Design Considerations for an Electric Locomotive

for

MECH223 Instructors

University of British Columbia

by

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Abstract

The objective of the Rail-Rider competition is to design a battery-powered locomotive prototype capable of safely transporting cargo around a track for Lectro-Rail. Lectro-Rail commissioned a prototype design of an autonomous, low-cost, and aesthetic locomotive for future applications in railway transportation. The locomotive must complete 4 courses with steep hills and tight corners while carrying the most cargo in the fastest time possible.

Our team's objective was to design a locomotive that could complete all the courses without derailing. We decided to neglect speed and focus on reliability in hill climbs and cornering situations. We began this approach by using function decomposition to identify the most important purposes of the locomotive. After generating conceptual solutions to these locomotive functions, we used a process of screening to eliminate ideas that violated regulations or were unachievable with our resources. We generated multiple physical and analytical prototypes to gather information on the remaining ideas. We selected the best concept by emphasizing prototype testing in combination with ranking and scoring.

The physical prototypes and simulations consistently demonstrated that a dual motor gear transmission was the best concept for the competition. We implemented this design alongside an electronic braking system which would allow us to travel faster along straightaways. However, this design performed poorly in the competition; our train failed to move due to loose connections in the circuitry. The design was also incapable of producing enough torque to climb hills or haul cargo. Poor implementation and planning of our design resulted in a 17th place finish.

We recommend a more reliable mechanical design based on the design of Team D3.

- Use a higher gear ratio to complete the track and haul cargo
- Use a heavier chassis to increase traction force
- Use a longer chassis to increase space for electrical and mechanical components
- Use an articulating joint to increase stability in corners

We believe our electronic braking system is promising; it is low cost compared to other forms of speed control and it allows for faster speeds on straight tracks. However, due to the time constraints in this competition, prioritizing a reliable mechanical design is more important to the prototype's success.

1 Introduction

Over a quarter of Canada's greenhouse gas emissions come from transportation; freight accounts for nearly half of all transportation. Electric trains are one of the most energy efficient and economical methods of transporting freight; however, they require conductive rails to operate (Ostafichuk, d'Entremont, Fengler, 2018). Our client, Lectro-Rail, suggests that a battery operated train could circumvent this issue and allow the trains to travel on already developed tracks. Additionally, Lectro-Rail requested that the train be capable of traveling across diverse topography, controlling speed, hauling cargo, and ascending steep hills.

Our team designed a G-Scale locomotive prototype to compete against 19 other teams in the following rounds:

1. A 45° hill climb
2. A timed course over flat track
3. A timed course while hauling cargo uphill
4. A timed course over dangerous track
5. A division relay race

Our team created a functional decomposition* diagram, Pugh chart*, and Weighted Decision-Making Matrix*(WDM) to aid in the generation of our final design. We compared our final prototype to others at the competition and chose the best aspects of each to recommend for future use if this competition were to occur again. The sections of this report reflect the design process we followed:

- Strategy
- Functional Decomposition
- Conceptual Solutions
- Evaluation
- Final Prototype and Competition Results
- Recommendations
- Conclusion

2 Strategy

We created a strategy that was derived from the specifications provided by the Rail-Rider competition. We considered the scoring system, physical attributes of the track, and our own expectations to create the design objectives for our train. Our resulting strategy, coupled with a formal design process, established a strong foundation for our team to begin the development of our locomotive prototype.

We analyzed the scoring system of the competition in order to generate an appropriate strategy. We prioritized reliable completion of the track in our selection process because derailment penalties and track completion points are present in each round. Since many courses require the locomotive to climb hills, we made high torque a priority in our design. Similarly, we prioritized cornering capability due to the large number of turns in many rounds. We accepted the resulting tradeoffs in other scoring criteria such as speed and cost. These criteria were consistent with our expectations of creating a reliable locomotive.

We followed a simplified design process to achieve our competition goals. To optimize our efficiency, we divided our team into sub teams (Electrical, Gear train, and Testing). We spent less time in concept generation and preliminary evaluation due to the strict time constraint on the project. This decision focused our energy into quickly identifying the most promising concept. We developed a prototype early and emphasized testing to provide the detailed information required for scoring. The extra time allocated to designing the final prototype provided the opportunity to iterate until a satisfactory design was conceived.

3 Functional Decomposition

We reduced the complexity of designing a locomotive by applying functional decomposition. Using our design objectives as guidelines, we identified the functions that the locomotive must complete. We dissected the problem into the top-level functions shown in Figure 1.

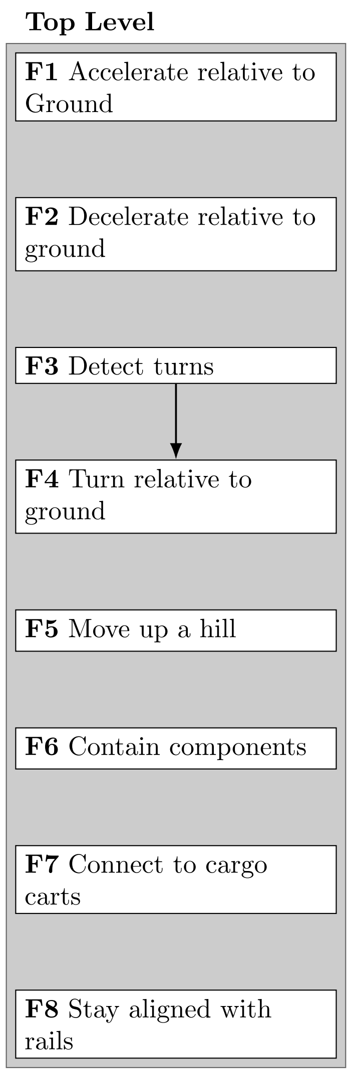

Figure 1: Top-Level Functions

We generated concept fragments* for each of the top level functions, prioritizing quantity and creativity. We ignored regulations during ideation to stimulate creativity. Some concept fragments had subfunctions that needed to be addressed for them to be incorporated. We used a function structure diagram to organize the concept fragments; an example of the function decomposition for the function Turn Relative to Ground is displayed below in Figure 2.

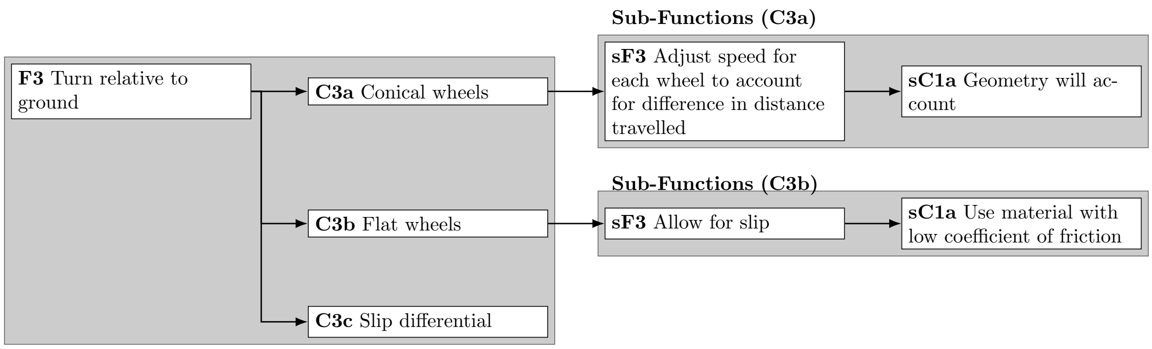

Figure 2: Function Decomposition, Turn Relative to Ground

The clear separation between different functions allowed us to quickly generate ideas for each function. The full function structure diagram is found in Appendix A: Function Structure Diagram.

4 Conceptual Solutions

We combined the generated concept fragments using a morphological chart* to form whole concepts. Each team member selected a set of concept fragments from the morphological chart and drew their interpretation of the whole concept; this process was done twice to ensure a variety of ideas. We decided that the concepts generated were adequately creative for our purposes. Time spent generating a greater variety of ideas would be better used for prototyping. Some of our most creative and promising solutions are presented below[1].

4.1 Creative Concepts

One of the most creative ideas we generated is The Very Hungry Caterpillar (TVHC, Figure 3). TVHC has multiple carts following behind it to allow for better turning capability; furthermore, it has a potentiometer* in front to detect turns and communicate them to the Arduino (a microcontroller)*. This segmented design primarily addresses our train's need to corner effectively while the need to generate torque is reflected in the design's more traditional gear transmission.

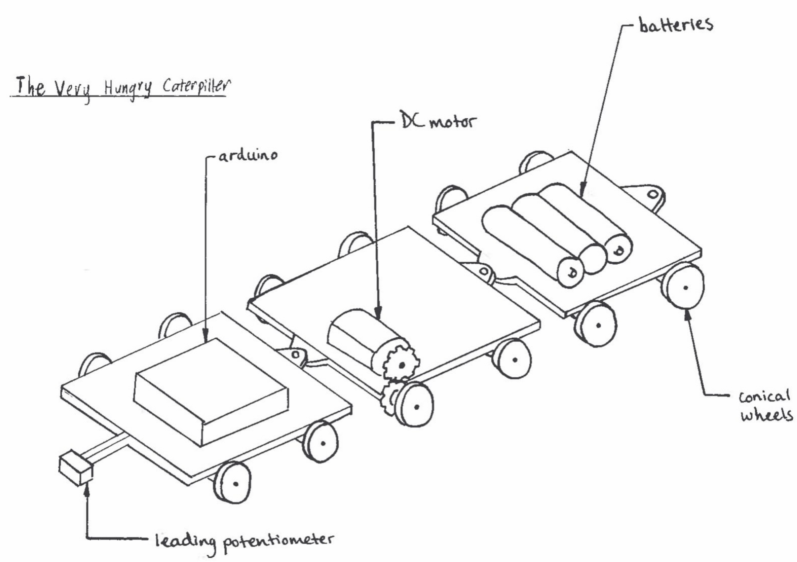

Figure 3: TVHC (The Very Hungry Caterpillar)

[1]The entire list of concepts generated can be found in Appendix B: Concepts Generated.

We created Tanky Train (Figure 4) as another alternative design. Tanky Train uses treads to drive both sets of wheels and increase friction. The design uses direct drive to transmit torque to the treads. This addresses our design objective of generating a high torque to climb the hills on the tracks. It also uses a potentiometer to detect turns and a drum brake to decelerate.

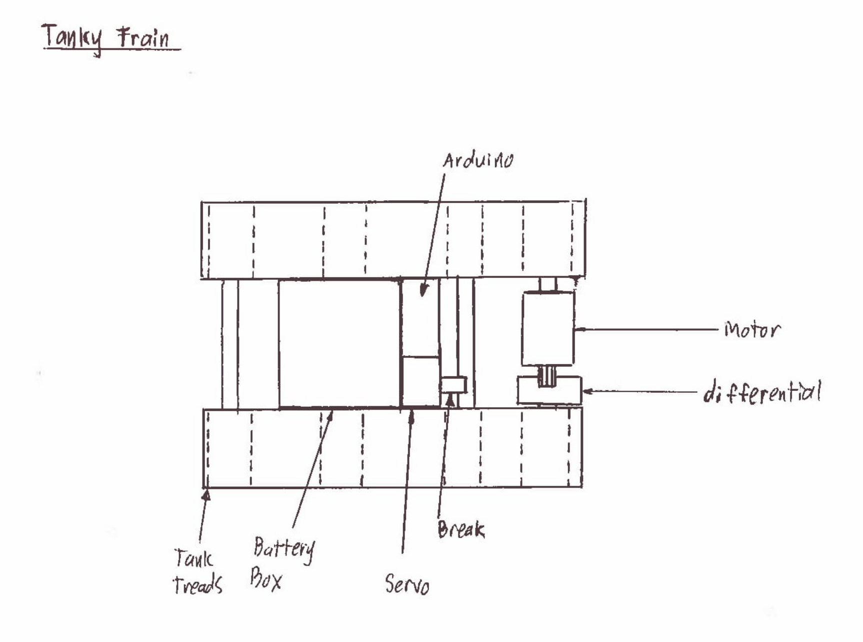

Figure 4: Tanky Train

4.2 Promising Concepts

Our most promising concept is Get Hitched (Figure 5). This design drives each axle with a separate motor to increase torque. Get Hitched is also designed to be low to the ground, increasing its cornering ability; this is further increased by the design's use of conical wheels. A light sensor is used for detecting its position along the track. This design addresses both of the attributes needed to complete the rounds and achieve our design objectives.

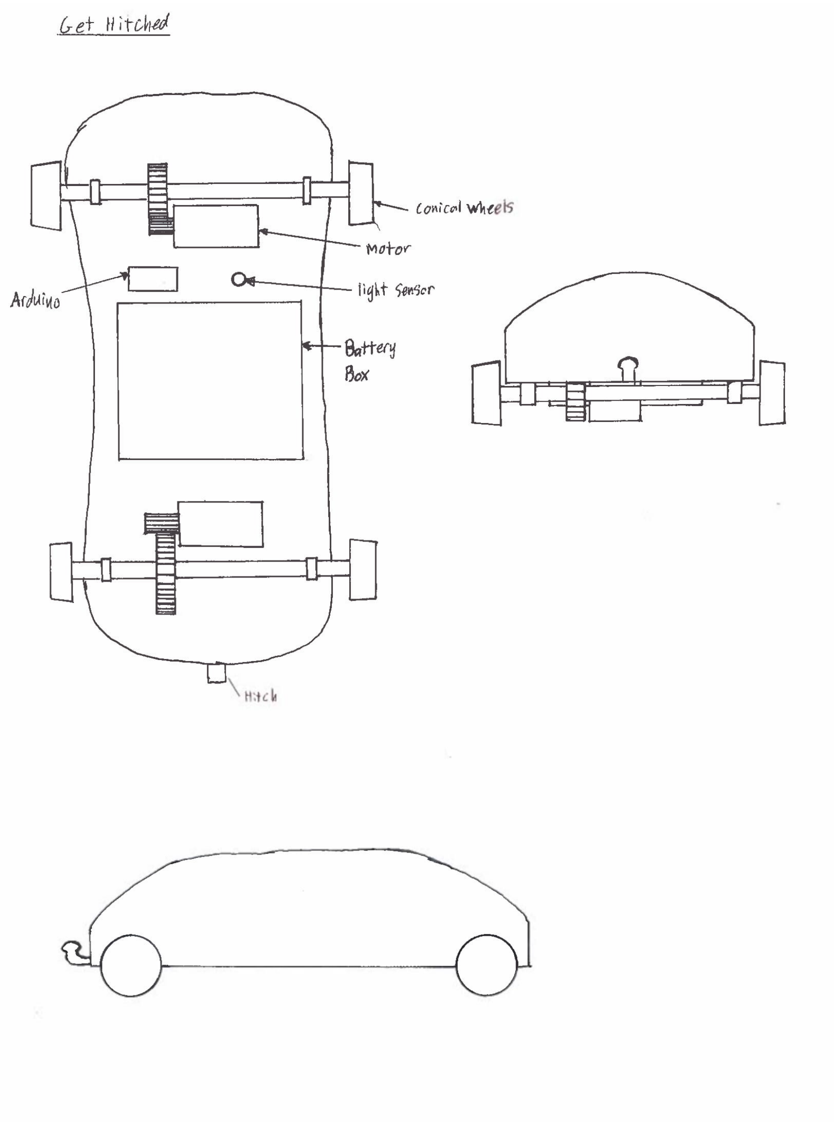

Figure 5: Get Hitched

The concept Puff (Figure 6) uses a variable gearbox to transfer the energy from the motor to the wheels. This addresses our primary design objective of increasing torque output, while also providing the ability to increase acceleration. It uses a potentiometer to detect turns and conical wheels to increase stability during turns. The design is promising because it has the ability to be easily modified for different rounds.

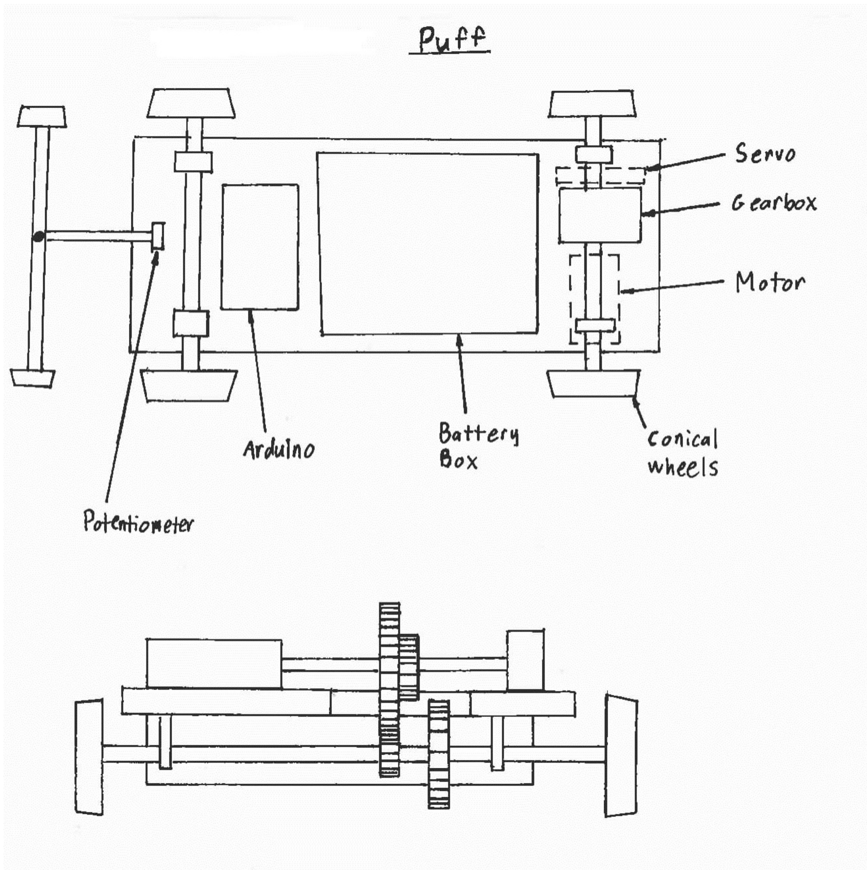

Figure 6: Puff

We also generated many promising designs such as Simplicity (Figure 7) that use belt drives. It does not include a turn detection device and uses simple wheels with o-rings. Despite poorly addressing our cornering objective, the design was simple and we were almost certain it would be built by competition. It could also be easily modified to include complex parts once a basic prototype was created.

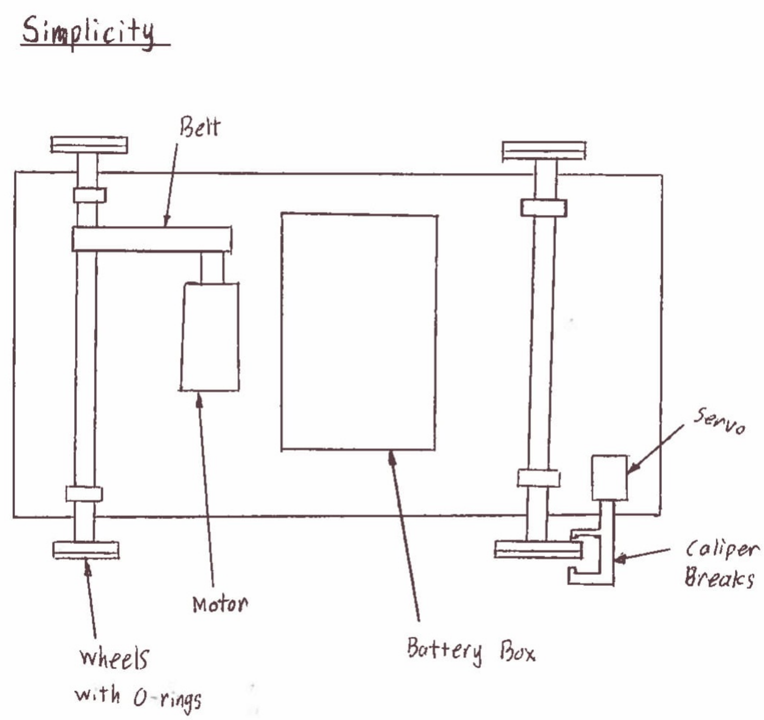

Figure 7: Simplicity

5 Evaluation

We began the evaluation process by winnowing our concept fragments based on feasibility, requirements and technical readiness; any concepts containing the eliminated fragments were winnowed immediately. Full concepts were ranked using a Pugh Chart. The process was repeated with a second datum to ensure accurate ranking. We advanced the four best concepts to scoring where we used multiple prototype tests and a WDM to select the best design.

5.1 Winnowing

We established our winnowing criteria based on the requirements of the Rail-Rider locomotive. We decided to winnow the concept fragments individually to expedite the process due to our time restriction and large number of concepts. The independent nature of our concept fragments made this process viable. Many of the creative concepts were eliminated due to feasibility issues or requirement violations[2]. We winnowed the full concepts and discarded any designs containing the eliminated concept fragments[3]. We noticed that some concepts were very similar, so we combined the best features between them to create an improved full concept. All remaining concepts were advanced to ranking.

5.2 Ranking

We advanced eight concepts to ranking where we used a Pugh Chart to compare their performance. In order to reduce the time spent on ranking, we used qualitative assessments of each design to complete the Pugh Chart. Our evaluation method for each criteria is described in Table 1.

[2]See Appendix C: Winnowing Table C1-C9 Concept Fragment Winnowing

[3]See Appendix C: Winnowing Table C10-C11 Concept Fragment Winnowing

Criteria	**Qualitative Assessment**
Aesthetics	Any remarkable, visual differences
Energy	Number of electrical components
Cost	Rough estimate of most expensive parts eg. gear trains and motors (intuition based)
Acceleration	Torque to mass ratio
Torque	Number of motors and best gear ratio
Stability	Based off performance of the type of wheel (Cylindrical vs Conical)

Table 1: Winnowing Criteria Description

Our Pugh Chart[4]favoured six concepts of the eight evaluated. We repeated the process using a second datum to test the differences between only the top-performing designs. The results of second Pugh Chart[5]showed that four designs were consistently outperforming the others. We decided to advance only these four concepts to further testing and scoring.

[4]See Appendix D: Pugh Charts Figure D1
[5]See Appendix D: Pugh Charts Figure D2

5.3 Prototype testing

We conducted several prototype tests to gather enough evidence to properly score the remaining concepts. We tested the cornering ability of conical and cylindrical wheels using a qualitative test[6]. The test demonstrated that the conical wheels have greater cornering ability particularly when the chassis has a low centre of gravity. We decided to move forward with the conical wheel design.

Our team attempted to maximize the frictional force experienced by the driven wheels on our train; not only would this allow us to pull more cargo, but it would also let us accelerate faster and turn better. We tested the coefficient of static friction of PLA filament*, rubber plasti-dip, and elastic bands in order to optimize the friction of our wheels[7]. The elastic bands were chosen over the plasti-dip due to their more durable nature; the plasti-dip wore off after a short amount of testing (Figure 8). We also distributed our weight closer to the driven axles; this would serve to further increase frictional force by increasing the normal force on those wheels.

Figure 8: Wheel Coating Test of Durability

Our best concepts used a gear or pulley transmission to transfer torque to the wheels. We tested the torque output by determining the largest angle each design could climb without stalling. We completed calculations[8] comparing a two motor system with a single motor gear train. The results of these tests indicated that a dual driven gear transmission system was the most effective at transferring torque.

[6] See Appendix E: Prototype Tests Table E1

[7] See Appendix E: Prototype Tests Table E3

[8] See Appendix E: Prototype Test Calculation of Dual Drive Torque

The pulley drive system had many issues during testing. The distance required to create enough tension for the system to operate spanned over half of our vehicle length which invalidated a variable pulley drive. The belt slipping or the motor stalling occured, producing enough heat to soften the PLA and left the pulley susceptible to falling off of the motor's axle and to rapid wear from the belt (Figure 9).

Figure 9: Wear on V-shape pulley

Our team opted for the variable gear drive due to the belt drive's problematic nature. Although, the possibility of stalled motors exists in the gear train option, the gear ratio prevents this from happening at smaller angles, making this unlikely during the competition. As an added precaution, we fitted grub screws with nuts to better connect the gear to the axle.

We generated a computer simulation of the train going around the track in each round. The model (Figure 10) indicated that the train would continue to increase in speed well above our tipping velocity[9]. We decided to create a braking system to solve this problem.

[9] See Appendix E: Prototype Tests Track Simulation

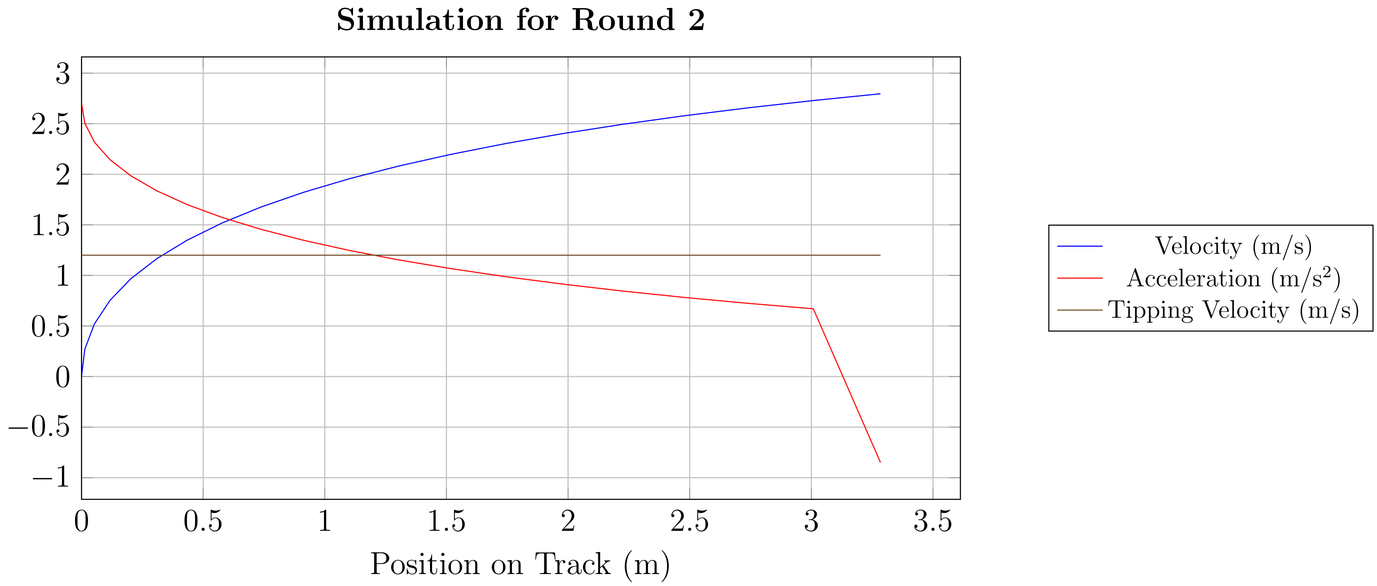

Figure 10: Simulation model

We tested a photoresistor* to determine its sensitivity to difference in colour changes. The photoresistor was accurate at differentiating between the table and track rungs across multiple trials and remained accurate at higher speeds[10]. We implemented this to determine our position on the track and when to begin braking.

5.4 Weighted Decision Matrix

Using the results of our prototype tests, we scored our remaining designs in a WDM. We evaluated the concepts based on cost, energy, derailment stability, cargo transfer ability, and risk. Our complete WDM can be found in Appendix F: Weighted Decision Matrix. We determined that the dual drive design, Get Hitched, was the best. A summary of the scores is shown in Figure 11.

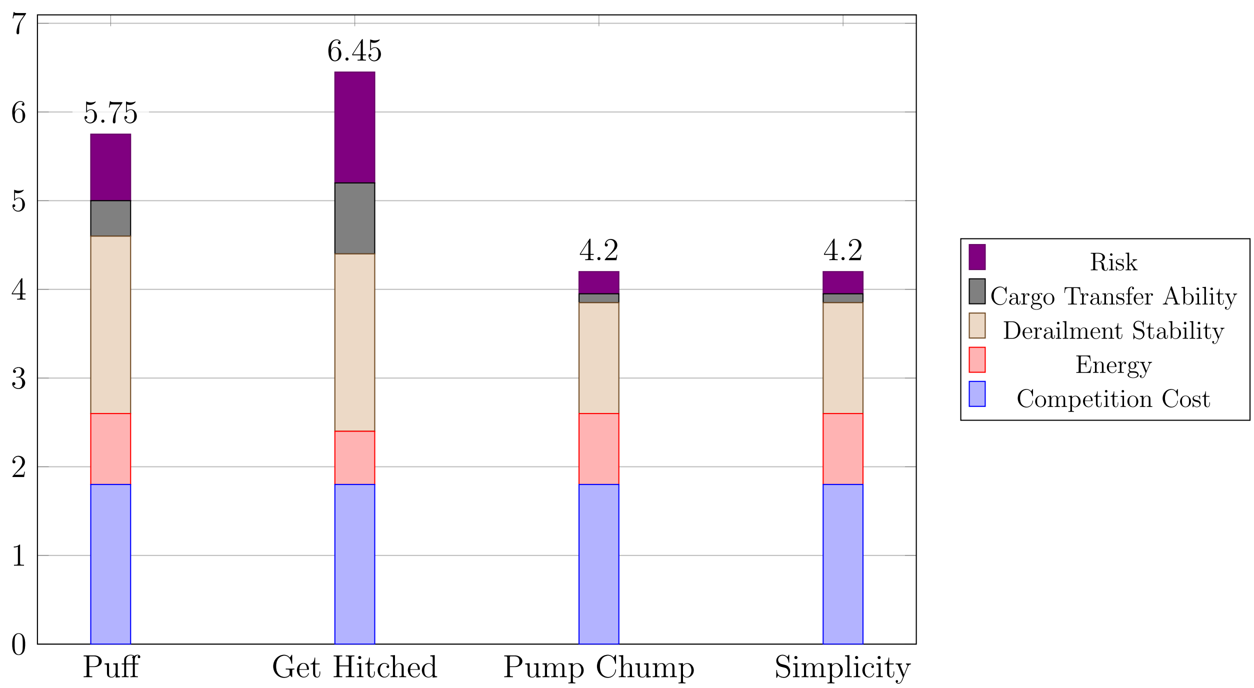

Figure 11: Simulation model

Limitations in space made producing two gear trains with sufficient gear ratios very difficult. We combined Puff with Get Hitched to create a design with a singular gear transmission driven by two motors. We could therefore utilize the positive aspects of the variable gear train as well as the strong attributes of Get Hitched.

[10]See Appendix E: Prototype Tests Figure E1: Photoresistor Track Detection Data

6 Final Prototype and Competition Results

We developed our final prototype from the best concept selected in the WDM. We combined a mechanical gear transmission with an electronic braking system. However, we scored poorly in competition because we ineffectively implemented reliability in our design.

6.1 Final Prototype

Our final prototype (Figure 12) uses two motors to power a single variable gear train. The chassis is low to the ground and contains all the mechanical components.

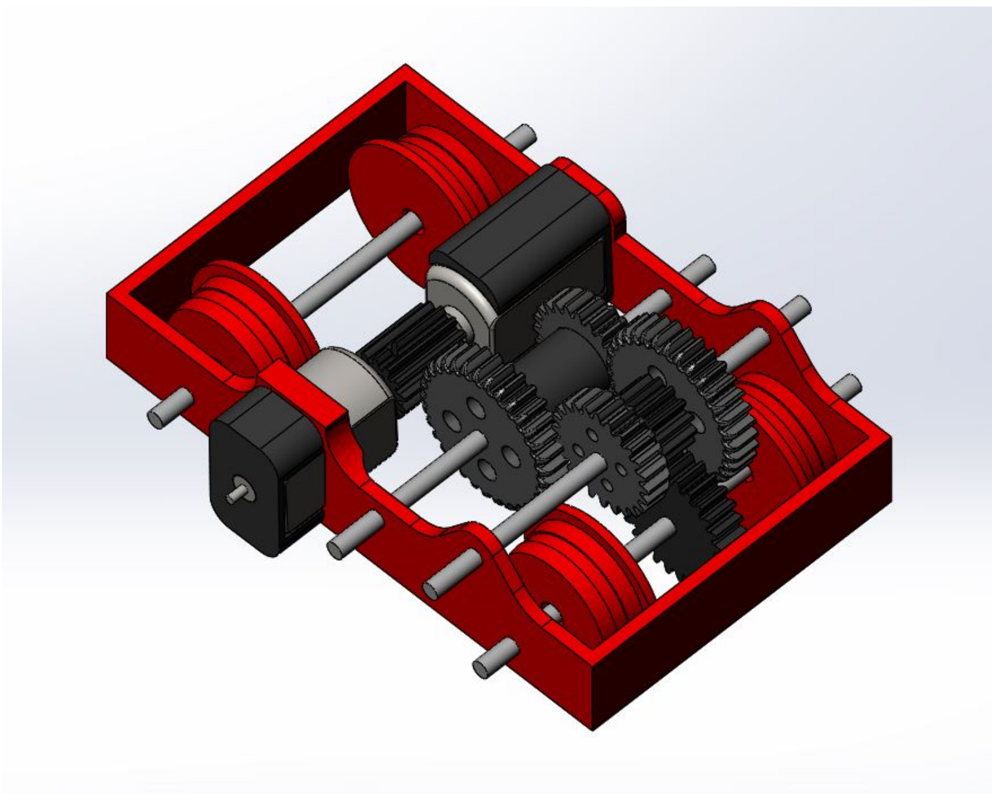

Figure 12: Mechanical System of Final Prototype

The circuitry is mounted above the mechanical systems[11]. A photoresistor detects the number of track ties the train passes over. After a certain number, the arduino reverses the polarity on the motor, causing the train to brake. Once acceleration reaches zero, a gyroscope sensor tells the Arduino to stop braking.

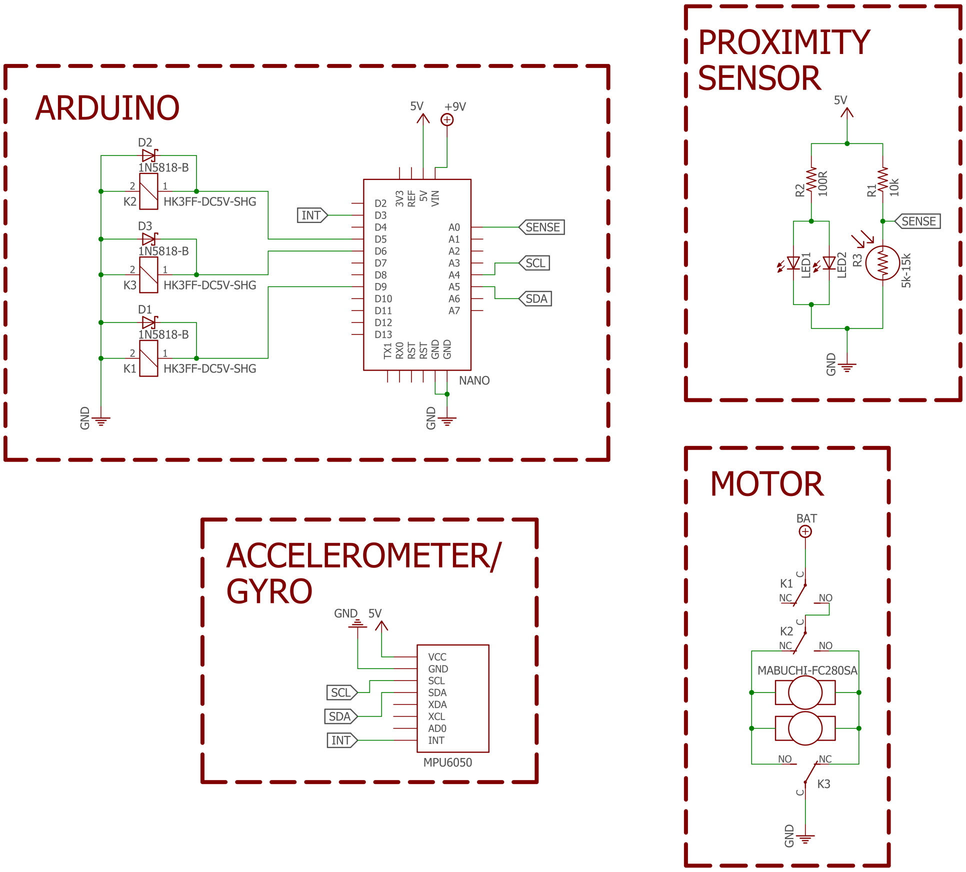

Figure 13: Electrical System of Final Prototype

Our final prototype can reach a top speed of 1.56m/s; this value was much higher than we desired due to underestimations of the gear ratio needed for competition. The train can climb 31° inclines; however, the locomotive is incapable of hauling more than an empty cargo cart. We use 3 batteries to power the train. The locomotive costs $80.43[12], where the primary cost is the arduino.

[11] A picture of the circuitry mounted onto the prototype is available in Appendix H: Final Prototype
[12] See Appendix I: Bill of Materials

6.2 Competition Performance

We scored 17th place in the competition with 14.9 points. Our train did not have enough torque to climb the 45 degree hill. However, the majority of points were lost because our train could not complete the track in rounds two through five. In the second round, we underestimated the locomotive's height and it was incapable of passing through the first tunnel. The braking system we used was not reliable and our train could not slow down for turns if it did not engage, which occured in our retrial of round two. The system also propelled our train backwards when the proximity sensor mistakenly counted track ties in round three. The circuitry connections were loose and this resulted in the train failing to start in round four.

7 Recommendations

Our design's mechanical system is insufficient for the requirements of the competition. We recommend the adoption of a reliable mechanical design such as that of Team D3 (Figure 14).

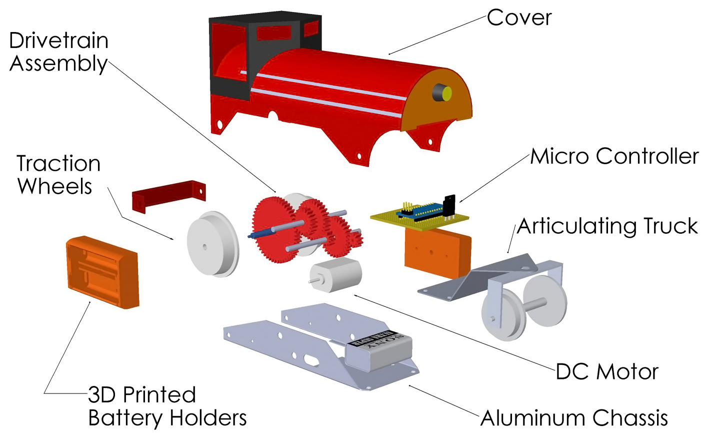

Figure 14: Exploded View of Team D3's Design

This design performed well in all rounds of the competition and scored second overall. We chose not to recommend the first place design (Team D5) since Team D3's design is less expensive and is more energy efficient. The deficiency in performance is minor compared to the lower operational cost of Team D3's train.

Using Team D3's design as a model, we recommend the following:

- Use a high gear ratio for travelling up inclines and haul cargo
- Machine a metal chassis for increased weight and propulsion force
- Use a long chassis for placing electrical components close to the track
- Include an articulating joint for increased stability

Our design has promise if developed further. However, due to poor implementation and an underestimation of the project's time constraints, our design is inadequate for competition. We believe with the improved mechanical system of Team D3's design, the locomotive would be reliable. With more available time, we recommend developing an electronic braking system as used in our design. This electronic braking system offers many advantages over other speed control systems:

- Higher speeds on straight sections of track
- Lower cost of components

With these recommendations, the locomotive would be capable of succeeding in competition; a reliable mechanical system is needed to remove the deficiencies of the current design.

8 Conclusion

To develop a strategy to approach the problem, we analyzed the competition requirements and decided to design a reliable locomotive. Using function decomposition, we divided the problem into simple tasks of the locomotive. We generated a variety of concepts that were creative and promising for the competition. We used prototypes and simulations to test the capabilities of our designs; however, our evaluation focused on the performance of various concept fragments instead of holistic performance. This resulted in a poor performance from our final prototype at the competition; specifically, the incompletion of over half of the rounds resulted in a very low base score. The mechanical system of our prototype is inadequate for competition. Therefore, we recommend using a design similar to that of Team D3.

With the future in mind, we believe it is important to develop a braking system for an electric train. Although the electronic braking system proposed by our team is unfeasible for the scope of the competition, it is promising for real world applications. Given enough time, combining the positive aspects of our electronic system with the mechanical aspects of Team D3's design would result in an overall superior train intended for full scale development.

9 References

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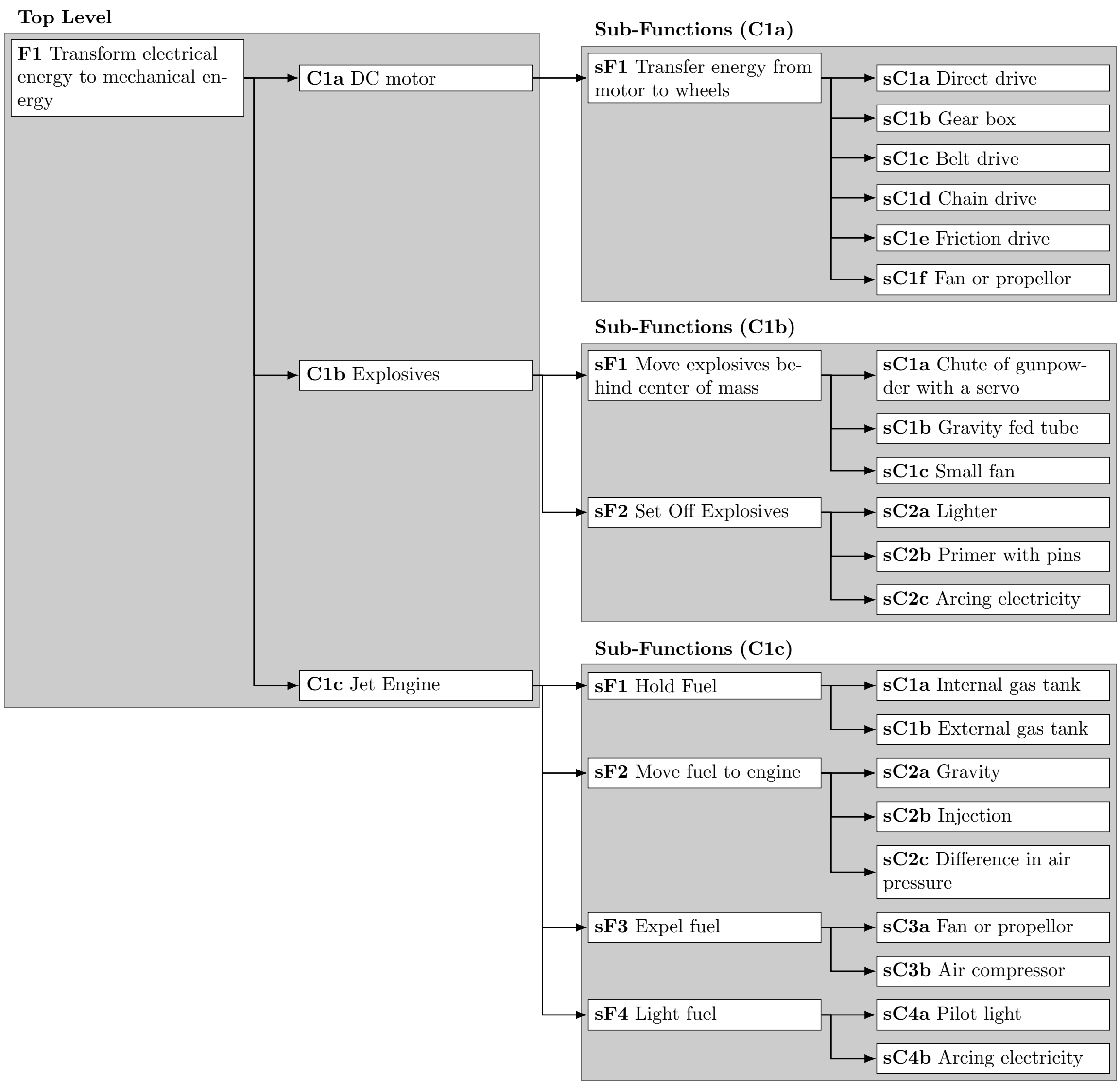
Mabuchi Motor Co., Ltd. (2014, October). *Model fc-280sa - carbon-brush motors.* ThomasNet. Retrieved from https://cdn.thomasnet.com/ccp/01311683/111062.pdf

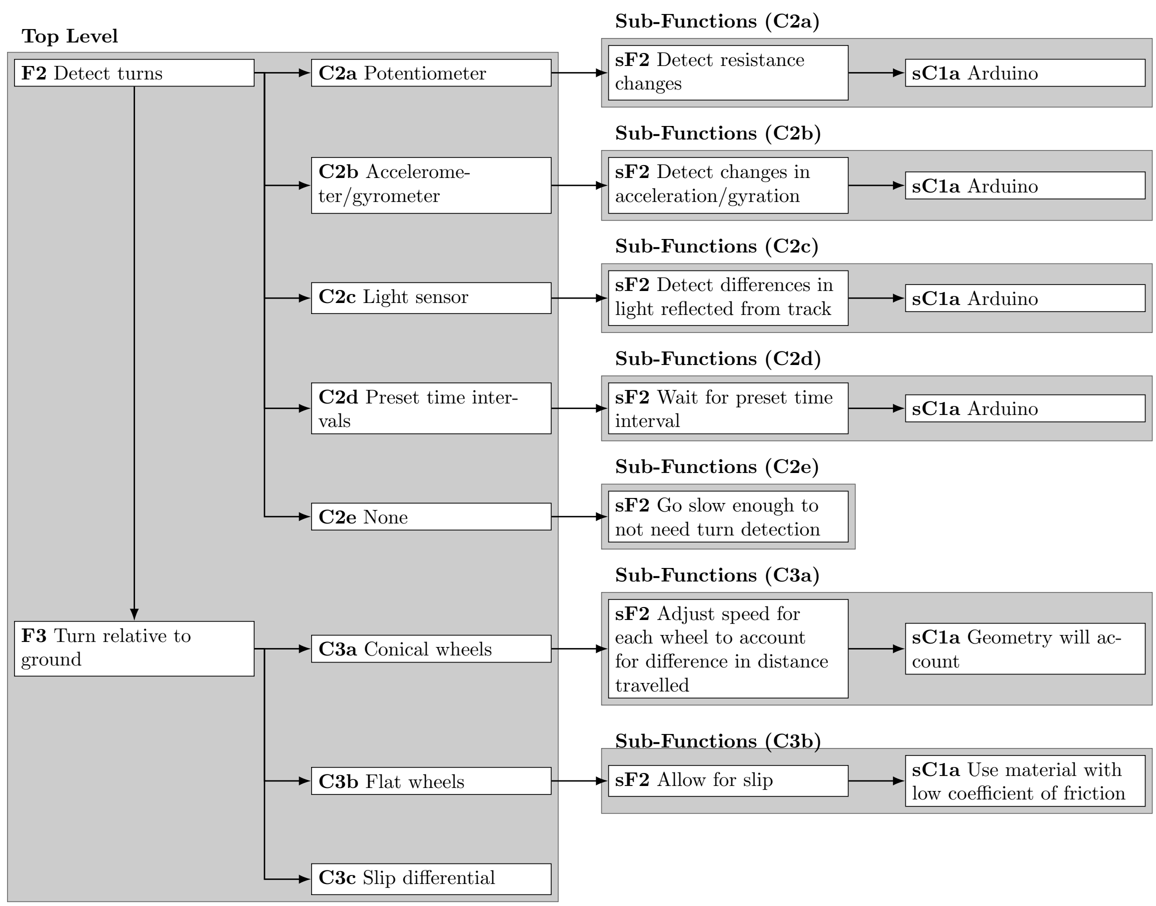
Ostafichuk, P., d'Entremont, A., & Fengler, M. (2018). Rail rider: Background: The benefits and perils of rail transport. Retrieved from https://connect.ubc.ca/bbcswebdav/pid-4293303-dt-content-rid-24660876_1/courses/CL.UBC.MECH.220.101.2017W1.99635/223-Rail%20Rider-Specifications%202.0.pdf

A Functional Decomposition Diagram

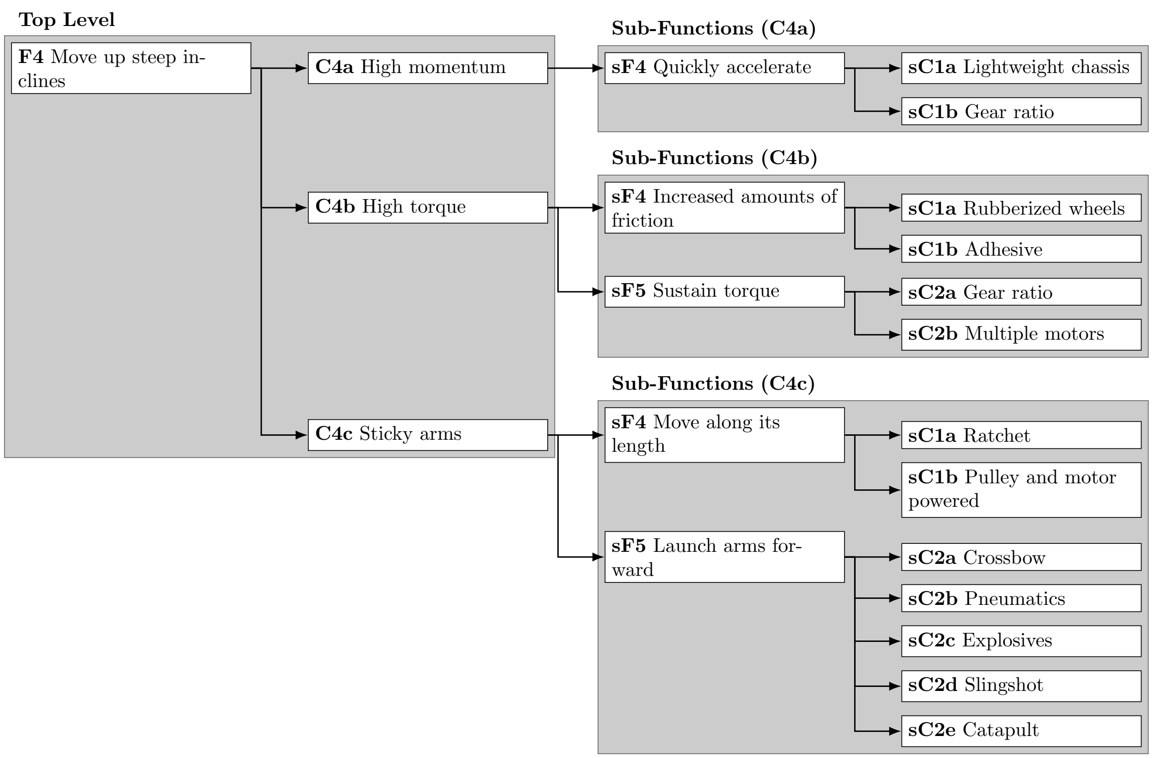
Figure 15: Function Decomposition Diagram



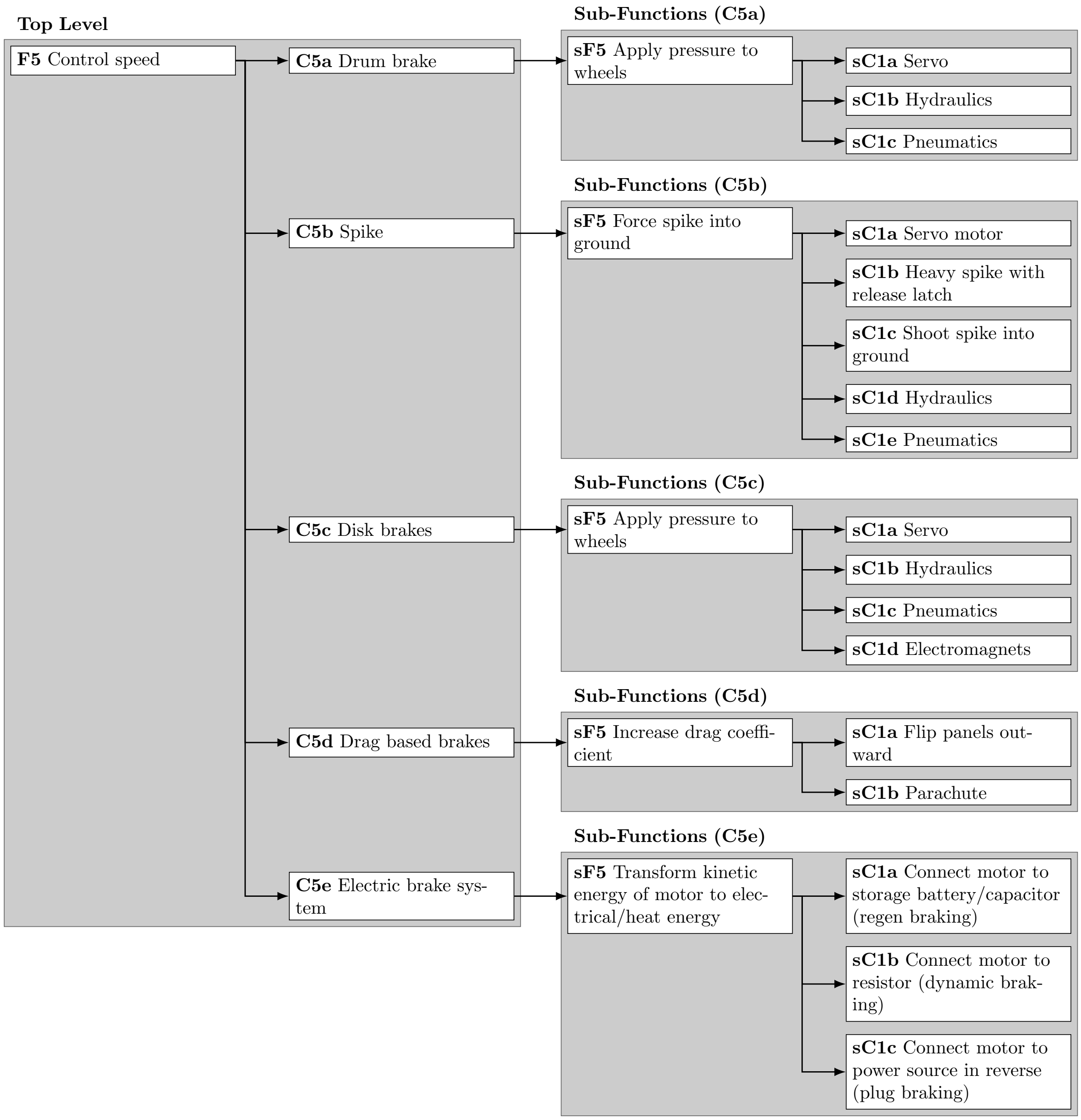
(15a) Functional Decomposition Diagram Part 1



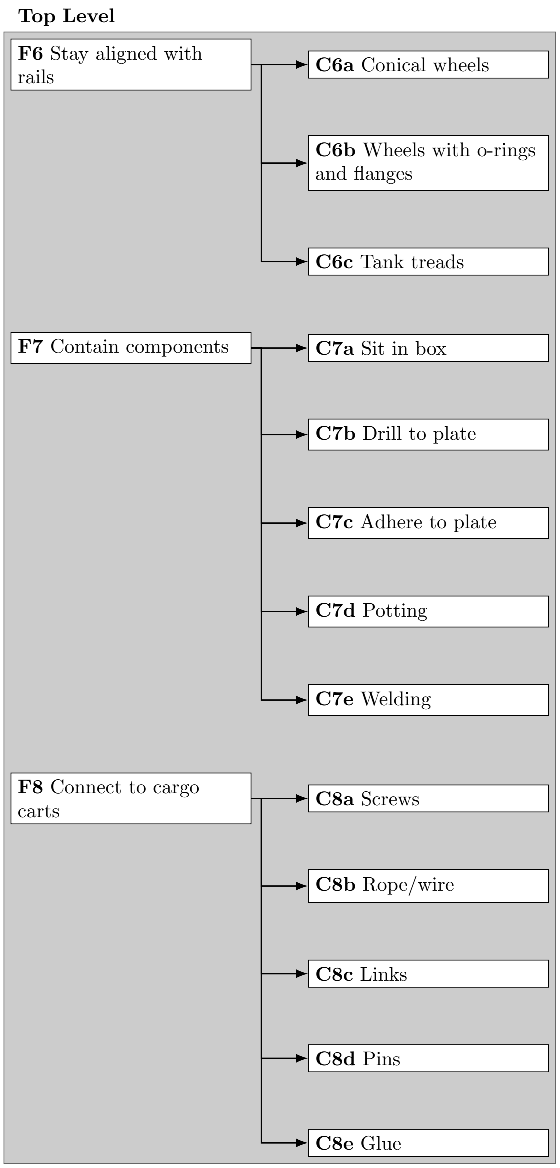
(15b) Functional Decomposition Diagram Part 2



(15c) Functional Decomposition Diagram Part 3



(15d) Functional Decomposition Diagram Part 4



(15e) Functional Decomposition Diagram Part 5

B Concepts Generated

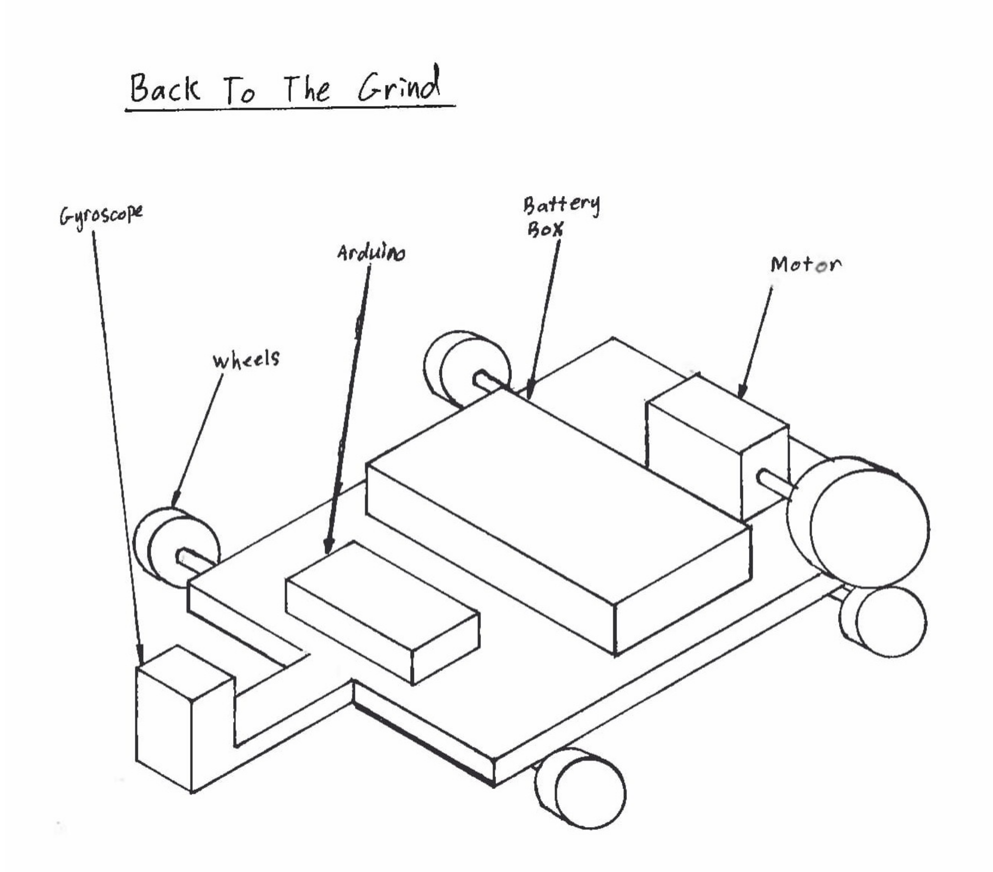


Figure 16: Back to the Grind Concept Sketch

Description: Back to the Grind is a friction drive locomotive; as the motor directly transmits power to the rim of the back wheel. The gyroscope reads the position and signals the Arduino when entering a turn; the motor then reverses, which causes the vehicle to brake.

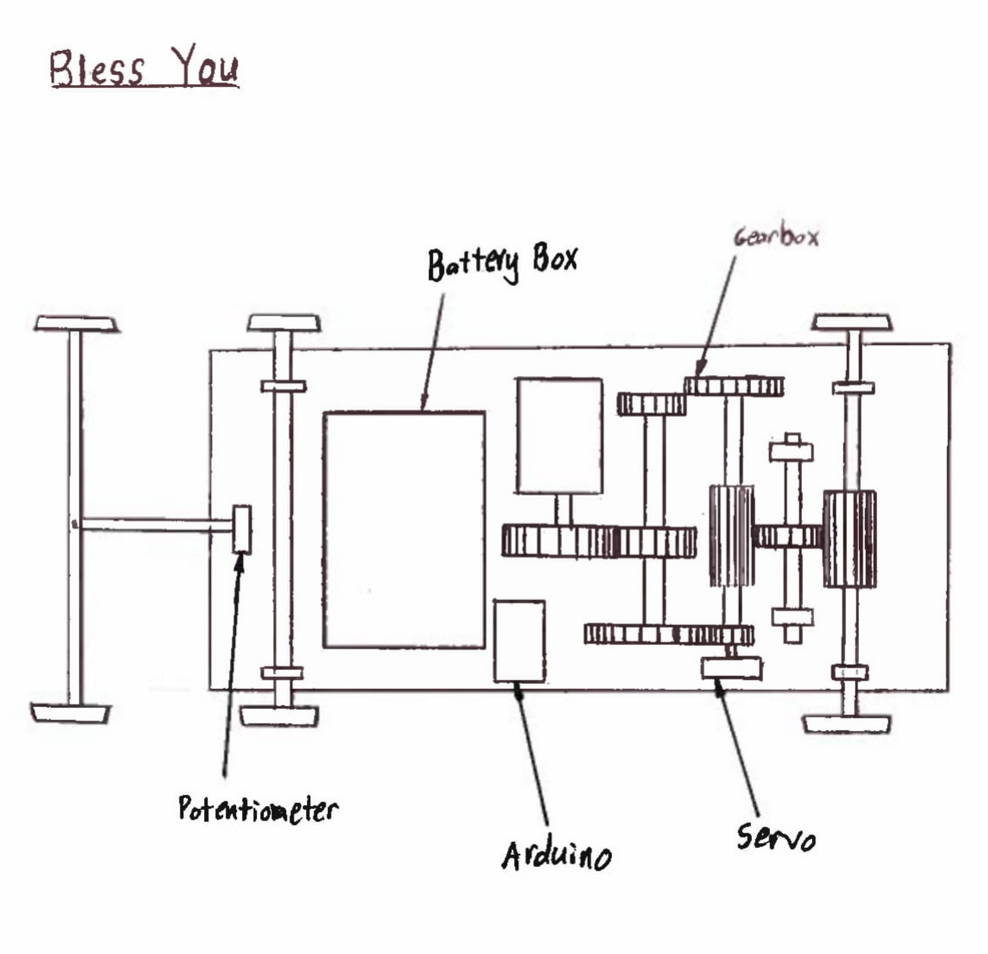


Figure 17: Bless You Concept Sketch

Description: A design which uses a gearbox to control speed. Wheels in front of the vehicle turn a potentiometer to detect turns. When a turn is detected the Arduino will signal the motor to run in reverse. Conical wheels will help with cornering.

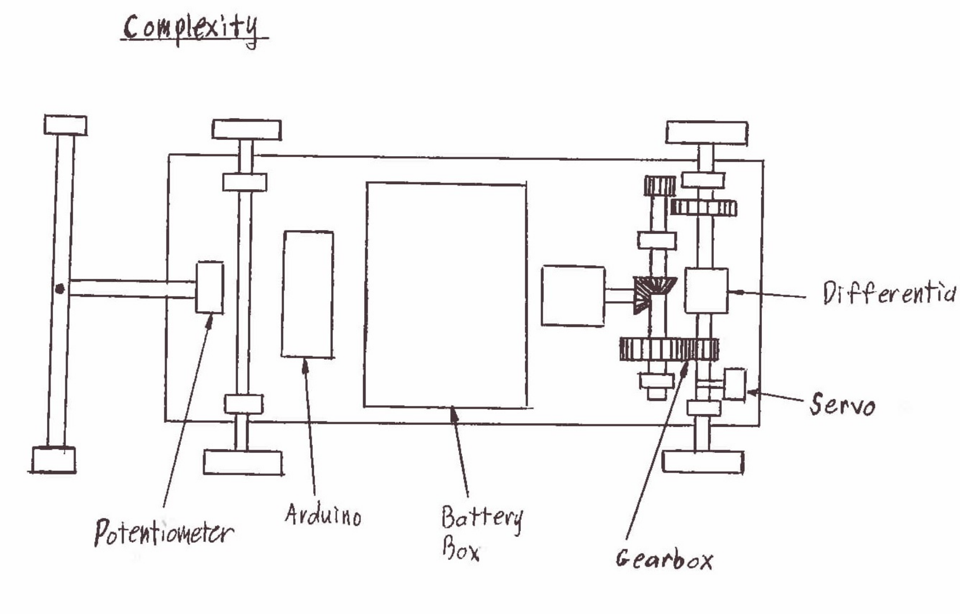


Figure 18: Complexity Concept Sketch

Description: A design using a variable gearbox with dual speed and a differential to enable smoother turning. Complexity uses a potentiometer on forward wheels in order to detect turns and slow down.

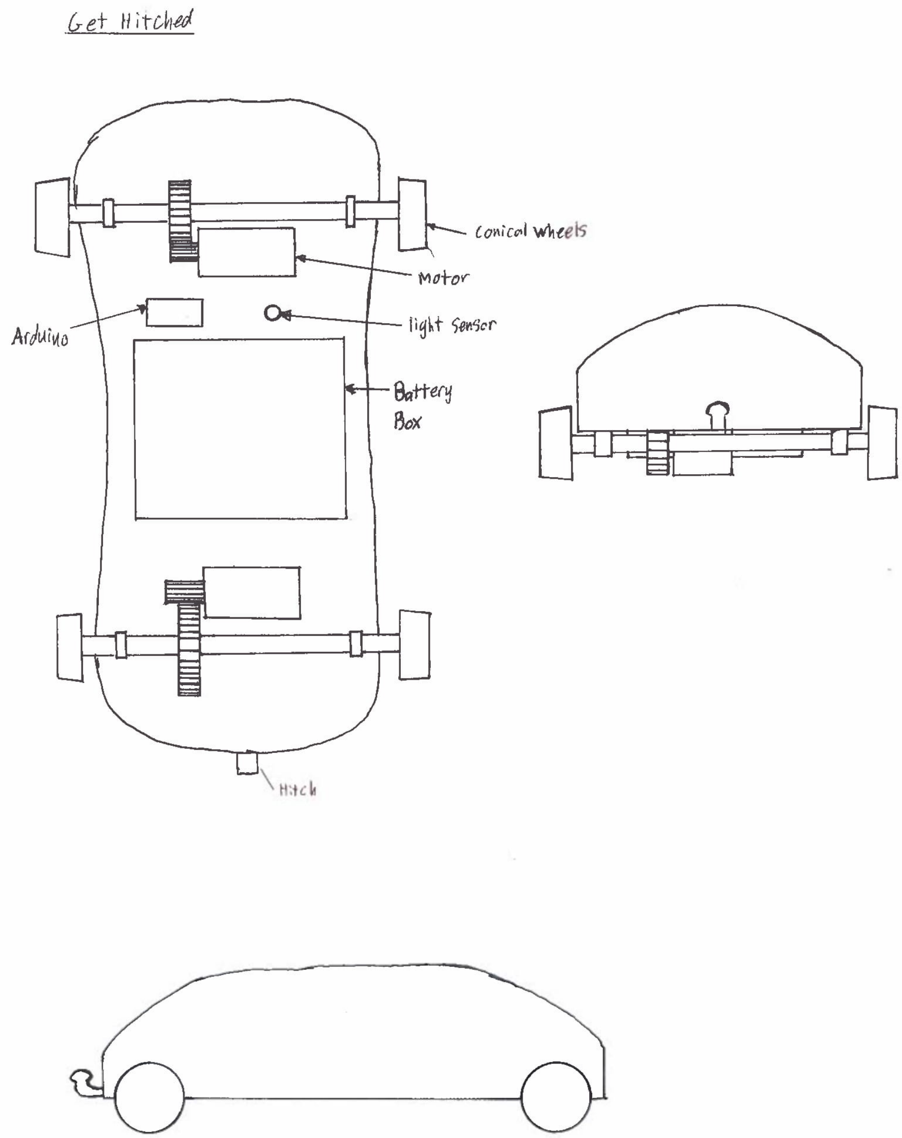


Figure 19: Complexity Concept Sketch

Description: Get Hitched is a four wheel drive vehicle powered by two DC motors. The design involves conical wheels for cornering and a light sensor that counts the rails in order to detect turns.

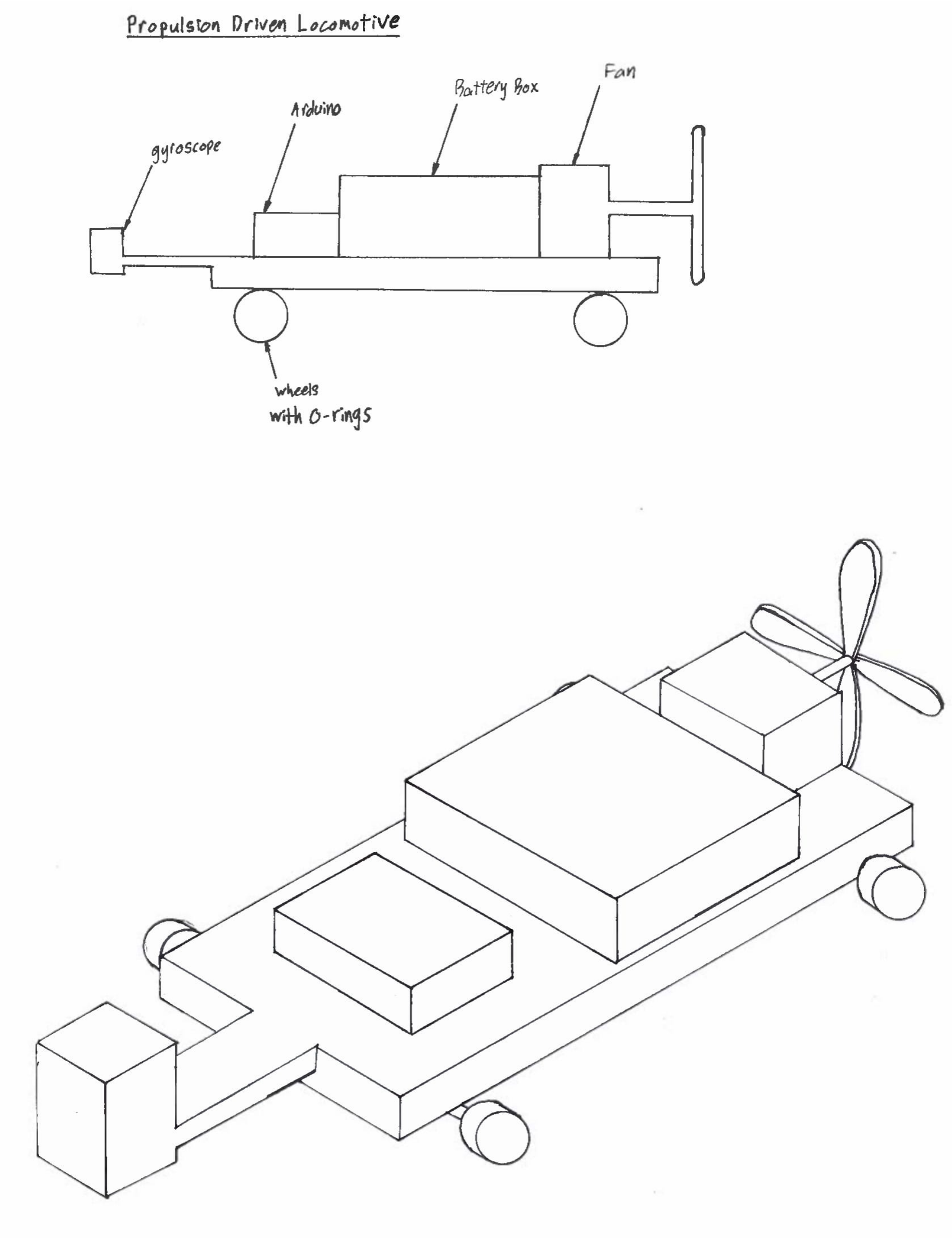


Figure 20: Propulsion Driven Locomotive Concept Sketch

Description: The motor directly powers a fan that propels the locomotive. The gyroscope coupled with the Arduino detect turns and lower the voltage on the fan to slow down. The wheels in this design use o-rings in grooves to increase traction.

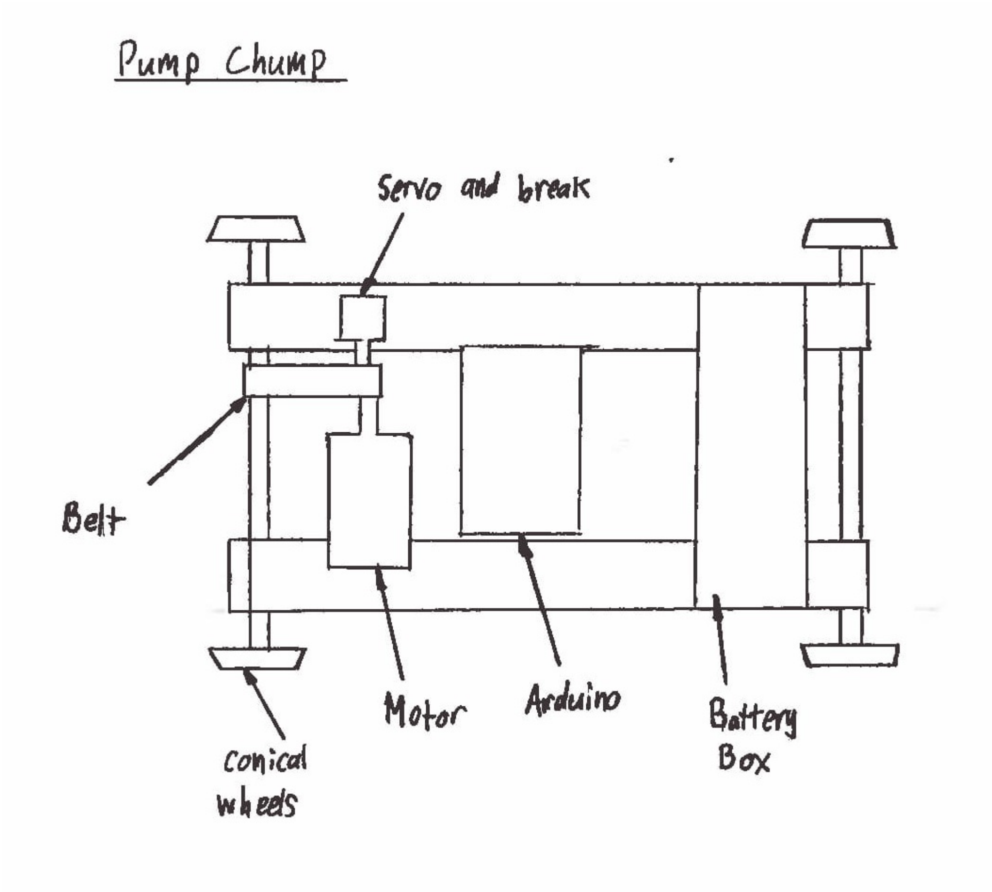


Figure 21: Pump Chump Concept Sketch

Description: Pump Chump uses a belt drive for propulsion and brakes to control speed. The Arduino is pre-programmed with track data and controls the motor and brakes. This design uses conical wheels for cornering.

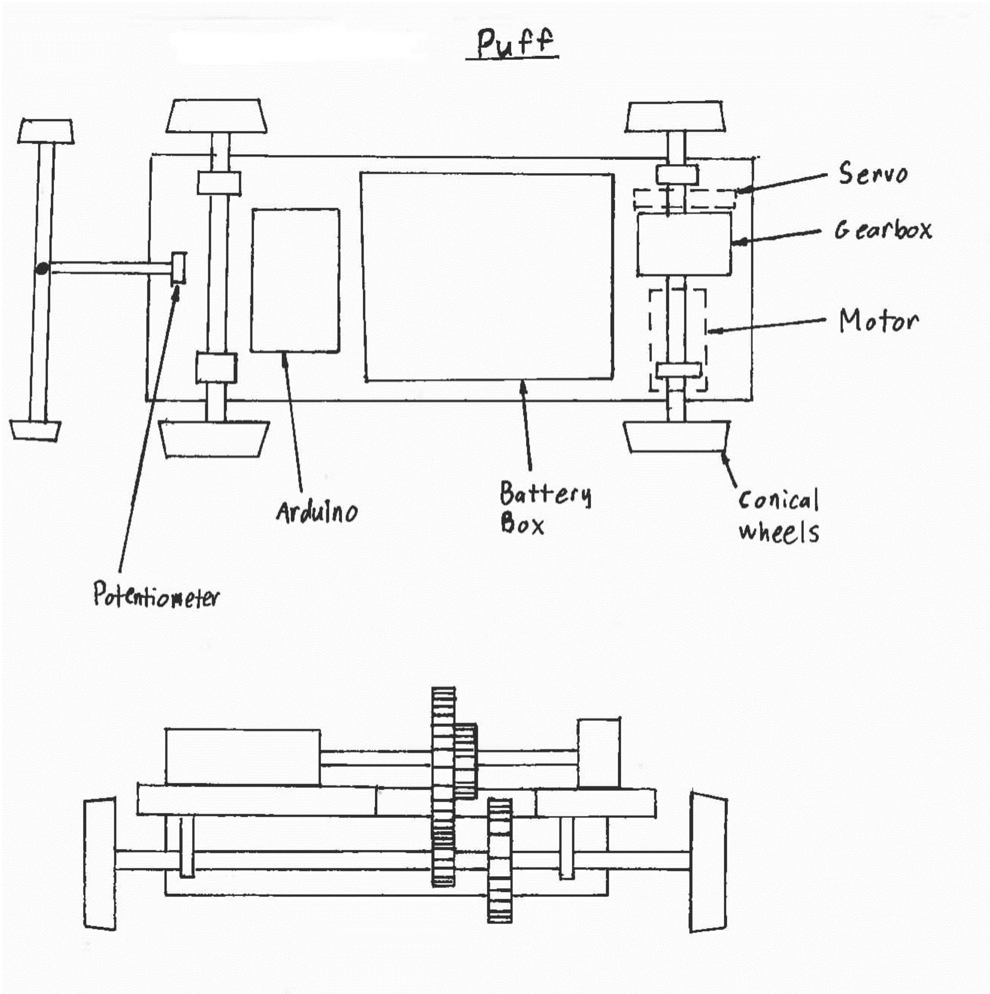


Figure 22: Puff Concept Sketch

Description: Puff is a rear drive locomotive with a dual speed gearbox and conical wheels. The servo switches the gears, rendering this design an automatic gear shift mechanism. Puff also involves a potentiometer that senses turns on the front wheels and transmits a signal to the arduino in order to slow down.

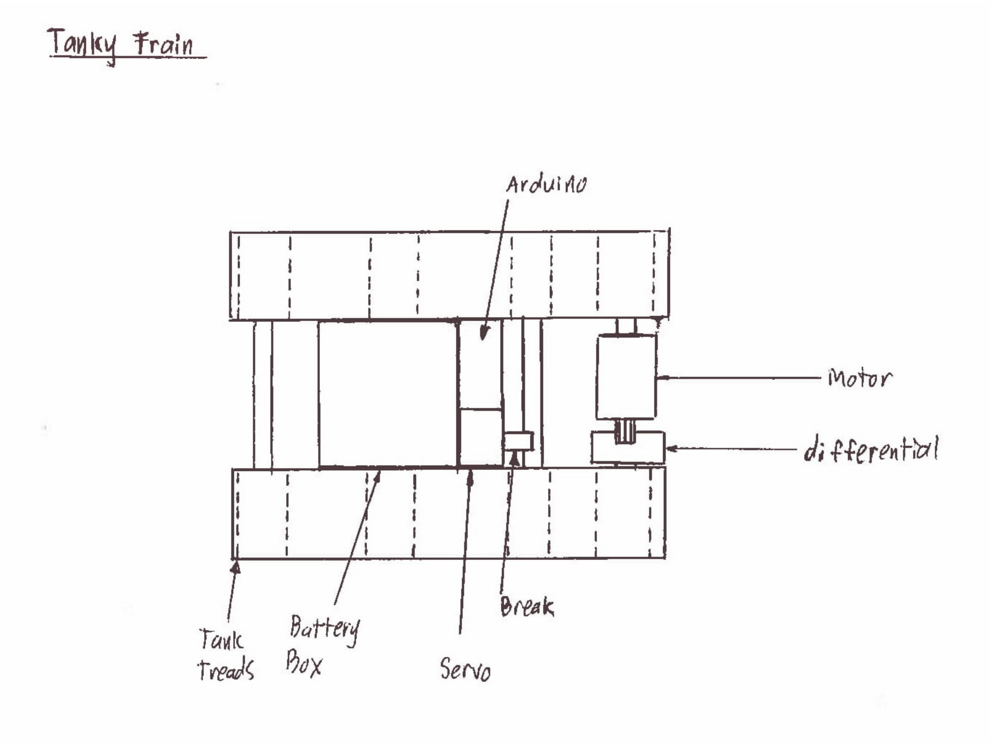


Figure 23: Tanky Train Concept Sketch

Description: The motor directly drives the treads on the wheels. A differential is used to give the vehicle better cornering. A drum brake will decelerate the vehicle before turns.

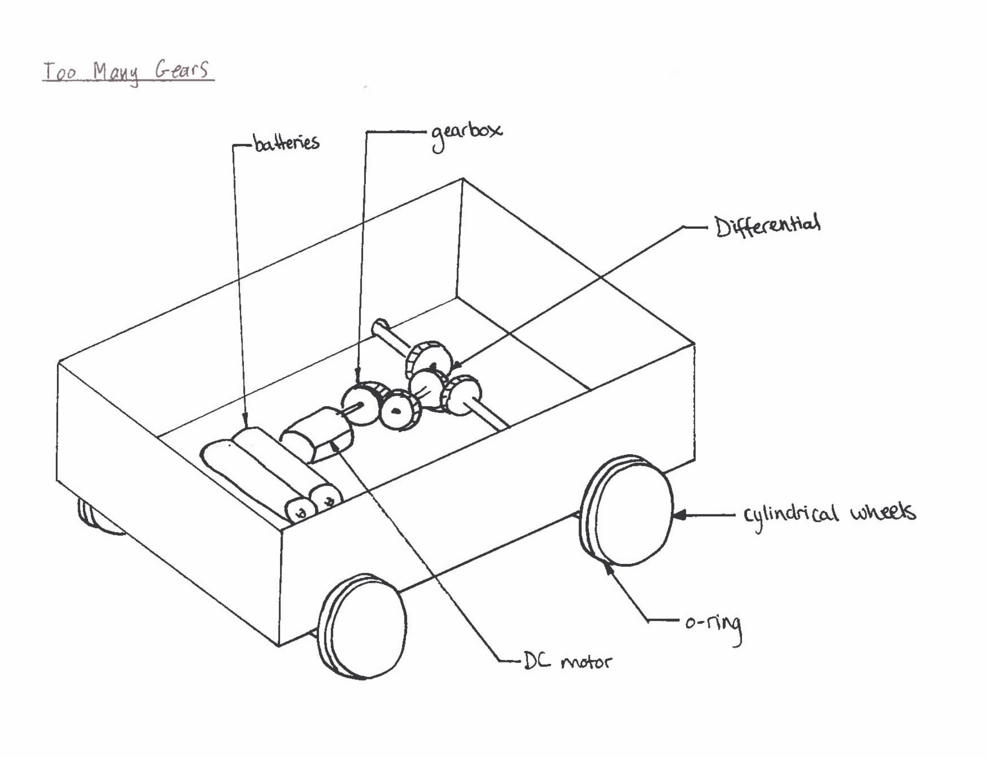


Figure 24: Too Many Gears Concept Sketch

Description: Too Many Gears involves multiple gears to step down the speed. The wheels have an o-ring to improve traction on a cylindrical surface. This design also involves a slip differential to enable easier turning.

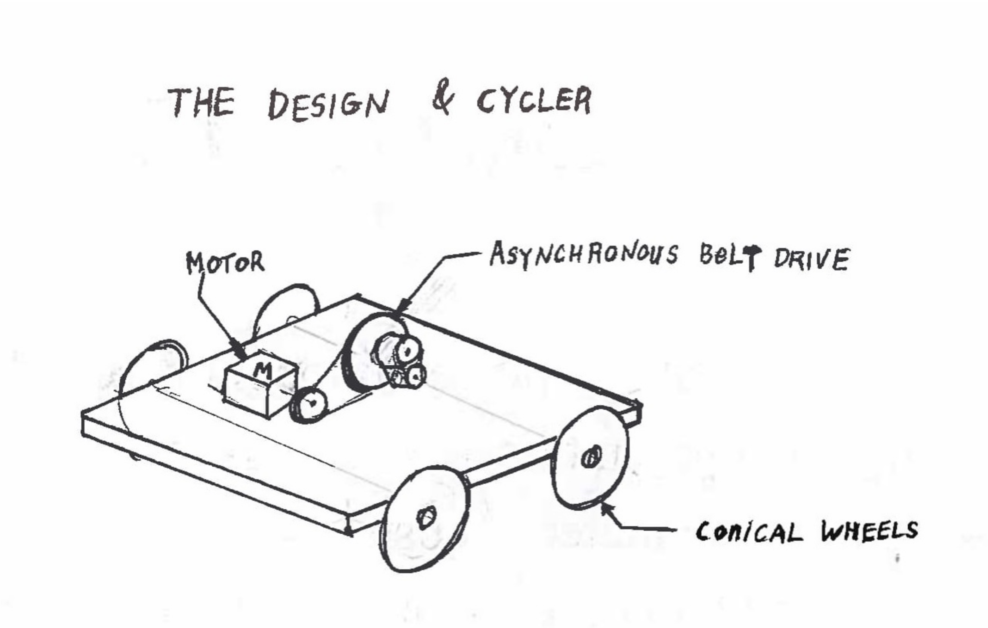


Figure 25: The Design Cycler Concept Sketch

Description: The Design Cycler involves a multiple asynchronous belt drive mechanism that reduces the speed. The motor is directly connected to the batteries and is controlled by a single switch, making this vehicle single speed. Conical wheels enable smoother turning and better control.

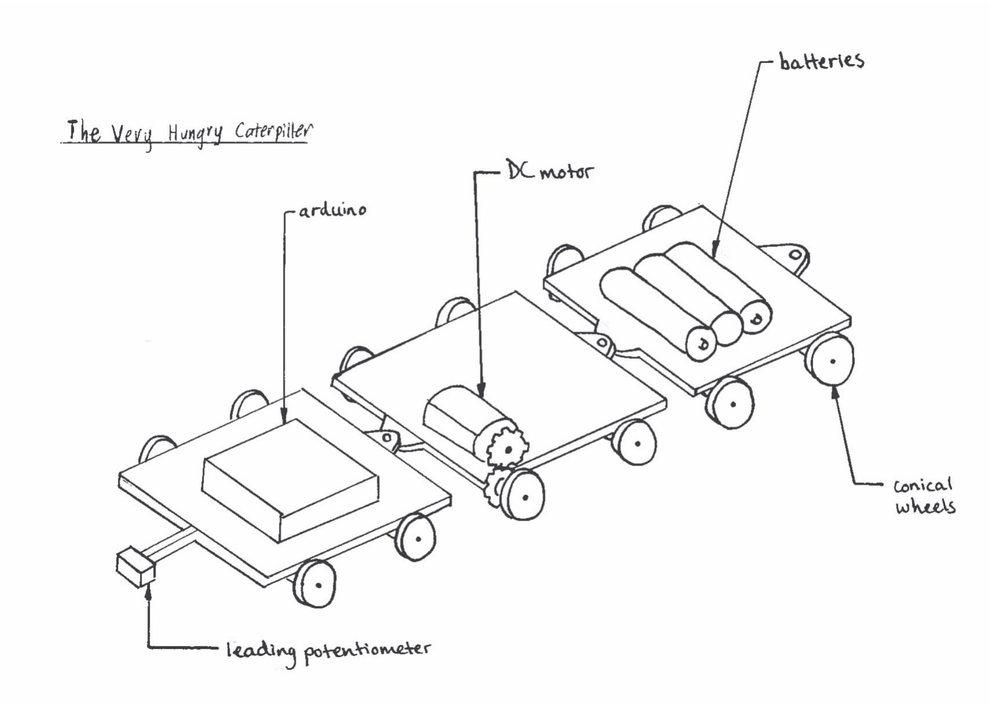


Figure 26: The Very Hungry Caterpillar Concept Sketch

Description: The Very Hungry Caterpillar (TVHC) is a multiple car locomotive design. Each car supports a different component; and the middle cart is directly driven by the DC motor. This design involves a potentiometer coupled with an arduino to detect turns and slow down.

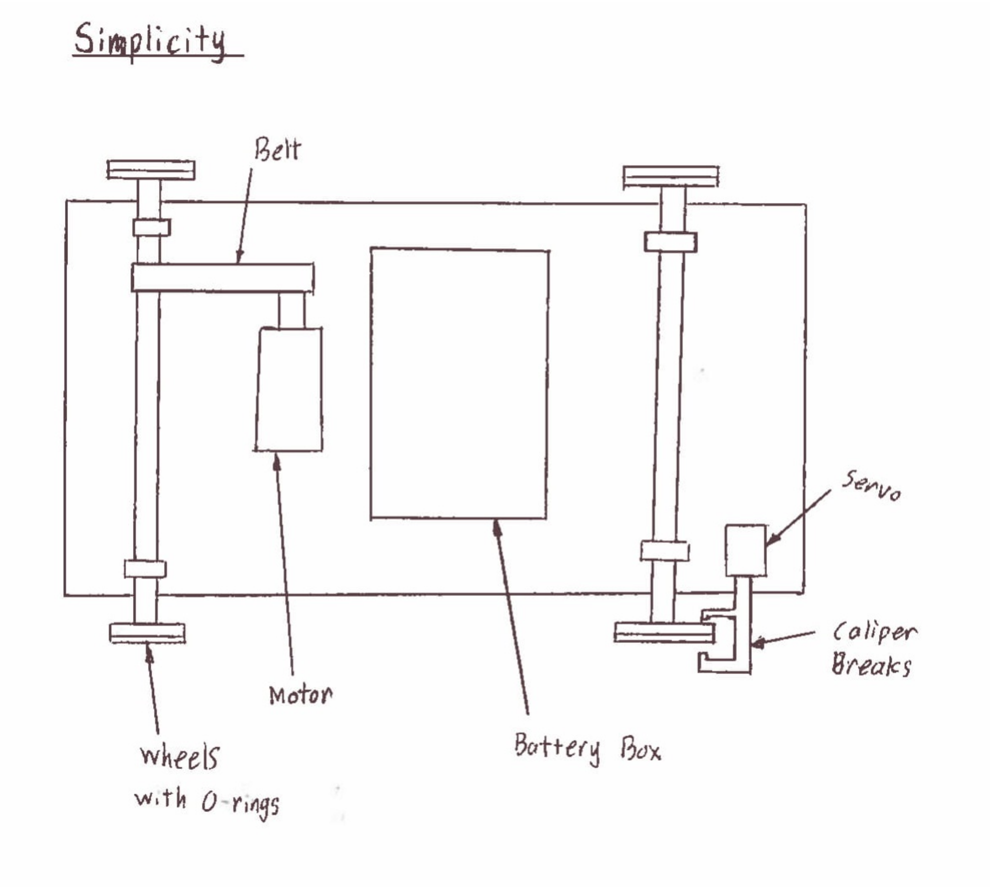


Figure 27: Simplicity Concept Sketch

Description: Simplicity has relatively few components. It uses a belt drive system and caliper brakes to control speed. Wheels with o-rings allow for better cornering.

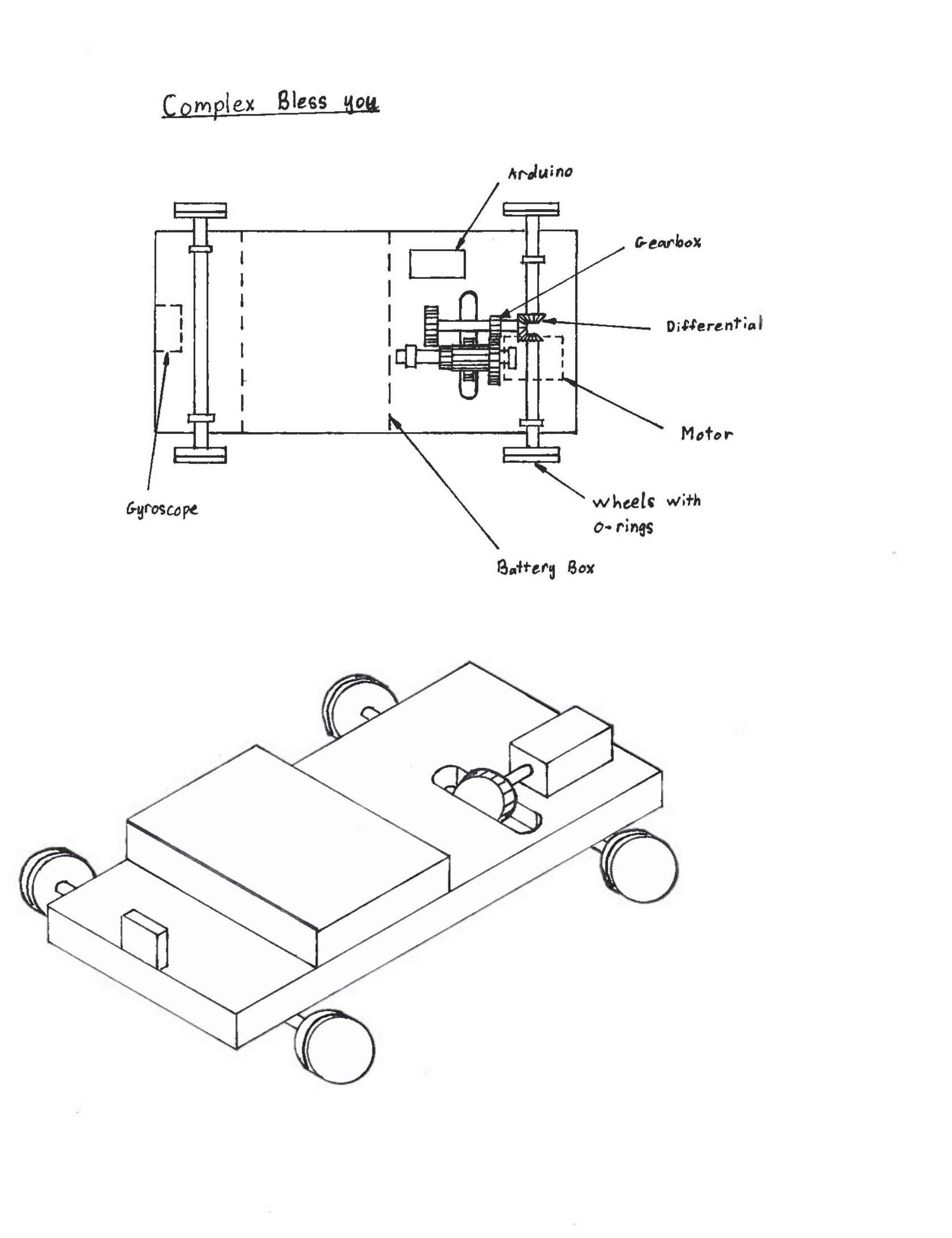


Figure 28: Complex Bless You

Description: After noticing the similarity between multiple concepts, we combined them into a single, improved design. Complex bless you is a combination of the above designs Complexity (Figure B3), Too Many Gears (Figure B9) and Bless You (Figure B2). This design features a gyroscope to detect turns and an arduino to control the speed in the gearbox. Wheels with o-rings and a slip differential allow for smooth turning. The gearbox is dual speed and can be controlled by the arduino through the servo.

C Winnowing

Concept Fragments	Jet engine	Fan/propellor	Friction drive
Feasibility	n	n	y
Requirements			
Only use DC motor for driving	n		y
Pass Fragment?	NO	NO	YES
Justification	Must use DC Motor	See calculations ASDFCHANGE	

Table 2: Turn Energy into Mechanical Energy Winnowing

Concept Fragments:	Direct drive	Gearbox	Belt drive	Chain drive	Friction Drive
Feasibility	y	y	y	y	y
Requirements					
Only use DC motor for driving	y	y	y	y	y
No hazardous/ prohibited materials	y	y	y	y	y
Only contact rails	y	y	y	y	y
Must stay the same dimensions	y	y	y	y	y
Battery supply <9.5V	y	y	y	y	y
Drive system must use provided batteries	y	y	y	y	y
Only electrical sources of batteries	y	y	y	y	y
Technical Readiness	y	y	y	n	y
Pass Fragment?	YES	YES	YES	NO	YES
Justification				Couldn't source; too difficult to manufacture in house	

Table 3: Transfer Energy from Motor to Wheels Winnowing

Concept Fragments:	Drum brake	Caliper brakes	Disc brakes	Electrical brakes	Air Brakes
Feasibility	y	y	y	y	y
Requirements					
No hazardous/ prohibited materials	y	y	y	y	y
Only contact rails	y	y	y	y	y
No affixing to track	y	y	y	y	y
No tethered or launched materials	y	y	y	y	y
Must stay the same dimensions	y	y	y	y	n
Battery supply <9.5V	y	y	y	y	
Drive system must use provided batteries	y	y	y	y	
Only electrical sources of batteries	y	y	y	y	
Technical Readiness	y	y	y	y	
Pass Fragment?	YES	YES	YES	YES	NO
Justification					The train must stay the same size

Concept Fragments:	Potentiometer	Gyroscope & accelerometer	Light sensor	Time based	None
Feasibility	y	y	y	n	y
Requirements					
No hazardous/ prohibited materials	y	y	y		y
Must be autonomous	y	y	y		y
Battery supply <9.5V	y	y	y		y
Only electrical sources of batteries	y	y	y		y
Technical Readiness	y	y	y		y
Pass Fragment?	YES	YES	YES	NO	YES
Justification				This would be an incredibly unreliable way of detecting turns because there is no feedback	

Table 5: Detect Turns Winnowing

Concept Fragments:	Conical wheels	Slip	Slip differential	Heavily segmented locomotive
Feasibility	y	y	y	y
Requirements				
No hazardous/ prohibited materials	y	y	y	y
Only contact rails	y	y	y	y
No affixing to track	y	y	y	y
No tethered or launched materials	y	y	y	y
Must stay the same dimensions	y	y	y	y
Take 24in (radius) corners	y	y	y	y
Technical Readiness	y	y	y	y
Pass Fragment?	YES	YES	YES	YES

Table 6: Turn Relative to Ground Winnowing

Concept Fragments:	High Torque	Sticky arms	Spike	High momentum
Feasibility	y	y	y	y
Requirements				
No hazardous/ prohibited materials	y	y	y	y
Only contact rails	y	n	n	y
No affixing to track	y			y
Must be autonomous	y			y
No tethered or launched materials	y			y
Technical Readiness	y			y
Pass Fragment?	YES	NO	NO	YES
Justification		It would be almost impossible to ensure that the sticky arms only contacted the rails	Spike would be in contact with track ties	

Table 7: Move Up Steep Inclines Winnowing

Concept Fragments	Conical wheels	Wheels with o-ring	Tank treads
Feasibility	y	y	y
Requirements			
Only contact rails	y	y	y
No affixing to track	y	y	y
Take 24in (radius) corners	y	y	n
Technical Readiness	y	y	
Pass Fragment?	YES	YES	NO
Justification			The tank treads would not be able to stay on the tracks and still take the turn

Table 8: Stay Aligned with Rails Winnowing

Concept Fragments:	Box chassis	Drill to plate	Adhere to plate	Potting	Gingerbread
Feasibility	y	y	y	y	y
Requirements					
No hazardous/ prohibited materials	y	y	y	y	y
Technical Readiness	y	y	y	y	
Pass Fragment?	YES	YES	YES	YES	YES

Table 9: Attach Components to Locomotive Winnowing

Concept Fragments:	Screw	Rope	Link	Pin	Glue	Clip
Feasibility	y	y	y	y	y	y
Requirements						
No hazardous/ prohibited materials	y	y	y	y	n	y
Connect to cargo cart	y	y	y	y		y
Technical Readiness	y	y	y		y	y
Pass Fragment?	YES	YES	YES	YES	NO	YES
Justification					The glue would damage the connection, and would not be removable	

Table 10: Connect to Carts Winnowing[13]

[13]None of these concept fragments were implemented as a connection was supplied by the instructors

Concept:	Tanky Train	Get Hitched	Pump Chump	Puff	Simplicity
Brought Forward	n	y	y	y	y
Feasibility		y	y	y	y
Requirements					
Max 6in tall		y	y	y	y
Max 8in wide		y	y	y	y
Accomodate rail width 3.51mm		y	y	y	y
Only use DC motor for driving force		y	y	y	y
No hazardous/ prohibited materials		y	y	y	y
Only contact rails		y	y	y	y
No affixing to track		y	y	y	y
Must be autonomous		y	y	y	y
No tethered or launched materials		y	y	y	y
Must have height between 0.5in and 2.5in for 0.1s		y	y	y	y
Must stay the same dimensions		y	y	y	y
Battery		y	y	y	y

Concept:	Complexity	The Very Hungry Caterpillar	Propulsion Driven Locomotive	Bless You
Brought Forward	y	y	n	y
Feasibility	y	y		y
Requirements				
Max 6in tall	y	y		y
Max 8in wide	y	y		y
Accomodate rail width 3.51mm	y	y		y
Only use DC motor for driving force	y	y		y
No hazardous/ prohibited materials	y	y		y
Only contact rails	y	y		y
No affixing to track	y	y		y
Must be autonomous	y	y		y
No tethered or launched materials	y	y		y
Must have height between 0.5in and 2.5in for 0.1s	y	y		y
Must stay the same dimensions	y	y		y
Battery supply <9.5V	y	y		y
take 24in corners	y	y		y

Concept:	Too Many Gears	The Design Cycler	Back to the Grind	Complex Bless You
Brought Forward	y	y	y	y
Feasibility	y	y	y	y
Requirements				
Max 6in tall	y	y	y	y
Max 8in wide	y	y	y	y
Accomodate rail width 3.51mm	y	y	y	y
Only use DC motor for driving force	y	y	y	y
No hazardous/ prohibited materials	y	y	y	y
Only contact rails	y	y	y	y
No affixing to track	y	y	y	y
Must be autonomous	y	y	y	y
No tethered or launched materials	y	y	y	y
Must have height between 0.5in and 2.5in for 0.1s	y	y	y	y
Must stay the same dimensions	y	y	y	y
Battery supply <9.5V	y	y	y	y
take 24in corners	y	y	y	y
Connect to	y	y	y	y

D Pugh Charts

Evaluation Criteria	Concept 5-Simplicity		Concept 2-Get Hitched		Concept 3-Pump Chump		Concept 4-Puff		Concept 7-The Very Hungry Caterpillar		Concept 11-the design cycler		Concept 12-Back to the Grind		Concept 13-Complex Bless You	
	Simple Belt-drive design		*Dual Motor 4 wheel drive with simple gears*		*Direct drive with servo brakes and light sensor*		*Motorized gearbox with potentiometer detection*		*Segmented lightweight design*		*Double belt 4 wheel drive with conical wheels*		*Motorized gearbox with slip differential and o-ring wheels*		*Friction Drive with a gyroscope*	
		Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification
Aesthetics	S	Datum	S	Will have the same cover as other designs	+	Looks better because in the final design there will be a mechanism that looks like a man pumping water	S	Will have the same cover as other designs	S	Will have the same cover as other designs	S	Will have the same cover as other designs	S	Will have the same cover as other designs	S	Will have the same cover as other designs
Energy	S	Datum	-	Requires more energy to power multiple motors	-	Has the same number of electrical components, requiring approximately the same energy	S	Has the same number of electrical components, requiring approximately the same energy	S	Has the same number of electrical components, requiring approximately the same energy	S	The same number of electronic components are used including a servo, batteries, and the motor. The system will consume roughly the same amount of energy	+	Fewer number of electronic components (same components except a servo)	S	Will have the same number of electrical components , requiring approximately the same energy
Cost	S	Datum	-	Greater number of high precision gears cost higher than a pair of pulley connected via belt	S	Very similar designs, with similar components	-	The gearbox is more expensive than the belt drive	-	Costs more to create all the different carts	+	A single belt and three pulleys are less expensive	+	Simpler components which cost less reduces the cost	-	It has many more mechanical components , of greater complexity, such as the slip differential which will increase cost
Acceleration	S	Datum	+	Less force on each motor, therefore we can get more acceleration	S	Approximately the same weight, and the same force provided by the motor	+	Due to variable gears, we could create more acceleration	-	Is being driven from only one cart, which makes it more difficult to accelerate	+	May accelerate faster due to the double pulley system	-	No gear ratio to increase the acceleration we can get from the motor	+	Has variable gear ratios, and so a greater gear ratio could be achieved to increase stability
Torque	S	Datum	+	If the load is added, independent motors are able to output higher power	S	Has the same number of motors, and the gear ratio would be designed the same	+	Lower gear ratios with the gearbox would give you more torque	S	Torque is supplied by one motor, so it'll be the same as the simplicity	-	Less torque because a single motor power is split between two pulley connected over a single belt	-	Friction by itself doesn't provide sufficient torque	+	The design includes a gearbox that provides higher torque.

Table 14: Pugh Chart using Simplicity as a Datum

Stability	S	Datum	+	Has lower centre of gravity since the motor is in line with the axle	+	Has conical wheels which are more stable because they sit within the tracks and will not slide off of the tracks due to flanges	+	Conical Wheels are expected to provide more stability throughout turns than a regular wheel	-	Each cart is respectively more likely to fall off of the tracks	-	Even with flanges around the central pulley, the object is unstable because of friction around the belt	+	Has a detector for turns, and therefore would be able to slow down before turns, increasing stability	+	Both have the same wheels, but being able to detect turns and adjust speeds would make it more stable throughout the whole course
Expected Durability	S	Datum	S	Has relatively simple components, that are easy to replace if they break	-	Belt wears off faster than the rest of the components	-	Has gears which are more likely to break than a belt	-	This has more parts to it, which are more likely to break	S	Faster wear of a single belt wrapped around three pulleys	-	The drive wheel will wear out very fast	-	Has many more moving parts that could become damaged upon impact or mishandling
Risk	S	Datum	-	More difficult to get the motors to drive in sync, and therefore, we risk not completing the design	S	Has the same types of components which we are familiar with	+	Gearbox is unfamiliar and difficult to make	+	Will be more difficult to get the carts to turn/follow each other properly	S	Expected to complete within the same period because the components are simple enough to make	-	Very difficult to have a functioning friction drive that is reliable. It would be very prone to slipping which would make the transfer of energy very inefficient	-	The design is much more complicated to design and complete on time.
∑+	0		3		2		4		1		2		3		3	
∑S	8		2		4		2		3		4		1		2	
∑-	0		3		2		2		4		2		4		3	
Net Score	0		0		0		2		-3		0		-1		0	
Rank [2]	2		2		2		1		8		2		7		2	

Table 15: Pugh Chart using Simplicity as a Datum

Evaluation Criteria	Concept 4- Puff		Concept 2 - Get hitched		Concept 3- pump chump		Concept 5 - Simplicity		Concept 11-the design cycler		Concept 13-complex bless you	
	Motorized gearbox with potentiometer detection		*Dual Motor 4 wheel drive with simple gears*		*Direct drive with servo brakes and light sensor*		*Simple belt-drive design*		*Segmented lightweight design*		*Double belt 4 wheel drive with conical wheels*	
		Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification	+/S/-	Ranking Justification
Aesthetics	S	Datum	S	Will have the same cover as other designs	+	Looks better because it has a nifty guy pumping the train like on an old fashioned train	S	Will have the same cover as other designs	S	Will have the same cover as other designs	S	Will have the same cover as other designs
Energy	S	Datum	-	Requires more energy to power multiple motors	S	Has the same amount of electrical components given that the man's arms are powered by the rotation of the wheels	S	Has the same number of electrical components, requiring approximately the same energy	S	Has approximately the same number of electrical components, requiring approximately the same energy	S	There's similar power output because they both have one motor
Cost	S	Datum	S	Cost of motor offset by the cost of high precision gears in the gearbox	S	Very similar designs, with similar components	+	The simple belt-drive would cost less than developing a gearbox	+	The pulley system required would cost less than the development of high precision gears	-	Requires us to fabricate a differential, which is more expensive than the fabrication of conical wheels
Acceleration	S	Datum	-	Cannot change the gear ratio, therefore would only be able to be driven at a (likely lower) acceleration	-	Because it is not variable, it performs worse than Puff	-	Fixed ratio between pulleys means that it wouldn't be able to accelerate much because we couldn't change gears	-	Puff has a gear box which allows it to change to a greater acceleration	S	The same gear ratio can be achieved with each design using a gear box
Torque	S	Datum	S	With 2 motors, this design could match the torque supplied by the gear ratio	S	Has the same number of motors, and the gear ratio would be designed the same	-	Unchangeable gear ratios mean the torque will always be at its maximum, and cannot go as high as Puff	-	Torque is less due to instability during turning	S	The same gear ratio can be achieved with each design using a gear box
Stability	S	Datum	-	Can't detect turns and so cannot slow down to be stable for turns	S	Both have conical wheels and a method of detecting curves	-	This train is more likely to slip off of the track because the wheels must roll on top	S	Even with flanges around the central pulley, the object is unstable because of friction around the belt	-	This design is just as stable since it has conical wheels and also has a sensor
Expected Durability	S	Datum	+	Has relatively simple components, that are not needed within small tolerances. Has more play with wear	-	Belt wears off faster than the rest of the components. Also the braking system acts on the belt itself which would make it wear down even faster	-	The belt is more likely to wear down than the gears, and it has caliper brakes which would wear on the wheels	-	The pulley may slip off the pulleys, and will wear especially when pulled against the side of the pulleys	-	The differential is more likely to wear out as opposed to the conical wheels
Risk	S	Datum	+	Has only the difficulty of syncing the motors, whereas the datum has the difficulty of setting the sensor and gearbox	+	There's no gearbox which lowers the risk of the design, but the light sensor is just as difficult to use as a potentiometer	+	The very simple design is manageable for our team experience with belt-drives as opposed to a gear box	-	Getting a design that is able to turn with the belt maintaining the same power transfer would be very difficult to accomplish in our time frame	-	This one is more difficult to create in time since we would need to figure out how to implement a differential and a gearbox, both of which we are unfamiliar with
∑+	0		2		2		2		1		0	
∑S	8		3		4		2		3		4	
∑-	0		3		2		4		4		4	
Net Score	0		-1		0		-2		-3		-4	
Rank [1]	1		3		1		4		5		6	

Table 16: Pugh Chart using Puff as a Datum

E Prototype Tests

E.1 Feasibility Calculation for Fan Propulsion

The force required to move is greater than the frictional force of the train:

$$F > \mu m g \tag{1}$$

We assume our train will have $m \approx 0.5\text{kg}$[14] and $\mu_s \approx 0.6$

$$F = (0.6)(0.5\text{kg})\left(10\frac{\text{m}}{\text{s}^2}\right) \tag{2}$$

$$= 3\text{N} \tag{3}$$

The force from the fan can be found using the following formula assuming the motor has a maximum power output of 19W (Mabuchi Motors, 2018).

$$P = \sqrt{\frac{F^3}{2\rho A}} \tag{4}$$

Solving for area:

$$A = \frac{F^3}{2\rho P^2} \tag{5}$$

$$= \frac{(3\text{N})^3}{2\left(1.225\frac{\text{kg}}{\text{m}^3}\right)(19\text{W})^2} \tag{6}$$

$$= 0.03\text{m}^2 \tag{7}$$

Assuming the fan sqeeps a circular path:

$$A = \pi r^2 \tag{8}$$

$$r = \sqrt{\frac{A}{\pi}} \tag{9}$$

$$r = 0.10\text{m} \tag{10}$$

Our train must have a height smaller than 6” (15.24cm) above the rails. The diameter of the fan is too large to fit within this restriciton.

[14] A cargo cart is 450g unloaded, this assumes we will carry roughly 50g of cargo

Prototype design	Number of derails
Conical wheels, low CoG	2
Cylindrical wheels, low CoG	5
Conical wheels, high CoG	9

Table 17: Wheel Design Test Results

E.2 Wheel Testing

We decided to test the wheel shapes due to the emphasis on stability in our strategy. We tested the wheel designs using the following procedure:

1. Create chassis with various centeres of gravity
2. Combine chassis designs with cylindrical or conical wheels
3. Release chassis from top of slope towards a corner
4. Record number of derailments across 9 trials

E.3 Calculation of Dual Drive Torque

We needed to compare the use of multiple motors to the use of a single motor. We used a simple calculation since this was much faster than creating a physical prototype. We compared a single motor and two motors in parallel (Figure 29).

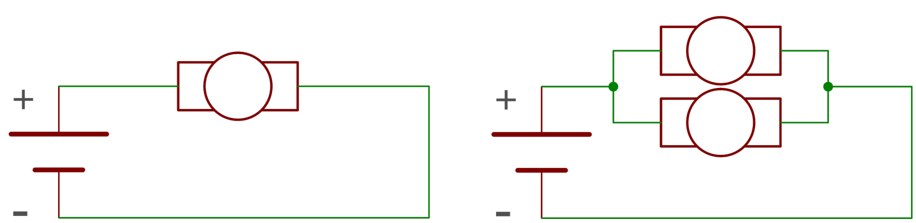


Figure 29: Possible Motor Configurations

If we can assume the two DC motors provide the same resistance in phase, then the total resistance will be half of the resistance when flowing through only one motor. This means the total current running through the source is double that of the current when only one motor is attached. The current in branch is the same (by Kirchhoff's Current Law) and each motor outputs the same torque as the single motor. Since we now have two motors, the total torque is twice that of a single motor.

By this logic, so long as other factors do not have a significant negative impact on our design, there is no disadvantage to using multiple motors provided our battery life is sufficient.

Mass	Max incline climbed
0.589kg	22°

Table 18: Torque Test Data

E.4 Calculation of Prototype Torque

This test was conducted to determine if the train could exert sufficient torque to push itself up the incline or if it could pull cargo as well. The train was placed on the track and the motor turned on. We began increasing the incline of the track until the motor stalled. We recorded this maximum incline for the prototype, and weighed the prototype. Using this data, we calculated the max torque output of the motor.

$$F_{x'} = ma_{x'} \tag{11}$$

$$a_{x'} = 0\,(\text{static}) \tag{12}$$

$$F_{x'} = mg\sin\theta - F_{\text{motor}} \tag{13}$$

$$\frac{T_{\text{motor}}}{r_{\text{wheel}}} = mg\sin\theta \tag{14}$$

$$T_{\text{motor}} = mg\sin\theta * r_{\text{wheel}} \tag{15}$$

$$T_{\text{motor}} = (0.589\text{kg})\left(9.81\frac{\text{m}}{\text{s}^2}\right)\sin 22^\circ * 0.015\text{m} \tag{16}$$

$$T_{\text{motor}} = 32.5\text{mN} * \text{m} \tag{17}$$

This output was much lower than we expected. We needed to increase the gear ratio we were using or we needed to add motors to increase the amount of torque supplied.

E.5 Frictional Data Test

We determined the coefficient of static friction of our wheels to determine the maximum amount of force that could be used. We locked the wheels of our train prototype and placed it on a slope with a variable incline. We varied the angle of the slope until the train began to slip, then we used the following equations to calculate a value for the coefficient of friction.

	PLA	Rubber coating	Rubber band
θ(degrees)	9.64	35	52.4
μ	0.17	0.7	1.3

Table 19: Static Coefficient of Friction Data

$$F_{x'} = ma_{x'} \tag{18}$$

$$a_{x'} = 0\,(\text{static}) \tag{19}$$

$$F_{x'} = mg\sin\theta - \mu mg\cos\theta = 0 \tag{20}$$

$$g\sin\theta = \mu g\cos\theta \tag{21}$$

$$\mu = \tan\theta \tag{22}$$

The drastic increase in friction demonstrated that we needed to use a cover on our wheels, and it showed that the rubber band would be best for this purpose.

E.6 Light Sensor Test

In order to test the feasibility of using a light sensor to count track ties we attached it to the bottom of our train with two LEDs to illuminate the tracks.

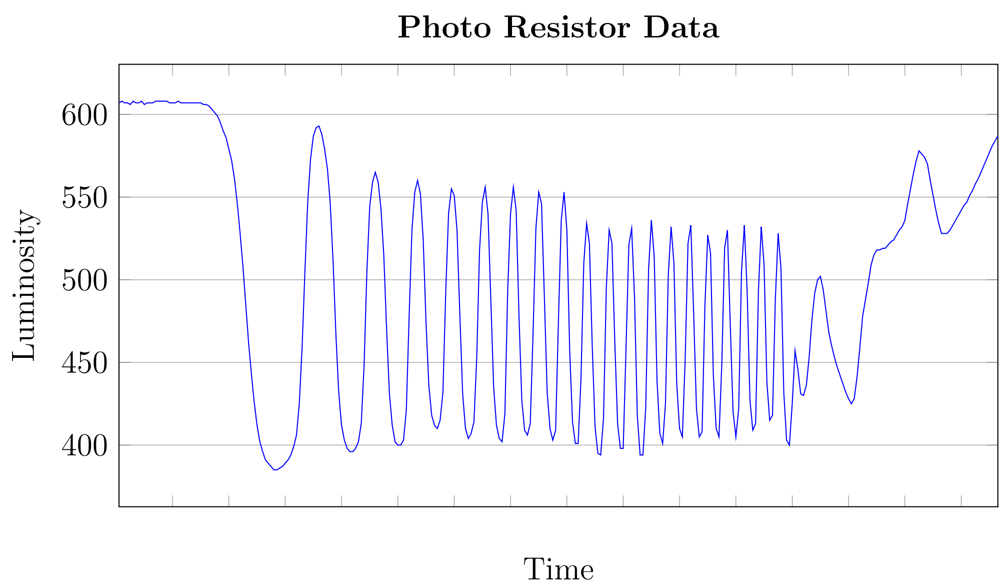


Figure 30: Photoresistor Track Detection Data[15]

This physical test allowed us to determine if the photoresistor would be able to differentiate between the track ties. The data above shows the peaks and troughs as the prototype passed over the rails. They become closer together as the prototype accelerated. This test demonstrated that our braking system was feasible since it was possible for an Arduino to count the number of track ties is passes from this data.

[15]The axes lack dimensions because they are raw values taken from an Arduino

E.7 Track Simulation

We wanted to test the parameters of our prototype on the tracks. Without access to the course, we decided to create a simulation that completed the following tasks (Figure 31) to model the prototype completing the track.

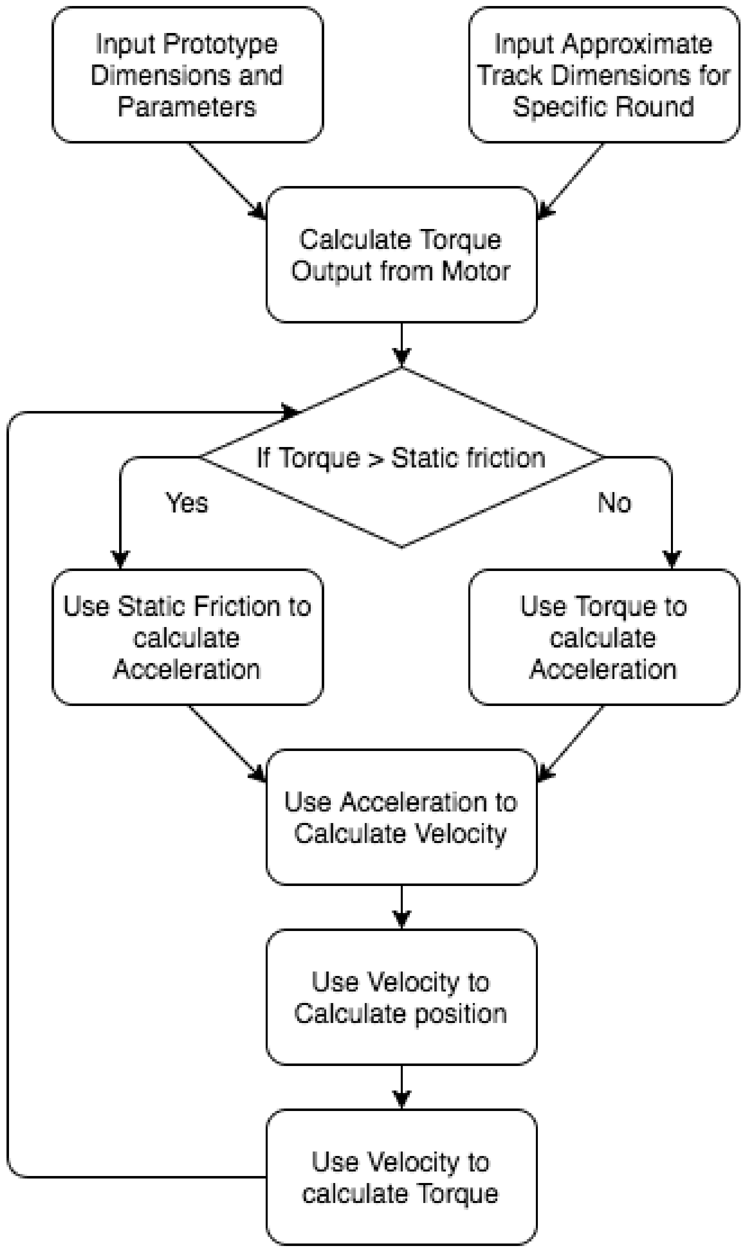


Figure 31: Simulation Flow Chart

The algorithm above was repeated until the train completed the length of track for the round, and the results were plotted. Our simulation showed that the prototype reached a speed much higher than the calculated tipping velocity of 1.2m/s (Desmos Graphing Calculator, 2018). This demonstrated that we needed to use a braking system to reduce our speed going into corners.

F Weighted Decision Matrix

Evaluation Criteria		*Concept 4- Puff* *Motorized gearbox with potentiometer detection*			*Concept 2- Get Hitched* *Dual motor 4 wheel drive with simple gears*			*Concept 3- Pump Chump* *Belt drive with servo brakes and light sensor*			*Concept 5- Simplicity* *Simple belt-drive design*		
	Weighting (%)	Rating (/10)	Rating Justification	Score	Rating (/10)	Rating Justification	Score	Rating (/10)	Rating Justification	Score	Rating (/10)	Rating Justification	Score
Competition Cost	20%	9	The calculated cost for this design was determined to be approximately $80	1.8	9	This design was calculated to be approximately $90 in price.	1.8	9	The calculated cost for this design was $85	1.8	9	The calculated cost for this design was determined to be approximately $80	1.8
Energy	20%	4	This design would require the same amount of energy as the other designs to pull up the same amount of weight.	0.8	3	This design is slightly heavier due to its extra motor and therefore would require slightly more energy to move the car.	0.6	4	This design would require the same amount of energy as the other designs to pull up the same amount of weight.	0.8	4	This design would require the same amount of energy as the other designs to pull up the same amount of weight.	0.8
Derailment Stability	25%	8	This design uses conical wheels, which derailed 2 times out of 9 trials. It has a low center of gravity.	2	8	This design uses conical wheels, which derailed 2 times out of 9 trials. It has a low center of gravity.	2	5	This design uses conical wheels, which derailed 2 times out of 9 trials. However it has a high centre of gravity, which derailed 9 times.	1.25	5	This design uses cylindrical wheels, which derailed 5 times with a low centre of gravity.	1.25
Cargo Transfer Ability	10%	4	This design was able to exert 32mN*m of force before stalling	0.4	8	This design is expected to perform twice as well as a similar design with only one motor	0.8	1	The belt drive could not transport cargo without overheating or slipping	0.1	1	The belt drive could not transport cargo without overheating or slipping	0.1
Risk	25%	3	In this design, our team will need to create a gearbox and figure out how to make potentiometer detection work properly. Therefore, this design is manageable, but will require lots of time to complete.	0.75	5	The light sensor is likely easier to program, and the motors may be more difficult to set up in sync. However, even if the motors are out of sync, this design will be able to compete.	1.25	1	The belt drive wore down extremely quickly (~2min), and reduced the diameter of our pulleys to the point where there was a visible difference.	0.25	1	The belt drive wore down extremely quickly (~2min), and reduced the diameter of our pulleys to the point where there was a visible difference.	0.25
Net Score	100%			5.75			6.45			4.2			4.2
Rank				2			1			3			3

Table 20: Weighted Decision Matrix

G Preliminary Cost Estimates

G.1 Puff

Component	**Weight(g)**	**Price ($)**
Motor	42	3
Battery container	50	3
Wheels	28	1.12
Chassis	185	7.40
Axles	16	0.64
Servos	50	10
Arduino	10	27
Arduino battery	25	11
Brakes	0	5
Transmission	50	0.75
Differential	n/a	n/a
Miscallaneous	50	10
Turn detection device	50	2
Total	556	80.91

Table 21: Cost and weight of Puff

G.2 Get Hitched

Component	**Weight(g)**	**Price ($)**
Motor	42	6
Battery container	50	3
Wheels	28	1.12
Chassis	185	7.40
Axles	16	0.87
Servos	50	10
Arduino	10	27
Arduino battery	25	11
Brakes	0	5
Transmission	50	0.75
Differential	n/a	n/a
Miscallaneous	50	10
Turn detection device	50	8.50
Total	556	90.64

Table 22: Cost and weight of Get Hitched

G.3 Pump Chump

Component	Weight(g)	Price ($)
Motor	42	3
Battery container	50	3
Wheels	28	1.12
Chassis	185	7.40
Axles	16	0.87
Servos	50	10
Arduino	10	27
Arduino battery	25	11
Brakes	0	5
Transmission	50	0.75
Differential	n/a	n/a
Miscallaneous	50	10
Turn detection device	50	6
Total	556	85.14

Table 23: Cost and weight of Pump Chump

G.4 Simplicity

Component	**Weight(g)**	**Price ($)**
Motor	42	3
Battery container	50	3
Wheels	28	1.12
Chassis	185	7.40
Axles	16	0.87
Servos	50	10
Arduino	10	27
Arduino battery	25	11
Brakes	0	5
Transmission	50	0.75
Differential	n/a	n/a
Miscallaneous	50	10
Turn detection device	50	0
Total	556	79.14

Table 24: Cost and weight of Pump Chump

H Final Prototype Details

Specification	Target value	Final value
Mass	0.500kg	0.350kg
Top Speed	2m/s	1.56m/s
Height	87mm	90mm
Length	152mm	193mm
Width	77mm	100mm
Cost	$100	$80.43
Batteries	4	3

Table 25: Key Specifications for Target and Final Prototype

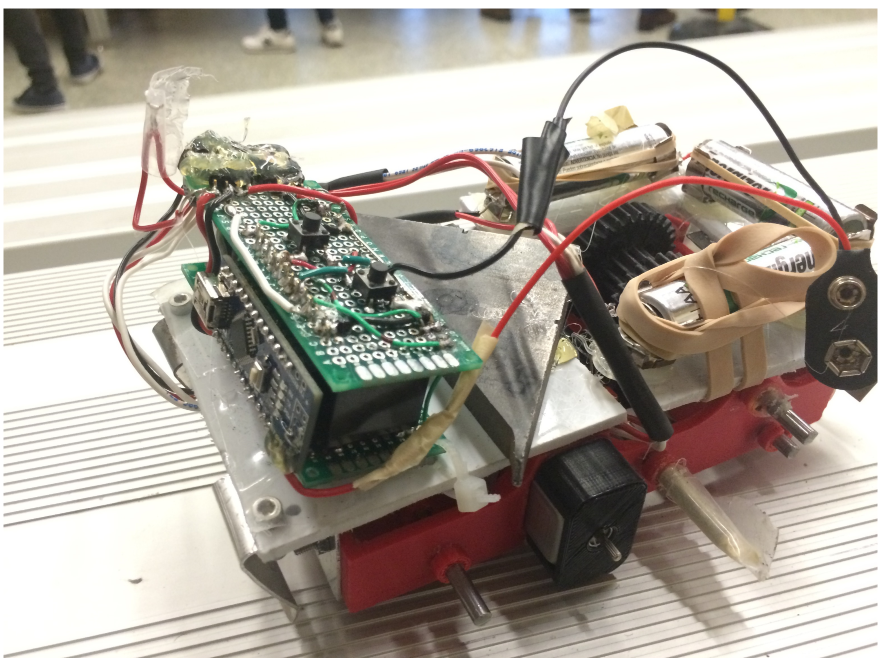


Figure 32: Final Prototype Circuitry Mounts

I Bill of Materials

Part	Part No.	Supplier and Website	Qty.	Unit Price	Currency	Unit Price (CAD)	Price
Nano Microcontroller	Elegoo Nano board CH340/ATmega328P, closest to A000005 Arduino product	Arduino https://store.arduino.cc/usa/arduino-nano	1	22	USD	$27.50	$27.50
PLA Filament (chassis, wheels, clips, gears)	N/A	MECH 223 Price Guidelines	80g	$0.04/g	CAD	$0.04/g	$3.20
Tight-Tolerance Multipurpose O1 Tool Steel Rod, 3.88mm Diameter x 915mm	47764	Fastenal https://www.fastenal.com/products/details/47764?term=O1+Steel+Drill+Rod&pageno=3	17.56"	$4.63/3ft	CAD	$4.63/3ft	$6.78
1/8" Acrylic Sheet	ACRY24470.187PM24X48	eplastics http://www.eplastics.com/ACRY24470-187PM24X48	76mm x 76mm plate + 85mm x 40mm plate	$46.96 /1152in^2	USD	$58.7/1152in^2	$0.72
Steel Sheet Metal (0.024")	S124	Metals Depot https://www.metalsdepot.com/steel-products/steel-sheet	5.49in^2	$9.24/2ft^2	USD	$11.55/2ft^2	$0.22
Cylindrical Battery Holder	534-092	Mouser https://ca.mouser.com/ProductDetail/Keystone-Electronics/92?qs=sGAEpiMZZMt13fpse6CWDYVh9FApKpUCF%2fjeT9O8KIw%3d	8.00	0.53	CAD	$0.53	$4.26
PM 4.5 V DC Motor Mabuchi	FC-280SA 2470	MECH 223 Price Guidelines	2.00	3.00	CAD	$3.00	$6.00
Subminiature Relay	HK 3FF	Lee's Electronics https://leeselectronic.com/en/product/3192.html	3.00	2.00	CAD	$2.00	$6.00
Photoresistor 5516 100V 540nm Light 5~10k Dark 500k	Photoresistor 5516 100V 540nm Light 5~10k Dark 500k DE4200	Dipmicro http://www.dipmicro.ca/store/PHRES-5516	1.00	0.38	CAD	$0.38	$0.38
Switch	TL3305AF260QG	Mouser https://ca.mouser.com/ProductDetail/E-Switch/TL3305AF260QG?qs=sGAEpiMZZMsgGjVA3toVBKeJCRa1nG8XqQWVbJ3%2fajg%3d	2.00	0.26	CAD	$0.26	$0.52
LED's	5588	Lee's Electronics https://leeselectronic.com/en/product/5588.html?search_query=LED+clear+orange&results=3	2.00	$1/5	CAD	$0.20	$0.40
370 ohm resistor	MF1/4DC3700F	Mouser https://ca.mouser.com/Passive-Components/Resistors/Through-Hole-Resistors/Images/_/N-7h7z5?P=1z0wl28	3.00	0.08	CAD	$0.08	$0.23
56 kohm resistor	SFR2500005602FR500	Mouser https://ca.mouser.com/ProductDetail/Vishay-BC-Components/SFR2500005602FR500?qs=sGAEpiMZZMsPqMdJzcrNwsdig2g%252bAcehw2AmwomhBHQ%3d	2.00	0.15	CAD	$0.15	$0.30
Battery Clip	HH-3449	Mouser https://ca.mouser.com/Power/Battery-Holders-Clips-Contacts/Images/_/N-cicxg?Nao=200	1.00	1.66	CAD	$1.66	$1.66
Circuit Boards	PC-3	All Electronics https://www.allelectronics.com/item/pc-3/solderable-perf-board-2-1/2-x-3-1/8/1.html	1 (split in half)	1.50	USD	$1.88	$1.88
Diodes	1n 58 18	Mouser https://ca.mouser.com/productdetail/?qs=JV7lzlMm3yJEIYWKtht%2FsQ%3D%3D	3.00	0.38	CAD	$0.38	$1.15
Accelerometer and Gyro Sensor	MPU-6050 GY521	Lee's Electronics https://leeselectronic.com/en/product/15544.html?search_query=Accelerometer+and+Gyro+Sensor+MPU-6050+GY521&results=1	1.00	14.50	CAD	$14.50	$14.50
9V Duracell Battery	610237	Walmart https://www.walmart.ca/en/ip/duracell-coppertop-9v/6000016956627	1.00	2.74	CAD	$2.74	$2.74
Miscellaneous	N/A	MECH 223 Price Guidelines	N/A	N/A	N/A	N/A	$2.00
Elastic Bands							
Hot Glue							
M3 Screws			6				
M3 Nuts			5				
Pop Bottle							
Paint							
Paper							
Bugles							
Yarn							
Electrical Tape							
Wire							
Headers							
Epoxy							
						Total	$80.43

Table 26: Bill of Materials