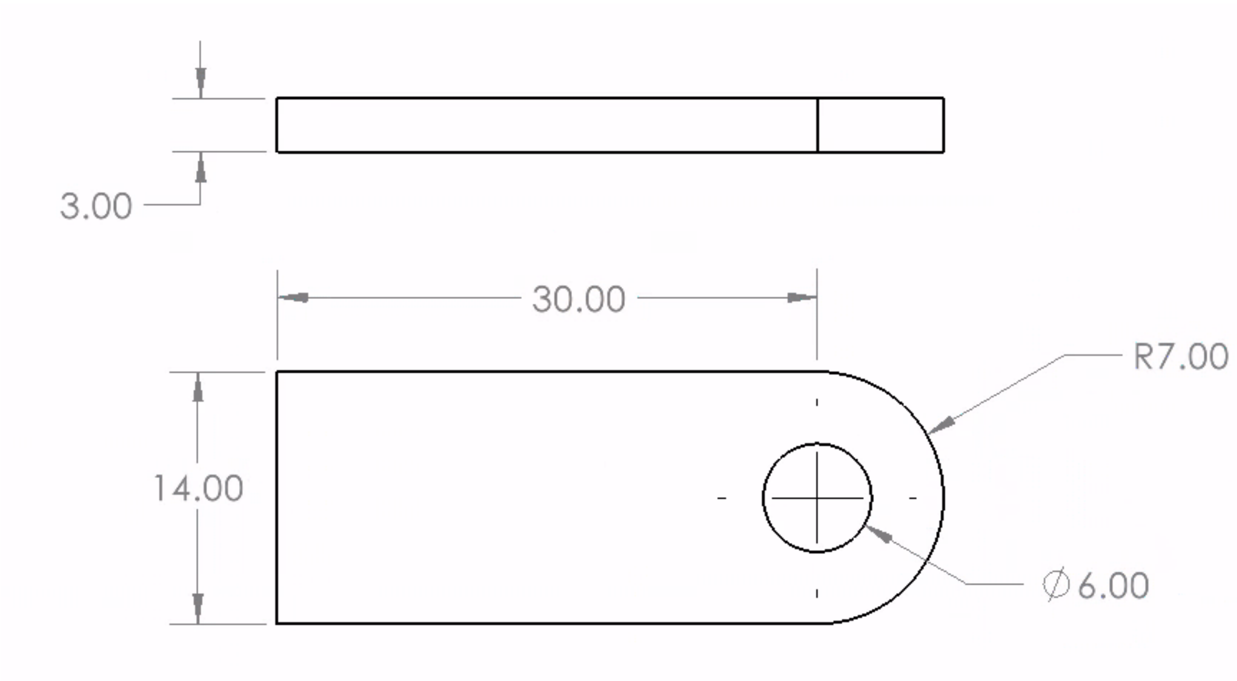
Step 10.) Mesh the pinion [4] and the ring gear [3] by fitting the differential housings [7] and [8] together. Bolt the housings together using four pan head machine screws [10] in the corner holes of the housing [8].



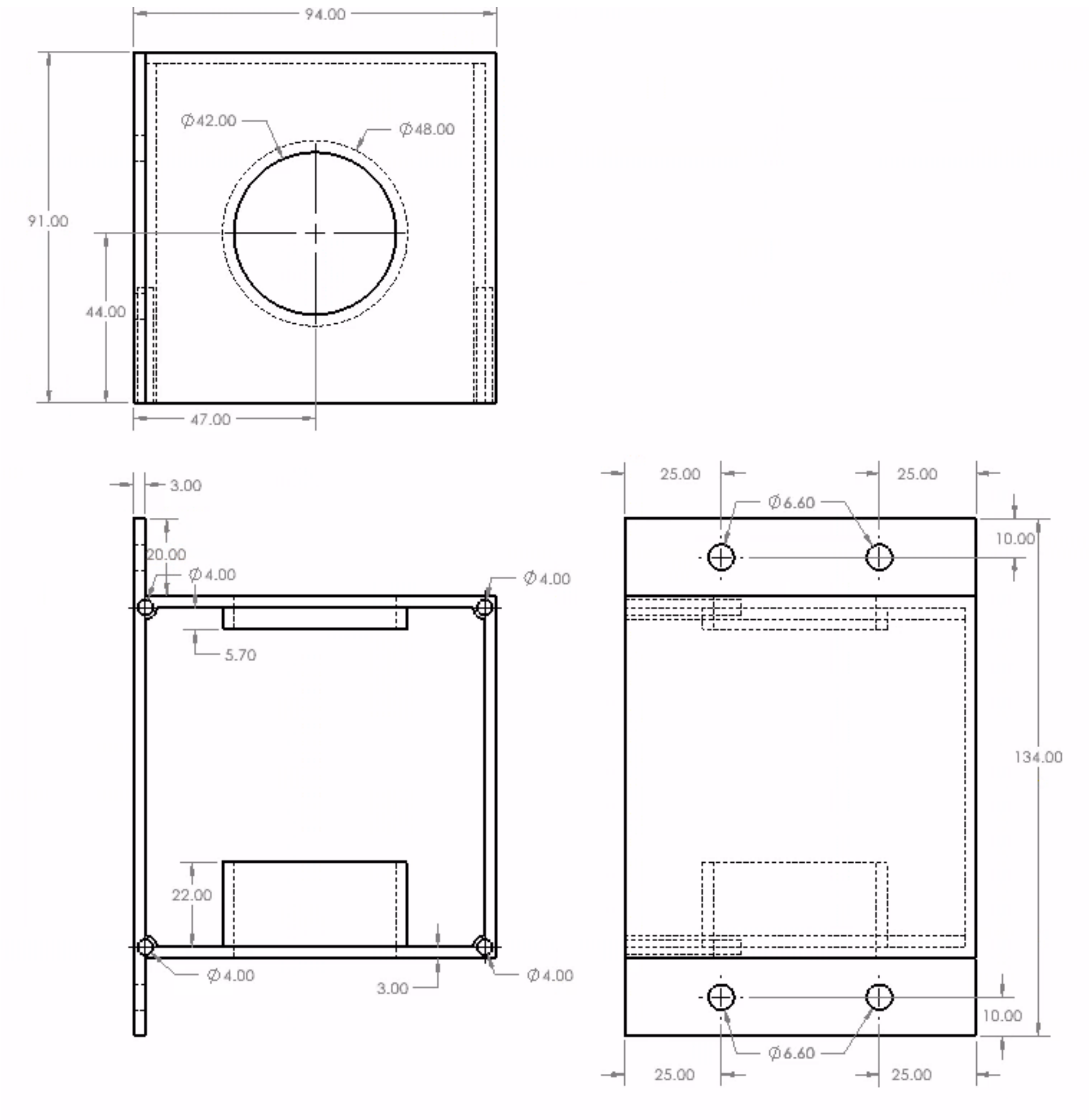
Custom Part Drawings

Dimensions in mm, tolerances ± 0.13 unless otherwise specified

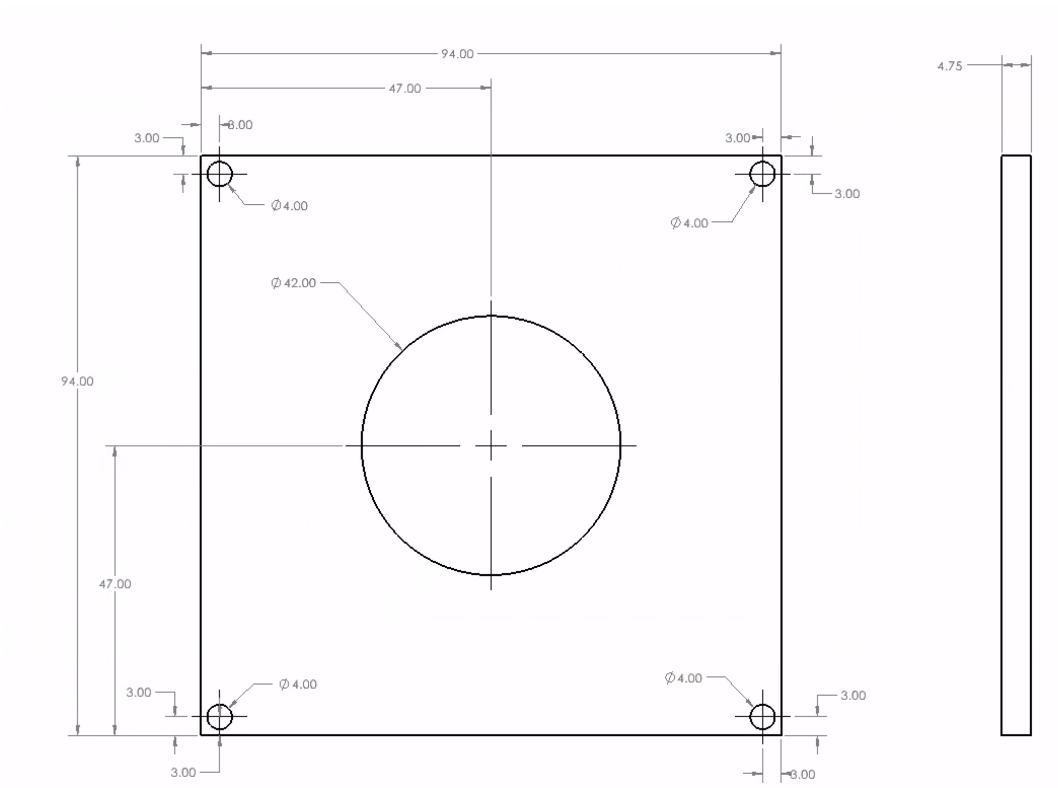
Differential-1: Connecting bar for the Ring Gear and the Spider Gears



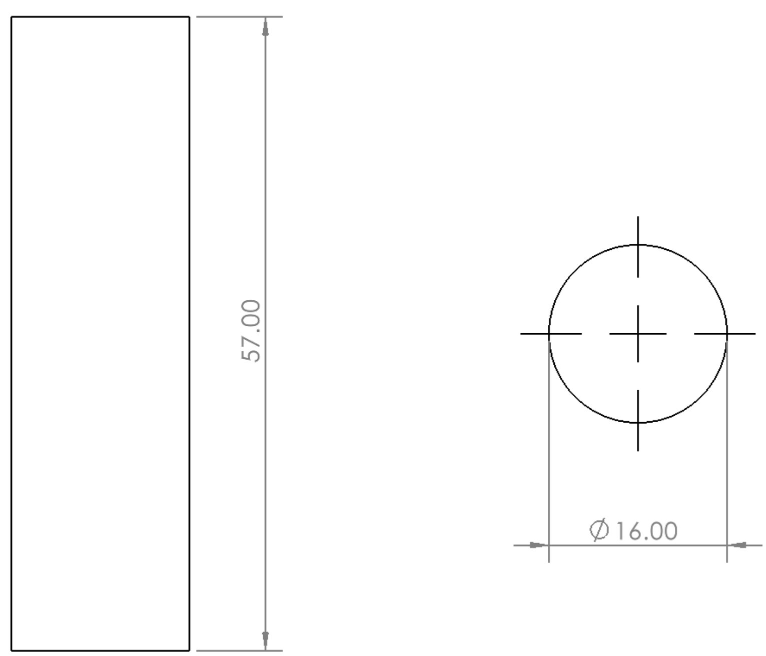
Differential-2: Larger housing piece that faces to the wheels



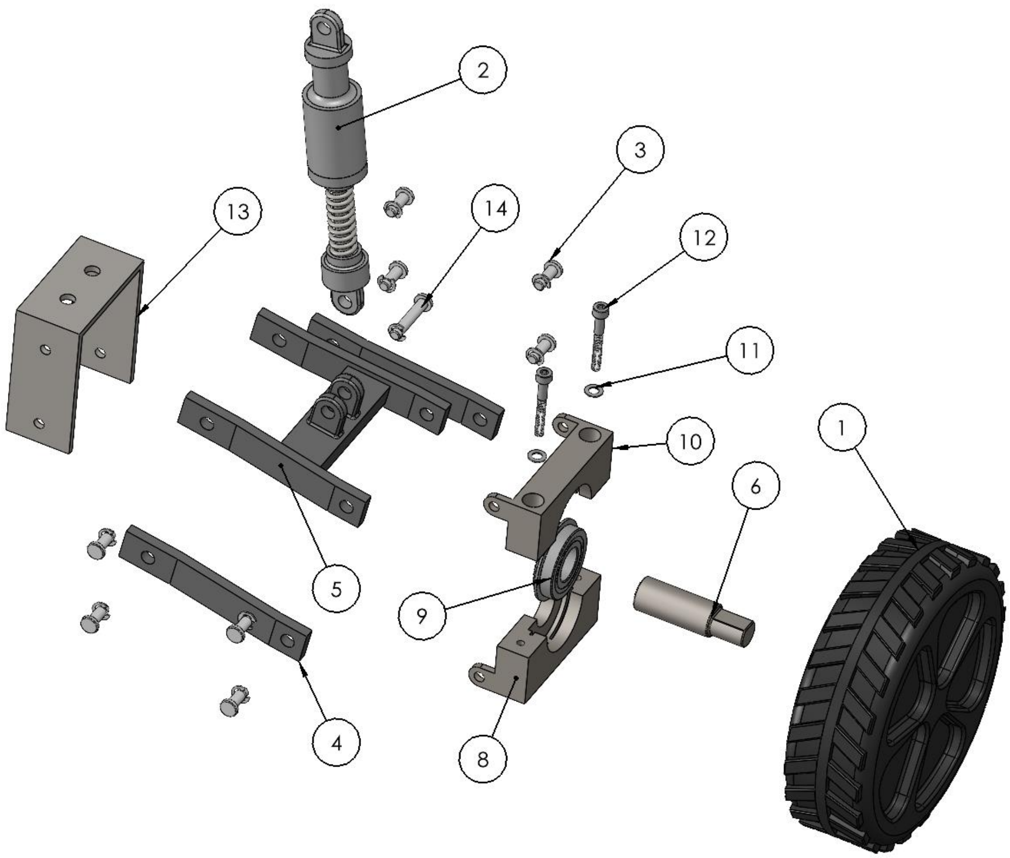
Differential-3: Smaller housing piece that faces the gearbox

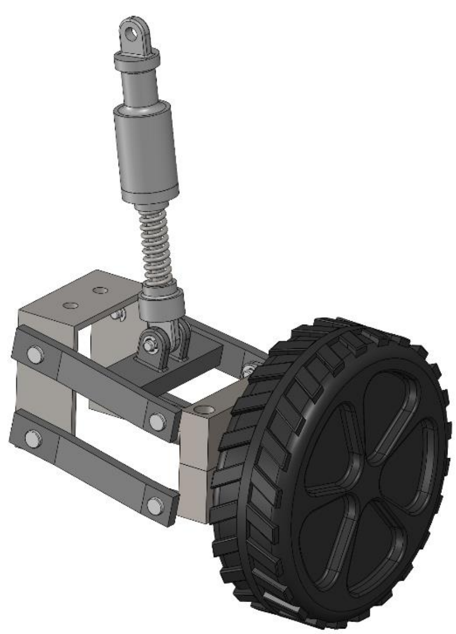


Differential-4: Differential output shaft



Rear Suspension Assembly



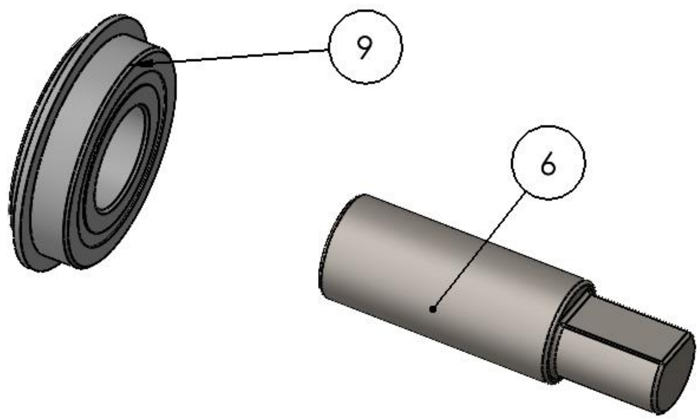


Materials (For Both Assemblies)					
[No.]	**Description**	**Supplier (Part Number) Or Drawing Number (Mat'l)**	**Number Required**	**Price Per Part ($)**	**Total Mass Per Part (g)**
[1]	Wheel	Rear Suspension – 1(PET)	2	-	297
[2]	Suspension Assembly	See Instructions for Subassy.	2 (10)	11.89	42.7
[3]	Clevis Pin with Retaining Ring 1/4" Dia. x 3/8" Lg.	McMaster-Carr (92735A670)	16	1.79	2.59
[4]	Lower Linkage	Rear Suspension – 2(Low Carbon Steel)	4	-	9.40
[5]	Upper Linkage	Rear Suspension – 3 (Low Carbon Steel)	2	-	39.2
[6]	Wheel Shaft	Rear Suspension – 4 (AISI 1020)	2	-	62.0
[8]	Bottom Bearing Block	Rear Suspension – 5 (AISI1020)	2	-	160
[9]	Ball Bearing, Shielded with Retaining Ring	McMaster-Carr (6661K33)	2	21.83	41.4
[10]	Top Bearing Block	Rear Suspension – 6 (AIS1020)	2	-	147
[11]	General Purpose 18-8 Stainless Steel Washer for M4 Screw Size	McMaster-Carr (98689A113)	4	0.03	0.16
[12]	Black-Oxide Alloy Steel Socket Head Screw, M4 x 0.7 mm Thread	McMaster-Carr (91290A180)	4	0.18	3.60
[13]	Linkage Mounting Bracket	Rear Suspension – 7 (6061 Aluminum)	2	-	126
[14]	Clevis Pin with Retaining Ring 1/4" Dia. x 7/8" Lg.	McMaster-Carr (92401A107)	2	1.43	4.32
Total for Both Assemblies			**46 (54)**	**99.78**	**1933.3**

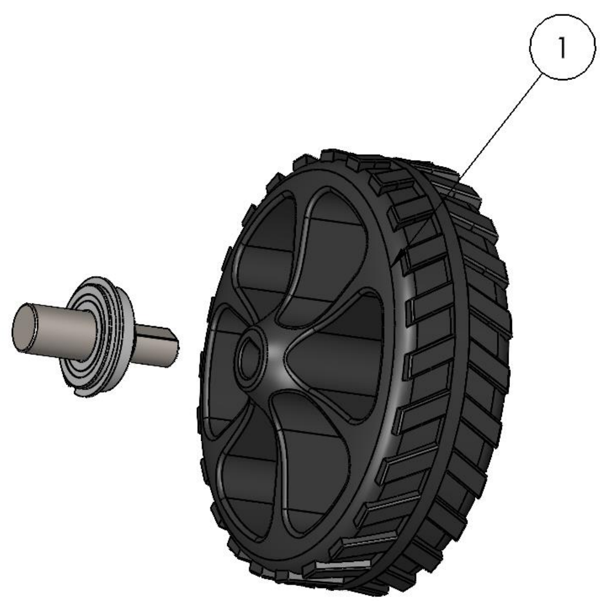
Assembly Instructions

Step 1.) Press fit [9] onto [6] shafts. See the following for tips for how to accomplish this without the use of a hydraulic press. Ensure that the bearing is located 5 mm from the shaft step for the wheel.

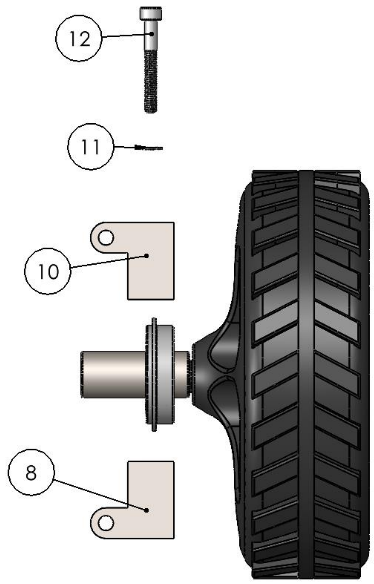
https://www.youtube.com/watch?v=s1pYIBriiP0

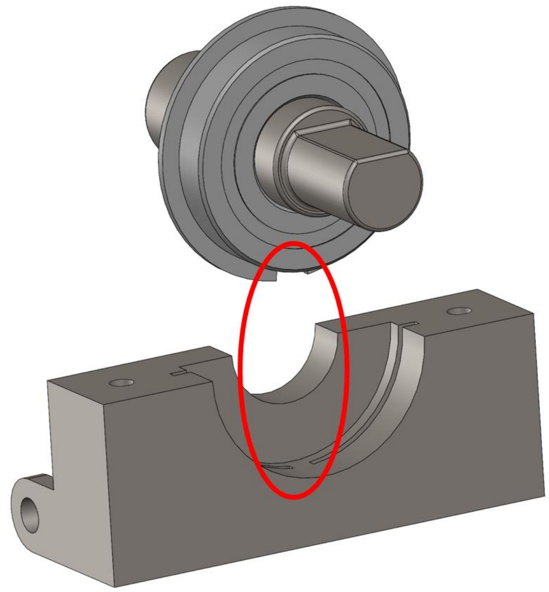


Step 2.) Press fit [1] onto [6]. Properly align the D-profile on the wheel and shaft. Ensure that the shaft is completely inserted into the wheel such that the shaft step is in contact with the surface of the wheel.

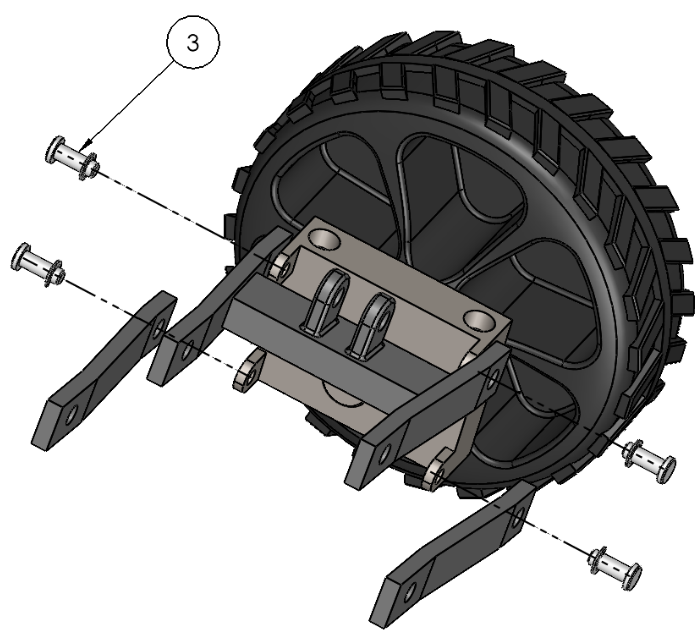


Step 3.) Assemble the steel bearing blocks around the ball bearing. The ball bearing has a flange to axially locate the bearing in the housing. Slide [8] and [10] around [9], ensuring the flange on the bearing is properly located. The notch on the flange should be placed around the slot on the base, indicated below with red. Use an Allen key to securely tighten [12] and [11] to fasten blocks [8] and [10] together.

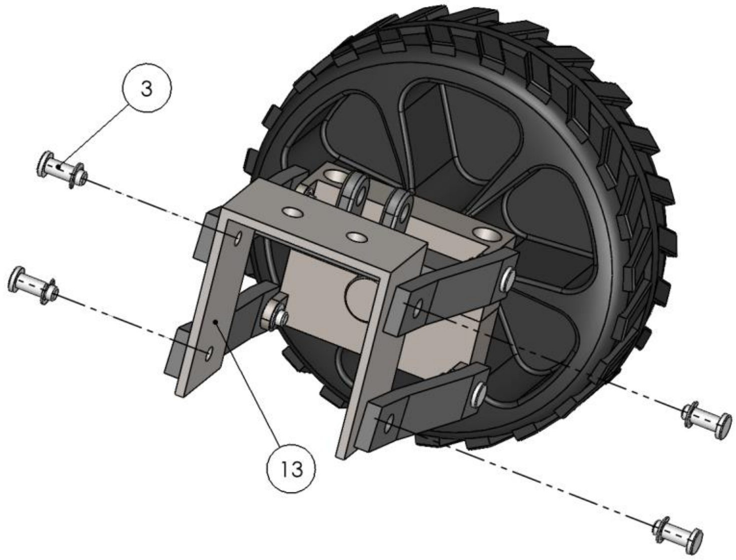




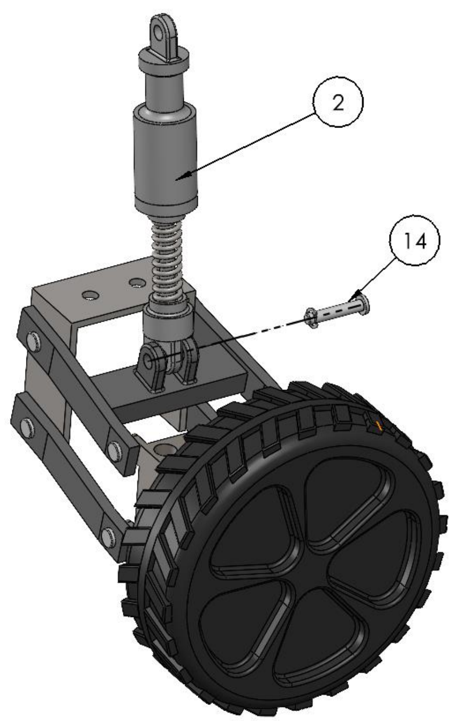
Step 4.) Use 4X [3] to pin 2X [4] and [5] to [8] and [10], respectively. Insert the pins through the corresponding holes, and once completely inserted, slide the retaining ring over the groove to secure the pins in place.



Step 5.) Similar to in Step 4.), use 4X [3] to pin 2x [4] and [5] (previously installed to bearing blocks) to [13].



Step 6.) Similar to Step 4.), use [14] to pin [2] to [5] as shown.

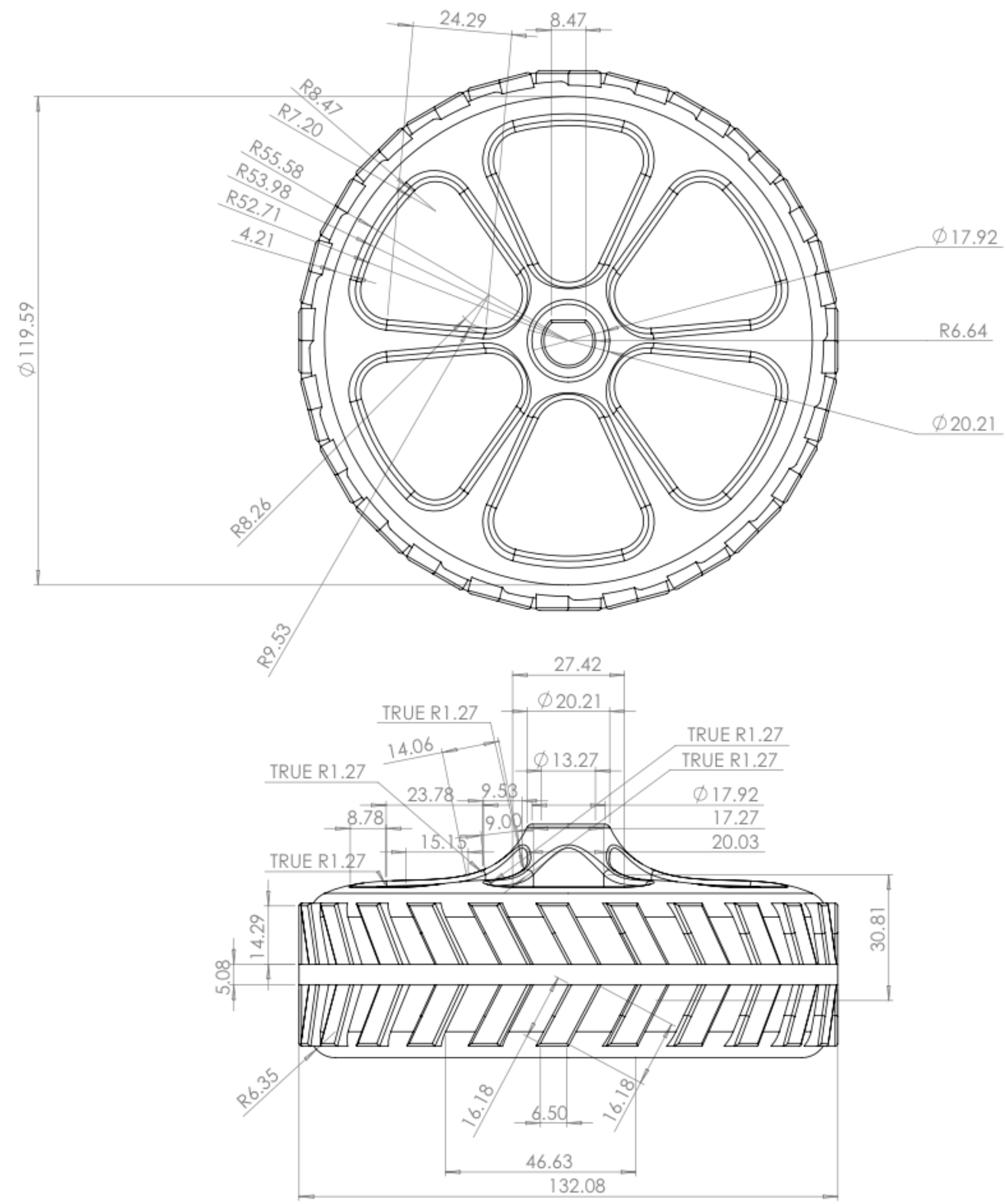


Step 7.) Repeat steps 1-6 for a second rear suspension assembly.

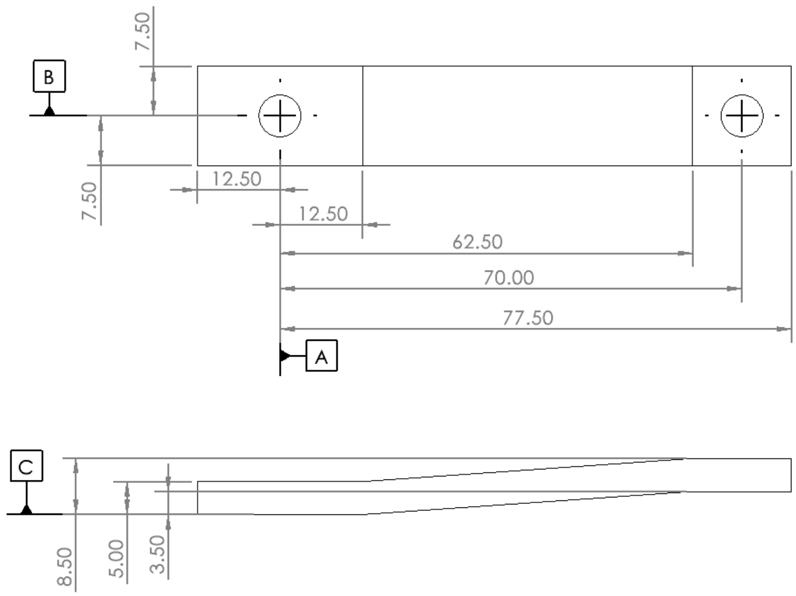
Custom Part Drawings

Dimensions in mm, tolerances ± 0.13 unless otherwise specified

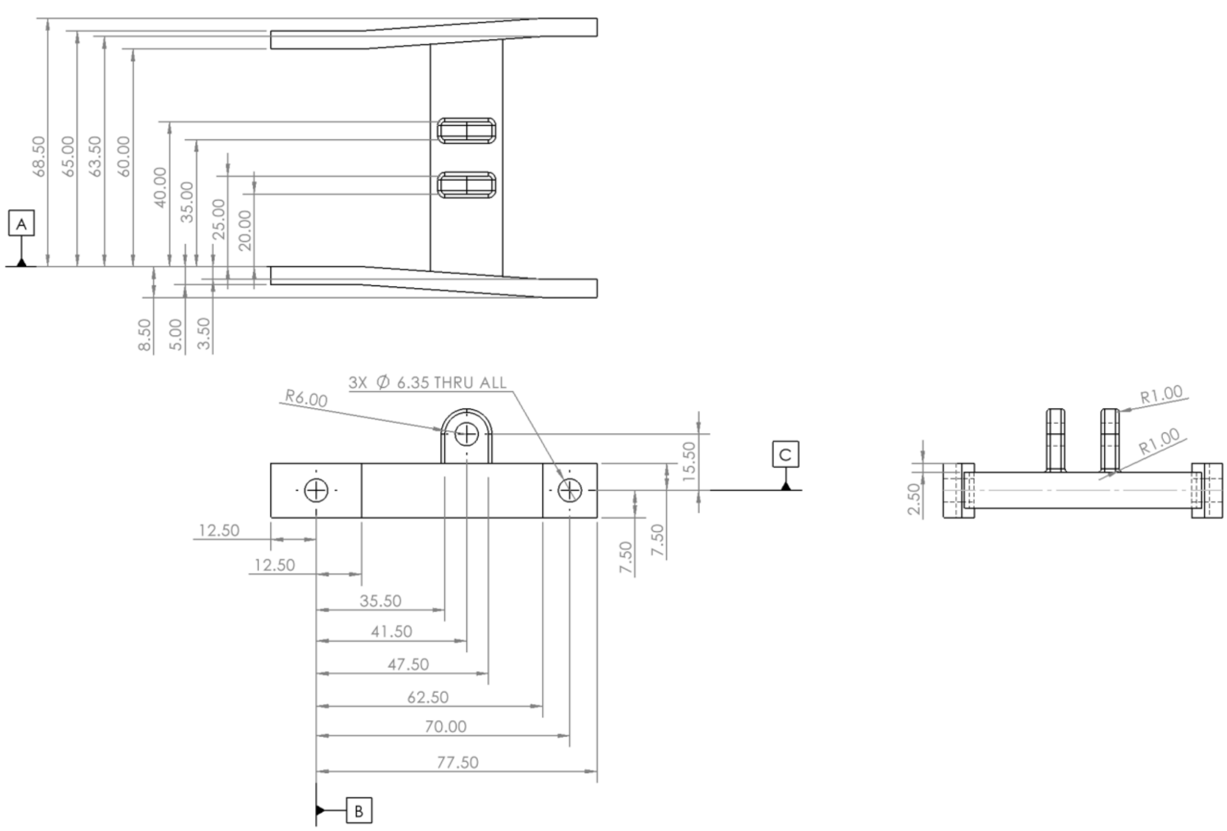
Rear Suspension-1: Wheel



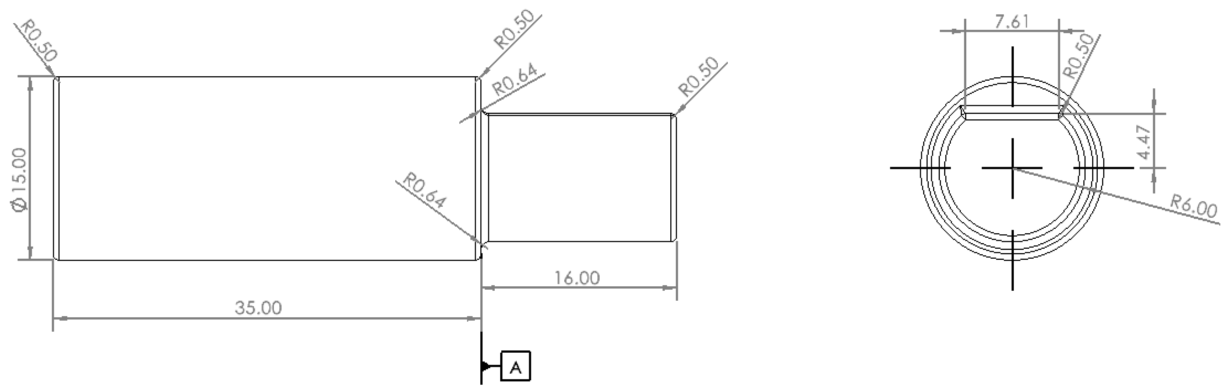
Rear Suspension-2: Lower Linkage



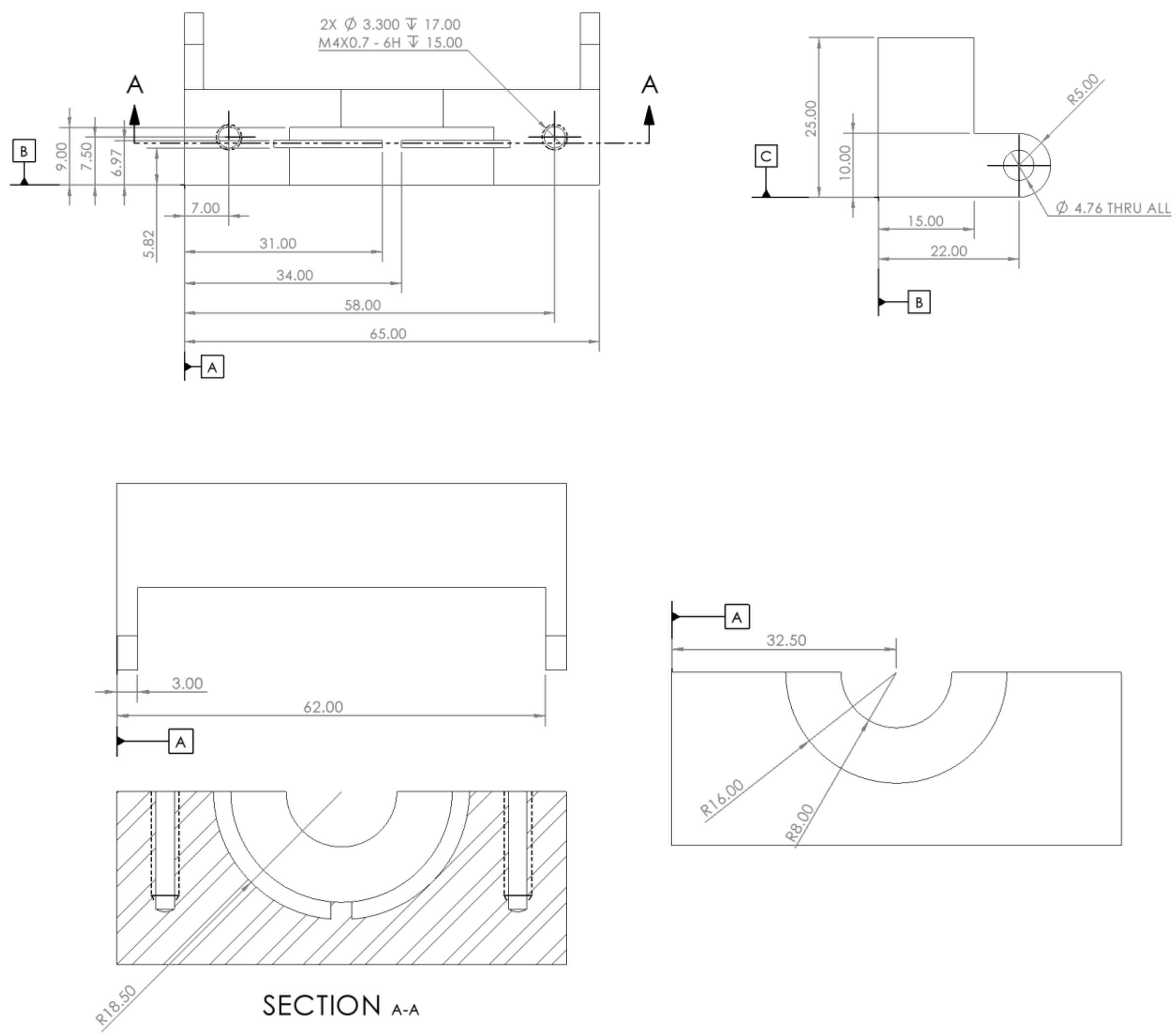
Rear Suspension-3: Upper Linkage



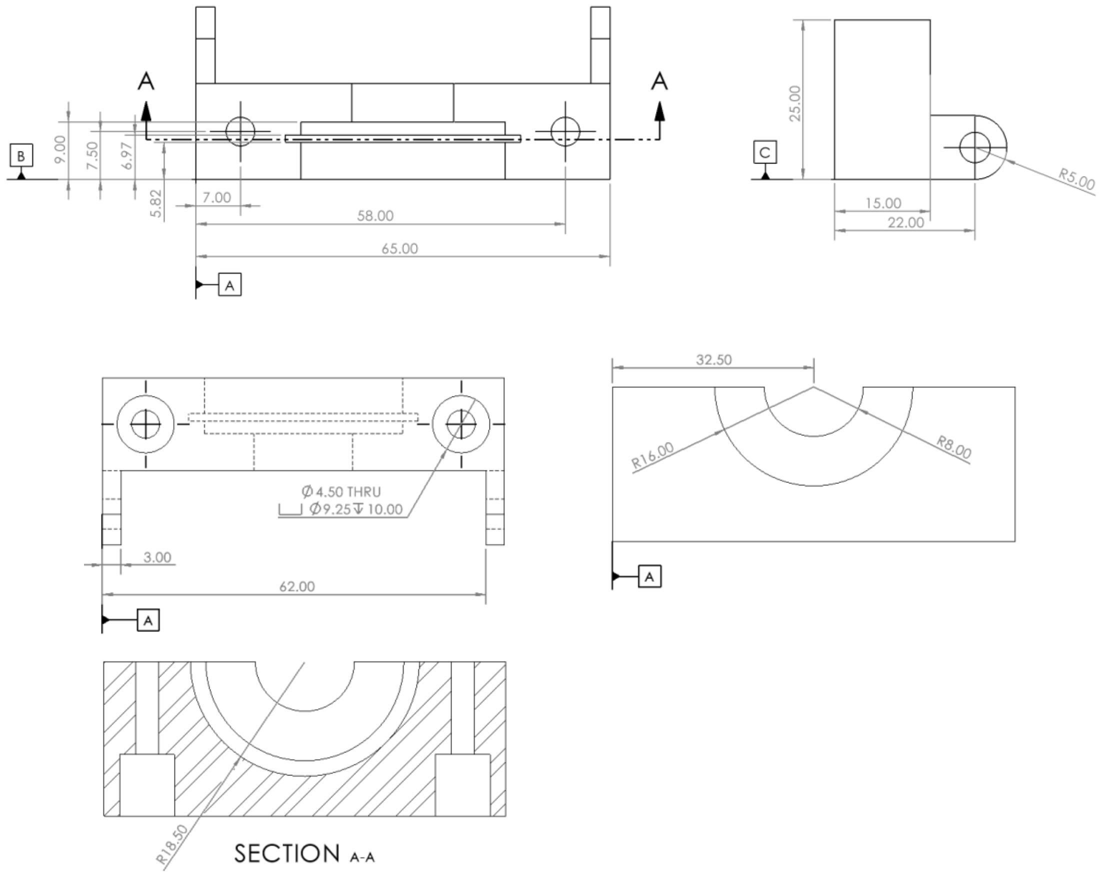
Rear Suspension-4: Wheel Shaft



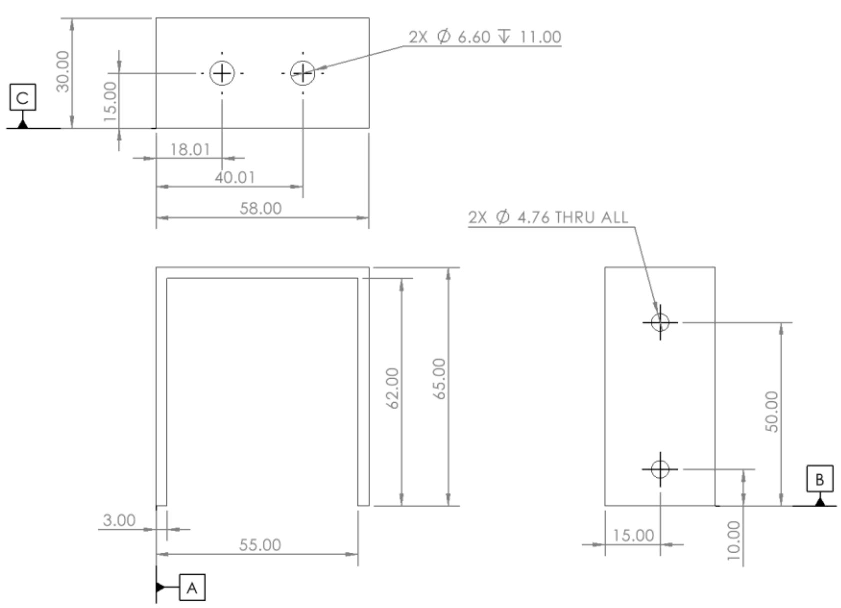
Rear Suspension-5: Bottom Bearing Block



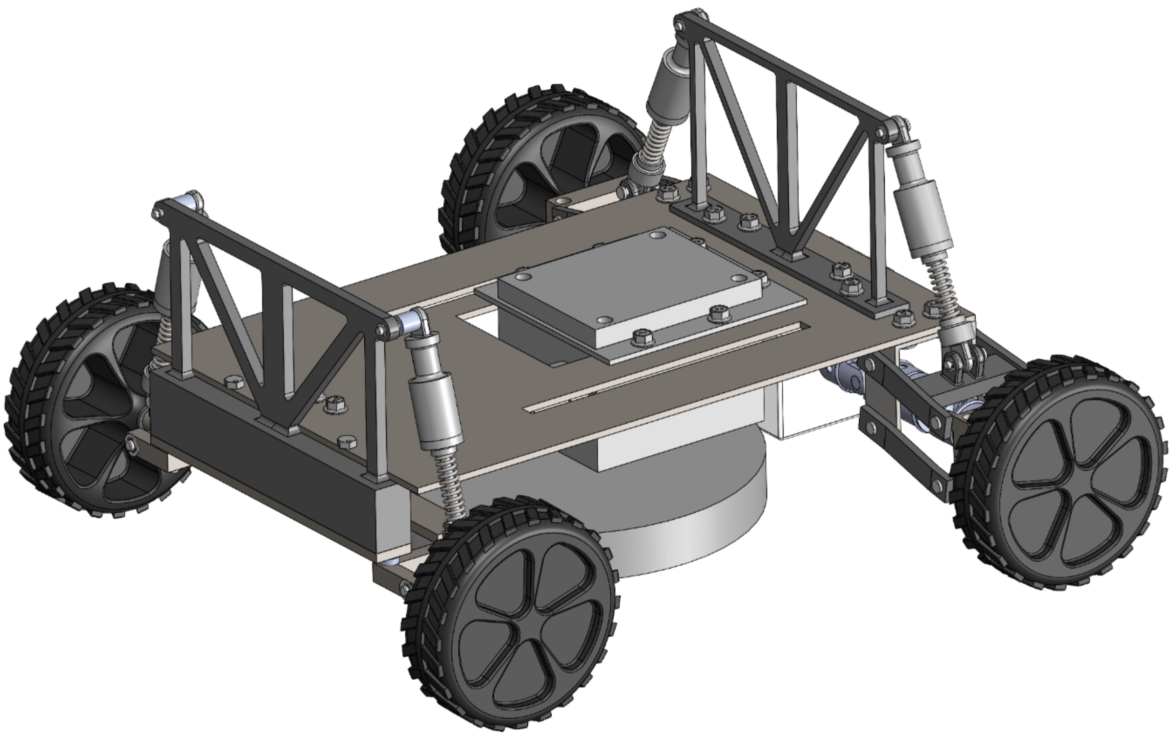
Rear Suspension-6: Top Bearing Block



Rear Suspension-7: Linkage Mounting Bracket



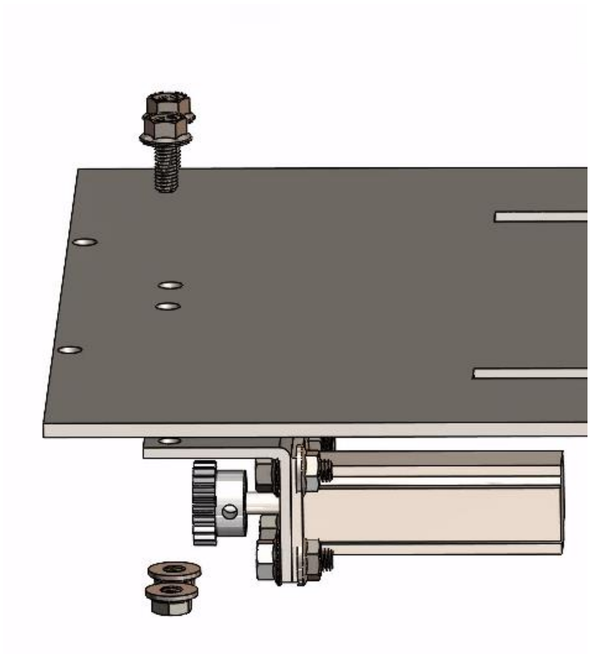
Overall Assembly



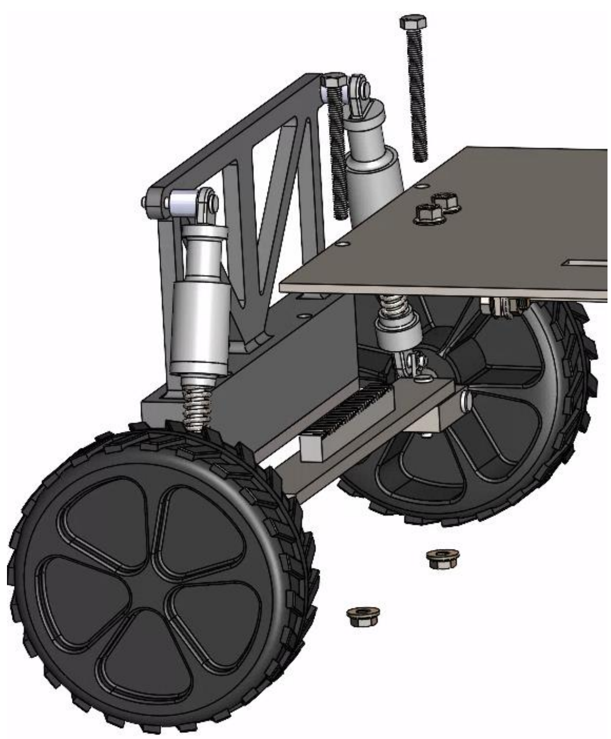
Materials				
[No.] Description	Supplier (Part Number) Or Drawing Number (Mat'l)	Number Required	Price Per Part ($)	Mass Per Part (g)
[1] Chassis	Overall-1 (AISI 1020)	1	-	2679
[2] Front Wheel Assembly	Assembled Component	1 (53)	460	2626
[3] 14mm M6 Bolts	McMaster-Carr (94036A525)	16	0.13	7.97
[4] M6 Flange Nuts	McMaster-Carr (90374A112)	10	0.63	4.20
[5] 60mm M6 Bolts	McMaster-Carr (91280A074)	2	0.19	13.77
[6] Gearbox Assembly	Assembled Component	1 (29)	300.09	1547.4
[7] Self-Tapping Screws for Plastic – No. 8 x 1.25"	McMaster-Carr (92325A319)	4	0.15	3.1
[8] M6 x 1mm Nylon Insert Lock Nuts	McMaster-Carr (90576A115)	8	0.32	2.90
[9] Rear Suspension Frame	Overall-2 (6061-T6 Aluminum)	1	-	147
[10] Differential Assembly	Assembled Component	1 (22)	739.41	2175
[11] U-Joints for 16mm Shaft	PTMotion (UJ-HD32)	4	56.41	227
[12] U-Joint Coupling Shaft	Overall-3 (AISI 1020)	2	-	63.3
[13] Rear Suspension Assembly	Assembled Component	2 (54)	49.89	967
[14] Clevis Pin with Retaining Ring ¼" Dia. x 5/8" Lg.	McMaster-Carr (92735A675)	2	1.81	3.45
Total for Component		55 (208)	1640.46	12409.6

Assembly

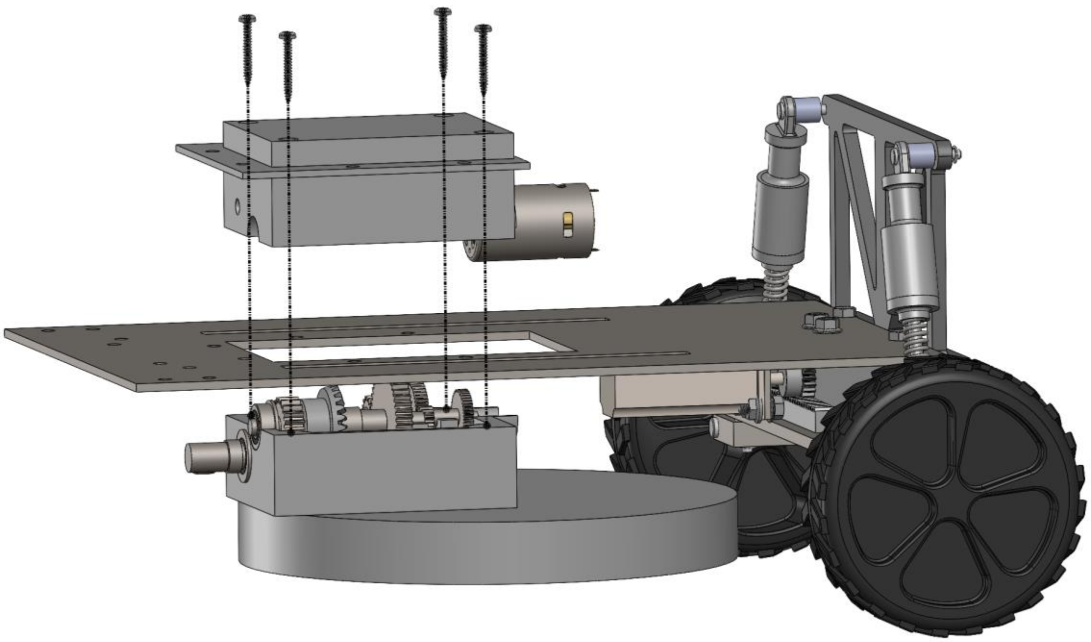
Step 1.) Using two 14mm M6 bolts [3] and nuts [4], attach the assembled stepper motor and gear to the chassis.



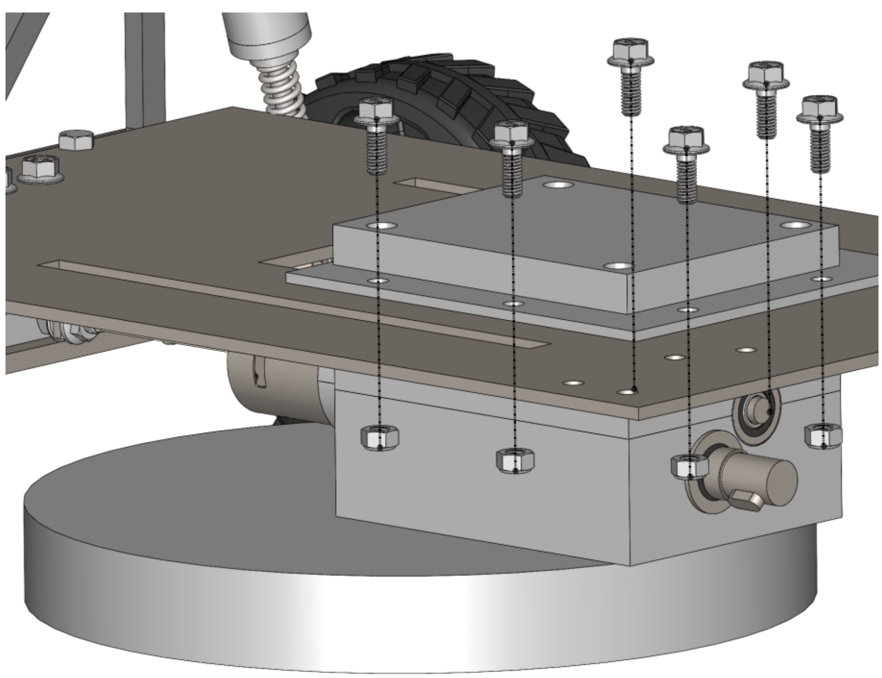
Step 2.) Using two 60mm M6 bolts [3] and flange nuts [4], attach the front wheel assembly to chassis [1] through the holes in the mounting tower. Ensure the gear teeth on the stepper motor gear and the linear gear are meshed.



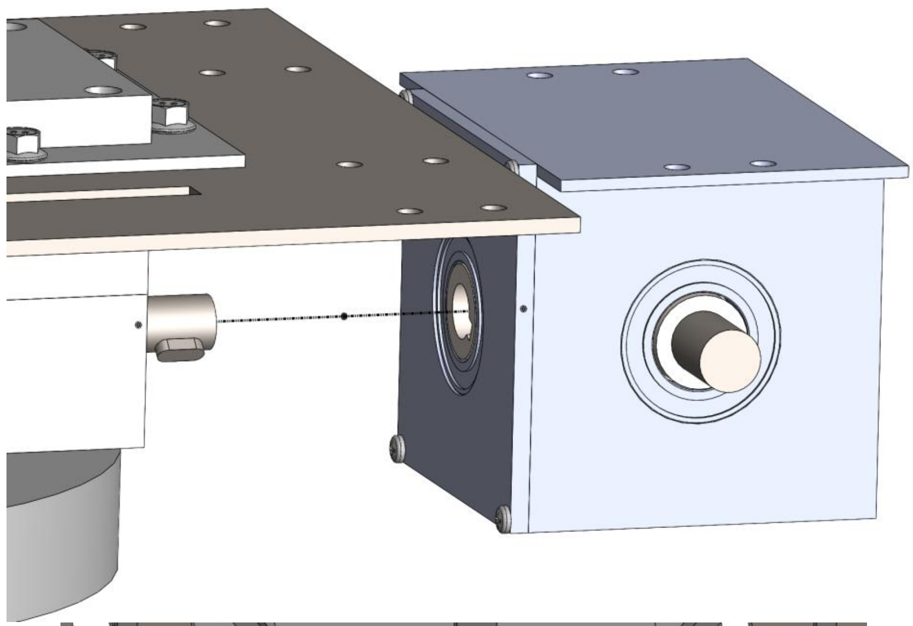
Step 3.) Slide the top portion of the gearbox assembly into the corresponding opening on the chassis. Bring the bottom of the gearbox into contact with the top half so that the four screw holes on the perimeter of the housings line up. Drive 4x plastic screws [7] into the screw holes to assemble the top and bottom components of the gearbox.

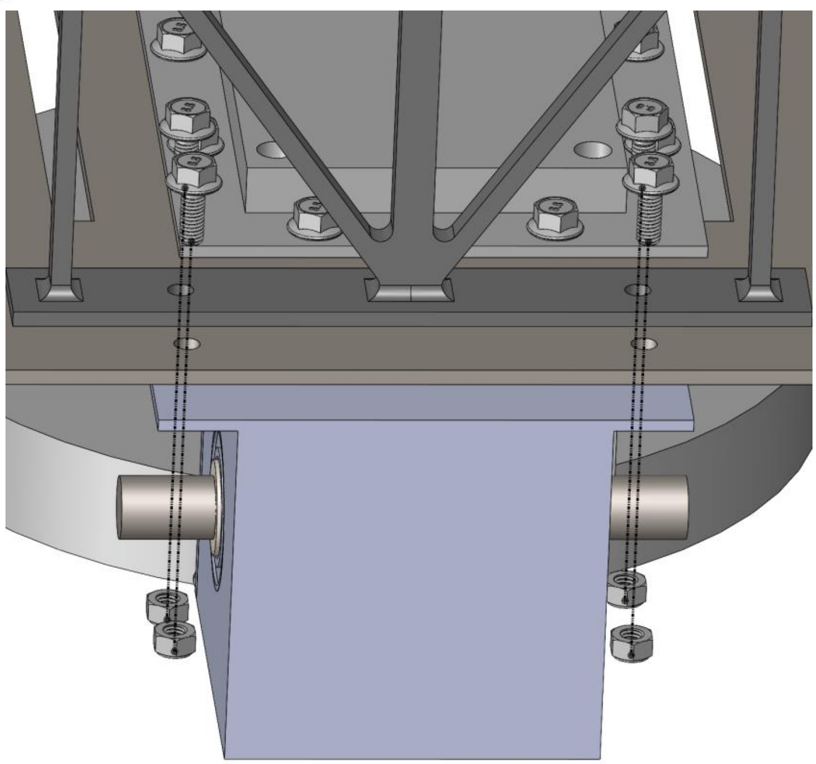


Step 4.) Use 6x M6 bolts [3] and 6x M6 Lock Nuts [8] to fasten gearbox assembly [6] to chassis [1].

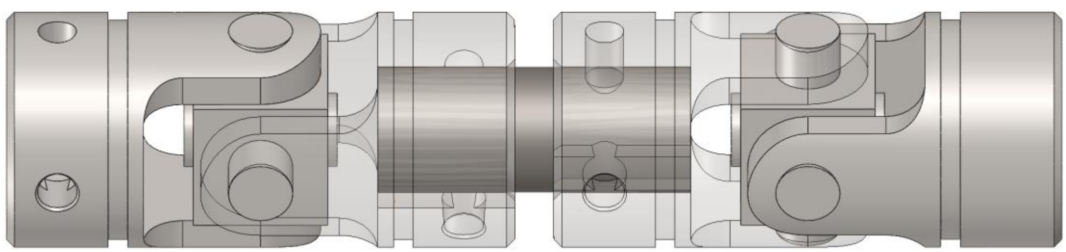


Step 5.) Attach the differential subassembly [10] to the drive shaft protruding from the gearbox [6], aligning the shaft key with the keyway on the gear in the differential. Then, bolt the differential and rear suspension frame [9] [9] to chassis [1] using 4x M6 bolts [3] and 4x M6 Flange Nuts [4].

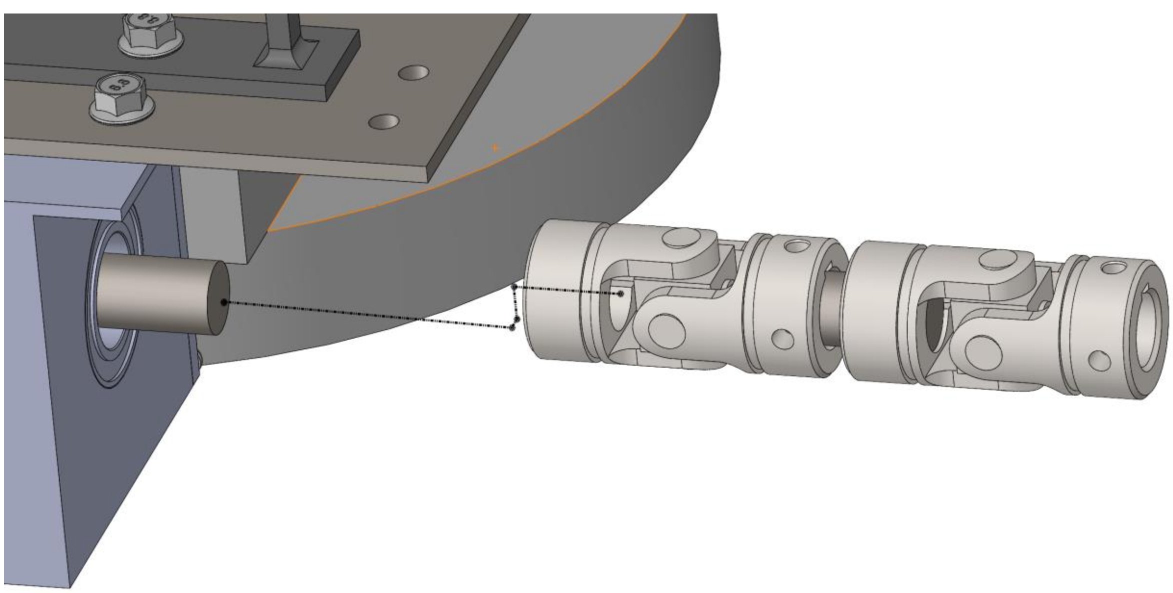




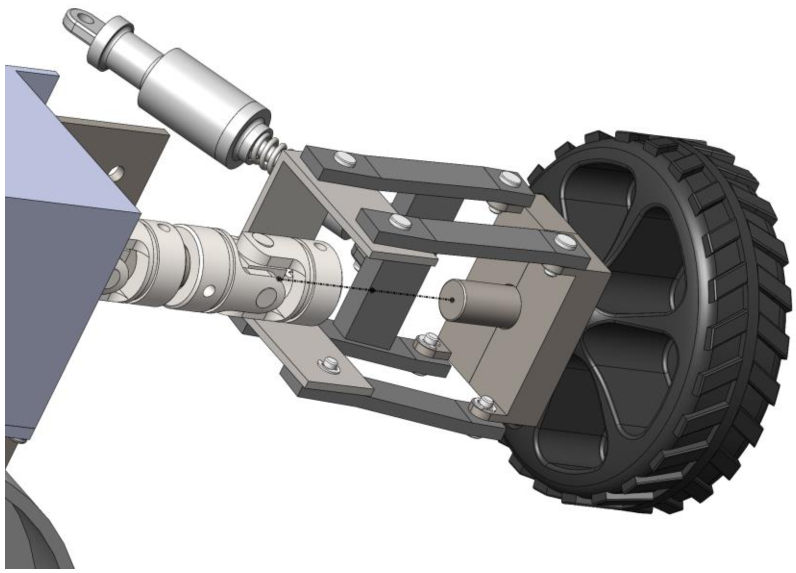
Step 6.) Connect two u-joints [13] together using a differential coupling shaft [14] and Loctite 638, applying pressure to the interface of the u-joints and shafts if possible and following the above instructions. Repeat for a second set of u-joints and coupling shaft.



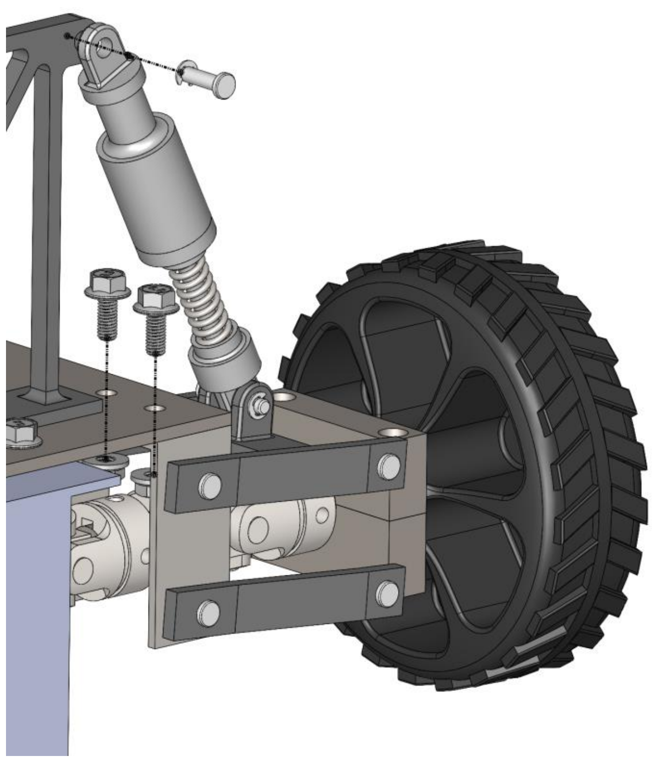
Step 7.) Assemble one u-joint to the output shaft of the gearbox, applying Loctite 638 to the surfaces. Follow previous instructions. Repeat for the other output shaft of the differential.



Step 8.) In a similar fashion, assemble the other end of the u-joints to the wheel shafts of one rear suspension assembly [14]. Again, follow previous instructions for proper setting and curing. Repeat for the other rear suspension assembly.



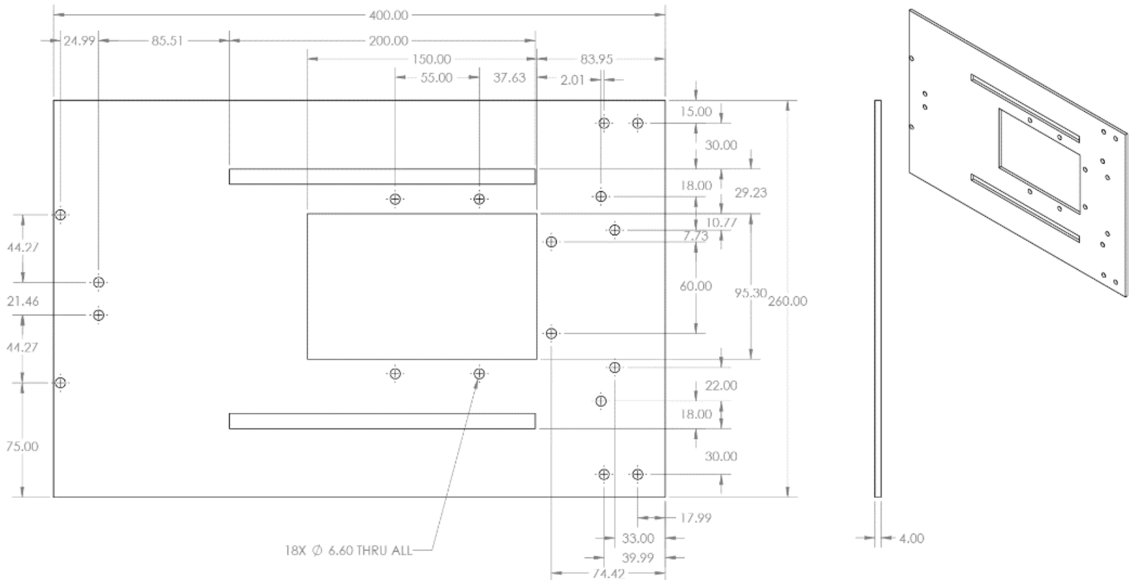
Step 9.) Assemble one rear suspension assembly [13] to chassis [1] using 2x M6 bolts [3] and M6 Flange Nuts [4]. Insert one ¼" Dia. x 5/8" Lg. clevis pin [15] to pin the upper chamber of the shock to the rear suspension frame. Repeat for the opposite side. Use retaining ring pliers to facilitate installation.



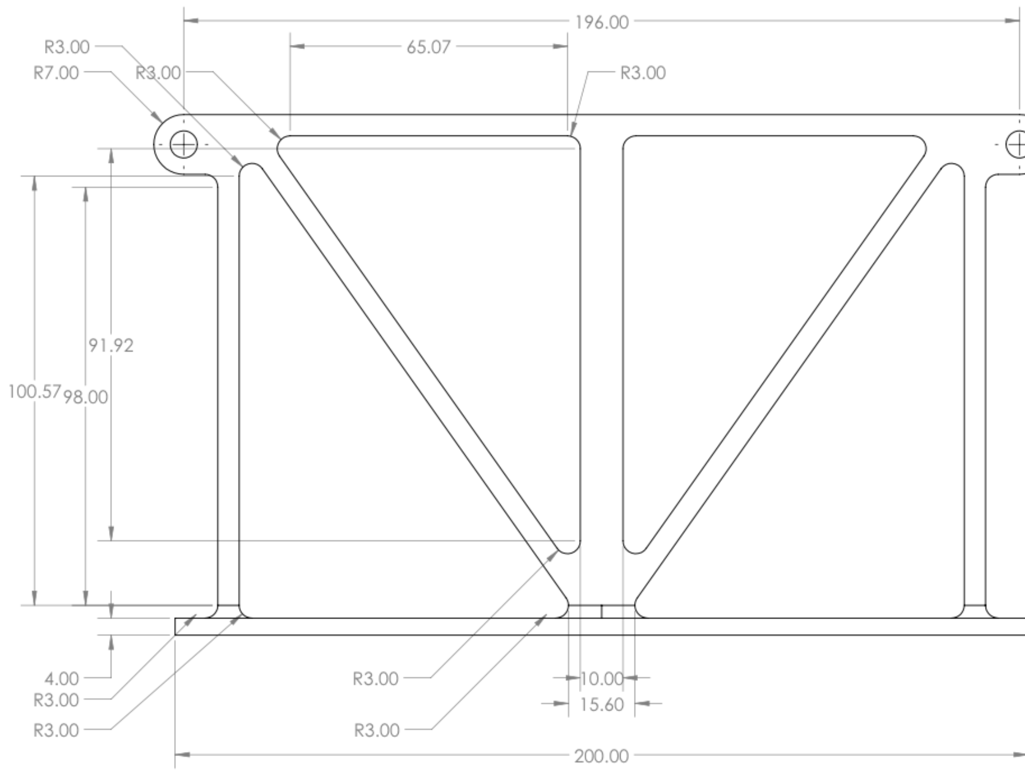
Custom Part Drawings

Dimensions in mm, tolerances $\pm$0.13 unless otherwise specified

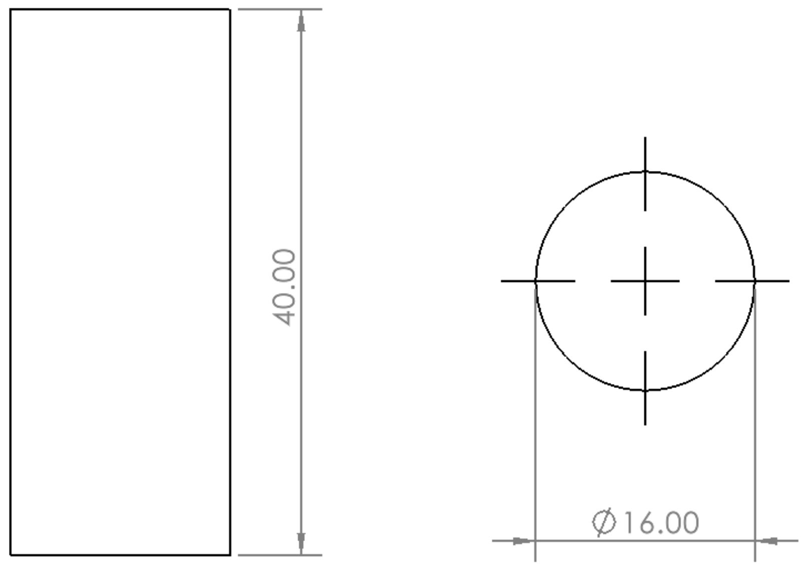
Overall-1: Chassis



Overall-2: Rear Suspension Frame



Overall-3: U-Joint Coupling Shaft



Appendix A – Global FBD & Analysis

To understand how our design would perform at the top level, we conducted a preliminary analysis of loads based on assumed assembly-level characteristics associated with normal operation of the device. Symbolic equations were developed for forces transmitted through the device's power distribution system, including the motor, gearbox, driveshaft, differential, and wheels. The assumptions are as follows:

<u>Routine Operating Conditions</u>:

1. The vehicle will operate on a flat yard with minimal incline (<5˚)
2. Left-to-right symmetrical weight distribution – the load on a wheel on one side of the mower is equal to that on the other side
3. Top speed: 1.5 [m/s] (approx. 3.5 [mph])
4. No wheel slippage
5. μ_s ≈ 0.2 for plastic on grass (0.35 for rubber)
6. Time to reach top speed: 2 [sec]
7. Total weight distributed across mower's length, center of mass located at a distance of 40% of the axle spacing from the rear wheels

With these assumptions established, a global free body diagram (Figure B-1) can be constructed for the mower along its length. Given a known total weight and location of the centroid and the fact that the mower is not rotating in space, the reaction force, R_{Front}, can be found through the summation of moments about the rear wheels from point O. The reaction force at the rear wheels R_{rear} can be found with the summation of forces in the vertical direction (normal to the surface the mower sits on).

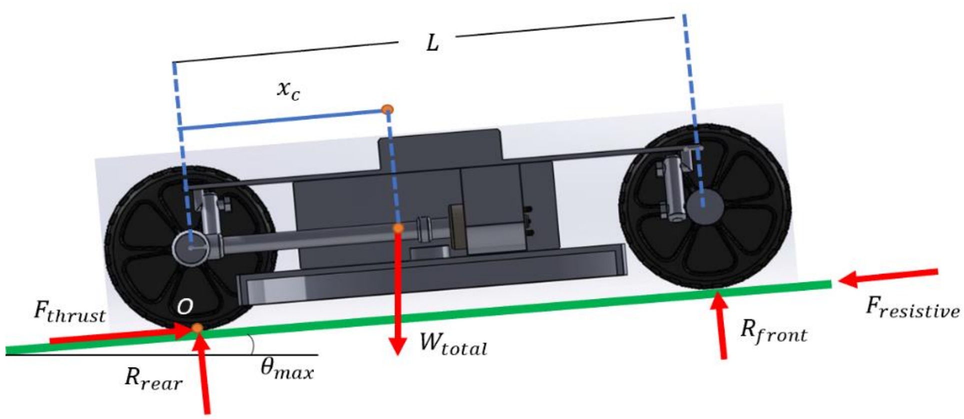


Figure A: Global Free-Body Diagram

To find the forces in the horizontal direction, first the summation of forces will be nonzero. Given a set of input parameters, the output of this analysis yields a force that drives the mower forward that ultimately occurs at the wheels. To verify our assumption that the wheels do not slip, we can check that the thrust force does not exceed the force of static friction before further analysis to determine whether the weight of the device must be reduced.

Based on this thrust force and the geometry of the wheels, we can obtain a torque that must be supplied from the output of the differential. This can be accomplished through a rotational second law analysis of the wheels. Note that each wheel receives a torque of $\frac{T_w}{2}$ but for simplicity the net effect on both wheels is considered. Figure B-2 depicts a free body diagram of the wheels:

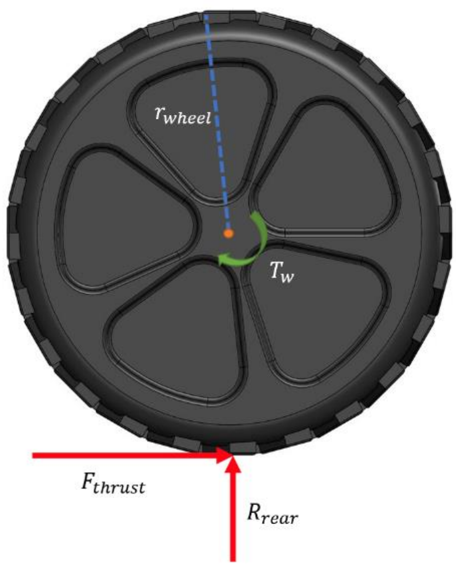


Figure B: Free Body Diagram of Wheels

Through our CAD model, we can obtain a moment of inertia for the wheels and subsequently the required torque output from the differential. Table B-1 contains a summary of the results of this study, and these results are included in the analysis presented in this report.

Appendix B: Rear Suspension – Determination of Forces & Geometry

The suspension components are idealized as a frame that supports a force-couple from the wheels. The following procedure was adopted to obtain a generalized model for the spring force (F_{sp}), angular position of the linkages (θ) and shock (ϕ), and ultimately the vertical height of the wheels below the top of the base (h_{wheel}). Individual steps contain the idealized model & resulting equations.

Construct static equilibrium equations for the shaft supporting the wheel.

Figure A-1 is a free body diagram used in the analysis of the wheel shaft:

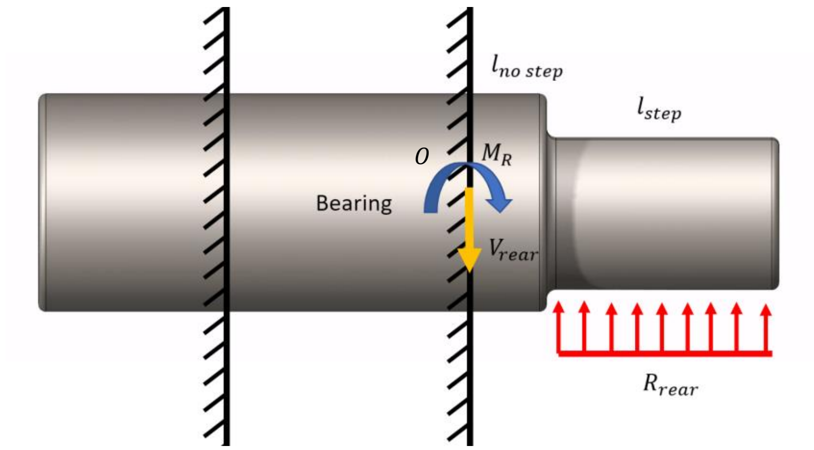


Figure A-1: FBD of Wheel Shaft

The equilibrium of forces in the Y direction and moments about the idealized support yield the following:

$$\Sigma F_y = 0\ N = R_{rear} - V_{rear}$$
$$\Sigma M_o = 0\ N \cdot m = R_{rear}\left(l_{no\ step} + \frac{l_{step}}{2}\right) - M_R$$

Construct static equilibrium equations for the bearing housing that is pinned to the linkages. This housing is idealized as a pin-pin beam with a couple and axial force applied at the midpoint along the beam's length.

Figure A-2 is a free body diagram used in the analysis of the bearing housing:

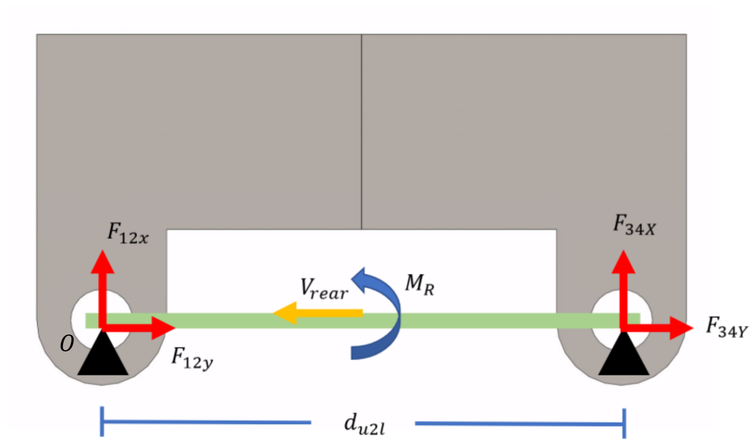


Figure A-2: FBD of Bearing Housing

The following equilibrium equations can be established:

$$\Sigma F_x = 0\ N = F_{12x} + F_{34x}$$
$$\Sigma F_y = 0\ N = F_{12y} + F_{34y} - V_{rear}$$
$$\Sigma M_o = 0\ N \cdot m = M_R + F_{34x} d_{u2l}$$

Construct static equilibrium equations for the lower suspension linkage using the X and Y reaction forces on the bottom pin of the bearing housing.

Figure A-3 represents a free body diagram of the lower linkage:

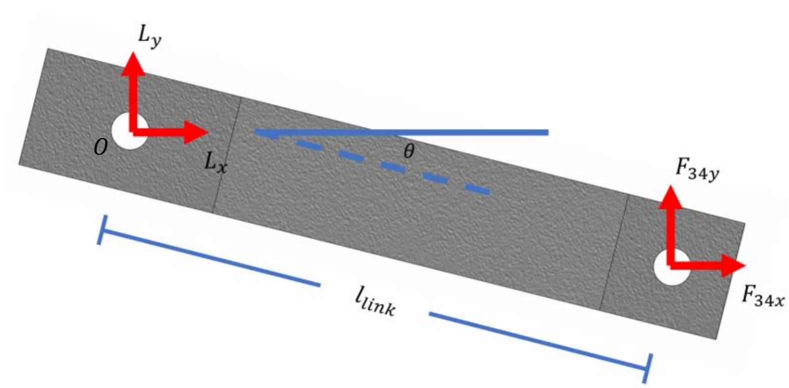


Figure A-3: FBD of Lower Linkage

The following equilibrium equations can be established:

$$\Sigma F_x = 0\ N = L_x + F_{34x}$$
$$\Sigma F_y = 0\ N = L_y + F_{34y}$$
$$\Sigma M_o = 0\ N \cdot m = F_{34x} l_{link} sin\theta + F_{34y} l_{link} cos\theta$$

Construct static equilibrium equations for the overall frame consisting of the upper and lower linkages and bearing housing. The wheels and wheel shaft are replaced by an equivalent force couple, and both the upper and lower linkages are pinned.

Figure A-4 is a global free body diagram for the rear suspension:

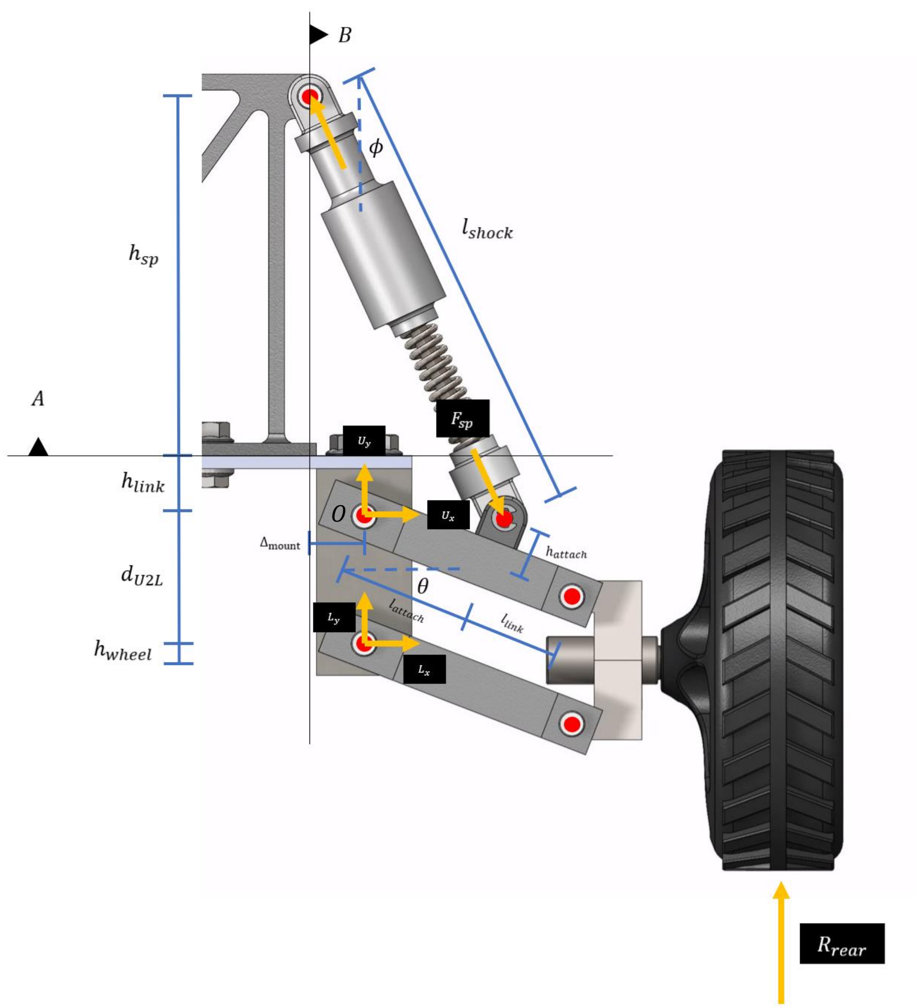


Figure A-4: Global FBD of Rear Suspension

The following equilibrium equations can be established:

$$\Sigma M_o = 0\ N \cdot m = L_x d_{u2l} + M_R + R_{rear} l_{link} cos\theta - F_{sp} sin\phi(-l_{attach} sin\theta + h_{attach} cos\theta) - F_{sp} cos\phi(l_{attach} cos\theta + h_{attach} sin\theta)$$

$$\Sigma F_x = 0\ N = L_x + U_x + F_{sp} sin\phi$$

$$\Sigma F_y = 0\ N = L_y + U_y - F_{sp} cos\phi + R_{rear}$$

Use trigonometric relationships to find a Pythagorean theorem expression for the distance between the two attachment points for the suspension, along with the tangent of ϕ.

The length of the shock can be expressed using the Pythagorean theorem. The uncompressed length of the spring and linkage are known, which will come into play in subsequent calculations. The length of the shock in the rear can be given by:

$$l_{shock} = \sqrt{(h_{sp} + h_{link} + l_{attach} sin\theta - h_{attach} cos\theta)^2 + (\Delta_{attach} + l_{attach} cos\theta + h_{attach} sin\theta)^2}$$

Furthermore, the tangent of ϕ can be found as follows:

$$\phi = \arctan\left(\frac{\Delta_{attach} + l_{attach} cos\theta + h_{attach} sin\theta}{h_{sp} + h_{link} + l_{attach} sin\theta - h_{attach} cos\theta}\right)$$

Using the known length of the suspension with the spring uncompressed, express the force F_{sp} as a function of the free suspension length minus the distance found in the previous step.

The force of the spring is known to be

$$F_{sp} = k_{spring}\left(l_{uncompressed\ shock} - l_{shock}\right)$$

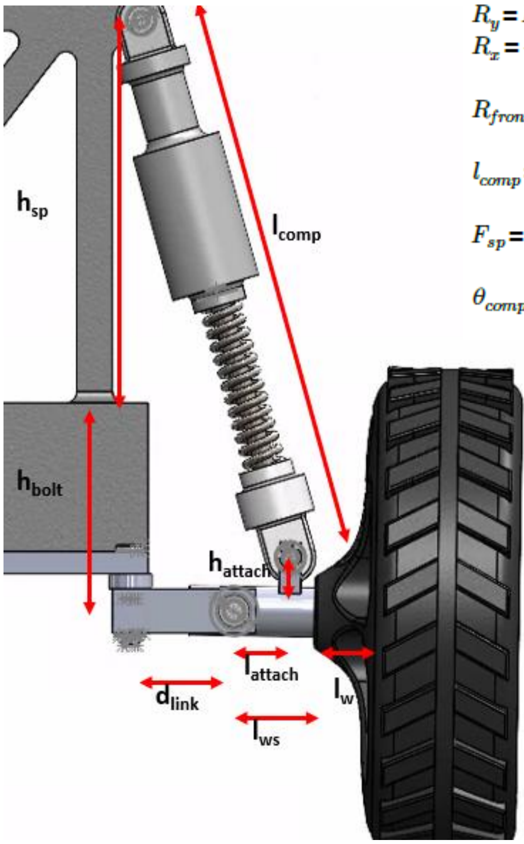
The result is a system of equations that can be solved simultaneously for all unknown variables. This procedure was repeated for the case in which the slider limits the travel of the suspension, where the geometry of the suspension would be fixed regardless of the applied load. This is critical to the calculation of forces, stresses, and deflections under the worst-case drop load.

The ride height can be calculated from these values and is equivalent to

$$Ride\ Height = h_{link} + l_{link} sin\theta + \frac{d_{u2l}}{2}$$

A similar approach was adopted in the front suspension, with differences arising from the fact that the wheels rotate vertically from applied loads rather than translate. The combined analysis of suspension forces in the front and rear was used to determine optimum mounting configurations so that the wheels would be level under normal loading conditions by back-solving the system of equations obtained in the front for h_{sp} under the assumption that the wheels were horizontal under normal conditions.

Figure 4-5 shows the geometry and equations used to analyze the front suspension. Equations come from geometric relations and Newton's second law. The key results of the front suspension analysis are summarized in Table 4-2.



$$R_y = F_{sp} \cdot \cos(\theta_{comp}) - R_{front}$$

$$R_x = -F_{sp} \cdot \sin(\theta_{comp})$$

$$R_{front} \cdot \left(l_{ws} + \frac{l_w}{2}\right) - F_{sp} \cdot \cos(\theta_{comp}) \cdot l_{attach} - F_{sp} \cdot \sin(\theta_{comp}) \cdot h_{attach} = 0$$

$$l_{comp} = \sqrt{(h_{sp} + h_{bolt} - h_{attach})^2 + (l_{attach} + d_{link})^2}$$

$$F_{sp} = k_{sp} \cdot (l_{unc} - l_{comp})$$

$$\theta_{comp} = \operatorname{atan}\left(\frac{d_{link} + l_{attach}}{h_{sp} + h_{bolt} - h_{attach}}\right)$$

Figure 1: Geometry and Equations Related to Front Suspension Study

Spring Stress Calculation

The spring used in the shock must be checked for yielding and buckling under load. Using the characteristics of the spring and music wire steel, the ultimate tensile strength was calculated by:

$$S_{ut} = \frac{2211}{d_{wire}^{1.45}} \; MPa$$

Equating to 2 GPa, with the yield stress being approximately 50% of this amount. Note that the deflection of the spring is 9 mm under normal loads and is limited to 25 mm by the upper housing. Under these conditions, the stress in the spring can be calculated:

$$\tau = \frac{8 F_{sp} \overline{D_{coil}}}{\pi d_{wire}^3}$$

F_{sp} was taken to be the 113 N and 328 N under normal and worst-case scenarios, respectively. Maximum stress would be 486 MPa under normal conditions and 1.3 GPa when fully compressed. This indicates that the spring will survive normal loading conditions but may yield if the device is dropped.