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Development of an Educational Kinetic Sculpture for Worcester Polytechnic Institute

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Development of an Educational Kinetic Sculpture for Worcester Polytechnic Institute

A Major Qualifying Project
Submitted to the Faculty of
Worcester Polytechnic Institute
in partial fulfillment of the requirements for the
Degree in Bachelor of Science
in
Mechanical Engineering
By

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Date: 29 April 2015
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Professor John Sullivan

Abstract

The goal of this Major Qualifying Project was to design a rolling ball sculpture that incorporates the different areas of study at Worcester Polytechnic Institute and conveys them in an engaging manner to potential students. This project was split into three stages: research, design, and fabrication. The team completed research and analysis of existing rolling ball sculptures. After formulating a design, our team began to fabricate the machine. Manufacturing techniques included woodworking, MIG welding, Oxy-Acetylene brazing, manual machining, CNC machining, laser cutting, rapid prototyping, and mechanism assembly. Upon completion, our team evaluated the functionality of the individual components and the unit as a whole and compiled our research into the following report.

Acknowledgments

Professor John Sullivan	Thank you for being an active project advisor and helping lead to the success of our project.
Washburn Shops	Thank you Toby Bergstrom and Washburn Shops for allocating space to store our project and providing the equipment required for fabrication.
Mik Tan	Thank you for your assistance with machining the helix component and various elements of our project along the way.
Thomas Cotton	Thank you for your donation of the wood for our frame and the assistance with cutting these wood sections.
Jonathan Labrie	Thank you for your time and assistance with machining several parts for our project.
Dave Privitera (IDEO)	Thank you for serving as a project mentor early on in the process.

Executive Summary

The goal of this Major Qualifying Project (MQP) was to design a rolling ball sculpture that incorporates the different areas of educational study at Worcester Polytechnic Institute and conveys them in an engaging manner to potential students. This project was student driven and inspired by the kinetic sculpture displayed in the Discovery Channel Headquarters in Maryland. It was determined that WPI could benefit from having a similar apparatus that provided a tangible representation of coursework to prospective students. Our project team developed a sculpture that would allow us to practically apply our mechanical engineering knowledge and serve as a tool to highlight important aspects of WPI to prospective students.

The MQP was split into three stages: a research stage on state-of-the-art kinetic sculptures, a design stage that incorporated iconic elements of the researched art with our original ideas, and a fabrication stage. The team first completed research and analysis of existing rolling ball sculptures that can be found in museums and airports. Research indicated that ball, track, and lift selection, in addition to manufacturing techniques, were the key design elements. A design map was created to layout the paths and elements that would be included in the sculpture. It was determined that the sculpture would contain four primary paths to represent the main academic areas offered at WPI, engineering, science, business, and liberal arts. Each of these tracks would have two major elements to represent that discipline.

Each of the major elements was designed using principle engineering and physics relationships to fit within our design constraints. The elements were limited by the budget provided to our team ($600) and the size restrictions of a standard doorway to allow for easy transportation. The elements were designed using conservation of energy and momentum relationships based on ball size and available vertical height. Essential non-element design

components included motor gear ratios, track spacing, bracket design, and structural support analysis. A tablet was mounted to the sculpture frame to display what each element represents and the engineering design required for its fabrication. Information about WPI is also displayed on the tablet to educate potential students.

After formulating a full design based on these elements, our team began to fabricate the machine. Manufacturing techniques included woodworking, track bending, MIG welding, Oxy-Acetylene brazing, manual machining, CNC machining, laser cutting, rapid prototyping, and mechanism assembly. The sculpture was painted crimson and grey to represent the WPI school colors. Black and white marbles were used to enhance aesthetics.

Once the sculpture was completed, our team evaluated the functionality of the individual components and the unit as a whole. The sculpture has been displayed at open houses and has received positive feedback from potential students and their families. Multiple parties, including the Bartlett Center, the Rubin Campus Center, Higgins Labs, and The Washburn Shops, have expressed interest in housing the sculpture on a permanent basis. The selected department will likely provide funding for a professional display enclosure. It is our intention that our sculpture will be used amongst the interested parties on admissions tours to excite potential students about WPI.

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List of Terminology & Acronyms

Term	**Acronym**	**Definition**
Worcester Polytechnic Institute	WPI	University
Major Qualifying Project	MQP	WPI Senior Year Project
Rolling Ball Sculpture	-	A form of kinetic art that involves one or more rolling balls.
Manually Pre-Loaded	-	Ball must be set into place before the machine is started.
Automatically Pre-Loaded	-	Ball will be set into place as part of the track design.
Component	-	A part of the kinetic sculpture.
Element	-	A component of the kinetic sculpture with which the ball directly interacts.

Chapter 1: INTRODUCTION

Worcester Polytechnic Institute's (WPI) undergraduate program incorporates a number of opportunities for students to complete projects. In fact, students at WPI are required to complete a major specific project their senior year known as the Major Qualifying Project (MQP). For this project, students work with a faculty advisor to complete either a faculty interest based research project or a student designed and driven project. These ventures yield very exciting results and, in many cases, WPI displays the final products around campus. The MQP, in combination with other project work at WPI, is one of many reasons why students make the decision to enroll. This report will discuss the MQP that was developed by mechanical engineering students and was advised by Professor John Sullivan.

Our project team decided to develop a project that would not only allow us to practically apply our mechanical engineering knowledge, but would also serve as a tool to highlight important aspects of WPI to prospective students. We determined that this could best be captured with a rolling ball sculpture, a form of kinetic art. We planned to showcase the range of opportunities available to new students in our kinetic sculpture by dedicating a particular function of the sculpture to each major academic area of focus at WPI.

The main purpose of our kinetic sculpture is to attract potential students. In order to most effectively convey what WPI has to offer to prospective students we needed to assess what college-bound students find important when selecting a university to attend. Specifically, we were interested in distinguishing factors that may set one school apart from another.

As we were all once prospective students, we found ourselves asking "How is this practically applicable? How will I be able to use this knowledge in a future career?" We believe that potential students are attracted to tangible manifestations of their coursework. They want to see what they will be able to do, build, design, and accomplish through their studies at a particular school. Therefore, our project will excite these students because they will be able to visualize how the MQP experience offered at WPI will allow them to productively apply the knowledge they have gained throughout their academic career.

Our design and concept was formulated to help WPI attract potential students. Whether the sculpture is placed in the Bartlett Center, the Rubin Campus Center, Higgins Labs, Washburn Shops, or, when finished, the renovated Alumni Gym, it must be easily accessible to tour groups and demonstrate how typical lecture knowledge can be taken and applied to both exciting and practical designs. Currently, WPI occasionally displays MQP projects in the admissions building. However, these projects are not specifically designed for the purpose of educating and fascinating tour groups. This is what makes our project superior to displaying another project that was created to fulfill some other need. Our sculpture provides a physical illustration of some of what the university has to offer while embodying the essential project experience that is so emphasized by WPI.

Chapter 2: BACKGROUND RESEARCH

This chapter outlines the prior art our team researched to gain an understanding of the functional requirements for a kinetic sculpture.

2.1 Discovery Channel Communication Kinetic Sculpture

The inspiration for our project came from viewing a rolling ball machine that was in the lobby of the Discovery Channel Communications building located in Silver Spring, Maryland. This machine was built on top of a stand approximately two feet raised above the ground as shown in Figure 1.

Figure 1: Discovery Channel Communication Ball Machine

This design has many notable features:

- Vertical Center Elevator Tower (Archimedes’ Screw)
- Multiple Paths
- Informational Display Screens
- Platform Base
- Display Railing
- 360 Degree Visibility

2.2 Kinetic Sculptures by George Rhoads

George Rhoads is well known for his rolling ball sculptures that attract and engage people throughout the world (“Ball Machine Sculptures”). Rhoads' ball sculptures are designed for airports, hospitals, art museums, science museums, shopping centers and other public places. Rhoads also makes private sculptures for homes and office spaces. The main goal of Rhoads' machines is to engage people in their operation, so he restricts himself to mechanisms that are easily understood. A sample of one of Rhoads' rolling ball sculptures are shown below in Figure 2.

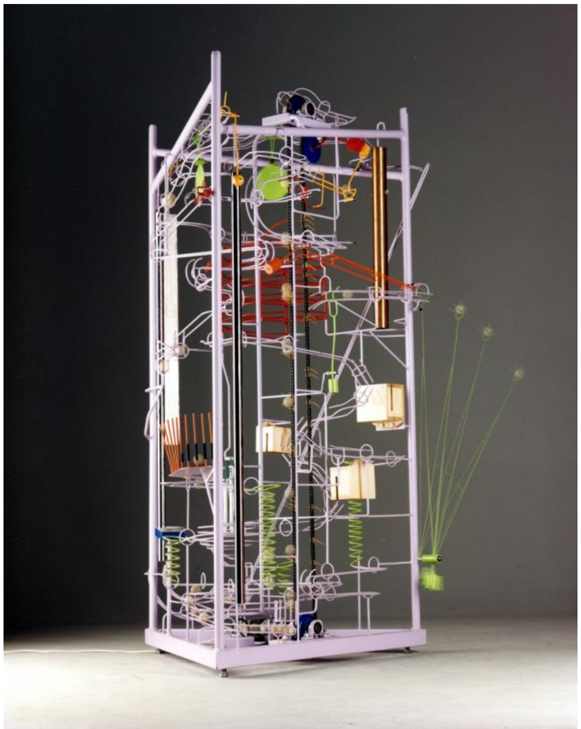


Figure 2: An Example of a Rhoads' Ball Sculpture

2.2.1 Logan Airport

George Rhoads is the main contributing designer for the rolling ball sculpture (Figure 3) found in the Logan Airport, Boston, Massachusetts.

Figure 3: Rolling Ball Sculpture in Logan Airport

One reviewer of this machine described that the machine was operating without error the first time he saw the machine in May 2010; however, when he returned in September 2010, the machine was not operating properly with most of the balls jammed on the ramp leading to the vertical lift ("Goldberg Variations"). This design review highlights that these types of machines have a certain level of reliability and this is an important design consideration. Even professional rolling ball sculptures are not free of errors. When designing a rolling ball machine, the structure must be simple enough to plan for error to enable continuous operation.

Another notable design choice for the kinetic sculpture in Logan Airport is the outer display frame. Adding protective glass to the outside of the structure is important as a safety boundary, as well as preventing the viewer from damaging the structure or littering inside of the sculpture.

2.2.2 ColorCoaster – Stepping Stones Museum

Another kinetic sculpture designed by Rhoads our team researched was the ColorCoaster found in the Stepping Stones Museum, in Norwalk, CT. This machine is 27 feet tall and the only permanent exhibit in the museum shown in Figure 4.

Figure 4: ColorCoaster Located in the Stepping Stones Museum

This kinetic sculpture operates continuously and uses energy, motion, gravity, color, and light to fascinate the guests of the museum. Once again there is a display case, creating a boundary between the sculpture and the spectator.

2.2.3 Archimedean Excogitation – Boston Science Museum

The Archimedean Excogitation machine designed by Rhoads is located in the Boston Science Museum (Figure 5). This sculpture has overall dimensions of 25' x 10' x 10'.

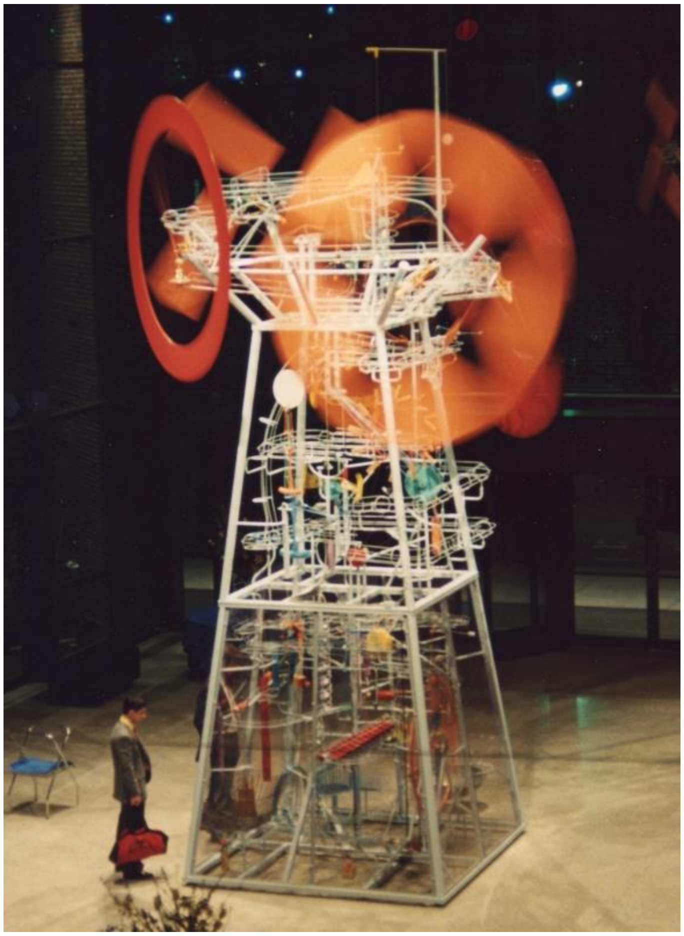


Figure 5: Archimedean Excogitation Located in the Boston Science Museum

For this machine, the balls move down nine different tracks simultaneously while bumping against various devices and musical instruments. Larry Bell, the associate director of the museum, is quoted saying “we have found that people watch 'Archimedean Excogitation' for much longer times than they watch exhibits containing similar mechanical devices - gears, levers, pulleys, and the like - that are displayed elsewhere in the museum in a more didactic fashion” (Ball Machine Sculptures”). Rolling ball sculptures are great educational tools because they gain the attention of their observer.

2.3 Franklin Institute Golf Ball Machine

The kinetic sculpture at the Franklin Institute was designed to illustrate properties of physics while also being an entertaining centerpiece for the science exhibit (Figure 6). Since it is intended to attract the attention of younger children, it contains many elements capable of making noise. In the figure below, note blocks, a cymbal, a bell, and a chime were incorporated into the design. Additionally, there is a yellow ball arm in the foreground, a mixing bowl, and a loop, among other interesting features. Another notable aspect of this rolling ball machine is its lift. The lift is air-powered, and functions by blowing air through a tube with a diameter close to the diameter of the ball. Upon entering the tube, pressure builds up behind the ball and launches it to the top of the machine, where a large basket-like structure is required to contain the ricocheting ball. This kinetic sculpture remains a highlight of the museum, since the late 1990s.

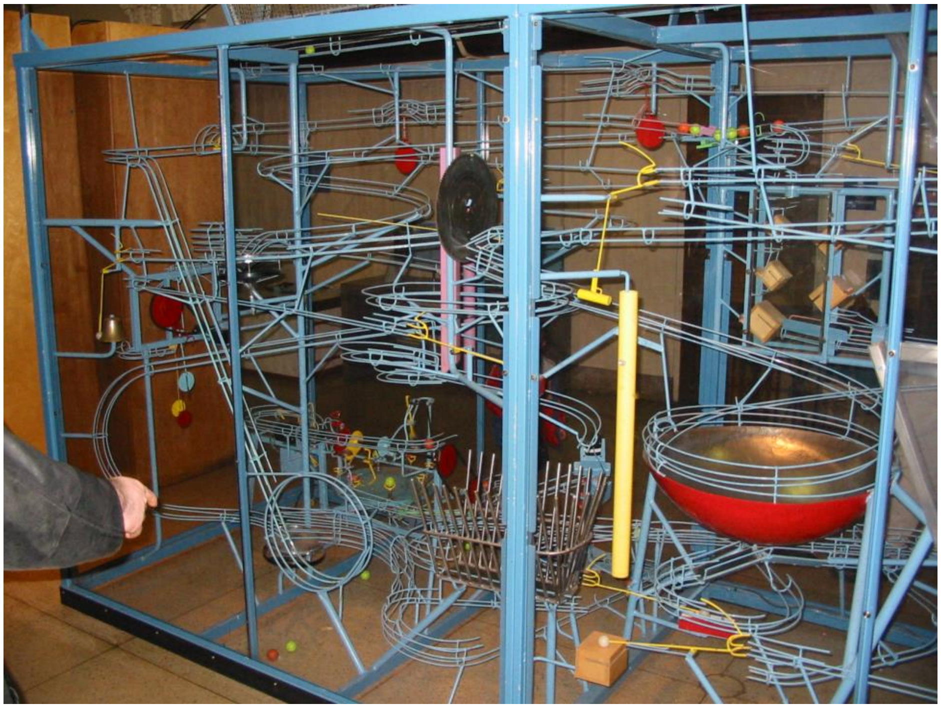


Figure 6: Franklin Institute Rolling Ball Machine

Chapter 3: PROJECT STRATEGY

This chapter details our goal statement, project objectives, and outlines the methodology our team followed to achieve our goal. The methodology includes information about how our team formed and bent track into the various shapes we required.

3.1 Goal Statement

The goal of this project was to design an educational, continuous Rube Goldberg apparatus, known as a rolling ball sculpture, which incorporated the various areas of study at WPI and conveyed them in an engaging manner to potential students.

3.2 Objectives

Our kinetic sculpture needed to be more than just eye-catching. The sculpture also needed to include information relevant to students considering WPI for their undergraduate education, and it needed to be designed to be nearly maintenance-free. The following section describes each of the objectives we needed to accomplish to achieve the goals set in our goal statement.

Above all else, we needed to design a kinetic sculpture that works with minimal failures. The entire structure needed to be free of frequent errors and be able to operate un-attended. Failures that we needed to avoid included requiring balls to be picked up and placed on the track, balls collecting on a track blocking ball flow, and the lift catching on track pieces nearby, causing damage to the motor, gearbox, and chain. We did not want our structure to fall into disrepair soon after its inauguration. It was also required that the sculpture fit into its designated locations. The Bartlett center’s display space is the most restrictive, allowing a 4’ by 5’ base. However, we also wanted it to fit through a standard doorway upright, so the sculpture’s dimensions were solidified at 5’ width, 2.5’ length, and 6’ height.

Although reliability is important, we could not go overboard with consistency to the point of making an uninteresting sculpture. The paths needed to contain a variety of bells and whistles that could keep a viewer entertained for five to ten minutes, an average amount of time someone would be waiting in the Bartlett Center for a tour to start.

We also wanted our kinetic sculpture to be related to the WPI experience. As such, different aspects of the machine showcase different aspects of WPI. The paths that the balls can take are linked to departments within WPI's educational structure, while the entire structure represents the project-based learning that is emphasized here.

The final goal for our kinetic sculpture was that its completion requires the skills we have learned at WPI. The structure required numerous calculations, from gearbox analyses to ideal track spacing to loop-d-loop force balances. Our project used the soft skills acquired during our time at WPI including: time management, planning and teamwork. Moreover, the sculpture construction continued to teach us the practice of designing for real world scenarios, where plans must be changed because ideal calculations do not always translate perfectly off the page.

By ensuring that our project met all of these objectives, it has the maximum positive impact on both WPI and us. These goals were in the back of our minds throughout the conception and construction of our kinetic sculpture.

3.3 Project Approach

The goal of this project was to design and fabricate an educational rolling ball sculpture that incorporated the various areas of study at WPI and conveyed them in an engaging manner to potential students. This section outlines the methods our team used as we worked towards our project goal. These methods are shown in Figure 7.

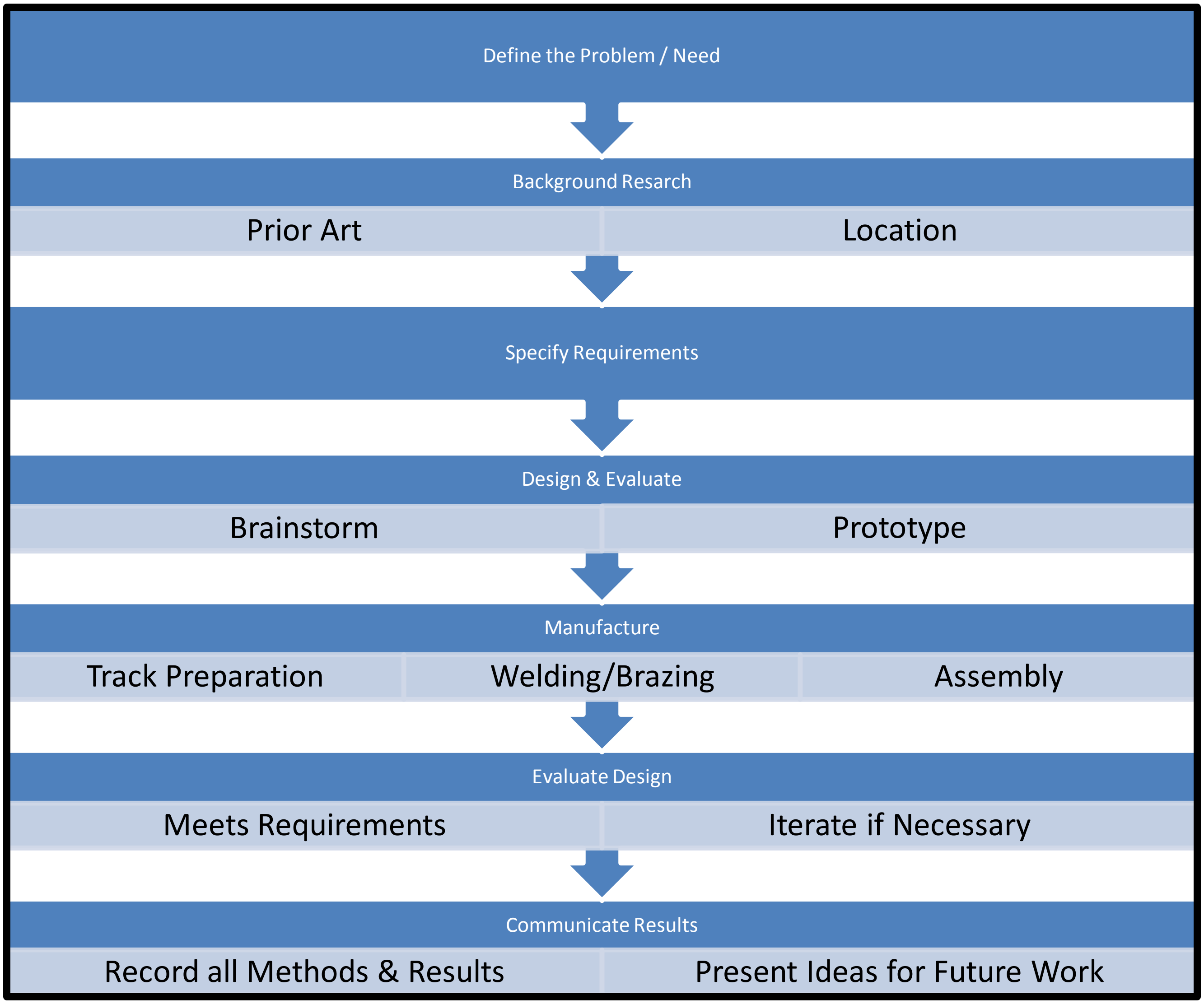


Figure 7: Methodology Breakdown

3.4 Design Environment & Space Constraints

This section outlines the number of locations our team considered for displaying our kinetic sculpture. The space constraints per each location are described and the advantages and disadvantages are discussed.

3.4.1 Option I: Mobile Teaching Tool

The goal of our project was to design an educational rolling ball sculpture that could be used to engage potential students about what WPI has to offer. Since our design included a number of elements critical to the discipline of engineering, the sculpture also serves as an educational tool for various engineering principles. Therefore, our machine may also be used as a teaching tool. Hence, our team designed our sculpture so it could accommodate a number of locations. The width dimension of our machine was designed to be 2.5’ so it would fit through a standard single doorframe. This passage dimension was critical to satisfy our portability requirement. Our machine was constrained to require an AC 120V power source to operate the motor.

3.4.2 Option II: Bartlett Center

Even though our machine was designed to be a mobile unit, the original vision was to have it stored and operated in one location. The first location considered for the final kinetic sculpture was WPI’s admissions building, the Bartlett Center. When prospective students come to tour WPI, this is often the first location they visit in order to collect resource information. This location is advantageous because campus tours generally start from this building. Therefore, one of the project requirements was to educate the prospective students and their families as they wait for a tour.

The Bartlett Center is designed to present visitors numerous resources. When entering the building, there are two alcoves on either side of the entrance as shown in Figure 8. These alcoves were identified as potential locations to display our project.

Figure 8: WPI's Bartlett Center with Potential Project Locations Identified

The ideal location for our final product would be on the alcove to the left when entering the building. This space has allowable dimensions of five feet wide by four feet deep. This area also has a height limit of fitting the machine through a standard door. This location is also advantageous because it allows for viewing from all four angles since the back side would be placed against a glass window.

3.4.3 Option III: Rubin Campus Center

The second permanent housing option for the sculpture was WPI's Rubin Campus Center. This building is always included on open house tours; it is also the location of many department presentations for open houses and accepted student days. The Campus Center is frequented by students and is a common location for events held throughout the year at WPI. This would provide our sculpture with plenty of exposure to our target audience.

Staff members of the Campus Center expressed an interest in housing the sculpture in the lobby by the information kiosk, outside the odeums, or on the stage in the dining area. The Campus Center building can be seen in Figure 9.

Figure 9: WPI's Rubin Campus Center

3.4.4 Option IV: Higgins Laboratory

Another potential space of our final product was in Higgins Laboratory in the lobby near the glass entrance (Figure 10). In this space, there is room under the staircase that could be used to display our rolling ball machine. The same design size as discussed above would be suitable for this space.

Figure 10: Higgins Laboratories Glass Entrance

The major advantage of this location is that the building is the designated mechanical engineering building. Therefore, our project would be a great representation of the mechanical engineering education offered by WPI and pay tribute to this program. This location is also a frequent stop on tours, still satisfying the design goal of educating potential students.

One major disadvantage of this location was that it is under a stairwell and a crammed space. The viewing space would be limited to two sides since the other two would be placed against a staircase and a wall.

Our team met with Patricia Howe, the operations manager in the mechanical engineering department office, to discuss using this location to display our project. Ms. Howe welcomed this idea and would consider this as a permanent home for our sculpture. This location could be used a final location if we decided to first display the machine in the Bartlett Center.

3.4.5 Option V: The Washburn Shops

The Washburn Shops is one of the oldest and most historically significant parts of WPI. These shops started with woodworking and manual machines and have evolved over the years to include the latest CNC machines and additive manufacturing technology. Our kinetic sculpture was designed to represent various types of manufacturing and fabrication techniques that engineers use and that are offered at WPI.

The shop managers have expressed an interest in displaying the sculpture in the shop to illustrate the various manufacturing techniques they offer. The Washburn Shops is a frequent stop on WPI tours and would provide a suitable home to display the completed project. The building can be seen in Figure 11.

Figure 11: The Washburn Shops Building at WPI

3.4.6 Option VI: Repurposed Alumni Gym

A final location our team considered for displaying our rolling ball machine was the proposed lobby of the repurposed Alumni Gym (Figure 12). Currently, there are plans to transform this building into a collaborative project workshop space.

Figure 12: Alumni Gym at WPI

This space would be used by students when completing projects such as Great Problems Seminars, Interactive Qualifying Project, and Major Qualifying Projects. Therefore, this would be anticipated as a focal point of tours showing students the critical project work of a WPI education. Moreover, this would be a great place for the final sculpture to show potential students directly what path a MQP could take.

Since the repurposing plans of Alumni Gym had not been finalized, the space constraints for our final machine were undefined. However, the height constraint would still be limited by the height of a typical door space. Furthermore, it could be expected that the final product would be of similar width and depth as described for the previous two options.

Chapter 4: DESIGN & FABRICATION

This chapter outlines the sculpture elements that our team had to design and select in order to develop and fabricate our kinetic sculpture. Next, this chapter discusses the operational elements our team decided to include in our design and their significance. Lastly, this section provides operational characteristics of the sculpture.

4.1 Sculpture Elements

The following sections cover the selection and design of the parts of our kinetic sculpture that were required for its operation. These included the track, the lift and its drivetrain, the balls, and the frame. While these elements did have an aesthetic component, they were the core of our machine and needed to be carefully selected to ensure maximum reliability of our sculpture.

4.1.1 Frame / Machine Footprint

When designing the rolling ball sculpture, it was important to have a big picture vision and understand the space, which would house the final machine. Our team's primary vision for the resting place of our machine was the WPI Bartlett Center. Prospective students and their families often visit this building first when coming to campus for tours and it would be a great place for our machine to education them about what WPI has to offer.

Our team visited the staff of this Bartlett Center and was told our machine could rest in one of the two alcoves in the building. This alcove has a glass window on one of the 4 sides. When measuring this space our team concluded that the space allowed for a design that had outer dimensions of 5 feet wide by 4 feet deep and a height restriction of what could fit through a doorway. One drawback of this location was that our project could only be displayed in this location for 3-4 months.

After further design discussion, our team decided that our machine should be able to be transported to different locations in case it was used for lectures as an instructive aid. Therefore our design needed to allow for easy transport and the assumption that it would need to be able to pass through a single door. The standard door has a width of 3 feet. Thus our team selected the final outer dimensions of our machine to be 5’ wide by 2’ 6” deep. Our sculpture has an operational height of 6’ and can be placed on a 1-foot high pedestal to allow for better visitation.

Based on the fixed dimensions, our team needed to determine how to house the track of our machine. Our team decided our machine should have an outer structure that could be used for mounting as well as enclosing the machine. This outer frame needed to have some form of a glass barrier to keep the audience separated from the moving components and protect the user from projectiles if the marbles were to fall off the track. Additionally it would prevent the user from reaching into the machine and getting injured, discourage vandalism and theft, and protect children from picking up and swallowing the balls. Other possible solutions are to extend wood railings off the outer frame or use a rope to keep the audience 2’ away from the machine at all times.

The materials our team considered for this outer frame were steel, copper, and wood. The copper frame would be easy to solder, however it is expensive when compared to the other two options. A steel frame is common practice among Rolling Ball Sculpture. A steel frame would be advantageous because the track could be welded straight to the outer structure for additional support. However, our team decided a steel frame would need to be done with extreme care to present professional quality. Therefore, our team decided to go with a wooden frame.

The preliminary design for our wood frame is shown in Figure 13. This includes the top portion where the sculpture would be created and a lower pedestal the sculpture sits in for display.

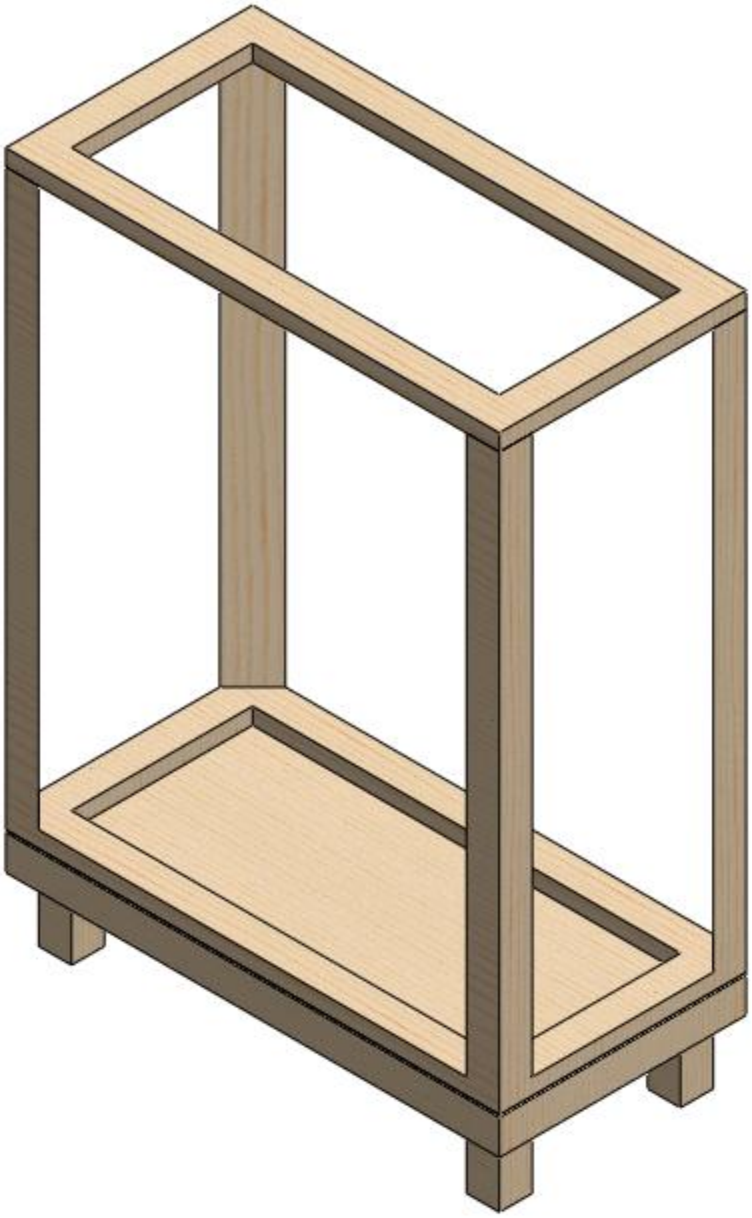


Figure 13: Wood Exterior Frame

Our team first assembled the bottom pedestal shown below in Figure 14 and Figure 15. Figure 14 shows just the pedestal that the main structure rests on. Figure 15 includes the bottom of the detachable main frame, held in place on the pedestal by four blocks on the underside of the plywood, so it can be easily removed (not shown).

Figure 14: Wood Frame Base

Figure 15: Wood Frame Base with Top Floor Board

Following the construction of the base, the vertical supports and top of the frame were added (Figure 16), yielding a finished frame almost identical to preliminary design shown in Figure 13.

Figure 16: Finished Frame Structure

Once the basic frame was completed, we added handles and casters to make sure our kinetic sculpture would be easily transported. The handles and casters can be seen in the following two figures (Figure 17 and Figure 18).

Figure 17: Frame Handles

Figure 18: Frame Casters

The frame was then painted (Figure 19). We decided to use gray for the color of the frame, since WPI's colors are crimson and gray, and of those two colors, gray is more subtle for the exterior frame. As such, attention will not be drawn away from the core elements of the kinetic sculpture. (Note: handles were removed for painting of the wood frame).

Figure 19: Painted Frame

Finally, we needed an internal support structure to mount track. The original design developed included five vertical half-inch steel rods extending from the base of the structure. It was planned that these rods we be located near the four corners and the center of the structure. However, we realized that this would be somewhat unstable, since the rods would have no horizontal support, and potentially unsightly.

Our final solution for supports was a pyramid-like structure out of four half-inch steel rods, extending from every corner of the frame to a middle point, where they are welded together. To accomplish this, we decided the best way of attaching the rods to the wooden frame was to screw on plates of metal to all the lower corners of the frame and then weld the half-inch rods to these plates. The plates can be seen in Figure 20 below:

Figure 20: Corner Welding Plates

Six-foot lengths of rod were then welded to each of the corners, and then welded to each other at the top. This yielded a strong structure of a 5’6” stature that was also appealing to look at. The completed frame can be seen in Figure 21.

Figure 21: Completed Frame

4.1.2 Track

Track is the most basic element in a kinetic sculpture. It must function as a way to get balls from place to place, but also be pleasing to the eye, as it will be very abundantly used. As such, we carefully considered all our track options to ensure that our project is entertaining to watch, but also reasonable to build.

4.1.2.1 Track Types

There are many types of track that are conventionally used in kinetic sculptures. Each has distinct advantages and disadvantages. The three basic designs of track are outlined in the following sections.

Two Rail

Two rail paths consist of two parallel rails with braces to maintain the correct spacing at regular intervals. This is the most commonly used style of track because it uses the least material and allows for higher speeds than many others. This is the style is the primary style of track used in all of the examples except Archimedean Excogitation in the Boston Science Museum. The two-rail path does not have any sliding on the main rails, which reduces wear. Construction is generally a thin aluminum or steel rail, 1/8” to ¼” thick, and the braces are welded in. However, if a sharp curve without banked rails is made, it is possible for the ball to fly off track due to centrifugal forces. As such, a guardrail is frequently added to the outside of high-speed unbanked curves.

Three Rail

Three-rail tracks are made of one center rail, and two higher rails designed to hold balls in place on the center rail. There are also bracers to maintain spacing, generally closer together than two-rail paths. It is used sparingly in many of the examples, usually on low-speed sections near the lift. This type of track is very consistent; it is very hard for the ball to fall off the track. However, this path design has a lot of significant drawbacks. It uses about 50 percent more material than two-rail tracks to accomplish the same thing. It cannot maintain high speeds, since friction against the side rails quickly scrubs off speed. The same effect causes wear on the two outer rails. It also is not as appealing to look at as two rail path.

Pipe

Pipe can be used as path as well, as long as the diameter of the pipe is larger than the diameter of the ball. There are two main variants of pipe: Transparent and opaque. Both types offer the benefit of completely eliminating the possibility of a ball falling off the track. However, this is not always a good thing. A ball that would have fallen off track will likely be subject to more friction than balls that would not have, since they would roll back and forth excessively within the pipe. The balls may get stuck and cause jams resulting in an inoperable track.

Opaque pipes are easy to come by, and hide the location of the ball. While this can be a cool effect when used sparingly, a kinetic sculpture made entirely of opaque pipe might as well not be a kinetic sculpture at all.

Transparent pipes allow viewers to see the ball as it passes through. They can either be pipe made out of transparent material, such as plastic, or be a pipe shape made out of 4 or more rails, bound together by O-shaped spacers. Archimedean Excogitation in the Boston Science Museum uses primarily the 4-rail pipe path, especially at the top, where balls could otherwise be at risk for falling on spectators. Many of the other towers use different versions of pipe-style track in places, but use two-rail as their primary.

Due to ease of construction, aesthetics, and conservation of materials, we elected to use two-rail pathways as the primary type of path for our machine. Of course, some sections of track required guard-rails, particularly on curves.

4.1.2.2 Material

Most kinetic sculptures use track made from 1/8” steel. There are spacers at regular intervals that are welded in, and supports welded to the track where needed. Sculptures that use balls that are significantly heavier than pool cues may use rod thicker than 1/8”, but this is not relevant to our sculpture, as we are using 1” marbles. The few creators of kinetic sculptures that included information on how they constructed track said that they hand-bent the track into its final shape.

MSC Direct, one of our preferred vendors, sells 6’ lengths of 1/8” steel rods. MSC also carries 1/8” aluminum rods in six foot lengths. However, the aluminum rods would not hold their bent shape as well as steel rods would, and therefore would require more support. Aluminum is more difficult to weld than the steel. Therefore, we selected to use 1/8” steel rods for the construction of our sculpture.

4.1.2.3 Track Spacing

The spacing between the two rails of the track is an optimization between the security of the ball on the track and ball spin relative to its linear velocity. For example, if a ball is rolling on a table, the ratio of translational velocity to the tangential velocity of the bottom of the ball is 1. However, if the point that the ball is rolling on changes to two points, a certain angle θ from perpendicular, the ratio changes. A θ of 15 degrees yields a translational velocity to tangential velocity ratio of sin(90°-15°) = .966. While this is very close to 1, the ball will also fall off the track very easily; the ball would only need a centripetal acceleration of g*sin(15°) = 2.54 m/s^2 to fall off the track. For reference, a ball moving at 0.75 m/s would fall off a curve with a radius of 20 cm, a fairly loose corner for this size kinetic sculpture. On the other end, a θ of 60° will yield a ratio of 0.5. While the ball would require a curve with a 6.6 cm radius to fall off, a ratio of .5 means the ball will have much more rotational kinetic energy than translational, which makes high-velocity elements such as loops require more vertical drop leading into them.

Another factor that can influence track spacing is ease of construction. Since the marbles we chose are small relative to the thickness of the steel rod, it is possible to pick a spacing that allows the spacers to be straight pieces of metal mounted on the bottom of the rails while still not disrupting the ball as it rolls over the spacer. This would save us a lot of work bending metal for spacers if the spacing was a realistic number. The calculation for the minimum spacing that would achieve this is shown below:

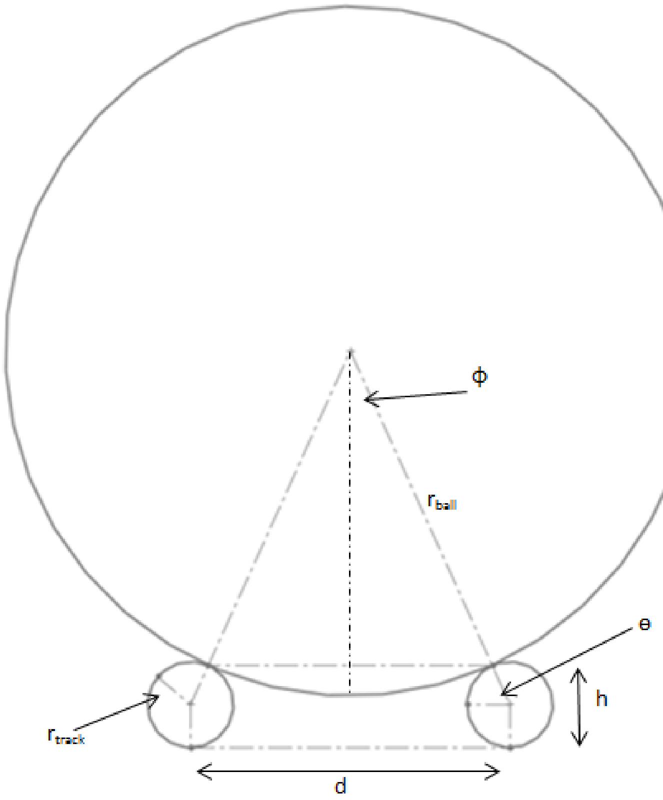


Figure 22: Calculation for the Track Spacing Based on Ball Size

From Figure 22, the following equations can be written:

$$\theta = 90 - \varphi$$

$$h = r_t + r_t \sin\theta$$

$$h = r_b - r_b \cos\varphi$$

$$d = 2r_b \sin\varphi$$

Using the first three equations:

$$r_t + r_t \sin(90 - \varphi) = r_b - r_b \cos\varphi$$

Plugging in the values $r_t = 0.0625$” and $r_b = 0.5$”, then solving for φ yields: $\varphi = 41.07°$

Plugging this into the equation for d yields $d = 0.657$”.

Velocity to tangential velocity ratio for 41.07° = sin(90° - 41.07°) = .754

Curve radius required for ball to leave track at 0.75 m/s:

$$\frac{v^2}{r} = a_{cent.}$$

$$\frac{0.75^2}{r} = gsin(41.07°)$$

$$r = \frac{0.5625}{9.8sin(41.07°)} = 0.0874\,m = 8.74\,cm$$

As indicated, the angle between vertical and the track on the ball could be no larger than 41.07°. This equates to a center-to-center distance between the tracks of .657”. To allow a reasonable tolerance when working, we used a center-to-center distance of just over half an inch. This ensures that marbles slightly smaller than spec will still be able to roll on the track uninterrupted. Additionally, the 41.07° angle yields a good balance between security on the track and translational velocity to tangential velocity ratio.

4.1.2.4 Spacers and Track Splicing

The primary method of joining our track was brazing. The spacers, designed to keep the track a uniform distance apart, were made of the same rod as the track, brazed underneath the rails. They measure about ¾” to give us a little room to weld, while not being so bulky that they are distracting to the eye. Similarly, the 6’ lengths of track (governed by supplier rod length) were welded at the ends, and the surface where the ball rolls were sanded down until smooth as needed.

4.1.2.5 Track Bending & Forming

This section details the methods our team used to bend and form the track of the kinetic sculpture.

Track Spacing Jigs

In order to properly maintain the track spacing during bending and welding of sections, a slotted clamping system was fabricated to hold and bend the track. Our team designed and machined two of these mechanisms as shown in Figure 23.

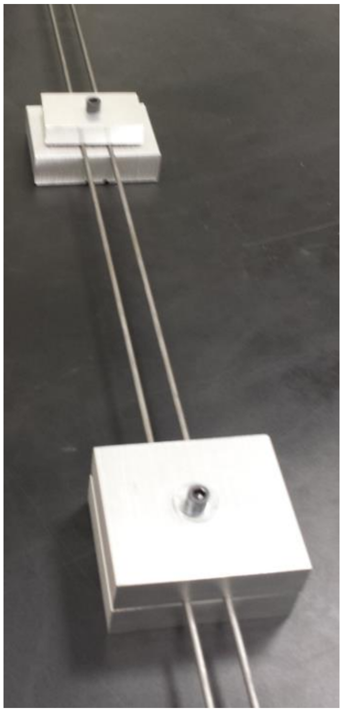


Figure 23: Two Types of Jigs Used for Track Spacing

The first jig our team made, shown on the top in the above figure, is one that clamps the track in place and serves as a fixed end. The detailed view of this "fixed end jig" is shown below in Figure 24.

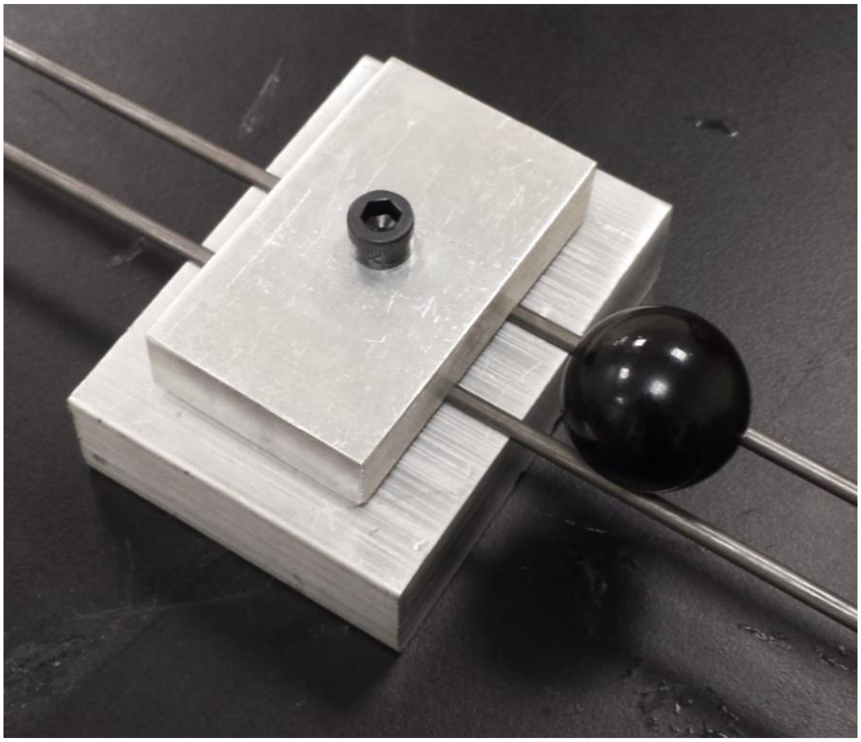


Figure 24: Fixed End Jig

The solid bottom block of aluminum has two 1/8” semicircles machined out of the top surface spaced 0.65” inches apart. A clearance hole is passed straight through both the top and bottom block. The bottom block is also threaded so the bolt that passed through can be secured. The track is placed between both blocks and then the bolt is tightened to apply force to the track and clamp it in place.

The second component of this system, shown on the bottom of Figure 23, was labeled the “sliding jig.” A detailed view of this slider is shown in Figure 25.

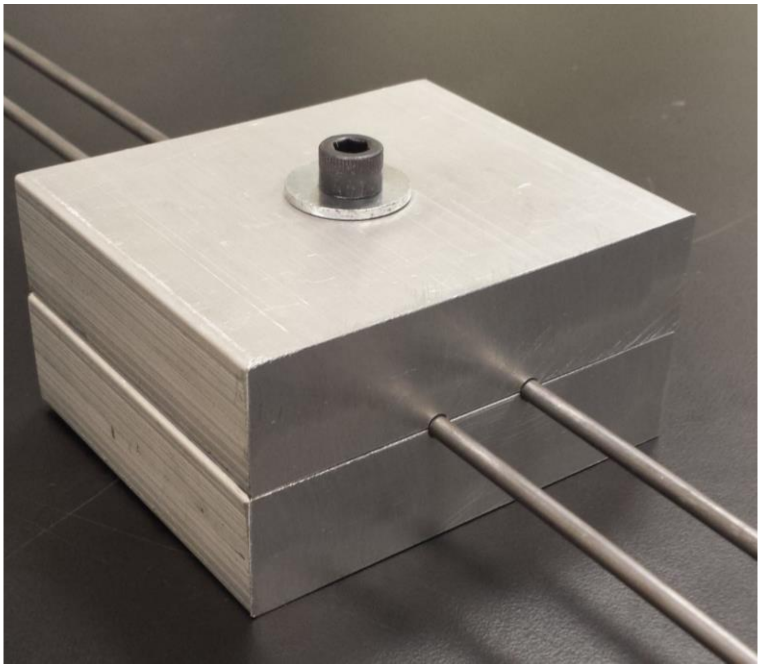


Figure 25: Sliding Jig

This jig is similar to the fixed end jig, but features the 1/8" track machined out of both the top and bottom block of aluminum with the same spacing of 0.65". This allows the track to fit in-between the blocks while retaining proper spacing. However, the track remains unclamped so the blocks can slide along the track. The bottom block of this jig was threaded so the bolt could lock in. This jig was used to bend the track while keeping the spacing uniform. Additionally, if we needed a second fixed end during track creation, we could flip the top block around so it could operate just like a copy of the first jig.

Figure 26 shows the fixed end jig being used to hold the track spacing while brazing the spacers on. Figure 27 shows a section of track being bent around the pipe.

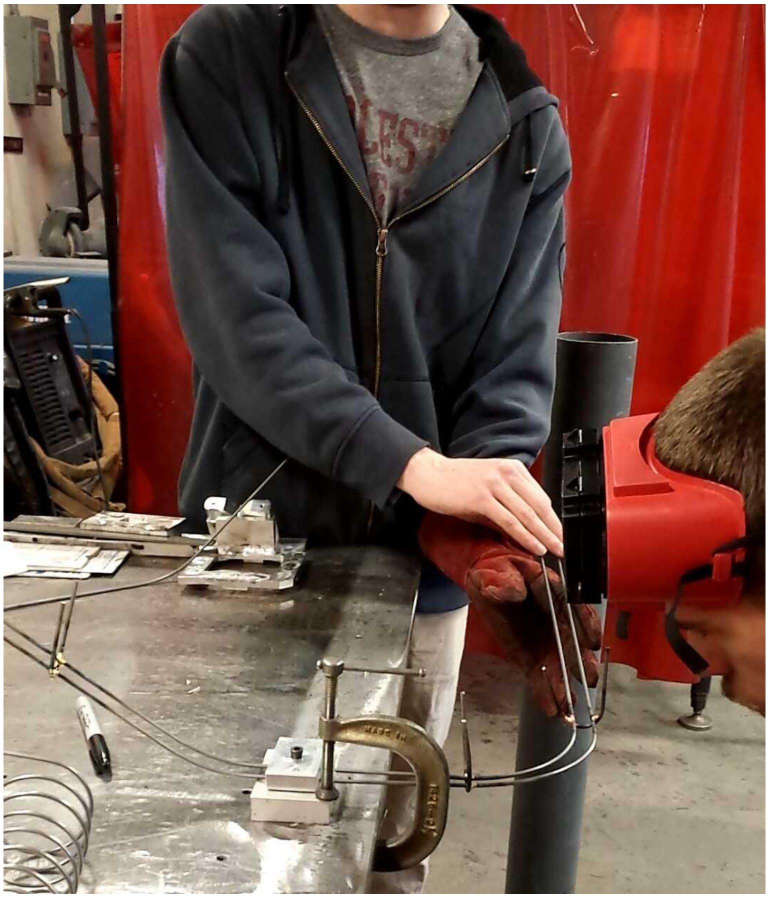


Figure 26: Track Being Bent into Desired Form

Figure 27: Track Being Bent with a Desired Radius

4.1.2.6 Welding Vs. Brazing

There are multiple ways the track can be connected together. The two main ways for doing this are brazing and welding. Brazing is a process of heating a filler rod above its melting temperature and allowing the filler to connect the two parts that are being connected. Brazing is very similar to soldering in electronic components but is at a higher temperature. An oxy-acetylene torch is the common method for heating the filler rod, which is usually brass.

Welding is a process of heating the metal to the melting point, adding a filler material and then let the pool of molten metal cool. There are two types of welding that are relevant to connecting the track and support structure; these technics include TIG (tungsten, inert gas) and MIG (metal, inert gas). TIG uses a tungsten electrode to weld and the operator manually adds in the filler rod. MIG uses a metal electrode that is automatically fed. The metal electrode is also the filler material.

Both welding and brazing have their advantages and disadvantages. Welding is great at making an extremely strong joint, sometimes stronger than the original metal. While brazing the materials does not fuse them together, they are just connected to the filler material. However, since brazing does not heat the metal up as much, the metal is less likely to distort or deform when working with smaller parts. Also, brazing leaves a smoother join over the non-uniform beads of welding.

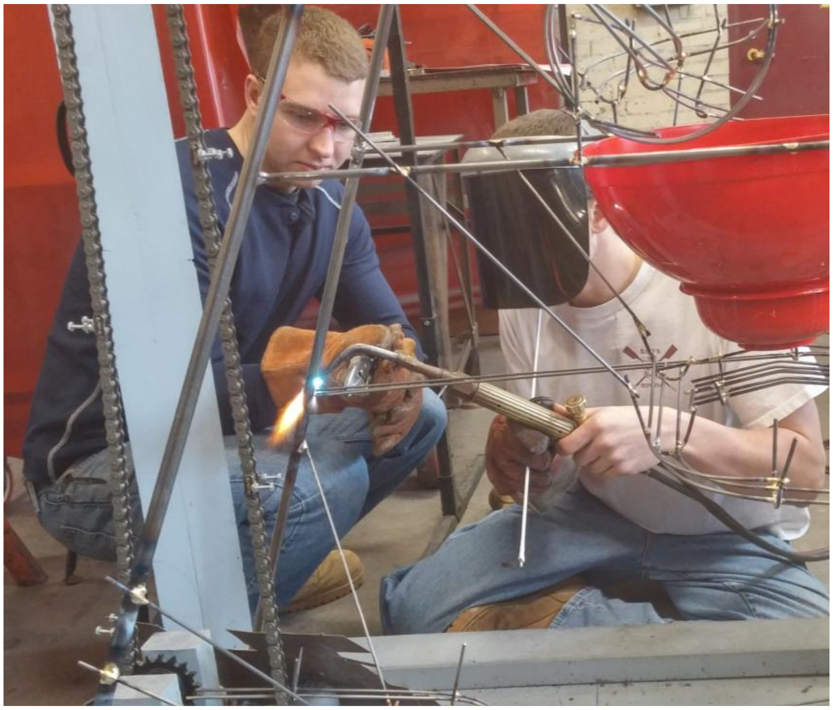


Figure 28: Team Brazing a Section of Track

4.1.3 Rolling Element

One of the most critical elements to the design of a successful rolling ball sculpture is fundamentally the ball. When selecting the ball, it is important to evaluate the following design characteristics:

- Material
- Elasticity
- Outer Diameter
- Aesthetics
- Uniformity
- Weight

Our design team began our search by looking at the available materials for the ball. When examining the available options, the most critical design characteristics that were considered were uniformity, durability, and hardness. From our research, we found that other rolling ball sculpture designers have used steel, acrylic, glass, and wood balls.

Table 1 presents the options for the balls our team considered with comments on the advantages and disadvantages of using each option.

Table 1: Ball Selection Options: Advantages and Disadvantages

Type	**Advantages**	**Disadvantages**	**Comments**
Billiard Balls	Uniformity	Weight Size	Billiard balls normally come in diameters that are greater than 2 inches
Acrylic Balls	Uniformity	Cost	-
Golf Balls	Uniformity Cost Availability	Texture (Not Smooth)	Used in the Franklin Institute Design
Ping Pong Balls	Uniformity Cost Appearance	Weight	Discounted due to their weight limitations
Steel Balls	Uniformity Weight	Accelerated Wear	Accelerate the wear on other parts of the machine
Glass Marbles	Uniformity Weight	Tolerance with increase size	Uniformity was decrease for larger sized marbles *Selected Option

	Appearance Availability Cost	Manufacturing	

The final selected option for the balls in our design was 1” glass marbles. These were selected because their uniformity (tight tolerance), assorted colors, price, weight, and elasticity. The glass marbles come in assorted colors which will attract the audience to come view the machine. The 1” diameter was selected to optimize the design space because of the corresponding track width. Glass marbles over 1” in diameter were advertised as having more variance in uniformity. The specific glass marble our team selected was the Game Boulder Asst. 1" offered by moonmarble.com shown in Figure 29 (SKU: 2BBG1→ 125 pack).

Figure 29: Glass Marble 1” Offered by Moonmarble.com (SKU: 2BBG1)

Our team will need to know the weight of each marble when designing specific components of the machine. Therefore, we used a scale to measure the weight of 3 marbles of both the Black and white colored marbles. The weights of the marbles are shown below in Table 2.

Table 2: Weight of Marbles

Marble Color	**Weight (g)**	**Average(g)**
Black	21, 22, 21	21
White	20, 20, 20	20

For the six marbles that were tested, the average weight would be 20.667 g ~ 21g. The scale used during testing was only accurate to 1 g increments.

The specific material used to manufacture this marble is still unknown to our team. The vendor was contacted and unsure of the actual composition and had no input on how to find out the material for these specific products. From basic research, marbles are typically made out of glass and game marbles typically consist of silica and sand.

4.1.4 Lift

This section will first outline the types of lift mechanisms that rolling ball sculptures often use to bring the lift to the top of the machine. The lift our team selected will then be discussed and how we arrived at this selection. Finally, the design of our lift will be discussed.

4.1.4.1 Lift Mechanisms

The driven part of a kinetic sculpture that carries balls from the bottom of the machine back to the top is called a lift. There are many different approaches to doing this; although, some are used more frequently than others due to reliability, complexity, speed, and operating power.

Chain

The chain lift is by far the most commonly implemented lift. A chain wraps around at least two gears, at least one of which is powered by a motor. Additional gears may be used to provide tensioning to the chain. The chain contains intermittently placed scoops or forks that pick the ball up from the end of the track at the bottom of the machine and carry them to the beginning of the track at the top of the machine. This lift is the most used because it is the simplest and most versatile. The scoops can be placed at any desired interval, and the motor speed can be adjusted, allowing the interval between balls to be easily manipulated.

Screw

The screw lift uses the principal of Archimedes' screw to escort balls to the top of a kinetic sculpture. This design may be used over a chain as it has fewer moving parts, and can easily carry many balls at once. The downside is that the screw can only be turned at a relatively slow speed to avoid jamming. As such, the balls spend a very long time on the lift, so the machine must contain a much higher number of balls than many of the other lift structures. In addition, screw lifts generally require a greater torque from the motor to ensure smooth operation. Because of this, screw lifts are generally only used for small changes in height. Figure 30 illustrates the concept behind a screw lift.

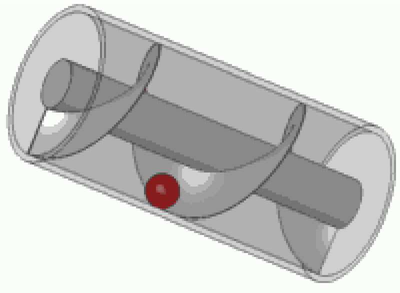


Figure 30: A Model of an Archimedes' Screw Raising a Ball

Air

Air powered lifts feature a tube, just larger than the size of the balls it is designed to ascend, and a fan, air compressor, or another method of creating air flow. The balls roll into the tube, and the air pushes them to the top, most often at a very high velocity. This lift requires the balls to spend much less time in the lift itself, and it is also entertaining to watch. Air powered lifts are; however, the hardest to design and can be unreliable if not made properly. An example of an air lift can be seen in Figure 31.

Figure 31: Example of an Air Powered Ball Lift

Launching

Launching lifts operate by propelling the ball upwards, from the bottom of the machine up to the beginning of the machine. The three main types of launching lifts operate as catapults, slingshots, or pitching machines. While these devices can transport the ball in a very short period of time, they are very unreliable in delivering the ball to the same spot repeatedly. These devices can also be difficult to build with a high enough accuracy to allow them to operate efficiently without operator intervention. An example of a launching lift can be seen in Figure 32.

Figure 32: An Example of a Launching Lift

4.1.4.2 Lift Selection

The chain lift type was selected over the other available choices based on the decision matrix shown in Table 3.

Table 3: Decision Matrix for Lift Selection

Lift Type	*Reliability (5)*	*Complexity (3)*	*Speed (4)*	*Power (4)*	*Safety (1)*	*Total*
Chain	5 (25)	4 (12)	3 (12)	4 (16)	3 (3)	**68**
Screw	4 (20)	5 (15)	2 (8)	3 (12)	4 (4)	**59**
Air	3 (15)	2 (6)	5 (20)	2 (8)	3 (3)	**52**
Launching	2 (10)	3 (9)	5 (20)	4 (16)	2 (2)	**57**

Chain lifts are the most reliable type of lift mechanisms used in rolling ball machines. Their increased reliability decreases the complexity of their design and construction and allows for variations to be added to the standard lift. While there are lifts that can transport balls more quickly, they are not reliable enough to use in a continuously operating machine. The decreased speed of the lift can be simply overcome by adding more balls. Chain lifts do not require a large power supply to operate efficiently, which decreases the size, noise, and cost of the motor. Safety was not weighted highly in our decision because the entire machine will be encased, thus preventing viewers from becoming entangled on moving parts.

4.1.4.3 Preliminary Design

Once the chain lift type was selected, we could begin the design of the lift for our machine. We considered the height of the lift, the lateral placement of the lift within the sculpture, the tensioning mechanism, and the power supply options.

Our rolling ball machine was designed with a height of 6 feet and a base of 5 feet by 2.5 feet. The height of the lift must match the total height of the machine in order to deliver balls from its base to its starting point. Thus, the lift should have a height of 6 feet that includes the length of chain as well as clearance room for the sprockets and attachment sections.

There were two main options for the placement of the lift. It could either rest in the center of the sculpture or be placed at the edge of the frame structure. In order to maximize the working room for track paths in the sculpture, the second of the two options was chosen. This would also allow room in the center of the sculpture for support rods.

Chains used for chain lifts gradually stretch over time. Due to this, it must be periodically tightened to keep the lift functioning properly. This could be done by manually removing the chain and detaching a segment of it or by using an additional sprocket that could be extended outward to stretch the chain to an optimal working distance. The second option was chosen as it would make tightening the chain less of a hassle.

In designing the lift, a motor must be selected that has enough power to drive the loaded lift smoothly and at a constant speed. A detailed overview of our motor selection can be viewed in the “Motor” section.

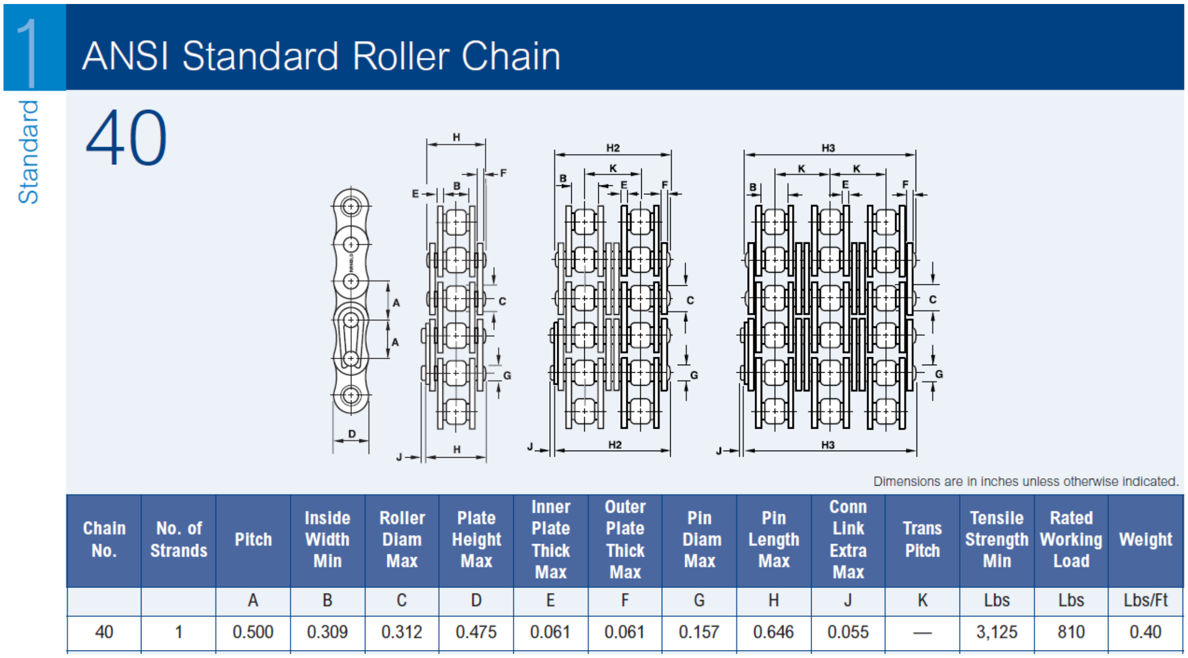
4.1.4.4 Lift Component Selection

The main design components consisted of: type of chain, attachment sections and sprockets. These components had to work within the constraints of the given design, interact with one another cohesively, and have a low relative cost compared to similar components available on the market.

Chain

The chain chosen for the lift had to fit three main criteria. It had to be small and light enough that it could be easily driven by the motor without unnecessarily straining it as it would be operating for long durations without a cool down period. It also had to be of a size that coincided with the selected sprockets so it could be properly driven. The selected chain size had to be common enough that specialty attachment chain links would be available for it.

Based on the above selection criteria, ANSI 40 roller chain was selected as the chain that would be used for our lift. This chain could be easily driven by our motor and is one of the most widely used chain types, so compatible sprockets and attachment links would be readily available. Figure 33shows the dimensions of the ANSI 40 roller chain.



1 Standard

ANSI Standard Roller Chain

40

Dimensions are in inches unless otherwise indicated.

Chain No.	No. of Strands	Pitch	Inside Width Min	Roller Diam Max	Plate Height Max	Inner Plate Thick Max	Outer Plate Thick Max	Pin Diam Max	Pin Length Max	Conn Link Extra Max	Trans Pitch	Tensile Strength Min	Rated Working Load	Weight
		A	B	C	D	E	F	G	H	J	K	Lbs	Lbs	Lbs/Ft
40	1	0.500	0.309	0.312	0.475	0.061	0.061	0.157	0.646	0.055	—	3,125	810	0.40

Figure 33: Spec Sheet for ANSI 40 Roller Chain

Attachment

Specialty attachment chain links would need to be added to the standard ANSI 40 roller chain to provide an attachment point for scoops to carry balls from the end of the track to the top of the lift. The primary requirement for these chain links was that they were compatible with ANSI 40 roller chain. After the available specialty links for ANSI 40 chain were found, the link pictured in Figure 34 was chosen for its dual wing design and size.

Figure 34: Selected Specialty Attachment Chain Link

The dual wing design would allow a bolt to be inserted on either side of the chain that would simulate a forklift to pick up balls and return them to the top of the lift. Its size was of particular importance as the center-to-center distance of the holes on the wings needed to be sized specifically for the one-inch diameter balls used. The spacing could not be greater than the diameter of the marble; otherwise the marble would pass through the forklift. An additional requirement is the spacing could not be too close. This would provide an unstable ride for the ball causing lift failures and ball dropping. A full list of size specifications are shown in the data table in Table 4.

Table 4: Specs for Connecting Link Segments for ANSI 40 Roller Chain

Technical Specs	
Type	K-1 Attachment
Chain Size	40
Pitch (in)	0.5
Distance Between Holes (in)	0.717
Max Allowed Load (LB)	595
Material	Carbon Steel

Sprockets

The main sprocket in the lift is the drive sprocket that attaches to the motor and delivers power to the chain. The size of this sprocket was selected based on compatibility with ANSI 40 roller chain. The number of teeth needed was determined with a calculation based on motor rpm and the desired balls per minute to be delivered off the lift. This calculation can be seen in the below section detailing the motor. The chosen drive sprocket can be seen in Figure 35.

Figure 35: Selected Drive Sprocket

The bore size of the sprocket had to be compatible with the drive shaft of our motor and the set screws needed to align with the shaft to provide a proper lock for the sprocket to eliminate slip. The overall diameter of the sprocket was restricted by the clearance needed for the attachment links between the drive shaft and the bottom floor of the sculpture. A full list of specifications for the drive sprocket can be seen in Table 5.

Table 5: Specs for the Drive Sprocket

Technical Specs	
Type	Fixed Bore
ANSI Sprocket Number	40
Outside Dia (in)	2.650
Pitch Dia (in)	2.405
Number of Teeth	15
Bore Dia (in)	1/2

The two remaining sprockets necessary for an operational chain lift were an idler sprocket and a tensioner sprocket. Both of these sprockets would be free spinning and compatible with ANSI 40 roller chain. The idler sprocket would be located at the top of the sculpture to guide the chain back toward the drive sprocket. The tensioner sprocket would be placed behind and slightly above the drive sprocket to keep the chain tight to prevent oscillations. The sprockets selected for these uses are shown in Figure 36.

Figure 36: Selected Sprockets for Idler and Tensioner

The sprockets for these two positions needed to be made of a material strong enough to resist wear from continuous use, but soft enough to provide a quiet operation when used with steel chain. Due to this, glass-reinforced nylon sprockets were chosen over steel sprockets. A complete list of specifications for the idler and tensioner sprockets is shown Table 6.

Table 6: Specs for the Idler Sprocket and Tensioner Sprocket

Technical Specs	
ANSI Chain Size	40
Number of teeth	17
Outside Dia (in)	2.98
Bore Dia (in)	.51 -.52

Bearings	Molded ABEC-1 High Precision
Material	Glass-Reinforced Nylon

4.1.4.5 Motor

When choosing a motor there are a lot of factors that need to be considered. These include the type of lift, weight of ball, speed of lift, and noise requirements. After these criteria were analyzed, the motor could be chosen. There are many different variations of electric motors; the two main types are alternating current (AC) or direct current (DC). The positives and negatives of each will be discussed.

DC motors work by changing the polarity of electro-magnets around or on a shaft causing the shaft to spin. There are four prominent types DC motors: permanent, series, shunt, and compound. Permanent DC motors have true magnets outside and the electro-magnets on the shaft. They are the simplest type but do not produce very good torque and are inefficient. Shunt motors have the winding on the shaft and the electro-magnets on the outside wired in parallel. A shunt motor has the ability to be controlled easily, meaning it can hold a precise constant speed but do not have the greatest torque. Also shunt motors can be run without a load and not damage themselves because the magnets are wired in parallel. They are usually used for HVAC fans. Series motors are wired with the electro-magnets on the shaft and outside in series, which gives them different properties. A series motor has the largest amount of torque out of any of the DC electric motors. This is since torque is proportional to I^2 and current it the highest in series wiring. They have excellent starting torque and are usually used as the starter in a car. Some draw backs are that they will continue to increase rpm when they have no load and they cannot hold a constant rpm like shunt motors. Compound motors are a combination of both series and shunt motors. Compound motors are a middle ground for the two motors.

AC motors are the other kind of electrical motor. The main difference between AC and DC motors is that AC motors the power is supplied only to the outside of the rotating shaft, to a part called the stator, and DC motor supply the power to the rotating shaft in the center and possibly the outside depending on the type of motor. There are two main types of AC motors; the first is an induction motor. Induction motors are asynchronous, meaning that the motor turns slower than the AC frequency changes. The other type is synchronous AC motor. These motors rotate at the same speed the AC frequency changes. A synchronous motor is stronger and more controllable but a lot more expensive. AC motors can also have varying phases. They can be the standard single-phase 110v (really two phase because it alternates) and the three-phase 220v. The benefit of the three-phase is that there is less of a current draw.

There are advantages and disadvantages to AC and DC motors. AC motors are quite, virtually maintenance free and no power converter. Advantages for DC motors are powerful, cheaper, and easier to control. Disadvantages for DC motors are the brushes wear out, brushes can cause sparks, brushes can cause RF interference, and you need an AC to DC converter.

There are three different motors we compared for our project. Table 7 shows the break down in performance. The CIM and Anaheim Automation motors will need a gearbox to reduce the rpms to around 20 rpms (See next section). The Dayton has a built in gear box to get to the right rpms already. The Dayton was removed from the selection because it was unknown of the reliability of the motor. The final decision on the motor was determined by the gearbox price. The Anaheim Automation motor was chosen since the price of the gearbox was cheaper.

Table 7: Motor Performance Comparison

Model	CIM M4-R0062-12	Dayton 3M287	ACP-M-2IK6N-AU
Operating Voltage	6v - 12v		
Normal Voltage	12v	115 VAC	110 VAC
No load RPM	5310	15	1800 (1550 load)
No Load Amp	2.7 A		.25 A

Stall Torque	343.27 oz-in	480 oz-in	14.4 oz-in (~320 oz-in with gear box)
Stall Current	133A	.55A	.41 A
Kt	2.58 oz-in/A		
Kv	443rpm/V		
Efficiency	65%		
RPM PK Efficiency	4614		
Torque PK Efficiency	45 oz-in/A		
Current PK Efficiency	19.8 A		

4.1.4.6 Gearbox

The gearbox is an important component. The gearbox is needed to reduce the output of the motor to a lower rpm allowing the lift to deliver 10 marbles per minute. This value of 10 marbles per minute was chosen to allow the viewer to keep interest in the sculpture without having the balls interfere with each other on the tracks.

There are multiple options for the gearbox. The first option is straight cut gears; this is when the teeth are at right angles to face of the gear. Straight gears are the cheapest and strongest type of gear but are very loud. These were ruled out since we need the sculpture to be relatively quiet. The next option was helix or spiral gears. These gears are when the teeth are at non-right angles to the face and can even be curves and not straight. This allows the gears to have multiple teeth engaged at the same time, which results in a reduction in noise. The issues with helix gears are the price; they need to be matched pairs, and only allows for minimal rpm reduction per set of gears. The last type of gearbox is a basic pulley and belt. This type is the simplest and the quietest. This option allows for the largest rpm reduction. A large portion of the price for any of the options is the bearings. Bearings are needed to make the gearbox quiet and to increase the lifetime of the entire sculpture.

$$RPM_{final} = \frac{RPM_{motor}}{Gearbox_{ratio}}$$

Table 8: RPM Output for Anaheim Automation Gear Boxes

Model	Ratio	Final Output (RPM)
ACP-G-2N60-K	60:1	25.83
ACP-G-2N90-K	90:1	17.22

$$Amount\ the\ motor\ turns\ for\ the\ length\ of\ chain = \frac{12\ balls}{Chain} * \frac{1\ min}{10\ balls} * \frac{17.2\ rotation\ of\ motor}{1\ min}$$

$$= \frac{20.8\ rotations}{chain}$$

$$Teeth\ on\ Sprocket = \frac{2\ links}{inch} * \frac{12\ inch}{foot} * \frac{13\ foot}{chain} * \frac{chain}{20.8\ rotations} = 15.2\frac{links}{rotation}$$

$$\approx 15\ teeth\ per\ gear$$

The last option had a total price of $46.86 without the bearings and the bearing added $97.02 for a total of $143.88. Because the price was so high a decision was made to get Anaheim Automation motor and gearbox combination for $130. Their gearbox uses helical gears and has ball bearings.

4.1.4.7 Final Lift Design

This section builds upon the Essential Machine Elements Section of this report and details the final design of the lift used in our rolling ball sculpture. Further, this section includes analysis of the operation of the lift.

Design

The final design of the lift includes a twelve foot long chain running from the base to the top of the frame. The design used is shown in Figure 37.

Figure 37: Final Lift Design

Twelve wing attachments links were placed every twelve inches along the chain shown in Figure 38. These attachments have two 6-32 X3/4” bolts passing through the link wings. Each bolt is secured to the wing with a nut and has a nut fixed to the end of the bolt to serve as a bucket that picks the marble up and secures it until it reaches the top of the lift.

Figure 38: Wing Attachment Link

Loctite was added to the nuts to secure them in place and prevent them from backing out due to operational vibrations.

The motor that powers the lift is attached to the base of the top platform with a bracket machined out of aluminum. Our initial design is shown in the following part drawing (Figure 39).

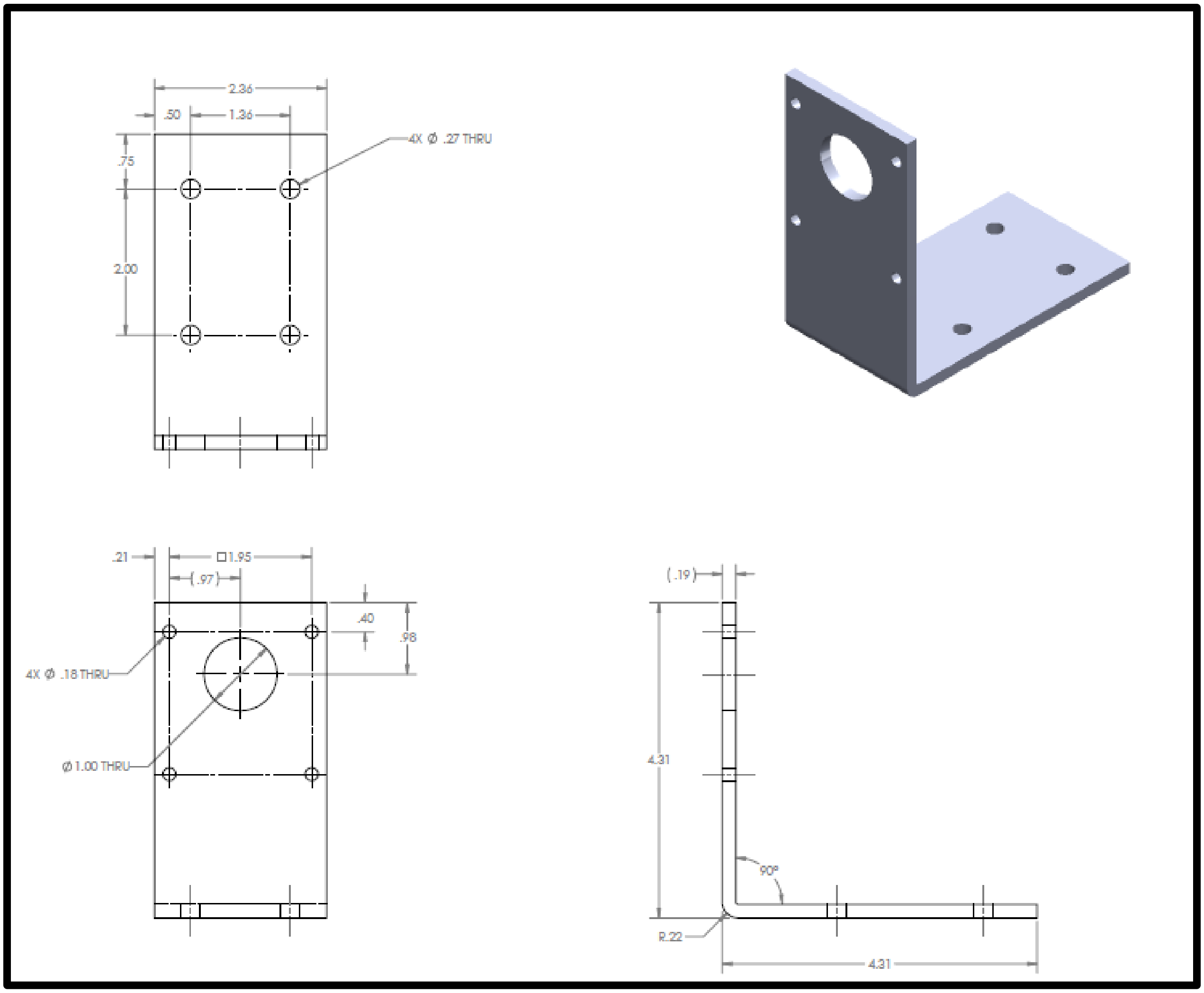


Figure 39: SolidWorks Part Drawing-Motor Mount Bracket

Notable features of this design are the bolt pattern and thru hole shown on the front view. These are designed to match the features of the motor used and secure the motor to the bracket. The other flat section that is perpendicular to this section has 4 clearance holes for ¼” bolts that would fasten the bracket to the plywood of the top frame. Since the motor bracket is being fastened to wood, our team decided that no rubber mounting pieces would be required to minimize the noise and vibration of the operation of the motor. If a metal frame were used, rubber mounts would be added in between the motor and the bracket to reduce extraneous vibration.

A scrap piece of aluminum was used for this motor bracket. The machined bracket is very similar to the designed model but the geometry of the scrap piece only allowed two bolt holes on the flat section that rests on the plywood. The machined bracket prior to being painted is shown in Figure 40.

Figure 40: Motor Bracket Prior to Painting

As shown in the above figure, the flat section with two clearance holes is not rectangular due to a prior cut. However, this piece was sufficient for the bracket our team required. This bracket was painted with the same paint used for the frame to be more aesthetically appealing. Our team's intent was to blend the bracket in with the frame so the observer's focus remains on the operation of the kinetic sculpture. The final painted bracket is shown in Figure 41.

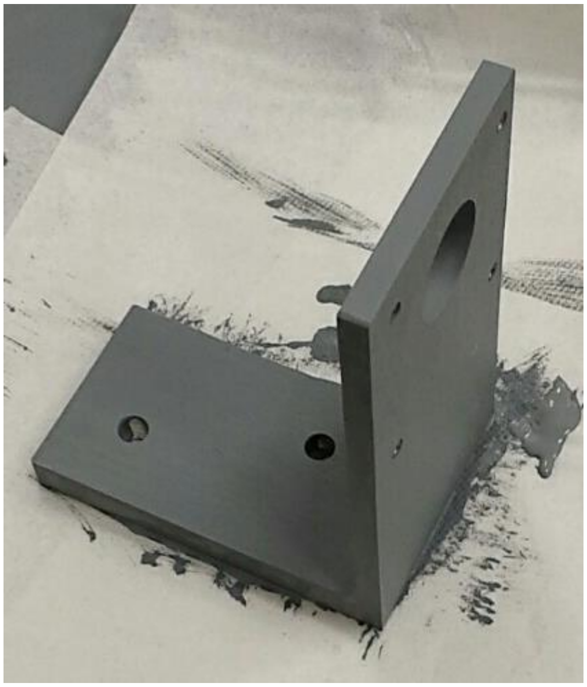


Figure 41: Motor Bracket Painted Gray

This bracket was then secured to the plywood by two bolts as shown in Figure 42. This bracket was positioned so the sprocket attached to the motor would be in the center of the frame.

Figure 42: Motor Bracket Secured to Frame

After the bracket was secured, the motor was fastened to the bracket, and the driving sprocket was attached (Figure 43). The wiring and switch with power cable were passed through the bottom of the frame. The switch was secured underneath the frame so the observer does not have access to the power switch, but can still be easily turned on by an operator.

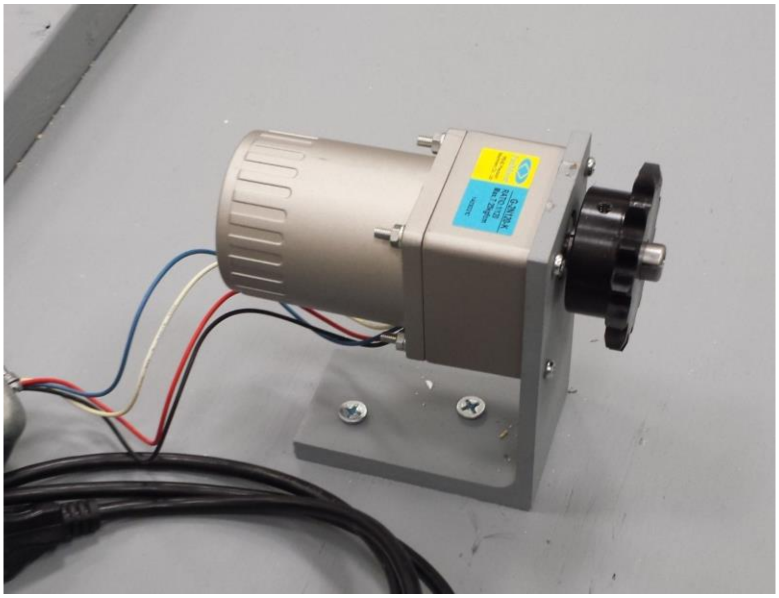


Figure 43: Motor Attached to Bracket

The next step in making the lift operational was to mount the top sprocket that the chain would pass over. Our team designed a mount that would span the width of the frame. This design involved a shaft that would be fixed to two mounts coming off the horizontal beams of the frame and aligned vertically with the motor sprocket as shown in Figure 44.

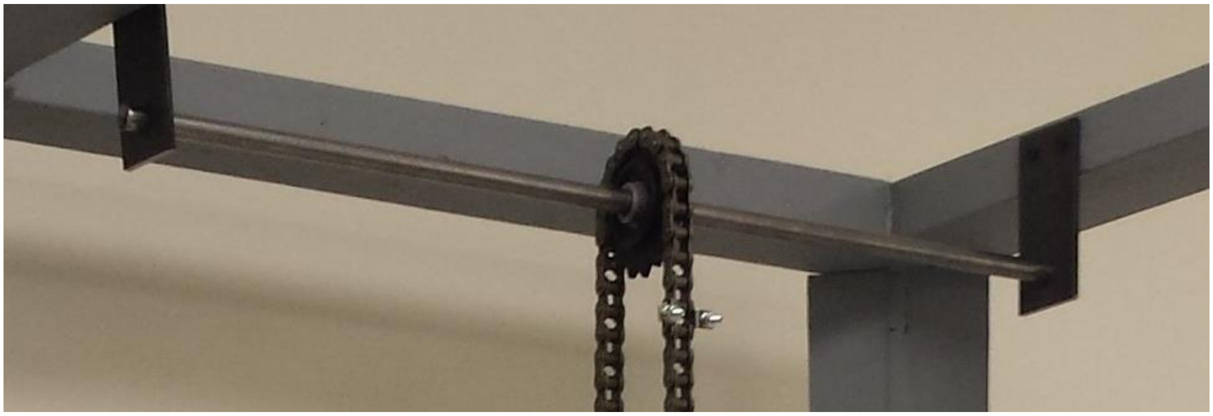


Figure 44: Top Sprocket Mounting Design

The steel rod shown in the figure above passes through two side steel brackets. This design consists of a clearance hole for the shaft and two clearance holes for screw that fasten into the wood. Steel was selected in case our team wanted to weld the steel rod to the brackets. These brackets are shown in Figure 45.

Figure 45: Side Mounting Steel Brackets

Shaft collars were placed on the ends of the rod to prevent the rod from sling through the side mounting brackets. These secured shaft collars are shown in Figure 46.

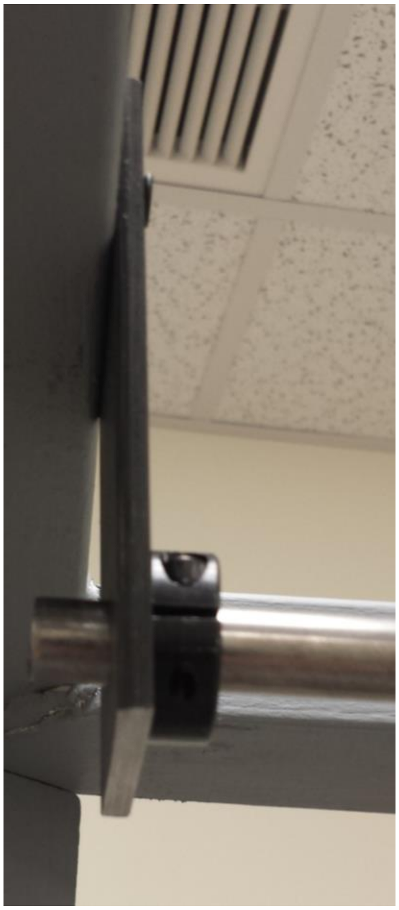


Figure 46: Shaft Collars on End Mounts

Additional shaft collars were used to locate the top sprocket as shown in Figure 47. These were included to ensure vertical alignment between the driving sprocket located on the motor and the top sprocket located on the mounting rod. This would prevent the top sprocket from sliding and torqueing the chain.

Figure 47: Shaft Collars Located on Top Sprocket

This design was selected so the steel rod could be used as a mount for supporting track. The alternative design would have been a mount similar to the motor mount coming off the back support of the frame. The design was not selected because it could not be used as an additional support for track.

The final step to making the lift operational was to mount a tensioning “idler” sprocket. This sprocket would keep the chain in tension and limit the amount it oscillates during operation. Our team’s design for mounting the idler sprocket was a steel rod with shaft collars that passes through two wood end supports as shown in Figure 48.

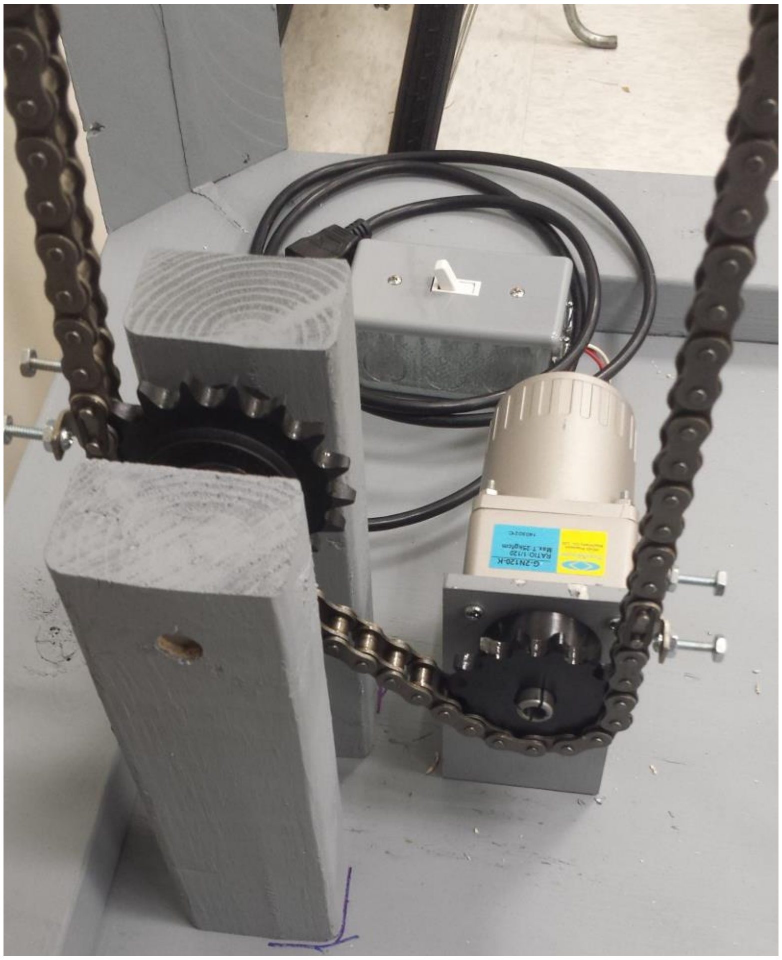


Figure 48: Idler Sprocket Mount

Screws were used to mount into the bottom of the two wood mounts. Since the chain will naturally loose tension over time, the wood pieces were not mounted directly against the back wood support. This allows our team the ability to move the wood supports back and to retention the chain. The holes drilled into the wood were strategically placed so when the wood supports are moved the holes will not be visible.

A top view of the mount used for the idler sprocket is shown below which details the shaft collar placement in more detail in Figure 49.

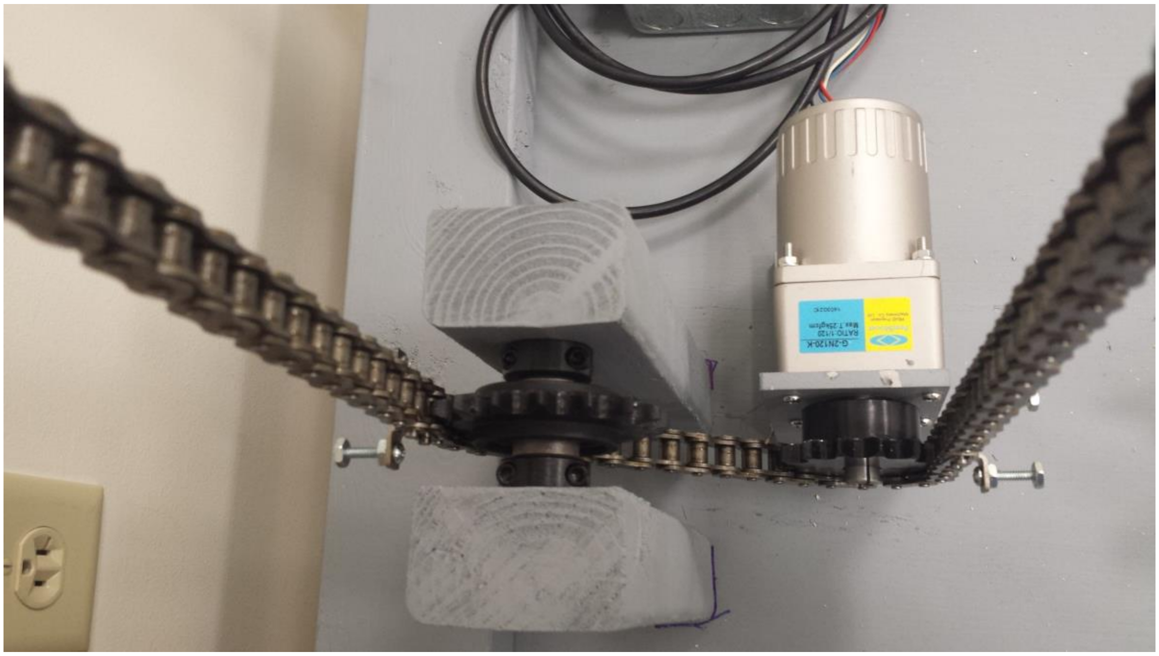


Figure 49: Idler Sprocket Mount Top View

In order to prevent marbles from resting against the chain while waiting to go up the lift, two vertical pieces were welded onto the end of the track (Figure 50).

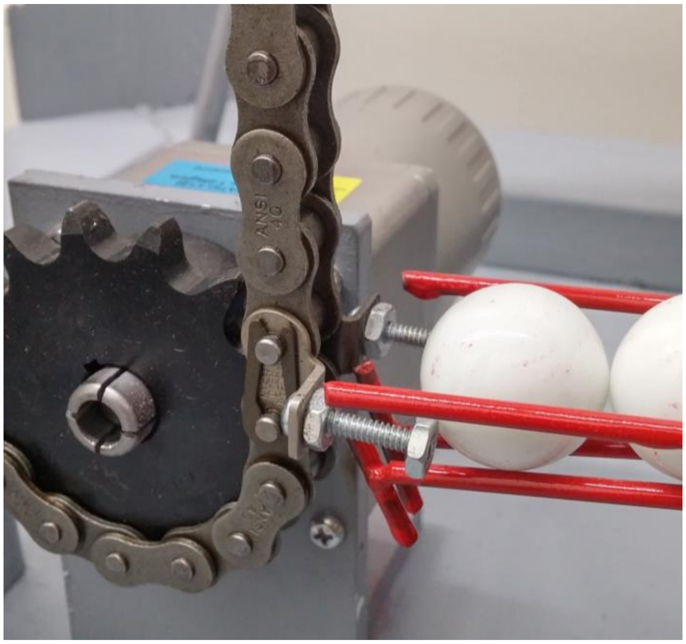


Figure 50: Ball Rest

Operational Data

The time between balls coming off the lift was recorded for nine trials and the values are shown below in Table 9. The balls exit the lift after an average retention time of 7.04 seconds. This rate delivers roughly 8.5 balls every minute.

Table 9: Time Between Balls Exiting the Lift

Trial	Time [Seconds]
1	7.05
2	7.05
3	7.06
4	7.19
5	6.77
6	7.01
7	7.19
8	7.05
9	7.03

Times were also recorded for the total retention time of the ball on the lift. This value was obtained as a measure of the time the ball spent on the lift from pickup to expulsion. The first time recorded was 40.8 seconds and the second trial took 41 seconds.

4.2 Operation Elements

This section outlines the number of operations the marble will undergo while passing through a cycle of the machine. First, an overall design map is provided. Next, each element is described and illustrated. Finally, the significance of each component is discussed.

4.2.1 Design Map

A preliminary design map for our machine labeling the various paths and operations is shown below in Figure 51. The ball will exit the lift and follow track over Earle Bridge to the first switch that will alternate between two other intermediate tracks. Each of these tracks will then lead to switches to two more tracks. The four tracks will now represent different disciplines of study offered by WPI including Engineering, Sciences, Business, and Liberal Arts. These four tracks will each have at least one major component that identifies it with its title. These four tracks will also eventually drop into a funnel labeled the “IQP Bowl” which will simulate the Interdisciplinary Qualifying Projects that all WPI students must complete. The marbles coming off each of the paths will simulate how each IQP team consists of students of different majors. The ball will then go one of two directions randomly simulated on campus or off-campus MQP. Lastly, the ball will pass back over Earle Bridge.

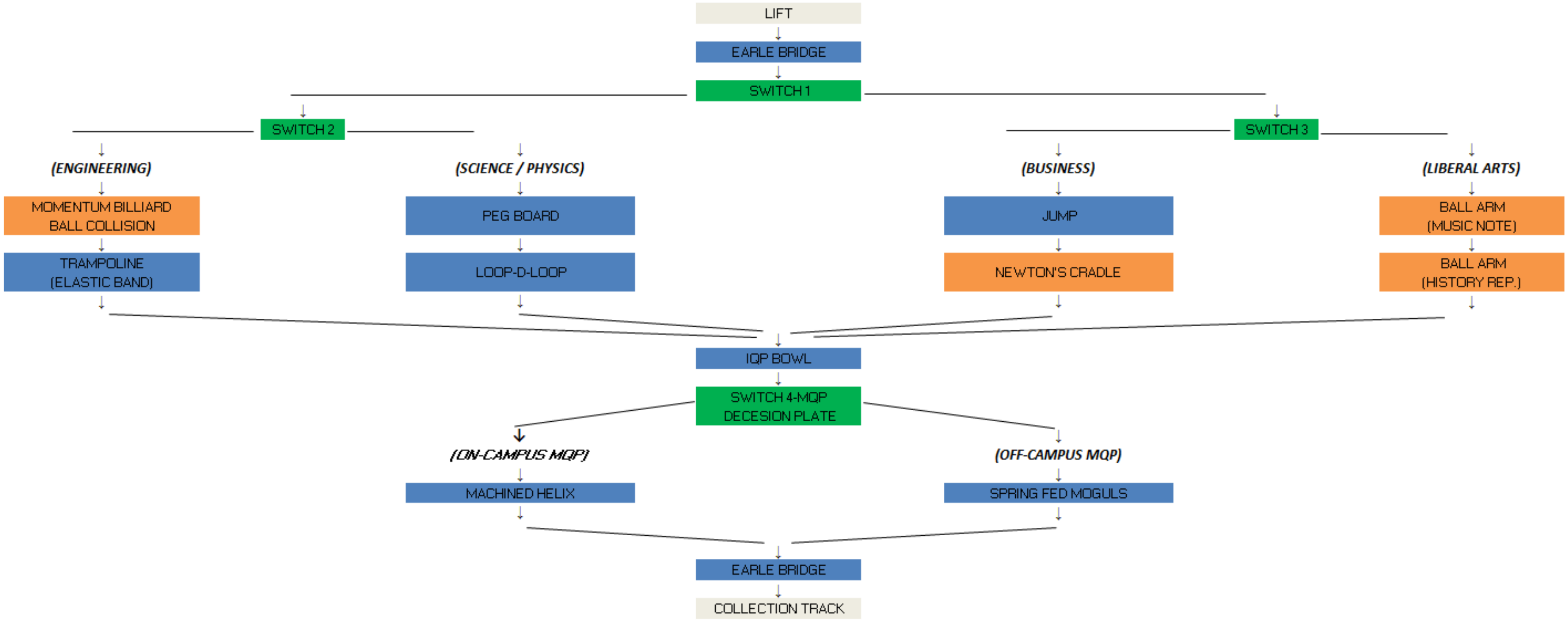


Figure 51: Design Map for the Various Machine Paths

4.2.2 Earle Bridge

A staple landmark of WPI is the Earle Bridge seen over the road when entering campus. The bridge is a significant element of the final machine because at WPI students walk over the bridge when starting their undergraduate studies and walk back over in the opposite direction when graduating to signify completion of a degree. This bridge was included in the sculpture and the ball travels in a similar manner at the beginning and end of a cycle. The track runs over the bridge to simulate the student walking over the bridge. This component appears twice in the design of the final sculpture, once at the beginning of the cycle and once before entering the collection track at the end. Below is an image of the Earle Bridge (Figure 52) as well as a SolidWorks model of the bridge (Figure 53).

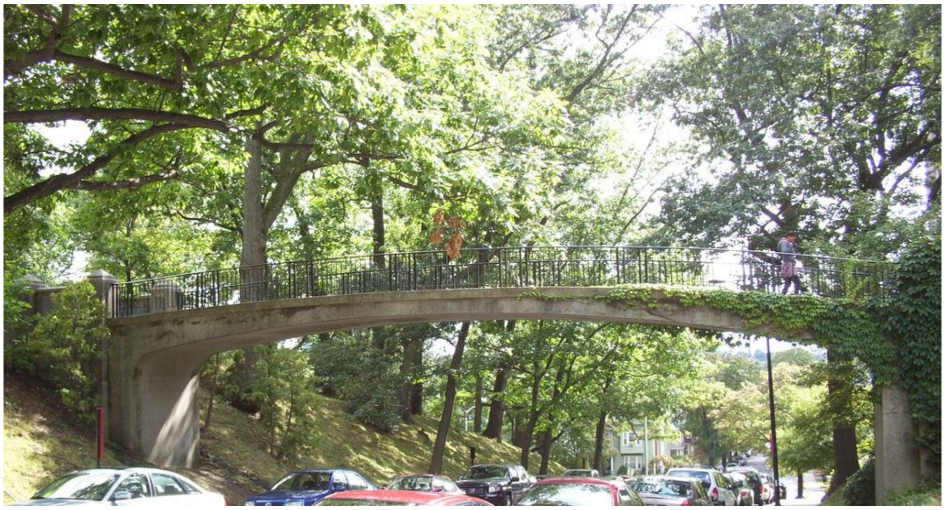


Figure 52: Earle Bridge on the WPI Campus

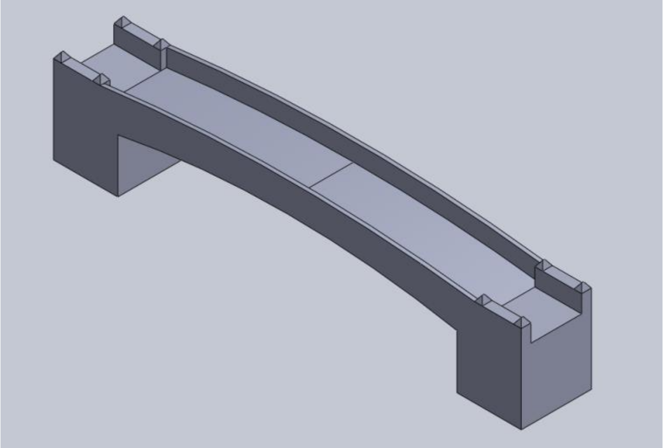


Figure 53: SolidWorks Model of Earle Bridge

Our team manufactured this component by means of rapid prototyping on the WPI Dimensioning machine. This machine can create a part that is 10 x 10 x 12" (height) and therefore an overall length of the bridge was selected to be 9". The bridge was constructed with the top of the bridge oriented down to limit the amount of support material required. The rapid prototype was made on the Dimensioning machine with low density. The color of plastic selected was ivory. Two rapid prototypes were completed and shown in Figure 54.

Figure 54: Rapid Prototype of Earle Bridge

As described above, the Earle Bridge appears twice on the sculpture. The first location is at the top of the sculpture as shown in Figure 55. As the ball exits the lift, it follows a 180 degree turn then passes over the bridge to simulate a freshman beginning their undergraduate career at WPI.

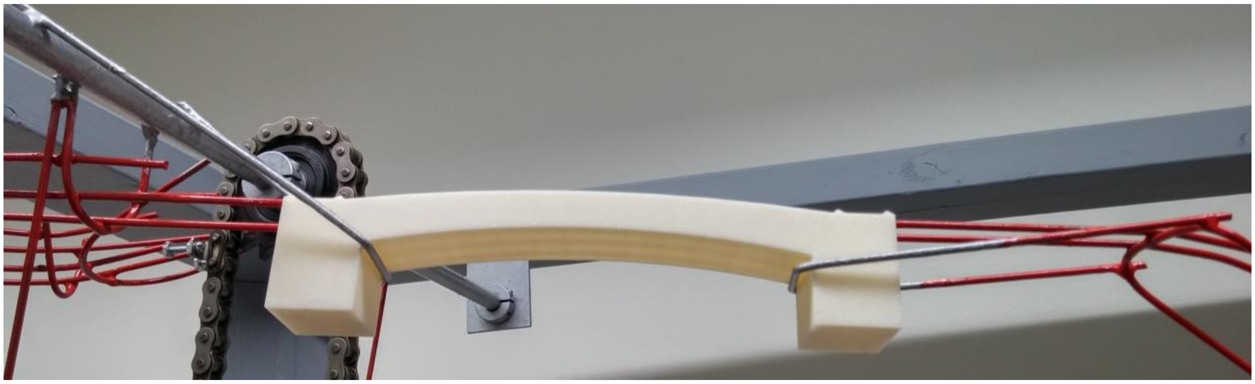


Figure 55: Earle Bridge Mounted at Top of Sculpture

The second location of the bridge is at the bottom of the sculpture along the collection track. As the marbles stack up to re-enter the lift, they pass over the bridge to simulate the walk of WPI's students on graduation day (shown in Figure 56).

Figure 56: Earle Bridge Mounted at Bottom of Sculpture

4.2.3 Switches

There are two main types of switches that are used in kinetic sculptures. The first type of switch is a vertical teeter-totter shown in Figure 57.

Figure 57: Vertical Switch

Vertical switches operate by moving back and forth from the weight of the ball. The ball lands on one side if the switch and the weight of the ball will cause the teeter-totter to rotate. The ball will then continue to role on the new path. The advantages of this type of switch are it is very easy to manufacture and orient. The disadvantage of the vertical switch is it takes up vertical height and involves a drop.

The other type of switch is a horizontal teeter-totter (Figure 58).

Figure 58: Horizontal Switch

This switch operates based on the same principle as the first type of switch but it uses the balls momentum to switch, not gravity. The ball rolls down the track and is diverted to one of the tracks by the top of the teeter-totter. The ball then hits a leg on the teeter-totter and the top of the switch moves to divert the next ball to the other track and allows the ball to construe on the selected path. The benefit of this kind of switch is that is takes up very little height. However, horizontal switches are very hard to align and get working properly. Both switch options can be made primarily with track.

Based on the consistency of vertical switches and allowance of vertical height, our team selected vertical switches to alternate the marbles between the four primary tracks. For our design, we used the 1/8” steel rods connected to a rotating shaft that was brazed to a washer. As a marble exits the starting track it passes over one vertical switch to one of two other vertical switches. This provides the even distribution between the four paths. The switch set up for our sculpture is shown in Figure 59.

Figure 59: Final Sculpture Switch Set-Up

Our team designed the switch set-up to be symmetrical. Guard rails were added to prevent the marble from bouncing out of the controlled track.

4.2.4 Pegboard (Laser Cut Acrylic)

A classic element used in a ball machine is a pegboard. The official name of this element is a Galton Board, named after Sir Francis Galton (Barile). A pegboard in the general sense is a very simple concept: an array of pegs arranged such that the ball falls on the middle of a peg, and has an equal probability of falling to the left or right of the peg. In our case, it will consist of a triangular shape that will produce six bins of outlet possibilities. These bins will be used to simulate a Gaussian distribution using statistical probability to predict that the ball is more likely to end in the middle bins with decreasing probability moving outward from the middle with increasing standard deviation. This element is the first component of the science path.

The AutoCAD drawing for our pegboard component is shown in Figure 60. The outer white rectangle represents the 11”x14” acrylic work piece. The red lines represent the paths the laser will cut along to produce the pieces needed to assemble the final component.

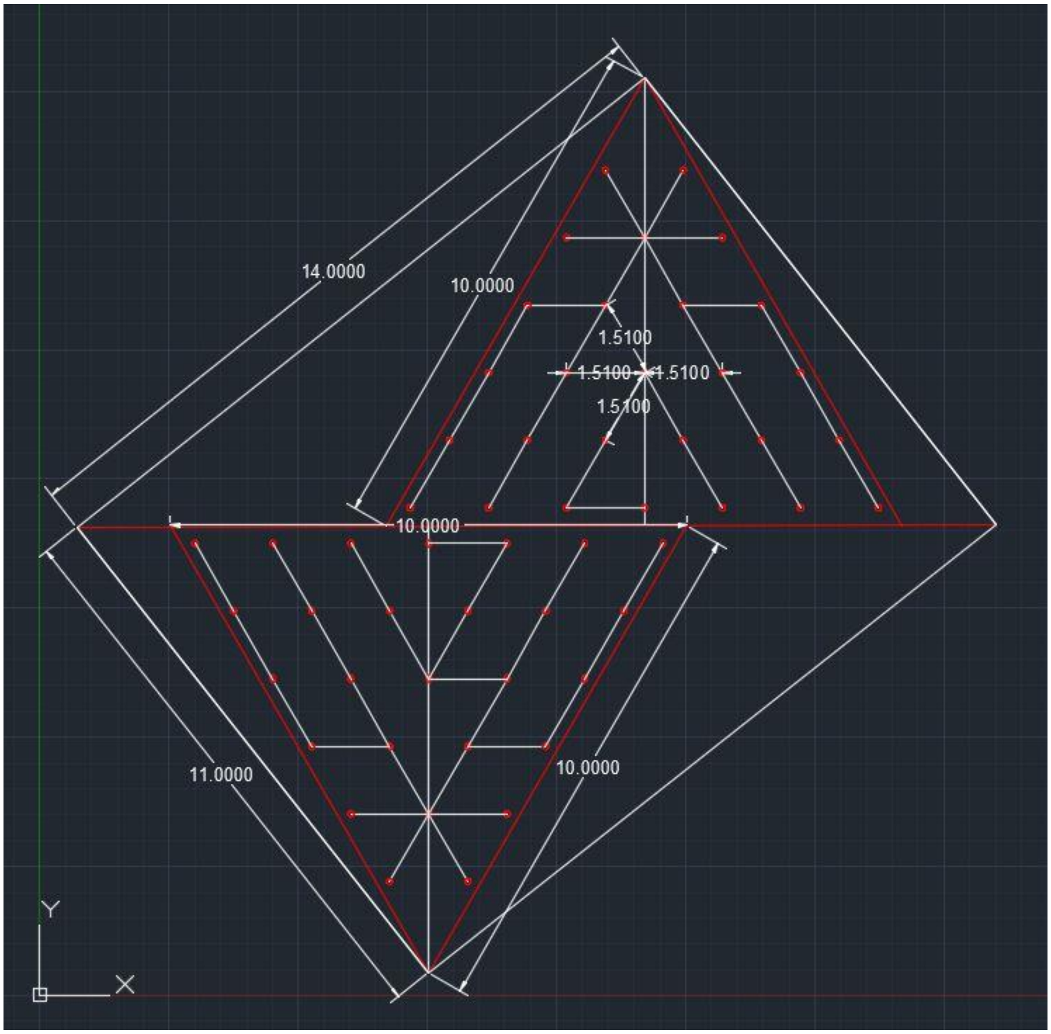


Figure 60: Peg Board AutoCAD Drawing for Laser Cutter.

Clear acrylic was chosen for the triangle cutouts so viewers could easily see the ball falling through the field of pegs. Two 10” equilateral triangles were cut to match the 60 degree angles used between the pegs. This also allowed us to maximize the number of usable bins at the base of the pegboard which increases the statistical accuracy of the Gaussian distribution.

The two clear acrylic triangles were connected via pegs placed in the cutout holes. The pegs themselves were made out of track, which was included in the track calculation. The peg length was chosen to only allow the ball to have two degrees of freedom; rattling of the balls between the two sheets of acrylic was undesirable, as this would produce a statistical error caused by friction and rapid dampening oscillations. This structure created a transparent sandwich pegboard that would contain the balls while remaining visible to viewers as seen in Figure 61.

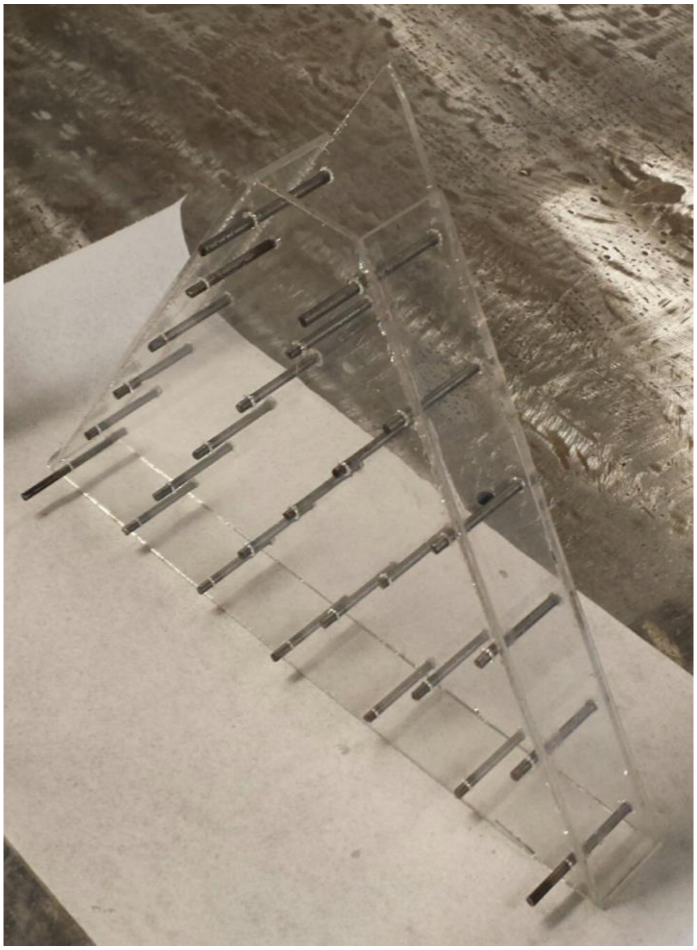


Figure 61: Acrylic Pegboard Assembled

The number of outlet bins dictates the spacing between pegs as there must be a peg directly above the sidewalls of each outlet bin. The next row of pegs is then placed on a horizontal offset equal to half the center-to-center distance between the pegs. The diagonal distance between pegs from one row to the next is kept the same as the center-to-center horizontal distance between pegs. This creates a 50% probability for a falling ball to be deflected to either the left or right. A constraint on the peg spacing is provided by the ball diameter. The peg spacing must be larger than the diameter of the ball to allow the ball to fall between the pegs. However, the peg spacing must be smaller than twice the ball diameter to prevent the ball from falling straight down the pegboard without being deflected by the pegs. Due to these constraints, a peg spacing between the minimum and maximum distances was selected. The chosen spacing of just over halfway between the minimum and maximum possible values was chosen to create a more accurate Gaussian distribution that also took the manufacturing tolerance of the ball diameter into consideration. Figure 62, below, shows the final peg board installed with the pained sculpture.

Figure 62: Installed Peg Board

The pegboard element represents the Gaussian distribution. As the marble enters the pegboard and hits the first peg, it has equal probability of falling to the left or to the right. Since there is an equal chance of the marble going to the left or right of each peg, if the balls were collected and piled up it would form the classic bell-shaped curve of the normal distribution. The formula for the binomial distribution is: $f(k; n, p) = \binom{n}{k} p^k (1-p)^{n-k}$. In this equation n is the number of rows, k is the bin number from the right, and p is the probability (p=0.5). $\binom{n}{k}$ is called a combination and is equal to n!/(k!(n-k)!).

The pegboard was repeatedly tested to find an accurate probability of the ball falling through each of the outlet bins. The distribution of outputs from our trials can be seen in Figure 63 below. A total of 148 marbles were tested on the pegboard. The distribution is accurate with a slight favor to the left side of the pegboard.

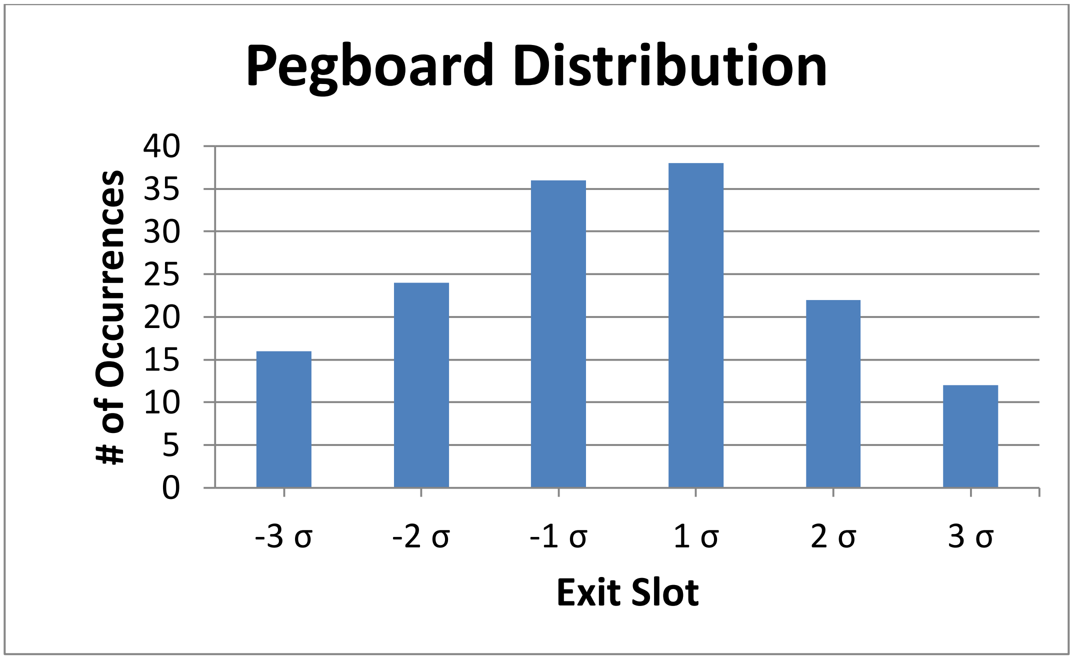


Figure 63: Pegboard Distribution in Standard Deviations

4.2.5 Double Loop-D-Loop

A loop-d-loop is a section of track in an inverted circular shape such that the ball goes “upside down” and still sticks to the track. It is a classic element that is almost required in all kinetic sculptures of this type. This element follows the peg-board on the science path.

Successful implementation of a loop requires some calculation. We wanted to have the biggest possible loop with the vertical drop that we had available. Since the same path that has the loops also has the pegboard, and feeds into the IQP bowl at the end, the highest vertical drop that could be estimated to be available was about half a meter.

The first step was to find the velocity of the ball on the flat section immediately before it enters the loop. To do this, conservation of energy was used, including both rotational and kinetic velocity:

$$mgz = \frac{mv^2}{2} + \frac{I\omega^2}{2}$$

$$I = \frac{2m{r_{ball}}^2}{5}$$

$$\omega = v/r_{ball}$$

$$mgz = \frac{mv^2}{2} + \frac{2mv^2}{5}$$

Where:

m is the mass of the ball,

g is the acceleration due to gravity,

z is the height of the initial drop before the loop,

v is the velocity of the ball at the bottom of the drop,

and r_{ball} is the radius of the ball.

When solved for velocity, this yields

$$v = \sqrt{\frac{10gz}{7}}$$

The inequality that must be met for the ball to stay on the loop is

$$\frac{m{v_{top}}^2}{r} > mg$$

This simplifies to

$$\frac{{v_{top}}^2}{r} > g$$

Where:

v_{top} is the velocity of the ball at the top of the loop and

r is the radius of the loop

Lastly, a similar conservation of energy equation must be used to find the ball's speed at the top of the loop. However, this was done assuming the ball slips while on the loop. Since this is the worst case scenario, following the result with a small margin of safety for friction guarantees the functionality of the loop:

$$\frac{mv^2}{2} - 2mgr = \frac{m{v_{top}}^2}{2}$$

Solving this system of three equations and simplifying yields the final inequality:

$$\frac{\frac{10gz}{4/r_{ball} + 5}}{r} > 5g$$

Substituting in the actual values,

$$r < 0.154z$$

This means that the height of the loop should be about 31% of the height of the drop that precedes it. For example, if the height of the drop was 50 cm, the height of the loop should be less than 15.4 cm

Assuming that friction is fairly weak, the second loop is the same size as the first, and the second loop is located below the first vertically, the ball should make the second loop if it made the first.

Figure 64: Double Loop-D-Loop

4.2.6 The Jump

This component is the first to appear on the business path and required no additional materials as it relied entirely on contorting the track itself into the necessary shape. It consists of a segment of horizontal track starting at some initial position. The track then descends rapidly to a positive parabolically curved piece of track that ends abruptly. The momentum of the ball launches it from the track onto a new segment of track that is placed slightly lower than the previous initial position. This element incorporates basic kinetics and conservation of energy. It is used to represent the constantly rising and falling economic market in business.

To calculate how far the ball will land from the end of the jump, the velocity and trajectory of the ball needed to be determined. For velocity, we assumed that the tip of the jump will be about 20 cm below its initial drop height. Conservation of energy was then used to find a launch velocity:

$$mgz = \frac{mv^2}{2} + \frac{2mv^2}{5}$$

Solving this equation for v yields

$$v = \sqrt{\frac{10gz}{7}}$$

Assigning applicable values gives a velocity of 1.67 m/s

Using this for the launch velocity, a 30 degree launch angle, and assuming the landing is the same height as the launch,

$$1.67\sin(30) - 9.8t = 0$$

And $$1.67t\cos(30) = x$$

Solving this system yields a distance of .123 meters or 12.3 cm. However, since there must be a large factor of safety to ensure results are as consistent as possible, the landing zone begins around half that.

Figure 65: Jump Element

4.2.7 Newton's Cradle

This component follows the jump feature on the business path. In addition to track, it required a Newton's cradle. As a ball rolls along a length of track, it approaches the Newton's cradle. The incoming ball activates Newton's cradle. The linear momentum is transferred from the ball to the cradle. The angular momentum from the spin of the ball causes it to press against the first ball in Newton's cradle. The ball is then knocked down the next section of track by the transfer of linear momentum from Newton's cradle back to the ball. This setup is shown in Figure 66. This design incorporates conservation of momentum and is used to represent trading in business.

Assuming the ball does not slip when it leaves Newton's cradle, the ball's speed after Newton's cradle could be calculated. The ball's initial linear momentum is represented by the expression mv_1. Since linear momentum is conserved through Newton's cradle, that can be assumed to be the momentum that is given back to it. That momentum is then split between linear and angular momentum. The calculation for exit speed is shown below:

$$mv_1 = mv_2 + I\omega = mv_2 + \frac{2mr_{ball}v_2}{5}$$

$$v_2 = \frac{v_1}{1 + \frac{2r_{ball}}{5}}$$

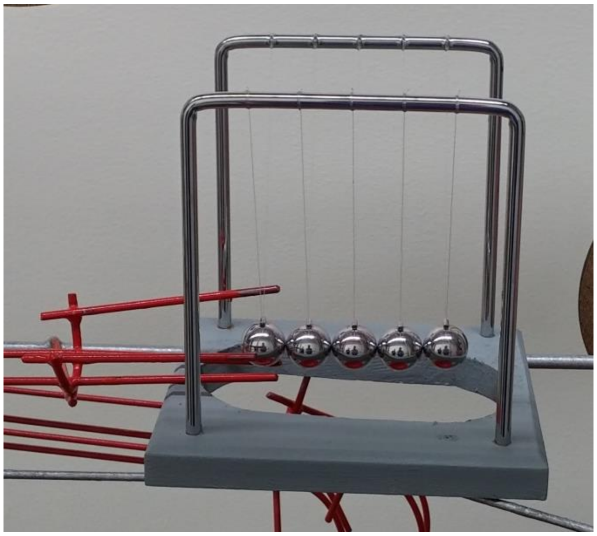


Figure 66: Newton's Cradle

4.2.8 Ball Tipping Arms

Ball tipping arms are traditional elements commonly used in rolling ball sculptures. The ball arms were made mostly out of track; a plastic cup was used to hold the ball. The incoming ball falls off a straight section of track into a plastic cup mounted to the end of a rotating arm. The rotating arm is positioned on a shaft just above the center of gravity to allow the element to reset in its initial upright position. The angular momentum of the incident ball causes the ball arm to rotate to a point just below the horizontal axis to allow the ball to roll from the plastic cup into the plastic cup on the second ball arm. The second arm then tilts down and is deposited on the track below. A picture of the finished product can be seen in Figure 68. The ball arms are the two elements to represent the liberal arts path. Aesthetic plaques were designed using AutoCAD software and fabricated on a VLS laser cutter (Figure 69 and Figure 70). The first plaque is an eighth note to represent musical theatre at WPI. The second plaque is a reproduction of Leonardo Da Vinci's Vitruvian Man to show the connection between humanities and the sciences.

A diagram of a ball arm can be seen below. The line AB is the total length of the ball arm, 45 cm, and the pivot point is represented by the triangle under the line. The mass m_2 is the mass of the plastic cup used to catch the ball, and lengths A and B are the lengths of the lever arms. Since the mass of the rod is evenly distributed, we approximated each side as a point mass at half the lever arm's length. The mass of the rod was calculated using the density of steel and the volume of the rod. The counterweight mass m_1 is the variable for which the equation is being solved.

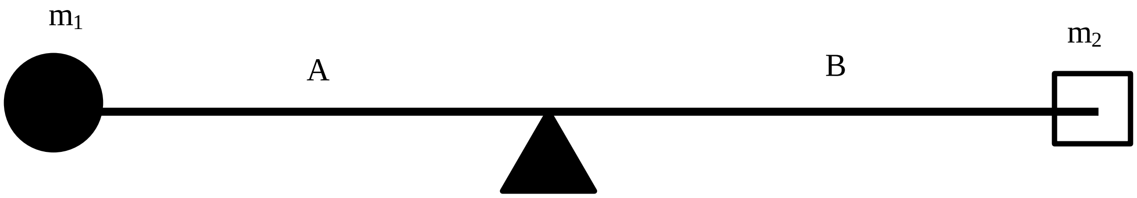


Figure 67: Moment Balance of Ball Arm

$$m_1 g A + \frac{m_a A}{2} = \frac{m_b B}{2} + m_2 g B$$

$$m_1 = \frac{\frac{m_b B}{2} + m_2 g B - \frac{m_a A}{2}}{gA}$$

Substituting in real values for the known variables yields:

$$m_1 = 19.7g$$

While this is the ideal case, measurements of the manufactured ball arm did not match perfectly, so some field testing and subsequent modification was required to properly balance the arm.

Figure 68: Ball Arms Final Design

Figure 69: Vitruvian Man Laser Cut

Figure 70: Music Note Laser Cut

4.2.9 Momentum Billiard

The first element on the engineering path is one of our own design. The momentum billiard represents the engineering principle of conservation of linear momentum. A ball rests at the trough of an arc. The incoming ball rolls down the arc, colliding with the resting ball. The linear momentum of the incident ball is transferred to the resting ball to knock it off the edge of the arc track and down to the next section of track below. The resting ball must be manually pre-loaded in position before the lift is powered. Due to the conservation of momentum, this element will work with additional balls resting on the arc track. This element will also function without the resting ball being manually pre-loaded. In this case, the incoming ball will simply launch off of the arc section and land on the section of track below. A photograph of the final momentum billiard element can be seen below in Figure 71.

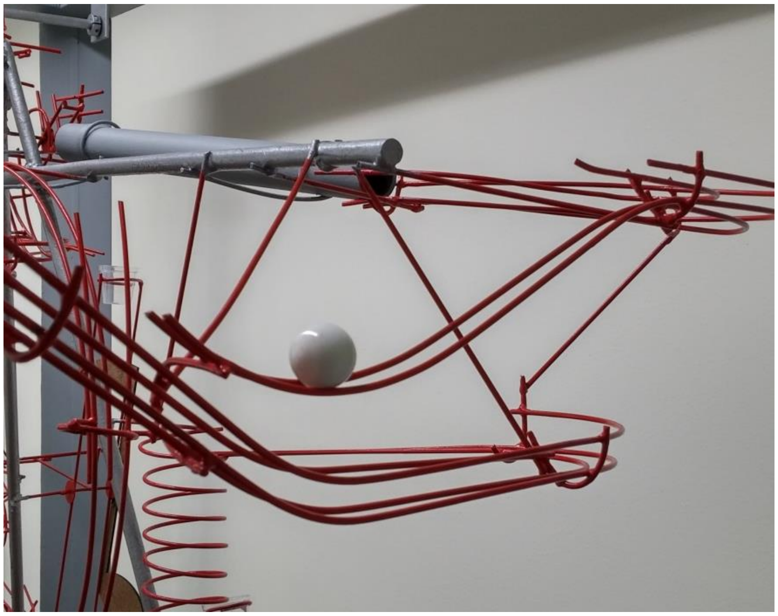


Figure 71: Momentum Billiard Element

Since Newton's cradle follows a similar principal of conserving linear momentum, many of the same equations still apply. The speed after the collision can be represented by the same equation:

$$v_2 = \frac{v_1}{1 + \frac{2r_{ball}}{5}}$$

If the collision is approximated as perfectly elastic, the energy retained can also be calculated:

$$K.E_i. = \frac{mv^2}{2} + \frac{2mv^2}{5} = \frac{7mv^2}{10}$$

$$K.E_f. = \frac{mv^2}{2}$$

$$\frac{K.E_f}{K.E_i} = \frac{\frac{mv^2}{2}}{\frac{mv^2}{2} + \frac{2mv^2}{5}} = \frac{5}{7}$$

So 5/7 of the energy of the initial ball is transferred, yielding a 2/7 loss.

4.2.10 Trampoline

The trampoline element follows the momentum billiard on the engineering path. The only material it required, in addition to track, was medical grade elastic band for use as the trampoline material. The incoming ball rolls down a segment of track, drops with a minimal horizontal velocity component, gains vertical velocity via gravity, and collides with a tensioned area of medical elastic. The collision alters the trajectory of the ball, launching it onto a separate section of track. This element simulates conservation of energy and momentum, as well as displacement, velocity, and acceleration vector sums.

The trampoline was installed at a 30 degree angle. We attempted to make the ball's velocity as close to 0 when leaving the track to fall onto the trampoline. The ball then falls 25 cm onto the trampoline with a negligible horizontal velocity. Therefore, the trajectory of the ball coming off the trampoline would be 30 degrees from horizontal. Assuming energy is conserved, the position of the catch track can be calculated:

$$mgh = \frac{mv^2}{2}$$

$$v = \sqrt{2gh} = 2.21 \text{ m/s}$$

Using the 30 degree trajectory, where x = 0 is where the ball contacts the trampoline:

$$v\sin(\theta) - gt = 0$$

$$vt\cos(30) = x$$

Plugging in values and solving the system yields

$$x = 21.6 \text{ cm}$$

Our catch was located from x=24 cm to x=16 cm, and at an angle perpendicular to the direction the ball is travelling at that point to maximize the consistency of the element. A picture of this setup can be seen in Figure 72.

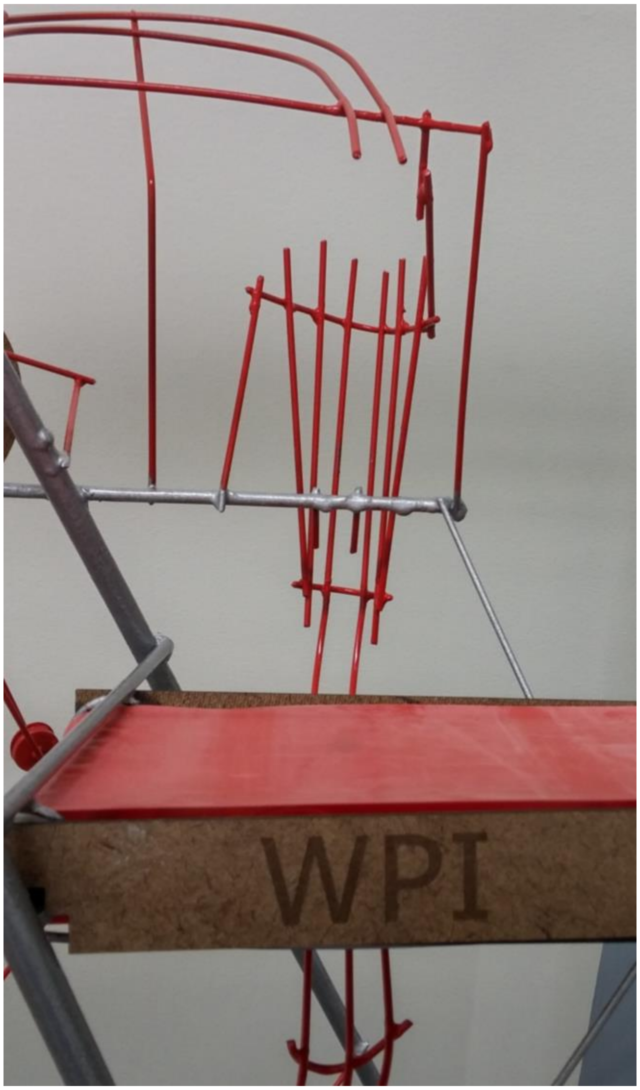


Figure 72: Trampoline Element

4.2.11 IQP Bowl

An Interactive Qualifying Project (IQP) is one of the requirements to receive a degree at Worcester Polytechnic Institute. An IQP involves applied research that connects science or technology with social issues and human needs. The objective of the IQP is to provide WPI students a chance to understand how their careers will affect society.

This project is one of the staples of a WPI education, and therefore is essential to represent on our sculpture. Our team selected to represent this by a gravity bowl. All four tracks lead and drop the marbles into this bowl. This represents how all the majors come together to work on the IQP as a team. The marbles then drop out of the bowl and land on the MQP decision plate.

Our team decided to use a standard bowl design for this element as represented in the CAD model shown in Figure 73. A detail drawing follows in Figure 74.

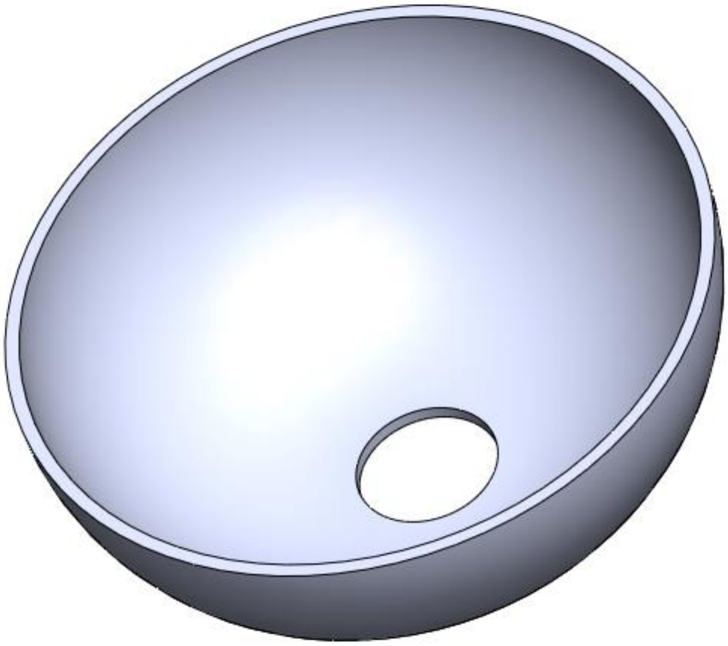


Figure 73: CAD Model of IQP bowl

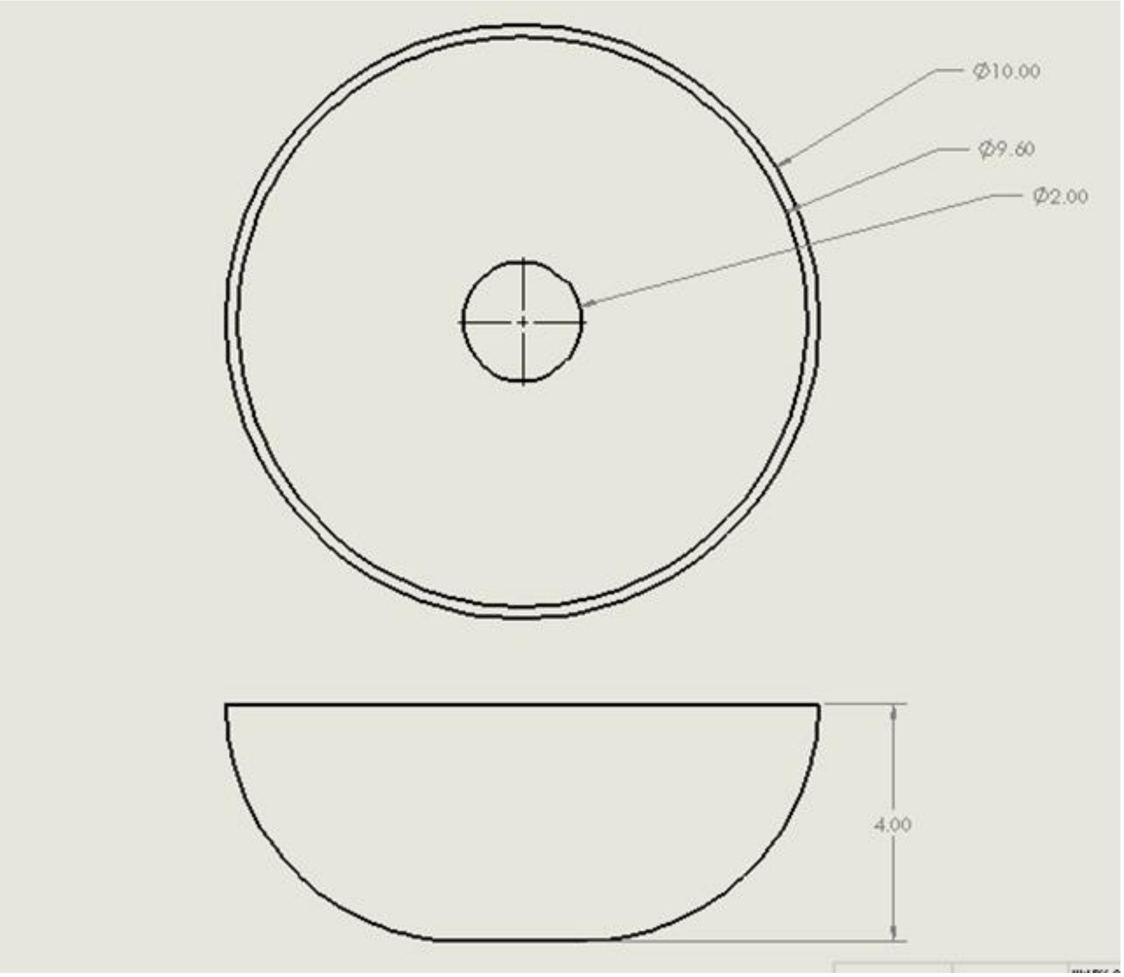


Figure 74: Detail Drawing of IQP bowl

We contacted David Morell of Avid Creations, a company that makes rolling ball sculptures, and he recommended that we use a Wok lid (~$12) for the bowl collector. For his designs, he explained that a hole is drilled in the base of the lid to allow the marble to fall through. David advised against the use of a conical shaped collector unless we can regulate the number of marbles entering at once (David Morrell, personal communication, 8 October 2014). He further explained that where the collector becomes narrower, the likely-hood of collisions is higher and they could possibly jam at the smallest part of the cone.

After browsing through many stores and websites seeking an appropriate bowl-shaped object to use as our IQP bowl, we found a suitable 12” diameter bowl. The only issue was a fairly large flat area at the bottom of the bowl, but we compensated for this by making the hole in the bottom of the bowl larger, leaving no space for the marbles to get stuck. The altered bowl can be seen below in Figure 75.

Figure 75: The Finished IQP Bowl

The final dimensions are 12” diameter, 5” height, and 5” hole diameter. When mounting the bowl, 1/8” steel rod was wrapped around the top lip of the bowl, and steel rod was welded to the pyramidal support structure. Figure 76 shows the bowl as it was positioned in the finalized sculpture.

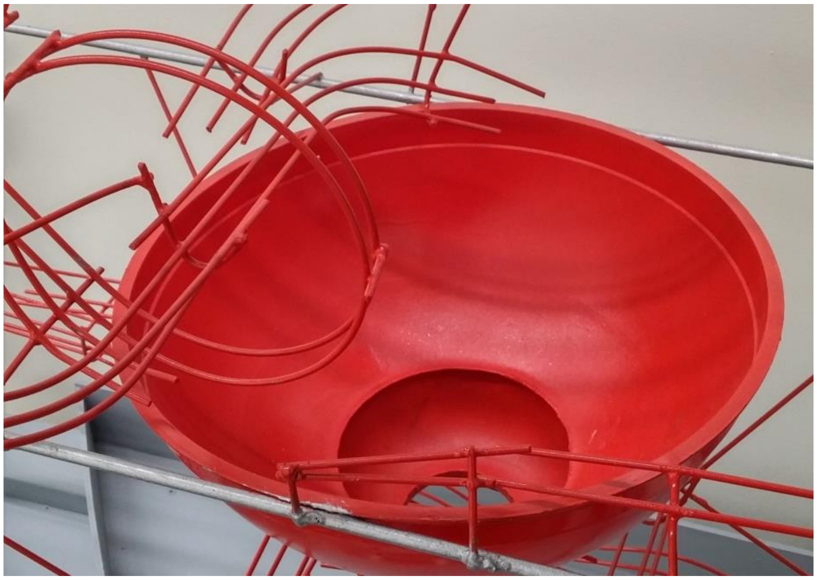


Figure 76: IQP Bowl Mounted Underneath 4 Main Tracks

4.2.12 MQP Decision Plate

This element is a random switch that follows the IQP bowl. The plate is made of evenly spaced 1/8” track brazed together as shown in Figure 77. As the marbles exit the bowl with different velocities and spin direction the ball either falls to the left or the right. This simulates how different students elect to complete MQP either on campus or off campus.

Figure 77: MQP Decision Plate

4.2.13 Machined Helical Spiral (On Campus MQP)

Our team selected a machined helical spiral to represent an on campus MQP at WPI. For this element, the balls fall off of track and run along the walls down pitched path until falling out an exit hole on the bottom. The ball then lands on more track and makes its way to the catch basin.

A 6” outer diameter by 3” thick aluminum stock round was donated to our team by The Washburn Shops on campus. The design for this component was constrained by these size limitations. Our team desired at least five steps for the spiral to maintain the attention of the viewer and to hold the ball within the spiral for a long enough period of time. We were able to achieve our task specification of five steps with our final design. Our team modeled our spiral with 0.25” wall height. This value was selected because it is half the marble’s approximate radius of 0.5”. This value would provide enough contact with the side of the marble to keep it rolling along the sloped path. This element was modeled in Solidworks using a helical sweep shown in Figure 78.

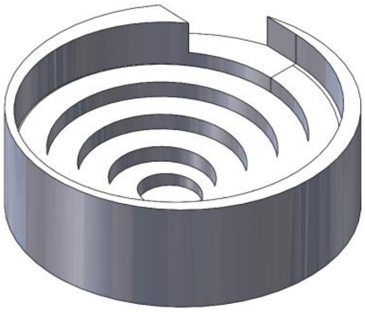


Figure 78: Machined Helical Spiral SolidWorks Model

The model was then uploaded to Esprit so it could be programed into the HASS CNC machines. Our team used a 3-axis mill to machine this profile so each sweeping path has visible steps. The following figures show the fixturing and machining process for the spiral.

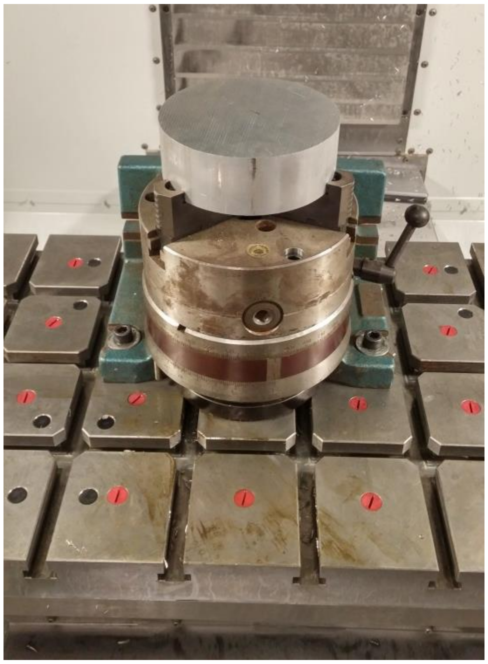


Figure 79: Machined Helical Spiral Stock Fixture for Machining

Figure 80: CNC Machining of the Helical Spiral

The machining operation took 28 minutes to complete. A second operation was completed to machine the outer profile of the helix. The final helix has 4 1/4x20 inch clearance holes tapped into the bottom for mounting. Doubled threaded screws were used to fasten the helix to four wooden support posts. The mounted helix is shown in Figure 81.

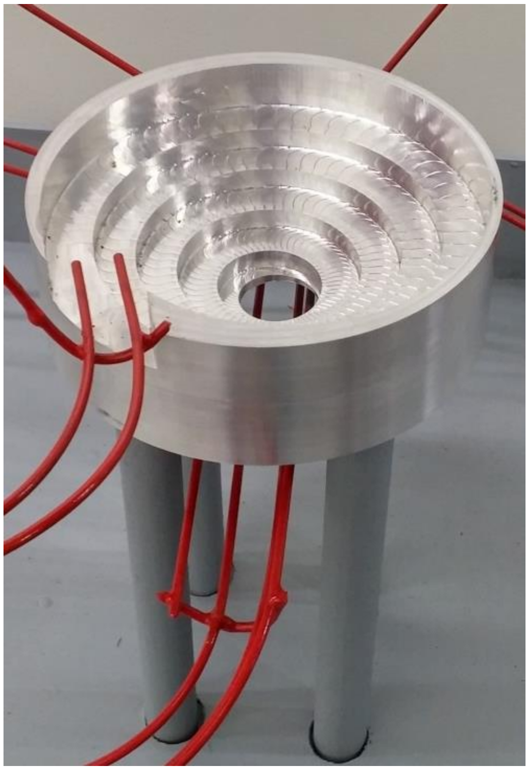


Figure 81: Machined Helical Spiral Mounted

4.2.14 Spring Fed Moguls (Off Campus MQP)

Vertical wavy track was used to represent an off campus MQP. This section of track varies in height to simulate moguls. The ball decelerates as it approaches the crest of each wave and accelerates as it descends each wave, approaching the trough. Incoming balls are provided with an initial velocity to propel them through this section of track by colliding with the spring shown in Figure 82. The entire stretch of moguls can be seen in Figure 83.

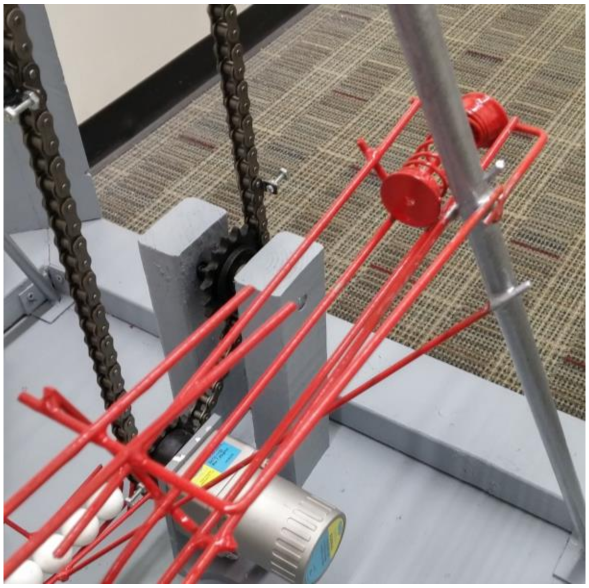


Figure 82: Spring Feeding the Wavy Track Moguls

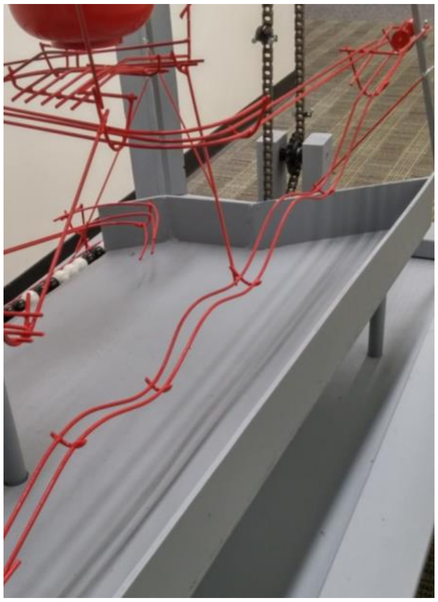


Figure 83: The Wavy Track Moguls Element

4.2.15 Aesthetic Elements

In addition to the main elements described above, there were sub-elements included on the sculpture. When connecting the main elements with track, it was not always necessary to follow a straight line from point A to B. These intermittent elements provide entertainment for the viewer between major elements and help connect the main elements together in an engaging fashion.

One of these sub-elements is a vertical helix on the engineering track between the momentum billiard and the trampoline. The track is bent into a helix with the spacing between the rods less than 1”, the diameter of a marble. This allows the ball to spin around the helix as it drops to the next section of track. The helix is shown in Figure 84.

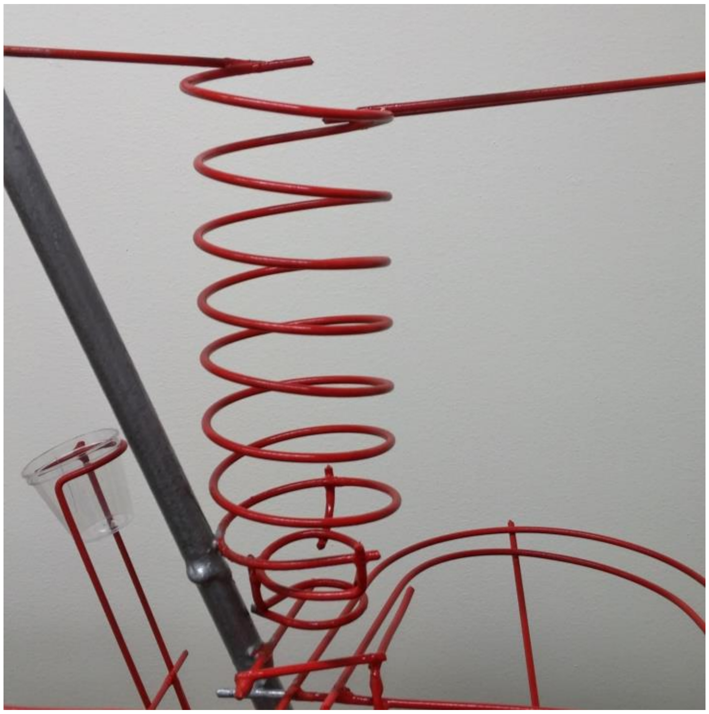


Figure 84: Vertical Helix

Another sub element is the half-loop; this element is on the business path between the switch and the jump. A half loop is a loop that changes the direction of the ball; the ball switches tracks while doing this. This half loop can be seen in Figure 85. There is another half loop that is between the jump and the Newton’s cradle. This one is smaller and changes the direction of the ball three times. The smaller half loop can be seen in Figure 86.

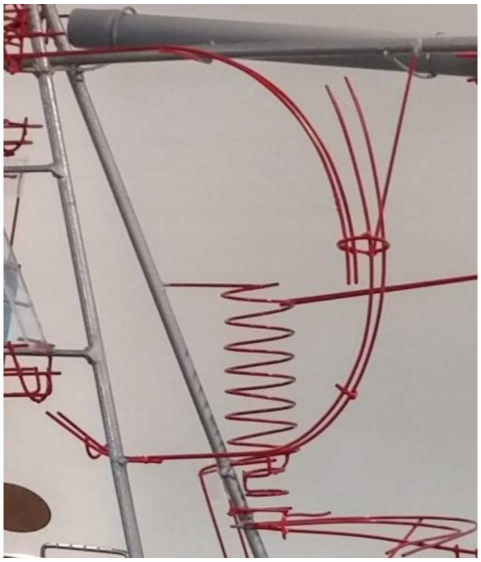


Figure 85: Large Half Loop

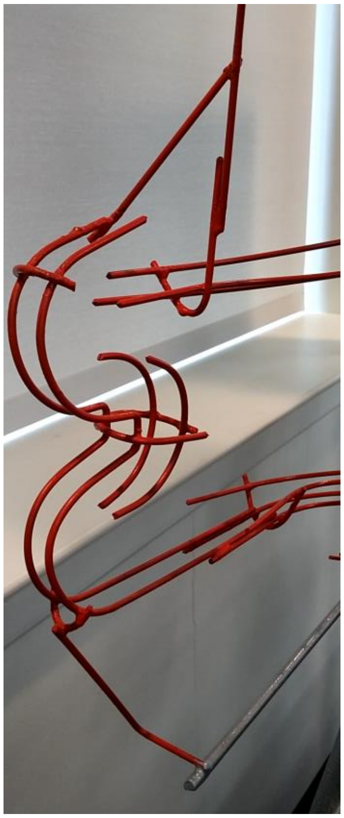


Figure 86: Triple Half Loop

After the moguls on the off-campus MQP path, the marble exits on a vertical drop-off (Figure 87). This allows the ball to slow down and prevents the ball from falling off the sculpture.

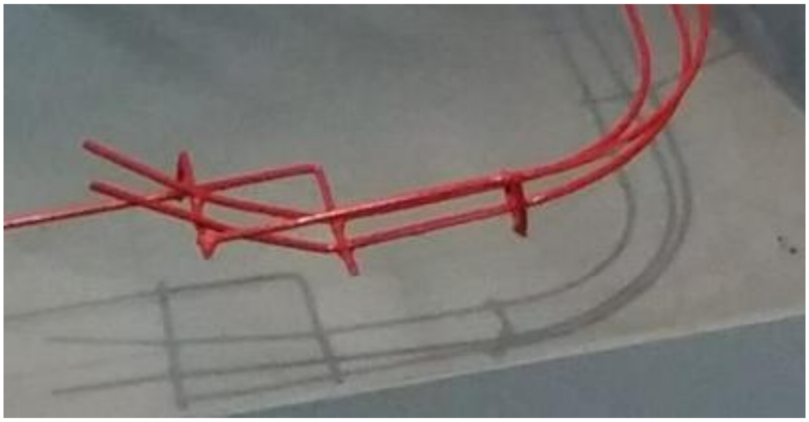


Figure 87: Mogul Drop-off

The last sub-element is the arc drop-off after the machined helical spiral. This section drops the marble off the track with a velocity that projects the ball in an arching pattern over the catch basin. This ensures that all the marbles can pass over Earle Bridge (Figure 88).

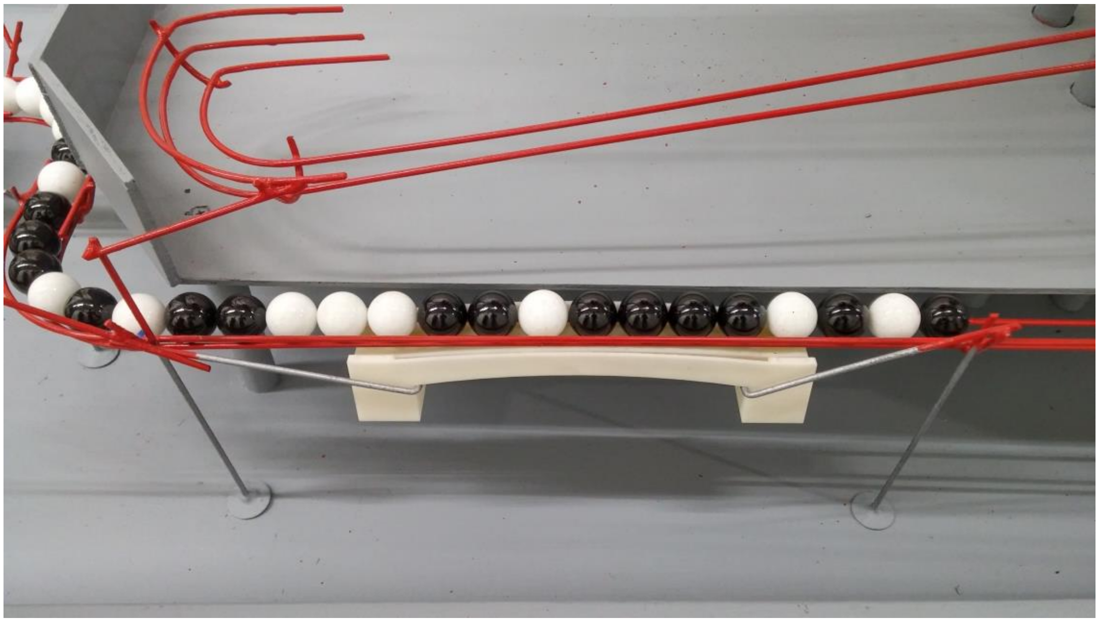


Figure 88: Catch Basin Arc

4.2.16 Informative Display Screen

The sculpture is equipped with a mounted tablet that serves as an informative display screen. The tablet displays a power point presentation on repeat sharing information about the sculpture and Worcester Polytechnic Institute. The power point communicates the following information:

- Defines a Major Qualifying Project (MQP)
- Project goal
- Significance of each sculpture path
- Areas of study under each pathway
- Representation of each element and governing design equation
- Fabrication methods used
- Worcester Polytechnic Institute facts and offerings

A tablet was chosen as the primary computing source for our sculpture due to its small size, ease of operation, and dual use as a display. We selected an RCA 7" quad core 8GB tablet with an android operating system as it fit our computing requirements, was within our budget, and came loaded with a power point program.

The tablet is mounted using the upper half of the original keyboard case and a steel bracket attached to the wooden support frame shown in Figure 89. The bracket was welded and designed to allow the tablet's display case to slide directly onto the bracket. The bracket with the tablet mounted can be seen in Figure 90.

Figure 89: Bracket for Mounting the Tablet

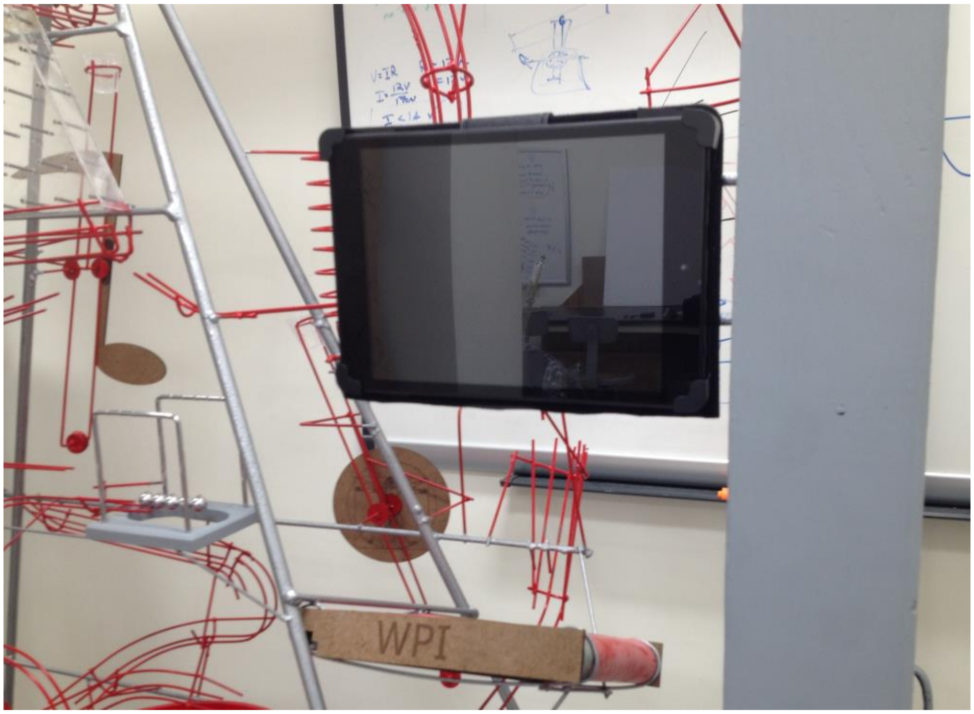


Figure 90: Tablet Mounted on Bracket

This bracket is mounted so that display glass can be added and the tablet will be enclosed inside the structure. The location of the tablet was selected in an area that would not restrict the viewer's vision of the structure. An image of the tablet with an example display slide is shown below in Figure 91.

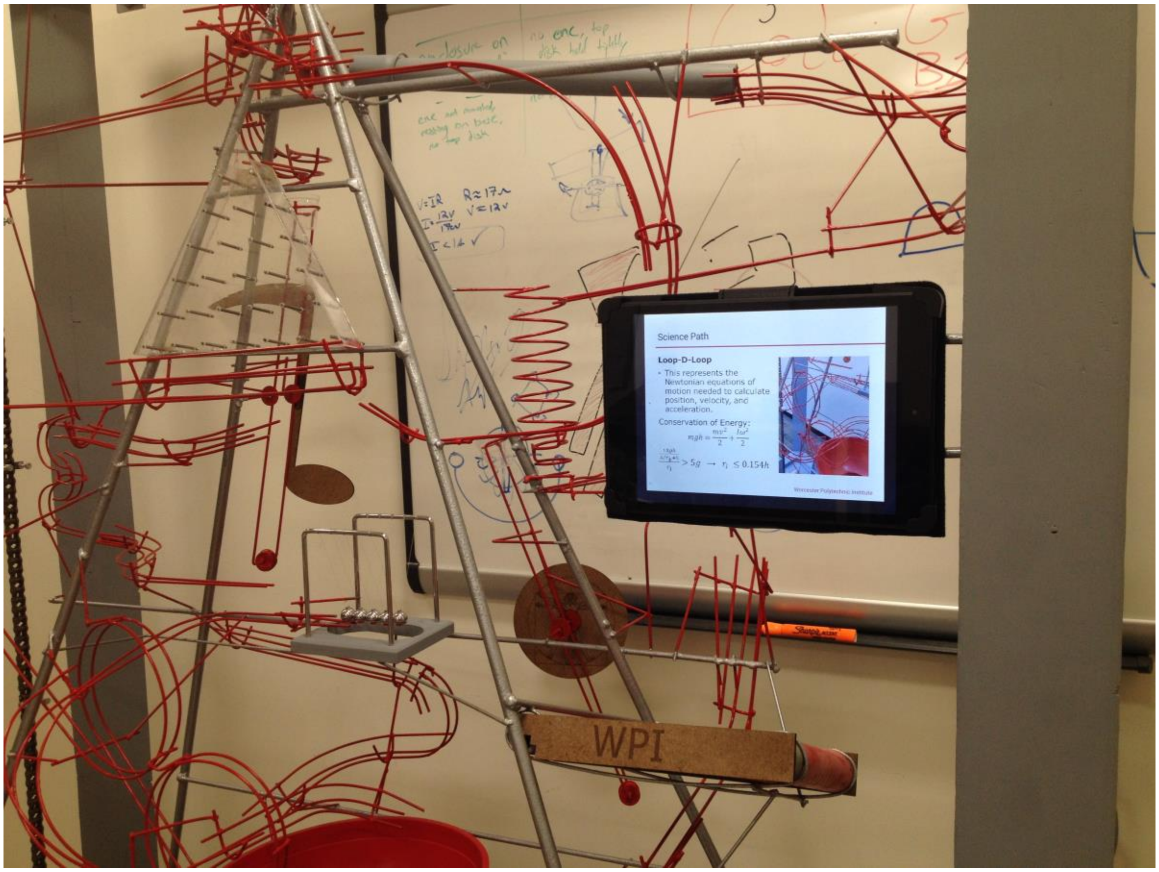


Figure 91: The Mounted Tablet Displaying the PowerPoint Presentation

4.3 Painting

The painting process for our sculpture was treated with a lot of attention. Our team wanted our sculpture to be aesthetically pleasing and eye catching. The most important characteristic of the painting process was that it yielded a professional product.

Our team selected a paint scheme that displayed Worcester Polytechnic Institute’s primary school colors, crimson and gray. We designated the track to be the crimson color and the frame and supports to be gray to contrast the red. WPI’s unofficial secondary school colors are black and white, which commonly appear on athletic uniforms and school apparel, so the marbles selected to run in our sculpture were black and white.

During the sculpture construction process, it was also important to make certain elements match the overall paint scheme. The IQP bowl was spray painted red to match the track as shown in Figure 92.

Figure 92: Painted IQP Bowl

During the painting process, it was also critical to not paint certain elements such as Earle Bridge, the chain, and Newton’s cradle. Therefore, critical elements were covered and tapped off during the painting process as shown in Figure 93.

Figure 93: Sculpture Taped off for Spray Paint

The track was then spray painted crimson in two coatings to make sure all the track was evenly coated as shown in Figure 94.

Figure 94: Spray Painted Track

Once all the 1/8” track was painted red, support rods of ¼” and ½” in diameter were hand painted a gray color with a hammered finish. The contrast is shown in Figure 95.

Figure 95: Crimson & Gray Contrast

The wooden frame was then re-painted the gray base color. The final painted sculpture is shown below in Figure 96.

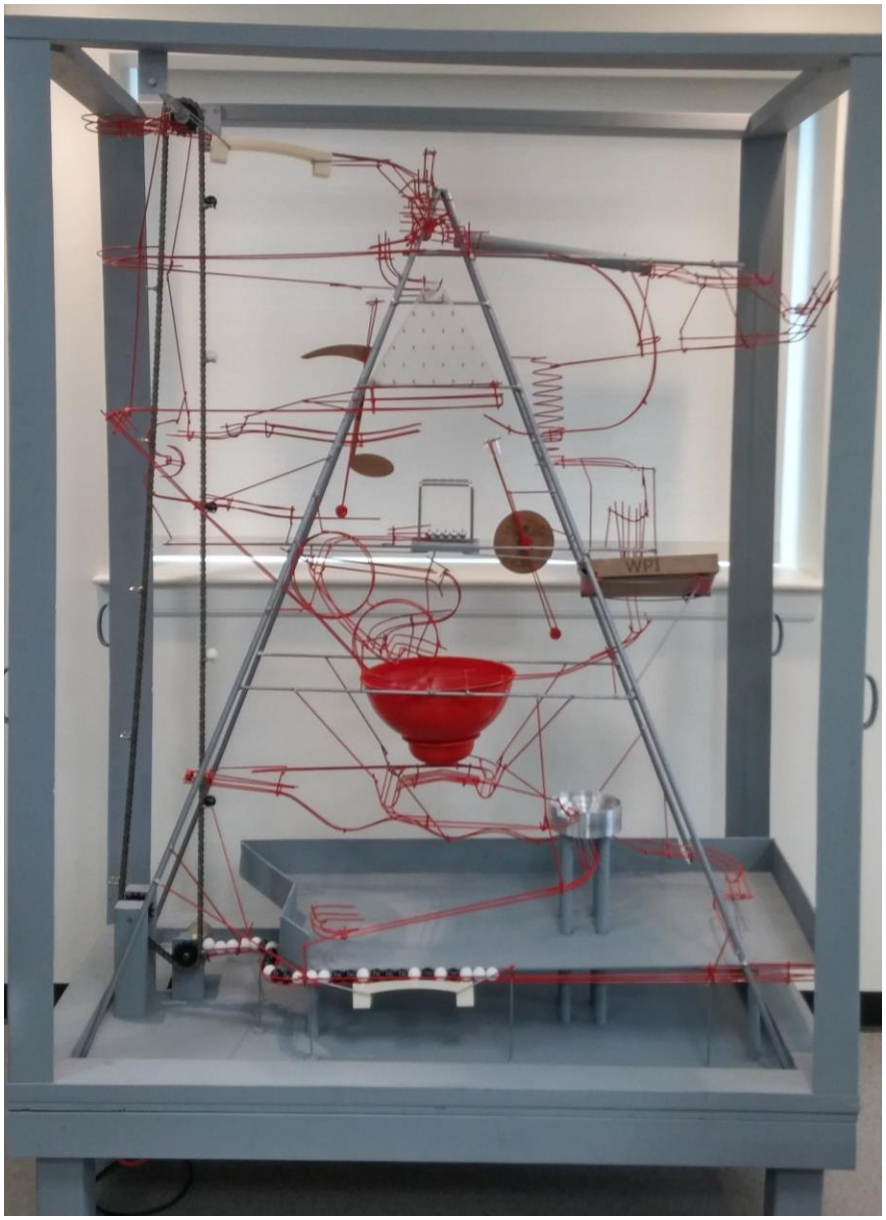


Figure 96: Completed Painted Sculpture

The completed sculpture with tablet is shown in Figure 97.

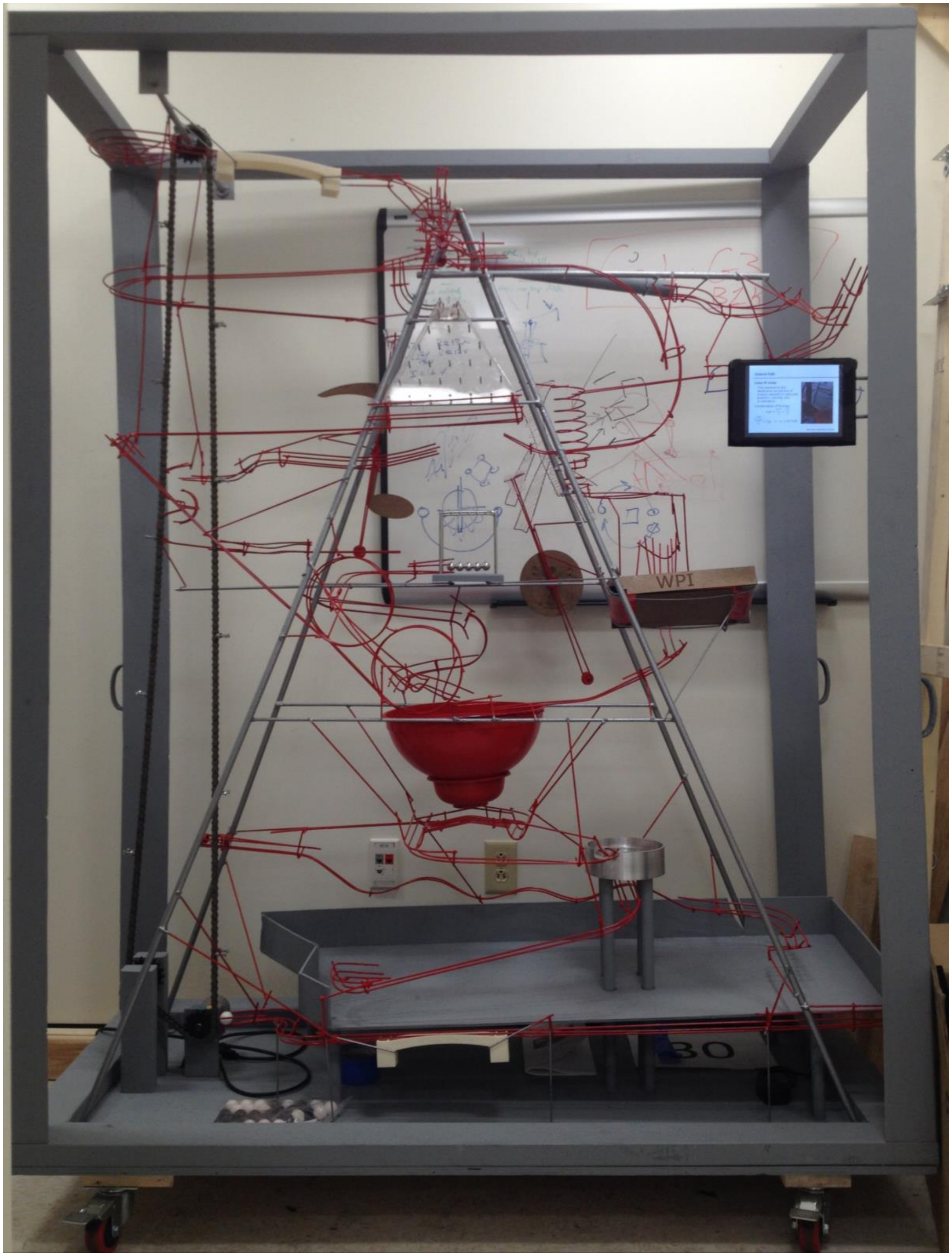


Figure 97: Completed Sculpture with Tablet

Chapter 5: CONCLUSIONS

Our goal of creating an engaging kinetic sculpture was achieved. By thoroughly studying prior art and the methods used to create a rolling ball machine, our team was able to successfully design and fabricate our sculpture. Not only does the sculpture incorporate principal elements commonly found on these structures such as loop-d-loops, it also includes unique elements such as the machined helix.

One important aspect of our machine set forth by our objectives was to serve as an educational tool. This was accomplished by using elements that clearly illustrate physics and engineering principles and the informative display screen. During a showing of the project at an open house, this objective was satisfied. A potential student explained to their father how the momentum collision element functioned. Observes stared intently watching the controlled chaos.

During the project presentation day, spectators were quoted saying they were mesmerized by the machine and many returned to view the sculpture multiple times. It was both rewarding and exciting to see the sculpture engaging and impacting such a large audience. In a years' time, an original concept became a real educational and entertaining tool.

Chapter 6: FUTURE WORK / RECOMENDATIONS

We believe there is still a number of exciting additions that could improve our project. These add-ons would also improve the educational quality of this sculpture, making it even more valuable to WPI. This chapter delineates potential improvements.

The first addition to the sculpture our team recommends is an LED display on the pegboard. Sensors would be added to the bins on the bottom of the board to count the number of balls that exit each bin. Once a ball would be counted, an LED would illuminate to display the number of balls that passed through that bin. Ideally, a bell curve would be displayed to denote the binomial distribution after a defined number of balls pass through. Then, after a set number of balls are counted, the display would reset. This would be a great opportunity to display the live distribution and keep the viewer's engagement with the sculpture.

The sculpture could be enhanced with sensors. Sensors could output ball velocity and acceleration on a number of elements. It would be exciting to display the marble's velocity as it changes through the loop-d-loop and other sloped elements within the sculpture. Having these values displayed on a tablet would have immense educational value and aid the viewer in understanding the marble's motion and the physics principles that dictate the sculpture.

There is potential for future MQP's to enhance the sculpture by adding the discussed sensor elements. Interactive elements could also be added to heightened user engagement and attention to the sculpture.

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Appendix A: Elements Not Included

This appendix outlines the number of elements that our team initially suggested to include in the sculpture and for one of many reasons did not make the final cut. Some of these elements still have potential to be added into the sculpture.

A.1: Pop-Up Letters

One element our team proposed involved spinning letters or a spinning object on the track that would display and decrease the marbles velocity. Our intention was to title this element "WPI Pop Up." This would consist of the marble rolling on the track and colliding with a piece of wood that would swing up and display a letter in sequence to spell out "W.P.I." The letters could be printed, laminated and then glued to the wood spinner. This was planned to involve an 8" section of track and letters of approximately 1.5" in height each. The pieces of wood that have the lettering would be attached to a piece of steel that runs perpendicular to the track over top. These rods of steel would attach to two steel rods that ran parallel to the track and attach to two steel support rings. A preliminary sketch design is shown below in Figure 98.

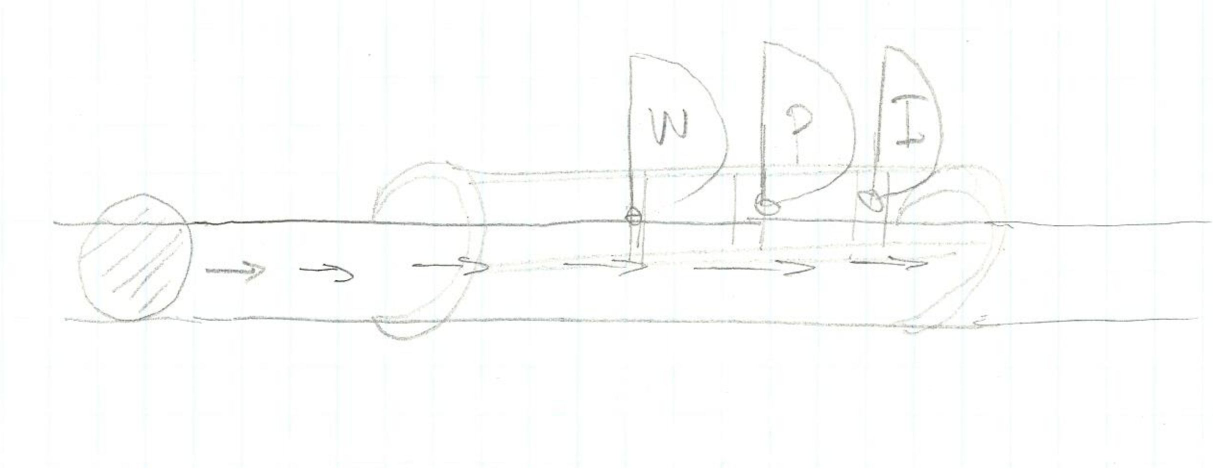

Figure 98: WPI Pop Up Letters Design Sketch

A.2: Airplane Slide

A second element that was planned out for the engineering path was titled airplane slide. The airplane slide would involve a linear guide (the airplane) sitting on an incline with a ball pre-loaded in front of the guide as shown in Figure 99.

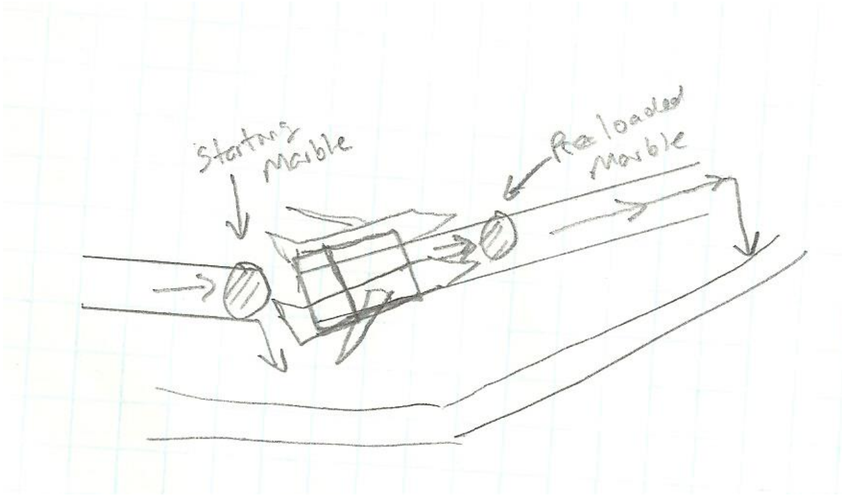

Figure 99: Linear Guide Airplane Slide Design Sketch

When another marble rolls and makes contact with the “airplane,” the guide would slide up the incline causing the pre-loaded ball to drop off the track. The ball that initiated the collision would also drop to this other track. This represents aerospace engineering by the means of an airplane taking flight and also involves the physics principle of energy transfer and conservation of momentum.

An IGUS linear guide was donated by Sperry Rail (a company in Danbury CT), but was very heavy and the rolling friction was too high for this application. It was challenging to spec out an appropriate liner guide that’s mass was less than the 21 g marble, so this element was not pursued for the sculpture. We replaced this element with the momentum collision element.

A.3: Accelerometer / Velocity Sensor

As described in the future work section of this report, it would be beneficial to have sensors along the track to report live data to the viewer. Our team planned to have sensors on the track to measure the speed of the marble then display the result on a screen. Another planned option was to have the ball drop and measure the force by an accelerometer. A Raspberry Pi device would be used to accomplish either of these tasks.

Each option has different pricing. The Raspberry Pi board has a base price of $40.99 and then the sensors are additional. The motion sensors would be $25.62 ($12.81 each), the accelerometer is $14.99, the simple display is $26.71, and the 7” LCD are around $75 for a non-touch. The total price would range from $82.69 (accelerometer and simple display) to $156.60 (accelerometer, motion sensors, and color display).

A.4: Inverted Ball Arm

A similar element to the standard ball arms that we planned to include in our sculpture but did not make the final design was the inverted ball arm. The inverted ball arm is fairly simple to build and entertaining to watch, but complicated to describe. A diagram of an inverted ball arm can be seen below in Figure 100:

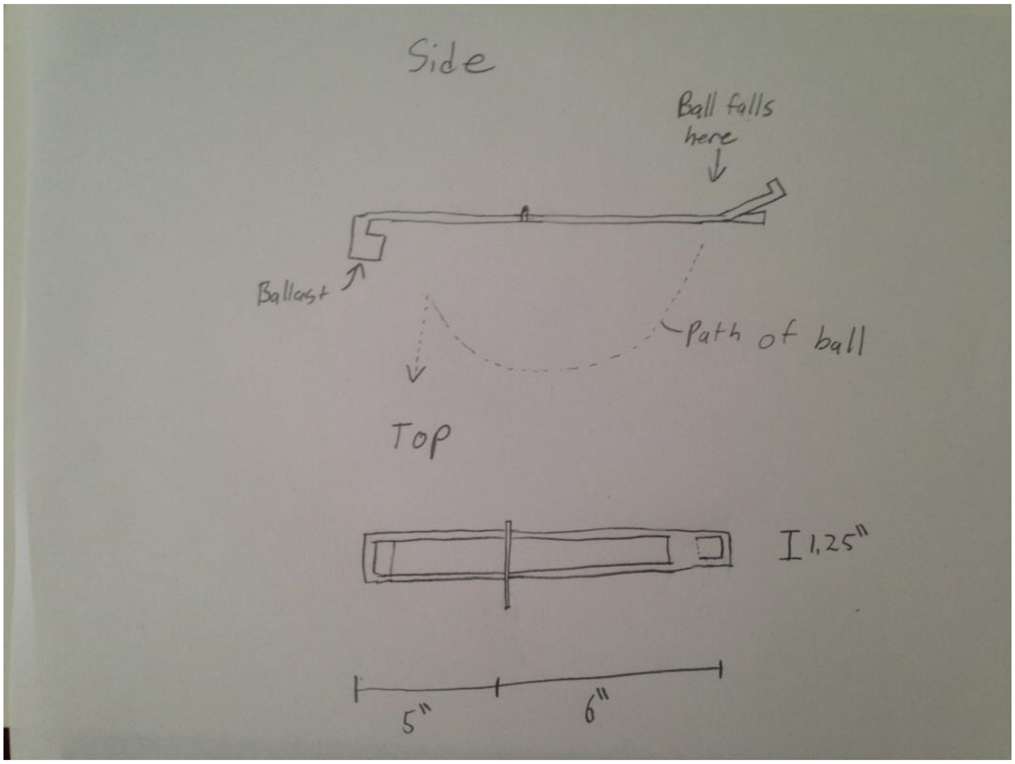

Figure 100: Sketch of Principle Operation for Inverted Ball Arms

First, the ball falls on a plate on the right side of the mechanism. The ball then catches on the angled pieces on the far right as the entire arm rotates around the pivot in the middle. Once the arm has rotated about 120 degrees, the ball falls out, almost straight down from where it was released. The location of the ballast then allows the mechanism to reset itself over a period of about 20 seconds. The design shown is the general form.

A.5: Ferris Wheel

The final element that we planned to include in our design that was not selected was the Ferris wheel element, which would represent MQP. This element would represent the MQP project by displaying the iterative nature of engineering design through the rotation of the Ferris wheel. The intention was to place it after the IQP bowl to complement its chaotic nature with a slower and more orderly process. Balls would exit the IQP bowl onto a section of track that would lead up to the Ferris wheel component.

The Ferris wheel itself was designed to consist of evenly spaced "cups" placed along the circumference of a circular disc that is on a free rotation axle. When a ball reaches the Ferris wheel, it would roll off the track into one of the "cups". The weight of this ball would cause the Ferris wheel to rotate angularly in the direction of the rolling ball. This would cause another ball that has been sitting on the Ferris wheel to move into a horizontally mounted steel rod that would gently tip the "cup" the ball sits in until the ball spills out and onto the next section of track. This process would continue happening as balls roll into the Ferris wheel. A sketch of the Ferris wheel design is shown in Figure 101.

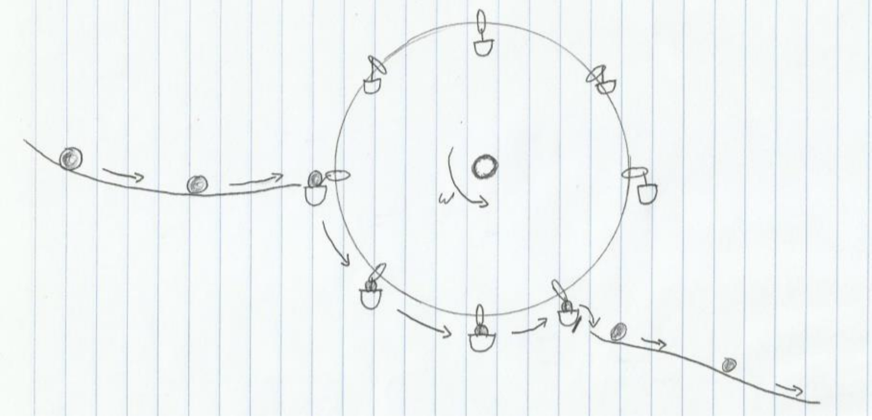

Figure 101: Sketch of Ferris Wheel Design

Appendix B: Operation Guide

This serves as an operation guide and outlines the required maintenance the sculpture requires.

Running the machine

Startup:

- One ball must be placed on the momentum billiard. The momentum billiard is the element located in the top right of the machine when looking at the side the pegboard is facing. See Figure 71 for what the element should look like.
- All the rest of the marbles should be placed on the section of track at the bottom of the sculpture that leads to the lift
- The switch to turn the sculpture is located on the underside of the sculpture near the lift.

Operation

- While the sculpture was designed to be as consistent as possible, it does occasionally fail. As such, the sculpture should always be monitored. There are three classifications of failures:
  1. **Minor:** Requires no maintenance. Marble does not follow intended path but still returns to the collection track.
  2. **Failure:** Requires periodic maintenance. The majority of failures will just be balls falling onto the bottom of the sculpture, outside the catch basin. These do not require immediate attention, though the balls on the bottom of the sculpture should be periodically placed back on the track.
  3. **Catastrophic** – Requires immediate maintenance. A marble might get jammed, causing all other balls that follow it to fail or get stuck. If this happens, that marble must be immediately removed to allow normal operation to be resumed.

Shutdown:

- Turn off the lift
- Remove the ball from the momentum billiard
- If the sculpture is going to be unused for an extended period of time, remove all balls from the track leading into the lift and store in a bag.

Moving the Sculpture

Before moving the sculpture, all balls must be removed, and a piece of tape must be wrapped around the wires of Newton’s cradle so that it does not get tangled. Once unplugged, the sculpture can be lifted off the base with one person on each side, pulling up on the handles simultaneously. The bottom of the sculpture is fitted with casters, so it can then be placed on the ground and rolled to its destination. The dimensions are such that it can fit through a standard doorway.

When putting the sculpture back onto the base, the main structure must be lifted onto the base. First, ensure that the lift on the sculpture is on the side where “Lift” is written on the base. If this is not the case, the sculpture will not sit correctly. The cord must be placed inside the base before the sculpture is lifted to ensure it doesn’t get caught between the sculpture and the base. The sculpture can then be lifted into the base. It must be lowered at the same time into both sides in order to sit correctly. Once all four corners are in, the machine may then be run. See “Running the machine” above for details.

Periodic Maintenance

In addition to replacing balls and removing jams, some periodic maintenance must be done. Approximately every 40 hours the machine is run or month the machine is on display, the chain should be oiled. If the chain appears loose, it may need to be tightened. To tighten the chain, the 2”x3” wooden supports holding up the gear on the back side of the chain must be moved backward. To do this, the two screws holding in each support must be removed, and after the supports have been moved back, put back in in new holes.

Appendix C: Personal Correspondence – David Morrell

**Note—This is a reply to an email inquiring about funnel design **

Hi Adam,

Thanks for your enquiry.

As a guide, I use a Wok lid for my bowl collectors. I then drill a hole in the base to allow for the marble to fall through.

I have seen a few conical shaped collectors, however I would be cautious to design something this way, unless you can regulate the number of marbles entering the collector. Where the collector becomes narrower, you may find that marbles will hit each other and possibly jam inside the smallest part of the cone.

I hope this makes sense.

Cheers

David

www.rollingballsculpture.com.au

www.avidcreations.com.au

Avid Creations