Laurentian University

Capstone

ENGR-4595

Final Report: Robot Drive System Redesign

Submitted by Group 2:
Dyson Chambers
Dominic Girard
Christopher Gravelle
Jacob Lachapelle
Geneviève Rodrigue

For project client:
Penguin ASI
Regional Road 55
Naughton, ON

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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.

2 Problem Statement

The initial communications robot produced by Penguin ASI had displayed many issues affecting its performance and 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 was inadequate and allowed water to enter the drive box as seen in Figure **??**

Figure 1

3 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.

3.1 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.

3.2 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.

3.3 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 **??**

4 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

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 **??**.

5 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 **??** gives general robots specifications.

The exploded view of assembly that can be seen in Figure **??** 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

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

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.

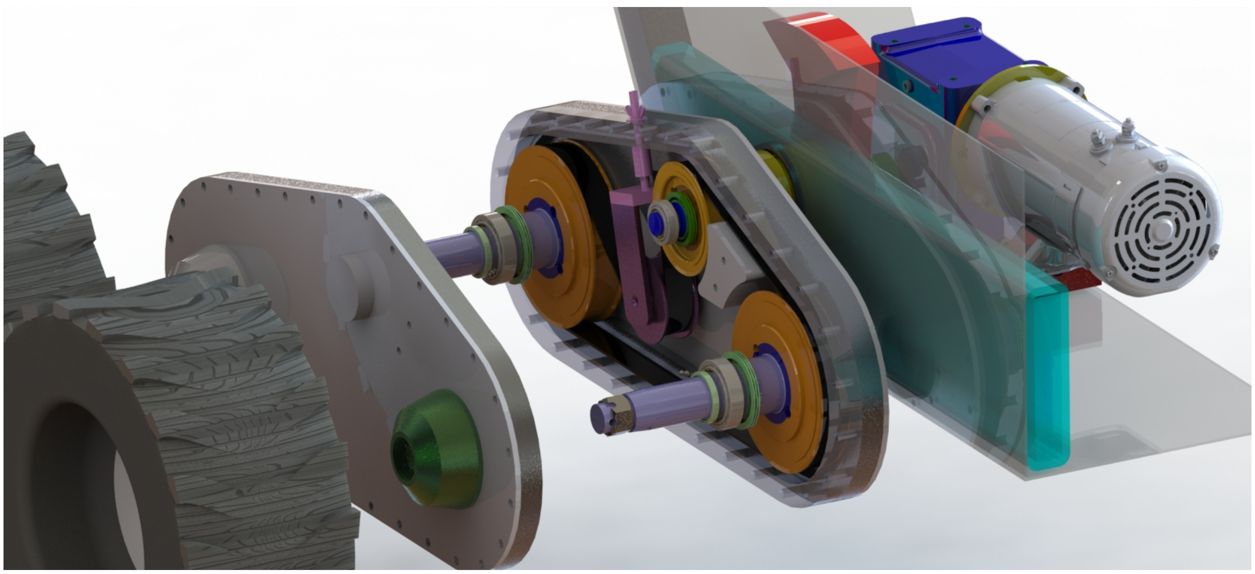

Figure 2: Rendering showing one quarter of robot exterior drive assembly with front case frame and wheels off.

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 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.

6 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. Table2 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**	

7 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

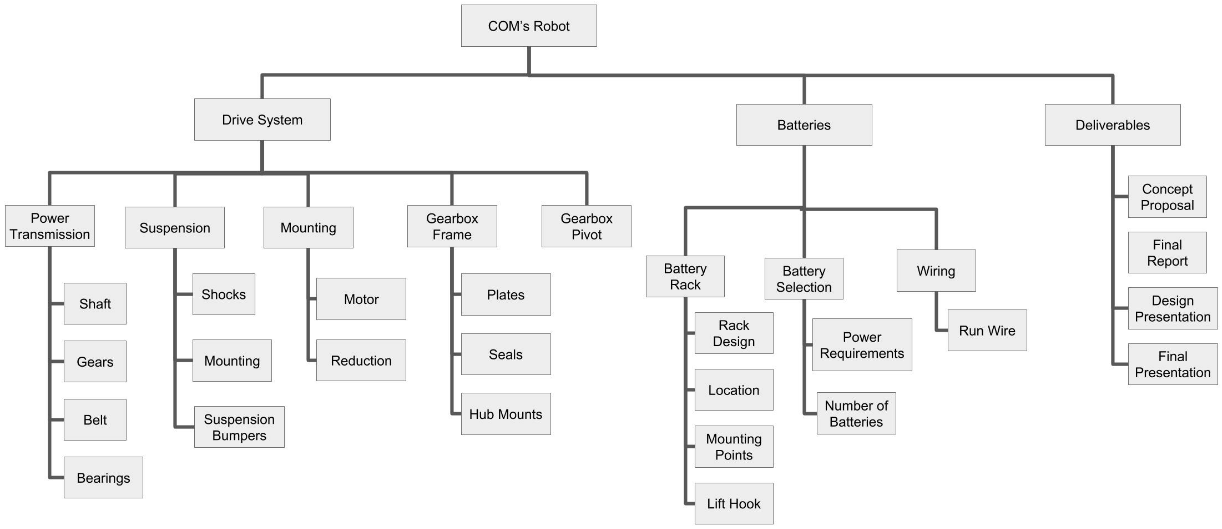

Figure 3: Work Breakdown Structure for the project