FLORIDA INTERNATIONAL UNIVERSITY

EML 4905 SENIOR DESIGN PROJECT

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REQUIREMENTS FOR THE DEGREE OF
BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Z4
Enhanced 4D Roller Coaster
100% Report

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This B.S. thesis is written in partial fulfillment of the requirements in EML 4905.
The contents represent the opinion of the authors and not the Department of
Mechanical and Materials Engineering.

Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of SERGIO PEÑA, MICHAEL PEREZ, and ASHLEY WILLIAMS and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

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Abstract

This project's focus is to develop a four dimensional roller coaster with enhanced performance to entertain people all across the world. Our design will modify an existing roller coaster and create a smoother ride with less mechanical failures. To do this, our conceptual design will have a single cart with the coaster tracks stationed to the side, thus improving cornering and visual thrill. It will also include a similar gear mechanism, as previous designs, to cause the rotation of the cart but with a different schematic to reduce wear and tear and prevent mechanical failure. Contact with several roller coaster manufacturers was done in order to incorporate safety standards and any further design details they suggest. Afterwards, extensive simulating and testing will be done to ensure it is in proper working condition. Ideas to improve current roller coaster breaking system as well as rotational mechanism will be visited with thorough research. This will prove whether a different type of system may lead to a more efficient, smooth ride, with safety as the top priority. The main objective is creating a 4-D coaster, with allowable time; creating a new rotational and breaking apparatus will lead to the intention of a professional company's selection of this coaster to one day build.

This thrill ride will increase amusement park guest attendance across the world. Most current roller coasters running lack new innovations, which in turn causes parks to slowly lose patrons. Another contributor to this loss is the consistent breaking-down of the coaster; common reasons are maintenance issues, which can be partially avoided by material selection and mechanism. Introducing the general public to a new type of extreme roller coaster with an alternate breaking and rotational device, tourism and profits will increase. As previously advertised roller coasters, this design will value well in the beginning, with the opportunity of it becoming more successful for years to come.

Chapter 1 - Introduction

1.1 Problem Statement

One of the major challenges of roller coaster companies is designing a roller coaster that can provide a lasting thrill for a long time. Several variations have been implemented in recent roller coasters including boosters, inverted tracks, and free-fall drops to increase the ride's excitement. An example of an original coaster design is the ride called *X2* in Six Flags Magic Mountain, California. While typical roller coasters use lateral and vertical forces throughout the ride, this type of coaster known as a four dimensional roller coaster introduces centrifugal forces to increase rider thrill. Previous attempts have led to frequent mechanical failures causing the ride to be shut down, costing the park thousands of dollars. Even during successful runs, these rides have met poor critiques, including been commented as rough and jerky rides. Such innovative roller coaster ideas can receive commercial success if they were further developed.

1.2 Motivation

For years, roller coasters have been a source of thrill for many daredevils around the world. Even for those who aren't looking for an extremely wild ride, roller coasters can provide entertainment and joy to those who are brave enough to get onboard. Coaster designers and manufacturers are constantly raising questions on how to improve on their design, how to introduce a new element, or how to increase ride performance. By answering these questions, designers have been able to revolutionize roller coasters and create different types of coasters such as:

- Launched roller coasters – uses mechanisms employing hydraulic or pneumatic power to initiate a ride and provide high amounts of acceleration instead of the traditional chain lift
- Pipeline roller coasters – positions the riders between the rails instead of above or below
- Suspended roller coasters – hangs from the bottom of the rolling stock by a pivoting hinge assembly
- Hyper coasters – delivers huge drops often higher than 60 meters
- Four-dimensional roller coasters – rotates passengers disregarding the orientation of the track

In particular, the four dimensional roller coasters have not seen much success because of mechanical failures and subpar ride performances. With some proper readjustments, our team sees possibilities for a these roller coasters to become an exciting feat in amusement park. Because the idea of rotational motion throughout a ride is relatively new, this leaves room for improvement to create a four-dimensional ride that would be a commercial success. Such unique ride would surely attract customers worldwide.

1.3 Literature Survey

Roller coasters are carts on specialized tracks in which it uses potential energy to complete a run. These tracks can have tight turns, heavy drops, or even create loops to give the riders different sensations. Due to the speed and turning of the coasters, these effects exert forces on the rider known as g-forces. Depending on the magnitude of the g-forces, one can tell just how extreme a certain roller coaster ride can be. To elaborate, the g-force associated with an object is its acceleration relative to free-fall. When an object is sitting on the Earth's surface, it is being exerted 1 g-force upwards due to the reaction of the ground, thus preventing the object from going to free-fall. Likewise, the object can be exerted 2 g-forces, which means it is embracing twice the original weight, Furthermore, when the object is exerted 0 g-force, it is considered to be in free-fall and is synonymous with weightlessness. By using these different combinations of g-forces, roller coaster designers have been able to manipulate coaster tracks in order to provide the people with a different experience in each ride.

1.3.1 History

Most roller coaster experts agree that the origin of roller coasters were the Russian Ice Slides during the 17th century. While these rides do not resemble the current roller coasters as it did not contain tracks or carts, it was the first form of entertainment in which a person would slide down a ramp 20 to 30 meters tall on a sled and go back to the other end of the ramp. By 1817, two coasters called Les Montagues Russes a Belleville and Promenades Aeriennes were built in France which featured carts with wheels locked to a track for the first time. After several years of running, both coasters grew out of fashion, and it would be several years later until a man named La Marcus Thompson would create and patent the first roller coaster in the United States and revolutionize the amusement industry.

1.3.2 Safety Standards & Regulations

All roller coasters have standards and regulations that they must abide by. These roller coasters must have in mind the safety of the passengers above all else. As a result, all rides have certain requirements that must be met including but not limited to:

- Keeping the amount of G-forces relatively low as to not harm the passengers
- At least one type of restraint that will prevent the rider from falling off
- Checking roller coaster function on a daily basis

- Periodically replace parts on the roller coaster and keeping everything up to date
- Amusement park standards are set by the American Society for Testing and Materials (ASTM) International, F-24 Committee on Amusement Rides and Devices.

Signs such as the ones depicted on Fig. 1 are placed at the front of all stations to warn passengers of all the rules that need to be followed to ensure a safe ride. Many requirements include reaching a certain height, having no health conditions, and avoiding rider misconduct. Even with such signs, passengers still fail to adhere to all the warnings. One study recorded and analyzed the amount of deaths caused by roller coasters from 1994 to 2004. Forty deaths were accounted for in which it was discovered that more than half of deaths related to roller coasters were due to rider negligence, while another quarter of them were actually employers working on the track. Many of these deaths were a result of medical conditions in which the deceased riders generally suffered cardiac arrest. Other deaths included mishandling the restraints and attempting to stand while the coaster was in motion. Only in few cases were the deaths caused by mechanical failure.

Figure 1: Roller Coaster Warning Signs before Riding

1.4 Roller Coaster Components

The designs of roller coasters can vary from a simple cart on train tracks to as complex as containing internal mechanical mechanisms to do specific movements. The basic components of roller coasters include a cart, a track, a braking system, a lift, and restraints. Each of these features needs to be manipulated in a different way depending on the design of the coaster in order to work successfully.

1.4.1 Cart

A roller coaster cart describes the vehicle which transports passengers across a circuit. These carts can be connected to other carts via a specialized joint and are then called a roller coaster train. Most roller coaster trains run on wheels that are locked on to the track, preventing it from "jumping" the track. As noted from Fig. 2, the most common type of wheel configuration involves three pairs of wheels, one pair on the top of the rail, one pair on the outside of the rail, and one pair underneath the rail.

Figure 2: Coaster Wheel Configuration

The top wheels are used as the main road wheels to drive the cart, and henceforth are the biggest wheels. The side wheels are used to guide the coaster from side to side and to prevent the coaster from separating from the track. The bottom wheels are used to interlock the whole coaster and prevent it from popping up when falling at high speeds.

Another feature of the cart is the geometry of the cart itself. While most wooden roller coaster involve the basic box-shaped cart that can fit two to four people, the introduction of steel roller coasters helped develop the inverted coaster design and expand cart design possibilities. Some common requisites of cart design involve an aerodynamic front to prevent kinetic energy loss from air resistance, a cart that is within a certain weight to prevent high levels of mechanical strain, and proper placement for restraints to prevent passengers from being injured.

1.4.2 Track

Probably the most important characteristic of a roller coaster that differentiates one ride from the other is the track design. An infinite amount of patterns can be formed by simply increasing the length of the track, making the turns tighter, adding an extra loop, increasing the drops, etc. The few factors designers need to consider in order to create a possible ride involve calculating the kinetic energy needed for the coaster to complete the run and calculating the amount of g-forces exerted on the passengers.

Most roller coasters use potential energy and convert it to kinetic energy to complete the run.

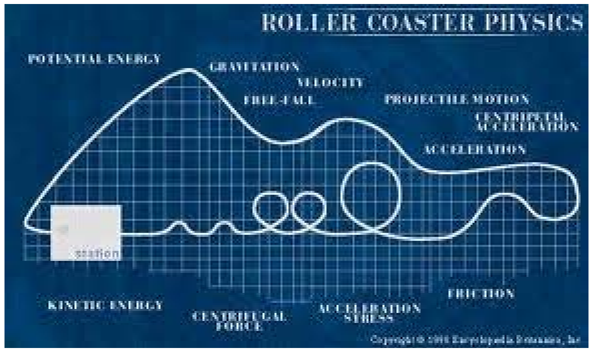


Figure 3: Roller Coaster Physics

To do this, these roller coasters are pulled or driven to the top of a hill via cables or chains and then released to pick up speed and start its run. Although there have been some roller coasters that use motors to run, the common ones still use exclusively potential energy to kinetic energy. As a result, depending on the height of the starting drop, a designer has to limit himself to those restraints. To elaborate, and we will neglect friction resistance, the equations used to determine speed at a certain point in the ride is the mechanical energy conservation equation:

$$PE_1 + KE_1 = PE_2 + KE_2 \qquad \text{Eq. (1)}$$

An expansion to Eq. (1) is:

$$mgz_1 + \frac{1}{2}mv_1^2 = mgz_2 + \frac{1}{2}mv_2^2 \qquad \text{Eq. (2)}$$

Where m is mass, g is the gravitational acceleration, v is the velocity at that specific point, and z is the elevation from the ground to that specific point. Because the mass is constant, we can cancel the m variable, thus:

$$gz_1 + \frac{1}{2}v_1^2 = gz_2 + \frac{1}{2}v_2^2 \qquad \text{Eq. (3)}$$

With Eq. (3), one can calculate the speed at certain parts of the ride and check if the parameters allow the cart to continue. Designers don't want to have a coaster fail to finish because it lacked the speed to completely rise over a hill or make a loop. In addition, designers would not want to the cart to take turns at incredibly high speeds and exert high g-forces on the passengers or high mechanical strain on the cart. Such high speeds should be used on the straight-a-ways or the loops and, in turn, have it take the tighter turns at lower speeds.

The other important designing factor is calculating the g-forces being exerted on the passengers. While it is a common feature for a roller coaster to induce greater g-forces, a high enough g-force can be harmful, even fatal, to the passenger. The way to calculate the g-force would be to compute the acceleration at that present moment, and divide it by the gravitational acceleration. There two types of acceleration that a coaster goes through, the first one is the falling and the second one is the curvature. Depending on the steepness of the drop, a passenger can experience zero-g force if the drop is exactly 90 degrees. As for the acceleration of curvature, it all depends on the radius of the turn as well as the speed coming through. The equation is:

$$a = \frac{v^2}{r} \qquad \text{Eq. (4)}$$

Where v is, again, velocity and r is the radius of the curve. These are the more important factors when track designing.

1.4.3 Braking System

Another common compartment of roller coasters is a braking system. Brake runs may be located anywhere along the circuit of a coaster and may be designed to bring the train to a complete halt or to simply adjust the train's speed. These brakes are placed on the track, not on the cart, and are controlled by a computer system. The main types of brakes are trim brakes and block brakes. Trim brakes are placed throughout the track in order to control the speed of the coaster. Block brakes are used to prevent collisions of roller coaster trains should more than one coaster run on the track. Advancements in designs have led to many different types brakes. The primitive designs are the skid brakes in which some type of material, often ceramic-covered, is raised when the brake is engaged and uses friction to slow down the cart. The more common brakes are the fin brakes in which a metal fin is attached to the underside of the cart and when the brake is engaged, two computer-controlled closing mechanisms squeeze the fin and slow down the train.

Figure 4: Fin Brakes

The most advanced brakes are the magnetic brakes. These brakes work by having a metal fin (typically copper or a copper/aluminum alloy) pass between the rows of neodymium magnets, thus generating eddy currents in the fin, which creates a magnetic field opposing the fin's motion.

1.4.4 Lifts

Another important aspect of roller coasters is the method of starting the coaster ride. The most basic form to start a coaster ride is to pull the coaster to the top of a hill using a chain lift or cable pull. A typical chain lift consists of a heavy piece of metal called a chain dog, which is mounted onto the underside of one of the cars which make up the train. The chain travels through a steel trough, and is normally powered by one or more motors which are positioned under the lift hill. At the crest of the lift, the chain wraps around a gear wheel where it begins its return to the bottom of the lift; the train is continually pulled along until gravity takes over and it accelerates downhill, which in turn causes the chain to disengage. The cable lift utilizes a cable loop in place of the traditional chain, which is attached to a short section of chain that engages the train's chain hook. Because a cable is much lighter than a chain, cable lifts are much faster than chain lifts and can be used on much steeper hills.

Figure 5: Chain Lift

Another method to drive the cart uphill is by a drive tire system in which multiple motorized tires push the train upwards. This type of lift system is mainly used on launcher roller coasters, in which excessive speeds can be reached within seconds of launch. An example of a roller coaster that uses this method is the Hulk in Universal Studios in Orlando. The coaster is able to reach 40 mph within 2 seconds.

1.4.5 Anti-rollback Device

A chief attention grabber of roller coasters, are their fearless dips and daredevils turns with intense speed, bringing guests in to experience these attractions again and again. The trains, in which guests are seated to ride the roller coaster, climb a portion of the track to reach its peak point before debarking on its plunge to begin the thrill. With multiple trains running through the coaster at once, there is an anti-rollback feature in place as the trains are climbing to the peak point.

Figure 6: Anti-rollback installed on track

The anti-rollback system has stops or cross bolts which is covered by continuous brush metal. The anti-rollback pawl rides above the fiber material on skis as the vehicle moves forward. If for some reason the vehicle moves in the backwards directions the skis will move downwardly through the brush material and the pawl engages to stop the cart or train the on the track, to prevent further reverse movement. The brush material prevents the pawl from banging over each stop on the track, which then leads to a noise reduction of "click-clank-click" and the wear.

1.4.6 Restraints

For roller coasters to be successful, the passengers most feel that they are safe. All roller coasters have some type of restraint to prevent the passengers from flying off. Basic requirements include making sure the passengers are secured and making sure no type of injury can result from the ride. Different types of restraints exist, some in combination with others. Restraints include lap bar, over-the-shoulder bar, and seatbelts.

Chapter 2 - Project Formulation

2.1 Project Overview

The overall goal of this project is to improve four-dimensional roller coaster performance by redesigning previous schematics and selecting an optimum solution. We are to create a completely working roller coaster model incorporating all the mechanics introduced in our new design, and the model must contain all requisites a real roller coaster needs.

2.2 Project Objectives

The main objectives of this project include increasing roller coaster performance while maintaining high levels of safety. In order to accomplish that, we must take the following into consideration:

1. Only two four-dimensional roller coasters top at around 80 mph (the faster being in Japan called *Eejanaika*). Our track design will include a higher drop than the *Eejanaika* allowing us to reach speeds faster than any four-dimension roller coaster ever created.
2. Although both the *X2* and *Eejanaika* are the top performing four-dimension roller coasters operating, their degree of rotation does not exceed 360°. Our coaster design will include an extra set of gears to increase degree freedom.
3. *X2* have gone through several modifications due to numerous mechanical failures. Our design will avoid such mechanical failures.
4. The cost for building *X2* was $46 million for a track length of 3,600ft and *Eejanaika* was roughly $42 million for a track length of 3,780ft. We are to design a track of similar length while reducing costs.

5. Whether it's in Japan, United States, or anywhere else in the world, we must uphold roller coaster safety regulations. Our design must be safe to ride and operate.

2.3 Project Constraints and Other Considerations

Building a roller coaster requires many considerations to riders safety, especially one as complex as a four-dimension roller coaster. We must be certain that no excessive g-forces are being exerted on the passenger. Typical max g-forces found on roller coasters reach four to five g, but they never exceed more than 7 g. While reaching high g-forces could be detrimental, it is actually the duration the rider endures under these g-forces that can be harmful. We must keep the track design from exerting high g-forces for more than a second to the passengers.

Another constraint to our project is the track length. As previously mentioned, the top two performing four-dimension roller coasters are roughly around 3,600ft to 3,700ft of track. While exceeding this track length might be enjoyable for the rider, our building costs would go through the roof, and in a project where our objective is to optimize costs, this will not be a good idea. We also cannot take away from rider experience and shorten the ride, so we will maintain within 3,600ft to 3,800ft of track length.

The final constraint is our method to operate the roller coaster. After speaking to several roller coaster manufacturers, we were informed to maintain the roller coaster completely mechanical, and if we were to use electrical parts, to change it to an indoor roller coaster. Because indoor roller coasters are expensive, we will keep it as an outdoor roller coaster and therefore, keep it mechanical.

Chapter 3 - Conceptual Design

During the preliminary design meeting there were two distinct manners to introduce the spin on a roller coaster car being either mechanical, electrical, or collaboration with both. For the electrical method it was decided that there would be an electrical motor within the car itself to rotate the seats. This gave the possibility of reprogramming the sequence of spins between seasons of operation or between each run. However, while there have been numerous roller coasters that have high-capacity electrical components embedded in a car for lighting and audio playback, the technology is extremely temperamental and prone to power leaks due to the demanding output. Along with the warnings of various amusement park engineers, this idea was scrapped altogether leaving a purely mechanical ride to be designed.

There are currently two methods in which lateral spins are achieved on roller coasters: one involving varying bends within the support rails and the other utilizing a separate set of rails altogether. From researching the previous patents, the prior method is usually a single car holding no more than eight patrons at one time while the latter operates with a train with over sixteen seats.

Figure 7: Varying Structure Mechanism (*Insane*/*Intamin*)

Figure 8: Secondary Rail Mechanism (*X*/*Arrow Dynamics*)

Also, for the prior, only two dimensions of movement are available, meaning there can be no turns throughout the ride. While these have been said to be smoother than the other method, it reduces the excitement park guests look for and, in turn, lowers the demand for such designs. Therefore the latter method was chosen to be built upon. At the bottom of Fig. 8 a “C”-shaped assembly of wheels wraps around the secondary rail which will move upward or downward with a rack.

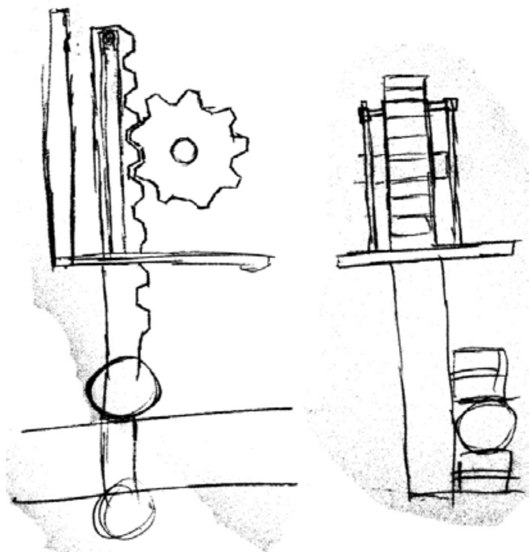


Figure 9: Secondary Rail Schematic

Seeing as the discarded method did have an advantage in terms of smooth rolling, one key element to the purposed design is to release a single car at a time. Without the extra mass behind the car caused by the conjoined train, the riders of the single car experience softer transitions around bends. Another form of roller coaster, known as a "heart-line", has the cars supported on both left- and right-sides rather than underneath. An example of this system is found in Fig. 10.

Figure 10: Heart-line Rail Support (*Ultra Twister/TOGO*)

Though this has not been proven to be more or less of a comfortable ride experience it should, theoretically, stabilize more smoothly through turns and twists. It was also decided to include this feature as it introduces a new perspective to the rider that no other four-dimensional roller coaster has.

During a follow-up design meeting, two more ideas were presented to take the place of the rack and pinion; springs and magnets. These mechanisms were presented as ways to enhance the rotational method, making it limitless. The sides of the cart would have large springs. The cart would rotate forward by the spring expanding, and to rotate backward by the spring condensing. In order for this expansion and condensing to happen, a catch and release system would be in placed on the tracks; winding area. Fig. 11 displayed this system.

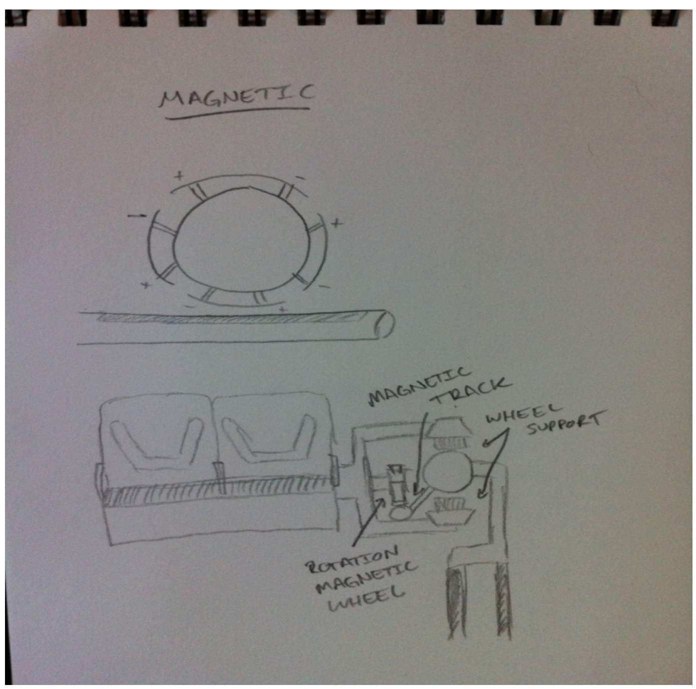


Figure 11: Magnetic Disk Rotation Concept

Unfortunately, many problematic features were discovered. The average life-expectancy of coil springs has no standard; nevertheless, they must be inspected frequently by a professional. Though in general, coil springs on heavier full-sized vehicles tend to last longer than those on smaller light weight applications. The springs used in this 4-D coaster must be very strong and large. With these requirements the life-expectancy of this spring may be shorter than desired as well as the reliability. The percentage error of the springs not catching at the precise moment leaves room for dangerous circumstances with the cart, as well as not having a fail-safe in place. The ultimate goal of the cart rotation, is designing a limitless rotation in one direction. However, even with the idea of springs, encountering some restrictions may rise in the catch and release area. As displayed in Fig. 12, the ramp would wind the spring to its max point, and then a mechanical catch would hold the spring in place while traveling with the cart along a guide, allowing the cart to rotate backward or forward.

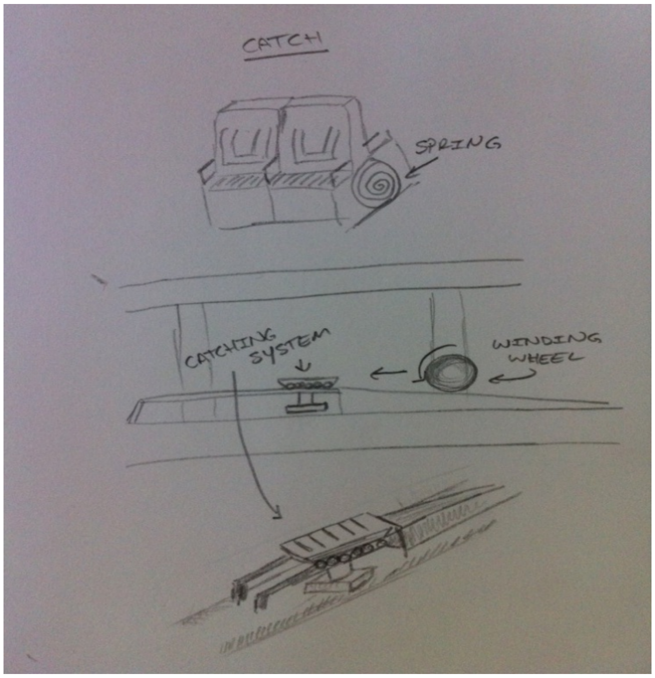


Figure 12: Torsion Spring and Catch Concept

The proposal of the magnets came with the idea of using polarized discs to spin the carts in the forward or backward directions, these panels are placed on the tracks. With this design came many margins of error which ultimately discouraged the further research. Speaking with electrical engineers, there is yet to be any data supporting the usage of magnets in roller coaster, for rotational purposes or breaking. The engineers discouraged this idea as there are many components. The positive and negative repulsions will start the spinning; this also included a lot of magnetic radiation around the tracks. The tracks are located in area where guest will be walking constantly. Having a large amount of magnetism exposed to humans can lead to many health problems, another hindrance to the proposed design.

Chapter 4 - Proposed Design

The ideal concept is to use a system of secondary rails to determine the orientation of the seats and to be supported along both sides. For increased stability and strength a total of 12 wheels are used strictly for support: two on the top, bottom, and inner-sides of each larger rail. These are also necessary to keep the structure stationary as the pivot arm rotates, or else the support wheels will move out from their proper center.

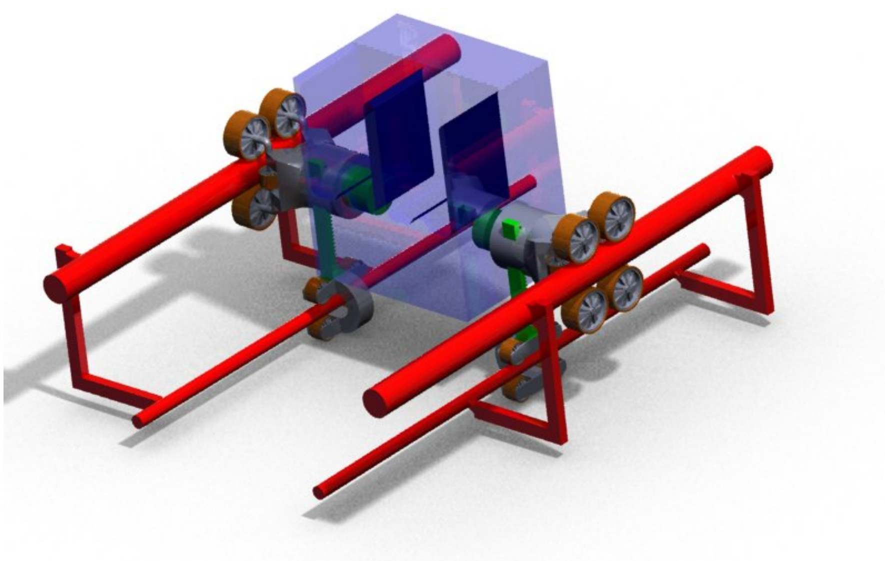


Figure 13: Proposed Design

Secondary rails follow the length of the track but are not load-bearing. These will vary in upward and downward directions, pushing or pulling the rack against the pinion connected directly to the pivot arm. Keeping the pivot closer to the center of mass of the car with riders included will decrease the strength needed in the secondary rail. The introduction of two support and two secondary rails help spread the load evenly, reducing the need for thicker rails, ultimately lowering costs.

The “L”-shaped connections between support and secondary rails are squared and kept relatively thin as they will only serve as links. These flat surfaces will be easier to manufacture and allow the placement of brakes or launching methods. At this point, neither the braking or propulsion methods have been established. A goal is to allow the implementation of skid brakes, or friction brakes, that make contact with the stationary supports. Likewise with the rails brakes would be located on both sides for even deceleration. As for lifting or launching the cars, the chain lift is the most promising as it requires no modifications to the base concept and is proven in countless amusement rides to function without trouble. However, the growing trend of propelling a car around the track by using magnetic repulsion, but most roller coasters with this technology are simplified with few moving parts and limited to a certain clearance from the magnets. A general fear of magnetic launching is a magnet catching the car instead of repelling, which could decrease structural integrity and cause bodily injury.

Chapter 5 - Timeline

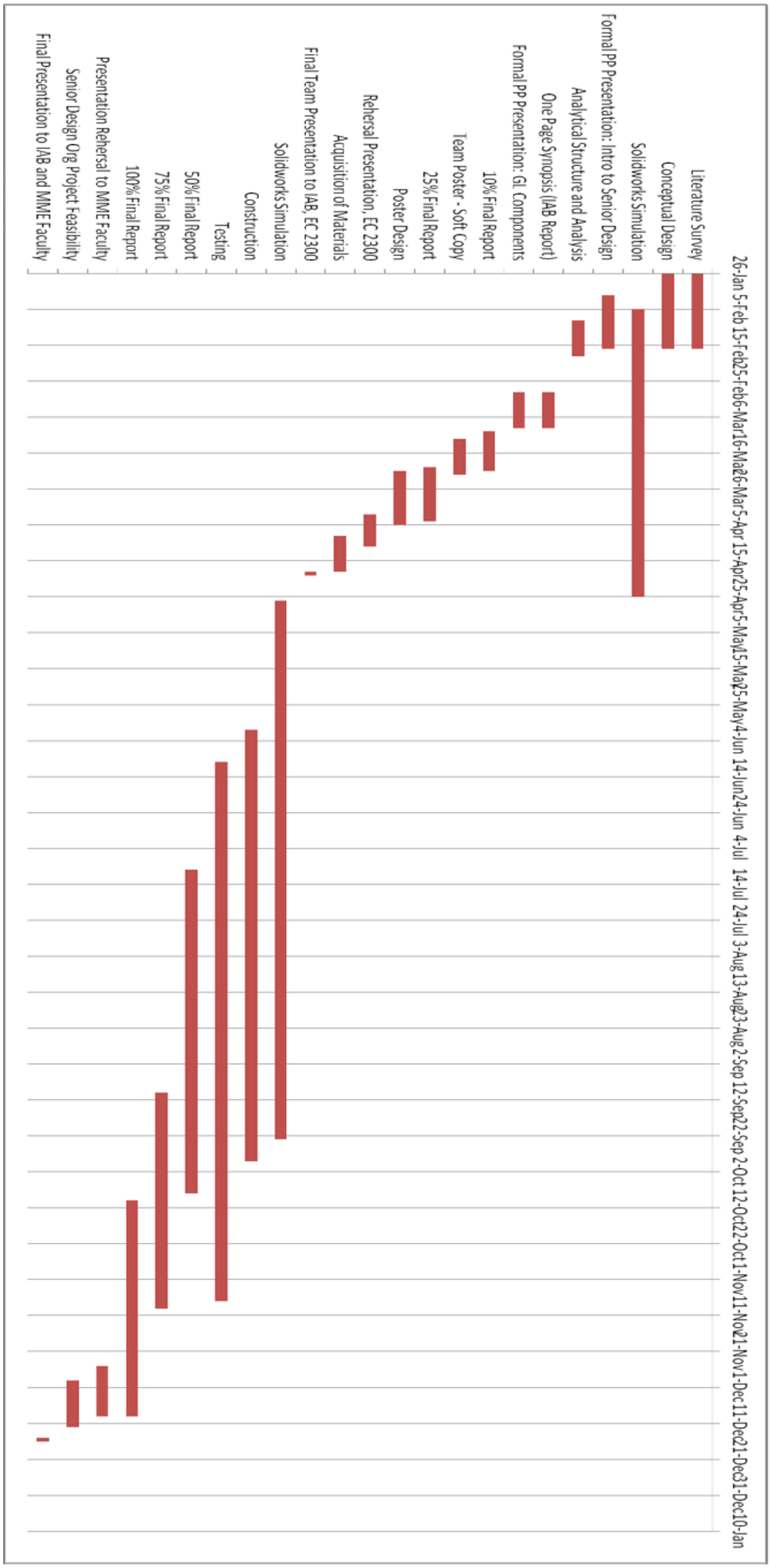
Table 1: Timeline Breakdown

Tasks	Start Date (2012)	Duration (days)	End Date (2012)
Literature Survey	26-Jan	21	16-Feb
Conceptual Design	26-Jan	21	16-Feb
Solidworks Simulation	5-Feb	80	26-Apr
Formal PP Presentation: Intro to Senior Design	1-Feb	15	16-Feb
Analytical Structure and Analysis	8-Feb	10	18-Apr
One Page Synopsis (IAB Report)	28-Feb	10	8-Mar
Formal PP Presentation: GL Components	28-Feb	10	8-Mar
10% Final Report	10-Mar	11	21-Mar
Team Poster - Soft Copy	12-Mar	10	22-Mar
25% Final Report	20-Mar	15	4-Apr
Poster Design	21-Mar	15	5-Apr
Rehearsal Presentation, EC 2300	2-Apr	9	11-Apr
Acquisition of Materials	8-Apr	10	18-Apr
Final Team Presentation to IAB, EC 2300	18-Apr	1	18-Apr
Solidworks Simulation	26-Apr	150	26-Sep
Construction	1-Jun	120	1-Oct
Testing	10-Jun	150	10-Nov
50% Final Report	10-Jul	90	10-Oct
75% Final Report	10-Sep	60	10-Nov
100% Final Report	10-Oct	60	10-Dec
Presentation Rehearsal to MME Faculty	25-Nov	14	8-Dec
Senior Design Org Project Feasibility	29-Nov	13	10-Dec
Final Presentation to IAB and MME Faculty	15-Dec	1	15-Dec

Responsibilities of team members:

- Sergio Peña: Solid Works Design, Materials, Model Form
- Michael Perez: Solid Works Simulation, Break Systems, Restrictions of Coaster
- Ashley Williams: Budget and Timeframe, Railing, Seats and Safety

Table 2: Gantt Chart



Chapter 6 - Engineering Analysis

6.1 Analysis Methodology and FEA

Starting with the proposed design dimensions created earlier each part is separated and reassessed to verify a proper initial testing foundation. Because this is a machine that will be carrying passengers the minimum factor of safety is decided to be 1.55. Preliminary analysis will be done on a piece-by-piece basis before creating assembled models that will then undergo a maximum design load, taken as four larger passengers taken at a safety-conservative estimation of three-hundred pounds, or 1334 newtons. Considering that the completed roller coaster could induce five Gs on the passengers, along with the increase in acceleration affecting the weight of the cart itself, the load could potentially be 6672 newtons per rider for a total of nearly twenty-seven kilonewtons.

Since the loading on the design is rather large and the risk of failing components is high, the analysis is best done with computer aided design. The resulting stresses and safety factors will come from a finite element analysis, FEA, simulation software known as Solidworks COSMOS Simulation from *Dassault Systemes* provided by the overseeing university.

6.2 Major Components

6.2.1 Paralleled-Rails

Contrary to most current roller coasters, the proposed design will have a support rail on both lateral sides of the car. This inspiration for this component came, originally, from the goal to allow a rider a different perspective of viewing from the amusement ride. Riders can now have their feet and legs move freely while in the seated position without the possibility of injury due to the track located underneath. However, it was later realized that the load could be shared across two separate rail supports rather than a single, necessarily larger support used when the rails are centered. To keep the view from under the cart unobstructed each left and right rails would be held by beams that do not cross over to the other side. While doubling the rail does not mean doubling the cost of materials, as the tracks can be slightly smaller from shared-loading and single-car operation, it may be more costly than a centered track in terms of labor and manufacturing. However, an investment in paralleled-rail-design allows for less costly maintenance; should only one side of the track need service or replacement, the other side can be left untouched, lowering the cost in materials, manufacturing, and labor.

6.2.2 Secondary “Guide” Rails

A secondary track will be attached beside each support rail towards the center of the track itself. These are not load-bear whatsoever, hence labeled “guide” rails. Since this is solely a mechanical system, the guide rails will provide the rotation relative to the track.

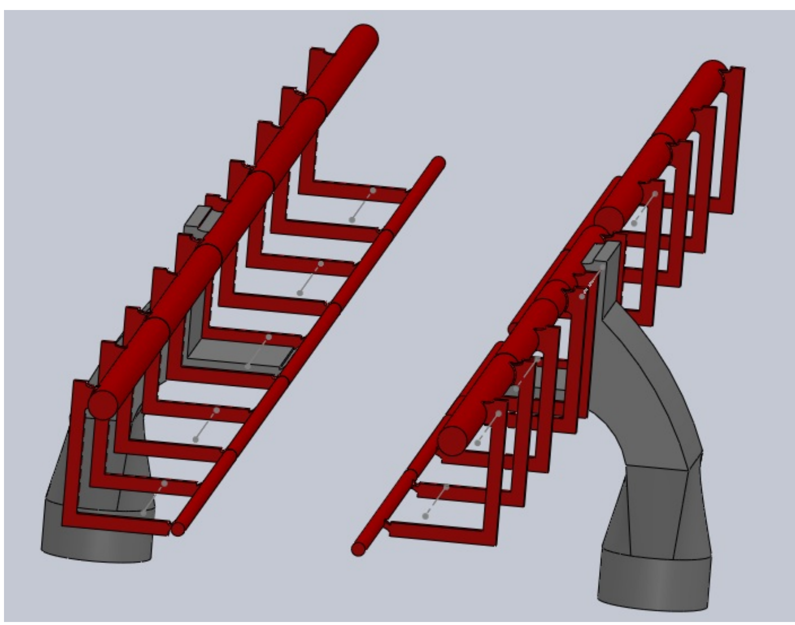


Figure 14: Rail Assembly with Support Arms

These will travel along the entire length of track in order to provide the moving cart with directions on how to change the pitch. They will be at a constant distance parallel to their respective support rail yet vary in vertical displacement, causing a mechanism built into the cart to change. This change results in a shift in the cart's pitch, maneuvering the seats to view between the ground and sky or ceiling. Because the cart will be supported at two ends each guide rail will not vary in position relative to each other; the guide rails must have equal positions to rotate the seats evenly. If these rails conflict one another, the seat-pitch will seize and creates the possibility of premature gear-tooth wear or even failure.

6.2.3 Limit Testing Track

One of the goals is to improve the boundaries of existing four-dimensional roller-coasters a test track was conceived to increase various limits. The current mock-track includes:

- A ninety-meter drop, increasing the largest 4D coaster drop built by 36% (*Eejanaika* of Japan has a sixty-six-meter drop)
- Ninety-degree vertical drop, matching that *Eejanaika* but all others are less
- 4.5-meter tightest turning radius, though unknown as to how much of an increase this is

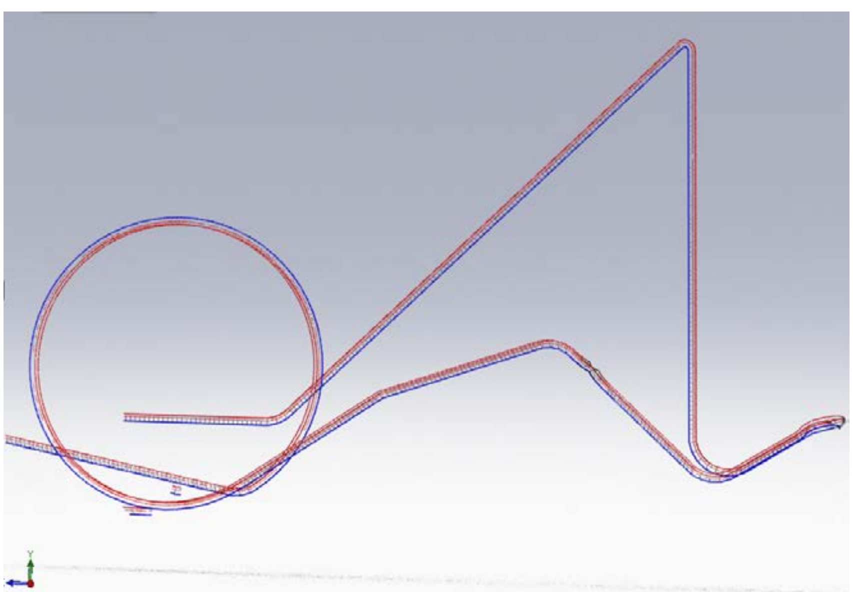


Figure 15: Analysis Track

The ninety-meter, ninety-degree drop is placed at the beginning of the ride as this will convert all the potential energy into the kinetic motion required to finish the circuit. Overall potential energy of the ride will be calculated with the follow equation:

$$PE = m_{car+riders} g H_{drop}$$

Some of this energy will dissipate with wind resistance, frictional drag on the rails and the inertial spinning of the wheels. In an ideal situation this particular design could reach a top speed of 42 meters-per-second, but may be closer to thirty-eight from the energy losses. This would still be a 10% increase in top speed when compared to the fastest 4D roller-coaster currently in operation. However, Eejanaika and X2 have a train of cars which increases the mass of the system, which could explain their high kinetic-energy resource to achieve high speeds.

A catch to a long train of cars is the limit to how tight a turn can be. While the energy available is theoretically greater by a factor of six due to larger mass, too sharp a turn could induce dangerous forces on the structure, and more importantly, the riders. “Banked” turns, the track twists inward towards the turn in order to decrease lateral forces, cannot be performed with a small turning radius. A single car of smaller mass can take tighter turns. How tight will depend on the assumed mass of the car with riders and whether the turn will be banked. Most roller-coasters, including those that are not four-dimensional, do not exceed a maximum of four-times the force of gravity. Anything higher may injure a rider or be considered more frightening than thrilling. This will be the maximum allowed force on the car when designing the lower limit to a turning radius.

6.2.4 Rack & Pinion Mechanism

There are two key features to this component: the rack-and-pinion assembly and the stationary structure to link with the track. A rack is attached to a set of four wheels that travel along the guide rail. As this rail moves up and down the rack will follow this movement and rotate the adjacent pinion gear embedded a cross-arm that holds the seats. This is the best conceptual method for creating a spin on a free-motion roller coaster without the aid of electrical motors.

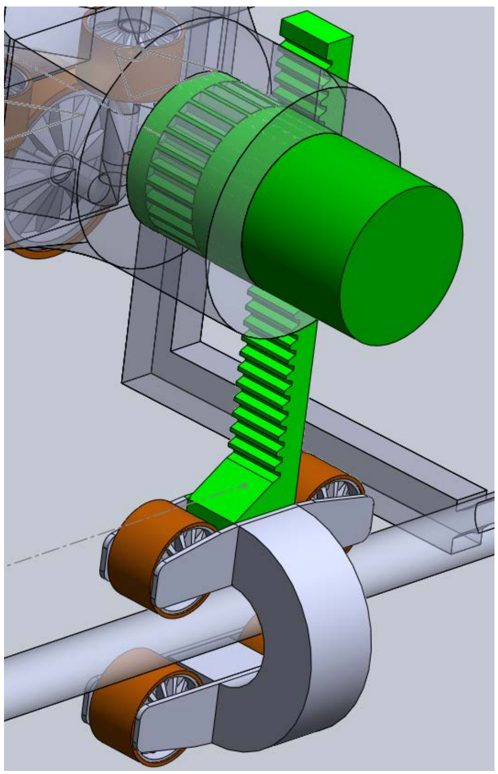


Figure 16: Rack and Pinion Assembly

This mechanism is limited to the length of the rack in relation to the diameter of the cross-arm. A longer rack with a smaller diameter pinion would allow for greater degrees of rotation, however, the pinion size is first determined by the safety factor regarding the weight of the cart during operation and the length of the rack should not be so large that it ruins the aesthetics of the ride.

Rack and pinion mechanisms are like any gear meshing system; they require a certain set of equivalent factors in order to function properly. These factors include the pressure angle at which the work of the rack teeth acts on the pinion teeth and diametral pitch. Industry standards have a broad range of diametral pitches to choose from for commercial hobbing and machining purposes. However, there are only two standards for the pressure angle: 14.5° and 20°. Custom designs can have higher pressure angles to deliver a greater amount of torque, but take much longer to machine than the industry standards.

The second structure is the stationary link that encompasses the wheels to travel along the support rails and the axel to which the cross-arm rotates. For stability purposes, a total of six wheels will be used per rail: two above, two beneath and two on the interior of the tracks. This way as the seats roll forward or backward the stationary structure does not roll in the opposite direction due to Newton's third law, although the axel assumed to be efficiently lubricated to reduce this effect. This structure also houses the rack, forcing it to be in constant contact with the pinion gear. The resulting contact pressure between the rack and pinion restricts them from slipping.

6.3 Structural Design

6.3.1 Car Weakness & Reinforcement

Every moving part must be properly sized to support the forces applied to the system. The defining factor of safety is the minimum factor found, meaning, should most parts meet a high value yet one is below acceptable, the overall safety factor is that lowest value. A few weak points have been assumed from the current proposed design, including support wheel axle connections, the simple-supported cross-arm, and the rotation mechanism. The seats must also be simulated as the plastic material for seating is going to be the weakest material on the cart.

6.3.2 Wheels

Wheel designs for most roller coasters are rather standard; a steel wheel with pockets milled to reduce material cost and weight fitted with an outer ring of rubber for traction on the painted surfaces of the track. Using photos of the *X2* roller coaster cart three different wheels were created for simulation: a support wheel which bears the load of the cart, a lateral wheel which reduces the jitter of the cart between the two tracks and a guide wheel that rolls along the secondary rail to push or pull the rack (Fig. 17 colored blue, yellow, and red, respectively).

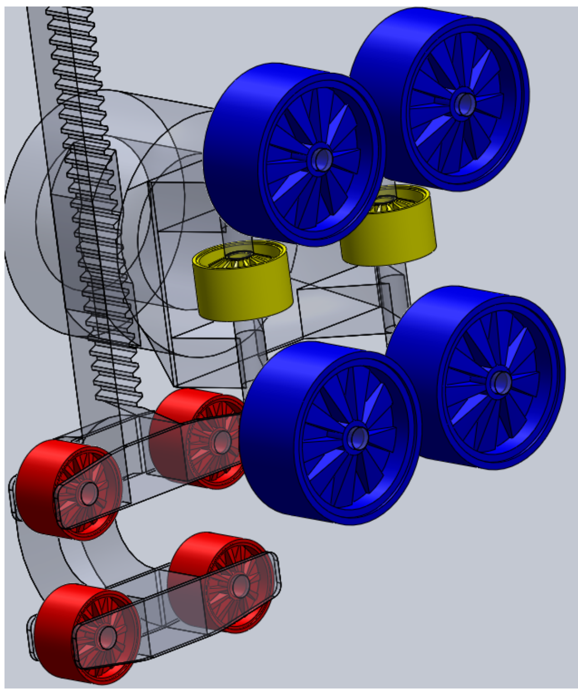


Figure 17: Cart Wheels

The reason for the configuration of two wheels on the top and bottom for each rail is for stability. Most roller coasters incorporate at least two wheels on either side of the rail for the same reason. The second set will eliminate the possibility of the structure rolling past a perpendicular orientation to the rail. Especially for this design which requires the seats to rotate relative to the stationary structure there can be no rolling. The same idea is applied to the guide rail, though not for stability, but rather for reducing the deviation needed in the guide rail to impart rotation. If the wheels were to be placed directly in-line with the rack the rail would need to be placed lower than what Fig. 17 shows.

Because the wheels are close to a standard specification and dimension of a model currently used for this purpose, the wheels will not be a focus for redesign. However, the placement and possibly the bore diameter will change for these should any alterations be made to the stationary structure.

6.3.3 Wheel Axles and Stationary Structure

The six support wheels on either side of the car will ultimately bear the most load. Considering the orientation of the cars structure will be up-right most of the time, with the secondary rails under the car, the top two wheels will carry downward forces for longer intervals than the other wheels. The underside wheels will only be necessary when the structure is oriented upside-down or from negative forces from the apex of a hill in the track. Lateral wheels should not be load-bearing, but may limit allowable lateral forces from turns. Conceptually, each pin or axle retaining the wheels is forty-centimeters in diameter. In the event that the design exceeds expectations decreasing the size will not be considered as the cost difference in fabrication would be miniscule.

When simulating with the full weight of the cart, including passengers and materials, the top two axles can maintain the static load. However, as the ride is in motion and the force is increased by the increases in acceleration, when simulated to the safe limit of five Gs, the axles begin to fail along with the structure holding the axles in place.

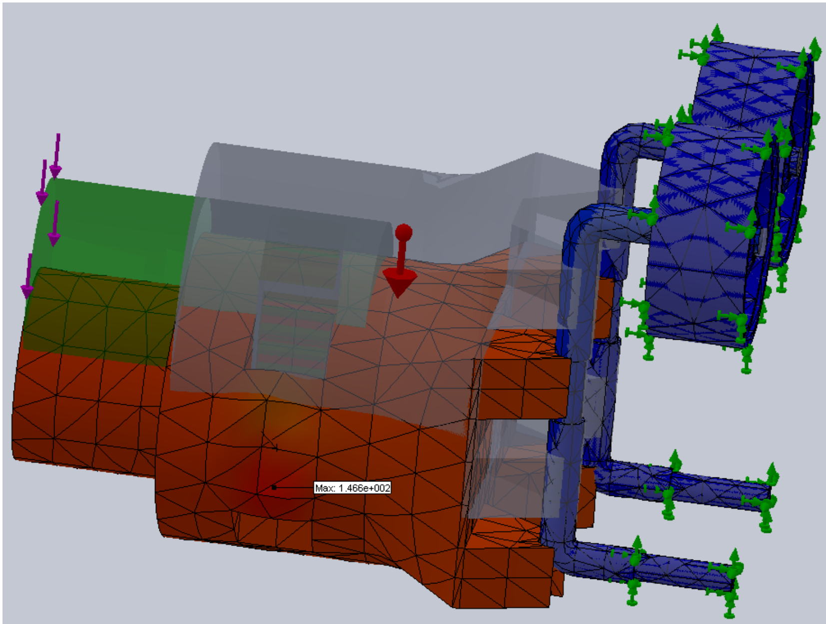


Figure 18: Initial Structure Design Failure

The stationary structure, the part to be constantly parallel to the rails throughout the operation of the roller coaster, is completely redesigned. Initially the concept proved to be too weak by the axle connections. While the section holding the cross-arm, in green in Fig. 18, seems to be holding to the five-G load, it will also be reinforced.

The next design increases the thickness of the connections between the structure and axles while increasing the axle diameters. This new concept also incorporates fillets in the sharper corners to reduce the stress concentration. Originally, these would be created for the manufacturing, but in reality these fillets will naturally occur when the axles are welded into the stationary structure.

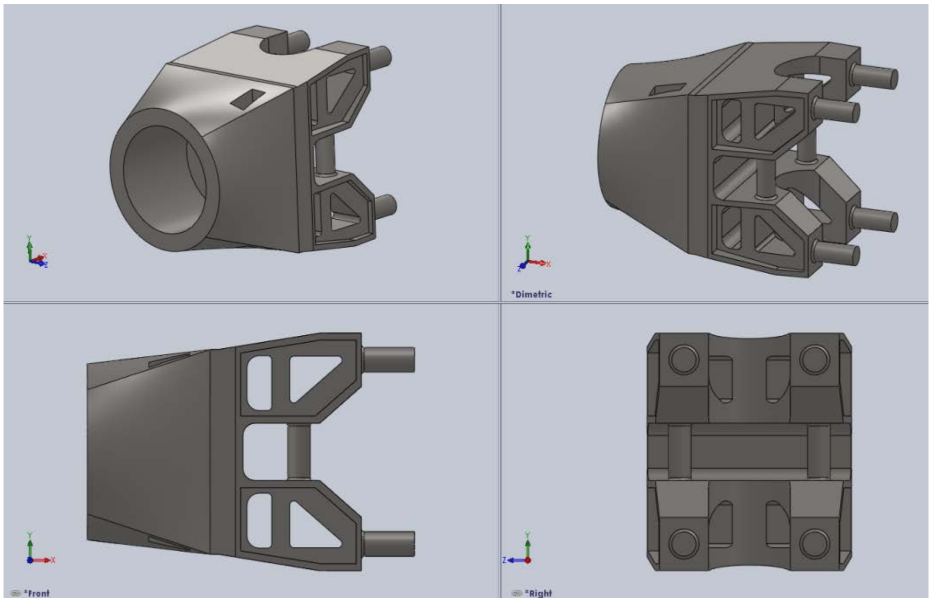


Figure 19: Stationary Structure Design

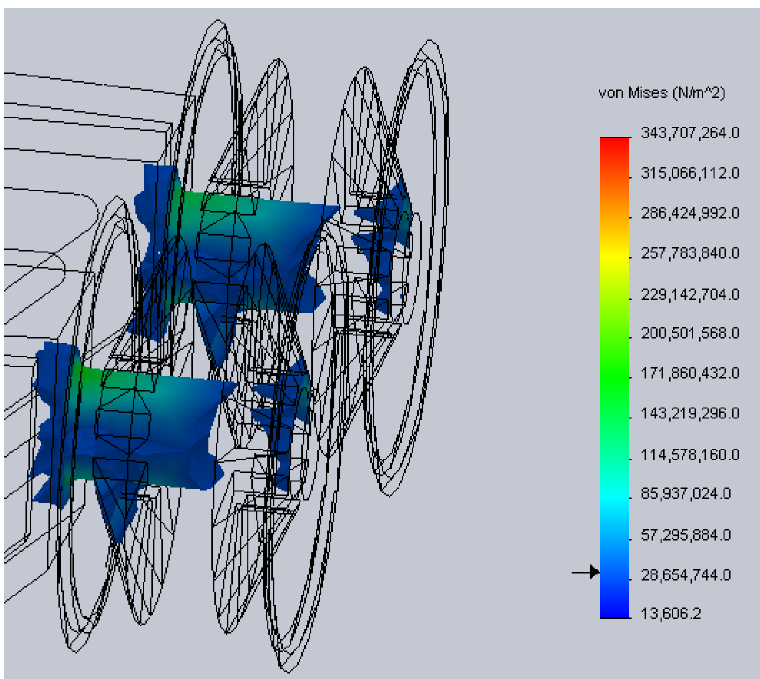


Figure 20: Final Design 5-G Stress Simulation (Wheel Axle)

Fig. 20 shows the completed simulation analysis of the wheel axle when the structure is subjected to a full capacity of riders and the weight of itself under a five-G moment of acceleration. As expected, the highest stresses are found where the axles meet the stationary structure. Though these stress concentrations are still present they do not fail according to the

FEA results with a minimum factor of safety of 1.86. These concentrations can be dispersed with a greater fillet which can take place during the welding process as mentioned. Theoretically the increased welding space would not increase the safety so much as it would lessen the fatigue of the steel material proposed for the stationary structure.

6.3.4 Cross-arm

A cross-arm connecting the left and right sides of the car resembles the design of a simple-supported beam, in that it has only two supports with the center receiving the load. As the analogy applies, the cross-arm will have equal shear forces on either end and a maximum bending moment in the center. These components of stress will decide its diameter. By design there should be no maximum limit to the diameter of the arm as the greater mass included with a larger cross-arm could increase momentum and the increase in material should make it stronger.

Depending on the number of cars a completed track can hold, the increase in material cost may not be considered important. However, the larger the diameter, the mass moment of inertia is also larger and less rotational freedom is allowed unless compensated with a longer rack. Stronger materials besides steel can be used for the cross-arm relieving the need for a larger diameter and, therefore, not reduce the rotational distance.

To keep the cross-arm as strong as possible, the teeth are to be machine-cut as hobbing requires the teeth to be cut across the entire length of the gear. A portion of the cross-arm is left un-milled towards the inside of the teeth to allow for roller contacts to be placed. The pattern chosen to be milled is the widely standardized twenty-degree pressure-angle, involute pattern. Assumingly, the cross-arm will last much longer than the rack and, if it should ever be replaced, the rack can be purchased commercially or easily be machined when commissioned. Initially, the outer diameter of the cross-arm was designed to be 0.43 meters, but an FEA showed the resulting factor of safety to be larger than necessary, even when subjected to higher-than-proposed forces, over five Gs. The cross-arm design is redone with a diameter of 0.325 meters and is tested under the same conditions in the analysis and is estimated to a lower, but still safe, safety factor of three.

The reason to shrink the diameter is not to decrease safety but to make better use and better allocation of the materials involved as to not over design the cart. This reduces the cost of materials slightly and increases the rotational range of the seats without needing to increase the length of the rack.

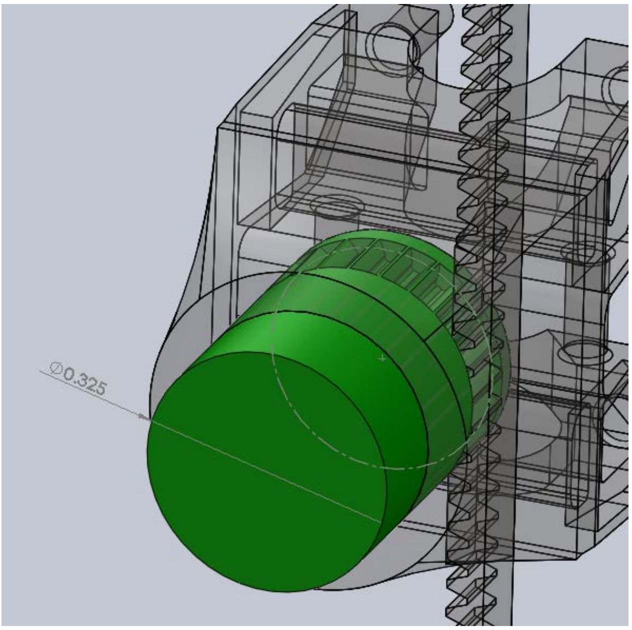


Figure 21: Cross-arm (in assembly)

The final cross-arm design, Fig. 21, includes twenty-four milled teeth at a pitch of sixty. Keeping the pitch a rational number allows a replacement rack to be obtained much more readily. The large pitch creates thicker teeth and wider faces on the milled section to handle the torque involved with rotating as much as 5.4 kilonewtons. A benefit from decreasing the nominal diameter of the cross-arm is that it allows more room for rollers to be placed within the stationary structure without drastically altering the already finalized design.

6.3.5 Rack Teeth and Dimensions

With the changes made to the cross-arm and stationary structure the rack will also undergo design changes. The final rack now meshes with the sixty-pitch teeth milled into the cross-arm while the thickness of the rack has remained unchanged. This is due to the already safe operation of the mechanism under load. Shrinking the overall thickness of the rack could still be safe for operation, but could introduce a shorter lifespan from fatigue caused by the necessary torque buckling. The length of the rack has been decided to be twice the circumference of the cross-arm to create seven-hundred-and-twenty degrees of rotation in the cart. This is not a strict length as a track design may find this two-meter high rack may seem unaesthetic depending on the theme of the ride.

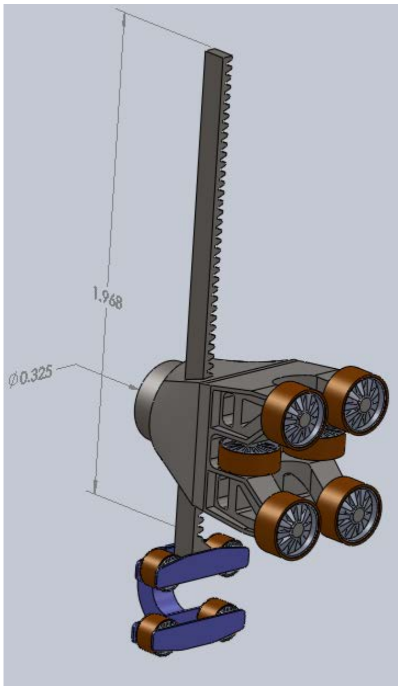


Figure 22: Completed Stationary Structure

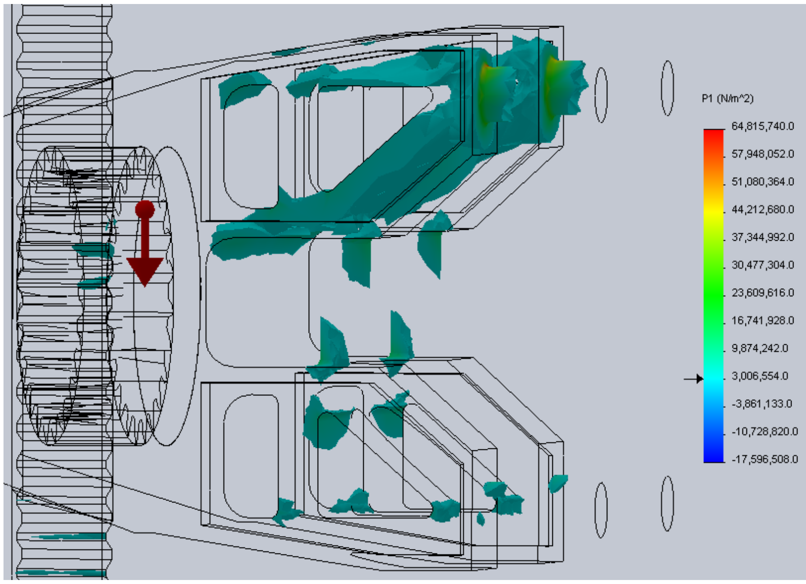


Figure 23: Completed Structure Principle Stress at 5G Load

Fig. 22 shows the length relation of the rack compared to the size of the rest of the structure. The guide wheel structure, in violet, has also been redesigned to use smaller wheels to help decrease the deviation of the secondary rail. Fig. 23 is the simulated stresses of the entire structure when at the maximum rated five-g load.

6.3.6 “L-connectors”

In order to connect the guide rails to the secondary rails, there were many factors to consider. First, the part connecting the two had to be strong enough to withstand the incoming force produced by the cart yet, light enough to avoid deforming the track rails themselves. Second, these connections had to avoid using the top and bottom of the rails in order for the cart wheels to get through.

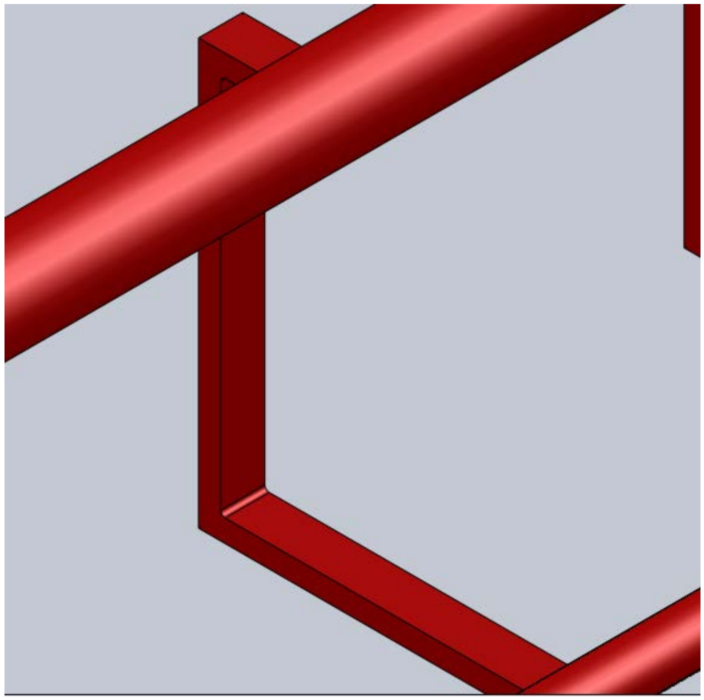


Figure 24: L-connections

This problem was solved by creating small L-connectors with the proper geometry to withstand the incoming load and also avoid bending the rails. We then place them 1 meter apart to secure the rails together and finally fillet the inside of the "L"s in order to prevent additional stress and eventually cracking. Fig. 24 shows the geometrical characteristics of the L-connectors, including the width, length, spacing, and fillet. The only dimension that is not given is the height of the L-connector. The reason for this is because the secondary rails will fluctuate on the vertical axis and thus, vary the height of the L-connector needed to secure both rails.

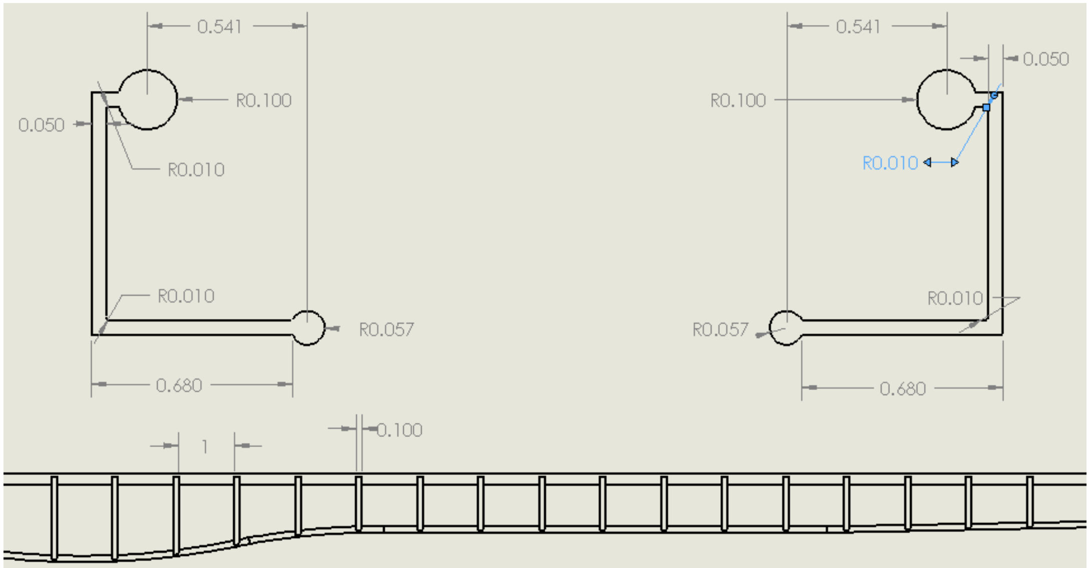


Figure 25: Track Schematic and Example Rail Variance

6.3.7 Track Stands

Another important component in building the static structure of the roller coaster is the stands. This project will not go in depth on where the stands should be placed on the track as the intentions of this report is to only demonstrate a new mechanism to add a feature to a roller coaster. Track designing is left to the manufacturer and as such, placement of the beams is track dependent. However, suitable design of stands will be done in order for said manufacturer to build accordingly. This stands will be designed to properly support and hold the guide rail from the ground. In order for the track for the roller coaster to be lifted and supported, there needs to be stands on both rails. What this will do is cut the load that a stand on a normal roller coaster will have in half. Therefore, the design of the stand can be smaller than typical roller coaster stands, and just proper positioning will hold the structure's integrity. A quick note, more stands will be needed at turns and loops, but this of course is left to the track designer to properly place this beams.

In order for the stand to hold the structure, it also needs to avoid using the top and bottom parts of the rail. Therefore, the stands have been designed to hug the outer part of the rails and held in place via heavy bolts. The main concern was the head of the beams, as pole length is also based on track design. Fig. 26 shows the head of the pole, and Fig. 27 shows a possibility of an entire stand.

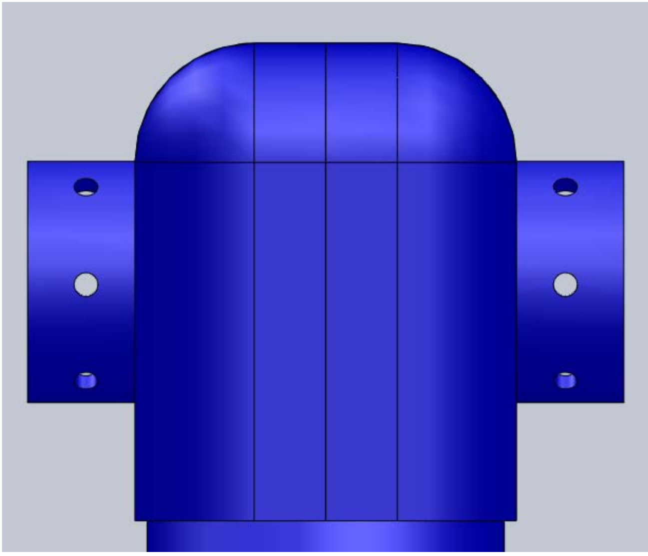


Figure 26: Head of Beam Stand

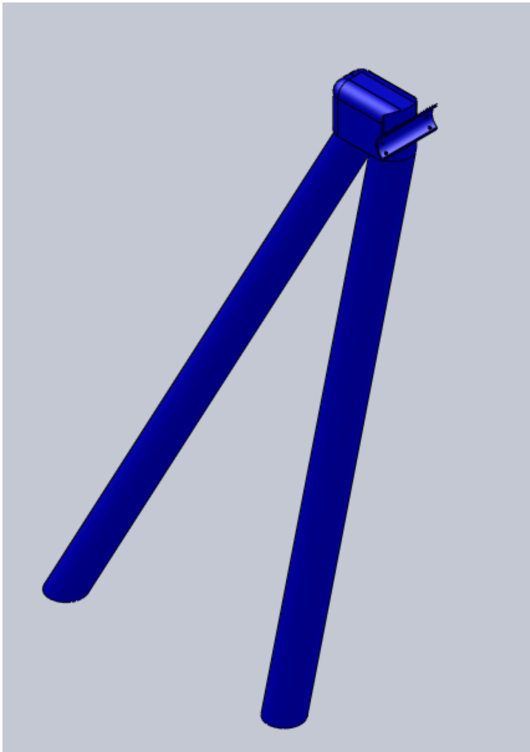


Figure 27: Beam Stand

6.3.8 Track Assembly

By combining the three previous parts, a static structure, or track, is designed. Fig. 28 shows a possible track part on a straight away. This will be used as the mock track for the roller coaster to get through.

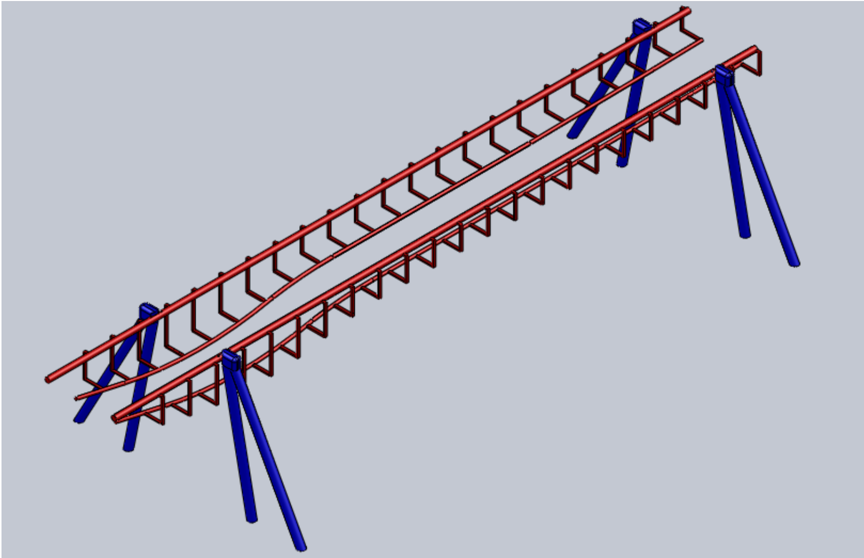


Figure 28: Simulated Track

A couple of things to note are the L-connectors varying in length throughout the course of the track, the beams situated between the L-connectors, and the beams avoiding any contact with any rail. Fig. 29 illustrates the connection of the stand to rail better.

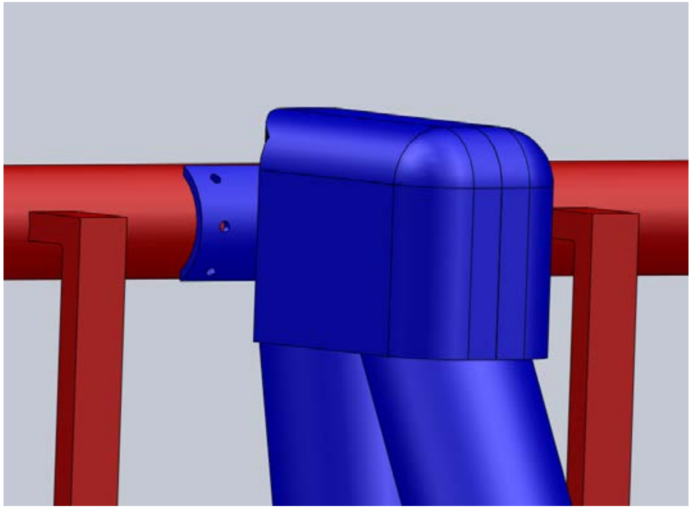


Figure 29: Stand to Rail Connection

6.3.9 Bolts, Screw and Nails

Typical roller coasters can have as many as 50,000 bolts and just as many nails if it's a wooden roller coaster, all coming with different lengths and diameters. Most of these fasteners are made of galvanized steel to prevent rust and corrosion. Bolts can be used for many attaching purposes, including the rails, the stands, seats, frames, metal housing and just about anything else that would need to be connected securely. While designing the seats, frames, rack and pinion assembly, etc., many thoughts were given to the placement of these bolts and the amount needed. In order to determine this, a static analysis was done on a standard M16 x 1.5 bolt. This name describes the size of the bolt with a fastener nominal diameter size of 16 mm and a thread pitch of 1.5 mm. Fig. 30 shows the bolt drawn in SolidWorks.

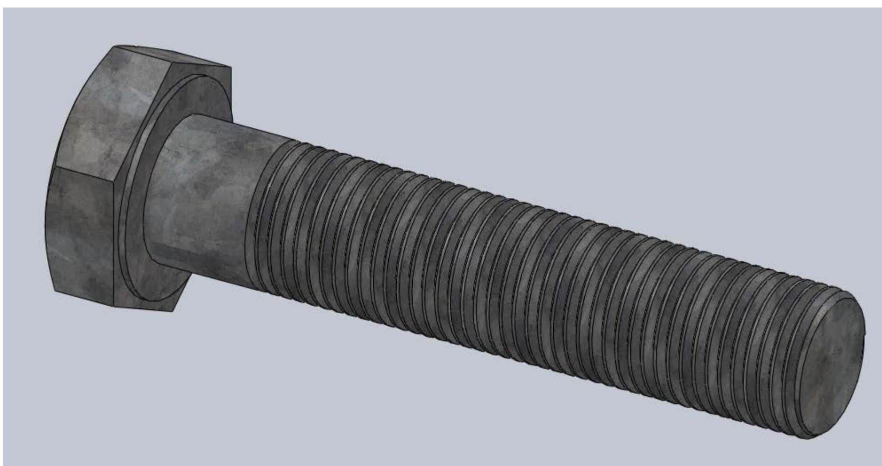


Figure 30: Seat and Rail Bolt

After drawing the bolt, the strength of the bolt was simulated on the seat attached to the metal case. On the extreme case that a 300 pound person was riding the roller coaster and was experiencing five Gs of force, the analysis will if this bolt was strong enough to withstand the load. Since the metal case was designed to be bolted at ten different locations, the actual load seen by the bolt would be cut to a tenth of the total load. As such, the bolt was simulated by fixing the inside of the head of the bolt and applying a downward force along the bolt. Fig. 31 shows the displacement of the bolt in millimeters and Fig. 32 shows the factor of safety.

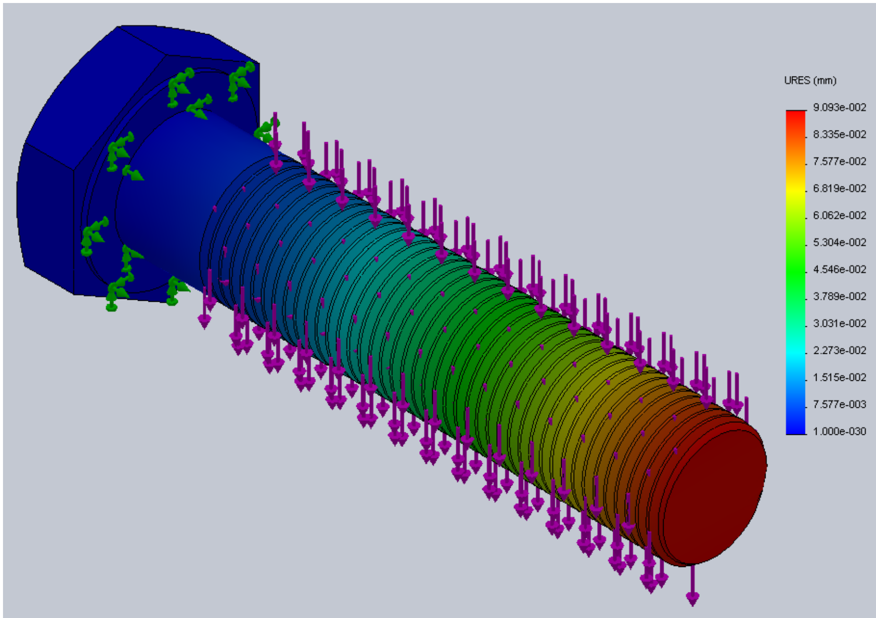


Figure 31: Displacement of Bolt under Load

As presumed, the largest deformation on the bolt was at the ends. With a displacement of only .009 mm, the bolt does not deform a large amount and can safely assume the load given. The lowest factor of safety on the bolt was 2.1, which is just above the desired amount.

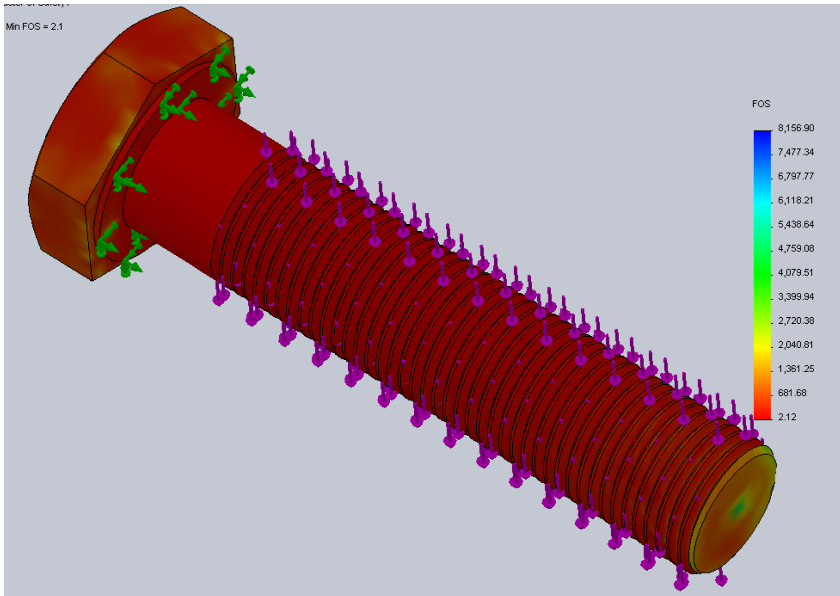


Figure 32: Bolt Safety Factor

As can be seen, the bolt is strong enough to withstand the load. While a bolt with a smaller diameter (though not much smaller) can withstand the load, a factor of safety of 2 is appreciated and so, will be used to fastened the seat and metal frame together.

6.3.10 Seat

For the seat itself, dimensions had to be taken to accommodate a variety of body types. While creating a universal seat that can comfortably situate all is impossible, seat dimensions were redesigned to fit the bulkier customers. The geometry of the seat included a head cushion, a body structure, and a bucket seat. Length, width and height of the seat were compared to the body shape of a 6 foot 2, 250 pound football player. Since most people would be smaller than our tested subject, it will fit them comfortably too.

As previously stated, no seat can be made universal, but it was decided to accommodate as many people as possible. Many different designs were created but had to be discarded because it would violate safety regulations. Others were not perceived as comfortable to the passenger. Fig. 33 shows one of the suggested designs that had to be disregarded. Reasons for it included and unsafe head rest and an uncomfortable bucket seat. Though the head rest can be moved up and down to the person's accommodation, it was deemed not safe to have separate parts of seat put together in that manner.

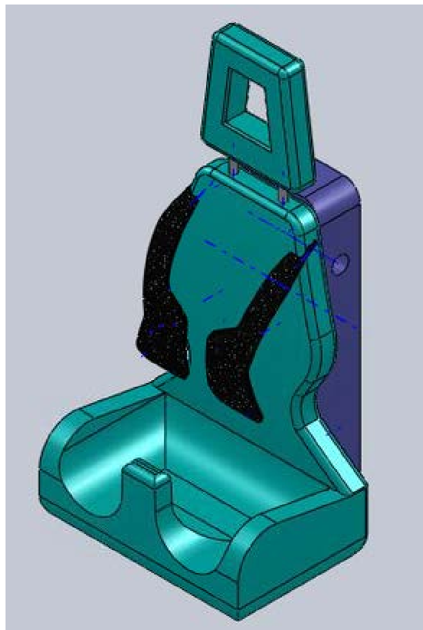


Figure 33: Failed Seat Design

Fig. 34 shows the final and approved seat design along with the different materials used to build it. Parts colored in black are the cushion and parts in red are the plastic casing components. It is a low-density polyethylene plastic to be exact.

Figure 34: Cushion Seat

6.3.11 Restraints

The most important features in a seat are the restraints. Riders want to feel secure while riding the coaster and proper designing of restraints is vital in building a fun yet safe ride. For the metal casing design, the front part would connect with the back part of the seat using bolts near the edges. These bolts will be hidden from view as the cushion part of the seat would cover them. In other words, the manufacturer should have the metal casing connected to the plastic seat first, and then insert the cushion on the seat. Fig. 35 shows the metal case with the tapered holes used to bolt the seat together. Also designed on the case are a hole and a cut section which will be elaborated in the next few sections.

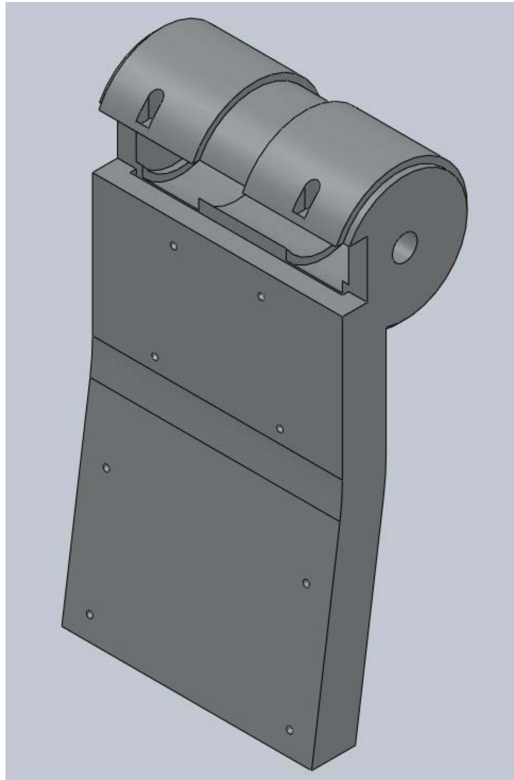


Figure 35: Metal Casing

As stated before, seats usually have up to two separate restraints, and this design will be no different. The first set of restraints is a metal tube which locks in place using a spool inside the metal casing. This locking mechanism prevents the metal tube to move up, but can move down, tightening to the rider's body type. The only way the mechanism can unlock is with the operator's control, in which the part stopping the spool from spinning the other way is moved. Fig. 36 illustrates how this mechanism works.

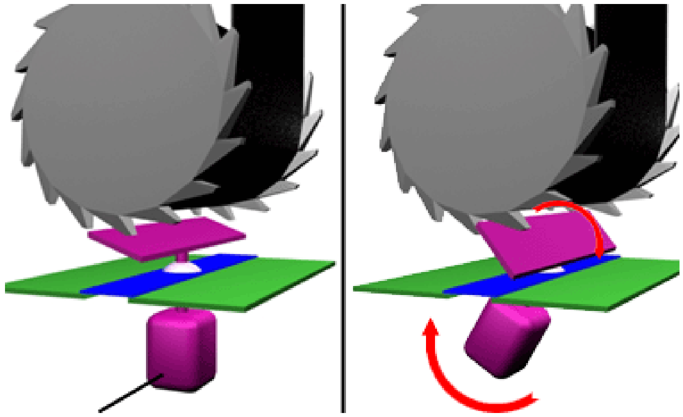


Figure 36: Spool Locking Mechanism

As stated, this mechanism is in the inside of the metal casing, and the metal tube passes through the case where the hole located at the top-sides of the case are.

Restrained by the metal case and with an applied force on the bucket seat of 1500 lbs along with a gravity force, the simulation concluded that the seat design was safe. Fig. 37 shows the displacement of the seat. As can be assumed, the highest amount of displacement was located at the end of the bucket seat with a magnitude of 10.95 mm. While this may seem quite large, a note to consider is that the material of the seat is a low density polyethylene. Normally, these materials are flexible and can be bent without causing failure. Another note is that the seat will not have to endure this load constantly throughout the ride. This analysis was conducted under the consideration that at a point in time, the rider was experiencing five Gs.

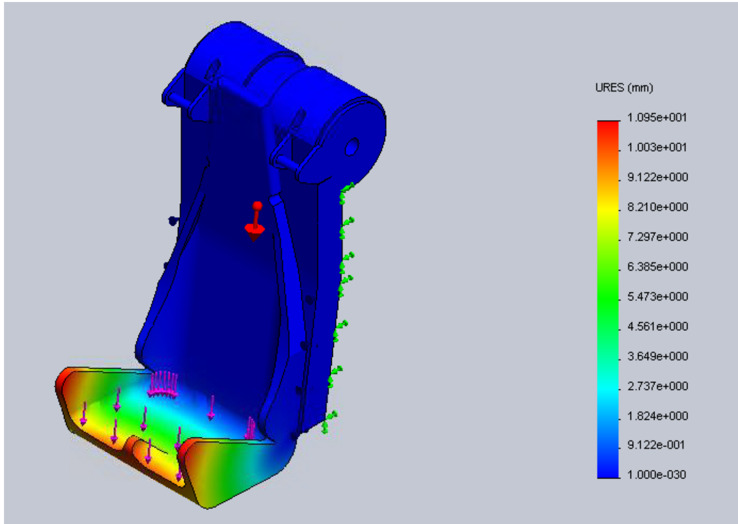


Figure 37: Seat Displacement

As shown in Fig. 38, the seat does not fail and can endure a track design in which the person has to endure five Gs of force. With a factor of safety of 4.2, the seat is safe to ride on.

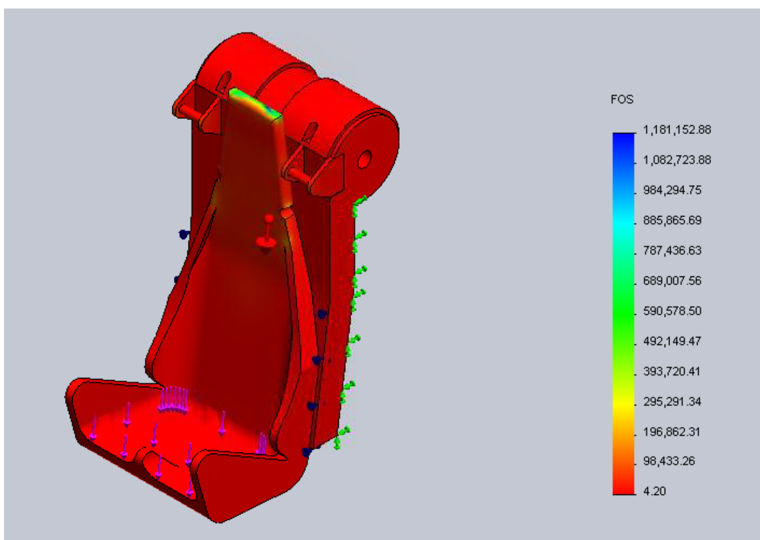


Figure 38: Seat Safety Factor

Attached to the metal casing is the chest-restraint. Made of cotton-nylon-polyester, this piece is meant to better distribute the pressure felt by the rider when his/her body is abruptly stopped by the restraint. In addition; with the material being elastic, some of the force is absorbed by the restraint and less pain is felt by the rider. This chest-restraint is attached to the metal case by another part specifically built for this purpose. This piece is mounted in the metal case and screwed in. This part has handles on each side for the purpose of holding the chest-restraint. Figs. 37-39 show each part separately in detail.

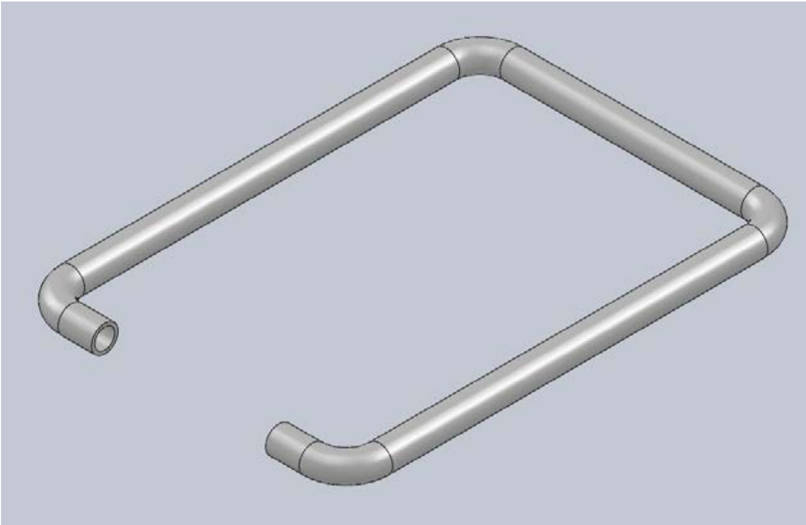


Figure 39: Restraint Metal Tubing

Figure 40: Chest-restraint

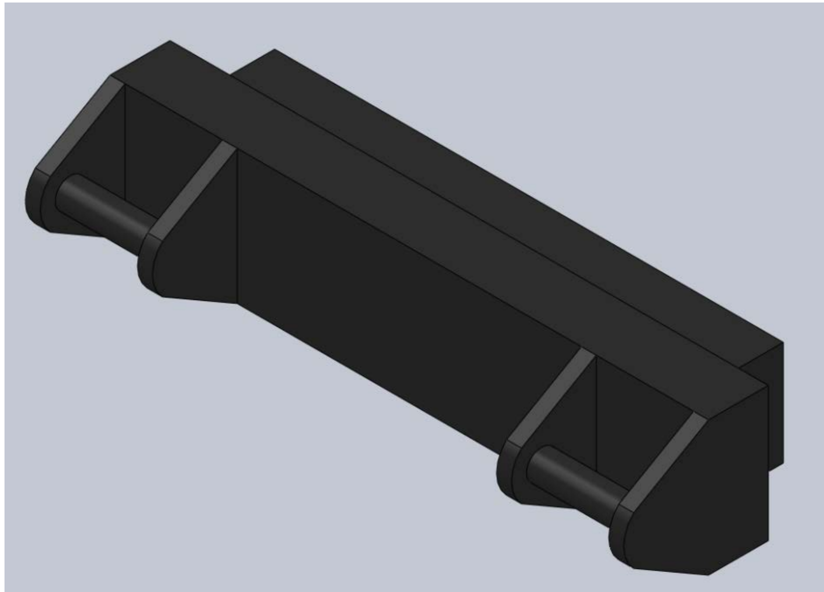


Figure 41: Chest-restraint Upper Connection

The second set of restraints used in this seat is the basic safety belt. Attached to the chest-restraint, this belt prevents the metal case from flying should the spool fail for any reason. This safety belt should be adjustable for any person sitting and therefore, was made a little long should the person be bigger. Like other roller coaster, these are clip on safety belt, and can be disconnected by applying pressure on either side of the metal head. Fig. 42 shows the safety belt part for this roller coaster.

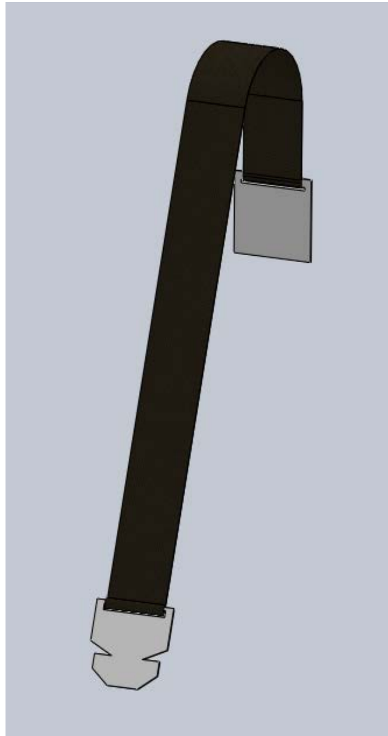


Figure 42: Safety Belt

6.3.12 Seat and Frame Design

After all the components were assembled together, Fig. 43 shows the final design. To reiterate, with the seats rotating forward and backward, a chest restraint was made to evenly distribute the external forces across the human body. It has the basic safety restraints of typical roller coaster seats; seat belt and harness. The seats are made out of plastic with vinyl placed on the bottom and back portion of the seat. The harness' material is a mixture of cotton-nylon-polyester, with reinforcement on the stitching. The metal tube is locked in place with a spool mechanism that only the rider operator can control. The connector piece is screwed into the metal case on the side and on the top (placing of the screws can be seen with from the indents of the metal case located at the top).

Figure 43: Single Seat Assembly

6.3.13 Seat Frame

A lot of consideration was given toward the housing of the seats. The frame needs to be able to hold 4 seats along with four passengers and at the same time connect them to the cross-arm that will cause the passengers to spin. The frame would be bolted to the metal case and as such, should hug the back side of the metal case smoothly. Fig. 44 shows the design of the roller coaster frame.

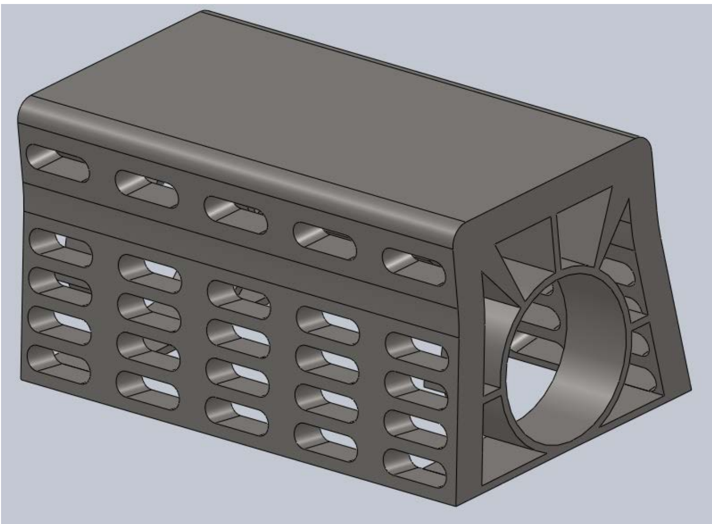


Figure 44: Seat Frame

The frame had to be thick to have enough strength to hold the entire load previously mentioned but also skinny enough to bolt it down. Although bolts can be made of extremely lengthy size, these bolts are expensive and should be avoided whenever possible. Oval-like holes were made to decrease weight. A bore was made on both sides to connect the frame to the cross-arm. It should be noted that the cross-arm and the seat frame are connected together and rotate as one. The spinning is not caused by friction and there is no slipping involved. This bore is connected with some fins around it to further increase its rigidity.

6.3.14 Passenger Protector

One of the many considerations in designing a safe roller coaster is rider negligence and how to prevent these accidents to happen. With all the rotating components and sheer velocity of the roller coaster, passengers should avoid contact with the mechanical structure of the rack and pinion, cross-arm, and railings at all costs. As such, some type of piece that prevents passengers from reaching out and getting injured had to be designed. Fig. 45 shows a plastic wall covering the moving parts of the roller coaster. Light and easy to connect, the plastic wall was not only designed to protect the passenger, but to avoid as much air resistance as possible. Because the roller coaster will be traveling at high speeds and moving from side to side (such as turning), the wall had to be designed to eliminate as much air resistance as possible. Ways of doing so include bending the edges round and inwards, and, though it is hard to see, the perforating the cover.

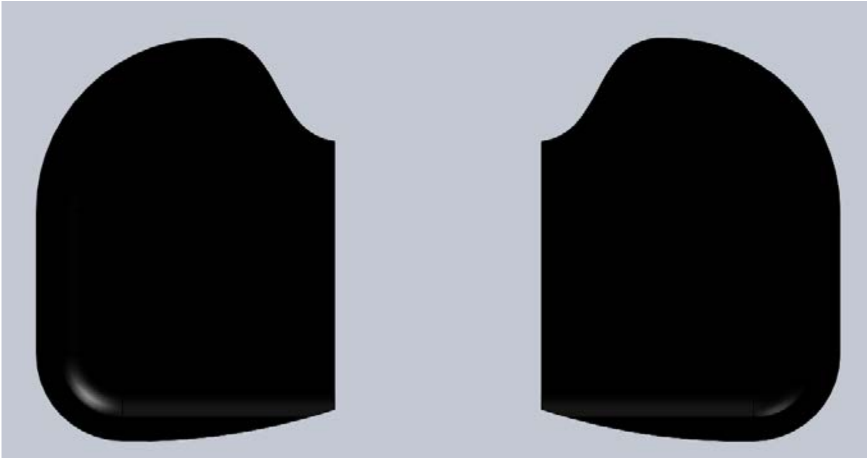


Figure 45: Plastic Blockers

6.3.15 Seat and Frame Assembly

With all the parts designed, constructed, and connected, a final assembly of the seats is made. This assembly includes four complete seats for the passengers to ride, two plastic walls to prevent injury, and the frame to house all the parts and connect them together. Fig. 46 shows the completed structure of the roller coaster seat.

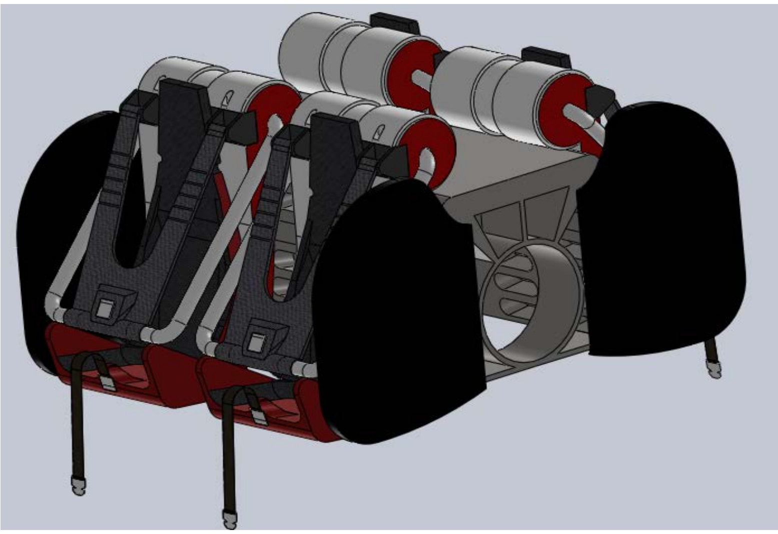


Figure 46: Seat and Frame Assembly

6.4 Completed Final Design

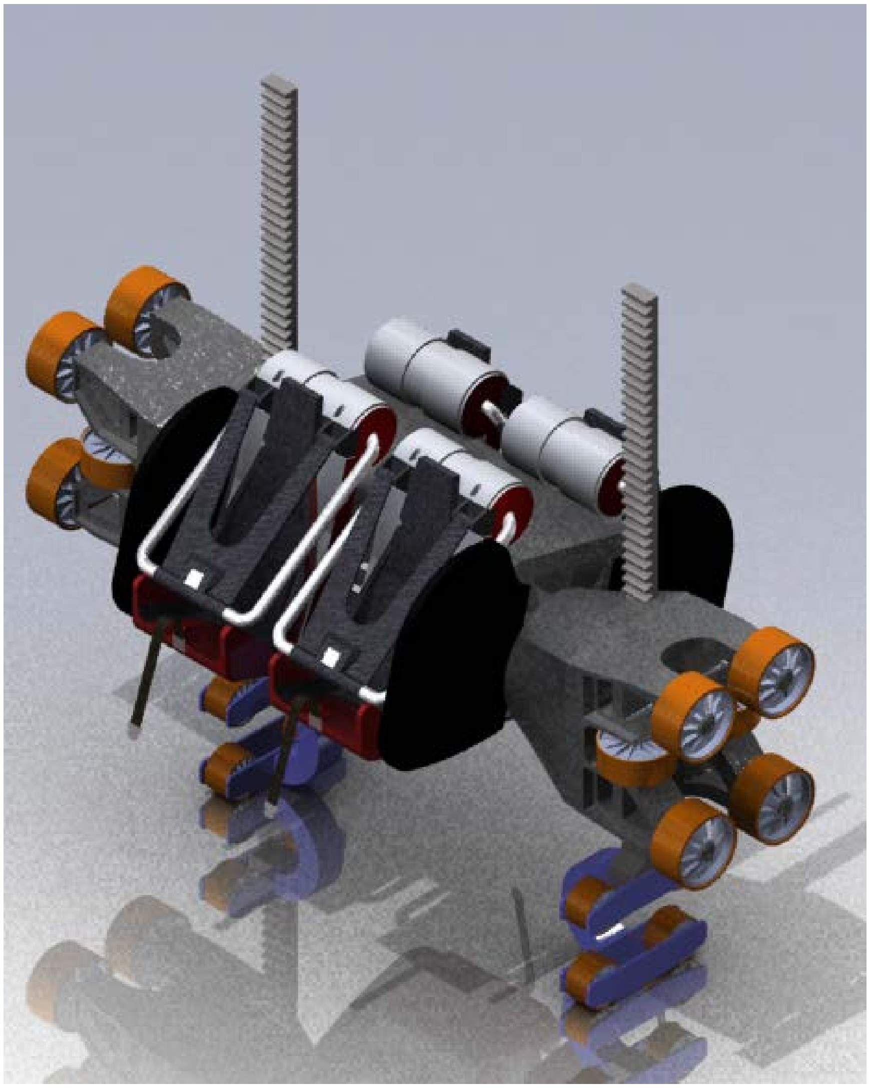


Figure 47: Z4 Assembly

Assembling all the components together form the final product in Fig. 47. The rendered picture is the Solidworks assembly which contains each part discussed in the structural design, barring the track.

Chapter 7 - Cost Analysis

7.1 Prototype Costs

The manufacturing process of a roller coaster begins with the design component. This roller coaster design, steel will be the main material used. By creating a unique 4D coaster from current ones, each detail must be designed from the foundation up. Therefore each component as well as budget must be calculated. Through research performed, the sections to an actual full formed coaster are in Table 3. One main objective is giving the guest a unique feel of the coaster. The track is formed in sections from a pair of welded round steel tubes held in position by steel stanchions attached to rectangular box girder or thick round tubular track supports. All exposed steel surfaces of the track are painted. The table is an estimate displaying the entire cost of the 4D roller coaster.

Table 3: Prototype Cost Breakdown

Item #	Description	Quantity	Cost
1	*Steel- Track, Support*	1100 m	$6,813,400
2	*Bolts, Nuts, etc.*	60,000	$500+/lb.
3	*Seats - Include Restraints*	4/each	$2,000+
4	*Loading/Unloading Platform*	2,000 lbs.	$631/ton
5	*Wheels - Road, Guide, Booster (Urethane)*	20	$1,000 +/each
6	*Chain Lift*	2	$20,000+
7	*Car*	5	$150,000+
8	*Queue Area & Paint*	45,000 sq. yd.	$40000+
9	*Break System*	10	$45,000+
10	*Tracking System - Sensors, Camera, Safety Checkpoints*	3608.9 ft.	$30,000+

7.2 Model Costs

The prototype cost analysis table displays the estimated prices of each component of what will be manufactured. The prototype will be a model form of the actual track as well as 4D mechanics of the car and the actual guest experience displayed by a camera. The factors shown in the prototype are much less than those of an actual full design. However the rotational aspects of the cars will remain the same, as the gears used for the rotation. A breakdown of each part is in Table 4. Instead of using steel as the main material in the prototype, Aluminum and Plastic will be used, and the chain lift will involve steel material. The prototype will be assembled on a measured piece of cardboard.

Table 4: Model Cost Breakdown

Item #	Description	Quantity	Cost
1	*Aluminum*	15 m	\$1-\$10/lb.
2	*Copper*	< 15 m	\$11.39
3	*Tin*	< 15 m	\$2.69
4	*Plastic*	15 m	\$2 - \$15/lb.
5	*Wheels - Support, Guide*	20 (d=0.3 cm)	\$4.95-\$7.95/each
6	*Seats*	4	\$10-\$20/each
7	*Restraints – Screws, bolts*	600	\$200+
8	*Foundation (Board) & Stand*	1	\$6.99 \$12.99
9	*Motor*	1	\$200-\$400
10	*Camera*	1	\$50-\$150
11	*Chain lift*	1	\$300+
12	*Gears Bag-2 Gear 2Rack*	1	\$19.99
13	*Track, Secondary Rails*	6 (36”)	\$5.39

Chapter 8 - Prototype Testing

8.1 Description

As previously stated building a life-sized roller coaster can take an extended period of time and cost millions of dollars. For this project, our team decided to build a scaled down version (1:20) of our roller coaster while still incorporating our spinning mechanism for demonstration purposes. With the dimensions of our model prototype this small, the forces exerted on the railings would be too minor to cause any type of deformation. As a result, the team decided to build the model using aluminum as our basic material for our railings, gears, and support beams, while the coaster cart itself was made mainly using plastic. The reason for using aluminum is its economical prize and strong physical properties as well as its smooth texture.

To construct the prototype, we first needed to extrude four 12-meter long aluminum rods, two with a diameter of 10-milimeters and two with a diameter of 4-milimeters. We then proceeded to shape the track using a special piece of equipment that has the cross-sectional specifications of the coaster track. The purpose of this equipment is to ensure that the width and height of each rail in relation to the other is constant, as any significant deviance of width would cause the cart to fail in completing the circuit. After shaping the heated aluminum to match or designed track we proceeded in building the coaster cart. The following picture shows an example of a possible finished product.

Figure 48: Example Prototype Model

8.2 Model Construction

To begin, the seats were decided to be made from foam. Initially a model of a seat was made out of modeling clay and left to dry. This model is to become the positive for an expandable foam mold.

Figure 49: Clay Model of Seat

Expandable foam, purchased as a pressurized can, is then sprayed around the positive mold inside of a cup and left to cure overnight, as the instructions suggest on the product. After curing, the positive mold adhered to the walls of the foam with greater force than what held the clay model together. Extracting the positive from the negative became effortful and later resulted in the destruction of the positive. Therefore, only a single negative mold has been completed.

The next step involved spraying the same expandable foam in the negative to create a foam seat to be used in the construction. Since the clay had become rigidly stuck to the foam in the first phase, the negative is lined with a thin layer of wet paint before new foam is injected to act as a release agent. Again, curing is to take one whole day.

During the first seat curing, the stationary structure is the next task. Using a thin sheet of tin a basic box shape is cut. Tin was selected for its pliable properties and ability to accept solder. Welding would not be an option for the tin sheet because its' low melting point would deform the metal rather than weld it. Solder is also the inexpensive approach when compared to welding and is the better option when it comes to hobby construction, as employees of the local hobby shop had suggested. The box shape is also easy to cut with straight lines and can be folded very easily.

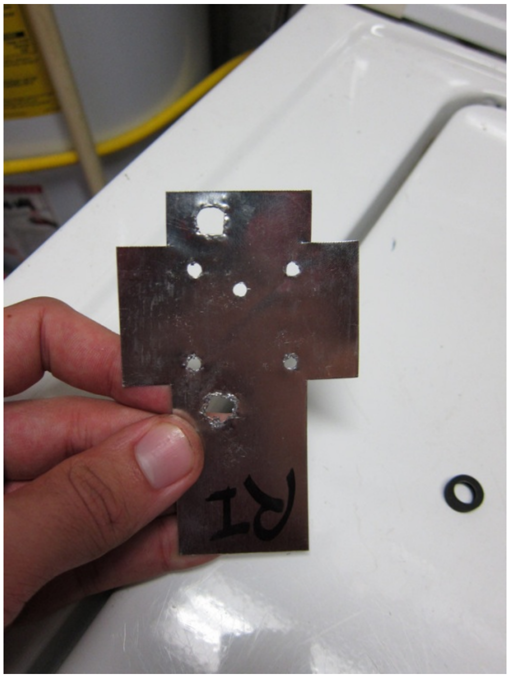


Figure 50: Stationary Structure for Model

In Fig. 50, four equally spaced holes are made to hold a 1/8" diameter aluminum tube to act as axles for the four support wheels. The spacing between each of these holes is designed to allow a 7/32" diameter copper tube to fit between two twenty-one millimeter diameter wheels. This follows the same construction as the proposed design.

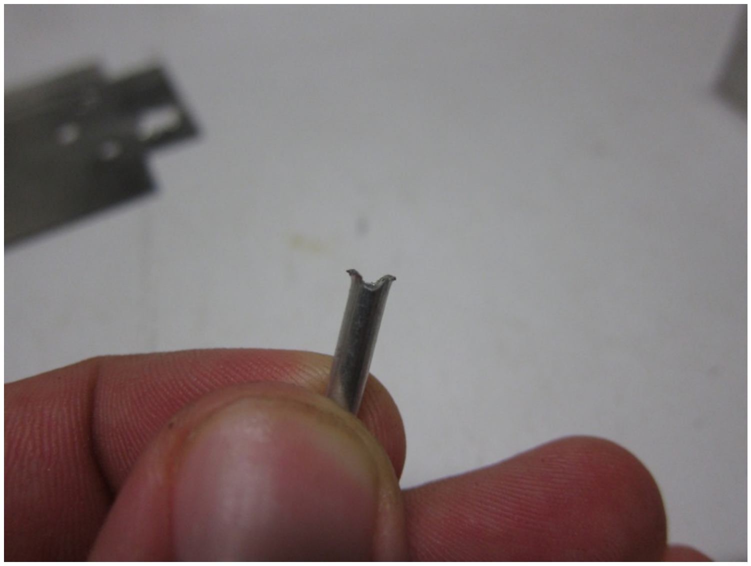


Figure 51: Aluminum Axle

Fig. 51 shows the small piece of aluminum to become an axle. Each end of the tube is sawed slightly to create two flanged ends to be bent over the wheels to hold them in place.

Figure 52: Support Wheel (above) and Guide Wheel

The support wheel had to be bored to fit the aluminum tubing as a shaft. The smaller guide wheels were intended for the same shaft idea to be placed along the secondary rail to move the rack. However, these are too small for a drill bit of that aluminum tubes' diameter and were later discarded.

The flared ends of the shaft were then bent to secure the wheel and axle in place to the stationary structure. Originally it was intended to solder the axles to the structure, but it was after a trial that the team then learned that aluminum does not accept tin-lead solder. Because of this, the same concept applied to keep the wheels in place was also used to keep the axles fixed.

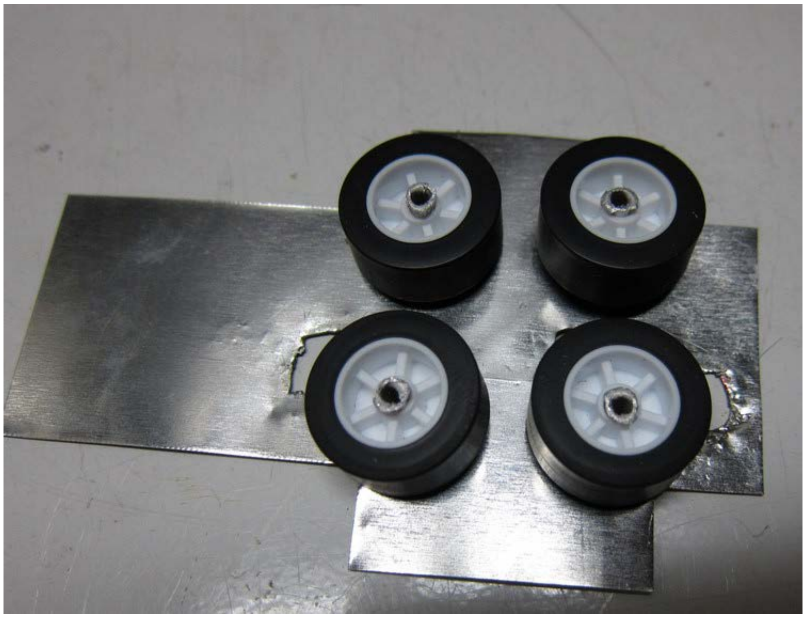


Figure 53: Wheel Assembly Complete

The hole placed within these four is to use the same tubing to create the cross-arm. The larger holes created in the upper and lower middle portion of the tin are what let a rack move up and down through the structure. These were bored with a large drill bit and then finalized to accommodate the dimensions of the rack using metal snips. The holes are roughly a quarter of an inch wide and proved difficult to cut with standard metal shears. This caused the holes to be slightly imperfect but the rack is still able to move with some clearance.

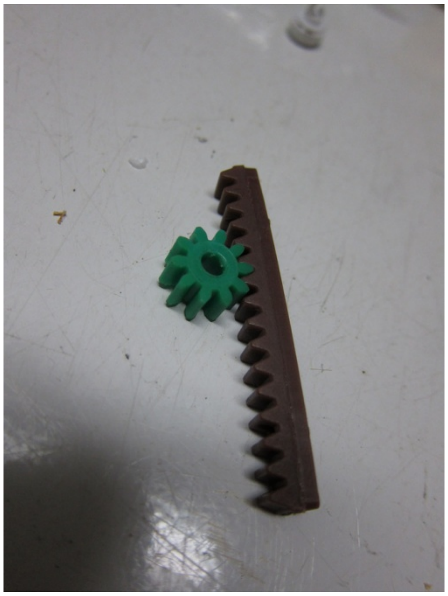


Figure 54: Prefabricated Rack and Pinion Components

The green pinion will be placed inside the stationary structure and have the aluminum tube adhere to it with glue. This is to replicate the cross-arm mechanism found in the design. The rack is then be inserted to impart the rotation.

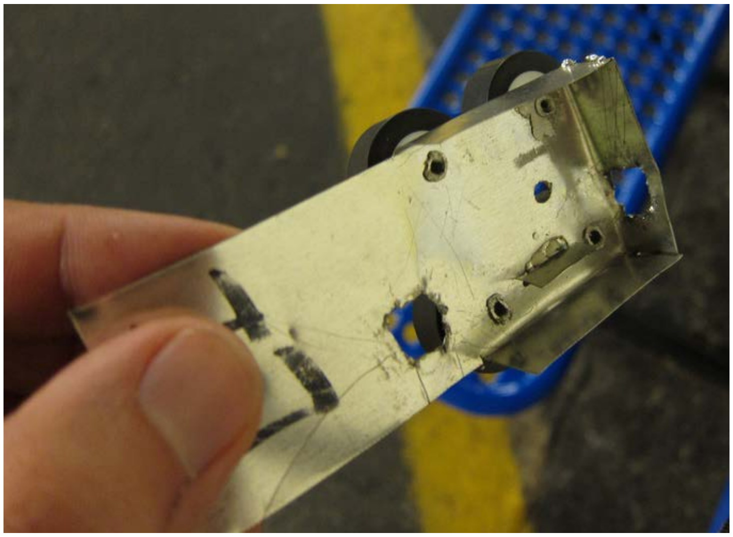


Figure 55: Stationary Structure Progress

During the folding of the box structure, Fig. 55, it was found that the rack may have difficulty passing through the structure so a small piece of scrap tin is soldered inside, between the lower two axles in Fig. 55, to help keep the rack aligned.

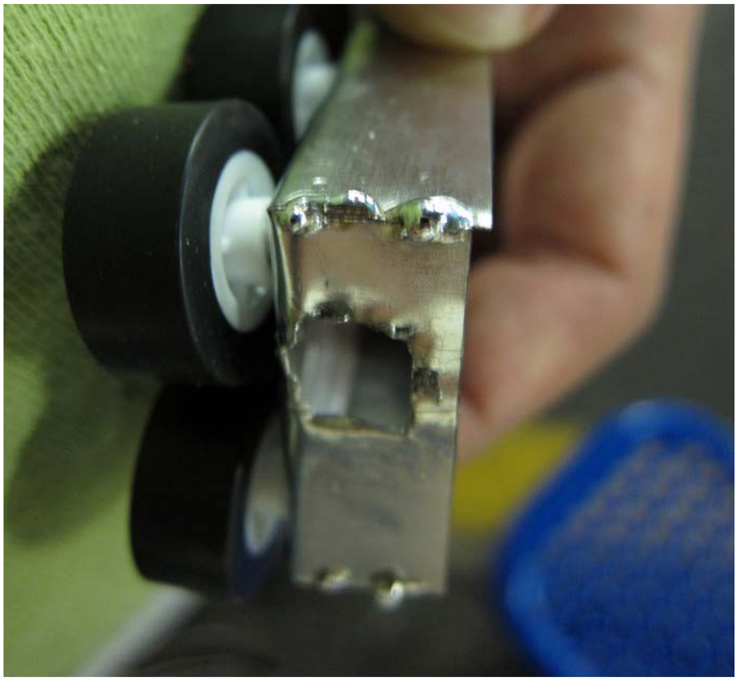


Figure 56: Soldered Edges

Because of the material choice, the box structure is easily held together with solder. At some sections where the two edges have a gap, soldering the space closed is difficult. But the joints created thus far hold the ends securely.

At this time, the new seat mold is ready to be removed. During the removal process, the weak foam, though the wet paint acted as a release agent as planned, still got destroyed. From this point on the seats were then decided to be carved out of foam blocks as the molding process proved more problematic than useful.

Figure 57: Four Foam Blanks Left to Cure

With the same expandable foam, four blocks were cured overnight in large cups to be later carved into individual seats.

Figure 58: First Foam Seat

Following the same basic contours and dimensions of the clay model, these new seats were carved each from one blank created. The foam is soft and flexible at this point, so a foam-specific paint and sealer is used to harden the seat to reduce the possibility of structural failure when attaching to the rest of the model cart.

Figure 59: Painted Seats

While the seats are left to dry, the attention is then turned to the copper tubing purchased for use as the track. The planned length for the track would be nine feet constructed of two 7/32" support rails and two 5/32" guide rails.

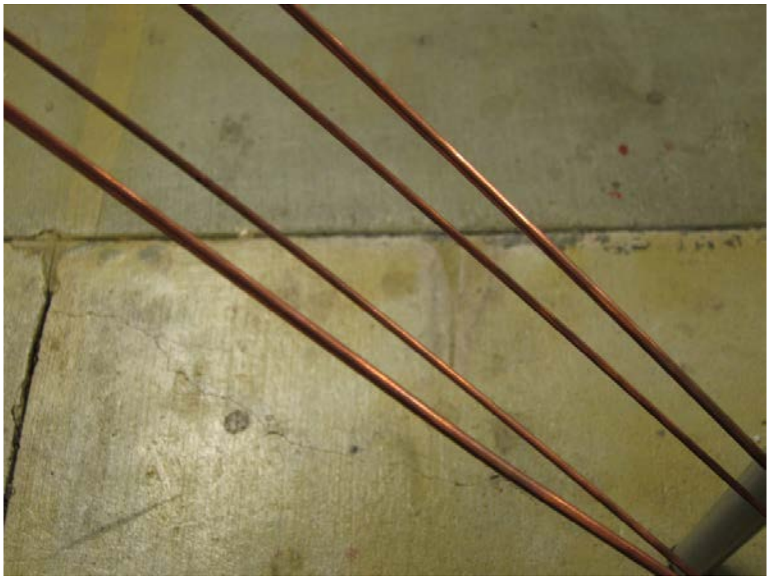


Figure 60: Basic Track Layout

The spacing between each copper tube will be congruent to that of the cart wheels. A template will be made of the cart to ensure the spacing is equal throughout the length of tubing. Currently the tubing is purchased as straight to make it easier to keep spacing even. The track will be bent around sturdy cylindrical forms to produce turns and hills in the copper. One method to produce these curves without buckling the tube is to fill the tubes with sand or salt to act as a temporary brace inside the bend.

At this moment, the construction has been halted due to possible redesigns of the stationary structure and the need for replacement guide wheels.

Table 5 shows the time taken throughout the current progress in the construction of this model. Track assembly slots are intentionally left blank as the completion of the model is expected to occur after the publication of this paper.

Table 5: Model Construction Timesheet

Testing Item	Evaluation Steps	Team Member	Time (hours)
Track	Track in Solidworks	Sergio	18
		Michael	9
		Ashley	5
Track	Track Manufacturing	Sergio	2
		Michael	2
		Ashley	2
Track	Track Assembly	Sergio	
		Michael	
		Ashley	
Car	Car Rotation in SolidWorks	Sergio	20
		Michael	20
		Ashley	13
Car	Car Manufacturing	Sergio	10
		Michael	10
		Ashley	10
Car	Car Assembly	Sergio	12
		Michael	10
		Ashley	9
Car	Car Attachment to Track	Sergio	
		Michael	
		Ashley	
Gears	Gears in Solidworks	Sergio	8
		Michael	16
		Ashley	6
Gears	Gear Manufacturing	Sergio	6
		Michael	9
		Ashley	5
Gears	Gear Assembly to Car & Track	Sergio	
		Michael	
		Ashley	
Car, Track & Gears	Car Testing on tack w/ Gears full test run	Sergio	
		Michael	
		Ashley	

Chapter 9 - Conclusions

Overall, this roller coaster idea came with the drive and passions for it to one day exist in a theme park. Taking the thrill of coasters one step further, interesting societies of the natural forces with a railing path, breaking system and car design to take people on an adventure like no other. Through our contact with several professional roller coaster companies, our literature survey guided the team with the tools necessary to complete this project in hopes to ultimately pitch the idea to a professional company. The roller coaster critiques will have a unique experience, using four dimensional notions throughout the attraction as the main design intention. Through research and ideas, many alternatives to the rotation of the coaster have arisen. Magnets and springs were two proposals which a detailed inquiry was completed. The main concern of safety, efficiency and material life term arose many times, which ultimately lead to the discarding of some of these ideas.

The final design is one of unique, unpatented construction and presentation, offering a new perspective to roller coaster enthusiasts. The paralleled rails and single-cart method provide a one-of-a-kind experience the project aimed for. Using the previously proven methods of the *X2* of Six Flags Magic Mountain and *Eejanaika* of Japan for the rotation mechanism, the rack and pinion movement has been optimized to increase the rotational freedom of the seats while continuing to be safe, meeting a number of design goals. However, the increase in speed or better comfort or smoothness the ride could provide could not be analyzed due to the lack of a true prototype and the limitations of the computer aided software. More sophisticated roller coaster simulation software is required to accurately test the various factors involved with the vibrations within the cart and track while operational.

At the completion of the analysis for the project, the concept model is still being assembled. As the original designs were focused on a real world prototype the concept model required different methods for construction which proved to be problematic at this time, but the mechanics proposed in the project design will be kept. At this time the full and complete running prototype is not fully developed, but is still being worked on till completion.

The completed design and analysis is the basis needed to create a new generation of roller coaster theme rides. Before the construction can begin, there needs to be an overseeing professional engineer to verify and sign off on the drawings. Also, as per safety standards, brakes are needed to be placed at key sections of the track and anti-rollback devices at every incline, decided by the track designer. A chain lift mechanism is also missing from a complete working prototype as the lack of open connections to amusement ride manufactures limited the research required to properly design a lift system. Companies such as Intamin or S&S Worldwide would be the prime associates to complete a fully functional roller coaster based off this project for their work on other innovative roller coasters.

A number of recommendations can be said with an open-ended project of this magnitude as several factors might have been over-looked. Changes in the objectives, the initial design, the simulation, and even the construction can improve the quality of any reproduction of this project. For starters, objectives should be set as reasonable goals that a team can achieve. While many of the initial goals were met, failure to produce a completed track caused the first objective of increasing top speed to not be met. It is recommended that a completed track is analyzed with the project's design in order to calculate the roller coasters characteristics such as top speed, length, and G forces exerted. The design of this roller coaster was drawn to achieve this project's objectives. By no means is it the best design for a 4-D roller coaster and improvements can still be done on it. While this project's design was able to increase the rotational degree of freedom, it is still bounded by the length of the rack. Possibilities of extending this loop to an infinite amount without having to use a motor would be the next step in redesigning this coaster.

Another design concept would be increasing a visual thrill. This project's intention was to increase visual thrill by having passengers ride a coaster without any obstructions seen vertically. The sense of dangling while riding a roller coaster is a thrill in itself, but possibilities of different and more thrilling visuals is also recommended. All of this project's simulations were done on SolidWorks provided by the Florida International University's Engineering Center. While a great tool to use for mechanical structures, there are other simulation tools that are specifically made to analyze and simulate roller coasters. It is believe that these programs are more accurate and more powerful, and as such, should be used instead of the SolidWorks educational version. As stated before, construction for this project was not completed and as such, no prototype testing has been done at this time. With insufficient funding, the prototype was limited in size and had to be built using small, weak, and delicate pieces. A reproduction of this project with a bigger funding can mean better and stronger materials. Keeping the model a decent size can help decreasing the dexterity of the work and make construction (welding, soldering, drilling, fastening, milling, etc.) easier.

Acknowledgements

A number of professors and faculty members of the Florida International University Engineering Center have been of great assistance throughout the course of this project. The team would like to specially thank Dr. Sabri Tosunoglu for his unbiased support and direction. While most of the staff rejected this topic, Dr. Tosunoglu encouraged the team to commit to finding a solution with continuous constructive advice. Though he was unable to aid throughout the entirety of this project, the foundation he helped create for us was more than enough to complete the task.

The team would also like to thank Devon Barroso, and junior mechanical engineering student at the university, for providing an enormous wealth of knowledge on roller coasters. His passion for coaster design was an inspiration to a number of solutions to each component involved in the final product.

Professional amusement park assistance was provided by Lee Wilson and Ramon Rodriquez of Disney World in Orlando, Florida. It was their involvement which narrowed down the possible and safe options for imparting the rotation on the cart.

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Appendix

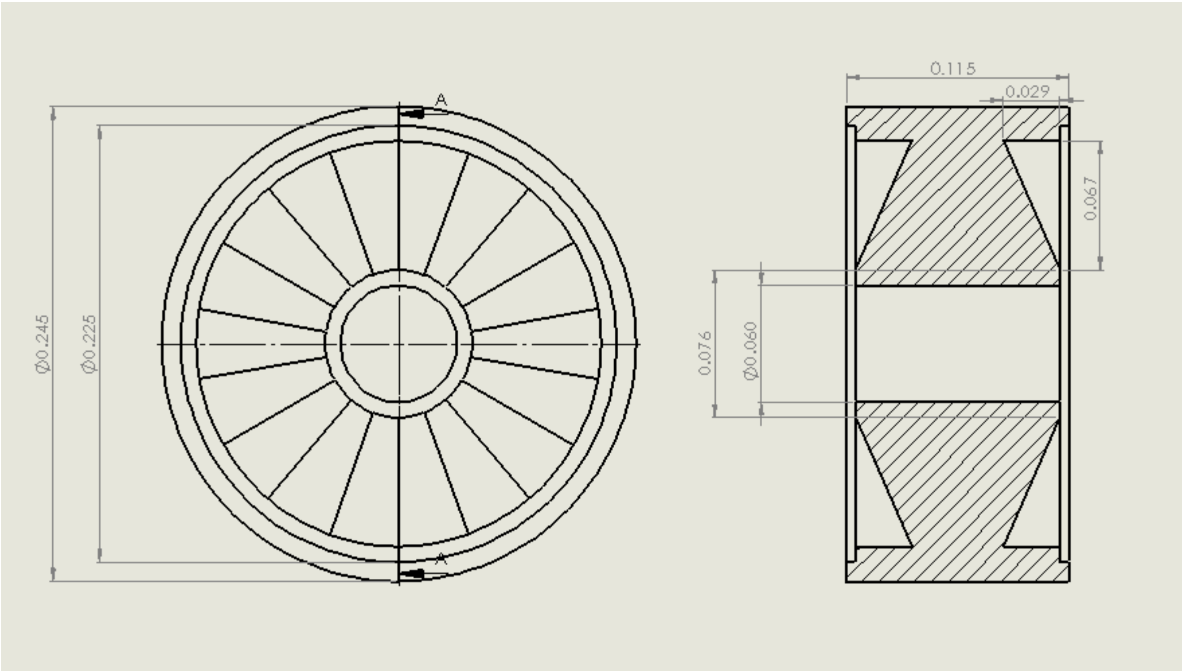

Figure 61: Support Wheel Design

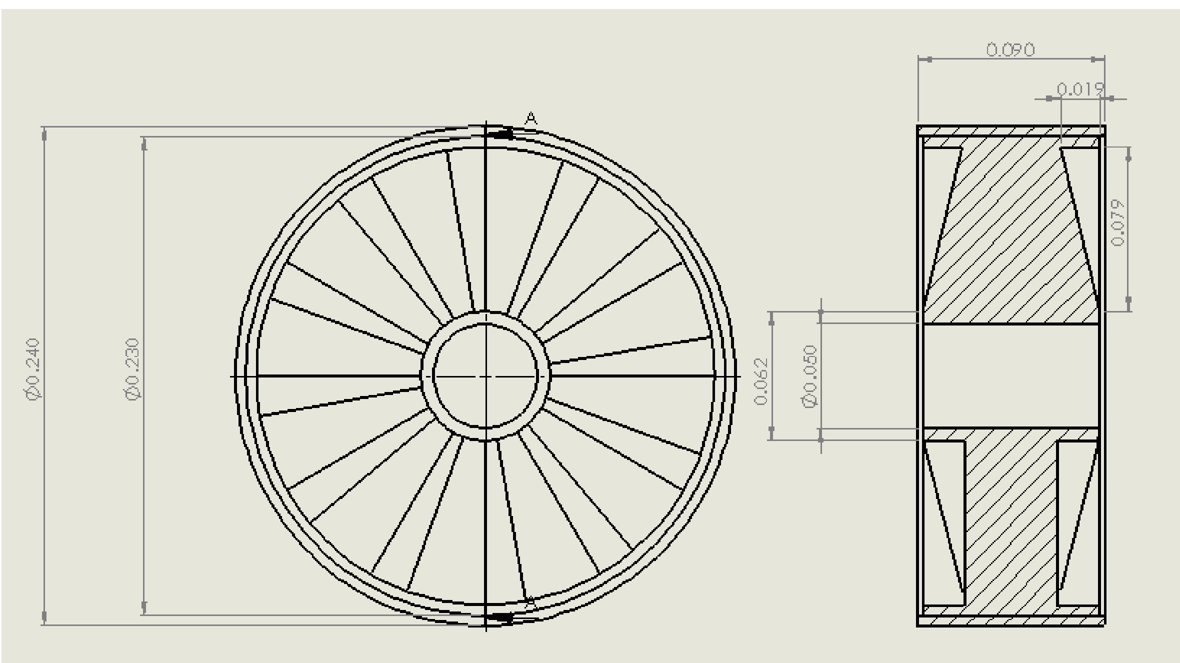

Figure 62: Lateral Support Wheel Design

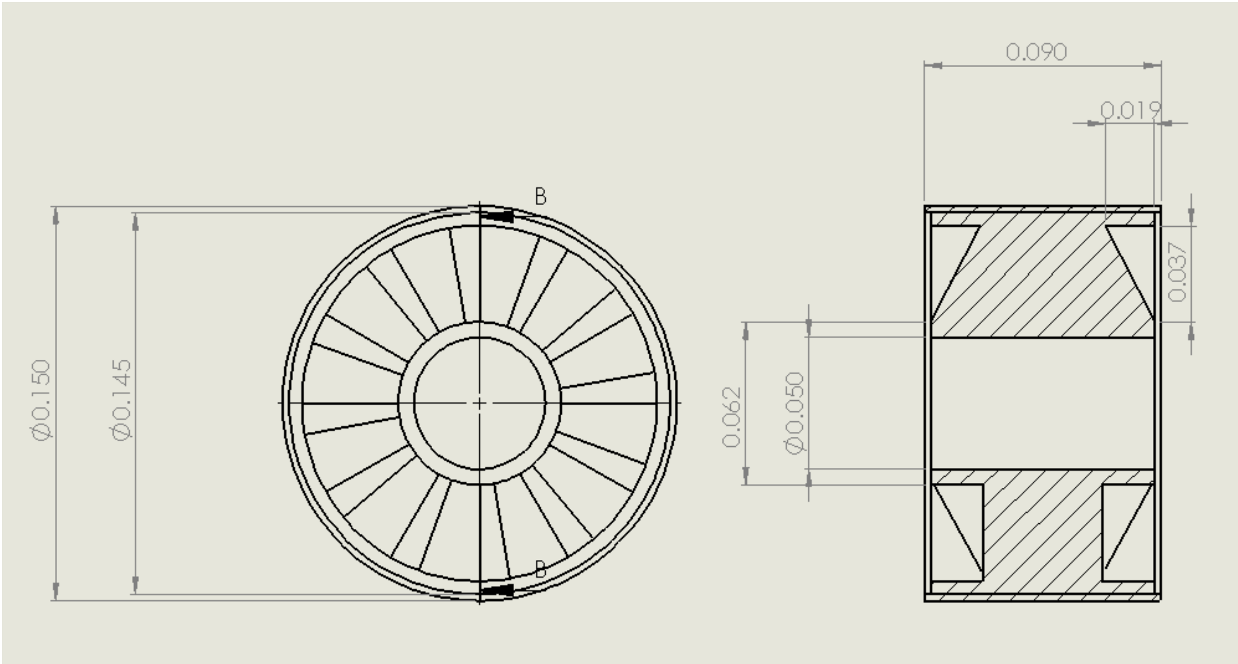

Figure 63: Guide Rail Wheel Design

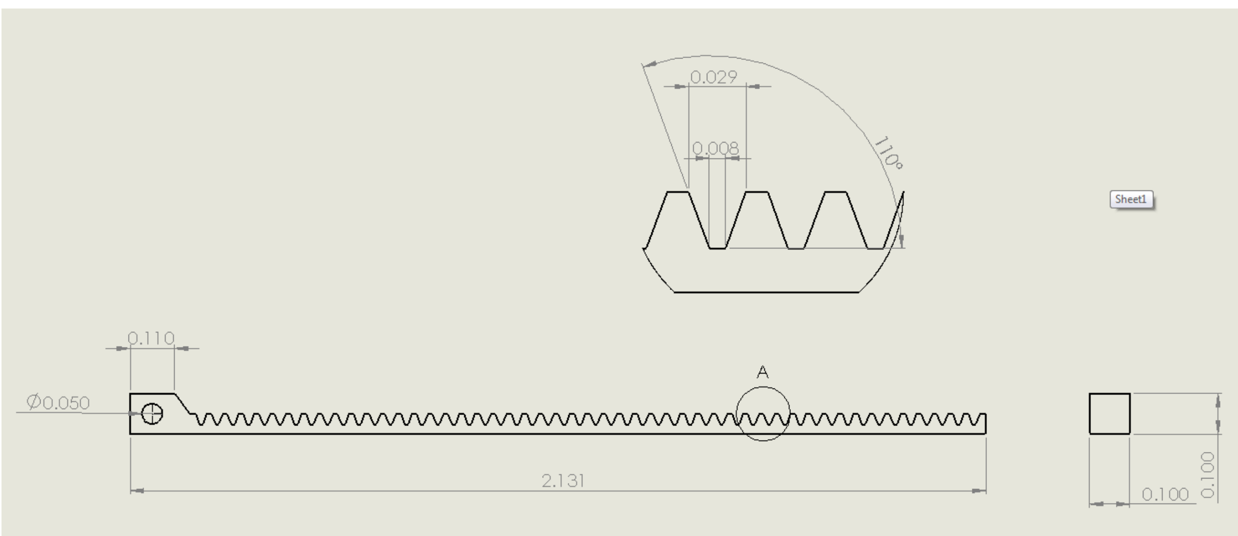

Figure 64: Rack Dimensions (48-tooth)

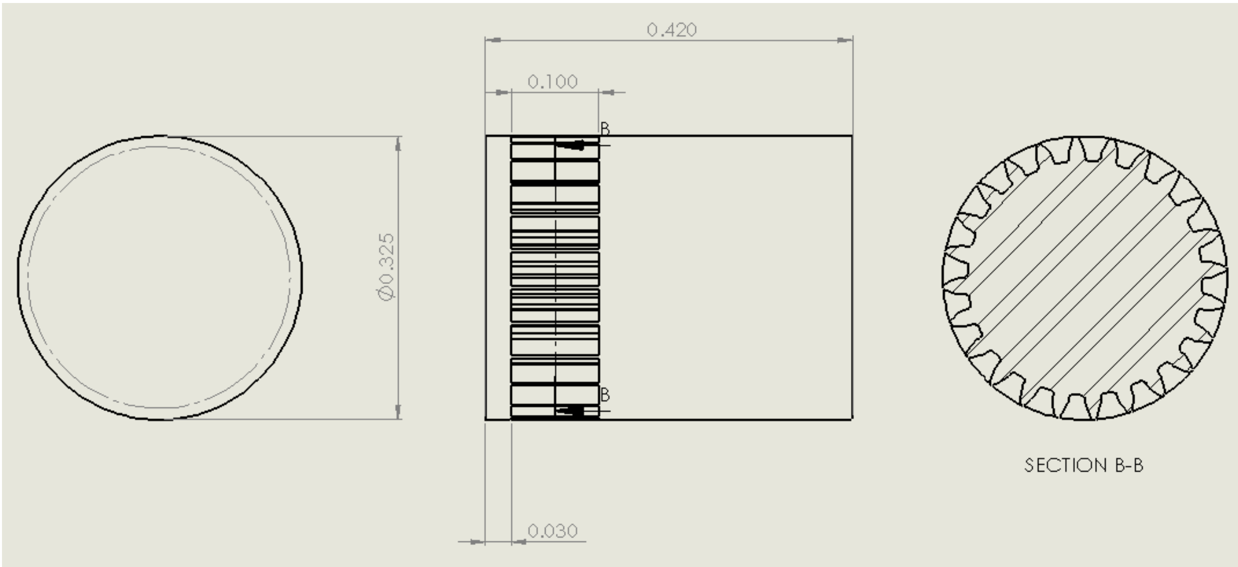

Figure 65: Cross-arm Design

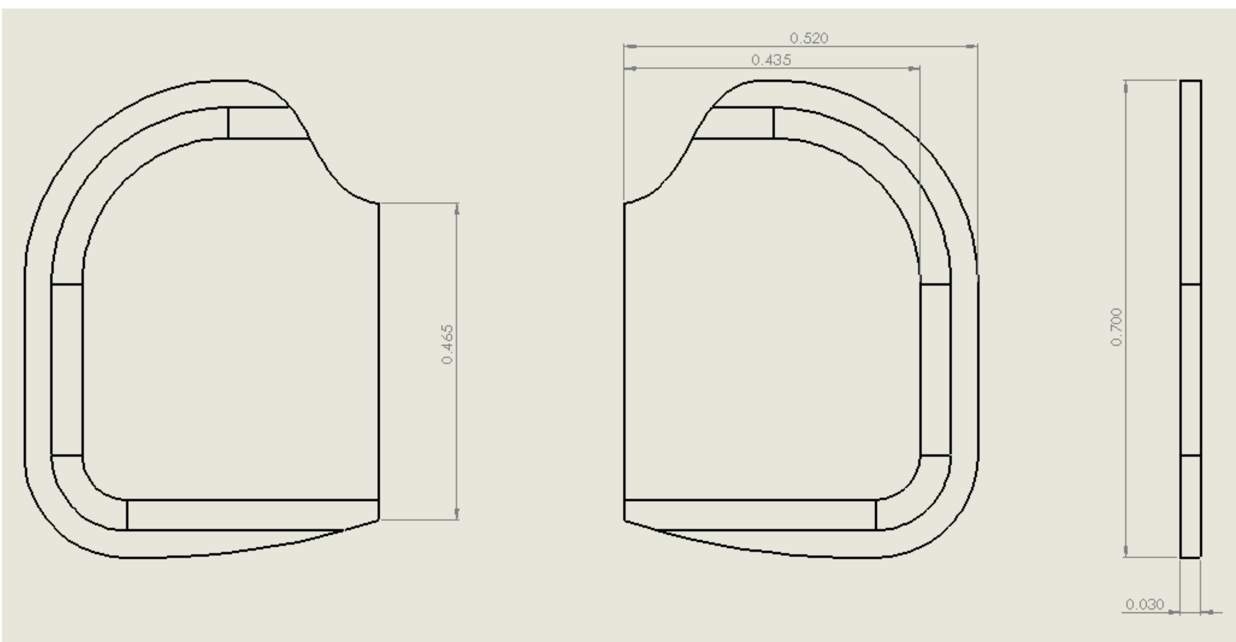

Figure 66: Plastic Blocker/Guard Design

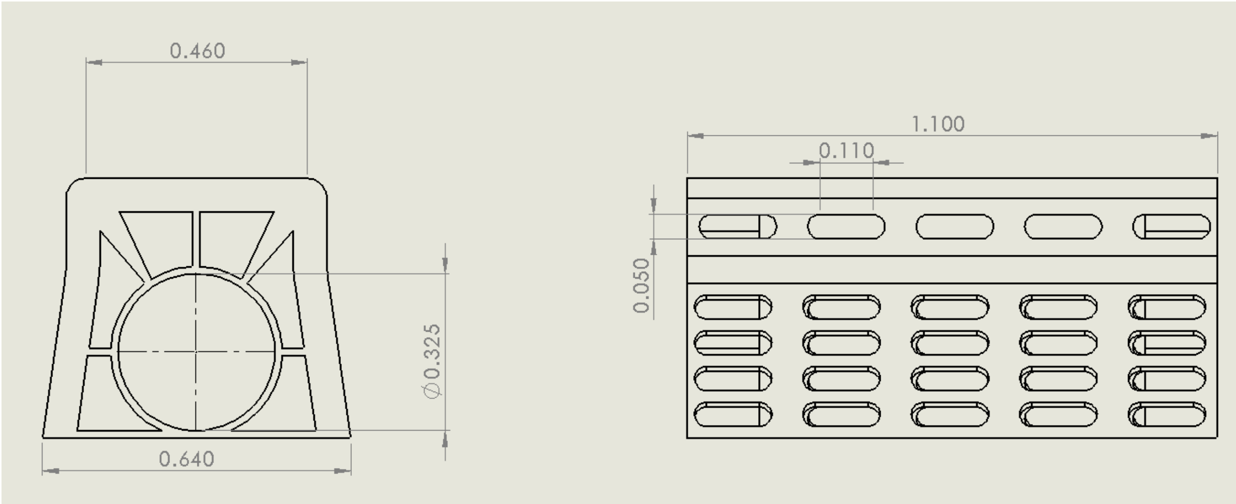

Figure 67: Seat Frame Design

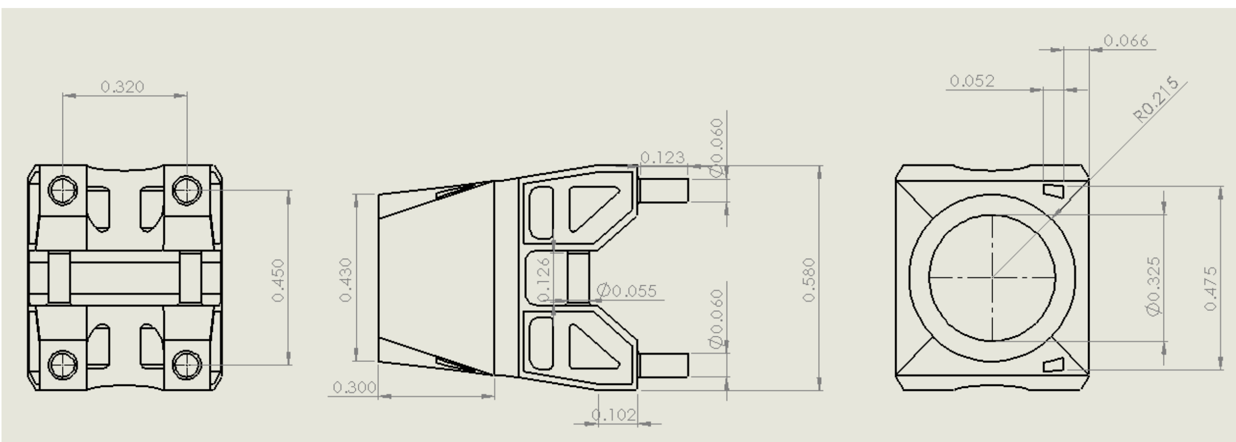

Figure 68: Stationary Structure Design

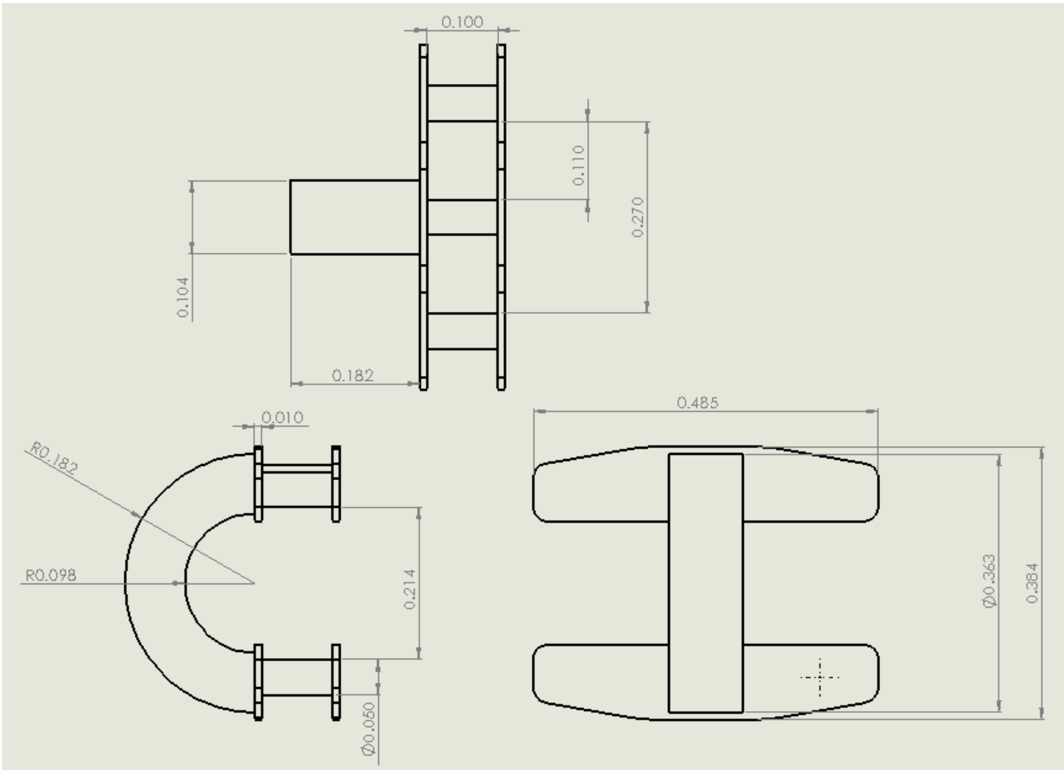

Figure 69: Guide Rail Wheel and Rack Holster Design

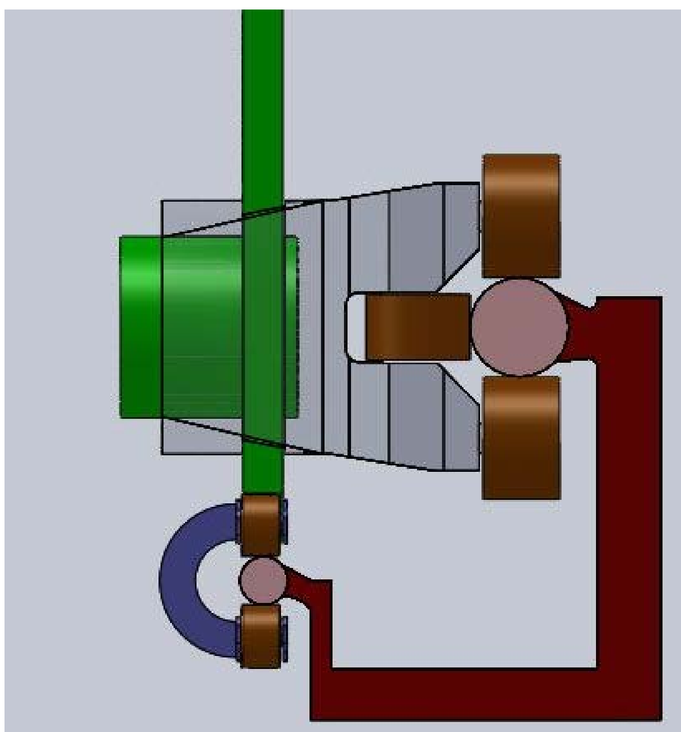

Figure 70: Initial Design Concept

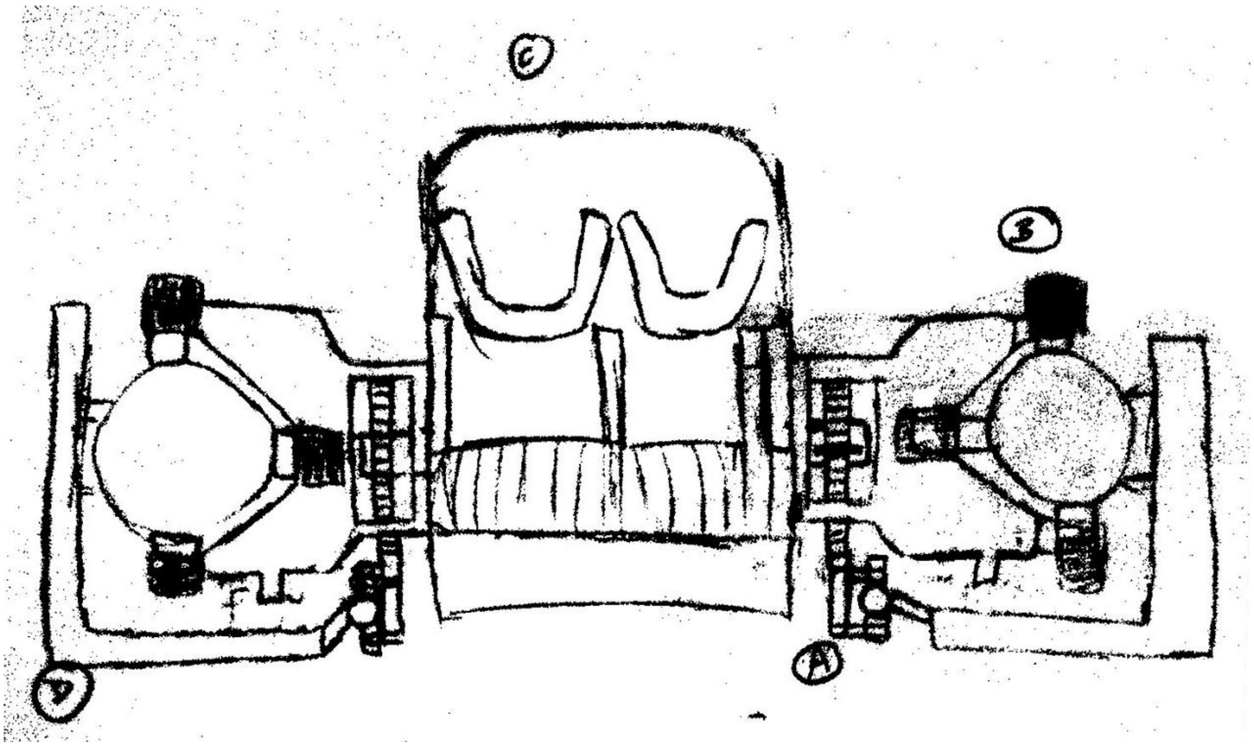

Figure 71: Preliminary Sketch of Rack-and-Pinion Solution

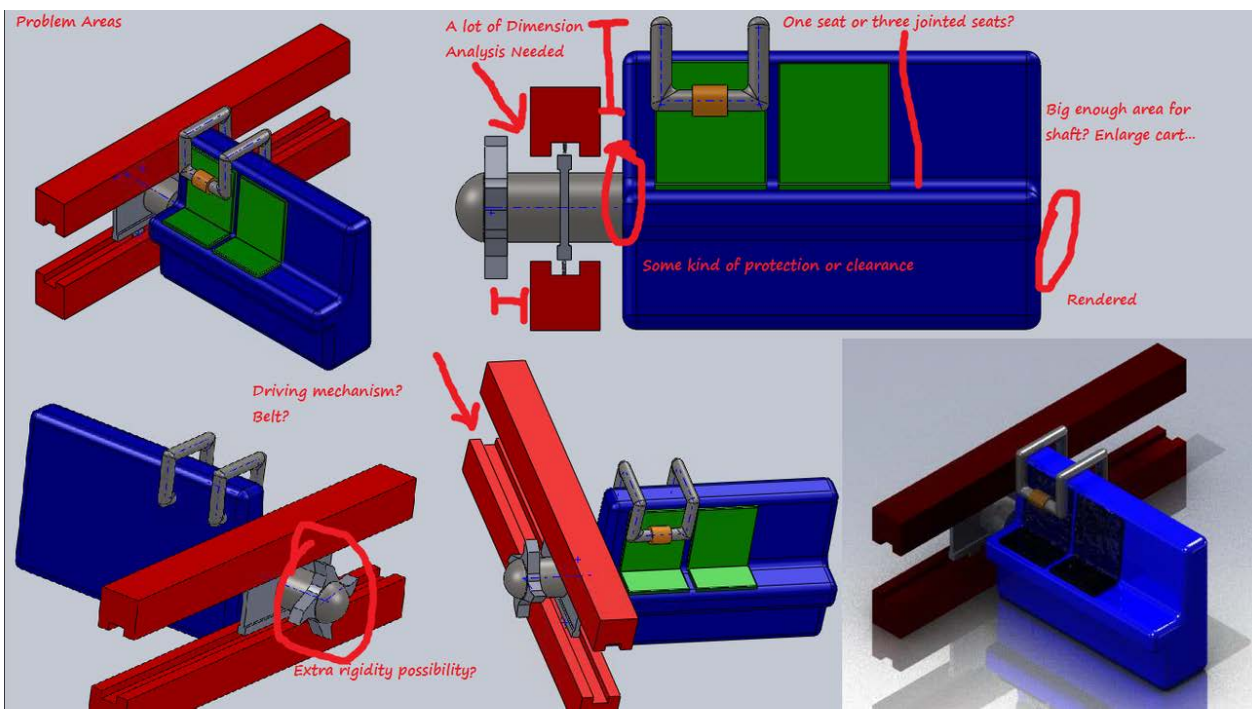

Figure 72: Preliminary CAD Concept

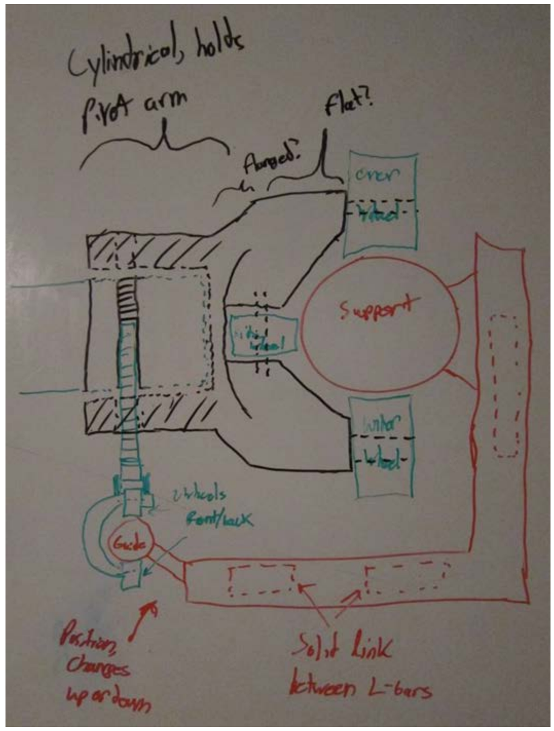

Figure 73: Rough Rack-and-Pinion Solution Sketch

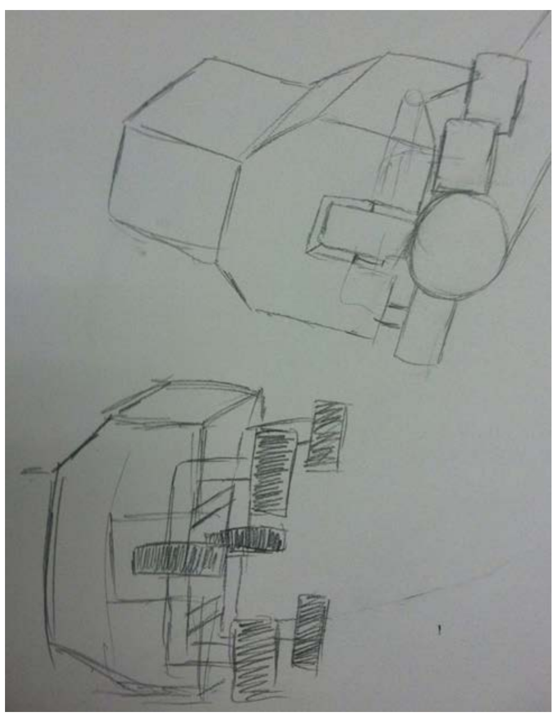

Figure 74: Perspective Drawing of Stationary Structure

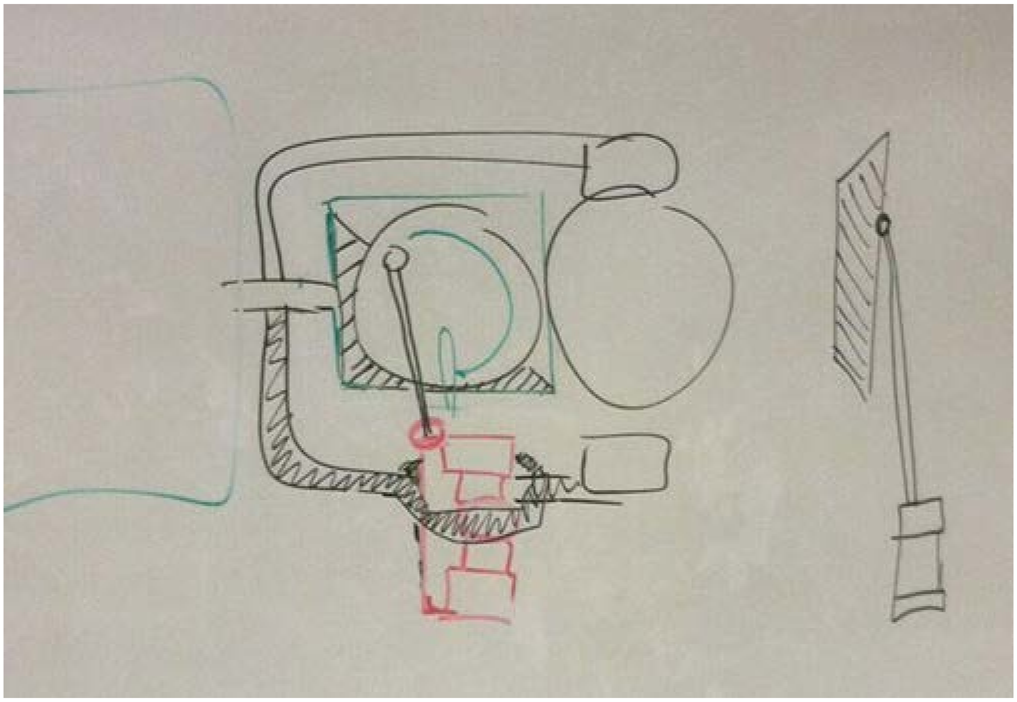

Figure 75: "Train Wheel" Concept

Figure 76: Referenced Seat for Final Design

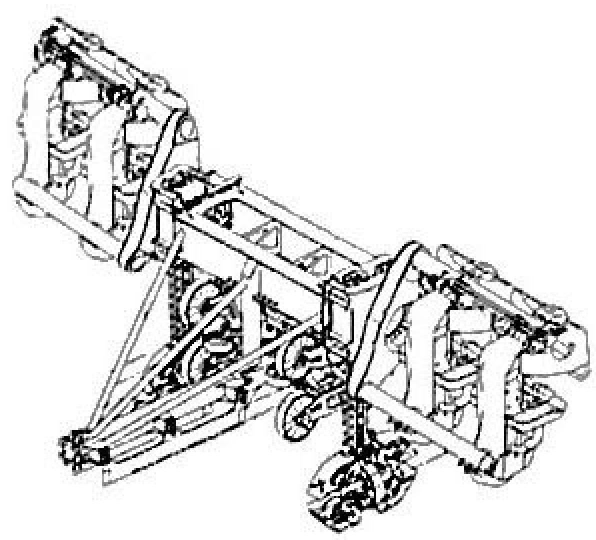

Figure 77: ***X1*** **Cart Drawing**