Team 18F02 Kinetic A

Report 2 (Final Report)

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DISCLAIMER

EXECUTIVE SUMMARY

A capstone team, consisting of four diversely talented engineering students, was given a task: to build a kinetic sculpture that exemplifies at least three engineering principles in a fun, engaging way and is easily transportable from room to room. The team began by discussing with the client, Dr. Sarah Oman, about the requirements for a final product. Once the customer needs and requirements were gathered, the team prepared for concept generation by conducting research and benchmarking of existing kinetic sculptures and by decomposing a kinetic sculpture to its basic functions. These preliminary steps were vital in having an in-depth knowledge of a kinetic sculpture. With this knowledge, the team generated around 20 concepts. These concepts were then evaluated through the use of a Pugh chart and decision matrix. These techniques helped select the concept best capable of meeting the customer requirements. The selected design, The Archimedes Screw, was then constructed in a 3D modeling software, Solidworks. This was so the prototype could be 3D printed, using a team members own 3D printers. The entire prototype took around 300 hours of printing time for total completion. This report details each step in the process to create a kinetic sculpture for the Northern Arizona University Engineering Building.

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1 BACKGROUND

1.1 Introduction

Engineering is one of the most important things in our world today. Without this discipline, a vast majority of products we use every day would not exist. Our goal is to build a kinetic sculpture that will showcase many different concepts of engineering such as fluid flow, gear mechanisms, and conservation of energy. If the group accomplishes this, it could lead to an increase in the interest and the enrollment of students in an engineering program at NAU.

1.2 Project Description

Following is the original project description provided by the sponsor, Dr. Sarah Oman;

“This project would involve creating a Kinetic Sculpture for the Engineering building at Northern Arizona University (NAU). The focus of this sculpture would be to provide a physical example of Mechanical Engineering principles in a fun and engaging manner. The system should be robust to moving from room to room if needed, and clearly illustrate at least three engineering principles. It should have signage that describes the principles and represents the ME department in a positive, marketable light.”

1.3 Original System

This project involved the design of a completely new kinetic sculpture. There was no original kinetics sculpture before this project began.

2 REQUIREMENTS

Contained within this section of the report are the descriptions of the requirements of the Kinetic Sculpture capstone project. Below, are sections containing the Customer Requirements, Engineering Requirements, Testing Procedures, House of Quality (QFD), and Black Box Model.

2.1 Customer Requirements (CRs)

The results of team meetings and discussion with the project sponsor brought about the customer requirements and ratings as shown below. The average weighting of the customer requirements was found by the team. The team rated each customer requirement and found the average of each one. The weightings used were on a scale of 1 to 5 with 1 being least important and 5 being most important.

Table 2.1.1: Customer Requirements and Weightings

Customer Requirements	Average Weighting
Moveable (Can Fit Through Door)	3.875
Cost Effective	2.5
Durable	2.75
Represent Engineering Positively	4.25
Safe to Use	4.25
Visually Pleasing	4
Reliable	4

The customer requirements, seen in Table 2.1.1 above, were found to assist the team to meet the requirements of the project. The customer requirements given directly from the client are as follows: that it is easily moved, under $5000, display at least three engineering principles, and to represent engineering positively. The group made some of the requirements more specific by applying more measurable values to the requirements. While the original requirements said to make the sculpture easily movable, the group decided to limit the sculpture to be able to fit through a door and be durable enough to last a few years. Also, the group decided that in order for people to freely use and interact with the sculpture, safety and reliability would be important customer requirements so that the sculpture will always work without the fear of injury. Lastly, the group added the visually pleasing customer requirement to the list due to the notion that sculptures should be aesthetically pleasing. After generating and weighing the customer requirements for the project, the group was then able to create engineering requirements to quantitatively measure the requirements.

2.2 Engineering Requirements (ERs)

After finding and evaluating the customer requirements (above) for the project, the group was then able to extract engineering requirements out of the customer needs to ensure that every need would be met in a measurable way. The engineering requirements, rational for choosing them, and their respective units determined are listed below:

- Less than 150 lbs (pounds)
  - The kinetic sculpture is required to be able to move relatively easily throughout the engineering building for demonstrations and events and so, it must be able to be lifted and moved by two people. The group decided that 150 lbs would be the maximum weight for the project by assuming that the average person can lift around 75 lbs with relative

ease.

- Less than 3x3x6 ft (ft^3)
    - The sculpture is required to be easily moveable and this includes being able to be carried through doorways and so, the group determined that a size of 3x3x6 ft would be the maximum size of the sculpture so that it may be carried through doorways and not be a “tight fit”.
- Under $5000 ($)
    - Because the kinetic sculpture will involve many moving parts, the group decided that the sculpture will cost no more than $5000 so as to not waste money where it does not need to be wasted.
- Material Strength (MPa)
    - Because durability is a customer requirement, the group determined that material strength is an important engineering requirement because the group does not want the sculpture to yield due to stresses put on it by itself or others interacting with it.
- Material Hardness (HB)
    - To further elaborate on the durable customer requirement, the group decided that knowing the Brinell hardness of the materials used will be important so to make sure the materials used are tough enough to withstand the stresses placed on them as well as to reduce pitting corrosion.
- Corrosion Rate (mm/year)
    - By knowing the corrosion rate (CPR) of the materials when interacting with each other, the group will be able to place materials together that will not diffuse and corrode each other as fast as others. Thus, adding to the durability and reliability of the sculpture.
- Factor of Safety
    - By finding the factor of safety for the kinetic sculpture, the group will be able to increase the safety of the sculpture and plan/design around potential dangers with the sculpture to decrease the risk to those interacting with the machine.
- At Least 3 Engineering Principles
    - The requirements of this project are to display at least three engineering principles in the sculpture and so, the group determined that this would be a measurable engineering requirement.
- Operational For At Least 30 Minutes Without Power (minutes)
    - The group determined that, in order to say the system is “reliable”, they would like the system to run for at least 30 minutes without power after receiving around 30 seconds to one minute of power through human energy input.
- Least Power Required (W)
    - For the reliable customer need, the group determined that the least amount of human energy required to run the sculpture is ideal and so, a requirement of least power required was determined to be necessary.
- 9/10 People Like the Aesthetics (People)
    - For the “visually pleasing” customer need, the group determined that a measurable

engineering requirement would be that 9/10 people surveyed like the sculpture and the way it looks and operates.

Once the customer and engineering requirements were all found and compiled by the group, they were then able to arrange and sort them all into a table with targets and tolerances (below).

Table 2.2.1: Targets and Tolerances

Engineering Requirements	**Target**	**Tolerance**
Less than 150 lbs	≤ 150 lbs	+5 lbs, -150 lbs
Less than 3x3x6	≤ 54 ft^3	+1 ft^3, - 54 ft^3
Under $5000	≤ $5000	-$5000
Material Strength	≥ 40 MPa	+100 MPa
Material Hardness	≥ 50 HB	+100 HB
Corrosion Rate	≤ -.25 V DC Potential	-1 V DC
Factor of Safety	1	±1
At Least 3 Principles	3 Principles	+5 Principles
Operational For 30 Minutes Without Power	30 min	±10 min
Least Power Required	≤ 200 W	±100 W
9/10 People Like	90%	+10%, -5%

Next, the group was able to create and organize a QFD (House of Quality) and ways to test each requirement from this information.

2.3 Testing Procedures (TPs)

After organizing and understanding the engineering requirements and the targets/tolerances for each one, the group was then able to determine procedures to test each requirement to ensure that they are all met. The procedure for each engineering requirement is discussed in detail below:

- Less than 150 lbs (pounds)
    - This requirement will be tested by putting the project on a scale and making sure that it is easily transportable by two people.
- Less than 3x3x6 ft (ft^3)
    - By taking measurements of the final design, this requirement can consistently be tested during and after the construction phase of the project.
- Under $5000 ($)
    - Through the use of and constant bookkeeping of a budget, the group can ensure that the cost of the sculpture stays within the $5000 budget.
- Material Strength (MPa)
    - When finished with the casting and surface treatment segments of this project, the group will be able to take measurements of the materials and extra materials to ensure the material has a high enough yield strength.

- Material Hardness (HB)
  - Through checks of Brinell Hardness tables and values for the alloy the group will be casting, the group can be sure to have the materials hardness kept in check. Also, if time allots, the group will be able to send samples to be checked and tested for their exact hardness.
- Corrosion Rate (mm/year)
  - By ensuring the group uses the proper materials and surface treatments, the corrosion rate of the material can be checked through the use of Galvanic Series.
- Factor of Safety
  - By using the power and torque found for the project, the group can back out a proper factor of safety for the sculpture to allow time and effort to be taken to ensure the correct safety measures have been taken.
- At Least 3 Engineering Principles
  - Throughout the design process, the group needs to determine that the sculpture will be containing at least three principles and keep track and lists of the concepts.
- Operational For At Least 30 Minutes Without Power (minutes)
  - By timing the sculpture (once created) while it unwinds, the group can fully wind it and let the piece go to determine if this requirement is met.
- Least Power Required (W)
  - Through the use of proper gear ratios and gear train designs, the group can minimize the power needed to run the sculpture. In order to measure the power, the group can find power required through the torque of the sculpture.
- 9/10 People Like the Aesthetics (People)
  - By taking constant surveys and asking for design input from staff and students at NAU, the group will be able to consistently test the requirement of a 90% approval rate.

Since the testing procedures have been fully developed and derived, the group was able to create a full, final QFD (House of Quality) for the project.

2.4 House of Quality (HoQ)

After the group created and compiled the customer needs and engineering requirements, they were then able to create a House of Quality, seen in Figure 2.4.1 below. This house of quality has helped the group to create concepts and design around the requirements given and created in order to create a kinetic sculpture that meets and/or exceeds the requirements of the project. The requirements of the project given to the group were to create a kinetic sculpture that displays at least three engineering principles in a positive manner and be visually pleasing while still being of a proper size and weight to easily transport throughout the engineering building and NAU campus.

Roof Matrix (NO INPUT IN THIS AREA)

	Less than 150 lbs	Less than 3x3x6	Under $5000	Material Strength	Material Hardness	Corrosion Rate	Factor of Safety	At Least 3 Principles	Operational For 30min W/out Power	Least Power Required	9/10 People Like
Less than 150 lbs											
Less than 3x3x6	**										
Under $5000		*									
Material Strength	*		-								
Material Hardness	*		-	*							
Corrosion Rate			*	*	*						
Factor of Safety			*	*	*	**					
At Least 3 Principles			*				*				
Operational For 30min W/out Power								-			
Least Power Required						-	*	-	-		
9/10 People Like											

**	Strong Pos. Correlation
*	Positive Correlation
	No Correlation
-	Negative Correlation
--	Strong Neg. Correlation

PHASE I QFD

Design Objectives	Customer Weights	Less than 150 lbs	Less than 3x3x6	Under $5000	Material Strength	Material Hardness	Corrosion Rate	Factor of Safety	At Least 3 Principles	Operational For 30min W/o	Least Power Required	9/10 People Like
Preferred (up or down)												
Moveable (Can Fit Through Door)	3.875	9	9					3				
Cost Effective	2.5	3	3	9					1	1		
Durable	2.75	1	1	3	9	3	3					
Represent Engineering Positively	4.25								3	1		3
Safe To Use	4.25	9	1		1		3	9				
Visually Pleasing	4								3	1		9
Reliable	4				1	1	1	3		3	3	
	ATI	83.38	49.38	30.75	33	12.25	25	61.88	27.25	22.75	12	48.75
	RTI	21%	12%	8%	8%	3%	6%	15%	7%	6%	3%	12%
	Unit of Measure	lbs	ft^3	$	Mpa	B	mm/year			min	W	People

Figure 2.4.1: QFD (House of Quality)

The House of Quality has helped the team in the design process by allowing the group members to keep watch of the requirements and details of the project while at the same time allowing them to create more creative designs due to the broad nature of the project. For example, since there are only seven major customer requirements, the group has not found much difficulty in concept generation while at the same time, meeting all customer requirements. Through the use of a QFD, the group was able to determine the most important ER's (engineering requirements) to be Less than 150 lbs, Factor of Safety, Less than 3x3x6, and 9/10 People Like. These engineering requirements will be important to the full design of the sculpture throughout the completion of the design process.

3 EXISTING DESIGNS

Through research, a plethora of designs for kinetic sculptures were unearthed. Most of these designs were fluid, motor, or spring powered. This is due to the ease of implementation of these power supplies. Renowned fluid sculpture artists include Anthony Howe and Theo Jansen. David Roy is the most well – known kinetic artist using springs to power his sculptures. Jean Tinguely and Anthony Calder are the most famous kinetic artists that primarily use a motor to power their sculptures. Although these are the three main power sources most kinetic artists use, there are multiple ways to power these sculptures. Other power sources could be gravity, electricity, and even computer programming. However, due to the team's background, it will be easier to analyze and calculate for motors and springs rather than Arduinos and circuit boards.

3.1 Design Research

All research of existing designs was found through the internet. First, the team wanted to get an idea of what a kinetic sculpture encapsulates. To do this, the team watched Youtube videos of various kinetic sculptures. We then would search artists by name and identify how they powered their sculptures. The first sculpture identified was Anthony Howe. He is most known for his wind sculptures. His website, howeart.net [1], gave an insight on how to harness the wind's energy. Anthony Howe has also created sculptures powered by motors. Since these sculptures are fairly large and made of metals, the motors powering these sculptures must be powerful. Realizing there are multiple ways to power a kinetic sculpture, the team found artist, David Roy. David Roy is known for his spring/tension powered kinetic wall sculptures. Compared to Anthony Howe's art, David Roy's sculptures are easily transportable. David Roy's website, woodthatworks.com [2], introduced the team to constant torque springs. With these springs, the team can design a sculpture that has a long duration time. Once the constant torque springs were discovered and researched, the team dedicated concepts to that power source. However, the search for various kinetic sculptures continued. Through rigorous internet searches that included videos, PowerPoints, CAD drawings, and sketches of kinetic sculptures, the team found a plethora of existing designs. These various kinetic sculptures showcased different subsystems that influenced the team's concept generation and final design.

3.2 System Level

Kinetic sculptures try to achieve perpetual motion. Since energy is finite and perpetual motion can't be reached, kinetic artists have found ways to power their sculptures for long durations. Through research, the team has found this to be an important requirement. As stated earlier, constant torque springs can create enough torque to last hours. To achieve this, a hand crank will wind a constant torque spring. The spring will be connected to a gear train. As the spring unwinds, it will activate the gear train, causing our design to activate.

3.2.1 Existing Design #1: Di-Octo by Anthony Howe

This was the design that pushed the team towards pursuing a constant torque spring powered device. On David Roy's website, he showcases the design on a video. He states that with a full wind of the spring, the design can last for 48 hours [3]. This design includes a "3-wheel 2-spring arrangement" [3] that is away from the moving pieces. This can be seen in Figure 1 below.

Figure 3.2.1: Kindala - Forest by David Roy [3]

This arrangement allows for more control of the torque output. Placing the torque springs away from the moving pieces and adding wheels and ropes gives this design a long duration time. This design demonstrates how the team can utilize tension in ropes/belts to add duration time to the sculpture. Since the team's sculpture will be on display, a longer duration time is desired.

3.2.2 Existing Design #2: Di-Octo by Anthony Howe

Di-Octo is a wind sculpture created by Anthony Howe in 2014. In 2017, Anthony Howe donated Di-Octo to Concordia -University [4]. This sculpture is powered solely by the wind. Di-Octo can be seen in Figure 2 below.

Figure 3.2.2: Di-Octo by Anthony Howe [4]

Figure 3 showcases how Di-Octo harnesses the wind's energy. Attached to the 'tentacles' are metal, concave plates. These scoop the wind as the wind blows. According to the Montreal Gazette, Di-Octo is 8 meters tall, weighs 725 kilograms, and only requires 2 km/hr of wind for its moving parts to activate [5]. This design showcases the ease of utilizing wind energy. If desired, the team could harness the energy of Flagstaff's high velocity wind to power a sculpture.

3.2.3 Existing Design #3: Serendipity by David Roy

Serendipity is one of Roy's earlier works. This design showcases the notion of controlling the movement of the sculpture. Serendipity can be seen in Figure 3 below.

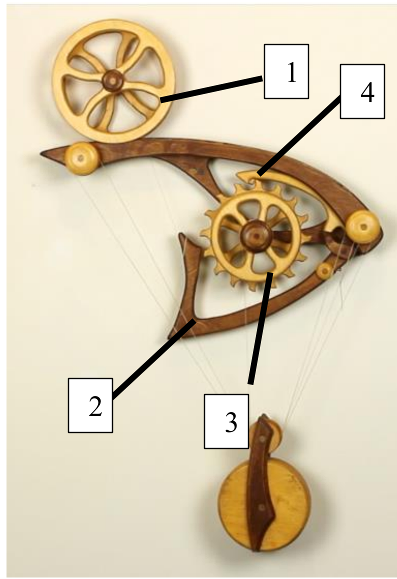

Figure 3.2.3: Serendipity by David Roy [6]

Serendipity's design is unique to his other sculptures. Strings are attached to every piece. The motion of the top disk, labeled 1 in Figure 3, activates the tension in the strings causing the other pieces to move. Once the top disk hits the bottom of the curve, it causes tension in the string causing the wooden piece, labeled 2 in Figure 3, to move up and push the gear. The gear, labeled 3 in Figure 3, is moved up, causing piece 4 to lift. While piece 4 is lifted, the gear rotates. Piece 4 then falls to stop the moving gear. This design exemplifies the beauty in a patient kinetic sculpture. Previously, the team was focused on continuously moving sculptures. This sculpture shows that a slow-moving sculpture can be equally as aesthetic. This design inspired some concepts such as the magnet pendulum and the double pendulum.

3.3 Functional Decomposition

Contained within this section is the team's functional decomposition of the Kinetic Sculpture project. Through the process of creating a Black Box Model, Work-Process Diagram, and description of each subsystem, the group was able to better comprehend their projects requirements.

3.3.1 Black Box Model

Through elaboration and clarification of the project, the team was able decide upon general inputs and outputs for objects, energies, and signals in order to determine and create a Black Box Model, seen in Figure 3.3.1 below.

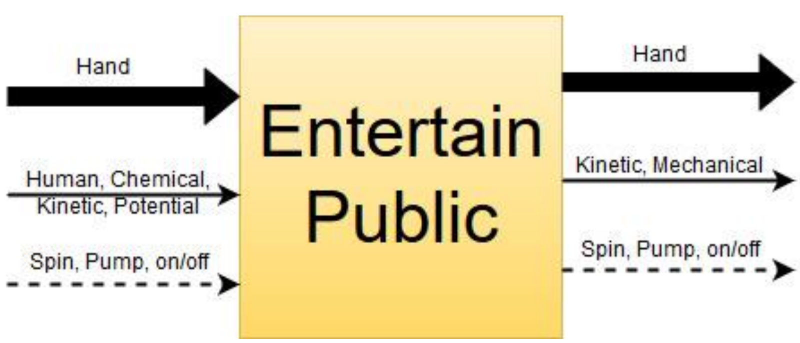

Figure 3.1: Black Box Model

This model helps the group to further understand their project as well as its general functions and flows in order to create concepts and better define them in a way that better meets the projects requirements.

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

Based on the Black Box Model that the team developed, a Work-Process Diagram was constructed to develop a more in depth look into how the overall function of our final design should work. The reason the team decided to use a Work-Process Diagram, opposed to a Functional Model or a Hierarchical Diagram, was because based on the scope of the team's project and design a detailed description on each function would be cumbersome, and so a broader look into the functions would be more appropriate. The Work-Process Diagram helped the team identify the key functions that are needed to accomplish the team's task and where those functions are required to be.

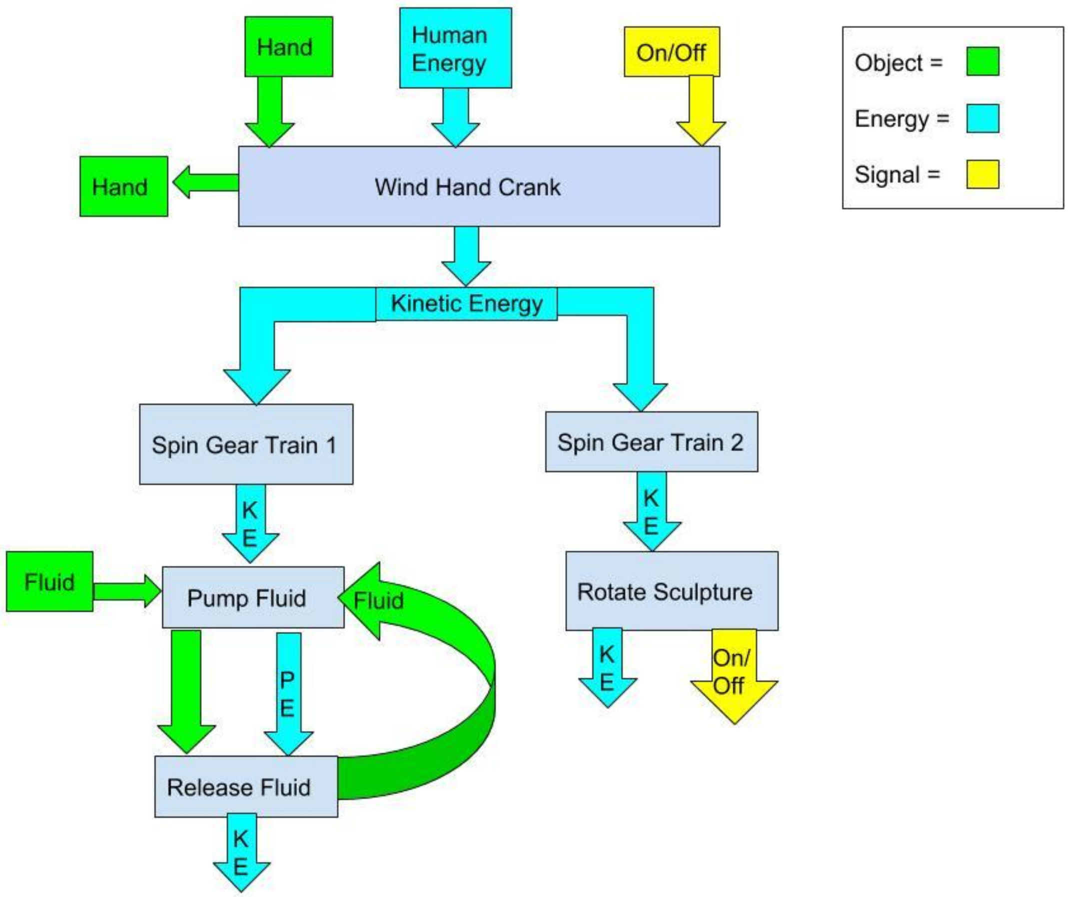

Figure 3.2: Work-Process Diagram

As seen in Figure 3.3.2 above, human energy begins the process of a kinetic sculpture. The team decided to start with this since most of our top designs utilized this. The user winds the hand crank, creating potential energy in a spring. When the stored energy within the spring is released, it activated a gear train using kinetic energy. The gear trains will either cause rotation of the sculpture, or it will activate the movement of the fluid.

3.4 Subsystem Level

There are many examples of kinetic sculptures crated by different artists which contain the same or similar subsystems to the groups' general ideas. These artists tend to use gears and constant torque springs in order to supply mechanical power to their pieces to allow them to run/operate for extended periods of time. The discussion of the important subsystems and existing designs are discussed below.

3.4.1 Subsystem #1: Wind Hand Crank/Spring

Through research, the most common kinetic sculptures were powered by wind energy or potential energy in a spring being converted to kinetic energy. The wind of a hand crank directly correlates with the latter. The hand crank would be connected to a spring. The team is considering a constant torque spring. The user will spin the hand crank, winding the constant torque spring. Once the user finishes using the hand crank, the spring will unwind. The team can use the rotation of the unwinding spring to make our sculpture move.

3.4.1.1 Existing Design #1: Duality by David Roy

This design utilizes the wind of a constant torque spring. In a video on David Roy's website, he showcases the sculpture. He starts by winding the spring by rotating the two main components clockwise. These two main components are labeled 1 in Figure 3.4.1 below.

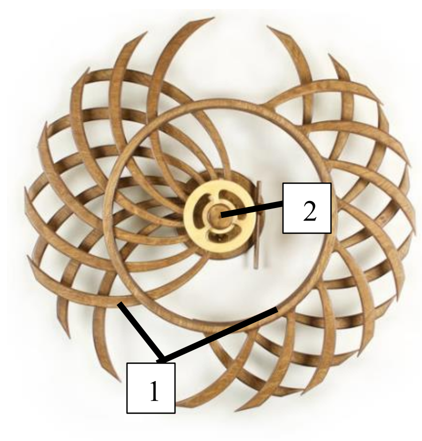

Figure 3.3: Duality by David Roy [7]

David Roy has been utilizing constant torque springs for years. He discreetly places the springs within the sculptures. For Duality, he places the springs in the center, labeled 2 in Figure 3.4.1 above. Roy states this design is called 'Duality' for the multiple balances needed to achieve while creating kinetic sculptures [7]. This sculpture's mechanical movements are in balance by a precise amount relative to gravity. Duality showcases the precise measurements and calculations the team needs to create a reliable, aesthetically pleasing sculpture. Also, Duality can run for approximately 8 hours off of one full wind of the spring [7]. If the team can fully understand how to efficiently implement a constant torque spring, the durability of our final design can be increased. The team is inspired by this idea because it is highly durable.

3.4.1.2 Existing Design #2: Zinnia by Clayton Boyer

Although very similar to Duality aesthetically, Zinnia differs in terms of how to wind the sculpture. With a constant torque spring placed directly in the middle, two opposing designs surround it. As seen in Figure 3.4.2 below, the two moving pieces rotate in opposite directions.

Figure 3.4: Zinnia by Clayton Boyer [8]

Unlike winding Duality, to wind Zinnia, the user must hold on to the moving piece in the background. Once the background moving piece is held, the user rotates the front piece clockwise, winding the constant torque spring. This method of winding the sculpture exemplifies the capabilities of torque springs. The team can manipulate the torque springs unwinding velocity, creating desired movements of our sculpture.

3.4.1.3 Existing Design #3: Circumvolve by Tom Boardman

This design utilizes a constant torque spring, however, the springs unwinding is manipulated by using ropes and tension. Circumvolve can be seen in figure 3.4.3 below.

Figure 3.5: Circumvolve by Tom Boardman [9]

Circumvolve is wound by rotating the mechanism on the bottom, which contains a stainless steel constant force spring, about 22 times [9]. The rope allows for minimal use of the constant force springs rotations, which gives the sculpture a higher duration time on one complete wind. A closer inspection of the design, as seen in Figure 3.4.4 below, reveals the use of two constant force springs.

Figure 3.6: Close-up of Circumvolve's winding mechanism [9]

The use of two constant force springs gives the sculpture a longer duration time. This design unveils the practicality of using two constant force springs. These springs combined with tension in rope to create motion can be implemented in the team's design to add duration to our sculpture's motion.

3.4.2 Subsystem #2: Spin Gear Train

If the team pursues the use of constant torque springs, a gear train might be added to create motion within our sculpture. With manipulating gear ratios in a gear train, the team can calculate a desired output speed for a sculpture.

3.4.2.1 Existing Design #1: Colibri by Derek Hugger

Colibri is a kinetic sculpture that simulates the movement of a hummingbird flapping its wings. This is achieved by the use of a gear train. This particular gear train spans horizontally at first, then rises vertically, as seen in Figure 3.4.5 below.

Figure 3.7: Colibri by Derek Hugger [10]

The various gear ratios create the separately timed movements of the wings, head, and body of the sculpture. The multitude of moving parts aids in the simulation of a flying hummingbird. This design showcases bio-mimicry and the creative liberties the team has with the movement of a kinetic sculpture.

3.4.2.2 Existing Design #2: The Promise by Andrea Davide

This design consists of a gear train that creates two moving pieces. These two pieces meet to create a visually pleasing sculpture. Once these two glass pieces touch, they stay connected for a few seconds, then they move apart from each other back to their initial places. As seen in Figure 3.4.6 below, the sculpture is powered by motors, Arduinos, and motion sensors [11].

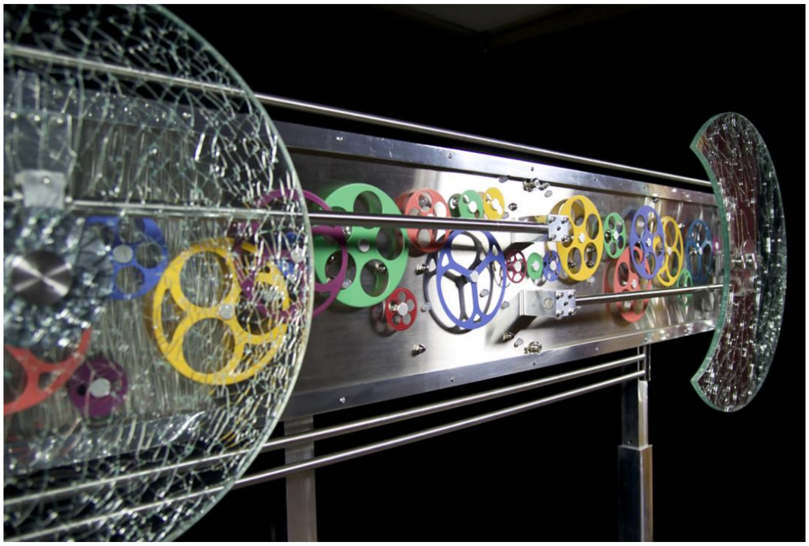

Figure 3.8: The Promise by Andrea Davide [11]

The gear train that causes movement of the glass pieces is seen above. This gear train is large and consists of various gears with different diameters and rotational speeds. The Promise showcases how gear trains can be manipulated to create an ideal linear or rotation velocity. The team can utilize this design to ensure our final design moves at a desired rate. Also, the gears in this piece are used as an aesthetic. So, the team can use this design as inspiration to use gears as a main aesthetic middle piece.

3.4.2.3 Existing Design #3: Viper by Clayton Boyer

This interactive design is inspired by the coiling of a viper. This sculptures motion depends heavily on a knowledge of gear trains.

Figure 3.9: Viper by Clayton Boyer [12]

At their initial position, the snakes are coiled vertically. As the user turns the crank, it causes the gear train to activate. The movement of the gear train uncoils the snakes, as seen in Figure 3.4.7 above. This unique design showcases the artistry behind the engineering and gives insight on train design and bio-mimicry. The placement of the gears is how the artist gives the illusion of a snake uncoiling. This sculpture showcases the importance and mechanical advantages of gear placements.

3.4.3 Subsystem #3: Pump Fluid

The team's last subsystem included a movement of fluid within the design. Researching existing designs utilizing this subsystem can broaden the horizons of concept generation. The fluid can either assist in the movement of the sculpture or it can add an aesthetic.

3.4.3.1 Existing Design #1: STRANDBEEST by Theo Jansen

Theo Jansen creates a series of extremely large wind-powered sculptures called STRANDBEESTs. These wind sculptures mimic animal movements. Theo Jansen posts videos of these sculptures 'walking' on a beach on YouTube.

Figure 3.10: STRANDBEEST by Theo Jansen [13]

Figure 3.4.8 showcases a STRANDBEEST sculpture created by Jansen. This sculpture requires the user to actively start the movement of the legs. Once the user creates motion, wind can carry this sculpture for a certain time period. The durability of this design is dependent on the force of the wind. This design shows the team how wind can be controlled to move large designs. Since Flagstaff has powerful wind forces, a large kinetic sculpture can be fabricated fairly easily using STRANDBEESTs as inspiration.

3.4.3.2 Existing Design #2: By the Bucket Full

This design includes water as its moving fluid. Made of metal, a bucket is filled with water. The velocity of the water hitting the full bucket causes it tip over, spilling the water. Then, the unbalanced weight causes the bucket to tilt back up to be filled with water again.

Figure 3.11: By the Bucket Full [14]

Figure 3.4.9 showcases By the Bucket Full sculpture at its initial placement. At this stage, the bucket is filled with water that is running through the pipe. Once the bucket is filled, the weight displacement causes the bucket to tip over, spilling the water. Once the bucket is emptied, the weight at the bottom of the bucket exceeds the top weight, causing the bucket to return to its initial spot. This design shows how the team can use a fluid to create motion in a sculpture. Alongside fluid, the team can use this piece as inspiration for weight displacement in a sculpture. The weight difference between the top and the bottom of the bucket gives the sculpture it's motion.

3.4.3.3 Existing Design #3: Synergy

This design consists of 5 metal pieces with water flowing off of them. The metal pieces represent human forms with different dimensions and water flow rates [15]. Each piece of this sculpture will take on different characteristics depending on the view angle, time of day, and amount of light reflecting off the sculpture.

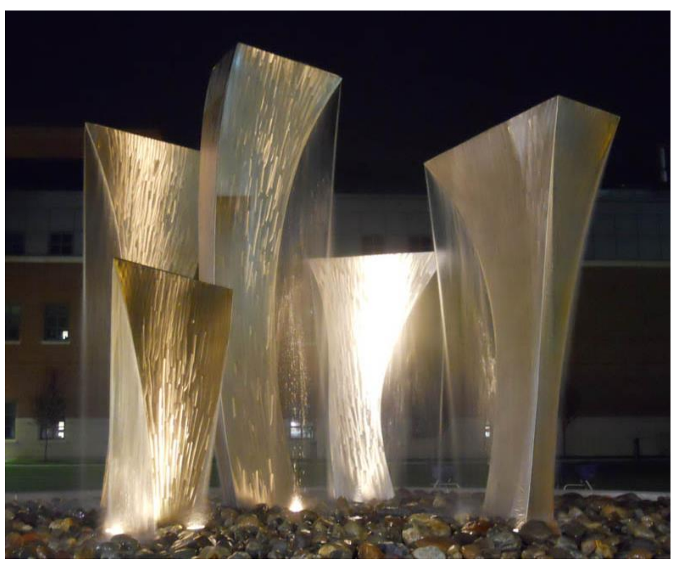

Figure 3.12: Synergy [15]

Figure 3.4.10 showcases the water sculpture, Synergy, viewed at night. The water cascades differently for each piece. This sculpture shows the team how a fluid can be used to add to the aesthetics of the whole sculpture. Since the metal structures in the design are simple and not visually pleasing, the fluid had to create the aesthetic. So, the team can use this sculpture as inspiration in concept generation to create an aesthetic.

4 DESIGNS CONSIDERED

After researching into existing designs of kinetic sculptures and using those as benchmarks, the team's next step was to begin the concept generation process. The first round of concept generation as done individually by each team member. After sharing the developed concepts with the entire team, the team began the second round by doing a 4-3-4, which is a version of the 6-3-5 method that was better suited for the size of the team. For the third and final round of generation, the entire team came together to create and combine the existing concepts that the team thought to be the most practical. In total, the team developed twenty concepts. The top designs are presented in descending order of how they scored on the decision matrix and Pugh chart, seen in Appendix B. The other designs generated are present in Appendix A.

4.1 Design #1: Archimedes Screw

An Archimedes Screw's purpose is to convert rotational energy into kinetic energy. It does this by using a helix pattern that has one end in a fluid and the other at the top of where the fluid is supposed to exit, cascading over a planetary gear system, as seen in Figure 4.1.1 below.

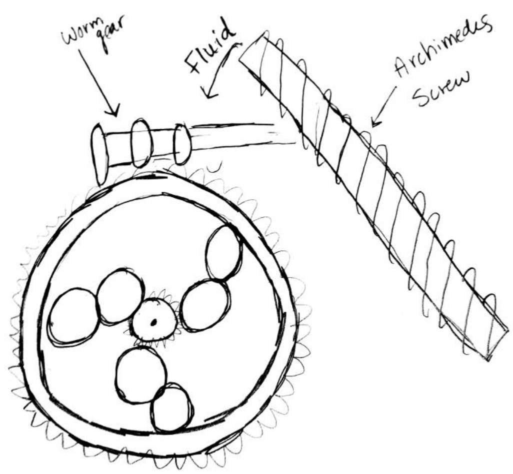

Figure 4.1: Archimedes Screw Concept

The screw should be tilted on a 30-60 degree angle to function properly. The Archimedes screw will be activated by winding a constant torque spring. The unwinding of the spring will activate a gear train. The gear train spins a worm gear, thus activating the planetary gear system. One positive aspect of this design is being able to pump a fluid with the use of only rotational energy, opposed to electric or hydraulic energy. A potential negative aspect for this design is the rate of which the fluid will be pumped for if the rate is too slow then it will not create the aesthetic look that the team is looking for.

4.2 Design #2: Solar System

A sun gear is placed in the middle. Surrounding the sun gear will be nine gears of various sizes that will spin around the sun gear, the nine gears will represent the nine planets, seen in Figure 4.2.1 below.

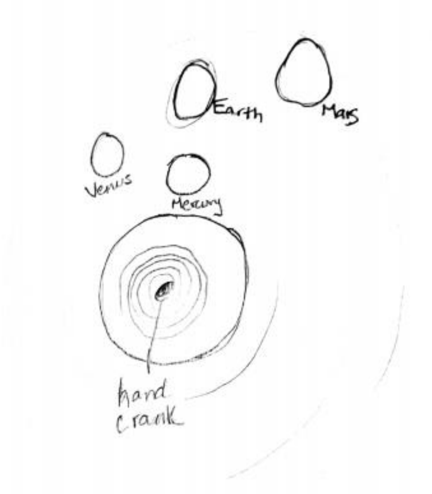

Figure 4.2: Solar System Concept

The goal will be to have them rotate around the sun gear proportionate to the planets revolution. A positive aspect of this design will be effectively using gears that are already in use to also create an aesthetically pleasing piece of art. A negative aspect of this design is the calculations behind the proportionality of the planets revolutions around the sun with the gears revolutions around the sun gear.

4.3 Design #3: 60 Seconds

The moving gear will make one revolution every 60 seconds, as seen in Figure 4.3.1 below.

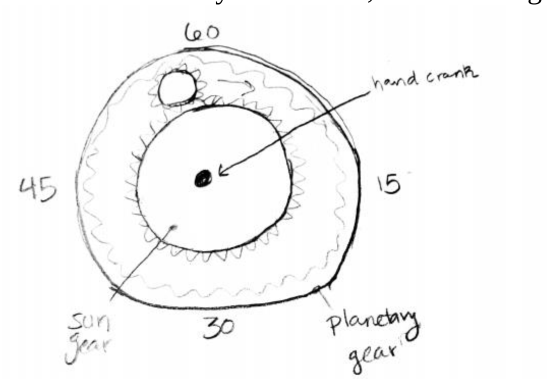

Figure 4.3: 60 Seconds Concept

Attached to this gear would be a minute hand that could then display the time by the minutes. The simplicity of this design is a positive aspect. The ease of implementation given gear sizes and input power, the team could easily make a gear that could run at one revolution per minute. However, the constant unwinding and winding of the spring will cause discrepancies in tracking time.

4.4 Design #4: Run Doggie, Run

Powered by a constant torque spring, a gear train will connect to a dog sculpture. The dog's legs are connected to two gears at the end of the gear train, as seen in Figure 4.4.1 below.

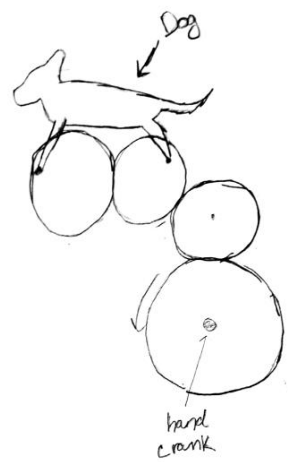

Figure 4.4: Run, Doggie, Run Concept

The rotation of the gears will simulate a dog running. This design is aesthetically pleasing and the cost would be low. However, this design has a lot of moving parts and tedious calculations, which increases the difficulty and feasibility.

4.5 Design #5: Bubble Blower

This concept involves a pipe that utilizes air as its moving fluid. This pipe will include several holes around the circumference. The velocity of the fluid and the diameters of the holes must be minimized in order to keep the durability of the design high. The pipe will be coated in a soap-like substance that will generate bubbles to be blown out of the holes on the pipes sides.

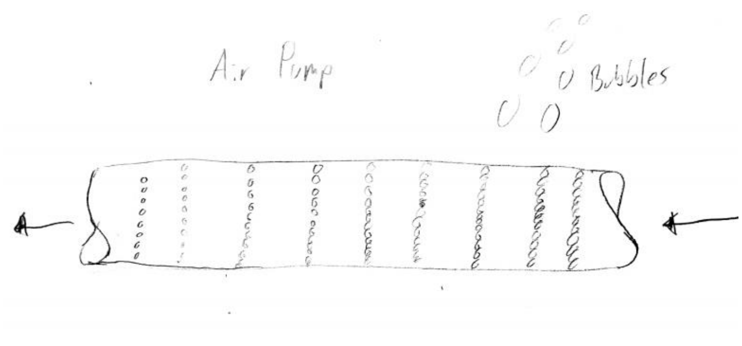

Figure 4.5: Bubble Blower Concept

Positive aspects of this design include the low price for purchasing a pipe and the ease of machining holes along the pipe. Negatively, the simplicity of a pipe with holes and flowing air decreases the aesthetic appeal. Also, constantly resupplying the soap lowers the durability of the design.

4.6 Design #6: Magnetic Pendulum

The magnetic pendulum concept uses the properties of magnets and how similar poles resist each other. By dropping the magnets from a height while having their north poles directed towards each other, they will reach a point of resistance and forcibly bounce away and their south poles will travel towards the top of the design which will be lined with south poles to "shoot" the pendulums back down. The concept is supposed to bounce back and forth indefinitely, simulating perpetual motion. This design concept can be seen below, in Figure 4.6.1.

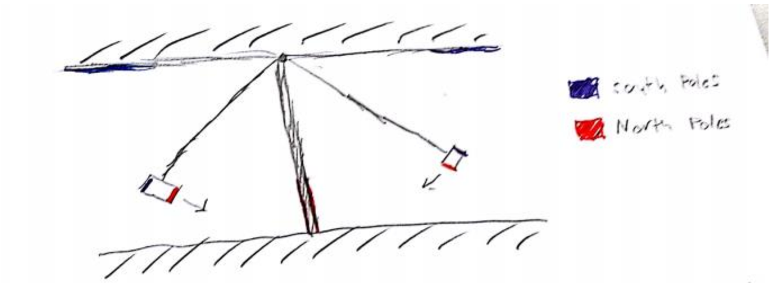

Figure 4.6: Magnetic Pendulum Concept

A positive aspect of this design is the single action by the user to drop the pendulums. This design could also be educational, teaching future NAU students about magnetism. Although the design seeks to find perpetual motion, it can never be achieved. Also, the magnets will need to be replaced fairly often as their poles unpolarize.

4.7 Design #7: Double Pendulum

The double pendulum concept is inspired by chaos theory. The behavior of the pendulum highly varies depending on the initial starting point, making it chaotic. The motion of the pendulum also depends on the material. A heavier material will cause different results than a lighter material. The double pendulum concept is seen below, in Figure 4.7.1.

Figure 4.7.1: Double Pendulum Concept

The bird on the top pendulum is added to create a visually pleasing image. The goal is to have a marker attached to the back of the bird to mark its path of movement. The pendulum will be attached to a circular piece of white board. The marker would be a dry erase, so the movement can be easily seen for multiple starting points. However, a negative aspect would be the constant replacement of dry erase markers. Also, the whiteboard would need replacing every few months. The durability of this design is much lower than others.

4.8 Design #8: 52 Card Shuffle

This design was highly inspired by Anthony Howes wind sculptures. This design would have 52 different air foils placed around a steel ring. The airfoils would be in the shape of the four different suits within a deck of cards. This can be seen in Figure 4.8.1 below.

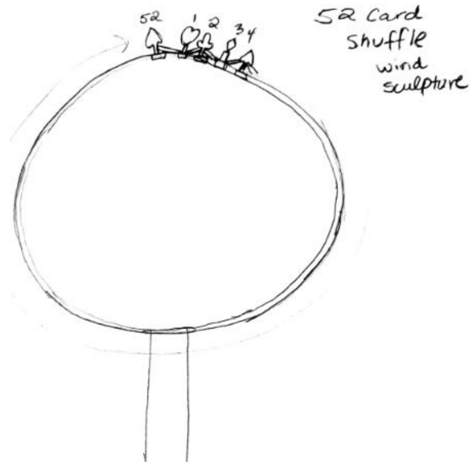

Figure 4.8.1: 52 Card Shuffle Concept

The air foils will be in an alternate pattern given the four suits. Each foil will be connected to each other. The goal is to have the air foils rotate consecutively. So, as the first air foil is rotating, it will cause the second air foil to rotate, which then causes the third one to rotate, and so forth. This would be accomplished by using various weights for the air foils. This concepts durability and duration depend on the power of the wind. However, a negative aspect is the size restraint. Since size is an important customer requirement, this design would not meet the necessary standards for the project.

4.9 Design #9: Magnetic Ball

This design focuses on the power of magnetism. A magnetic ball will be placed atop a bowl-shaped device. The ball will be within a track to prevent the ball from falling off. A magnet will be placed directly opposite of the ball. This is seen below in Figure 4.9.1.

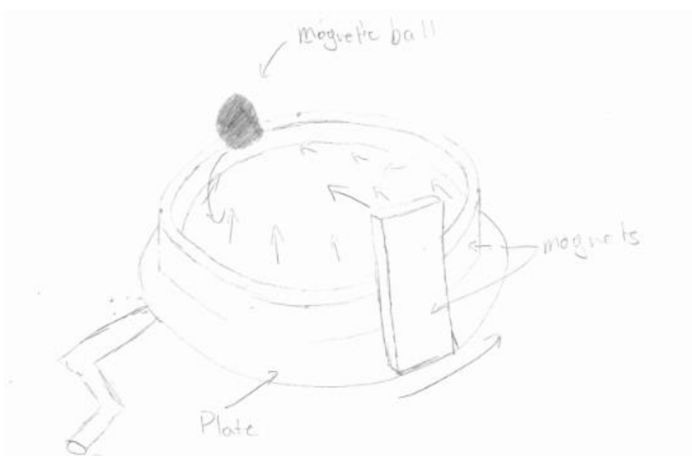

Figure 4.9.1: Magnetic Ball Concept

The user will wind the sculpture using a hand crank. The stored tension will then be released, spinning the magnet. The movement of the magnet will cause the ball to move, as it will be repelled from the magnet. The durability and reliability of this design is inferior to other designs. The magnets would unpolarize after a certain duration, making this design obsolete.

4.10 Design #10: Dual Railguns

This design involves the use of two railguns. The first railgun fires directly into the second railgun. The second railgun then uses the energy from the first railgun to then shoot directly back into the first railgun. This process will repeat until the energy between then dissipates. This concept can be seen below in Figure 4.10.1.

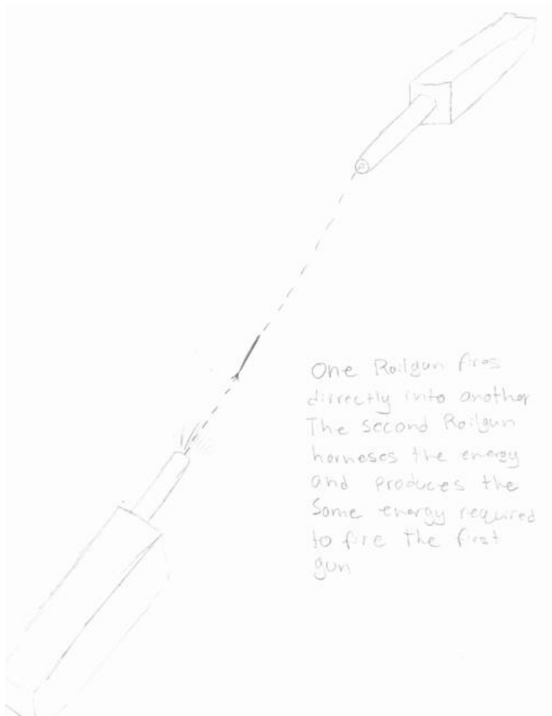

Figure 4.10.1: Dual Railgun Concept

Although this concept would be fun to execute, the reality of building this design is thin. Not only would this design be highly dangerous, the idea of harnessing the entire energy from the first shot of the first railgun is improbable.

5 DESIGN SELECTED – First Semester

From the team's twenty designs considered they have decided to combine a few of the better designs into a single final design of their kinetic sculpture. The design selected will be a combination of the following designs; Archimedes Screw, Solar System, 60 Seconds, and Run Doggie Run. The gear trains in each of these concepts can help the team finalize the proper gear ratios for a final design.

5.1 Rationale for Design Selection

After evaluating all twenty designs considered through a Pugh Chart, found in Appendix B, the team was able to narrow down the designs to the top seven designs. The seven concepts that scored the highest on the Pugh Chart all show strong correlations to the desired customer needs of the project, the seven designs include; Archimedes Screw, 60 Seconds, Run Doggie Run, Music Box, Bubble Blower, Solar System, and Magnetic Pendulum. While the thirteen other designs considered were not necessarily bad ideas, they did not correlate with the project's customer needs as well as the highest scoring concepts. The team then evaluated these seven designs in a decision matrix, found in Appendix B, and again narrowed down their selection to the top four designs; Archimedes Screw, Solar System, 60 Seconds, and Run Doggie Run. Those top four designs are the four designs that the team has decided to focus the most on, since these are the designs that scored highest on the Pugh Chart as well as the decision matrix meaning that these four designs fit the project's customer needs and engineering requirements better than any other concepts that the team had developed. The Archimedes Screw is the perfect solution for adding more fundamental engineering principles, which is a key customer requirement for the team, for it brings together rotational motion and fluid dynamics and while there was another option to introduce fluid dynamics into the final design (i.e. the Bubble Blower), the Archimedes Screw was the easiest way to implement that principle into a kinetic sculpture. The Solar System, Run Doggie Run, and 60 Seconds designs are all heavily influenced by gear trains that could be easily implemented together with the rest of the team's final design. The gear systems within these designs will help the team design and calculate a gear system that produces desired outputs.

5.2 Design Description

The final design will consist of a hand crank that will begin to wind up a constant torque spring that will then lead to a constant motion of the rest of the sculpture for a long period of time. Connected to the constant torque spring system will be a gear train. At the end of the gear train will be a worm gear spinning the planetary gear system seen below in Figure 5.2.1.

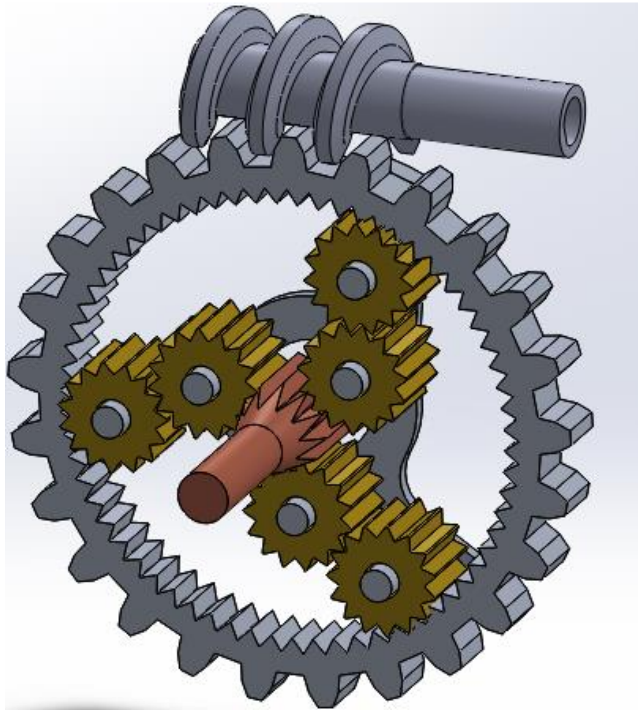

Figure 5.1: Planetary Gear System with Worm Gear

As the gear train causes the worm gear to spin, the movement of the planetary gear system will cause the movement of the Archimedes screw. The screw will be connected to the planetary gear system using a bevel gear that is connected to a rod. The rod is connected to a 2 gear system that directly activates the Archimedes screw. The Archimedes screw will be submerged in a fluid. The rotation of the screw will carry fluid up. The fluid will cascade down a shelf placed over the ring gear system, seen in Figure 5.2.1 above, creating an aesthetically pleasing sculpture.

6 PROPOSED DESIGN – First Semester

Contained within this section of the report is the final proposed design for the end of the first semester. This concept will be manufactured throughout the next (second) semester and will be fully completed by the UGRADS presentation date.

6.1 Prototype

The prototype was created using three different 3D printers. Since the design is large, some components were printed in separate pieces and glued together. To activate the sculpture, the user must use a hand crank to create a tension force. The stored energy will release, activating the first gear train, seen below in Figure 6.1.1.

Figure 6.1.1: First Gear System

This gear system was created to give the ring gear a desired three revolutions per minute. Since the ring gear system is one of the main aesthetics of the design, it should spin at a slow, constant rate. The gear ratios and gear diameters of this gear train were calculated by backtracking speeds starting from the ring gear. The ring gear system is seen below in Figure 6.1.2.

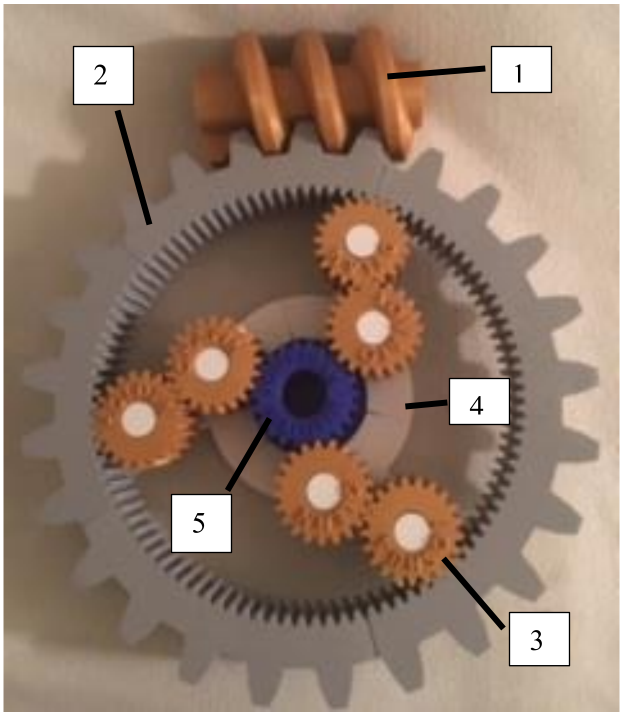

Figure 6.1.2: Ring Gear System

The main ring gear system is seen above. The gear train in Figure 6.1.1 is connected to the worm gear, labeled 1 in Figure 6.1.2 above. The rotation of the worm gear activates the ring gear, labeled 2 in the figure above. The ring gears rotation activates the planetary gears, labeled 3. The sun gear, labeled 5, is stationary and connected to the sculptures stand. The planetary gears are held by the holder, labeled 4. Sculpted into the back of the holder is a bevel gear that activates the connected rod. The connecting rod is seen below in Figure 6.1.3.

Figure 6.1.3: Connecting Rod

The connecting rod directly connects the ring gear system and the Archimedes screw. The gray part of the rod is connected to the back of the planetary gear holder. The white part of the rod is connected to the

Archimedes screw. The gear ratios of this connecting rod determines the rotational speed of the Archimedes screw and the flow rate of the cascading fluid. The Archimedes screw is seen below in Figure 6.1.4.

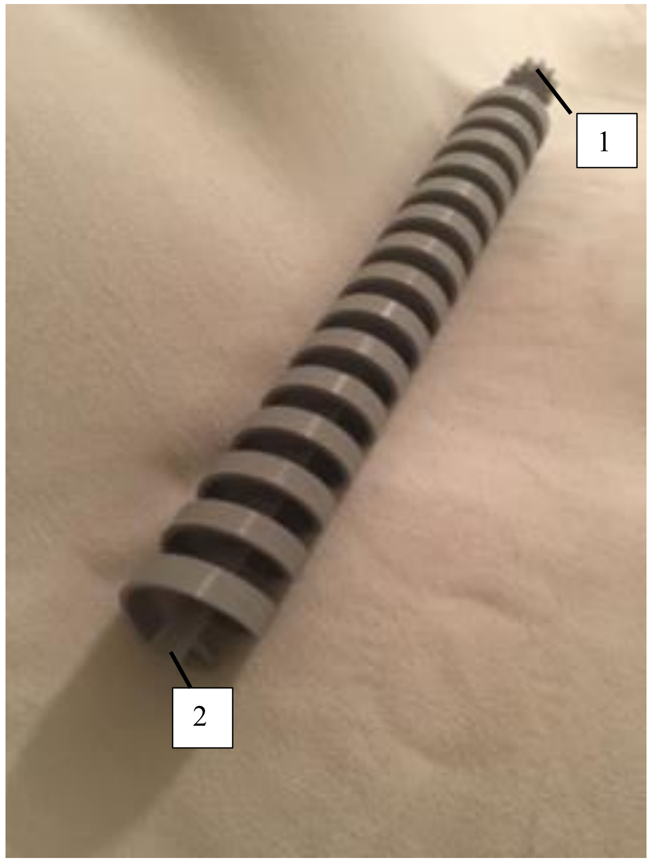

Figure 6.1.4: Archimedes Screw

The bottom of the Archimedes screw is labeled 1 in Figure 6.1.4 above. This piece is connected to the connecting rod. For the prototype, a 3-to-1 ratio is used between this piece and the connecting rod. The top of the Archimedes screw is labeled 2 in the figure above. This part is positioned over a shelf, directly above the ring gear system. The fluid will flow out of the Archimedes screw, down the shelf, and over the main ring gear system.

6.2 Resources Needed

For the prototype, the only resources the team utilized were Solidworks and 3D printers. However, the final product will be of a higher quality than the prototype. The team plans to create the final sculpture of aluminum and steel. For this, the team will need access to a foundry, casting materials, an anodization set-up, time, and money. This section will detail the resources needed to create the final product.

6.2.1 People

The final product will be made of aluminum and steel. The aluminum will be melted and cast by the team. The team plans to melt aluminum cans for the material. The aluminum cans are being collected by the team, with collection bins in two on-campus buildings. The team plans to outsource to a metal finishing company in Phoenix to anodize the aluminum parts within the main ring gear system. The assembly of the final product will be conducted by the team.

6.2.2 Materials

The needed materials for the final product include aluminum, steel, and plexiglass. The aluminum will be collected and melted by the team. The main ring gear system, the Archimedes screw, and the worm gear will be casted with aluminum. The rest of the sculpture will be machined using metal. The plexiglass will house the entire sculpture, protecting the sculpture from human interaction and vice-versa. A belt and handcrank will also be needed to complete the sculpture. These pieces will be purchased.

6.2.3 Facilities

The team is currently researching a place to melt the aluminum. For the anodization, the team plans to outsource to ChemResearch Company in Phoenix. The company is currently estimating the cost of the required anodization process. The machining and assembly of the final sculpture will be done at a team members family-owned machine shop. This is to add safety and professional supervision.

6.3 Bill of Materials

Listed within Appendix C, the Bill of Materials lists the materials used when developing the proposed design and their respective costs. To construct the full-scale prototype, the team spent roughly $130, solely on 3-D filament, with an additional six dollars to cover assembly costs. The foundry the team created, used to cast the required gears, was a total of $102.59, while the casting process itself is estimated to cost $135, based on the commercial values of required materials. To recycle aluminum cans used for gears, the team must first collect aluminum cans. This process totaled a cost of $21 for boxes and garbage bags. Based on a quote from the CEO and President of ChemResearch Company, the anodization process can total around $1500. As for the final design the team is anticipating that all gears would be casted themselves to cut down costs. However, due to the complexity of some pieces, such as the Archimedes screw, the team will need to outsoure for the machining, which is estimated around $200. To complete the rest of the sculpture the team also needs belts and bearing, estimating to cost $50. After the construction of the sculpture the final costs will be the plexiglass, to protect the sculpture, and a placard, to showcase the engineering principles found within the sculpture. The total cumulative cost, tabulated in the Bill of Materials, is $2,596.51, with potentially $500 of which being covered by the Green Fund's contributions.

6.4 Costs Compared to Budget

When observing the costs of the project to the final proposed budget, the group is able to see that there will be around $900 left over at the end of the project. Through the use of recycled aluminum cans for all of the casting materials, and machining most of the components themselves, the group has been able to remain under budget.

When looking at the prototype section of the Bill of Materials, one can see that the full prototype of the project (at full scale) was created with a cost of under $150. Also, this prototype will be what is used for the molds of the sand-casting process to save money in that process. Next, within the foundry creation section of the B.O.M, the creation of the foundry and all tools required cost just over $100. This process was inexpensive and has allowed for a large amount of savings in the manufacturing process of the sculpture. Next, within the casting process section of the B.O.M, the estimated total for the crucible, tongs, sand, and molding wood is approximated to cost around $135. In the can collection section, the total costs of this process is just under $30 for boxes, trash bags, and tape to allow the group to collect the cans from around NAU's Engineering and Business buildings. Next, the budget for the anodization process for ten main pieces is around $1500. This is the most expensive process in the teams design. This process is necessary to protect the sculpture from the moving fluid. Finally, within the full-scale model section of the B.O.M, the group has an estimated cost of $700. This includes the final finishes of the project such as the stand, engraved plaque, and wood for the placard.

After completing and comparing the costs to the full budget of the B.O.M, the group has concluded that, if everything goes to plan, the project will finish around $900 under budget. While the group does not currently anticipate using the left over $900, they plan to hold it in contingency in case unexpected expenses occur over the remaining life of the project.

6.5 Detailed Schedule

Contained within this section of the report are the full, detailed, schedules in the form of Gantt Charts for both the first and second semester of the Kinetic Sculpture capstone project.

As the first semester comes to a close, the group has evaluated the first Gantt Chart (Figure 6.5.1) and ensured that every assignment and task has been completed on time and in an above-average manor. By ensuring the proper finishing time for these tasks, the group has enabled themselves to end the first semester ahead of schedule by about two weeks.

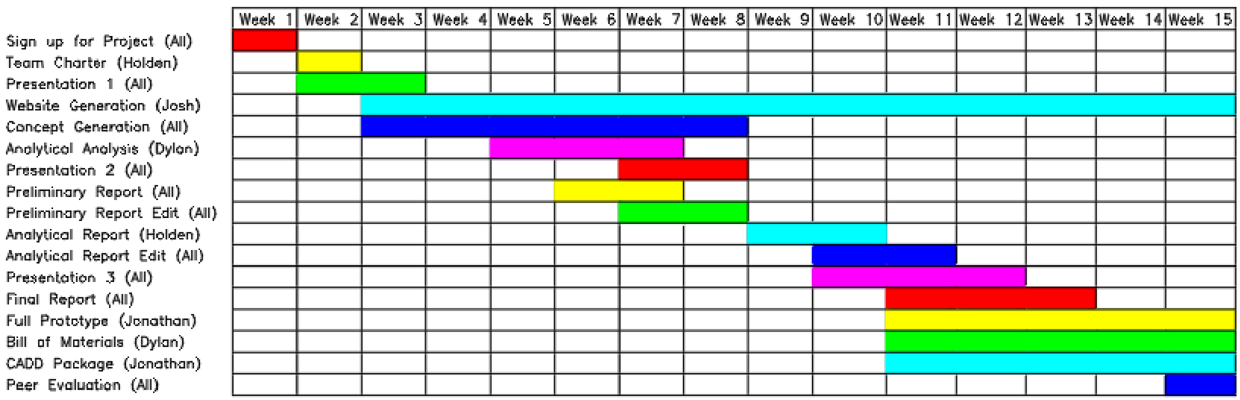

Figure 6.5.1: First Semester Gantt Chart

For the second semester (Figure 6.5.2), the group has begun working on the tasks required already so as to ensure their two-week lead stays. As can be seen in the Gantt Chart, the group plans to have all of the recycled cans collected by week 4 of the second semester and to have all of the ingots created by the end of week 5 of the semester. After the can collection and ingot creation phase of the project is finished, the group plans to begin the casting process of the project by week 4 and complete it by the end of week 6. After the casting process has been finished, the group plans to anodize their significant parts and, perhaps, apply other surface treatments to the project. This phase is planned to be finished by the end of week 8. At the same time as the surface treatment phase of the project, the group will also be assigned the second analytical task assignment to complete. This will be done between week 6 and week 7 of the second semester. Then, after the surface treating phase of the project has been completed, the group will continue to construct the remaining parts of the sculpture (stand, placard, etc.) and plans to have the final assembly finished by the end of week 10. After completion of the physical project, the group will complete the semester with different assignments such as the Design Poster, Operation Manual, Final Report, Final Poster, and Bill of Materials. Lastly, the final CAD package will be completed and turned in by the end of week 15.

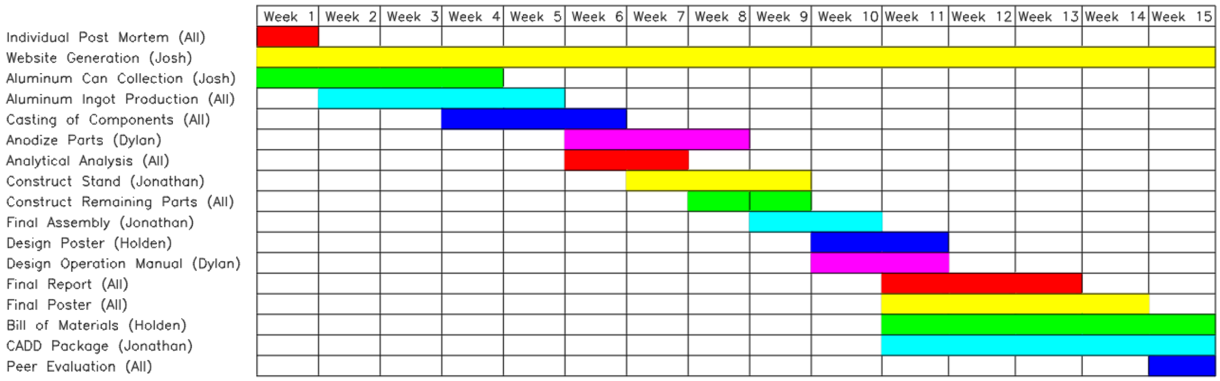

Figure 6.5.2: Second Semester Gantt Chart

With the completion of the full schedule for the first and second semester of the project, the group is able to know what is required of them, so they can continue to meet and exceed expectations throughout the full length of the project.

6.6 CAD Model

Once the team knew what our final design was supposed to look like, a model was generated using SolidWorks. In total there are 32 different parts that form the sculpture with the planetary gear set and the worm gear set being the center, focal point, of the sculpture. Figure 6.6.1 below shows an assembly view of our final proposed design. Figure 6.6.2 shows how the entire sculpture will be put together and how the 32 different parts come together.

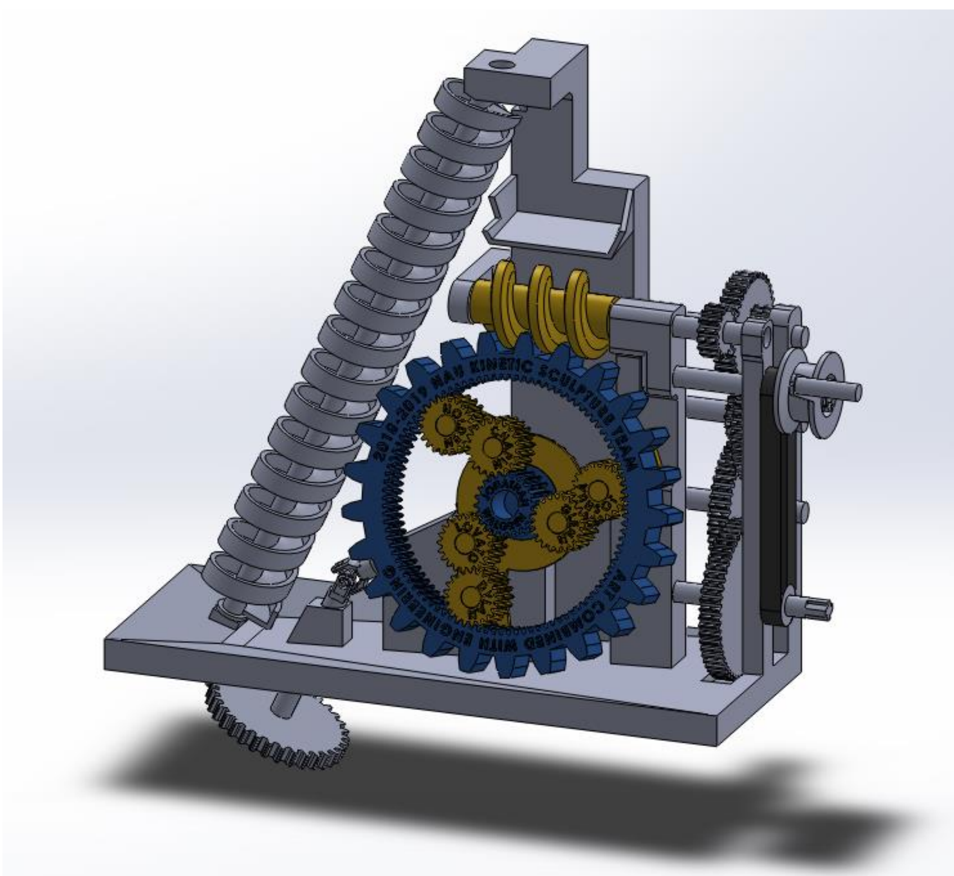

Figure 6.6.1: Assembly View of Kinetic Sculpture

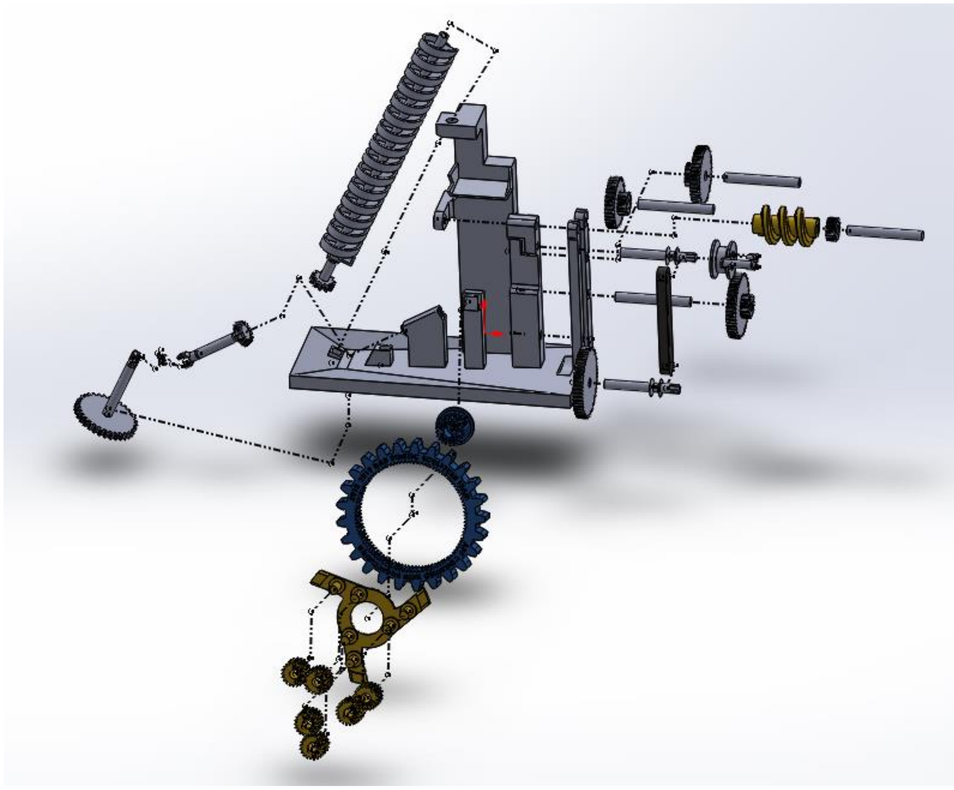

Figure 6.6.2: Exploded View of Kinetic Sculpture

In order to operate the sculpture, the user would first use the hand crank to lift up a weight. Once the weight is lifted all the way, the hand crank would lock itself onto the shaft where it would turn a belt attached to a shaft connected to gear number 5. The power from this is them transmitted through 4 separate gear sets where it finally turns the worm gear and planet gear assembly. From there a bevel gear, attached to the back of the planet gear holder, is used to turn the Archimedes screw which lifts up a fluid to a shelf located just above the worm gear. Finally, the fluid is dumped onto the shelf where it then cascades itself down the entire face of the planetary gear assembly.

7 CONCLUSIONS

This report details the teams progress, thus far. Starting with a project description, the team was able to derive customer needs and engineering requirements, research and benchmark existing designs, generate concepts, and eventually evaluate and select a concept to further pursue. The selected concept was then created in a 3D model software, Solidworks. The team then used this Solidworks model to 3D print a prototype. This prototype will detail the failures of the design and how it can be improved. These 3D printed parts will also be used as sand casting molds in future work.

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9 APPENDICES

9.1 Appendix A: Concepts not Discussed

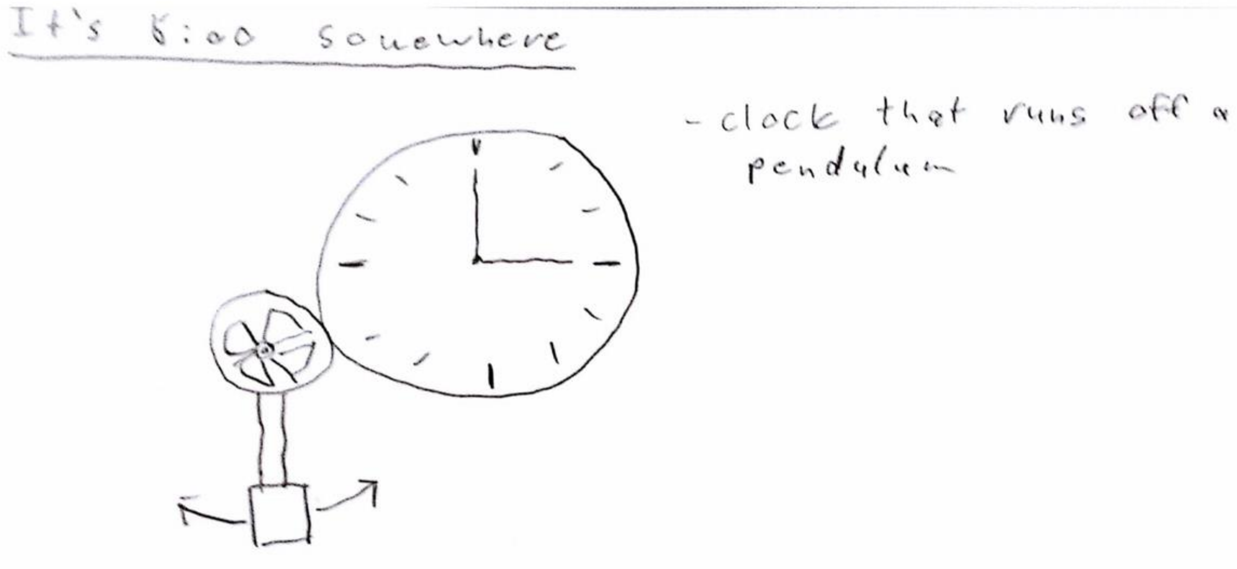

Figure 9.1: It's 5 o'clock Somewhere

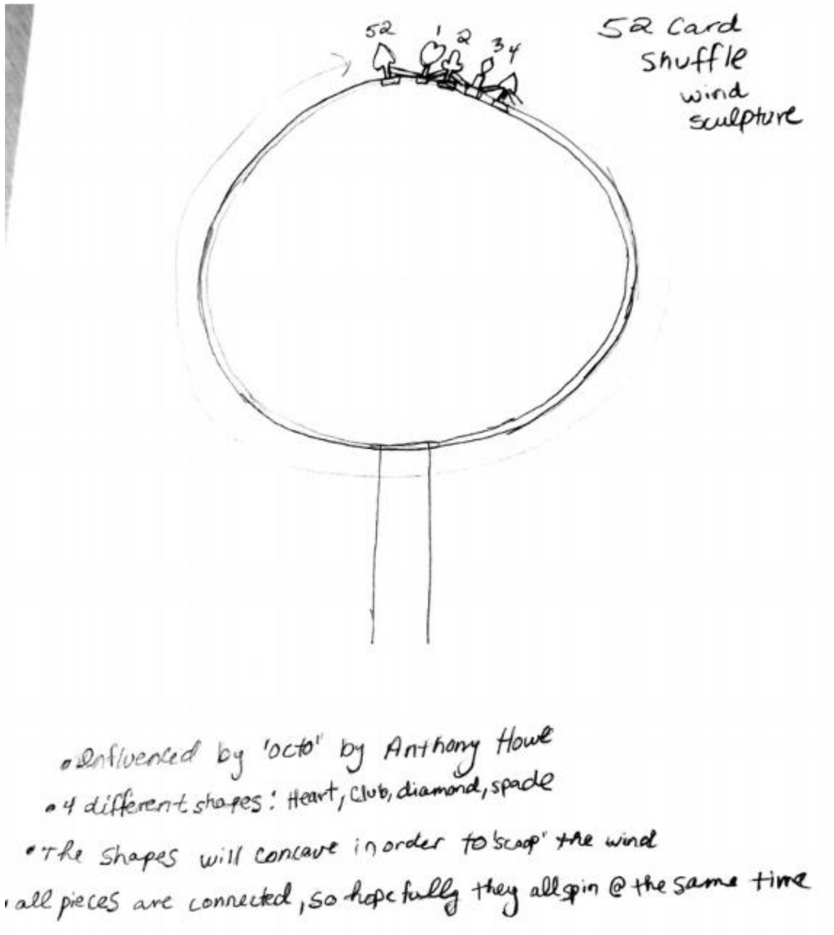

Figure 9.2: 52-Card Shuffle

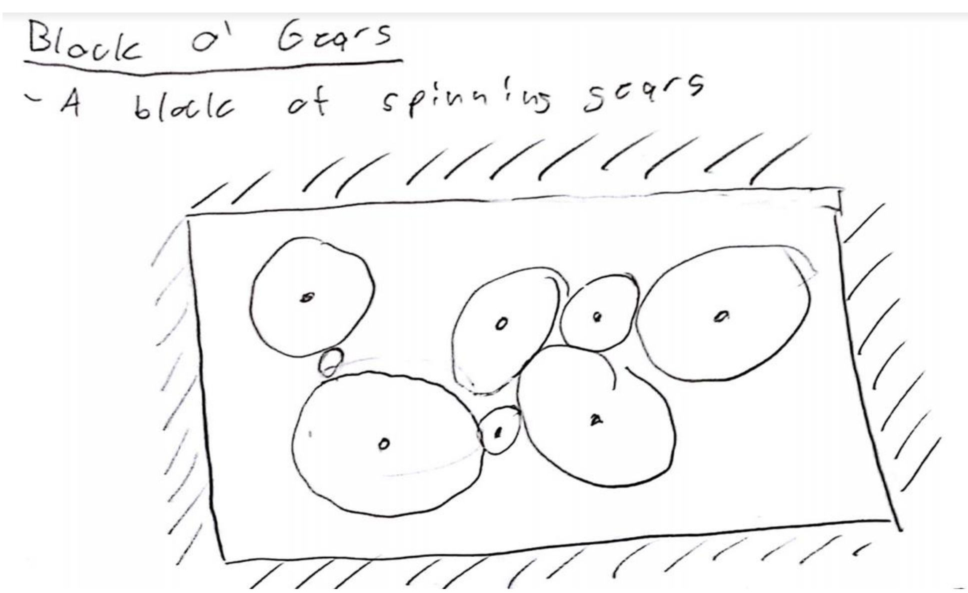

Figure 9.3: Block O' Gears

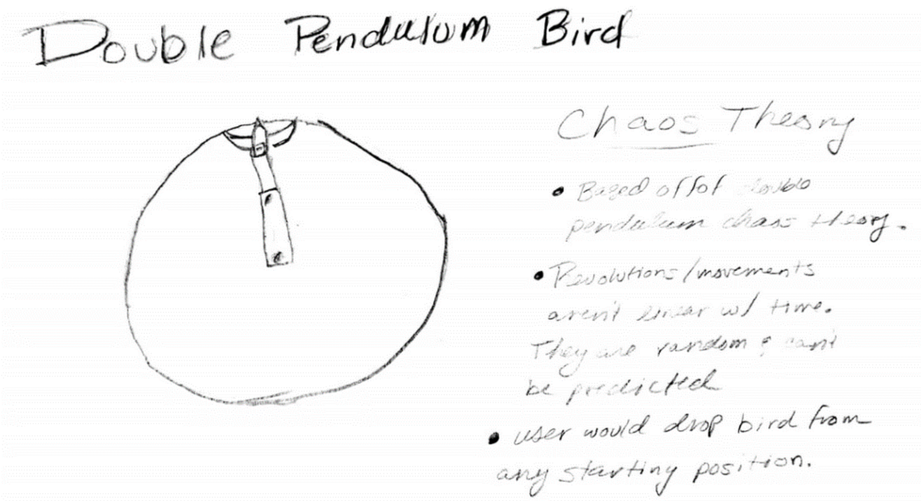

Figure 9.4: Chaos Theory: Double Pendulum

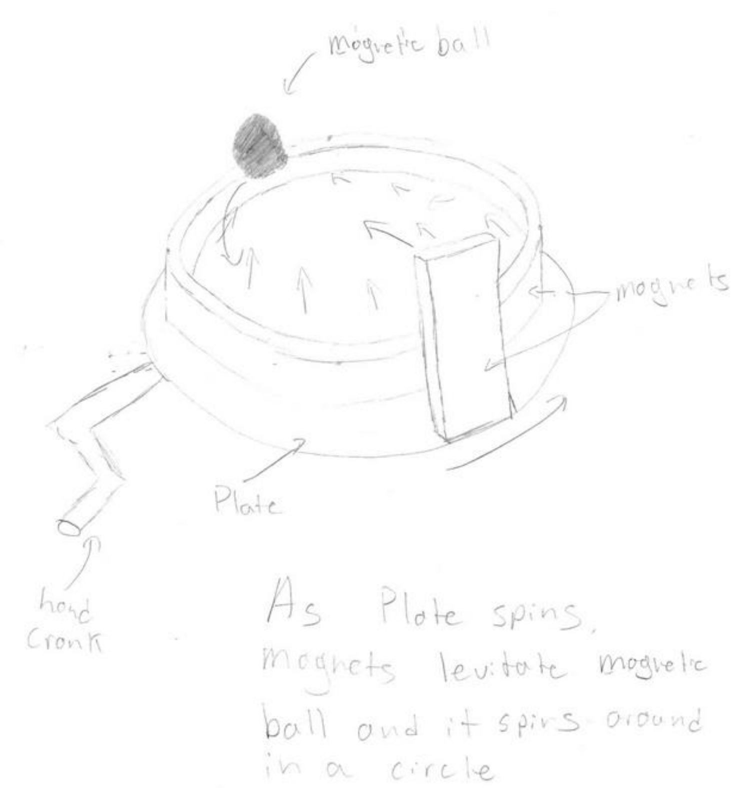

Figure 9.5: Magnetic Ball

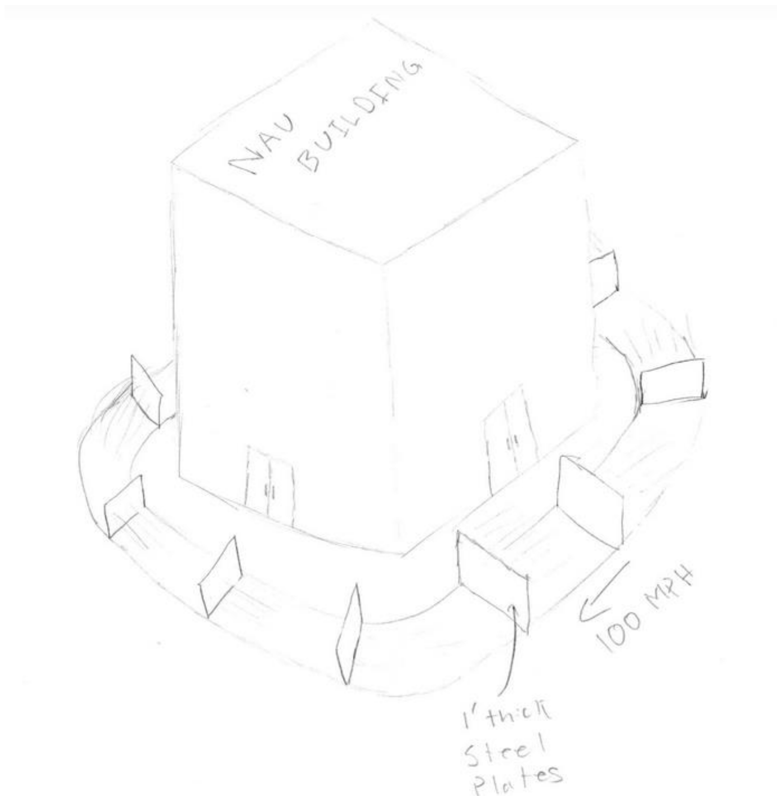

Figure 9.6: Tech-Tonic Plates

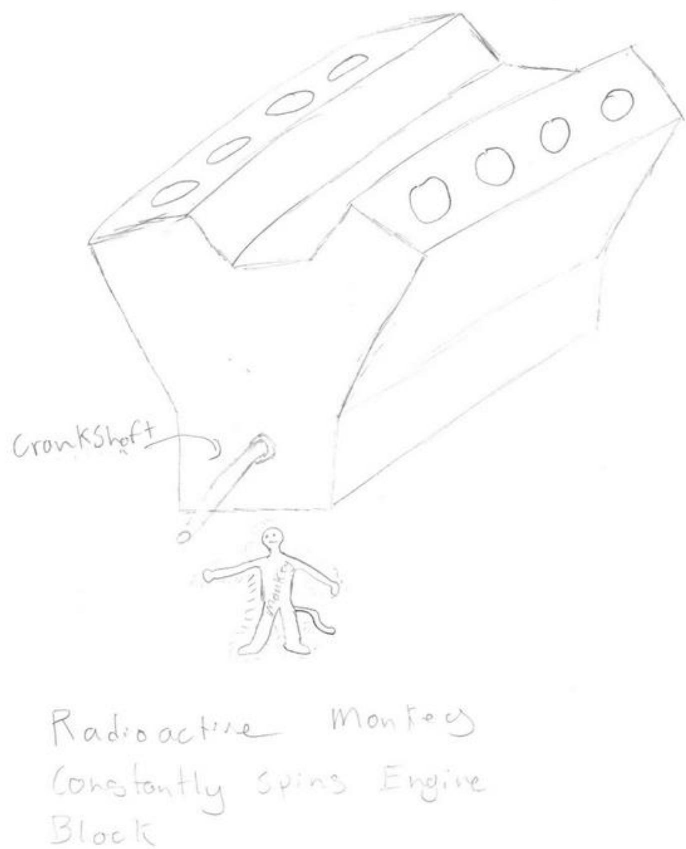

Figure 9.7: Radioactive Monkey

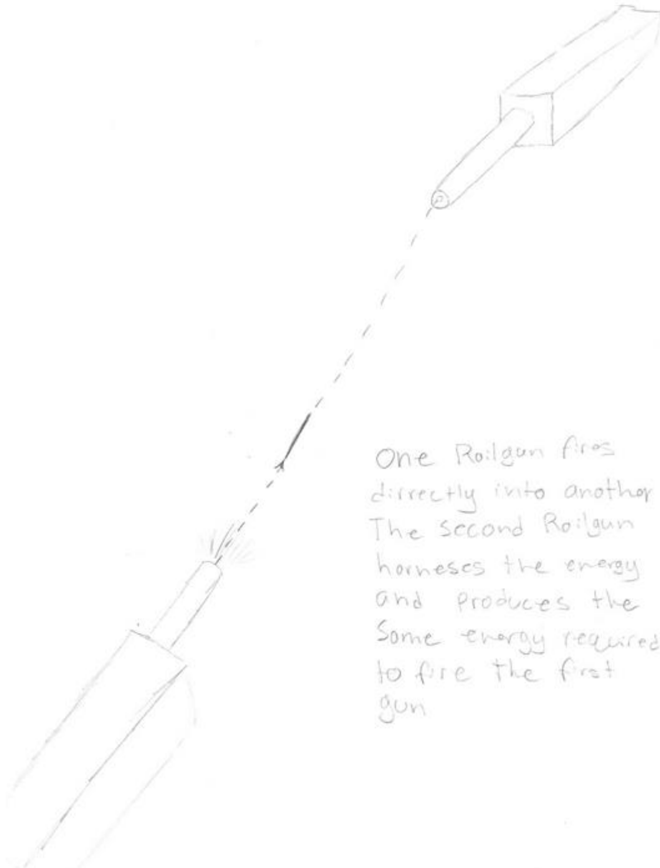

Figure 9.8: Railgun

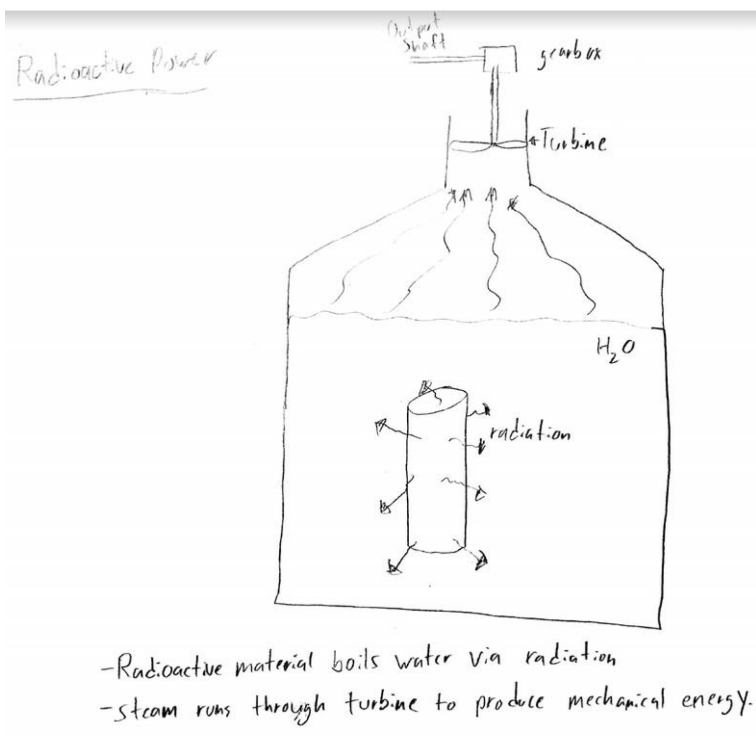

Figure 9.9: Radioactive Power

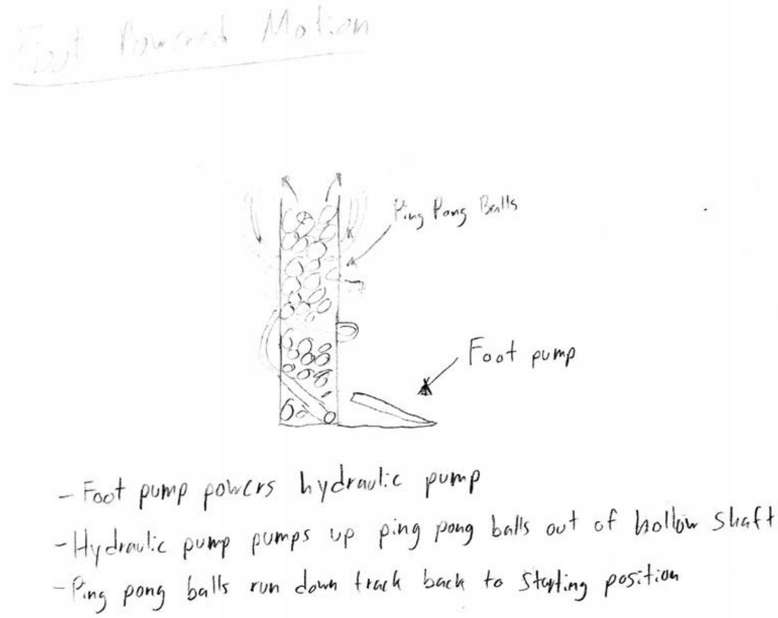

Figure 9.10: Foot Pump

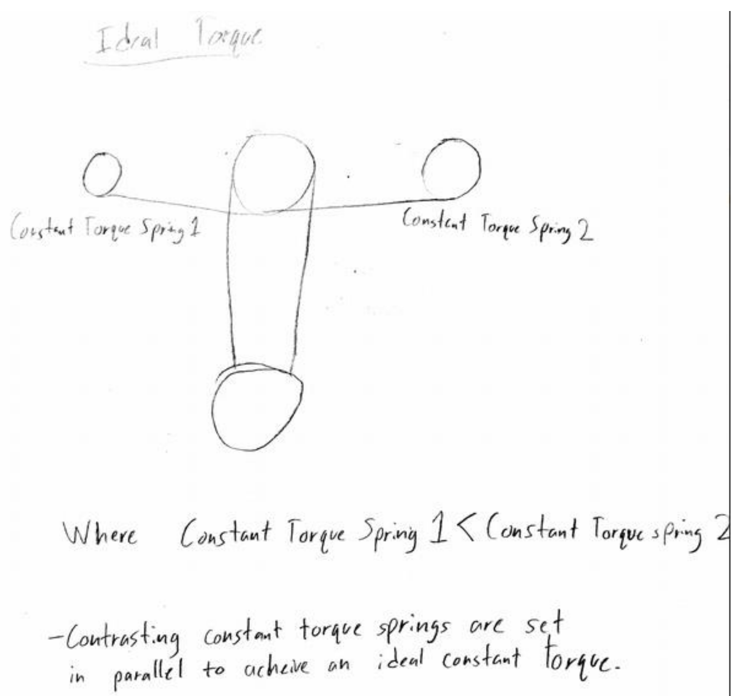

Figure 9.11: Ideal Torque

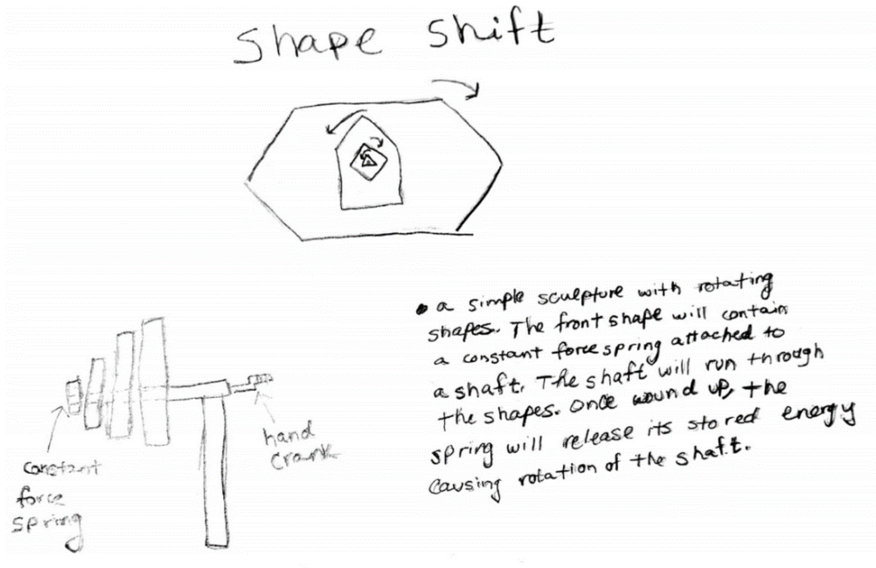

Figure 9.12: Shape Shift

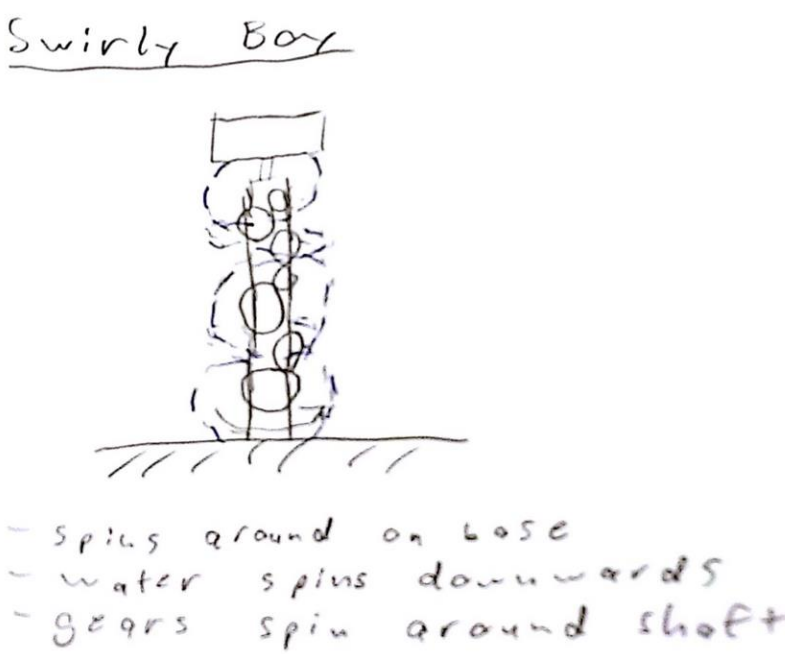

Figure 9.13: Swirly Boy

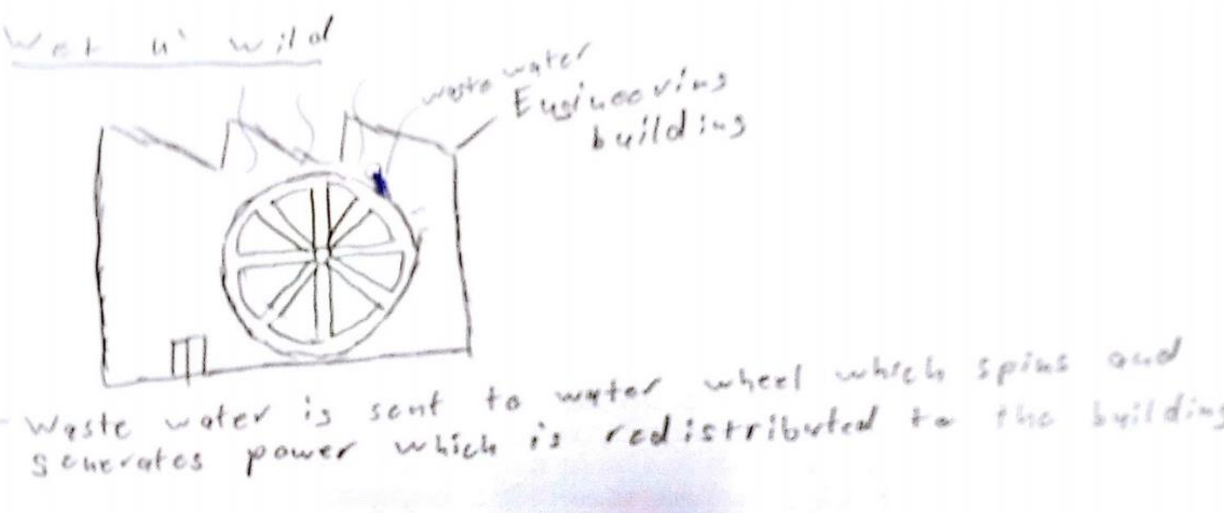

Figure 9.14: Wet N' Wild

9.2 Appendix B: Pugh Chart and Decision Matrix

Table 9-1: Pugh Chart

Pugh Chart

Kinetic Sculpture 18F02 - A : Art Combined with Engineering (ACE)

Criteria \ Concept	52 Card Shuffle	Archimedes Screw	60 Seconds	Run, Doggie, Run	Double Pendulum	Shape Shift	Solar System	OG	5 o'clock Somewhere	Block O'Gears
	1	2	3	4	5	6	7	8	9	10
Moveable (Can Fit Through Door)	-	D	S	#	S	-	S	S	-	S
Cost Effective	-	A	#	#	#	-	S	-	-	S
Durable	S	T	S	S	S	S	-	-	S	S
Represent Engineering Positively	S	U	-	-	-	-	#	S	-	-
Safe To Use	-	M	S	#	S	S	S	S	#	S
Visually Pleasing	#		-	#	-	S	#	-	S	-
Reliable	-		S	S	-	-	-	-	S	-
∑# (Positive)	1		1	4	1	0	2	0	1	0
∑- (Negative)	4		2	1	3	4	2	4	3	3
∑S (Same)	2		4	2	3	3	3	3	3	4
Total Positive or Same	3		5	6	4	3	5	3	4	4

Criteria \ Concept	Magnet Pendulum	Swirly Boy	Wet N' Wild	Magnetic Ball	Tech-tonic Plates	Radioactive Monkey	Railgun	Music Box	Bubble Blower	Radioactive Power
	11	12	13	14	15	16	17	18	19	20
Moveable (Can Fit Through Door)	-	-	-	#	-	-	#	#	S	-
Cost Effective	#	S	-	#	-	-	-	#	#	-
Durable	-	-	-	-	-	-	-	S	S	-
Represent Engineering Positively	#	-	S	-	-	-	#	S	-	S
Safe To Use	#	S	-	S	-	-	-	#	#	-
Visually Pleasing	S	S	-	#	-	S	-	S	S	-
Reliable	S	-	S	-	-	-	-	#	-	-
∑# (Positive)	3	0	0	3	0	0	2	4	2	0
∑- (Negative)	2	4	5	3	7	6	5	0	2	6
∑S (Same)	2	3	2	1	0	1	0	3	3	1
Total Positive or Same	5	3	2	4	0	1	2	7	5	1

Table 9-2: Decision Matrix

		Criteria	Weight (RTI)	1 Archimedes Screw	2 60 Seconds	3 Run, Doggie, Run	4 Music Box	5 Bubble Blower	6 Solar System	7 Magnetic Pendulum
				Sculpture Concepts (Scale 0-100)						
Engineering Requirements	1	Less Than 150 Lbs	21%	90	80	80	70	70	80	80
	2	Under 3x3x6	12%	90	80	90	70	70	60	90
	3	Under $5000	8%	90	80	90	50	60	90	70
	4	Material Strength	8%	70	60	60	50	50	50	40
	5	Hardness	3%	60	60	60	40	60	60	60
	6	Corrosion Rate	6%	60	70	50	70	40	70	90
	7	Factor of Safety	15%	20	50	40	60	80	80	40
	8	At Least 3 Principles	7%	100	80	100	100	80	70	100
	9	Operational For 30 min	6%	80	80	80	50	60	80	40
	10	Low Power Requirement	3%	80	80	80	50	70	80	80
	11	9/10 People Like	12%	90	90	80	90	90	80	70
			Raw sco	75.9	74.7	74.2	67.8	70.2	74.9	69.8
			Relative Rank	**1**	**3**	**4**	**7**	**5**	**2**	**6**

9.3 *Appendix C: Bill of Materials*

Budget from NAU EGR Department	$3,000.00
Budget from Green Fund	$500.00
Total Expenses	$2,596.51
Budget Left	$903.49

Prototype		$136.98	Total
	3-D Printer Filament	$130.68	Amazon
	Super Glue	$6.30	Amazon
Foundry		$102.59	Total
	Pearlite	$36.97	Home Depot
	Concrete	$9.97	Home Depot
	Trash Can	$21.77	Home Depot
	Home Depot Bucket	$10.62	Home Depot
	PVC Pipe	$3.90	Home Depot
	PVC Coupler	$4.34	Home Depot
	Eye Bolts	$5.25	Home Depot
	Trowel	$9.77	Home Depot
Casting Process		$135.00	Total
	Crucible	$50.00	Amazon
	Tongs	$20.00	To be made by us
	Casting Sand	$60.00	Amazon
	Casting Mold	$5.00	Home Depot
Can Collection		$21.94	Total
	Cardboard Boxes	$7.25	Home Depot
	Trash Bags	$6.01	Home Depot
	Tape	$8.68	Home Depot
Anodizing		$1,500.00	Total
	Planet Gears	$900.00	ChemResearch Corporation
	Planet Gear Holder	$150.00	ChemResearch Corporation
	Ring Gear	$150.00	ChemResearch Corporation
	Worm Gear	$150.00	ChemResearch Corporation
	Sun Gear	$150.00	ChemResearch Corporation
Full-Scale Model		$700.00	Total
	Planet Gears	$0.00	To Be Sand Cast from Recycled Aluminum
	Planet Gear	$0.00	To Be Sand Cast

Holder		from Recycled Aluminum
Ring Gear	$0.00	To Be Sand Cast from Recycled Aluminum
Worm Gear	$0.00	To Be Sand Cast from Recycled Aluminum
Sun Gear	$0.00	To Be Sand Cast from Recycled Aluminum
Connecting Rod	$0.00	To Be Sand Cast from Recycled Aluminum and Machined to Final Dimensions
Connecting Gear	$0.00	To Be Sand Cast from Recycled Aluminum and Machined to Final Dimensions
Swivel	$0.00	To Be Sand Cast from Recycled Aluminum and Machined to Final Dimensions
Archimedes Screw	$200.00	To Be Machined from Recycled Aluminum
Gears 2-6	$0.00	To Be Sand Cast from Recycled Aluminum
Ratchet and Parts	$0.00	To Be Sand Cast from Recycled Aluminum and Machined to Final Dimensions
Rods to Hold Gears	$0.00	To Be Sand Cast from Recycled Aluminum and Machined to Final Dimensions
Belt	$20.00	AutoZone
Steel for Stand	$200.00	Havasu Iron and Steel
Plexiglass	$100.00	Home Depot
Engraved Plaque	$100.00	Awards for Anything
Plaque Board	$50.00	Home Depot
Assorted Bearings	$30.00	Amazon