Design Considerations for an Electric Locomotive

for

MECH223 Instructors

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by

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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.

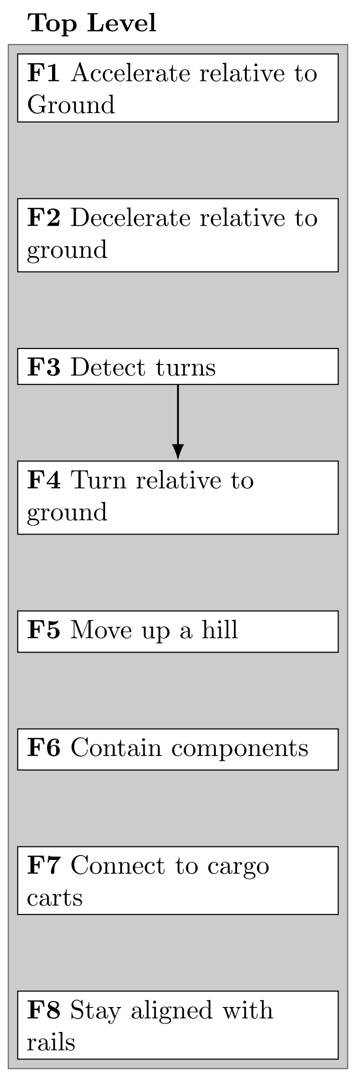

Figure 1: Top-Level Functions

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.

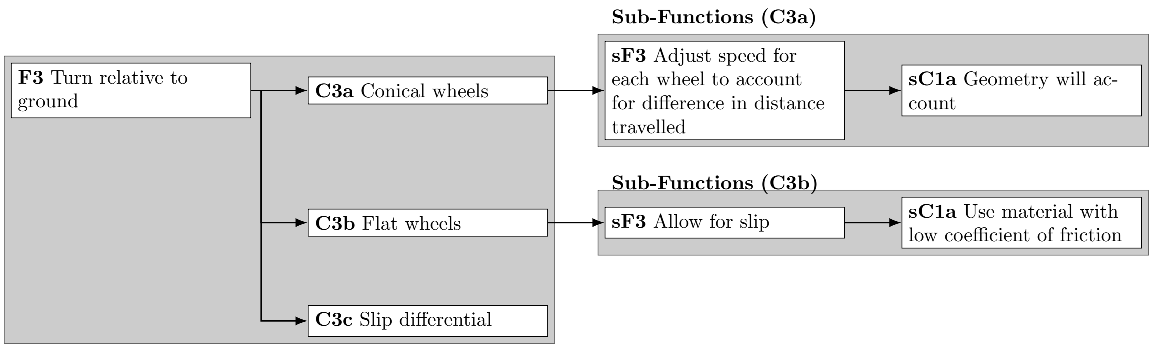

Figure 2: Function Decomposition, Turn Relative to Ground

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.

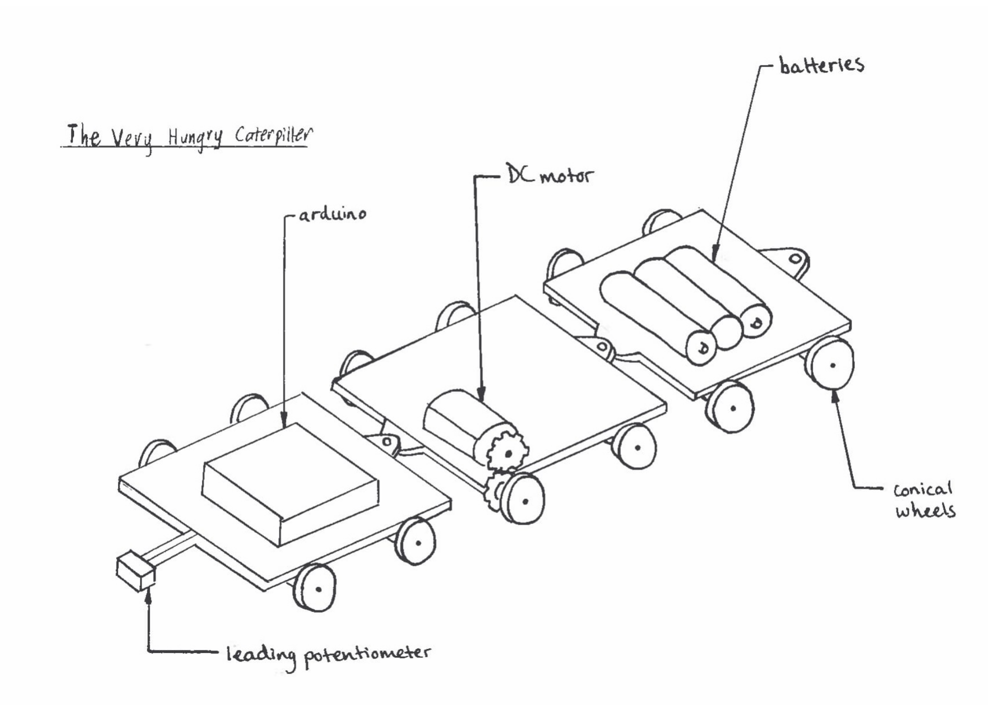

Figure 3: TVHC (The Very Hungry Caterpillar)

[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.

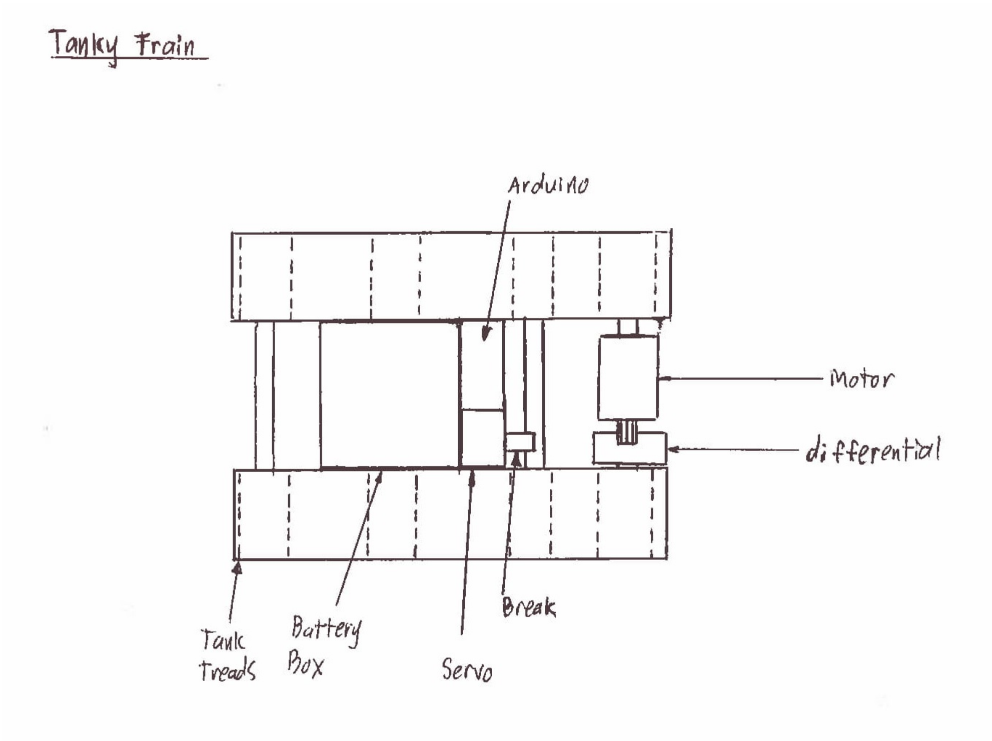

Figure 4: Tanky Train

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.

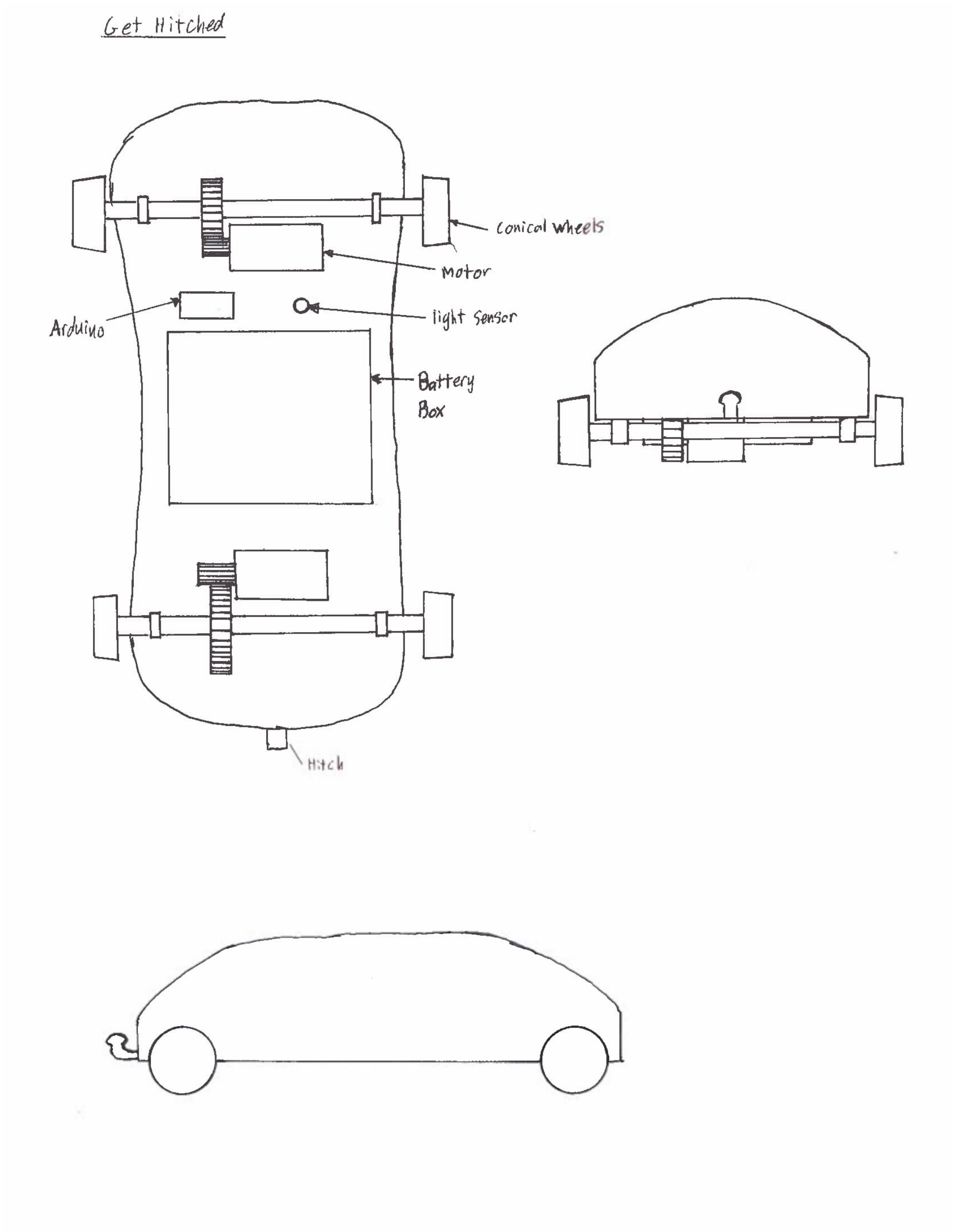

Figure 5: Get Hitched

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.

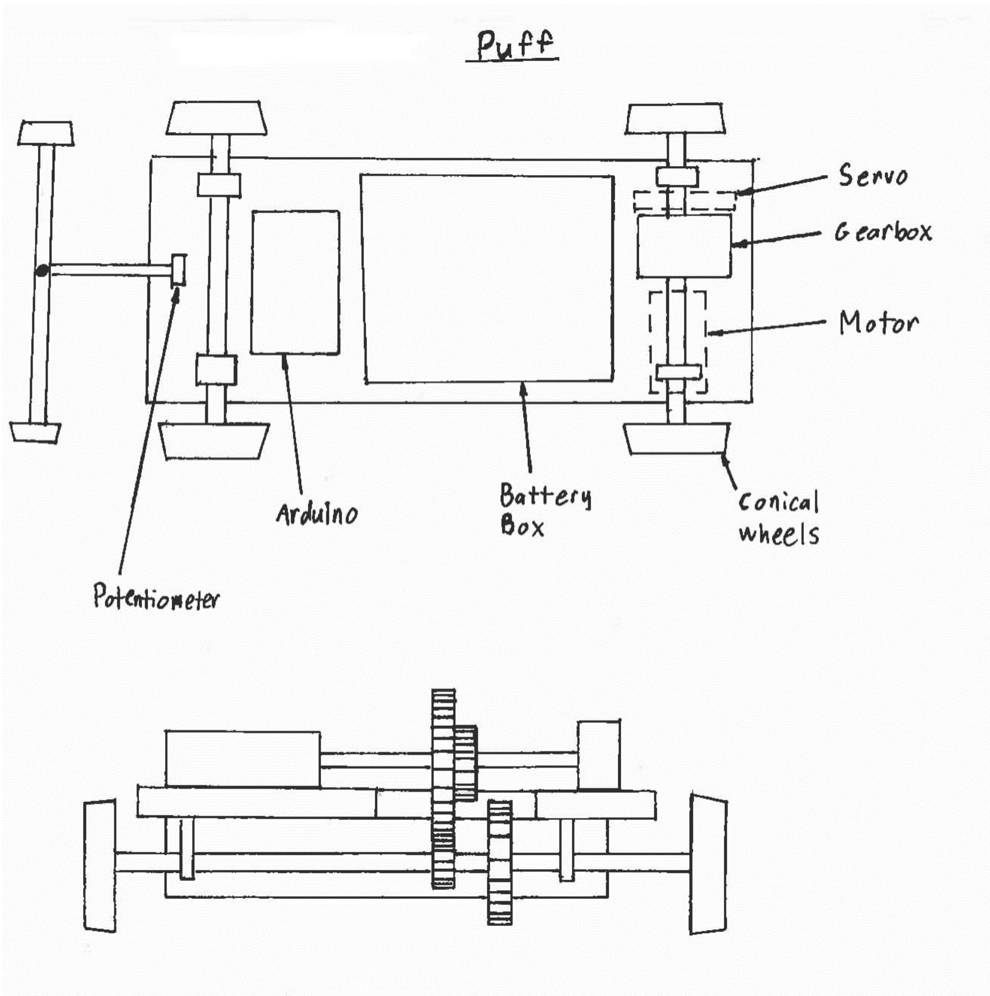

Figure 6: Puff

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.

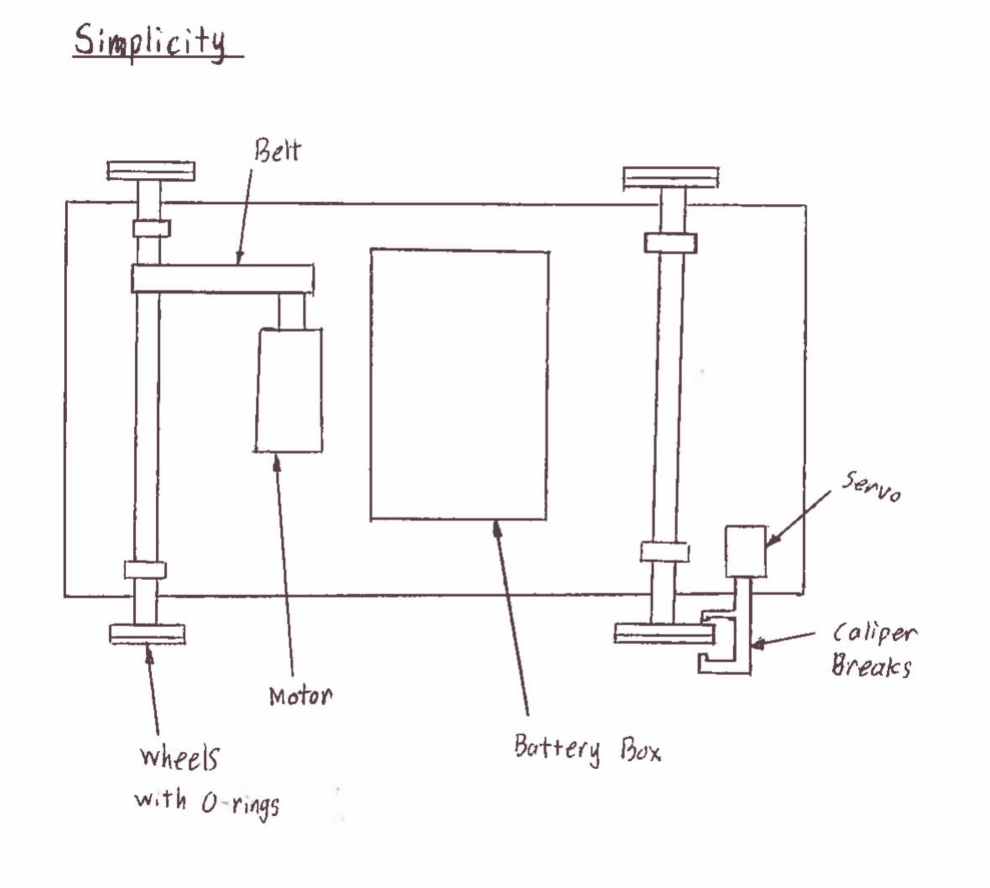

Figure 7: Simplicity

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.

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.

[2]See Appendix C: Winnowing Table C1-C9 Concept Fragment Winnowing
[3]See Appendix C: Winnowing Table C10-C11 Concept Fragment Winnowing
[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.

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).

[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

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.

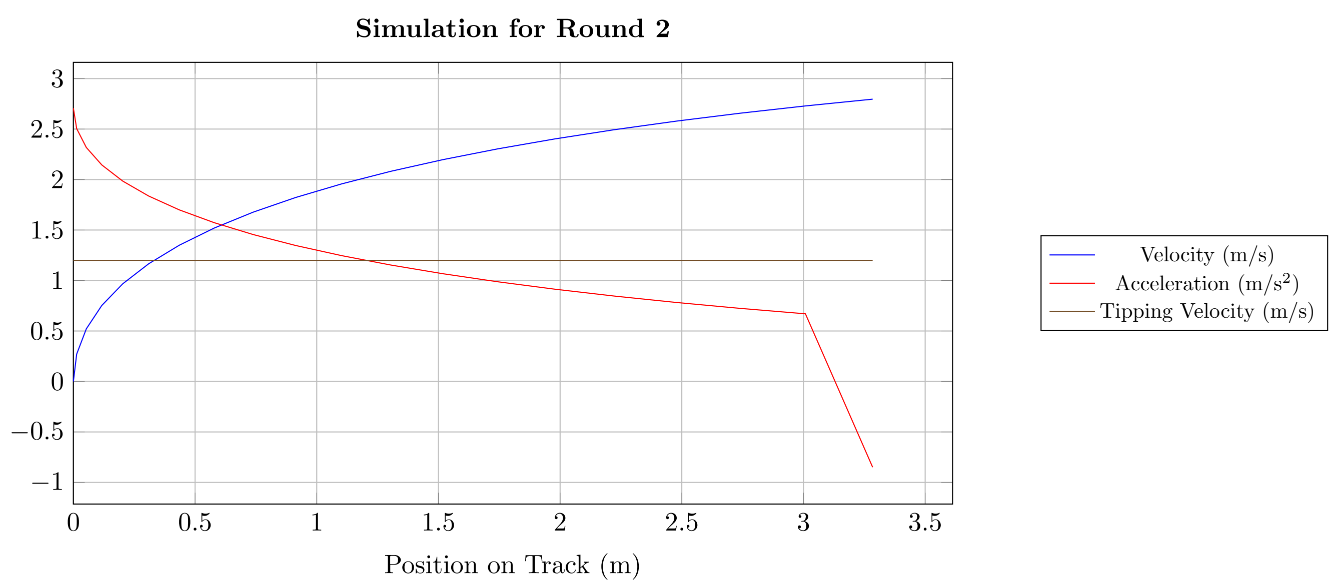

Figure 10: Simulation model

[9]See Appendix E: Prototype Tests Track Simulation

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.

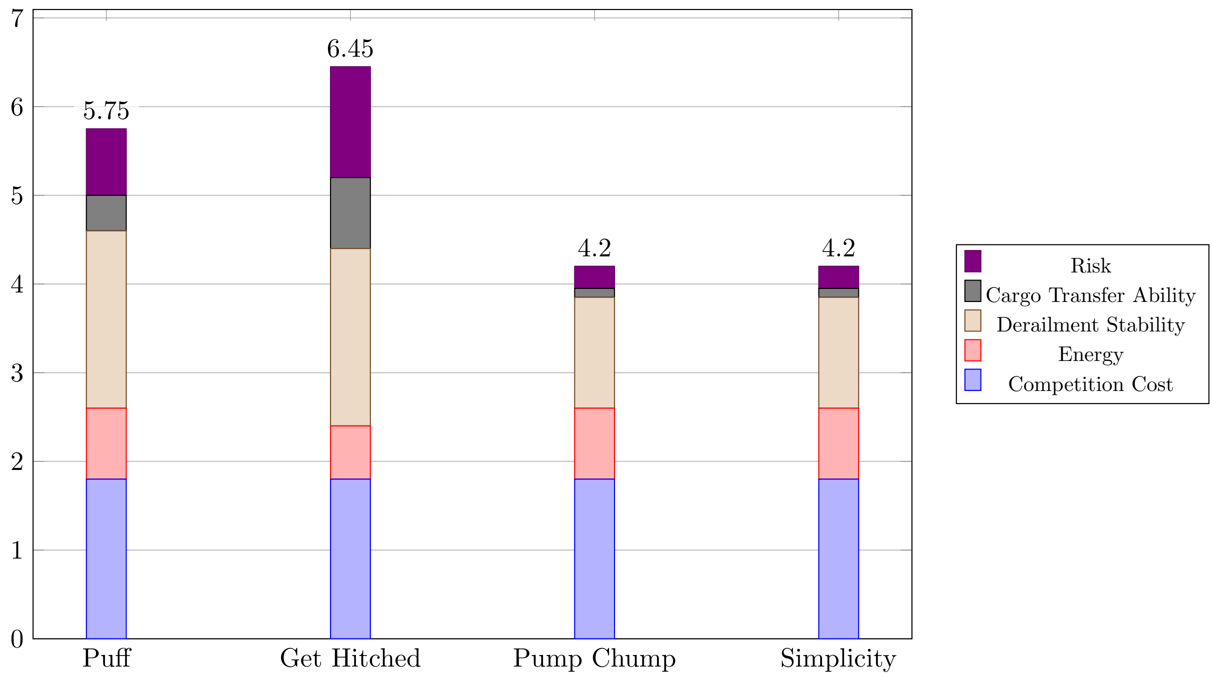

Figure 11: Simulation model

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.

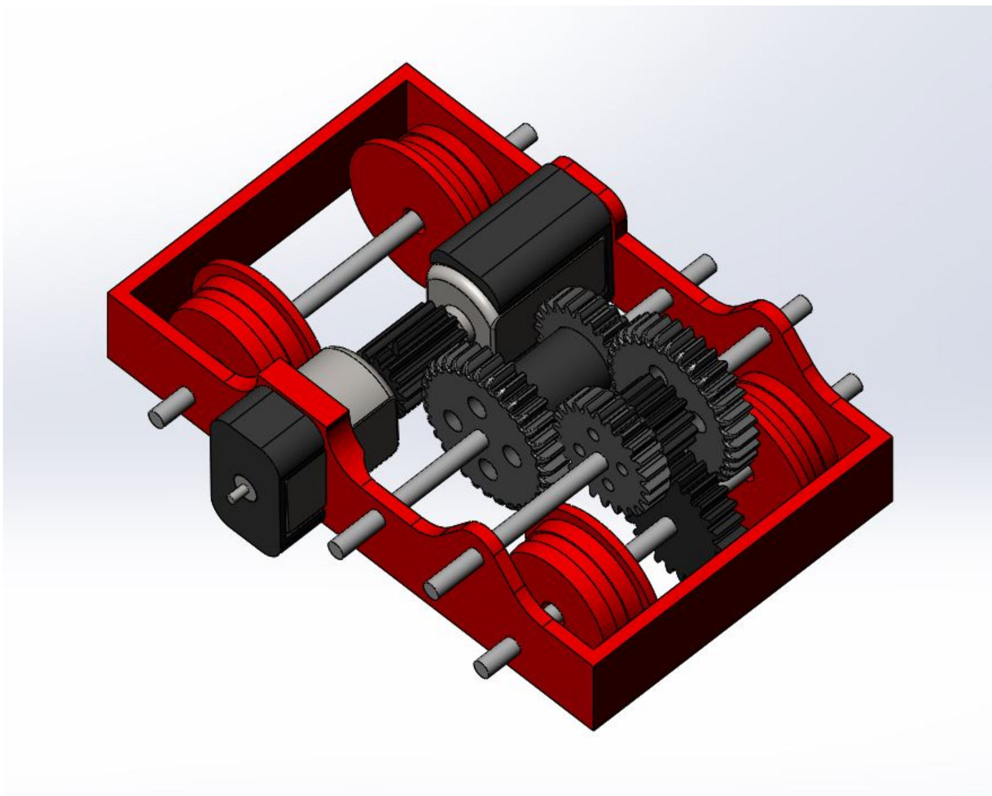

Figure 12: Mechanical System of Final Prototype

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.

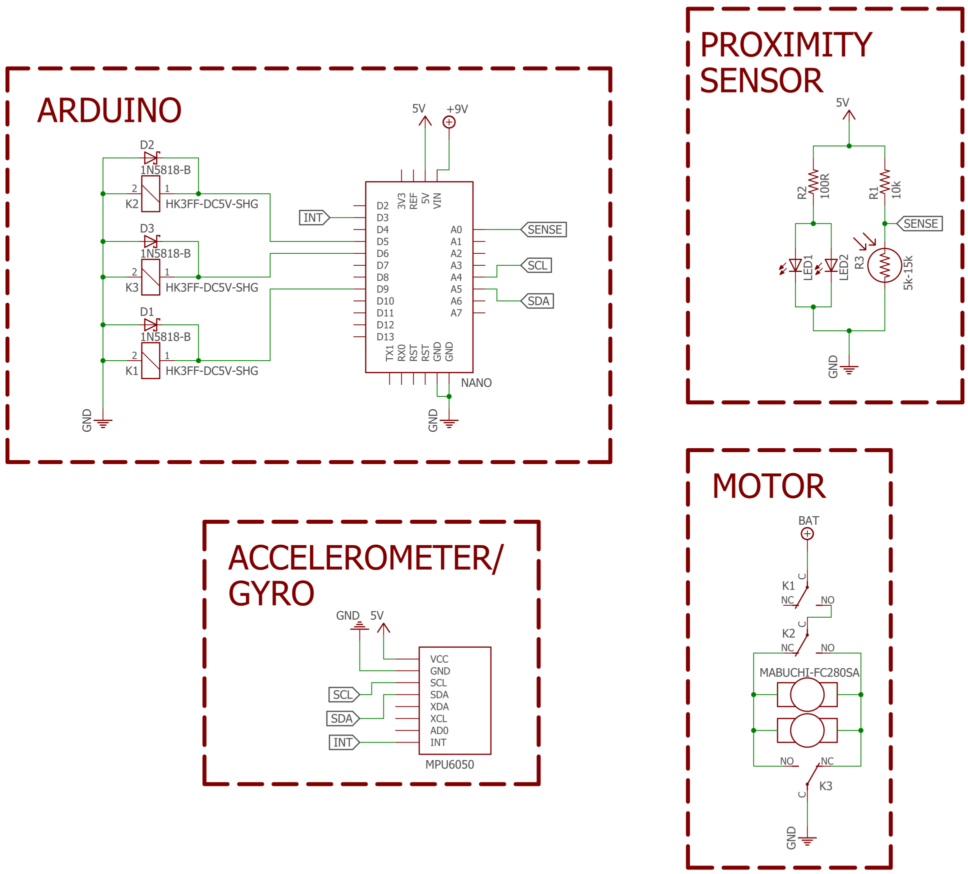

Figure 13: Electrical System of Final Prototype

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.

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.

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

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).

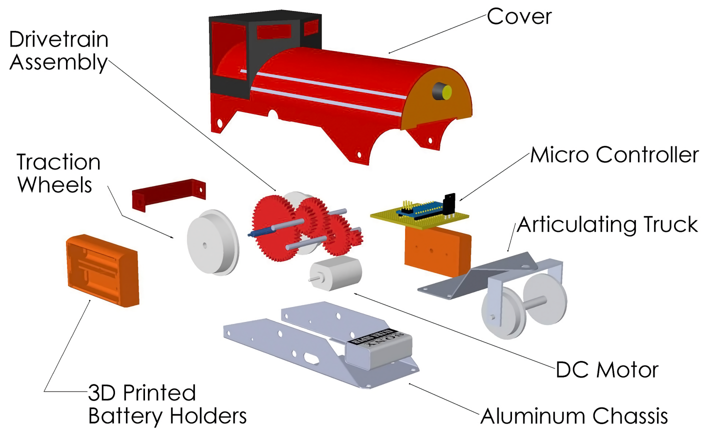

Figure 14: Exploded View of Team D3's Design

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.