Laurentian University

Capstone

ENGR-4595

Final Report: Robot Drive System Redesign

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1 Introduction

Penguin ASI is a robotics firm engaged in the development of automation strategies for the mining industry and the development of telerobotic systems to work in extreme and hazardous environments. As the use of automated technology becomes more prevalent in the mining industry there comes a need to develop a telecommunications network. In order to prevent the need to retrofit an existing mine with a communications network, Penguin had developed an optical communications range extender and mounted it on a teleoperated, mobile platform to be able to relay the signals. The first iteration of this platform had some issues with its design that Penguin had wished to resolve in a second iteration prototype. In order to produce a functional prototype all issues with the previous version must have been addressed, and the robot must have been able to achieve certain functional requirements laid out by the client, Penguin ASI.

1.1 Problem Statement

The initial communications robot produced by Penguin ASI had displayed many issues affecting its performance that needed to be addressed. Its operating environment was intended to include traversal through wet and rough terrain, which required all drive components to be sealed against water and dirt. To seal the original drive boxes gasket maker was used, but proved to be inadequate and allowed water to enter the drive box as seen in Figure 1. Secondly, the drive box travel was not limited to ±30°rotation initially, and a spring system was implemented as a temporary solution. Only two, 746 W motors were used, and after testing were deemed insufficient to drive the vehicle and payload up hills of a 20% grade. Furthermore, each motor drove four wheels and transmitted power through a long chain extending the length of the vehicle as seen in Figure 2. The length and complexity of the chain driven system introduced many modes of failure, slapped the bottom of the vehicle during skid steer operation and change of direction, and did not have an adequate tensioning device.

Figure 1: Original Drive Box Interior Demonstrating Improper Sealing

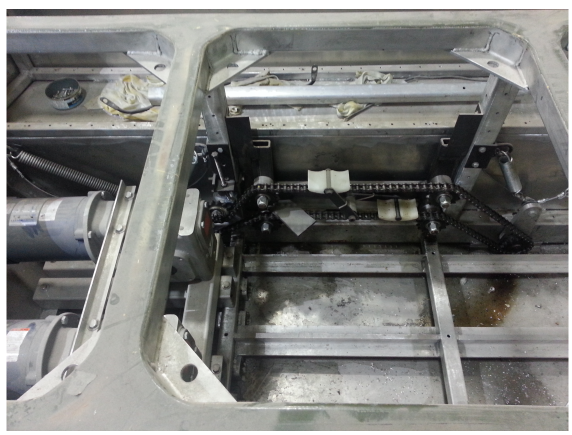

Figure 2: Chain Driven System Inside Vehicle Body

The disassembly of the original driveboxes was difficult and it was observed that there was no way to determine oil levels without opening them up. Also, under skid steer operation it was reported that the drive boxes underwent significant deflection which was not desireable.

Each drive box was chain driven, however there was no method to determine the chain tension, which was problematic and was suspected to be the cause of premature failure of chains. Other components that were failing included radial bearings used on the drive shafts and wheel shafts. After opening the drive boxes it was observed that these radial bearings were paired with a single taper roller bearing and it was suspected that the cause of failure was the axial loading on the radial bearing.

1.2 Functional Requirements

Overall the vehicle was able to drive and maneuvre with limited capabilities, however it was in the interest of the client to address these issues for a redesign of the product. In order to meet the needs of the client a list of requirements for the final design were agreed upon. The requirements were broken down into six main categories, with each highlighting the necessary functionality for the redesign of the communications robot.

1.2.1 Power

The vehicle was to be fully battery powered using six EV Traction Dry Cell Industrial Battery Blocks. To drive the vehicle, four 746 W DC motors were provided by Penguin ASI. The drive time of the vehicle was to exceed one hour at peak operating conditions, and the batteries were to be seated in the vehicle to provide clearance between battery terminals and frame components.

1.2.2 Operating Conditions

The vehicle was to be used in aboveground and underground mining applications, and as such would be subject to varying temperatures, however the client had specified the need to operate primarily in 2 ℃. The vehicle also needed to be able to climb and descend a maximum grade of 20% and have every component sealed from external water.

1.2.3 Size and Weight

All components of the vehicle were to remain within the dimensions of the frame with the exception of the wheels. The robot needed to be able to carry a payload of 230 kg in addition to its own weight, and be able to reach a top speed of 3 km/h under these conditions.

1.2.4 Interfacing

Penguin ASI had specified the need to reuse the frame from the existing robot, however minor frame modification were permitted. Motor interfacing needed to be done using a Roboteq controller, and battery charging was to be carried out by employees at Penguin. The redesign of the vehicle needed to ensure that that existing communications devices and telescoping arms could still be mounted on the upper platform of the frame, and that space be left in the wings of the vehicle to accomodate electrical components.

1.2.5 Robot Control

The motors on each side of the vehicle were to be controlled independently. A Roboteq controller was to be used, and appropriate voltage limits were to be programmed into the controller to prevent damaging the motors. For testing purposes, the use of a laptop to and joystick to control the motors was permitted. The implementation of wireless control was to be carried out by Penguin employees upon the successful demonstration of an operable vehicle.

1.2.6 Care and Maintenance

All new components were to be designed with the intent of improving functionality and maintainability. It was desired that all components be easy to assemble/disassemble, internal components be easily accessible, and grease nipples be incorporated to grease bearings. Furthermore, a means to check belt tension was to be incorporated in the final design.

2 Design Alternatives

The main feature to the project was based off of power transmission from the motors to the wheels. For this, three different methods were explored.

2.1 Chains

The first consideration was a chain drive which was also found on the previous iteration of the robot. However, chains proved to require quite a bit of maintenance and must operate in a sealed and lubricated gearbox. Aside from sealing concerns, corrosion and stretching from use were other issues that posed problems and increased maintenance time. Many of these robots will be on standby and must be ready to use whenever needed, therefore any maintenance or checks require before every use are unfavorable.

Chains did prove to have some advantages such as great operating efficiencies, being a cost efficient option and consisting of replacement parts that are readily available in most industrial settings.

2.2 Shafts

The second was a serial shaft configuration that would require many 90°joints which are expensive, bulky and are high maintenance as well. This option was nearly eliminated right off the hop but was kept for comparison and analysis in the decision making process.

2.3 Belts

The third and final option was a synchronous belt drive system. After some research and discussions with the engineers at Gates, one of the world's leading manufacturers in belt systems, it was concluded that a belt drive would be very suitable for the application at hand. Operating in a dry gearbox, virtually no stretch over it's lifetime and a significant increase in longevity over a chain drive are all features that made belts much more attractive. Synchronous belts also have operating efficiencies similar to chains, thus making them just as viable. As claimed by Gates, belts are to last 3 times longer than chains and sprockets for belts are to last 10 times longer than ones for chains. It is to note that belt don't take side loading or twisting very well, therefore much emphasis on reducing these affects were a main focus in the design of the drivebox structure. Corrosion was also an important consideration for every option, and even though belts won't rust, other components such as the sprockets and shafts very well could. Some part sourcing revealed that aluminum sprockets could be purchased and other steel components could be sprayed with a durable, anti-rust coating that wouldn't contaminate the belt and bearings.

Belts were chosen after careful evaluation against the other alternatives as seen in the Pugh matrix in Appendix **??**

3 Project Management

From the beginning, project management was an important tool used to keep our team working efficiently and on time to be able too build and finish our proposed final design. Do to the inherent structure of the course, we added two main milestones, the design and build phase.The first haft of our semester was dedicated to designing our solution to the problem. During this time, we created a work schedule using WBS (Work Breakdown Structure) to get a better visual understanding of the scope and after created our initial Gantt chart. Since the first scope breakdown, the WBS and Gantt chart underwent many revision because of the fluctuating scope of work of our project kept adjusting to what would be reasonably possible to complete in the allocated amount of time. The final WBS can be found 4 in Appendix **??**.

During the building phase, it became evident of the amount of work needed to finish the project. Milestones were set at many point to ensure that we kept on schedule. Our first major milestone was to get the first outer drive box completed to ensure that all designed components would fit and interact properly before creating the other drive boxes. After completion of the first drive box and implement minor changes for manufacturing ease, we then started our stretched goals which was completing all three other drive boxes. During both manufacturing phases of the drive boxes, one or two of our group members worked on the structural frame modification which ended up being one of the most times consuming area of the building phase.

Critical documentation deadlines were also set as milestones. These reports and presentations were typically done nearing the end of the every phase. This had as advantage to include all current changes before submission of the documents and to have all necessary information to complete the report at once, instead of someone waiting on the information.

Finally, our team spent hours on building and manufacturing. Our initial estimate of the time needed to complet the project was 182 hours on the CNC Lathe, 146 on the CNC mill and 61 hours on frame accommodation. This thus needed us to spend at a minimum 30 hours a week on manufacturing alone. In total, all member of the team gave 270 hours in manufacturing which is reflected in the Gantt chart. The final Gantt chart can be found **??** in Appendix **??**.

4 Final Design

The final design of the robot's drive system is very similar to the proposed design provided to Penguin ASI and Laurentian University in December. Using a belt drive over a chain drive was accepted through our proposal along with keeping it battery powered. In the final design the batteries used were ones that were provided by Penguin ASI. Four batteries were still required to power all four brushless DC motors and two other batteries required to supply power to the other electronic components on board the robot. The final design also had features that were in the proposed design, such as removable interior components, easy serviceability and keeping it as a modular design. Having the components easily removable will allow anyone who is maintaining the drive system have access to all the bearings for re-greasing and easy vision for inspection of belts condition. After assembling one exterior drive box, some small design changes were made that were not noticed in the CAD model assemblies or were notified to us from Penguin Employees after the proposal report had been submitted. None of these changes required the proposed design to drastically change but actually improved the overall design and reduced the amount of machining time required for some components. An example of reducing machining time would be the new hubs located at the back side do the drive boxes. In the proposed design the rear hubs required machining on both the exterior and interior, but with the new design all exterior machining was not required. Table 1 gives general robots specifications.

Table 1: Robot Specifications

Component	Value	Unit
Total Mass	1385.99	kg
Top Speed	3	km/h
Total power	2,982.8	W
Location of centre of mass (height off ground)	0.477	m

The exploded view of assembly that can be seen in Figure 3 shows how each individual drive box goes together along with its connection to the robots frame. All four motors sit inside the robot frame and are each coupled with a flexible Lovejoy coupling to the output shaft that rotates within the pivot. The torque from the motor is then transferred through the output shaft and is then transmitted through the belt to two wheel shafts. Those wheel shafts each have a foam filled tire attached to the end with a tapered fit mount and a castle nut ensuring the mount doesn't come off the tapered shaft mount.

What makes this design a more acceptable design over the previous design that Penguin ASI originally had is the simplicity of it. In their previous design their was only two motors used to power the four ex trier drive boxes, which required that two output shafts on one side had to share the output from one motor. In the new design each drive box will be getting its own motor to provide power and this reduces the amount of moving parts needed. Such as, a chain to allow each output shaft to be sharing one motor and tensions along that chain. Each component added arises a new point of possible failure during operation, so reducing the amount of moving parts also reduces this possibility. Another feature that the new design has over the old is the accessibility of the components inside the drive box for maintenance and repair if required. The new design gives you full access to all the interior components once the front case plate is removed. From this you can easily remove the wheel shafts and to remove the output shaft, only a set screw at the coupling is needed to be removed. All moving components can now be accessed easily

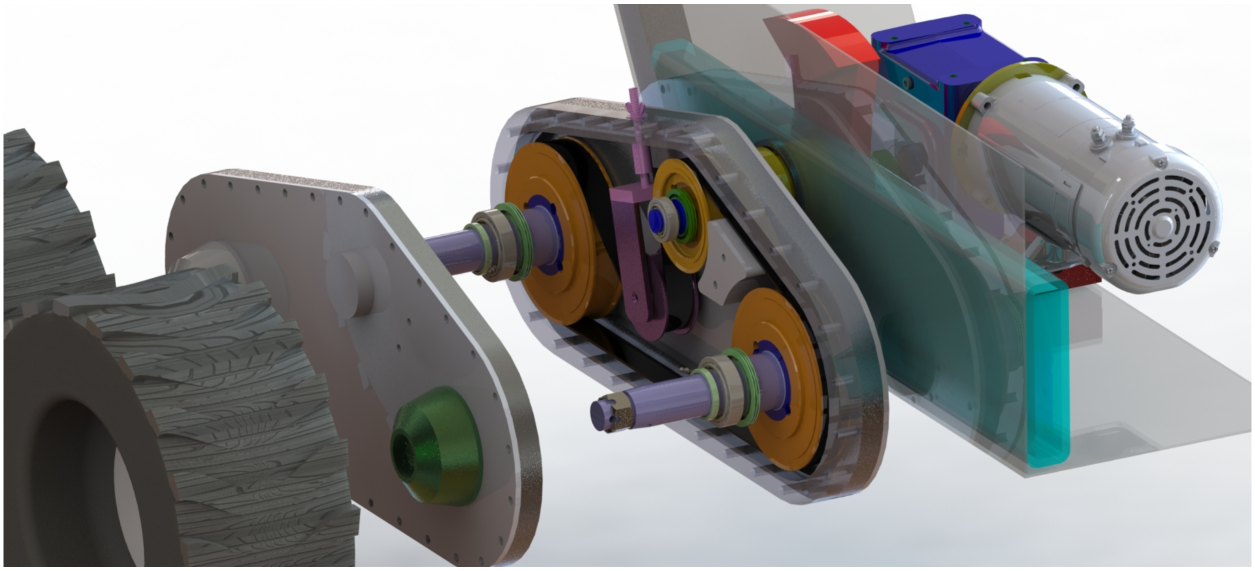

Figure 3: Rendering showing one quarter of robot exterior drive assembly with front case frame and wheels off.

and reduces the time required for an individual to work on. Using belts over chains reduces the maintenance cost, since belts do not require any lubrication and run in a dry casing.

5 Loading Conditions

As with any off road vehicle, it is always difficult to predict loading conditions as there is an infinite amount of scenarios due to the varying environment and terrain, however it can usually be generalized to a few simple, yet appropriate cases. Also, it is important for one to remind themselves what the vehicle is being designed for. Although it is an off-road vehicle, it is not designed for extreme conditions or dangerous scenarios. It's the same logic for someone who owns an economical car; they wouldn't be taking this vehicle into the bush through deep mud or rough terrain as it will most likely end up with broken parts. In this case, the robot is to be operated in a normal mining environment where the environment conditions are assumed to be a regular mining road built from crushed, roughly fist sized rock, and a max ramp grade of 20% or incline of 11.3 degrees. Driving forward up a ramp and a skid steer turn on a ramp were then evaluated. As one could imagine, the skid steer motion when the robot is balancing on two, opposite diagonal wheels resulted in the highest forces, therefore these were used for analysis. With the weight distribution of the coupled wheels being 40/60, the 60% wheel is used for analysis and its design is to be duplicated to the other wheel. The resulting forces are summarized in
INSERT TABLE
It should be noted that only a static analysis was conducted for this project due to slow operating speeds. With a top speed of 3 km/h, the forces due to dynamic loading would only differentiate slightly. To compensate for this, a larger factor of safety was desired for each component. Given an adequate time line, one could conduct a full dynamic simulation to obtain more accurate results and confirm that the design to follow is indeed adequate for the imposed loading conditions.

6 Belt Drive

6.1 Description

Synchronous belt drive systems are said to be efficient, reliable, virtually maintenance free and are supposed to outlast any comparable chain drive system. The system used on this vehicle will consists of a Gates PowerGrip GT3 belt which is rated for high torque transmission at variable speeds while the sprockets and accompanying bushings will be supplied by Martin Sprocket for cost saving reasons.

6.2 Design Constraints

The overall width of belts and sprockets proved to be a considerable constraint in itself. While there was a specific width required to ensure power transmission without failure, this same width also hindered the design of the drive box as it would result in a thicker and bulkier drive box. The engineers at Gates were consulted regarding optimization of belt width and sprocket diameters. After a couple weeks of back and forth by email, it was decided that a 30mm wide belt would be best suited.

Next constraint proved to be the diameters of the sprockets as there was an overall size constraint of the drive box. It should also be noted that larger diameters lead to a substantial increase in weight and cost. Therefore finding the happy-medium between required diameter for belt life, overall size, weight and cost was a challenge. There was also the ratio between diameters of the driving sprocket and idlers that needed to remain constant. This ratio, determined by required output speeds and torque transmission, was found to be 1.6.

The position of the idler was also a challenge due to dimensional constraints imposed by the location of the small and large sprockets and ensuring sufficient wrap angle on the driving sprocket. A constraint that wasn't discovered until part sourcing began was the availability of the sprocket diameters and material selection for these. This proved to be the biggest constraint to overcome since all of those mentioned above also came into play with this constraint.

6.3 Functional Requirements

The goal of the belt drive is to have an efficient and reliable power transmission method that requires minimal maintenance and is easy to assemble and disassemble. Lower operating costs, a dry running drive box and reducing the need for a well sealed drive box are criteria that benefited the design.

6.4 Analysis and Design

For the design of the belt system, calculations were done following the design procedure in the Gates PowerGrip GT3 Design Manual and results were verified using the Gates Design IQ software. Using a max torque output from the motors of 156 N-m (at 1.2 HP) with an output speed of 60 rpm, a required belt width of 30mm was calculated both by hand and using the software with sprockets having an acceptable size of 72 teeth for the large sprocket and 44 for the small sprocket. A triple check was conducted by the engineers at Gates. They were provided all the details mentioned above and conducted their separate analysis using different software to confirm the results.

It is important to mention that the belt system will be alternating from clockwise rotation to counterclockwise rotation. This was discussed with the engineers at Gates and they confirmed that since a robust slotted idler is being used, the change between slack and tight side shouldn't be an issue for this system.

7 Wheel Shaft Assembly

7.1 Description

7.2 Design Constraints

7.3 Functional Requirements

7.4 Analysis and Design

7.4.1 Wheel Shaft

7.4.2 Wheel Bearings

7.4.3 Shaft Seals

7.4.4 Front Bearing Housings

7.4.5 Rear Bearing Housing

7.4.6 Rim Mount

7.5 Pivot and Travel Limiter

7.5.1 Description

The minimum required shaft diameter was calculated using two iterations of DE Goodman shaft design theory. The second iteration took into account more realistic stress concentrations allowing for the reduction in required shaft diameter. The shaft layout and loading assumptions are illustrated in Figure 24 forces at the ends representing the radial forces applied from the taper roller bearings and the force at the middle being the resultant force of the sprocket determined from the Gates Design IQ software. Bearing calculations were performed according to the procedure outlined in the SKF bearing design manual for taper roller bearings. It is important to note that the free body diagram in Figure 24 only represents the radial component of the force from the taper roller bearing, and axial forces not shown were also taken into consideration. Design constraints and requirements are outlined in Table 18.

7.5.2 Design Constraints

7.5.3 Functional Requirements

7.5.4 Alternate Solution

7.5.5 Analysis and Design

The finite element analysis report for all three revisions of the output shaft can be found in Appendix A. The revisions 0 and 2 can be seen in the Figure 25 and Figure 26 below. In revision 0 the stresses experienced at the end of the output shaft actually exceed the yield strength of the 4340 steel. The changes between the two shaft layouts are significantly different since the first revision was designed to mount radial bearings onto and the final revision now has a taper roller bearing on each end of the sprocket. Seals are also located on both sides of the taper roller bearing to provide a seal. The stresses experienced in the final revision are greatly reduced and do not exceed the yield strength of the material selected. Fillets were also added to reduce the stress concentrations at the shoulders of the different diameters on the shaft.

8 Drive Shaft Assembly

8.1 Description

8.2 Design Constraints

8.3 Functional Requirements

8.4 Analysis and Design

9 Drive Box Assembly

9.1 Description

9.2 Design Constraints

9.3 Functional Requirements

9.4 Analysis and Design

10 Final Budget

The final budget was reduced from the proposed cost breakdown since some material that was required for the manufacturing of components was already at Penguin ASI as spare material. Cost that were reduced off the proposed list were the 1" Aluminum plates, 1/4" Aluminum plates, 8"x2"x1/4" Aluminum tubing, and the 2"x2"x1/8" Aluminum L beam and tubing. Water jet cutting of the plates was stated in the design proposal report, but that cost was not applied since we had decided to use the CNC mill provided to us by Penguin ASI. The lead time estimated by Stainless Technologies was two weeks, but we were able to complete the drive box plates at Penguin within one week since we had received help from their machinist. The total cost reduction from the original estimated cost was \$2,494.02 CAD dollars, that is not including the water jet cutting since it was not a method that was not decided upon during the proposal to Penguin ASI. Some of the most expensive components of the design included the belt and both the small and large sprockets. The larger sprockets had a lead time of 4 to 5 weeks but they did not come in until the 8 week mark from BDI. Some parts such as seals and tapered roller bearings were ordered twice and were placed for return to BDI to be refunded. With those reduced costs the final budget comes to \$7,413.01 CAD dollars. This total does not include the cost of machining time along with the cost of the employees wages that had contributed to helping with the project when their assistance was needed. Table3 shows the cost breakdown for the components and the material that was required to complete the project with the lead times and prices for each.

Table 2: Final Budget and lead times for purchased parts before taxes and shipping fees.

Component	Manufacturer	Supplier	Price/Unit	Quantity	Total	Lead time
Hub O-rings	DAE	BDI	$0.23	8	$1.84	Stock
Bearing Housing O-ring	DAE	BDI	$0.35	16	$5.60	Stock
Wheel Hub O-ring	DAE	BDI	$0.35	8	$2.80	Stock
Pivot O-ring	DAE	BDI	$0.28	12	$3.36	Stock
Drive box Custom O-ring	-	BDI	$17.51	16	$280.16	4 Days
Large Sprockets	Martin Sprocket	BDI	$179.21	8	$1,433.68	4 to 5 Weeks
Small Sprockets	Martin Sprocket	BDI	$101.29	4	$405.16	Stock
Large Bushing For Sprocket	Martin Sprocket	BDI	$20.00	8	$160.00	Stock
Small Bushing For Sprocket	Martin Sprocket	BDI	$16.31	4	$65.24	Stock
Belt	Gates	BDI	$125.00	4	$500.00	Stock
20 mm Sealed Ball Bearing	Amcan	BDI	$20.17	8	$161.36	Stock
45 mm Tapper Roller Bearing	Amcan	BDI	$12.19	16	$195.04	Stock
25 mm Tapper Roller Bearing	Amcan	BDI	$7.00	8	$56.00	Stock
45 mm Radial Seal	DAE/DMR	BDI	$1.84	8	$14.72	Stock
68 mm Radial Seal	DAE/DMR	BDI	$3.18	8	$25.44	Stock
60 mm Radial Seal	SKF	BDI	$26.15	8	$209.20	Stock
38 mm Radial Seal	SKF	BDI	$20.00	8	$160.00	Stock
25 mm Radial Seal	DMR/DAE	BDI	$1.38	4	$5.52	Stock
3/8” - 24 Thread Repair Kit	Recoil	BDI	$0.00	4	$0.00	Stock
1/4” Grease Nipple	-	Rastall	$0.00	4	$0.00	Stock
Continued...						

Component	Manufacturer	Supplier	Price/Unit	Quantity	Total	Lead time
1/4” Idler Shaft Bolts	-	Rastall	$0.00	8	$0.00	Stock
1.25” Castle Nut	-	Rastall	$0.00	8	$0.00	Stock
3/8” Housing Bolts	-	Rastall	$0.00	32	$0.00	Stock
5/16” Bolts For Drive Box	-	Rastall	$0.00	140	$0.00	Stock
3/8: Wingnut For Idler Adjustment	-	Rastall	$0.00	8	$0.00	Stock
3/8” Threaded Rod For Idler	-	Rastall	$0.00	4	$0.00	Stock
5/16” Bolts For Pivot	-	Rastall	$0.00	88	$0.00	Stock
Estimated Cost For All Fasteners	-	-	-	-	$500.00	
				Total:	**$7,149.12**	

Table 3: Final Budget and lead times for purchased parts before taxes and shipping fees.

Component	Supplier	Price/Unit	Quantity	Total	Lead time
2x2x1/8 6061 Aluminum L Beam	ASA Alloys	$51.58	10 ft	$51.58	Stock
2x2x1/8 6061 Aluminum Tubing	ASA Alloys	$180.87	20 ft	$180.87	Stock
96.5x48.5 x 1" 6061 Aluminum plate	ASA Alloys	$947.87	2	$1,895.74	Stock
96.5x48.5x1/4" 6061 Aluminum plate	ASA Alloys	$296.32	1	$296.32	Stock
8"x 2" x 1/4" 6061 Aluminium tubing	ASA Alloys	$69.51	2x[6 ft]	$69.51	To be determined
Travel limiter stock					
SAE 660 Bronze tube OD: 4" 1/4, ID: 3"1/2	BDI	$263.89	1 ft	$263.89	Stock
			Total:	**$2,757.91**	

11 Testing

11.1 Initial Build

While the first drive box was being manufactured, the code for the controller was tested with the motors and the batteries as a dry run to ensure that the program functioned as required, with a top speed of 3 km/h. The controller was tested by adjusting the voltage that the controller provided to the motors and both direction of rotation. After the completion of one assembled drive box it was placed into the chassis of the robot with the motor and the controller. The assembly was then tested without wheels or loading to ensure that all components within the drive box worked together and that no rubbing or undesired out comes were to happen. During this testing all components operated correctly and was able to handle the maximum rotation to achieve the desired speed of 3 km/h. During the manufacturing of the initial drive box some design changes were brought up that would help both improve our design along with decrease the manufacturing time of some components. The 1/4" aluminum plate that was required on the back plate was dropped and the hole was filled on the first 1" plate to enclose the drive box. The rear hubs were also changed to ensure that sealing would be achieved at the back. The rear hubs design also changed to reduce machining time and to make the assembly easier for inserting both the shaft seals and bearing races. A flexible Lovejoy coupling was implemented instead of the custom one that was proposed to allow mounting of the output shaft to the reduction shaft a simpler task during assembly and to help with any misalignment that may have occurred between the two during the frame modifications. The cut outs on the 1" rear and front drive boxes were changed to decrease the stress concentrations at the corners and to reduce the amount of machining time for each plate. For pivot the numbers of fasteners used to mount to the drive box was reduced from 12 bolts to 10 since it was unnecessary to have that many and it decreased the amount of fasteners used in the assembly, while reducing machining time. A snap ring grove was added to the output shaft to prevent the coupling from sliding back on the shaft and losing the connection to the reduction shaft.

11.2 Final Build

When the final build was completed it was tested using the same program and controller as the initial test and the assembly worked accordingly. The improvements made allow us to cut the amount of machining time used and allowed for an easier assembly while keeping the same desirable outcomes of the design. In the final testing done by us the controller was connected to two drive boxes and running them under no loads to ensure that but operated correctly together. The controller and the assemblies of the drive boxes work as designed for both the forward and reverse directions of rotation.

11.3 FMEA

12 Project Management

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A Pugh Matrices

Table 4: Pugh Matrix to select Placement of the Four Motor. The options for the motor placement are inside the chassis or outside.

Category	Division	Weight	Datum (Original Design)	Motor in	Motor out
Cost	Manufacturing Cost	1	0	2	-2
	Servicing Cost	4	0	0	1
	Material Cost	4	0	2	-1
	Subtotal		**0**	**10**	**-2**
Design	Repair Accessibility	4	0	-1	1
	Amphibious	5	0	2	-1
	Power Supply Accessibility	3	0	1	0
	Ease of Assembly	4	0	1	0
	Reliability	4	0	2	1
	Size	2	0	2	1
	Durability	4	0	2	1
	Weight	2	0	1	-2
	Weight Distribution	3	0	1	2
	Complexity	3	0	1	-1
	Subtotal		**0**	**41**	**8**
Schedule	Design Time	3	0	2	-1
	Manufacturing Time	3	0	1	-2
	Subtotal		**0**	**9**	**-9**
Totals	**Sum**		**0**	**60**	**-3**
	# positives		**0**	**13**	**6**
	# negatives		**0**	**1**	**7**

Table 5: Pugh Matrix to select drive mechanism. The options are belts, chains, and direct drive.

Category	Division	Weight	Datum	Belt	Chain	Direct
Cost	Manufacturing Cost	1	0	0	0	-2
	Servicing Cost	4	0	1	-2	2
	Material Cost	4	0	-1	2	0
	Subtotal		**0**	**0**	**0**	**6**
Design	Repair Accessibility	5	0	1	1	1
	Amphibious	5	0	2	2	2
	Ease of Assembly	3	0	0	0	2
	Size	4	0	0	0	1
	Reliability	5	0	1	1	1
	Durability	5	0	1	0	2
	Jerk Feedback	3	0	2	1	2
	Weight	2	0	1	0	2
	Feasibility	5	0	1	2	1
	Complexity	2	0	0	0	-1
	Maintenance	5	0	2	1	0
	Weight Distribution	2	0	0	0	0
	Subtotal		**0**	**48**	**38**	**53**
Schedule	Design Time	4	0	-1	0	-2
	Manufacturing Time	3	0	0	0	-1
	Subtotal		**0**	**-4**	**0**	**-11**
Totals	**Sum**		**0**	**44**	**38**	**48**
	# positives		**0**	**9**	**7**	**10**
	# negatives		**0**	**1**	**1**	**4**

Table 6: Pugh Matrix to select between coupled versus independent wheel suspension

Category	Division	Weight	Datum	One Wheel	Coupled Wheels
Costs	Material Cost	4	0	-1	0
	Maintenance Cost	3	0	0	0
	Part replacement Cost	4	0	-1	0
	Subtotal		**0**	**-8**	**0**
Design	Size	2	0	0	0
	Reliability	4	0	2	0
	Durability	4	0	0	0
	Width increase	2	0	0	0
	Complexity	4	0	-2	2
	Changes to existing frame	3	0	-2	0
	Subtotal		**0**	**-6**	**8**
Traction	Weight distribution from tires	1	0	1	0
	Ability to roll-over objects	5	0	0	0
	Braking Ability	4	0	1	0
	Subtotal		**0**	**5**	**0**
Steering	Torsional strength	4	0	2	1
	Subtotal		**0**	**8**	**4**
Robot Stability	Tipping side to side effects	4	0	2	0
	Subtotal		**0**	**8**	**0**
Totals	**Sum**		**0**	**7**	**12**
	# positives		**0**	**5**	**1**
	# negatives		**0**	**3**	**0**

Table 7: Pugh Matrix to select suspension type for coupled wheels.

Category	Division	Weight	Datum (Spring)	Spring and Damper	Coil over
Costs	Initial Cost	3	0	-1	-2
	Maintenance Cost	4	0	0	-2
	Part replacement Cost	3	0	-1	-2
	Subtotal		**0**	**-6**	**-20**
Design	Size	3	0	-2	-1
	Ease of assembly	4	0	0	1
	Off the shelf components	5	0	0	0
	Reliability	4	0	1	2
	Durability	4	0	1	2
	Complexity	3	0	-1	1
	Has Damping	5	0	2	2
	Changes to existing frame	1	0	-1	-1
	Subtotal		**0**	**8**	**29**
Setup	Ease of initial setup	4	0	-1	-2
	Suspension tuning	2	0	-2	1
	On site access	2	0	0	0
	Subtotal		**0**	**-8**	**-6**
Totals	**Sum**		**0**	**-6**	**3**
	# positives		**0**	**2**	**5**
	# negatives		**0**	**7**	**6**

Table 8: Pugh Matrix to select taper roller bearing arrangement.

Category	Division	Weight	Datum	Back-to-Back	Front-to-Front
Loading	Radial Loading	3	0	0	0
	Imposed axial loading	4	0	1	-1
	Subtotal		**0**	**4**	**-4**
Assembly	Size	4	0	0	0
	Ease of assembly	5	0	2	0
	Complexity	3	0	1	0
	Shoulder heights	2	0	1	0
	Sealing contacts	3	0	1	-1
	Subtotal		**0**	**18**	**-3**
Totals	**Sum**		**0**	**22**	**-7**
	# positives		**0**	**5**	**0**
	# negatives		**0**	**0**	**2**

B Excel Tables

Table 9: Results of Mass Analysis Performed in Solidworks

Assembly	Mass kg	Qty	Total kg
Battery Rack End Section	4.71	2.00	9.43
Battery Rack Mid Section	4.96	1.00	4.96
Frame	120.00	1.00	120.00
Drive box	21.50	4.00	86.00
Motor Mounts (incl. motor and reduction)	38.18	4.00	152.73
Pivot	8.30	4.00	33.20
Wheel Shafts	7.80	8.00	62.40
Batteries	62.73	6.00	376.36
Wheels	13.64	8.00	109.09
Payload	227.27	1.00	227.27
Electrical	36.36	1.00	36.36
Fasteners	68.18	1.00	68.18
Belts	2.27	4.00	9.09
Misc.	90.91	1.00	90.91
bfseries	bfseries	bfseriesTotal	bfseries1385.99

Table 10: Tractive Effort Calculation Results

Name	Variable	Value	Units
Gross Vehicle Weight	GVW	0	N
Number of Drive Wheels	NW	8.00	-
Weight on each drive wheel	WW	0	N
Radius of wheel/tire	RW	0.2286	m
Desired top speed	Vmax	0.8333333333	m/s
Desired acceleration time	Ta	6.10	s
Maximum incline angle	alpha	0.1972222055	rad
Worst working surface	Crr	0.04	-
Gravitational constant	g	9.81	m/s^2
Resistance factor	RF	1.15	-
Coefficient of Friction	mu	0.60	
Rolling resistance	RR	0	N
Grade resistance	GR	0	N
Acceleration force	FA	0	N
Total tractive effort	TTE	0	N
Wheel torque	TW	0	N-m
Wheel torque per wheel		0	N-m
Maximum tractive torque	MTT	0	N-m
Torque per wheel for constant speed	T_{cs}	0	N-m

C Work Breakdown Structure

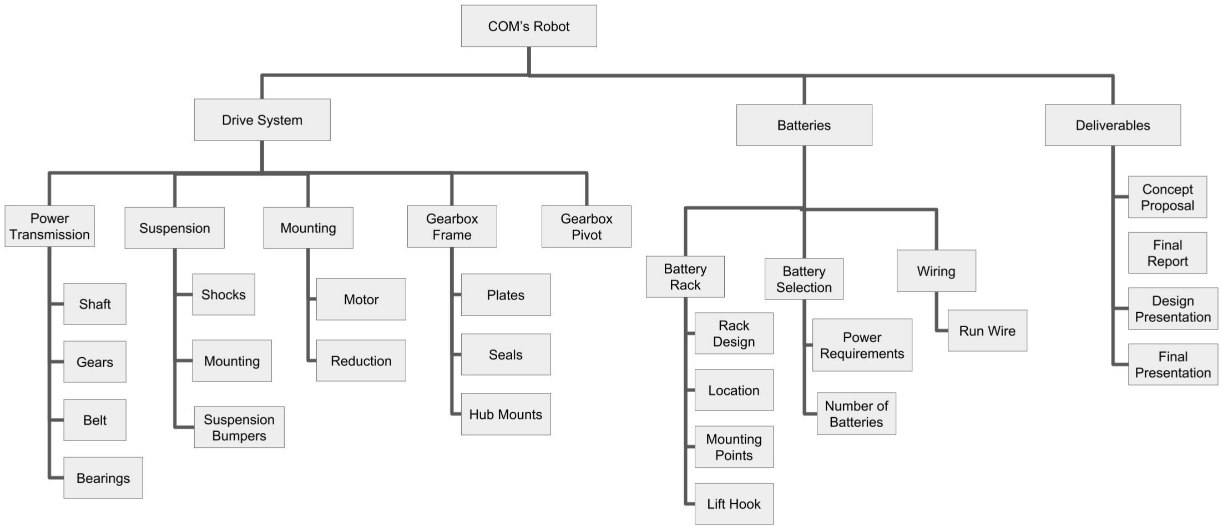

Figure 4: Work Breakdown Structure for the project

D DFMEA

Table 11: Design Failure Modes and Effect Analysis for Drive Box

Purpose	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Cause of Failure	OCC	Current Controls Evaluation Method	DET	RPN	Recommended Actions
Seal	Plates bend, create gap	Premature wear to belts/reduced belt life	7	Plate cannot support robot weight	4	O-rings damaged, water in drivebox, belt slip	9	252	Reinforce plates, check bolt tension
	Seals fail	Cause belt slip	8	Deflection in drive box components	4	Water inside drivebox, belt slippage	6	192	Reinforce plates, check bolt tension
Transmit Torque	Belt breaks	Vehicle doesn't move	9	Sudden tension increase	3	Wheels don't turn, vehicle output reduced	3	81	Replace the belt
	Belt slips	Vehicle partially moves	8	Seals fail	3	Vehicle output reduced, less responsive, noise	6	144	Revise sealing issue
	Bearings too tight, cause friction	Premature wear of bearings	6	Improper fitting of bearing	2	Wheels don't turn freely	8	96	Machine to proper tolerance
	Bearings break	Wheels stop rolling, vehicle skids. Damage to belts	7	Improper fitting of bearing	1	Unwanted noise	3	21	Replace bearing and observe cause of breaking
	Back plate deforms	Inoperable vehicle	10	Material strength too low	6	Angled drivebox	7	420	Reinforce back plate
Support Robot Weight	Pivot pierces through back plate	Dysfunctional drivebox	9	Plate not thick enough, too much force	5	Dragging drivebox, drivebox falls off	1	45	Redesign back plate
	Plate deflection	Belt snaps, possible break of seal - vehicle cannot drive	5	Plate not thick enough too much force	3	Snapped belt, visual/angled drivebox	6	90	Increase radii of plate cutouts
	Wheel shafts deflect	Added stress on bearings	3	Excess weight on shaft	1	Angled wheels	2	6	Revise shaft design
	Bushing failure	Drive box dismounts from frame	7	Bushing can't handle skid steer	3	Play in bushing, drivebox doesn't spin freely, noise	1	21	Replace bushings
	Fasteners fail at pivot/drivebox interface	Drive box dismounts from pivot	7	Skid steer forces greater than estimated	3	Dragging drivebox, drivebox falls off	1	21	Use a higher grade of fastener