Systems Engineering Report

ISU Ride Engineering Competition 2022

Prepared for: Iowa State University Ride Engineering Competition (REC) Planning Committee

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Submitted by: Theme Park Engineering and Design Group (TPED) at Northwestern University

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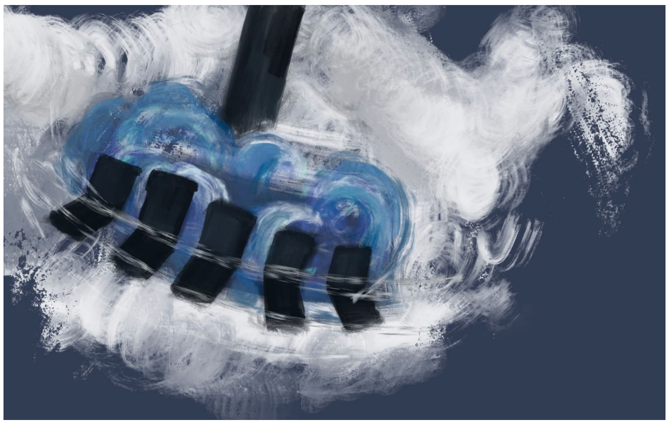
Executive Summary



Experience the exhilarating force of a monsoon in *Monsoon Mayhem*! Themed after the raging winds and terrifying tides of the powerful monsoon storm, *Monsoon Mayhem* gives riders the ride of their lives with thrilling rotations and scream-inducing swings.

Iowa State University's Ride Engineering Competition presented the Theme Park Engineering and Design group at Northwestern University with the opportunity to, quite literally, engineer a unique experience for a rider. *Monsoon Mayhem* was conceived as a land ride that gives riders the thrill of (safely) being in the eye of a monsoon storm. With both the rotation of the carriage and the simultaneous swing of the arm, *Monsoon Mayhem* emulates the journey of breaking through rain clouds as you get caught in the whirl of winds and water.

At its core, *Monsoon Mayhem* is a pendulum ride that swings from a horizontal shaft that is held up by four converging angled supports[1]. However, NU TPED hoped to add an additional dynamic element (simultaneous rotation of the carriage) in order to execute the aforementioned vision. In doing so, we created a model that swung 120° and achieved a height of about 500mm, well above the required height, while staying within the 90x75x75 cm box. This process involved figuring out the expected loads, designing a structure that could withstand them, assembling and coding a gearbox that controlled the rotational and swing motors, and keeping the rider experience in mind as the carriage was designed. Bringing these different components together, NU TPED presents: ***Monsoon Mayhem***

MONSOON
MAYHEM

[1] See: Zamperla Giant Discovery

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Overview

Monsoon Mayhem is a pendulum ride that features two types of rotation: 240° pendulum rotation of the arm and 360° carriage rotation. It can hold 24 riders with 4 per vehicle. The designed amusement ride was modeled after a pendulum ride like the Zamperla Giant Discovery shown in Figure 1 but made according to the competitions design requirements.

Figure 1. *Zamperla Giant Discovery*

The model for *Monsoon Mayhem* is designed in two parts which are (a) mechanical systems design and (b) control systems design.

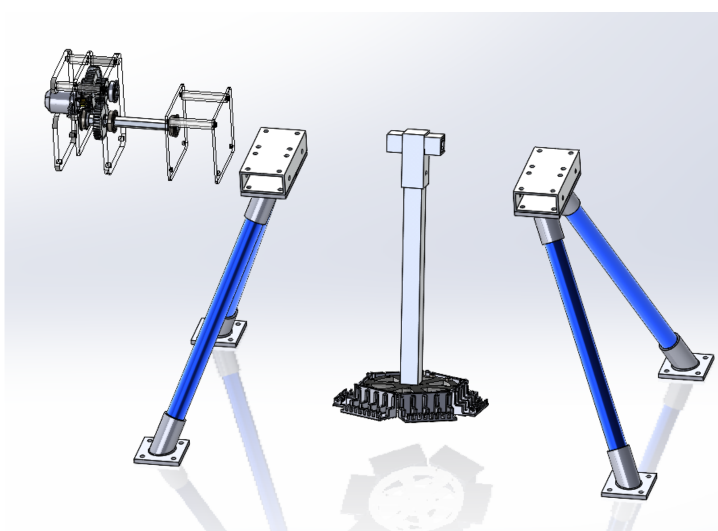

Figure 2. *CAD Model of the different components of the design.*

Mechanical Systems Design

1 Overall Design Description

Monsoon Mayhem uses two different types of motion to give riders a variety of experiences in a relatively small footprint. The two motions are (a) pendulum motion and (b) carriage rotation.

The pendulum motion involves a 240° arm rotation that accelerates up to 3Gs for riders to experience. The carriage motion involves a constant rotation of the carriage which provides a 360° view of the park for the riders. This motion also varies the rider's experience between swings.

The mechanical system is composed of three components which are (a) base structure, (b) gearbox, and (c) carriage and d) arms. These components are described below.

2 Base Structure

2.1 Base Structure Design Description

The base structure aims to support the functioning ride and carry the acting loads to the ground. The design components and their associated rationale is summarized in the table below. These parts are shown in Figure 2. below:

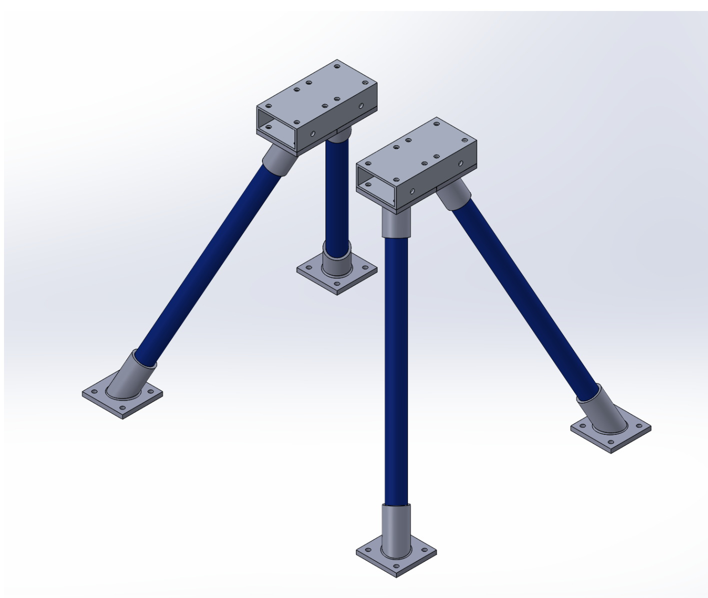

Figure 3. *CAD model of the base structure.*

Table 1. Base Structure Component Breakdown

Component	Description	Rationale
Pillar Supports	Unlike a swing set with vertical supports, the supports of this ride are angled inwards towards the top as seen in the reference ride in Figure 1.	Initially, an intuitive model was made using recycled materials based on the ride in Figure 1. Through building this model we were able to get an understanding of what lengths and distances of the supports were needed to achieve a stable structure that fit within the required 'box'. Figure 4 shows the initial mockup which was made using a box of 90x75x75cm. The schematics from Fig 5 and 6 allowed us to calculate the distances and angles that accompany the schematics. Aluminum was used for its strength and resistance to buckling.
Base Bolts	Supports bolted to the base plate using ¼-20 bolts	From prototype, this clamping mechanism was sufficient at securing the supports to the base
Adapter "Blocks"	Hollow rectangular aluminum tube with machined holes on each side	We needed a way to connect the pillar supports to each other as well as connect the gearbox to the base structure. Since the walls of the gearbox are vertical and the plates of the pillar supports are horizontal, we found that using a block with machined holes at different intervals would allow us to efficiently make use of that space and securely attach and distribute the loads of the arm gearbox system. This "block" was originally a solid bar of aluminum, but we found that the additionally mechanical strength that a solid bar provided was negligible to its role in the model as a whole and found that using a hollow tube instead decreases system weight and cost, which lowers the load on the base structure pillars.

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Figure 4. *Initial ride mockup*

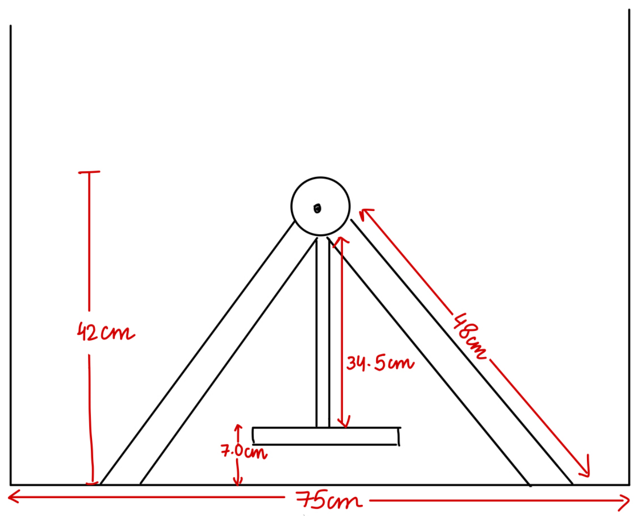


Figure 5. *Dimensions of front view of mockup.*

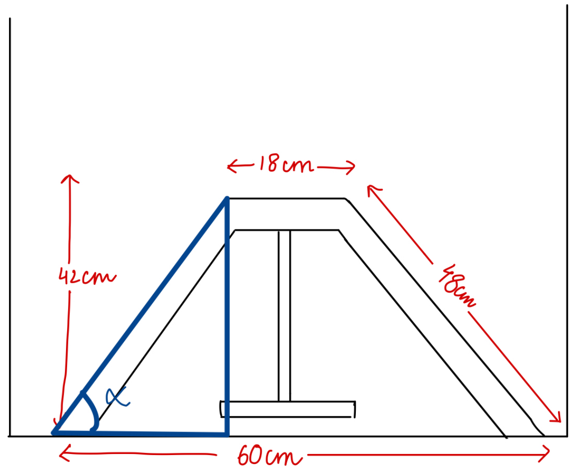


Figure 6. *Dimensions of side view of mockup.*

2.2 Base Structure Design Optimization

From the mockup we noted that the length of the distance between supports was so wide that it resulted in bending in the top horizontal shaft when the arm swung. In order to reduce that bending, the distance between the support ends was reduced. Additionally, this increased clearance for the carriage as it swung which in the mock up was grazing the wall restrictions. By optimizing the rough values from initial mockup as described, the final dimensions were optimized.

2.3 Calculations and Verification

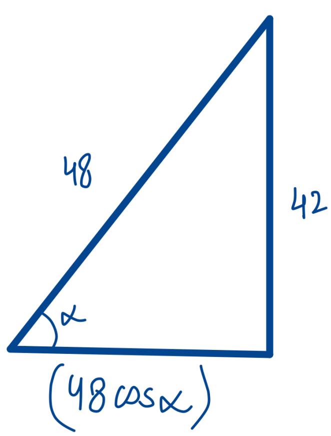


Figure 7. *Geometric setup to calculate angle and distance in mockup*

From the geometry of the initial mockup, a rough angle needed between the supports and base was found:

$$sin\alpha\ =\ 42/48$$

$$\alpha = 61.05°$$

From the calculated angle, an approximate base length was found:

$$2(48cos\alpha) = 46.48 \text{ cm}$$

These calculated dimensions were optimized as shown in the Optimization section. However, at the time of writing the report the Finite Element Analysis of the supports has not been conducted. We intend to do this before the ride's operation to verify that the supports will not buckle under the applied loads.

3 Gearbox

3.1 Gearbox Design Description

The gearbox subsystem was designed to power and control the central swinging arm of our ride model. The gearbox is directly powered by a Neo 550 brushless and uses two parallel gear reductions to achieve the desired maximum load speed and torque required for the ride to safely and efficiently operate with the specified cycle time and load capacity. The gearbox results in an approximately 10:1 reduction, with specific input and output properties detailed in Table 2.

Table 2. *Properties of inputs and outputs to the gearbox system*

Input Motor Free Speed	11000 RPM
Input Motor Load Torque	9.891 kg-cm
First Reduction (32DP)	20:3
Second Reduction (20DP)	20:13
Total Reduction	400:39 ~ 10:1
Output Free Speed	1072 RPM
Output Load Torque	101.48 kg-cm

As shown in Figure 8, the first stage gear reduction transmits power from a 12 tooth motor pinion to a 80 tooth steel spur gear constrained on a ⅜ inch hex shaft. Both gears are 32 DP and are positioned so that their pitch circles are tangent to each other. The ⅜ inch hex shaft is allowed to freely rotate and constrained translationally by a set of two anti-parallel bearings and retaining rings. In the second stage gear reduction, rotational motion of a 26 tooth steel spur gear on the ⅜ inch hex shaft transmits power to a 40 tooth steel spur gear on the ½ inch hex output shaft. Both gears are 20 DP and are positioned so that their pitch circles are tangent to each other. The ½ inch hex output shaft is constrained by three bearings on either side of the central arm and the entire gearbox system uses five parallel plates to position the individual components and constrain them all to the base structure.

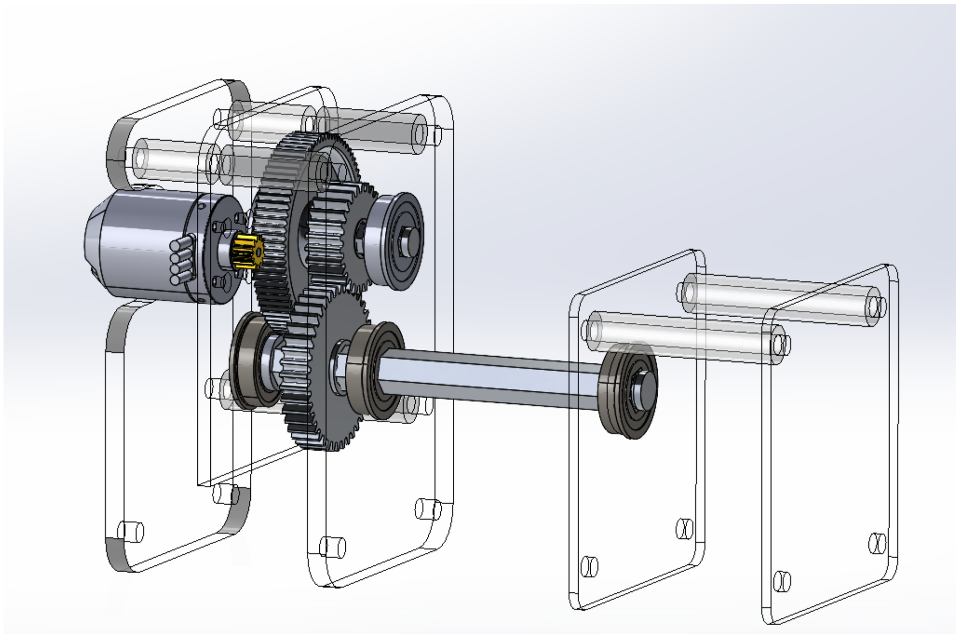


Figure 8. *Solidworks CAD model of the isolated gearbox system.*

3.2 Optimized Gearbox Design Rationale and Calculations

A power transmission gearbox is required for our model since there does not exist a readily available motor that has the exact load torque and speed properties that fit our model specifications. Thus, we can not implement a direct drive mechanism and must use gear reductions to reduce the speed of the gear in order to increase the output torque. We calculated the desired output torque and speed using a simple pendulum model for our ride, considering the weights of both the arm itself, the carriage motor, and the carriage. The equation of motion that was derived is presented in Figure 9. We used this model to develop a descent model of the pendulum portion of the ride, which told us the g's experienced by the riders and the speed of the carriage at different points during the descent. Most importantly, we were told the maximum free speed the motor must exert. These values are contained in Table 3. Once we had our descent modeled, we used inverse dynamics to determine the motor output torques required to match the model. We also considered the dynamic deceleration model, as well as an E-stop situation model to find the largest load torque required for the motor to exert. The compiled results of our calculations that we used to decide on a design for our powertrain is found in Figure 10.

Once we had our maximum torque and free speed, we shopped around for motors that directly met our specifications. We started with servo motors that come with built- in gearboxes and have simple control systems, but it quickly became apparent that servos did not have even close to enough torque or free speed for our model. If we did implement these motors, we would likely encounter catastrophic failure at the maximum load points where the motor torque must exceed its stall torque. Instead, we chose to focus on DC motors with built-in or external gearboxes. We found that most DC motors for common hobby applications also did not exert the necessary load torque to meet our specifications and would require an external gearbox to boost the torque output. However, these DC motors also lacked a high free speed that would allow the reduced speed to match the maximum speed of our model. For this reason, we considered applications for which high speed and high torque are both required.

We found that motor vehicle drivetrains and robotic arms are real world applications for which these types of motors and gearboxes are necessary. We considered implementing a gearbox similar to a motor vehicle drivetrain but found that this type of design would result in an excessively complex and expensive design. Additionally, most gearboxes found in motor vehicles are not scalable to a small model and would require difficult to source materials and difficult to machine components. One key takeaway from this research was the use of planetary gearboxes to simplify packaging and save space. The very first iterations of our gearbox designs included a planetary gearbox. However, we also could not find a planetary gearbox and motor combination that was on the scale of our model. In order to keep manufacturing, assembly, and replacement simple and efficient, we decided to go with a DC motor with a parallel reduction gearbox. This system requires a relatively large footprint, but would allow us to have more customization and control over the gear reductions as well as allow us to use readily available steel spur gears.

We also had to make a decision between brushless and brushed DC motors and we chose the brushless Neo 550 motor since it sported a much lower weight and footprint, while outputting a very high amount of torque and free speed. The exact design decisions that led to the design of the 2 stage gear reduction were made based upon the availability of parts, with the Neo 550 only being compatible with a 32DP motor pinion with 12 teeth. We also knew that we wanted the 1/2 inch hex shaft attached to the arm to have as large of a cross section as possible in order to prevent bending along the shaft due to forces from the arm. 32DP gears are not compatible with 1/2 inch hex shafts, which would require us to convert from 32DP gears to 20DP gears. We found that the best way to solve this problem is to split the gearbox into two stages, with the first stage involving a conversion along 32DP gears and the second stage using 20DP gears. This would also have the added benefit of reducing the footprint of the gearbox since the individual gears can be smaller with a distributed reduction. The decision to use hex shafts was a result of a balance of torsional/bending strength considerations as well as transmission failure considerations. We found that the torsional forces exerted on the shaft were not significant enough to warrant requiring a round shaft and keys are harder to machine, have the ability to slip and are difficult to troubleshoot in the middle of the ride. Instead, we chose to use a power transmission hex shaft that meets the mechanical properties requirements and allows for consistency and easy troubleshooting. While our model uses a parallel reduction gearbox, in a full-scale ride, we would advise using a planetary gearbox to achieve a similar reduction.

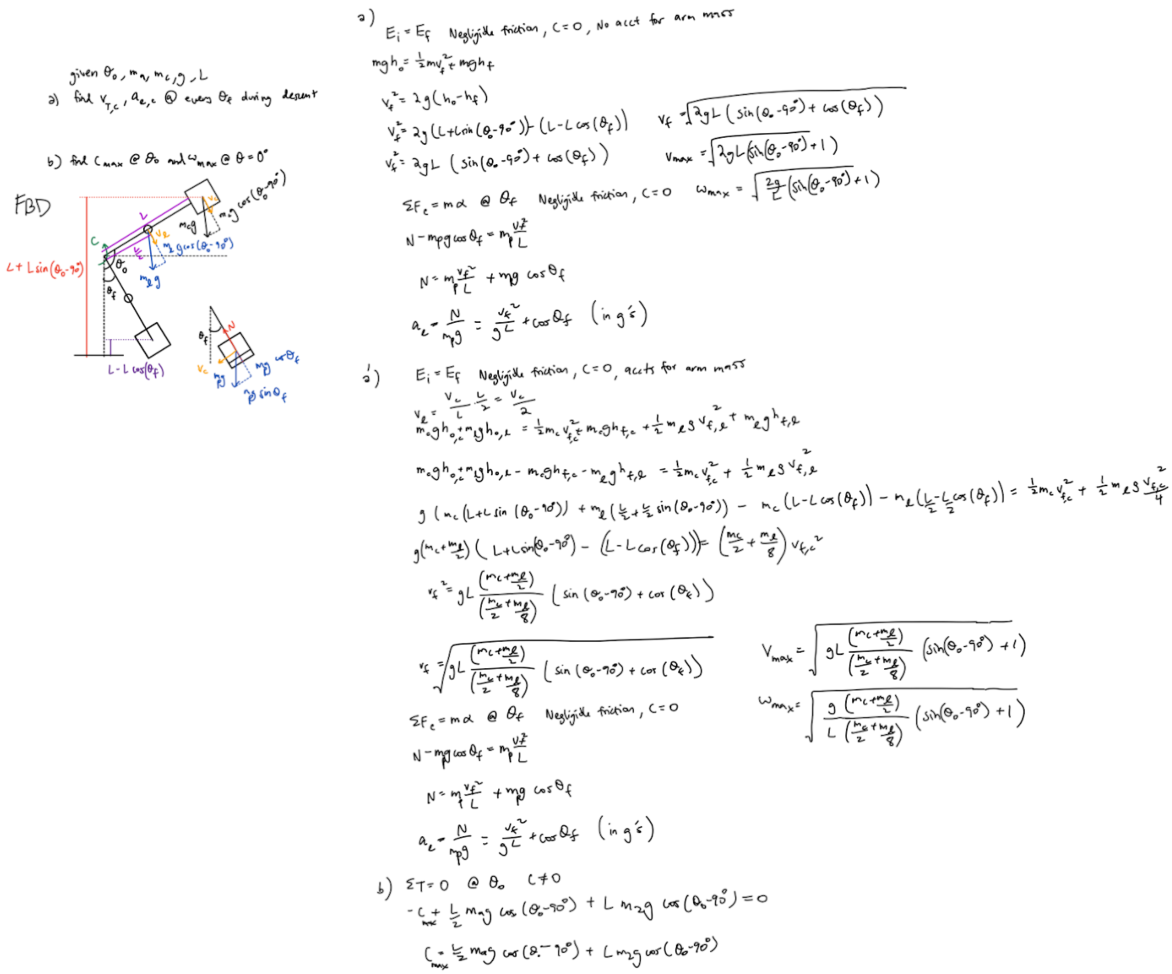


Figure 9. *FBD and energy calculations for the pendulum arm .*

Table 3. *Descent model of the pendulum arm.*

Final Angle theta_f (deg)	Final Tangential Velocity v_f (m/s)	g's experienced	Motor Load Speed (RPM)
110	1.011363828	-0.01720161511	189.0399679
100	1.453615617	0.4973558404	271.7038537
90	1.799250207	1.028037799	336.30845
80	2.088445416	1.558719757	390.3636291
70	2.33489739	2.073277213	436.4294188
60	2.544524045	2.556075598	475.6119711
50	2.720127874	2.992445327	508.4351166

40	2.86306386	3.369127528	535.1521233
30	2.973965645	3.674676902	555.8814289
20	3.053102948	3.899809486	570.6734482
10	3.100570942	4.037684741	579.5459704
0	3.116392775	4.084113396	582.5033224

Input Variables		Constants		Output Variables	
Initial Angle/ Theta_0 (degrees)	120	Acceleration due to gravity - g	9.81	Max velocity (m/s)	3.116392775
Mass of arm	0.05			Max RPM	582.5033224
Mass of carriage (incl. passengers, DC motor, seats)	0.4333267249			Max Torque (N-m)	1.44327544
Length of arm	0.321			Max Torque (kg-cm)	14.71731366
				Max g's experienced	4.084113396

Figure 10. *Calculated values used to select a motor and gearbox design.*

3.3 Gearbox Design Verification

The assembled gearbox was tested with the motor and ride arm attached. Using the code mentioned and ran 1 full ride cycle on the gearbox. We ran the code given in the Controls System Design section of this report and the gear box worked as expected.

In the future, we will be running additional tests to see how the gearbox responds to the emergency stop and its behavior when the power is cut off mid-motion. A longer performance test is also planned to assess whether the gearbox heats up or if parts wear out quickly as it continues to be operated.

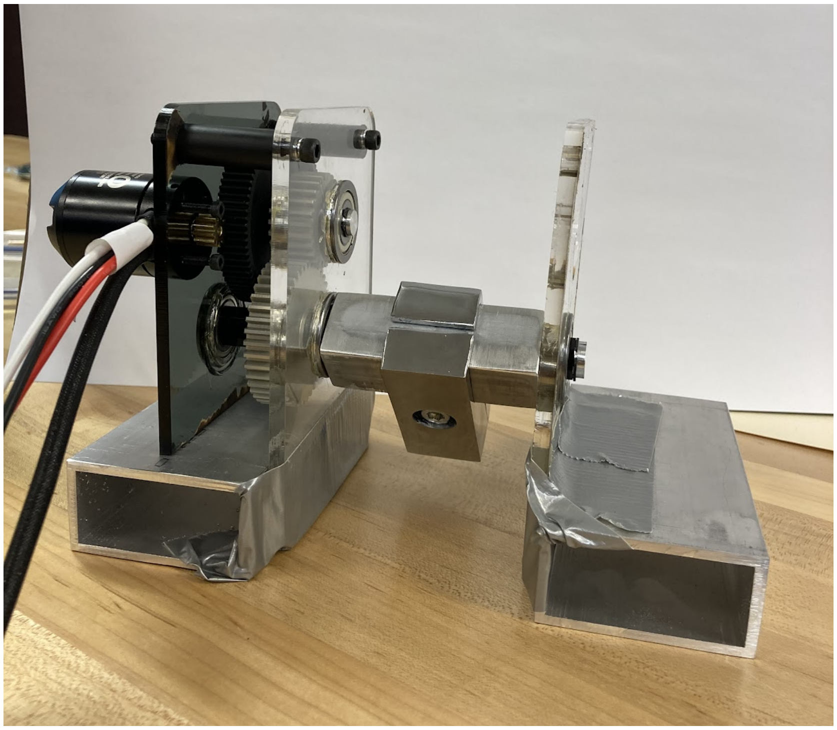


Figure 11. *Gearbox assembly that drives swinging pendulum motion*

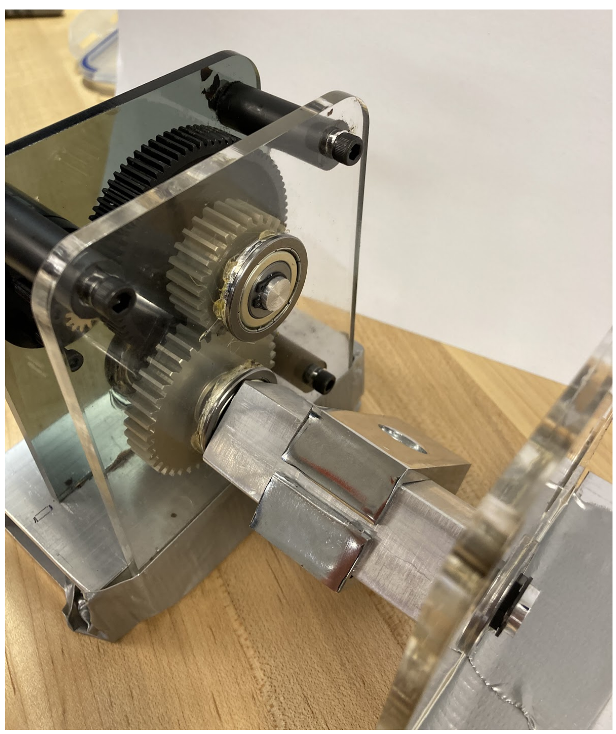


Figure 12. *Close-up of gearbox assembly that drives swinging pendulum motion*

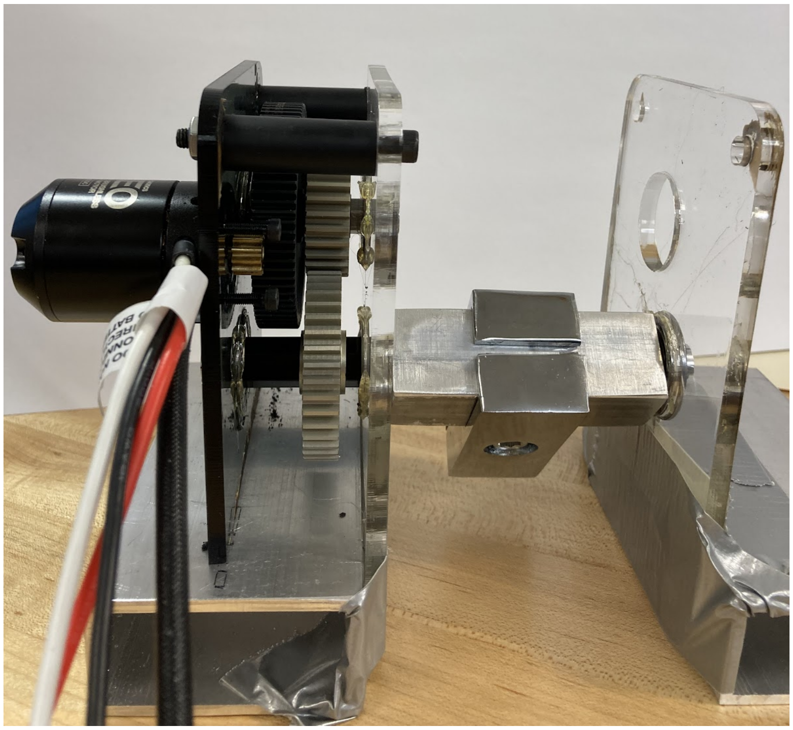


Figure 13. *Side view of gearbox assembly that drives swinging pendulum motion*

Figure 14. *Pendulum motor (Rev SparkMax) used to drive swinging motion*

4 Carriage, Rotational Motor, Seats

4.1 Design Description, Rationale, and Optimization

The first bullet is the design feature, the second bullet is the design rationale, and all bullets after refer to design optimization.

4.1.1 Number of Riders

- 24 Riders in total, 4 per each vehicle
- This gives a throughput of 37.89 riders per minute
- Other options were either 3 or 5 riders for each of the cars. We determined that three riders would have a throughput lower than we desired and five riders would create cars that were too wide to fit on our carriage design.

4.1.2 Space for each rider

- The width and depth of each box is exactly 1 mm wider and deeper than the largest possible rider.
- This gives extra room for rider comfort while also ensuring they are securely in their seats. Additionally, the restraining mechanism can close to fit the rider snugly. The rider shouldn't be able to move significantly even without the restraint.
- We considered numerous different widths and depths for each of the cars. We determined that a minimal amount of movement was optimal, but the ride needed to still hold the largest individuals. Therefore, the restraint was used to make the seat more "snug" for the smaller riders while the largest riders have 1 mm of extra space for comfort.

4.1.3 Restraint

- The restraint for the rider is an overhead bar that locks in the front of the seat
- This restraint will ensure the rider is held into place both due to horizontal and vertical motion. It matches the ASTM guidelines for a ride of this caliber with over 3 G forces (this ride has up to 5 Gs).
- We considered restraints coming from either side, but determined that the best restraint would mimic those used on actual rides and be an overhead restraint. A "lap bar" would be inadequate for keeping the rider in the seat on this attraction. The overhead restraint has the added benefit of keeping the rider in from both the vertical and horizontal directions. The only negative is that the rider is rectangle shaped, so the restraint will touch the top corner of the rider.
- The current restraint is made from zip ties/a 3d printed locking attachment. Originally, lego hands and a wooden bar were considered for the design. These ended up being very costly, harder to install, and less effective in restraining the rider. As a result, the current restraint system was put into place

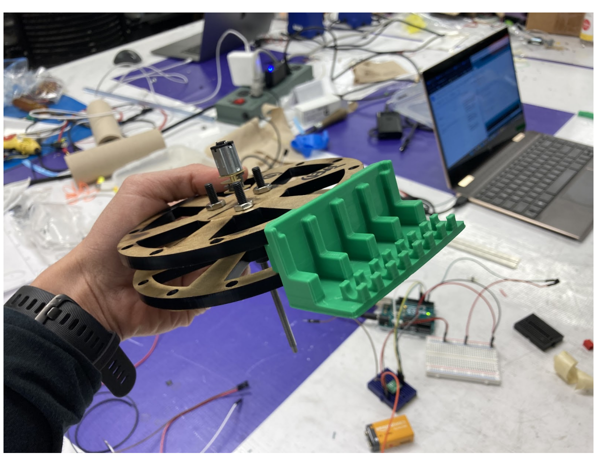
4.1.4 Connection between Seats and Carriage

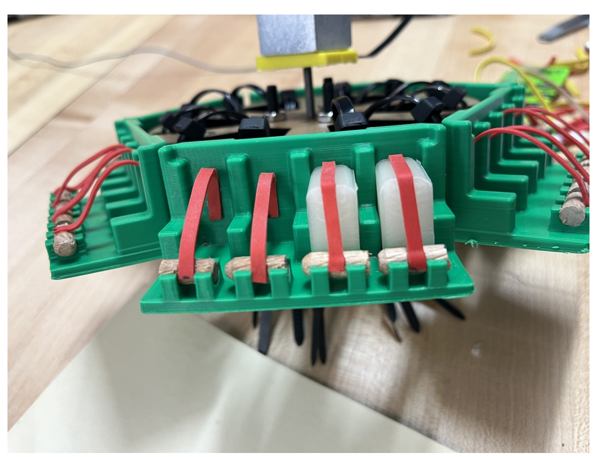
- The seat system slides into the carriage and is attached with a nut and bolt in two different points; Allows for modular seating - easy repairs
- This enables the system to be secure and prevents any motion of the ride vehicles. It also ensures there is no rotational movement with the two different connection points.
- There were other connections suggested including one only on the exterior. The exterior idea was scrapped due to the connection not being strong enough. Now, the car slides in between the two circular plates which better secure the car in addition to the nuts and bolts. Printing the cars as a part of the carriage would have been more complicated and would have made the prints harder. Additionally, having the cars separate makes the ride more serviceable in the real world.

4.1.5 Walls Separating riders

- There is a horizontal wall between each of the seats.
- This prevents the riders from sliding "left and right". The walls are tall enough such that they adequately separate the riders while also giving them room for their upper body and arms. Due to the shape of the riders, these walls needed to be 5 mm tall as well as flat such that the riders would fit comfortably. There is a small amount of wiggle room on either side due to the varying width of each of the riders.
- There were multiple interior car designs that were considered. There was one design with very tall walls, but that didn't give adequate room for the rider's arms so that design was adjusted accordingly. Additionally, there was a model with only 2mm tall walls, but this didn't provide enough of a horizontal restraint and the riders were moving around in their seats too much during a ride cycle. This posed a risk of a rider falling out of the attraction. Therefore, 5 mm walls were used.

Iterations of carriage seats:





Figures 15, 16. *Latest iteration of seats, without and with restraints*

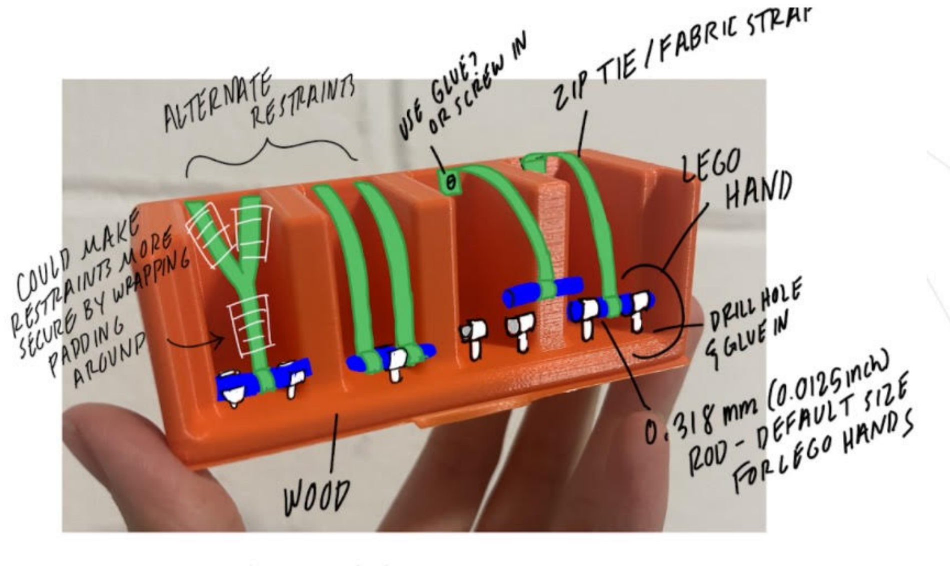


Figure 17. *Earliest version of seats.*

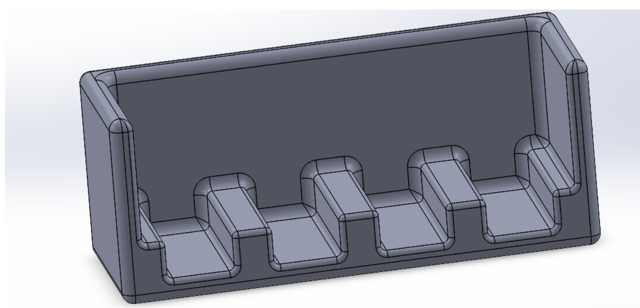


Figure 18. *Iteration of seats; armrests moved lower for clearance*

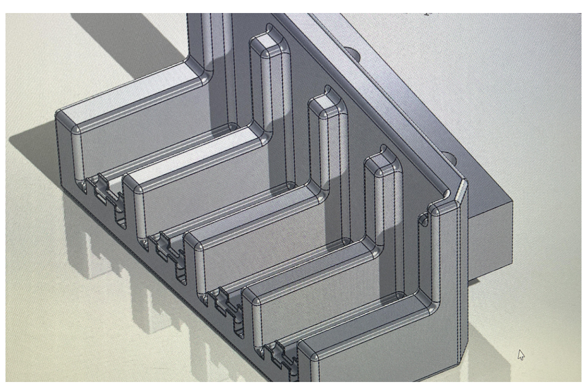


Figure 19. *Iteration of seats; narrower frame/notched corners for clearance, first incorporated clasp design*

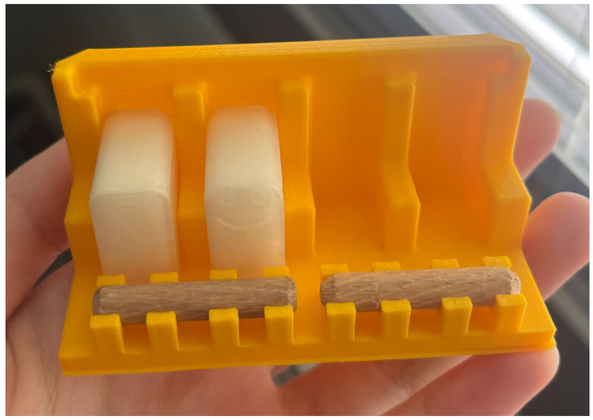


Figure 20. *Penultimate iteration of seats; final clasp design, missing cutout on back to allow closer fit to carriage*

4.1.6 Seat Materials

- The seat is made out of 3D printed plastic - PLA (2.85mm) filament
- This seat is strong enough such that it can withstand the forces placed on it. Additionally, it can be in the exact shape desired with exact measurements to ensure rider safety due to the width and size of the seats.
- 3D printing allows for more intricate and custom designs that can exactly fit the riders. Wood was another consideration, but it was going to be heavier and harder to fit to our specifications. It was possible to use the CNC to design the seats, but the CNC cannot make horizontal cuts while the 3D printer can lay plastic horizontally as desired.
- 3D printing also enabled us to have a material that was light but also strong. The material being light was important because the moment of inertia was minimized by having as little mass at the bottom of the arm as possible. Additionally, there are cost considerations for using plastic, so using the minimal amount of material was optimal.

4.1.7 Carriage Center Materials

- Laser-cut Acrylic stacked plates
- Lightweight and sturdy; simple and fast machining
- Decided not to go with a solid chunk of milled aluminum (weight and machining time), decided not to use an existing wheel (lack of attachment points for seats), decided not to use solid plates and instead use cut outs to minimize weight without compromising the structural integrity (use Ansys FEA to check stress points)

4.1.8 Carriage Drive

- Direct drive of a small DC gearmotor with threaded shaft and locknut

- Threaded shaft allows for transmission at a small scale. Do not expect a lot of torque required. High inertia, but the only moments around the center are friction forces inside of the motor
- Direct drive from a gearmotor lowers the mass and cost of system and simplifies manufacturing, decided not to use a gearbox to lower cost, weight and complexity, decided not to use a servo because of limited space and excessive controls capabilities (only need to rotate at a constant speed in one direction),

4.1.9 Overall Carriage

- The overall carriage is in a "spoke" type shape with a solid center connected to the arm and then six arms attached to the outer circle
- This design uses a minimum amount of material while maintaining the strength of the ride. It also enables each of the cars to be securely attached to the carriage. The gap between the two plates on the carriage means that the cars slide into the carriage, being supported on both top and bottom. The plates of the carriage are securely attached together through three bolts and the entire carriage system is driven by a small DC gearmotor with a threaded shaft
- One other consideration was using a solid disk rather than a carriage with holes cut out. This was worse for two reasons. Firstly, it would be heavier and costlier due to the additional material needed. Secondly, it meant the cars would only be attached on the exterior rather than sliding into the carriage and being attached from the interior. This is a much stronger attachment that is better for the ride due to the number of G forces and the motion experienced.

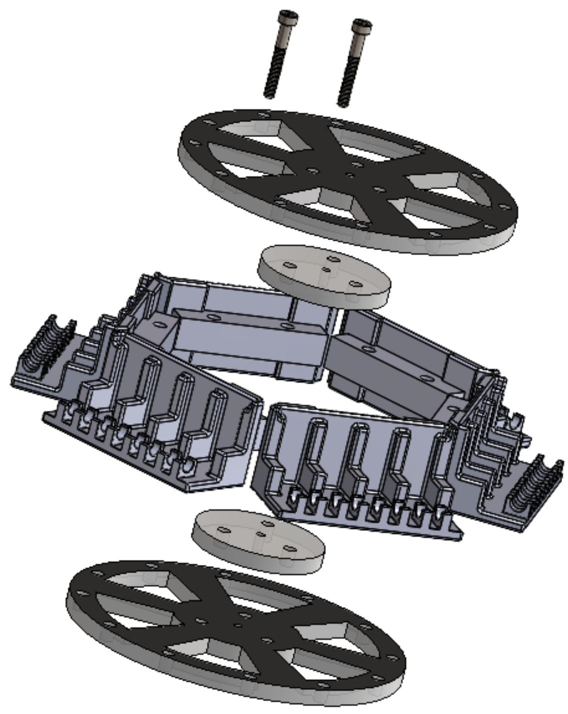


Figure 21. *CAD Model of the carriage components.*

4.2 Calculations and Verification

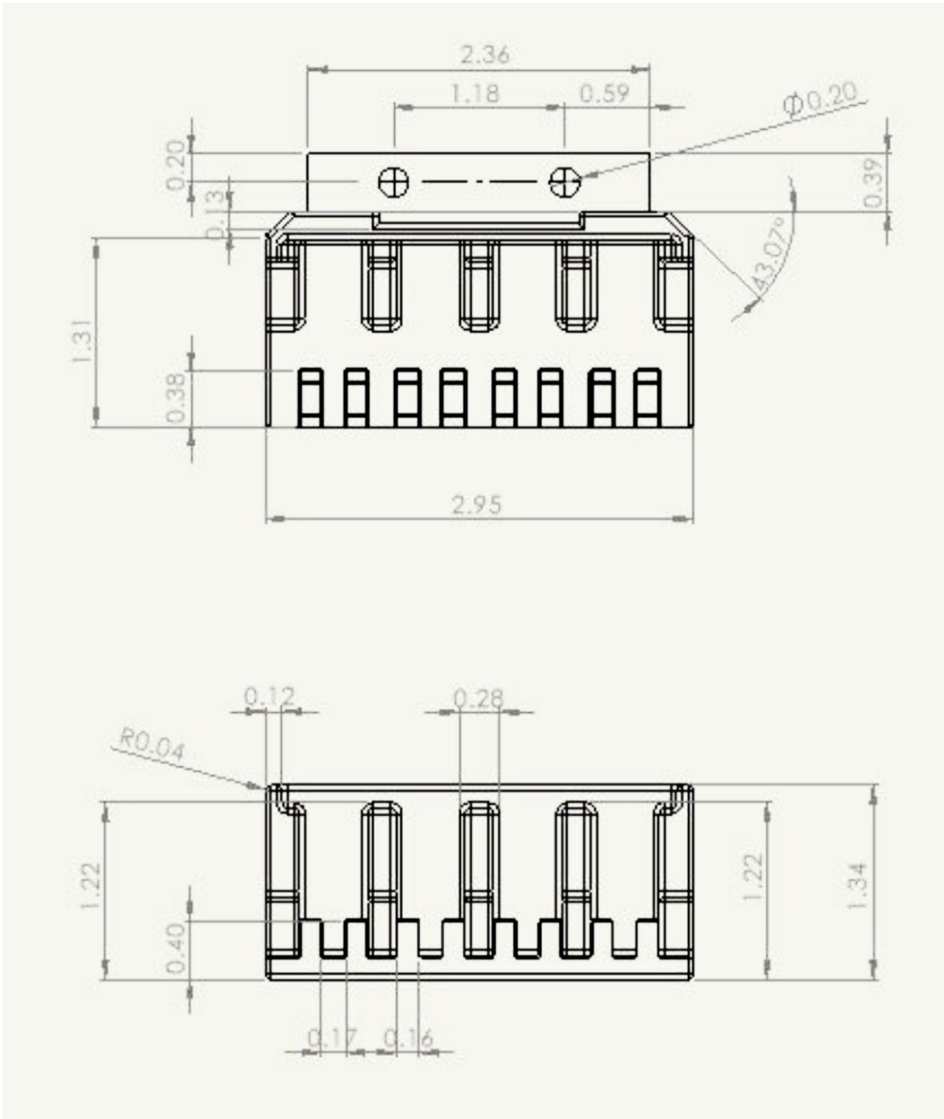


Figure 22. *Schematic of the seats.*

4.2.1 Vehicle width

- 2.95” = 75 mm wide vehicle; 6 vehicles of this width can fit on a circular carriage plate of diameter 130 mm with corners notched and the carriage inset slightly

4.2.2 Vehicle height

- 1.34” = 34 mm tall vehicle; 34 mm height - 4 mm floor thickness = 30 mm space; this is adequate space for a 22 mm tall passenger to fit

4.2.3 Seat width

- Seats are 12 mm wide; this is adequate space for a 11.5 mm wide passenger to fit

4.2.4 Seat depth

- Seats are 23 mm deep; this is adequate space for a 22 mm deep passenger to fit

5 Arm Connection and Attachments

5.1 Design Description

The main arm comprises a T-shaped aluminum tube that connects the rotating pendulum shaft to the bottom of the ride carriage. The rotational motor is housed within an arm-carriage connector piece (see Figure 23) that fits within the square aluminum tube arm and attaches to the ride carriage.

5.2 Design Rationale

We determined that the major potential modes of failure of the arm would be due to tensile forces within the arm, or bending of the arm.

The maximum tension in the arm occurs when the pendulum carriage is at its lowest point. From the calculations below, it was determined that the maximum tension experienced by the arm is less than the maximum tensile strength of the aluminum arm (90MPa). Calculations can be found below in section 5.5

As for bending considerations, the maximum bending moment occurs when the arm is at the 90 degrees position as shown in Figure 25 below. We will be calculating the maximum bending moment of the arm in this position and ensure that it is less than the maximum tensile or compressive strength of the aluminum arm. By comparing the second moment of inertia of a circular and square cross-sectional area, it was also determined that the square cross-sectional area gives a smaller bending moment. As such, the final design has a square aluminum tube arm design. The calculations can be found below in section 5.4.

5.3 Optimization

Multiple iterations were performed on the arm-carriage connector piece through rapid prototyping methods. This is a crucial part of the entire system, as it connects the pendulum motor motion to the rotational motor motion of the carriage through the arm. Through this iterative process, the design was optimized to give a good fit in the square arm tubing, while accommodating the rotational motor and its wires.

Iterations of the arm-carriage connector piece:

Figure 23. *Latest version of arm-carriage connector piece opened*

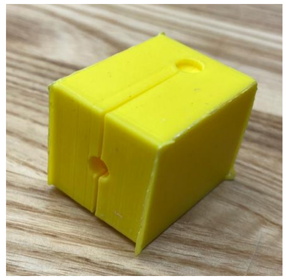


Figure 24. *Previous iteration of arm-carriage connector piece closed*

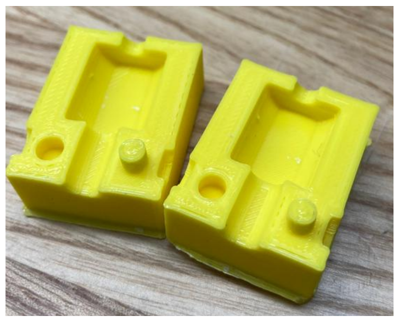


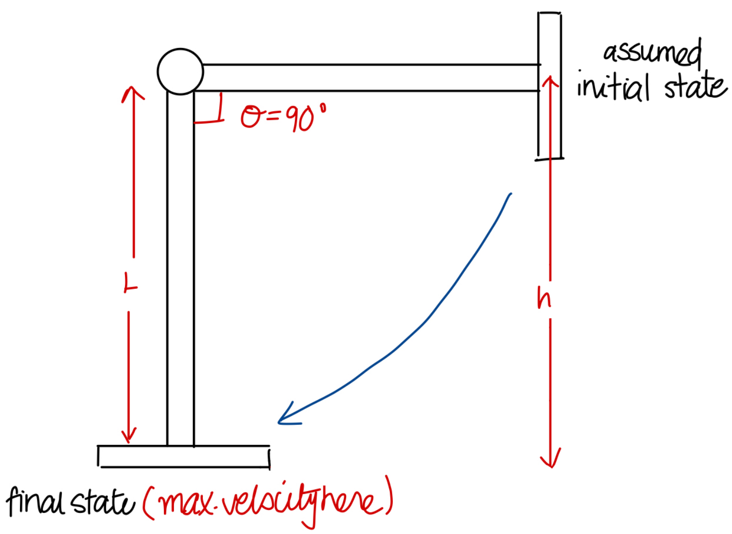
Figure 25. *Previous iteration of arm-carriage connector piece opened*

Figure 26. *Internal view of the arm-carriage connector piece that houses the rotational motor.*

Figure 27. *Final set-up of rotational motor and carriage assembly*

5.4 Calculation and Verification

Maximum Tension:
As mentioned earlier, the maximum tension in the arm was found to be when the arm and the carriage, during the pendulum motion, reach the lowest point. This position is shown in the diagram below:



Using Conservation of Energy:

$$sum\ of\ initial\ kinetic\ and\ potential\ energy\ =\ sum\ of\ final\ kinetic\ and\ potential\ energy$$

$$U_i + K_i = U_f + K_f$$

$$gh = \frac{1}{2}v^2$$

$$v_{max} = \sqrt{2gh}$$

Using Sum of Forces:

$$centripetal\ force = tension - weight$$
$$F_c = T - mg$$
$$\frac{m(V_{max})^2}{L} = T - mg$$
$$\frac{2mhg}{L} = T - mg$$
$$Max.\ Tension = mg(\frac{2h}{L} + 1)$$

Maximum Bending:

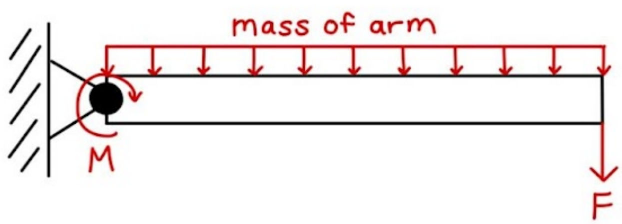


Figure 28. *Diagram of ride arm with labeled forces*

To calculate the bending of the arm at 90°, we evaluate the ride arm as a cantilever beam with a rotating pin support, a moment at the pin support, a load at the free end, and a distributed force across the arm. *M* is the rotating moment at the pin support. *F* is the combined weight of the riders, carriage, and arm. We also evaluate the arm with a square cross section. From this balance of forces, the maximum bending stress does not exceed the yield strength of aluminum material of the arm.

Control Systems Design

1 Design Description

As *Monsoon Mayhem* uses two types of motion, (a) pendulum motion and (b) carriage motion, the control system has three design features to accommodate the mechanical system. The three features are (a) start/stop, (b) carriage spin control, and (c) pendulum control. Table 4 describes the design features and the corresponding rationale.

Table 4. *Description of the control system design feature and design rationale*

	Design Feature	Description	Rationale
(a)	Start/Stop	We are using a button to start and stop the ride. When the button is first pressed the ride will start and run as normal. If the ride is running and the button is pressed it will cut power, allowing for an emergency stop. When the power is cut the brushless DC motor acts on a coast mode so that the ride will safely move to a stop.	We decided to make our start and stop a button because it is the easiest thing for an operator to push in an emergency and to push for a sudden reset. We decided to cut off power instead of breaking because our motor works on coast mode. This allows us to let air resistance and friction in the motor stop the ride, creating a gradual stop. We opted for a gradual stop instead of abrupt breaking because abrupt breaking could cause injuries such as whiplash for the passengers.
(b)	Carriage Spin Control	We are using a motor driver and DC motor to control the carriage spinning motion. We have programmed the carriage to spin for 26 seconds and then stop for 12 seconds for loading and unloading. During the 26 seconds the carriage spins in one direction for 13 seconds and then spins in the opposite direction for 13 seconds. The DC motor does not vary in speed throughout the time it is running, only in direction.	We opted to use a motor driver and DC motor to control the carriage spinning motion. We decided on a DC motor over other types of motor such as a servo because it is more powerful and we needed a greater amount of torque and rotations per minute. We are using a motor driver as it is necessary to control the DC motor. We decided to have the carriage change direction of spinning for a better ride experience.
(c)	Pendulum Control	We are using a hall encoder, electronic speed controller, and a brushless DC motor to control the pendulum motion of the ride. To mimic the motion of an actual pendulum we provide force at regular intervals and utilize gravity. The	We opted for a brushless DC motor for the pendulum motion because of the amount of torque and rotations per minute necessary for our ride to function. It also is easy to control with the electronic speed controller.

		pendulum goes a full 240 degrees of motion, swinging back and forth between 0 and 240 degrees for the 26 seconds of ride time. The hall encoder is used to track the position of the pendulum. Our code then calculates the speed the motor must spin and in which direction in order to mimic the motion of a pendulum modeled by a sine function. Then, the electronic speed controller relays this information to the motor to tell it how fast to spin and in which direction.	We decided to use a hall encoder because it calculates the position of the pendulum arm at a high precision.

2 Prototype

The prototype used an Arduino UNO as a microcontroller board with its designated Arduino IDE software. To simulate the pendulum, the Arduino UNO attached to an MD30a Pololu Motor Driver Carrier to power an M4-Threaded DC Motor. The carriage was modeled by the Arduino UNO attached to a REV Spark Max Motor Controller, controlling a NEO 350 Brushless DC Motor. Prototyping the emergency stop procedure, a 2-pin button connected to the Arduino UNO with the carriage's assigned motor driver in order to power off the movement in that circuit. The NEO Spark Max Motor Controller will be powered by a 12V battery while the rest of the components are powered by a 9V battery.

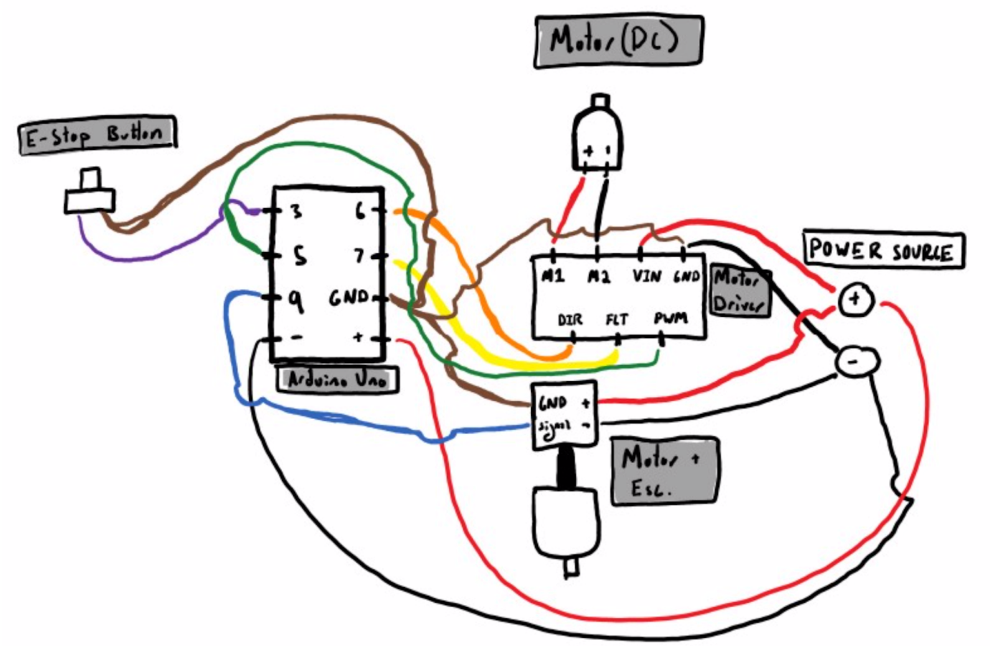


Figure 28. *Schematic of the controller circuit.*

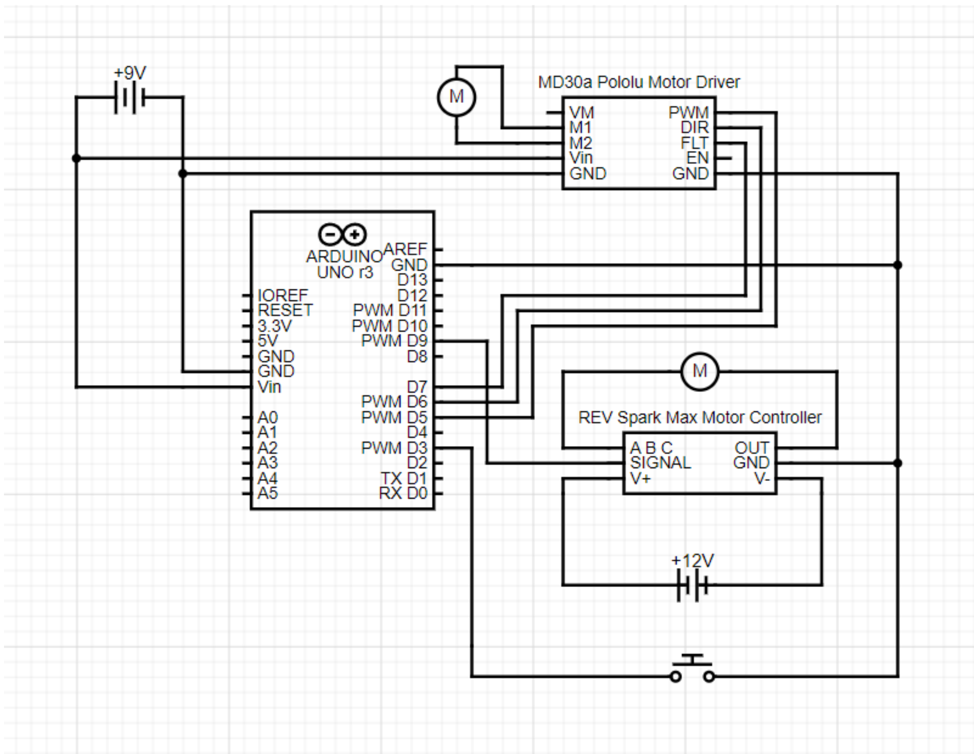


Figure 29. *Overview of Circuit connections.*

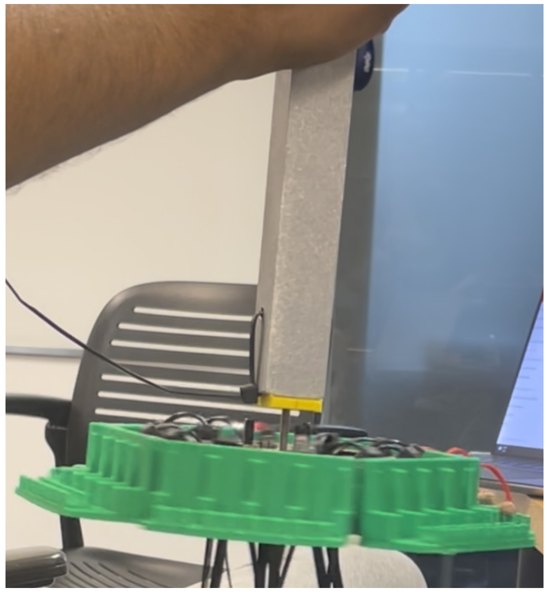


Figure 30. *Testing motor with full carriage assembly.*

3 Calculations and Verification

There are two significant calculations involved to design the control system. The two calculations are for (a) ride cycle calculations and (b) numbers used in the code.

(a) Ride Cycle Calculations
- Time is ~7x faster it would be at human scale
- Actual ride time is approx. 3 min
- Model ride program time should be ~26 sec or 0.4285 min
- $Model\,ride\,cycle\,time\ =\ program\,time\ +\ 0.5\ *\ (\#\,of\,riders)$
- For a throughput of between 32 and 64 riders per min in model, we need between 19 and 58 riders on our model.
- Add 0.5 seconds per rider for simulating passenger loading and unloading
- *Monsoon Mayhem* seats 24 passengers, hence
  $Total\,time\ =\ 26\ +\ (0.5\ *\ 24)\ =\ 38\,seconds$
- $Throughput\ =\ \frac{riders}{ride\,time}\ =\ \frac{24*60\,riders}{38\,min} = 37.89\,riders\,per\,min$

(b) Numbers used in the Code
- Ride time calculation of the 26 second ride program followed by 12 seconds of loading/unloading are used as the base of the code.

- Both the carriage motor and the pendulum motor run for 26 seconds each followed by a pause for 12 seconds before restarting.
- The ride experience is enhanced by changing the direction of the rotation of the carriage at the halfway point. Therefore, the carriage motor changes direction at 13 seconds.
- The power setting of the carriage motor was determined through testing multiple settings of the motor with the actual carriage assembly to determine the appropriate speed by comparing it to human-scale equivalents. Trial and error proved the most useful method as the impact of the carriage weight and physical resistance could only be accurately determined through testing.
- Similarly, the speed settings of the brushless pendulum motor were also calibrated through testing and analyzing how the weight of the pendulum interacted with the motor.

Verification of the functioning of the ride was conducted through testing of the equipment. The different components were tested individually and together.

4 Code

The Servo code is documented in Appendix F: Code for Control Systems Design.

Appendix A: Project Charter and Requirements

1 Mission Statement

The goal of this project is for team members to learn and develop mechanical, controls, and engineering report-writing skills through designing and manufacturing a working scale model of a flat ride that fits in a 750x750x900mm box and runs for 8 hours in a systematic manner.

2 Background Context and State-of-Art Research

Flat rides are commonly defined as theme park rides that move riders in 3D space from a stationary base that powers the ride. Due to its broad definition, a wide variety of rides can be categorized as flat rides. One of the earliest forms of the flat ride is the carousel, which originated from 12th century European jousting games but can now be found at almost every amusement park. Flat rides provide theme parks the ability to pack a relatively low-cost attraction into a small footprint, which is why they are found scattered throughout almost every theme park.

Due to the diverse nature of flat rides, there is no single mechanism that is common to all rides of this category. However, all flat rides can not rely on the gravity and momentum to power the coaster and instead must have a robust powering mechanism that moves the riders. Therefore, we can group together the many different flat rides by their common powering mechanisms.

The first group of flat rides rely on pure rotational motion to bring riders thrills and these rides include the carousel, swing rides and rotor-based rides. These rides use a motor-pulley system to carry riders through circular motion around a vertical stationary base. More recent iterations of this concept add on additional hydraulic arms to shift the height and angle of rotation (e.g. Genting Skyworld's Global Defender).

Another group of flat rides include drop towers that rely on vertical motion. These rides are often powered by several lift motors positioned on the top of the tower to carry riders to the top of the tower and electromagnetic brakes to slow riders down after being dropped. Many rides combine vertical and circular motion for increased thrills, resulting in more unique rides like the Giant Swing Ride at Valleyfair.

The final group of flat rides mimic a pendulum to swing riders back and forth. These rides are often powered by pneumatic cables that drive the riders' motion in a consistent manner. Rides that utilize this mechanism include the Buccaneer attraction that can be found in many theme parks and Knott Berry Farm's Screamin Swing.

There are many other flat ride concepts that combine the features we have already identified or add new features. However, we can derive a basic understanding of flat ride operation and the priorities when designing flat rides from the existing products that are being operated at theme parks across the world.

We aim to use the collection of existing flat rides as inspiration for our project, to use our creativity to come up with a composite or even a new concept of a flat ride.

This project also aims to be compliant with the ASTM F24 standards. The F24 committee establishes standards on amusement ride design and manufacturing, testing, operation, maintenance, inspection, and quality assurances.

3 Stakeholders

In order to bring this project to fruition most successfully, it is important to identify stakeholders who must be kept in mind throughout this process. These stakeholders include:

Table 5. *List of stakeholders.*

Stakeholder	Role	Communication		
		Content	Frequency	Method
Team members	Their ideas, experiences, and research will shape the deliverables of the project	We aim to learn about theme park industry standards, state-of-art rides; build the relevant skills and experiences for a good footing in theme park design; work with and find peers across different teams; and further our creative and professional development goals	Constant update from members and sub-team leads in group chats Weekly meetings within sub-teams Weekly meetings between team leads	Verbally or via documentation In-person meetings Online Zoom meetings

Faculty advisors, mentors, and resources	Source of reference and support	Seek advice to help us learn relevant skills and guide us in this process. Ask for feedback for major developments made in the project to help verify the computations and calculations involved in the design	Depends on milestones set by sub-team leads	Find office hours held by relevant faculty Set up meetings with relevant faculty for project design reviews
REC Planning Committee	Planned the competition and guides the project through guidelines, prompts, and evaluations	Seek for valuable guidance and our projects will shape how future competitions are planned Deliver the deliverables to ensure that the project is on track and compliant with the guidelines	Depends on the deadlines set by REC Planning Committee Depends on whenever the team requires further clarification on the competition prompt or guidelines	Directly contact via email
Potential users	Provides feedback based on experience and interest	Seek feedback and advice from and utilize their feedback to help mold our project.	At least once before finalizing the design and once before finalizing the model.	Conduct surveys on user testing. Surveys can include an illustrative user scenario for survey takers to understand the design concept.
Theme park professionals	Provides feedback based on experience and interest	Seek feedback and advice from and utilize their feedback to help mold our project. This project may also	At least once before finalizing the design and once before finalizing the	Research for potential points of contact to set up meetings. Presentations

		impact them should it be taken further and implemented or inspire future rides.	model.	should be prepared for the meetings. Meetings can be held in a manner similar to design reviews.

4 Initial Resources

The team will rely on both internal and external resources to put together our submission for the competition. This is an initial list of what skills and resources are available on our team and potential people we can reach out to and learn from as we prepare.

1. External Resources:

   Resources outside the team that can be utilized to upskill and prepare for the competition include:
   - LinkedIn Learning, Coursera, and other online learning tools
   - Professors and mentors
   - Feedback from potential users, theme park industry professionals, or peers

   Some potential we may contact include:

   Table 6. *List of potential experts that can be points of contact.*

Professor/Expert	Area of Knowledge
Heidi Huckabay, Senior Design and Prototyping Specialist	Custom fabrication, metals.
Prof. Randy Freeman	Digital control systems.
Prof. Nick Marchuk	Mechatronics
Prof. Ilya Mikhelson	Electrical control systems etc.
Prof. Hooman Mohseni	Electrical control systems etc.

2. Internal Resources:

Team members bring the following skills and will work on developing more as needed by the project. These skills include CAD, design sketching, programming, soldering, electronics, manufacturing, and industry experience with theme park design.

Table 7. *List of team members and corresponding skills.*

Team Member	**Skills**
Sheyla Adaya	Soldering, CAD, some design sketching
Ashley Burwell	Basic soldering, basic CAD, basic programming
Natalie Norquist	Very rudimentary CAD
Yujie Wang	Basic CAD, programming
Atishay Saraogi	CAD, programming, working in the shop
Marisabel Aguilar	Electronics, programming, soldering
Eliana Storkamp	Soldering, some CAD and some programming
Cristian Hernandez	Soldering/Programming (Python, C, C++)/Electronics
Maia Traub	
Ethan Cheng	
William Marchetta	some CAD, Python, design sketching
Orion Jusuf	CAD, Manufacturing (Manual and CNC), some coding
Valeria Yzaga	Design sketching, some circuits and coding
Jorge Mena	
Jesus Renteria	some coding, industry knowledge
Jasmin Ali-Diaz	some coding (python, java), some circuits, basic design sketching
Hajra Malik	
Nigel Nicholas Chew	CAD, Design Sketching, Industry Knowledge,
Gass Iyacu	Design sketching

Ryan Kessler	Some programming (Java, Matlab, python), circuits, design sketching, basic shop skills
Max Rothfeder	Industry knowledge, design, shop skills, manufacturing, some python, sketchup, some autoCAD
Nadiah Zamri	CAD, design sketching, concept art, c++
Marco Contreras	Industry knowledge, CAD, design sketching, some Python
Anna Cao	CAD, Design sketching, concept art, some coding
Kevin O'Brien Brunner	Basic CAD, Embedded Programming, Electronics

3. Sources of Funding
   Our team is obtaining funding from the McCormick Student Activities Grant that was given to the Theme Park Engineering & Design Group at Northwestern University. Additional sources of funds to cover costs will be obtained from corporate gifts and fundraising activities.

5 Scope of Work

1. Written Deliverables
- Project Charter
- Risk Assessment
- Mechanical Systems Design
- Control Systems Design
- ASTM F24 Compliance Analysis
- Drawings and Schematics
- Bid documents
- Preliminary Design Review
- Final Design Review

2. Non-Written Deliverables
- Physical Model
- Team Outreach

- Final Presentation
- Final Poster (24” x 36”, 300 dpi or less)

3. Constraints

The only constraints are the deadlines set by the REC Planning Committee to submit deliverables. This is summarized below.

Timeline

Full Competition

- **October 22 2021:** Registration Opens and Prompt is Announced
- **Friday December 3 2021:** Registration Closes
- **Specific Date by Team:** Project Charter, Preliminary Design Review, Initial Concept and Initial Risk Assessment
- **Monday February 7 2022:** Event Details and Registration Opens
- **Specific Date by Team:** Final Design Review
- **Friday March 18th 2022:** Event Registrations Close
- **Friday April 2 2022:** Final Hand-in
  Systems Engineering Report, Poster
  Proof of Life Video
  Outreach Report Due
- **Fri.-Sat. April 8-10 2022:** Competition Event
  Service Plan
  Final Presentation

4. Project Timeline

The team has three primary groups responsible for different aspects of the project. This includes (a) leads, (b) mechanical sub-team, and (c) controls sub-team. Groups (b) and (c) have established individual estimated schedules of work in accordance with the overall project timeline as found in the GANTT chart for group (a). The GANTT chart for the three groups are listed below.

(a) Overall project timeline
(b) Mechanical sub-team

(c) Controls sub-team

6 Design Criteria

1. Primary Design Needs

Table 8. *Primary Design Needs.*

Need #	Metric	Units	Marginal Value	Ideal Value	Notes
1	Ride must fit within a theoretical size box 750mm wide, 750mm deep, and 900mm tall at all times during operation	Boolean	Yes	Yes	
2	Design compliant with ASTM F24 Standard	Boolean	Yes	Yes	
3	Ride must include an Emergency Stop function	Boolean	Yes	Yes	The function shall be in red and clearly labeled "Emergency Stop" or "E-Stop". Activating the function shall initiate a Ride Off Function Consistent with ASTM F2291 Section 11.3.8.
4	Ride operates during a period of 8 hours	Boolean	Yes	Yes	
5	An operation Cycle consists of the ride program, followed by a pause of approximately 0.5 seconds per rider to	Seconds	0.5	0.5	

	emulate loading and unloading				
6	Rides operates primarily in a Continuous Automatic Operation, where no operator intervention is required between operation Cycles	Boolean	Yes	Yes	
7	Riders will stay on the ride for one hour as the ride operates in Continuous Automatic Operation. Every hour, teams shall safely halt their ride after a completed Cycle.	Boolean	Yes	Yes	After a completed cycle, riders must be then removed from the ride and new riders shall be placed on the ride.
8	Rides will have a throughput between 32 and 64 riders/min when in continuous automatic operation	riders/min	32	38	Throughput = (# of Riders per Cycle) / (Cycle Time).
9	Riders shall be lifted 300 mm above their initial loading height	mm Frequency	300 1 per cycle	300 4 per cycle	
10	Riders shall change orientation by at least 45 degrees in any direction during the ride cycle.	Degree (°)	45	240	Riders can end a ride cycle in a different orientation than at the start of the ride cycle
11	Riders shall experience at least 2G of absolute acceleration force in any direction	Acceleration in m/s^2 Frequency	19.6 1 per cycle	29.4 4 per cycle	This includes acceleration from gravity

2. Secondary Design Needs

Table 8. Secondary *Design Needs.*

Need #	Metric	Units	Marginal Value	Ideal Value	Notes
1	Ride designs must emulate existing ride concepts or be an original idea	Similarity to existing flat ride concepts	Emulates existing ride concept	Original idea	
2	Ride should minimize frequency of downtime instances	Frequency	2	0	
3	Team should return ride to operation when a downtime instance occurs	Frequency	0 per downtime instance	1 per downtime instance	
4	Ride must be durable		Able to operate for 8 hours with passengers weighing 4.5-5 grams	Able to operate for 8 hours with passengers weighing 4.5-5 grams	The design attempts to meet ASTM F24 standards to ensure safety, and durability is a part of this.

3. Design Constraints

1. The design must fit within a 750mm wide, 750mm deep, 90mm tall box
2. A minimum of 8 riders is allowed on the ride during a single cycle. There is no maximum number of riders.

3. Bidding points:
    - The team with the highest value bid will receive a deduction of 100 points. The team with the lowest value bid will receive no deduction. Remaining teams will receive deductions tiered linearly within that range based on their relative value rank.
    - Manufacturing time performed by the team must be added to the Bid at a rate of $20.00 per hour. This only means time spent altering parts or creating new parts.
    - 3D Printed parts are discouraged and will have a manufacturing cost of $1.00 per gram.

Appendix B: Risk Assessment Analysis I (Potential Hazard)

Potential hazards are evaluated based on the risk matrix below. For risks that score greater than or equal to 16, the risk must be mitigated.

	5 x 5 Risk Matrix					
	Impact					
Likelihood		Negligible (1)	Minor (2)	Moderate (3)	Significant (4)	Severe (5)
	Very Unlikely (1)	1	2	3	4	5
	Unlikely (2)	2	4	6	8	10
	Possible (3)	3	6	9	12	15
	Likely (4)	4	8	12	16	20
	Very Likely (5)	5	10	15	20	25

Keys:

Potential Person in Risk	
Operator	**O**
Rider	**R**

Bystander	**B**

Approach		
Accept	**A**	If mitigating the risk costs more than tolerating the risk.
Reduce	**R**	
Eliminate	**E**	

Table 10. *Potential risks on the overall ride, the risk score, and contingency plan based on the approach.*

Item	**Risk**	**Person In Risk**	**Likelihood (1-5)**	**Impact (1-5)**	**Risk Score**	**Approach**	**Contingency Plan**
Rain	Cause sensors to malfunction	R	1	4	4	E	Stop running the ride if the rain becomes too heavy.
Wind	Affect the path of the ride, and accelerate or decelerate the swinging motion	R	3	3	9	R	Moderate the speed accordingly if it were to happen.
Lightning	Lightning striking the ride and operator being injured	O	2	5	10	E	If lightning gets too close to the ride, stop operation.
Lightning	Lightning striking the ride and hurting the passengers	R	2	5	10	E	If lightning gets too close to the ride, stop operation.
Snow	The ride will become more difficult to operate	O	3	3	9	R	Have specific instructions for operation during this occasion.
Snow	Extra weight can cause arm to break	R	2	5	10	R	Clean the extra snow as much as possible to reduce the most weight.
Snow	Build up of snow can add weight to ride, and arm breaking can lead to bystander injuries	B	2	4	8	E	If this possibility arises then stop operation of the ride.
Loss of	Ride will not be able to manually be	R	1	3	3	E	Have a power generator available and

power	stopped, and it might exceed the maximum desired speed.						ready to use in order for the operator to safely stop the ride.
Extreme winds	Might lead to the collapse of the ride, and hurt people within close proximity.	B	2	4	8	R	Provide extra support for the column. If it leads to the possibility of happening, clear the area and stop operation of the ride.

Appendix C: Risk Assessment Analysis II (FMEA for Mechanical Systems)

Steps of FMEA (failure modes and effects analysis) based on our arbitrary criteria:

1. Identify potential failures and effects
2. Determine severity/impact (we chose to arbitrarily rank on a scale of 1-5 with 1 corresponding to negligible, 2 to minor, 3 to moderate, 4 to significant, and 5 to severe
3. Then gauge the likelihood of occurrence, with 1 corresponding to very unlikely, 2 to unlikely, 3 to possible, 4 to likely, and 5 to very likely
4. Next, we will determine the difficulty of detecting potential failures, on a scale of 1 to 5, with 1 being very easy to detect, 2 being easy, 3 being neutral or unknown, 4 being difficult to detect, and 5 being very difficult to detect.
5. We then created a variable "risk score" that is calculated as the product of the likelihood of the hazard occurring, the severity of the failure, and the difficulty of failure detection. If this risk score is 48 or greater, the risk must be eliminated. If it is between 8 and 47, the approach will be to minimize the severity, followed by reducing the occurrence. If it is less than 8, then no adjustments need to be made.

Each component of the mechanical systems will have an individual FMEA.

(1) Arm and Base Structure

Table 11. *FMEA table for Mechanical Systems' Arm and Base Structure*

Potential Failure Mode	**Potential Effect(s) of Failure**	**Severity**	**Potential Cause(s)/ Mechanism(s) of Failure**	**Occurrence**	**Detection**	**Risk score**	**Service plan during operation**
Arm fractures under bending	Injuries to the passengers.	5	The bending on the arm is greater than what it can withstand.	2	2	20	Replace the arm.

Arm detaches from the swinging motor.	Injuries to passengers.	5	Direct stop of the swinging motion when the arm is above 90 degrees.	2	1	10	Reattach the arm and add (?)
Arm fractures under loads above the yield strength	Injuries to the passengers.	5	The weight of the carriage and passengers is greater than what the arm can take.	2	2	20	Replace the arm.
Columns Detach	Ride will collapse towards the direction of the detached column.	5	The swinging of the arm loosens the attachment screws.	1	1	5	Reattach the column, and replace and tighten the bolts.
Columns break due to bending	The whole ride collapses and causes damage to the passengers.	5	The force at which the pendulum is swinging is greater than what the columns can handle.	1	2	10	Replace the column that was broken with a new one, and any other part that might have been damaged.
Resonance in the columns	Lead to the detachment and/or breakage of the columns,	5	Usage of the ride.	2	1	10	Provide service to the columns, or gearbox depending on where it is required.

	and the ride will collapse.						
Model flips over	Passengers will be injured and the model will come apart.	5	Swinging of the arm greater than the supporting forces, or if a support column breaks.	1	1	5	Flip it back over and reattach and/or replace the components as needed.

Throughout the course of designing and modeling the ride, in scenarios where we noticed a possible failure we have applied measurements of safety in order to prevent the failure from occurring. For example, in order to prevent column detachment we decided to secure the columns to the ground with an adapter that has four bolt holes, which we will use all of, to make sure the column stays in place. Additionally, in order to prevent the arm from breaking in any way we did numerous calculations for the yield strength, bending stress, max torque and max tension. Along with the calculations we were very careful in material selection as they had to fulfill our building requirements, and needed to satisfy the adequate constraints for the calculations that we previously made.

(2) Carriage Gearbox

Table 12. *FMEA table for Mechanical Systems' Carriage Gearbox*

Potential failure mode	**Potential effects of failure**	**Severity**	**Occurrence**	**Detection**	**Risk score**	**Service plan during operation**
Motor shaft bending or breaking due to heavy load	Arm breakage, Slow spin of shaft, abnormal noise during cycle run	5	1	2	10	Replace shaft with a back up one made from sturdier material

Gears stuck or gear's teeth chipped	Motor stops running which halts the ride and puts passengers at risk of injury	4	1	2	8	Repair or remove blockage. Lubricate gears if needed. Replace gears or motor depending on severity of condition.
Gearbox motor burnout	No power delivered to the arm, which stops the ride promptly and puts passengers and bystanders at risk	5	1	2	10	Replace motor with a backup one and conduct repair on broken motor
Plate fracture	Plate falling apart, no motor support to avoid heavy load on motors	4	1	2	8	Use backup plate made with sturdier material (if thicker then a longer backup shaft is needed)
Bearing failure due to load capacity	Shaft stops turning	5	2	3	30	Use backup bearing

Appendix D: Risk Assessment Analysis III (FMEA for Control Systems)

Table 13. *FMEA table for Control Systems*

Potential Failure Mode	Potential Impact of Failure	Severity	Occurrence	Detection	Risk score	Service Plan during Operation (if applicable)

Carriage Motor Power Loss	There will be no power driving the spinning of the carriage, so the carriage will come to a stop.	4	3	1	12	If this failure is not due to motor burnout or gear failure, power loss for the carriage motor can be addressed.
						Action Plan: (2 - 20 min)
						- Check visually if any wires are disconnected between the Arduino and the motor driver, as well as the motor driver and the carriage motor
						    - If so, bring the ride to a halt, reconnect the wire, check all other wires, and restart the ride
						- If disconnected wiring is not the cause, check the voltage of the battery to check if power is being supplied
						    - Check using a voltmeter
						    - Replace the battery in the system with a working alternate power source and restart the ride
						- If the above options are not the cause, see “Carriage Motor Burnout”, “Arduino Burnout”, “Motor Driver Burnout”, and “Gear Teeth Failures” for more severe causes

Carriage Motor Burnout	There will be no power driving the spinning of the carriage, so the carriage will come to a stop. The carriage motor becomes damaged and eliminates the possibility of spinning.	5	2	1	10	This failure is not fixable, as it would require a new motor. Although the carriage will no longer spin, pendulum motion may still be possible for the ride.

Brushless Motor Power Loss	There will be no power driving the pendulum motion, so the carriage will coast to the initial starting spot.	4	3	1	12	If this failure is not due to motor burnout or gear failure, power loss for the carriage motor can be addressed and likely fixed.
						Action Plan: (2 - 20 min)
						- Check visually if any wires are disconnected between the Arduino, hall encoder, electronic speed controller, and brushless motor
						    - If so, bring the ride to a halt, reconnect the wire, check all other wires, and restart the ride
						- If disconnected wiring is not the cause, check the voltage of the battery to determine if power is being supplied
						    - Check using a voltmeter
						    - Replace the battery in the system with a working alternate power source and restart the ride
						- If the above options are not the cause, see “Brushless Motor Burnout”, “Arduino Burnout”, “Gear Teeth Failures” for more

						severe causes
Brushless Motor Burnout	There will be no power driving the pendulum motion, so the carriage will coast to the initial starting spot. The brushless motor becomes damaged and renders the ride unable to swing.	5	2	1	10	This failure is not fixable, as it would require a new motor. Although the ride will no longer swing back and forth, carriage spinning may still be possible for the ride.
Ardunio Burnout (likely caused by incorrect wiring)	There will be no power driving either the pendulum or the spinning motion, so the pendulum will coast to a stop as the spinning carriage comes to a halt. The damaged Arduino would render the ride unusable.	5	1	1	5	This failure is not fixable, as it would require a new Arduino. Neither pendulum motion nor carriage spinning would be possible in this scenario.
Motor Driver Burnout	As the motor driver is connected to the carriage motor, there will be no power driving the spinning of the carriage, so the carriage will come to a stop. The damage to the motor driver will eliminate spinning as a ride feature.	5	2	1	10	This failure is not fixable, as it would require a new motor driver. Although the carriage will no longer spin, pendulum motion may still be possible for the ride.
Fraying Wires	Frayed wires create	4	3	3	36	This failure is likely fixable with

	electrical dangers to humans through the possibility of electric shocks or redirecting current into the system. Power to both motors may also be lost, which would cause the ride to coast to a stop and halt its spinning.					replacement wires.
						Action Plan (10-15 min):
						- Check visually to see what wires are disconnected in the setup
						    - Likely indicator is problems with either the spinning or pendulum motion
						- Bring the ride to a halt and disconnect all wires connecting to the power source
						    - Prioritizing safety by avoiding electrical dangers from frayed wires.
						- Replace frayed wires with new wires and restart the ride
						    - Ideal to keep additional, already stripped wires on hand

Gear Teeth Failures Connecting to Motors	The gear teeth failing and thus disconnecting will lead to a loss of power in the motors, and both the pendulum motion and spinning will come to a stop.	5	2	1	10	If the gear teeth can be reconnected while the ride is stopped, this failure is fixable. If the failure is due to worn-down teeth or physical damage to the gears, this failure is not fixable as it would require a new gearbox.
Physical Damage from Dust Buildup	Large buildups of dust are flammable, and a fire would harm ride equipment and endanger riders. The motors and	5	2	3	30	This failure occurs due to long-term use and is not likely to occur during the competition. However, the electronic components (Ardunio, wires, motors) should be dusted with a clean, dry cloth

	Arduino could shortcircuit from the buildup of heat in the system, which					after prolonged usage. Time: 20 min.
Physical Water Damage from External Environment	Water could damage the Arduino and motors which would render the model unusable. Additionally, water and wire interactions may introduce a risk of electrocution to operators and riders.	5	2	3	30	If saltwater is spilled on the Arduino, the Arduino should immediately be rinsed in freshwater. To dry the Arduino, it should either be placed in a bowl of white, clean rice. If the water impact is minimal, the Arduino can be dried using a stronger blower (such as a hairdryer on cold). Time: 10 - 60 min.

Appendix E: ASTM F24 Compliance Analysis

We are responsible for compliance to F2291-21 Standard Practice for Design of Amusement Rides and Devices. (2021).

F2291 is written specifically for rides carrying human riders, and has many specific values and figures that are not feasible for the context of the Ride Engineering Competition's roughly 1:50 scale inanimate riders. Additionally, there are many requirements in the standard that are outside the scope of the competition, or are impractical or impossible for teams to comply with. Due to these differences, this ASTM Adaptation Document provided by ISU REC shall be used to filter the standards to accommodate the scope of the competition.

Sections or subsections that are not shown in the ASTM F24 Compliance Analysis are sections or subsections that are omitted according to the REC 2021 ASTM Adaptation Document as they do not fall within the scope of the Ride Engineering Competition.

The ASTM F24 Compliance Analysis is documented in this file.
(https://docs.google.com/spreadsheets/d/160fIl_oyOSW5dUDR6WHXdkf-eOpGq0bIjNA0GDq-r0U/edit#gid=986457000)

Appendix F: Code for Control Systems Design

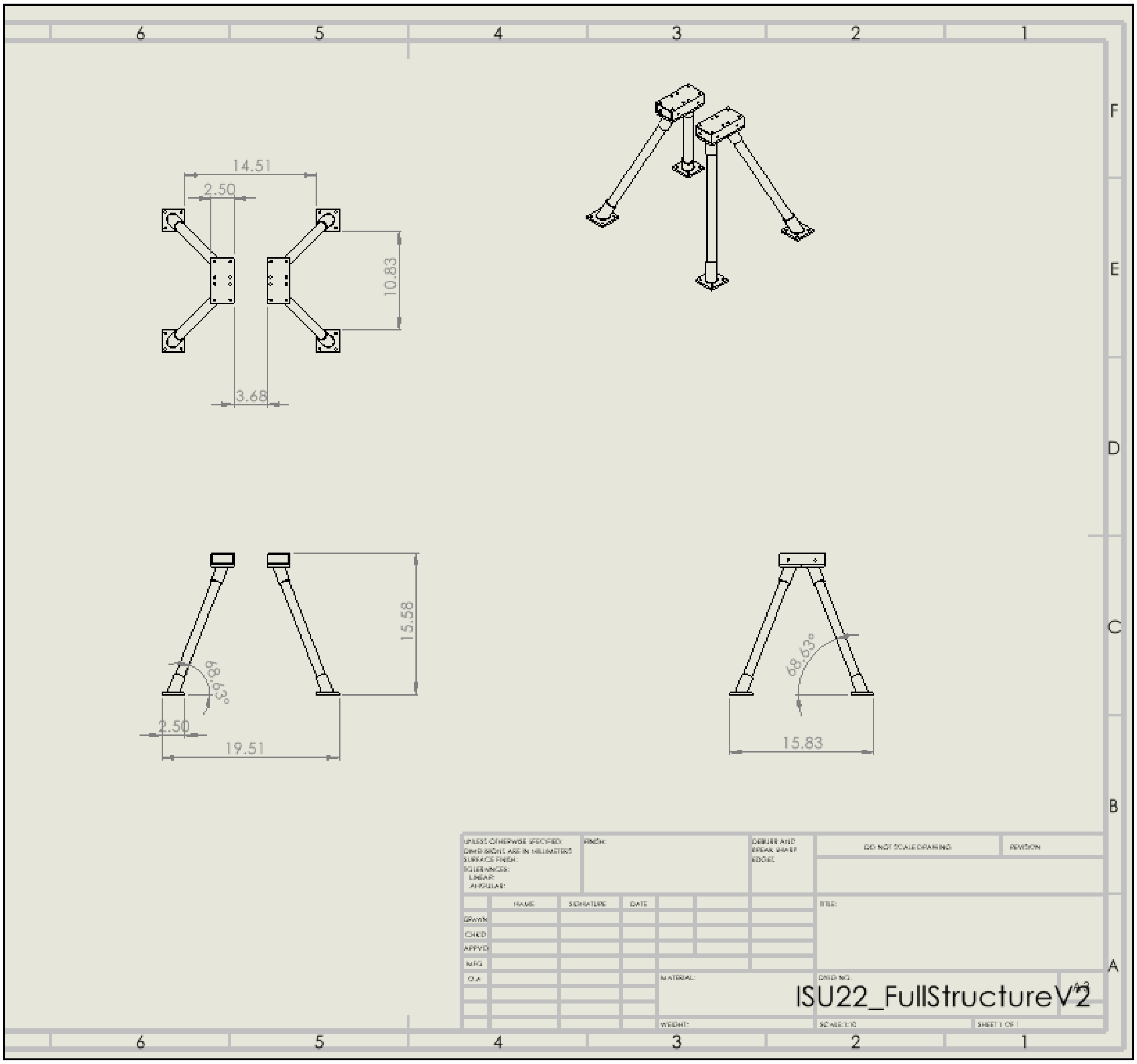
```
#include <Servo.h>
Servo m;

bool rng = false;
unsigned long rstart;
unsigned long rtime;

#define PWM 5
#define IN2 6
#define IN1 7

/*
 * VIN/GND to battery
 *
 * GND to Arduino GND
 * M1, M1 to motor
 * PWN to 5
 * DIR, FLT to 6, 7
 *
 * FOR REVSPARK:
 * white to 9, black to GND
 *
 */

void setup() {
  Serial.begin(9600);

  pinMode(PWM,OUTPUT);
  pinMode(IN1,OUTPUT);
  pinMode(IN2,OUTPUT);

  pinMode(3, INPUT);
  digitalWrite(3, HIGH)
```

```
  rstart = millis();
  rtime = 0;

  m.attach(9);
  m.writeMicroseconds(1500);
}

void loop() {
  int bt = digitalRead(3);

  if(!bt){
    rng = !rng;
    delay(1000);
    rstart = millis();
  }

  rtime = millis() - rstart;

  if(rng){
    // motor power
    float pwr = 100;
    int dir = 1;
    int pdl = 1500;

    if((rtime/1000)%4 == 1){
      pdl = 1600;
    }
    else if((rtime/1000)%4 == 3){
      pdl = 1400;
    }

    if(rtime > 13000){
      pwr = 100;
      dir = -1;
    }

    if(rtime > 26000){
      pwr = 0;
      pdl = 1500;
      if(rtime > 38000){
        rstart = millis();
      }
    }


    // signal the motors
    setMotor(dir,pwr,PWM,IN1,IN2);
```

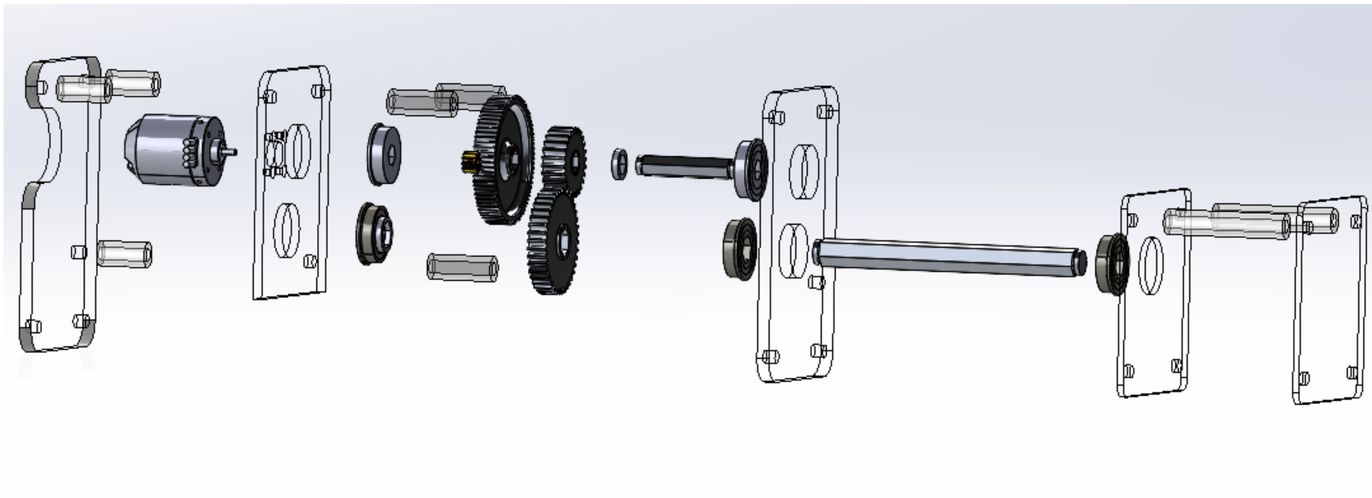
```
    m.writeMicroseconds(pdl);
  }
  else {
    m.writeMicroseconds(1500);
    setMotor(1,0,PWM,IN1,IN2);
  }
  Serial.print(rng);
  Serial.print(" ");
  Serial.print(bt);
  Serial.print(" ");
  Serial.print(rtime);
  Serial.println();
}

void setMotor(int dir, int pwmVal, int pwm, int in1, int in2){
  analogWrite(pwm,pwmVal);
  if(dir == 1){
    digitalWrite(in1,HIGH);
    digitalWrite(in2,LOW);
  }
  else if(dir == -1){
    digitalWrite(in1,LOW);
    digitalWrite(in2,HIGH);
  }
  else{
    digitalWrite(in1,LOW);
    digitalWrite(in2,LOW);
  }
}
```

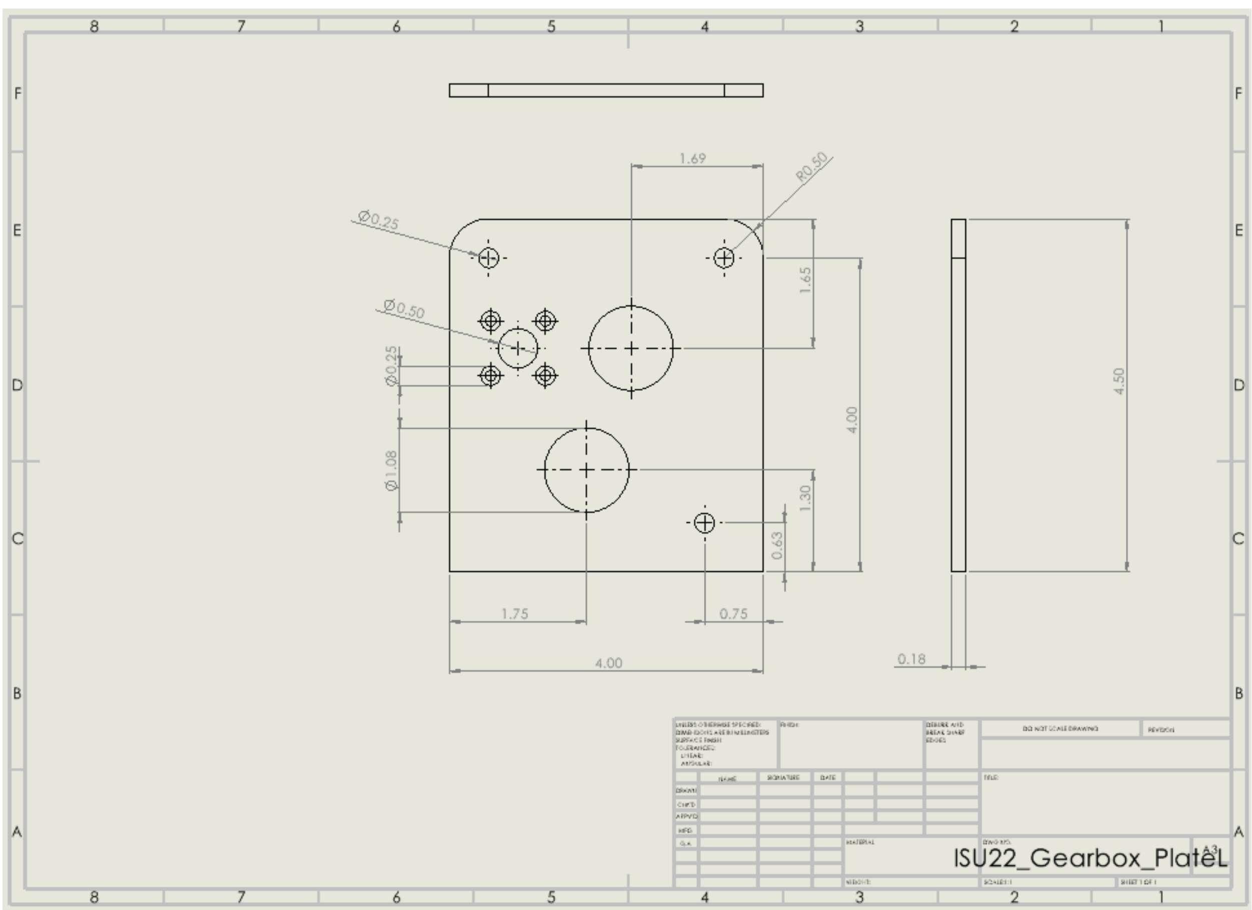
Appendix G: Schematic Drawings for Mechanical Systems Design

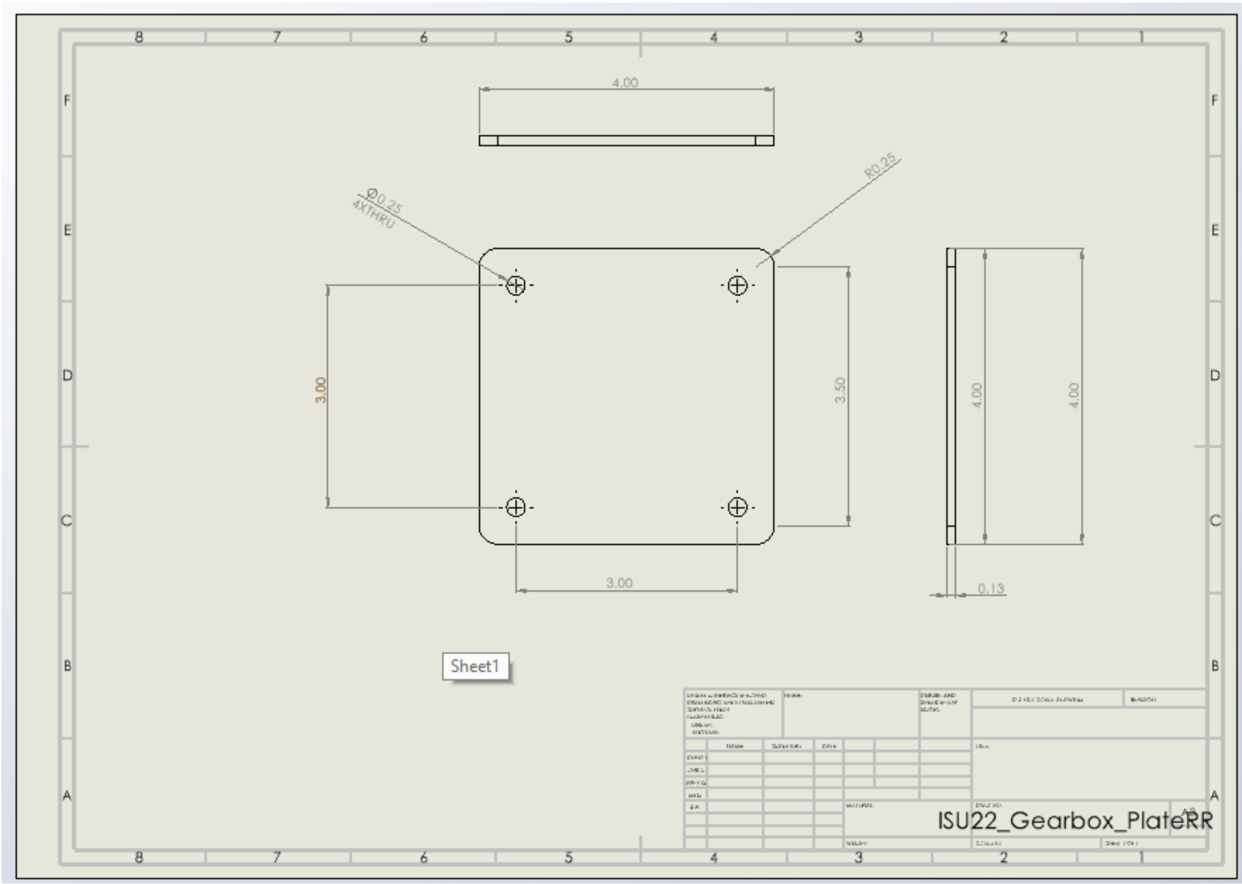
Schematics for 1a Base Structure

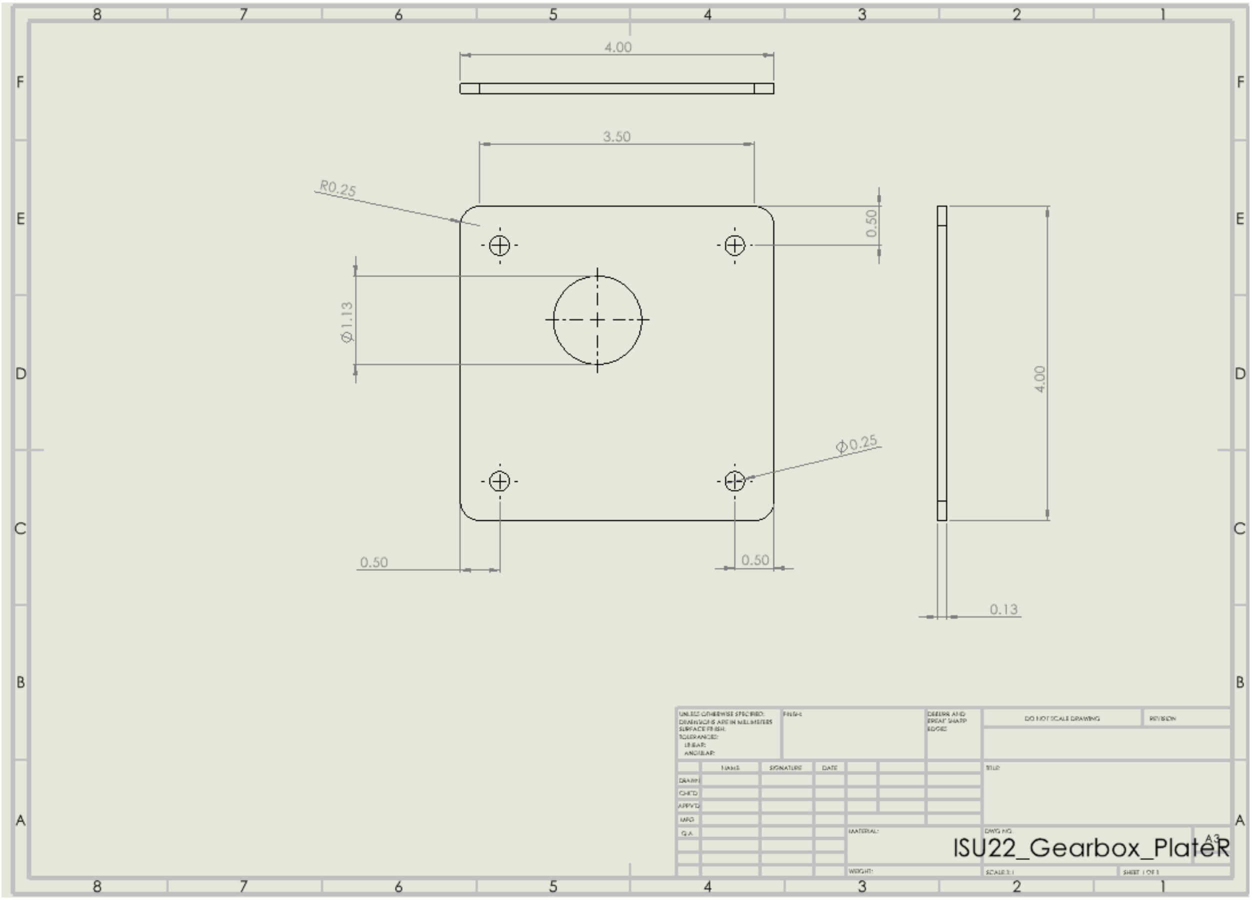


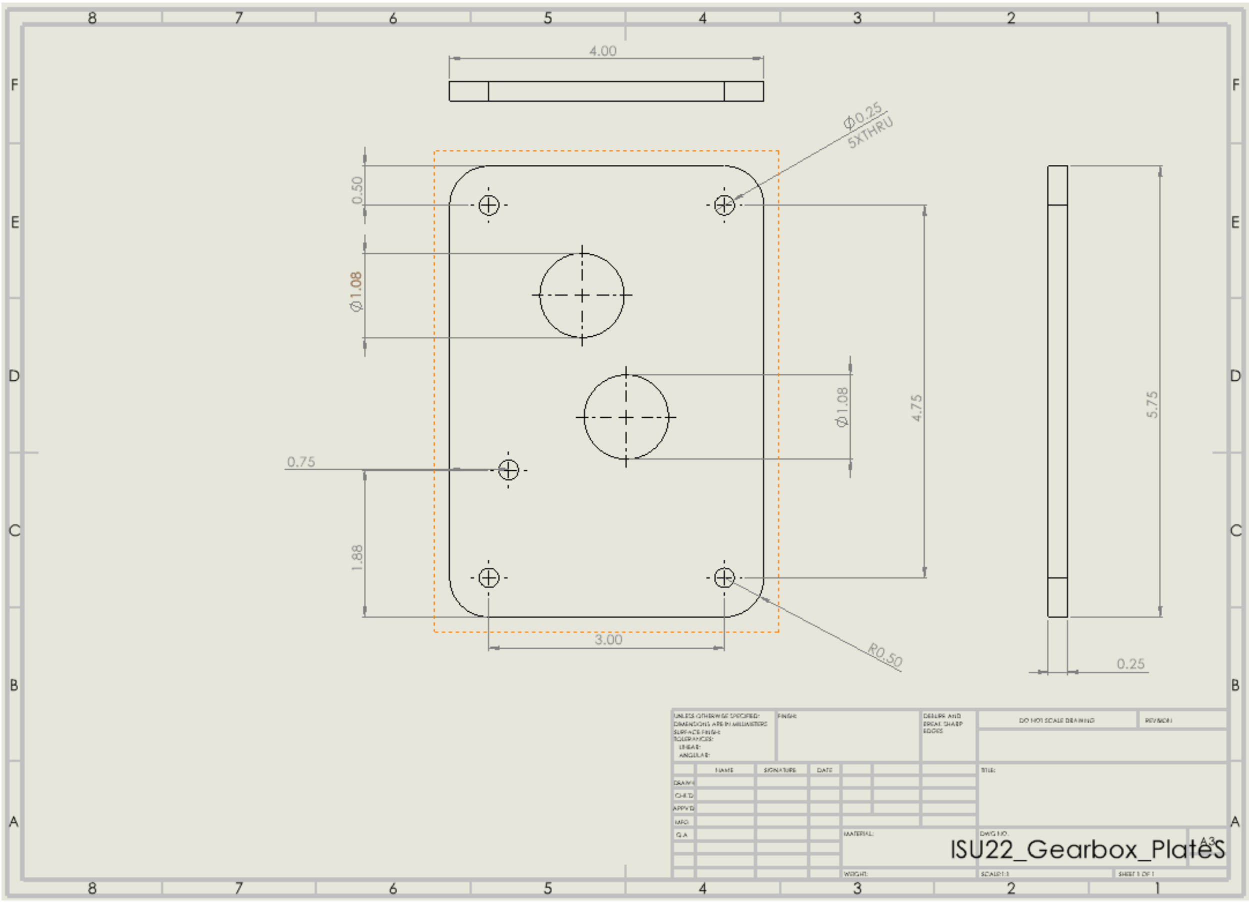
Exploded view of gearbox and schematics for 1b gearbox plates






4.00
Ø0.25
4XTHRU
R0.25
3.00
3.50
4.00
4.00
3.00
0.13
Sheet1
ISU22_Gearbox_PlateRR


4.00
3.50
R0.25
0.50
Ø1.13
4.00
Ø0.25
0.50
0.50
0.13
DO NOT SCALE DRAWING
ISU22_Gearbox_PlateR
A3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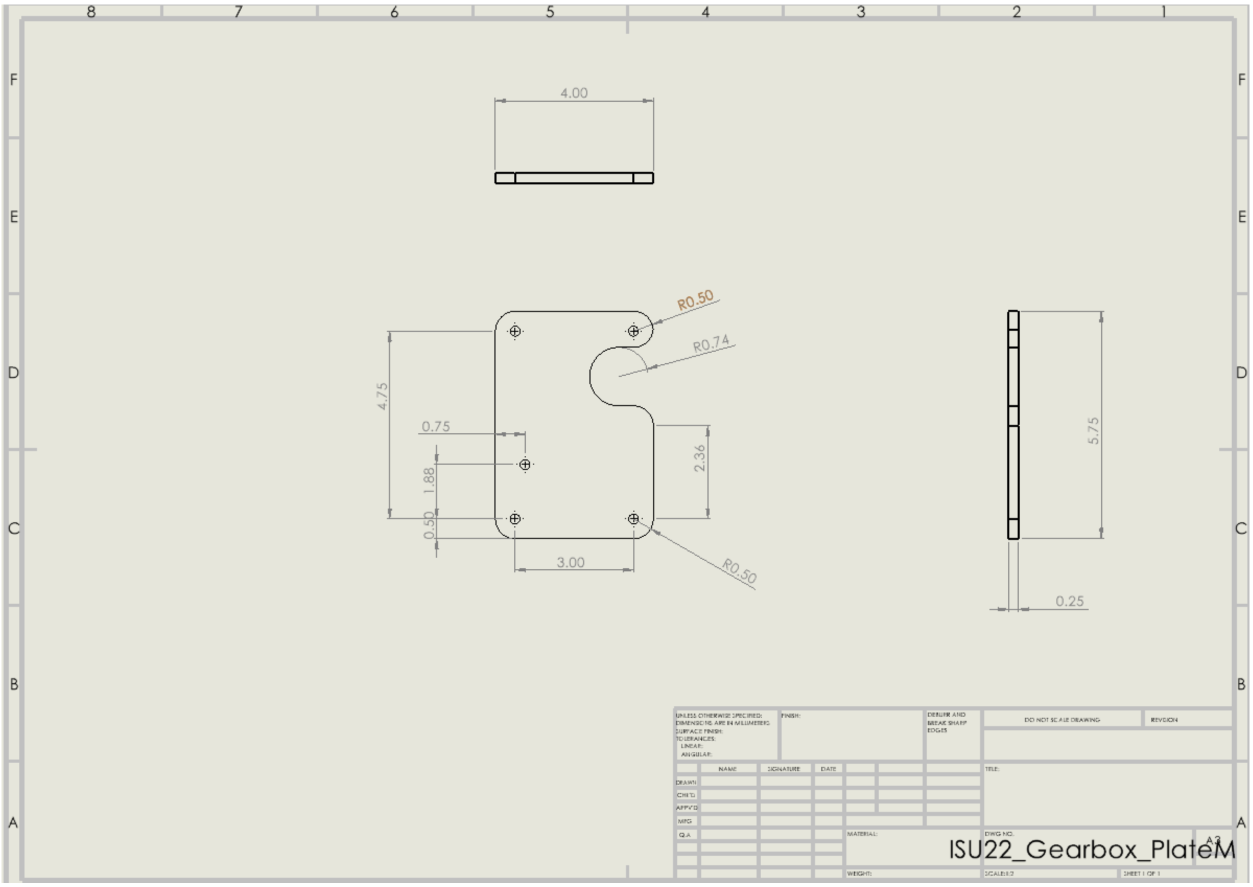
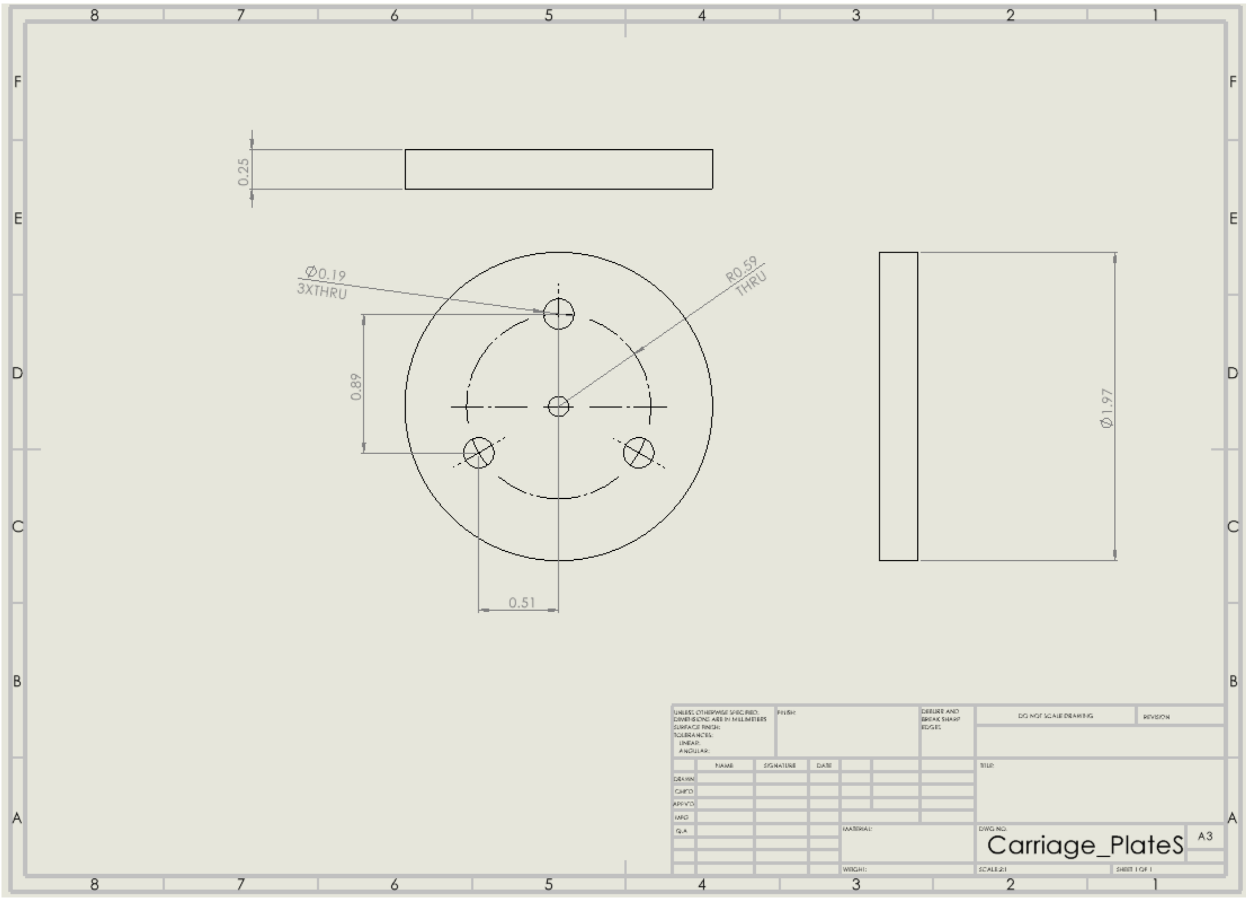
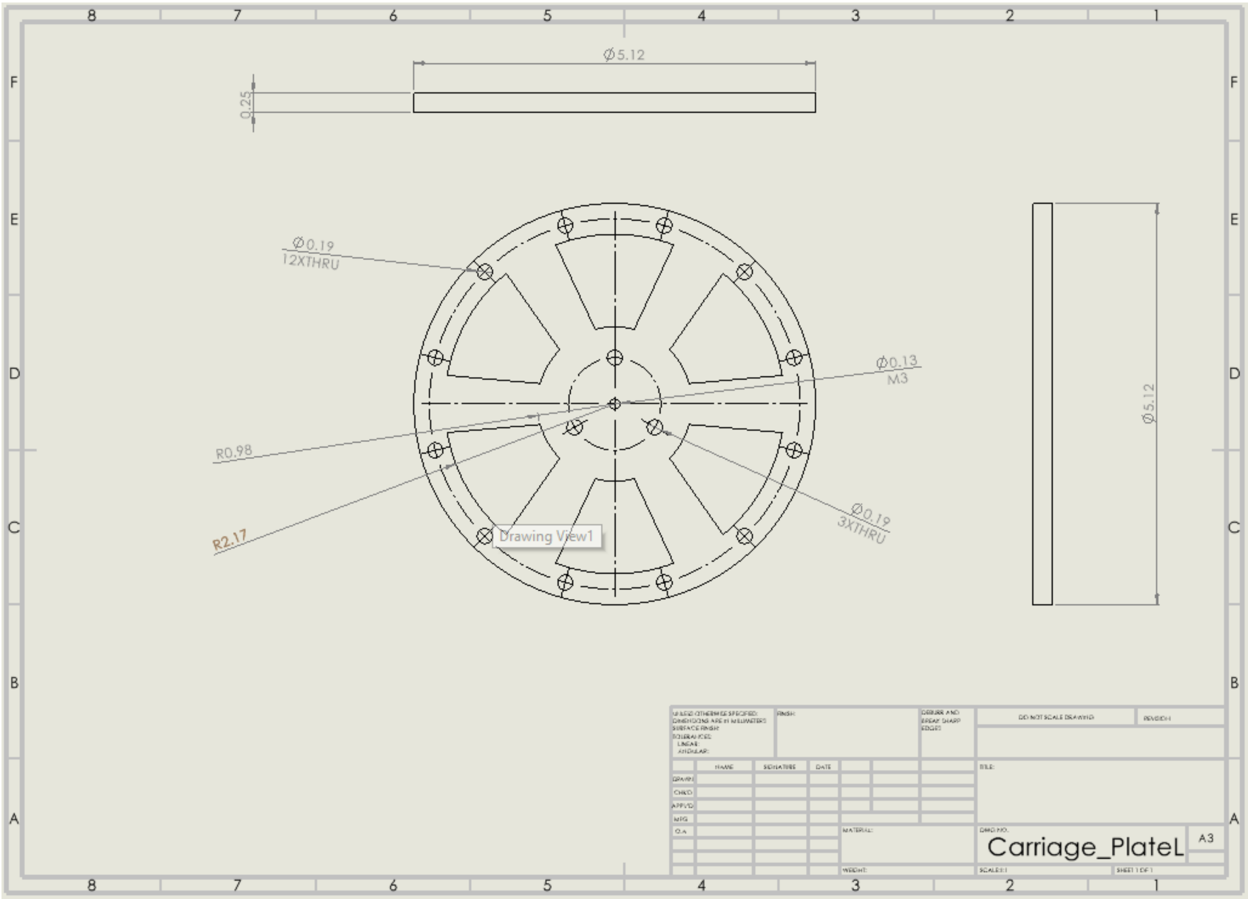
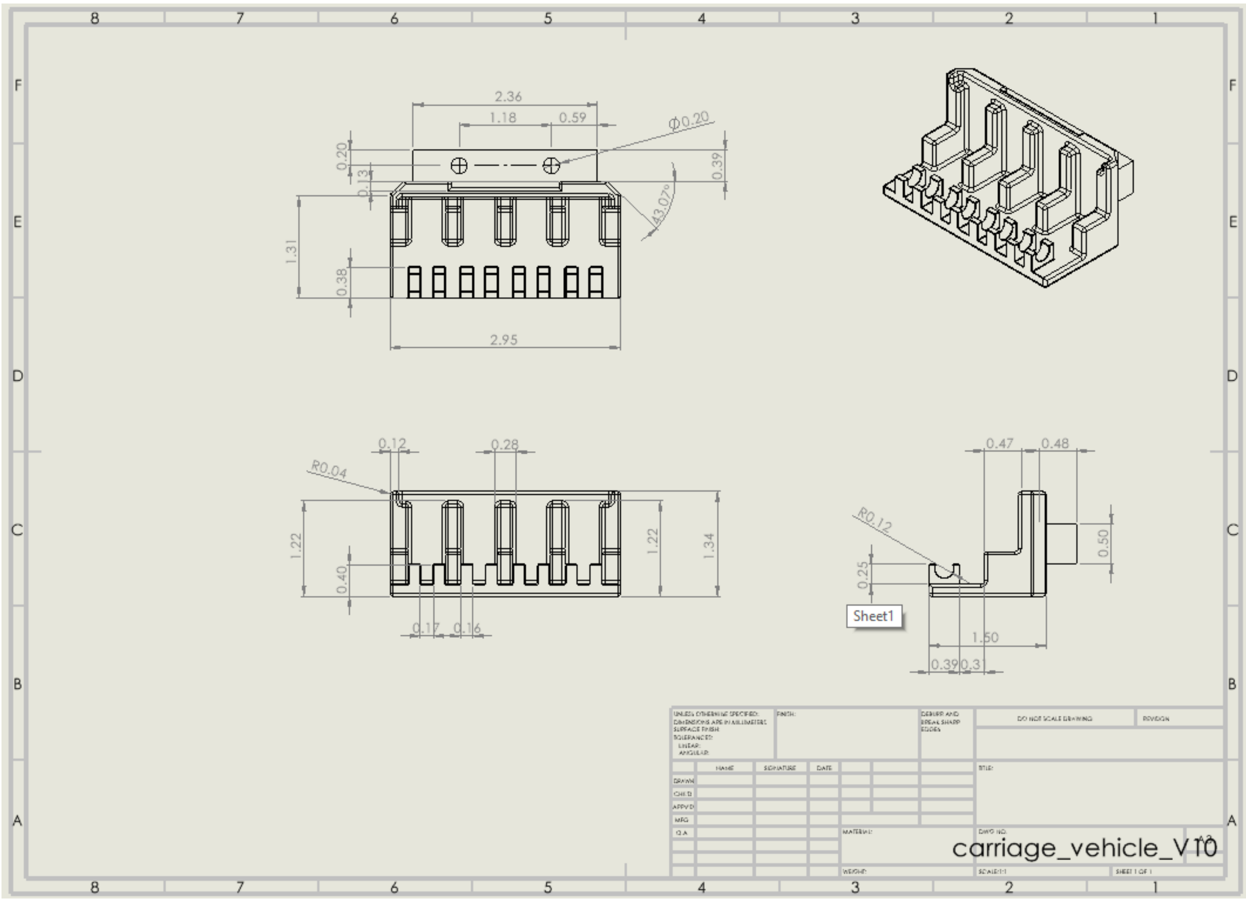
Ø0.25
5XTHRU
0.50
Ø1.08
Ø1.08
4.75
5.75
0.75
1.88
3.00
R0.50
0.25
ISU22_Gearbox_Plates


4.00
R0.50
R0.74
4.75
0.75
1.88
0.50
3.00
2.36
R0.50
5.75
0.25
ISU22_Gearbox_PlateM

Schematics for 1c Carriage, Rotational Motor, Seats




Ø5.12
0.25
Ø0.19
12XTHRU
Ø0.13
M3
R0.98
R2.17
Ø0.19
3XTHRU
Drawing View1
Ø5.12
Carriage_PlateL
A3


2.36
1.18
0.59
Ø0.20
0.20
0.13
0.39
43.07°
1.31
0.38
2.95
0.12
0.28
R0.04
1.22
0.40
1.22
1.34
0.17
0.16
0.47
0.48
R0.12
0.50
0.25
1.50
0.39
0.31
Sheet1
DO NOT SCALE DRAWING
carriage_vehicle_V10

Schematics for 1d Arm Connection and Attachments