**Worcester Polytechnic Institute**
**Mechanical Engineering Department**

# Major Qualifying Project 2023-24:
# Design of a Kinetic Sculpture

A Major Qualifying Project submitted to the faculty of
Worcester Polytechnic Institute in partial fulfillment of the requirements for the degree of
Bachelor of Science

Submitted by:
Liam W. Bry, Lucy Buda, Magnus Crooke, Patrick Healey, William Mara, Gabriel Pardo Cota

Advisor:
Professor Eben Cobb

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# Abstract

The intersection of art and engineering is crucial to solving complex problems with elegant solutions. The design process in mechanical engineering is usually applied to solve problems in manufacturing and in performing work. Here, we have applied the design process and creativity in attempting to make a mechanism that can move in a pleasing pattern determined by its jointed structure. Our kinetic sculpture is a wind powered walking machine made of PVC, wood and other individually sourced components. We chose to use wind power to take advantage of the frequent windy days on the WPI campus. This type of sculpture was inspired by Theo Jansen's Strandbeest.

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# 1.0 Introduction

The intersection of art and engineering is crucial to solving complex problems with elegant solutions. Through kinetic art, mechanisms can be used to present an art form dependent on motions perceived by a viewer. Movements from an artwork's mechanisms present an opportunity for learning. This project aims to create a kinetic sculpture, that being a sculpture that incorporates an aspect of movement. It is preferred that the sculpture itself moves, rather than containing something that moves within it. The project is to be completed during the 2023-2024 school year, spread across the 4 terms of WPI's academic calendar. The target audience is WPI students, and the sculpture should be entertaining to them. The sculpture may also act as a useful tool for ME students, who can study the physics at play.

## 1.1 Goal Statement

The goal of this project is to create a kinetic sculpture that is entertaining to WPI students and can serve as a study to ME students.

# 2.0 Background

## 2.1 Kinetic Sculpture

A kinetic sculpture is defined as a sculpture with elements of movement. These sculptures contain elements that are moved by forces such as wind, air, magnetism, and electromechanical mechanisms. An example of a wind powered kinetic sculpture can be seen below, (Figure 1). The complexity of this classification comes in what is defined as a sculpture, however. Due to the nature of art, what is defined as sculpture is often up to interpretation, so for the purposes of this project, we relied on our own discretion as a group, taking input from others and our advisor, to determine where this line had been located. We believe that by taking these relatively simple and known mechanical concepts and imaginatively combining them into our own idea, we have fulfilled our expectations of what art can be. That being said, like art, we are not without our inspirations, and we will do well to give background on what inspired our eventual design.

Fig. 1 - Octo 2014 by Anthony Howe

## 2.2 Sources of Inspiration

One of our largest inspirations was Theo Jansen and his strandbeest. According to his personal website, strandbeest.com, Theo Jansen, a Dutch artist, began experimenting in the early 90s with wind-powered structures. He was inspired by concepts for wind powered machines that would maintain shorelines, but soon became interested in the idea of creatures. He made these creatures with PVC as the main structural material, cloth for sails, and various means of fastening, including string. An image of one such creature can be seen below, (Figure 2).

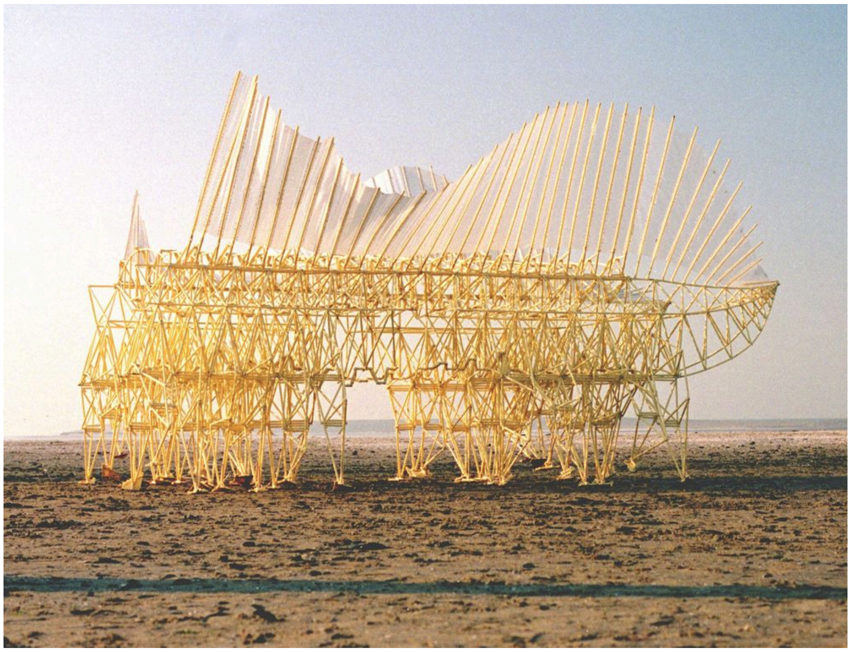


Fig. 2 - 1993 Currens Ventosa

As impressive as these structures were overall, our area of interest was their legs, and how they moved. These legs, each an 8 bar linkage system, take the rotation of a central shaft and translate it into a planar walking motion. A diagram of this system, in a pair, can be seen below, (Figure 3)

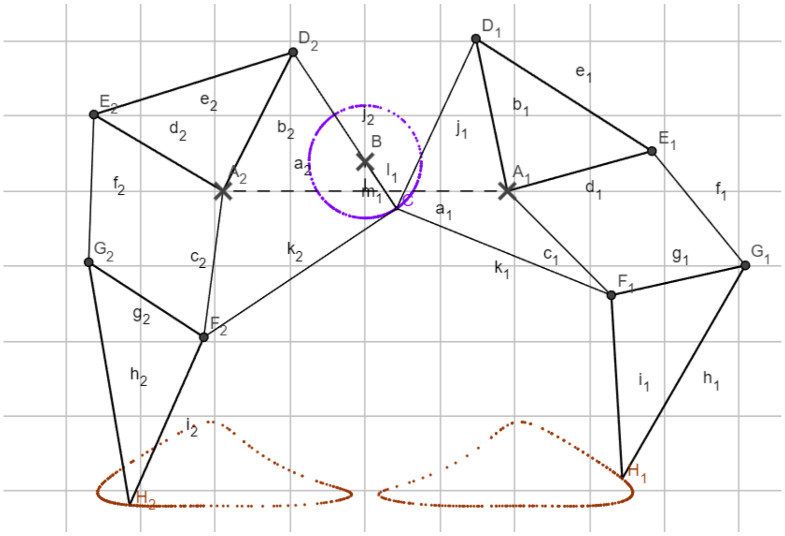


Fig. 3 - Strandbeest Leg Pair

In our research of kinetic sculptures we came across stationary wind powered sculptures. One artist, Anthony Howe, particularly inspired us with his wind sculpture that consists of 256 linked mirrors that oscillate when wind spins cups on the backside of the sculpture. The concept of harnessing the wind was intriguing to us as we did not want to use an electric motor to achieve motion in our project.

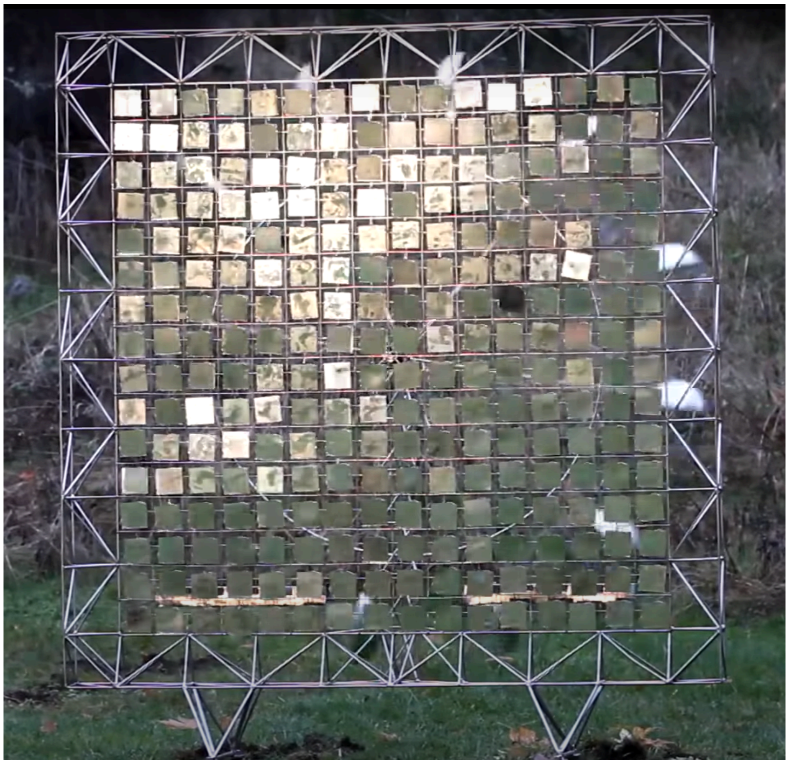


Fig. 4 - My Father's Influence by Anthony Howe

## 2.3 Mechanisms

The purpose of our kinetic art sculpture is to utilize mechanisms in a way that combines the engineering design process and artistic expression into one piece. Without these mechanisms, the visual intrigue and dynamic motion of the sculpture would not be. Their specific role is to take input forces and movement and transform them into a desired output force or movement. In engineering there are copious mechanism types such as gear trains, cams, linkages, and springs, but our kinetic sculpture mainly involves specific linkages and gear trains.

A linkage is a type of mechanism where two or more levers are connected together to change the direction of a force. Different fasteners are used to join these levers together but allow certain ranges of motion. We aimed to propel the attached base forward in a constant and stable manner. To do so, multi-bar linkages are necessary to create a particular path of a tracer point which will interact with the ground. As shown above, (Figure 3), the red shape outlines the path of a tracer point on each side of the mechanism. This path is a crucial factor in deciding what linkage to use because it shows the interaction a point has with the ground surface and therefore the force that will propel the system forward. Ideal requirements of walking linkage mechanism include a uniform velocity while the feet are in contact with the terrain, a long stride in relation to walking mechanism, a return stride tall enough for clearance, the majority of stride in contact with terrain, and the ability for the mechanism to move forward and backwards.

These design goals allow the most efficient “walking” mechanism because of the path they create. Specifically, the Jansen’s linkage is ideal for the purpose of a walking mechanism. What makes this linkage so efficient is its path’s similarity to a human’s gait path. As shown in Figure 5, the velocity of a human’s foot increases and peaks during the return stride whereas the ground contact remains an approximate constant velocity.

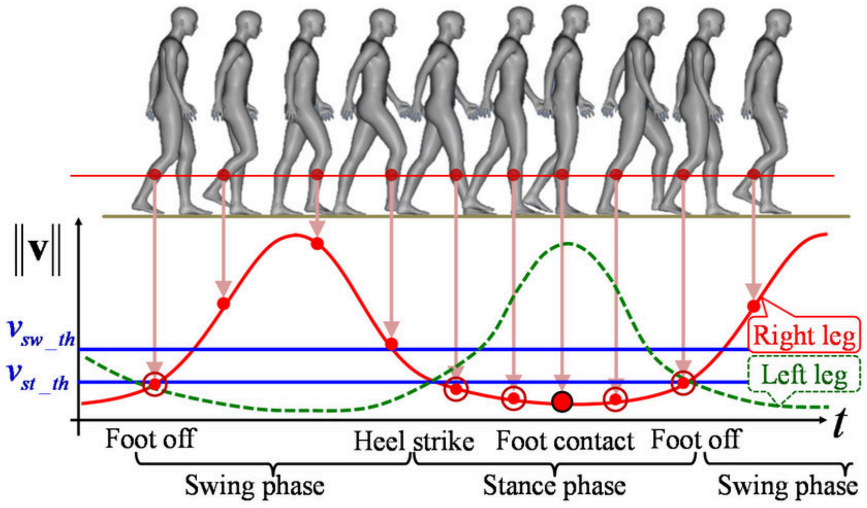


Fig. 5 - Human Gait Analysis

A gear train is a mechanism that translates rotational motion from one gear to another, changing the torque, speed, or direction as desired. By changing the radius and number of teeth in a gear, or by compounding gears together, rotational motion is transferred with particular speed and torque outputs. Using multiple gears can result in a mechanical advantage that is used in the kinetic sculpture or other like systems. Gear trains come in many different forms with different components including spur gears, helical gears, bevel gears, and worm gears. Each type of gear is made for a particular purpose in delivering a desired output, such as a worm gear that's most commonly used for high torque outputs and reductions in speed. Gear trains play an important role in the kinetic sculpture's function as they will translate the input force by wind into rotation force output for the system's crankshaft.

## 2.3 Functional Requirements

In order to gauge our project success, and guide our decisions over its course, our team created functional requirements early into our brainstorming. These requirements pertained to the target use and audience of our design, its size, its weight, its source of power, its use conditions, and its longevity. We reached these requirements through discussion within our team, getting advice from our advisor, and reaching out to outside parties for feedback.

Our first requirement, the intended use and target audience of our design, was inspired by our advisor's vision for our project. Our advisor hoped for a sculpture that incorporated an aspect of movement, that, above all, was entertaining and accessible to college students, such as those at Worcester Polytechnic Institute (WPI). This assigned goal led us to aim for a novel structure that is entertaining to college age people, that can also demonstrate one or more mechanical concepts.

Our second requirement, size, was determined by the need to fit our design through a doorway. The doorways we were concerned with were 80 by 32 inches, so that became our width and height. For length, we considered the need to be able to turn into a hallway, after fitting through a door. This constraint led us to pick 72 inches, after considering which specific hallways on campus may be relevant.

Our third requirement, weight, was determined by the need of the user to be able to move and relocate our design. Since our target audience was college age people, we decided to use members of our team for this metric. To set a max weight, we asked members of our team what they could reasonably carry or move between two buildings on campus. We paired together the lowest two responses to get a max weight of 100 lbs. This specification was chosen so, in theory, the sculpture could easily be affected by the efforts of one person, and easily moved by the efforts of two.

Our fourth requirement, source of power, was determined by level of interest by our group and practicality. In what could be justified as an artistic choice, we decided passively and non-electronically powered sculptures resonated with us more, and seemed more interesting. By powered sculptures, we mean sculptures powered directly by wind, moving water, the sun, or human interaction. Such a design requires no batteries, wires, or motors. This preference also allows us to demonstrate more mechanical concepts and for simpler maintenance in the future when required. Out of the listed power options we selected wind, due to its general accessibility.

Our fifth requirement, use conditions, were determined by safety concerns and expected materials. Due to the nature of a relatively large wind-powered moving structure, it did not seem safe to recommend use in strong winds. We determined the upper limit of safe use to be 30 mph, where anything higher would be above a 6 on the Beaufort Wind Scale, and be classified as a "near gale". High winds, beyond concern for the user, may also be damaging to the design itself. Other harmful conditions for the design were determined to include snowy conditions of any sort and rain over 0.1 in/h. Ice and snow may inhibit motion attempted by the design, while also being harmful to the longevity of its mechanisms. Our design also includes elements vulnerable to rust with moisture exposure.

The final requirement is longevity. For our design to be successful in its efforts of entertainment and education, it should also not impose unreasonable maintenance demands on its keepers. Collectively, our team selected to aim for a five year lifespan. If the design is used within the conditions specified, and stored indoors when not in use, it should reasonably last this long without the need for major repairs.

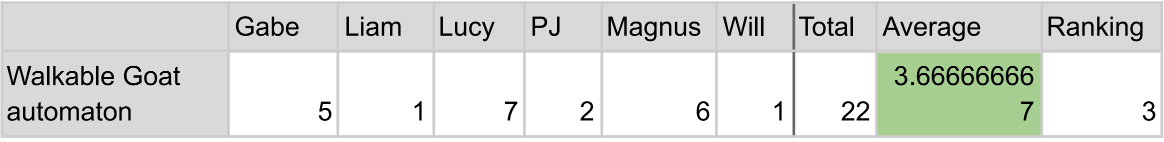
Beyond these selected requirements, there were also limitations beyond our control. These limitations included the time frame in which we had to work, and the budget from which we drew funds. On the WPI academic calendar, our group had from A term 2023 to D term 2024 to complete this project. In terms of funds, each team member was given $250, combining for a total of $1500 for our six members.

| | |
|---|---|
| Dimensions (LxWxH) | 80x32x72 in$^3$ |
| Max weight | 100 lbs |
| Max rainfall | 0.1 in/h |
| Max winds | 30 mph |
| Goal duration (assuming stored indoors) | 5 years |
| Total budget | $1500 |
| Budget per teammate | $250 |

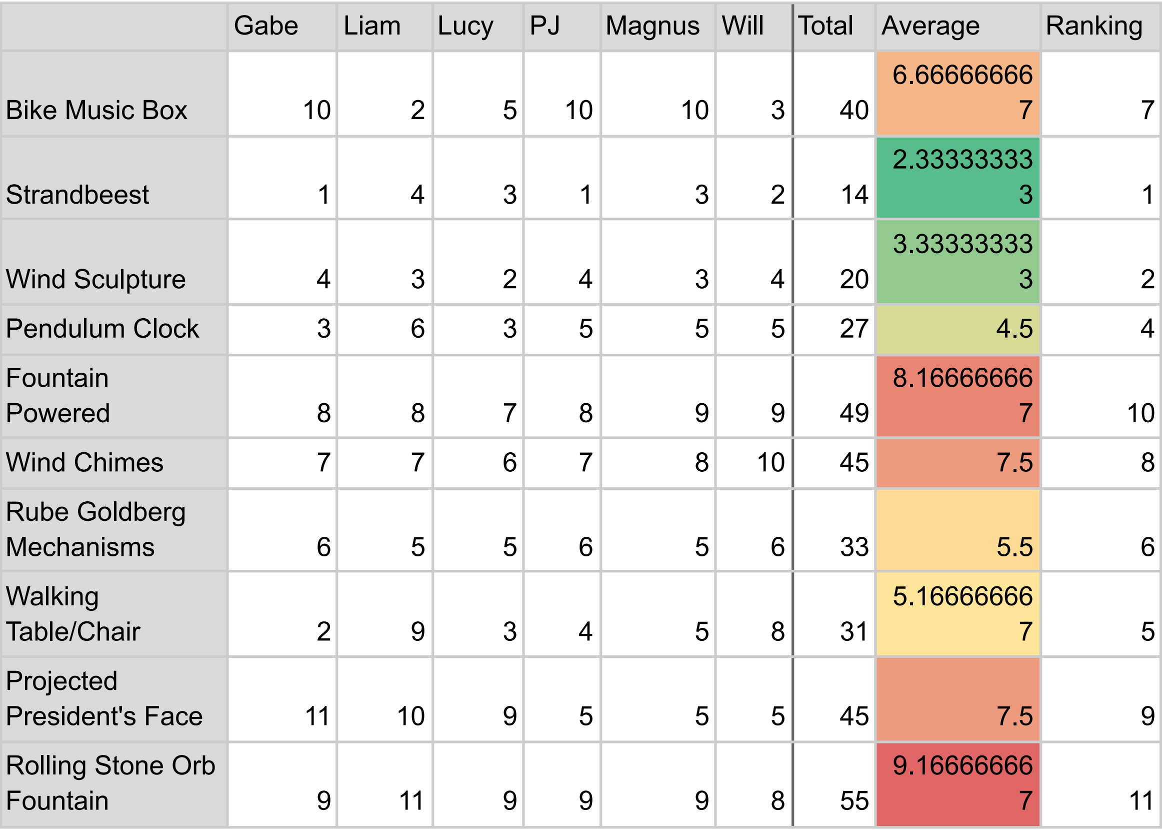
Table 1 - Requirements

# 3.0 Design Concepts

In the early stages of our project, we came up with numerous ideas for how to approach our problem, and how to meet our design requirements. Through group brainstorming our team came up with ideas such as, but not limited to, the creation of a strandbeest, a wind sculpture, a music box, a pendulum clock, and a Rube Goldberg mechanism. We narrowed the raw list of 11 ideas down to a final four to consider based on rankings by team members. These Rankings can be seen below, (Table 2).



| | Gabe | Liam | Lucy | PJ | Magnus | Will | Total | Average | Ranking |
|---|---|---|---|---|---|---|---|---|---|
| Walkable Goat automaton | 5 | 1 | 7 | 2 | 6 | 1 | 22 | 3.666666667 | 3 |



| | Gabe | Liam | Lucy | PJ | Magnus | Will | Total | Average | Ranking |
|---|---|---|---|---|---|---|---|---|---|
| Bike Music Box | 10 | 2 | 5 | 10 | 10 | 3 | 40 | 6.666666667 | 7 |
| Strandbeest | 1 | 4 | 3 | 1 | 3 | 2 | 14 | 2.333333333 | 1 |
| Wind Sculpture | 4 | 3 | 2 | 4 | 3 | 4 | 20 | 3.333333333 | 2 |
| Pendulum Clock | 3 | 6 | 3 | 5 | 5 | 5 | 27 | 4.5 | 4 |
| Fountain Powered | 8 | 8 | 7 | 8 | 9 | 9 | 49 | 8.166666667 | 10 |
| Wind Chimes | 7 | 7 | 6 | 7 | 8 | 10 | 45 | 7.5 | 8 |
| Rube Goldberg Mechanisms | 6 | 5 | 5 | 6 | 5 | 6 | 33 | 5.5 | 6 |
| Walking Table/Chair | 2 | 9 | 3 | 4 | 5 | 8 | 31 | 5.166666667 | 5 |
| Projected President's Face | 11 | 10 | 9 | 5 | 5 | 5 | 45 | 7.5 | 9 |
| Rolling Stone Orb Fountain | 9 | 11 | 9 | 9 | 9 | 8 | 55 | 9.166666667 | 11 |

Table 2 - Early Idea Rankings

From these rankings, a final four of a strandbeest, a walkable goat, a walkable table, and a wind sculpture were selected for further consideration.

We based the strandbeest concept on the works of Theo Jansen, who has created wind powered kinetic walking sculptures on the beaches of the Netherlands. The name, strandbeest, comes from his projects. The idea for our project would be to make our own wind powered walking sculpture using Jansen's six bar linkages. We planned on using a wind turbine and to translate wind into rotation we could use to crank legs made of these six bar linkages. This walking machine would provide entertainment on windy days while demonstrating mechanical concepts in a fun way, or be an interesting display when not in use.

The walkable goat concept was based on the idea that a person, student or otherwise, would be directly interacting with our sculpture. Powered by said person pulling the mechanical system, this goat-shaped structure would perform a sort of walking motion. This motion was to be achieved by a combination of decorative moving front legs, wheels, and functional back legs. Both sets of legs would perform a walking motion when pulled, but only the back would bear weight. One  goal with this idea would be to have something people could borrow from the library for fun.

The walkable table concept was based on a design by Wouter Scheublin, a Dutch designer. This table would perform a walking motion when pushed, allowing it to move across one axis without sliding. This system would be based on a set of connected four bar linkages that would move using a student or other user as an input. Similar to the walkable goat, the active engagement with the user is a core part of this idea.

The wind sculpture concept was a collection of smaller ideas, all based on directly translating forces from wind into motion for small parts of a larger system. We were inspired by the works of Anthony Howe, whose works can be seen in Figure 1 and Figure 4. These designs ranged from directly using wind to rotate components in an interesting way, similar to Figure 1's "Octo 2014", to using wind to move a larger system, similar to how Figure 4's sculpture uses a turbine on the back to move all the mirrors mechanically. If we selected this option, there would be an additional step of narrowing down our wind sculpture ideas, which ranged from a static goat statue with wings that would move in the wind, to a series of smaller designs more similar to "Octo 2014" that could be placed around campus.

## 3.1 Deciding on Concept

| | Safety (1st) | Performance (2nd) | Cost (3rd) | Reliability (4th) | Simplicity (5th) | RANK |
|---|---|---|---|---|---|---|
| Weight | 30% | 25% | 20% | 15% | 10% | 100% |
| Strandbeest | 8 | 8 | 6 | 2 | 4 | 28 |
| Strandbeest - weighted | 2.4 | 2 | 1.2 | 0.3 | 0.4 | **6.3** |
| Wind Sculpture | 9 | 8 | 7 | 9 | 7 | 40 |
| Wind Sculpture - weighted | 2.7 | 2 | 1.4 | 1.35 | 0.7 | **8.15** |
| Walkable Goat | 6 | 9 | 7 | 6 | 5.5 | 33.5 |
| Walkable Goat - weighted | 1.8 | 2.25 | 1.4 | 0.9 | 0.55 | **6.9** |
| Walking Table | 9 | 7 | 8 | 8 | 6 | 38 |
| Walking Table - weighted | 2.7 | 1.75 | 1.6 | 1.2 | 0.6 | **7.85** |

Table 3 - Decision Matrix One

To narrow down between these four concepts, our team made use of a decision matrix. Through what would be our first of two decision matrices, we settled on the wind sculpture concept, as seen above, (Table 3). After discussion within our group as with our advisor, however, we elected to revise our matrix and make a second decision. In our second matrix, seen below, (Table 4), we collapsed the "simplicity" category and redistributed the weight. Keeping in mind our advisor's advice to make use of our group size, we adjusted our goals to not shy away from a more complex system. Our opinions of the other categories also changed in this second matrix, as we gained more information since our first.

| | Safety (1st) | Performance (2nd) | Cost (3rd) | Reliability (4th) | | RANK |
|---|---|---|---|---|---|---|
| Weight | 35% | 30% | 20% | 15% | | 100% |
| Strandbeest | 9 | 8 | 6 | 5 | | 28 |
| Strandbeest - weighted | 3.15 | 2.4 | 1.2 | 0.75 | | **7.5** |
| Wind Sculpture | 8 | 4 | 5 | 8 | | 25 |
| Wind Sculpture - weighted | 2.8 | 1.2 | 1 | 1.2 | | **6.2** |
| Walkable Goat | 7 | 4 | 5 | 4 | | 20 |
| Walkable Goat - weighted | 2.45 | 1.2 | 1 | 0.6 | | **5.25** |
| Walking Table | 9 | 3 | 4 | 5 | | 21 |
| Walking Table - weighted | 3.15 | 0.9 | 0.8 | 0.75 | | **5.6** |

Table 4 - Decision Matrix Two

# 4.0 Synthesis and Analysis

## 4.1 Leg Analysis / Proof

The Jansen Linkage our team intended to adapt was already a proven system, but to do our due diligence, we put the proportions for such a linkage, (Nansai, 2013), into the program “Linkages” to ensure it would move as we hoped. The linkage did function as intended, and we continued to use these proportions going forward.

## 4.2 Material Selection

Polyvinyl chloride (PVC) is a key material in modern engineering, chosen for our leg construction for a wide variety of reasons. Known for its versatility, durability, cost-effectiveness, and corrosion resistance, PVC is a preferred choice for many applications and industries.

One of the main advantages of using PVC pipes in our project lies in their availability and accessibility. Unlike other materials that may require sourcing from specialized suppliers, we were able to acquire the PVC pipes at hardware and retail stores. These pipes were also relatively low cost compared to many other materials. Another advantage of using PVC pipes is their ease of cutting, allowing us to trim the pipes to the designed lengths to construct the linkages.

PVC pipes exhibit exceptional resilience to cyclic loading due to their inherent flexibility and fatigue resistance. Their ability to absorb and dissipate energy during repeated loading cycles minimizes the stress concentrations. Below, (Figure 6), is an S-N curve for polyvinyl chlorite, showing the amount of cycles the material can undergo until failure. Our project is projected to last 5 years, undergoing about 10^6 cycles in that time frame. As seen on the curve, the pipes will be able to withstand this cyclic loading.

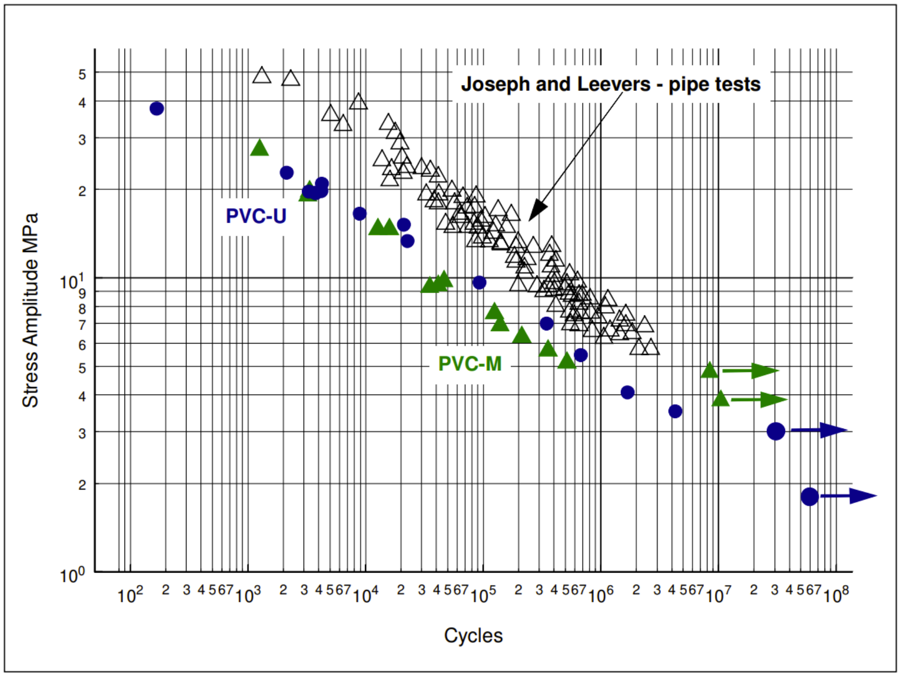


Fig. 6 -SN Curve for Polyvinyl Chloride

Despite its numerous advantageous properties, it is essential to note that prolonged exposure to outdoor conditions can pose challenges for PVC materials. While PVC is inherently resistant to corrosion, ultraviolet (UV) radiation can induce degradation over time. UV radiation has a relatively shallow penetration depth into PVC materials; however, its effects can manifest in alterations to the material properties. These changes include an increase in tensile strength and the modulus of tensile elasticity, and a decrease in impact strength. Therefore, we do not recommend long exposure to ultraviolet light.

# 5.0 Design Selection

Once we determined the idea we were moving forward with, and what materials to use to achieve it, we began to pin down specifics of our design. This process began with the separation of our overall goal into smaller, more specific ones. For a wind powered walking sculpture, this broke down into the topics of the walking mechanics themselves, with the legs, and with the translation of wind power, to drive them. For this purpose we divided our six person group into three and three for the wind team and the Leg Team.

## 5.1 Leg Team

The Leg Team subgroup began work by looking at the Jansen linkage itself, the core of our movement. The proportions of its links are public information, but the Leg Team was interested in adapting these proportions to fit our scale, outlined in our function requirements. To do so, the overall size of a leg, and later a leg pair, was modeled in solidworks, and scaled for our purposes. This method allowed us to estimate the final width and height of our system, depending on how large we made the links. Steps in this process can be seen below, (Figures 7 to 9), and final link lengths can be found below in Figure 10.

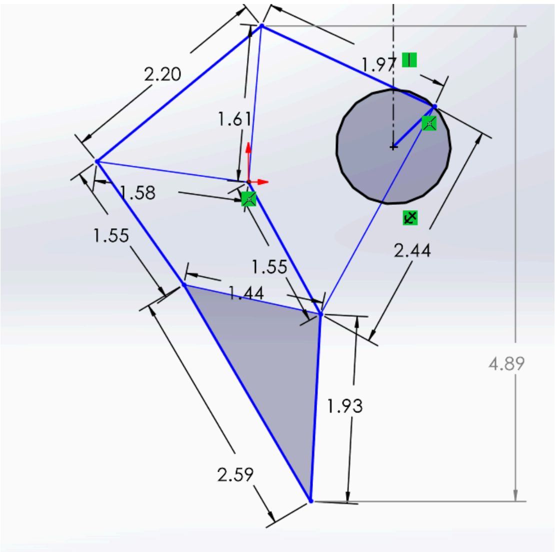


Fig. 7 - Early Draft of Leg (Dimensions Not Final)

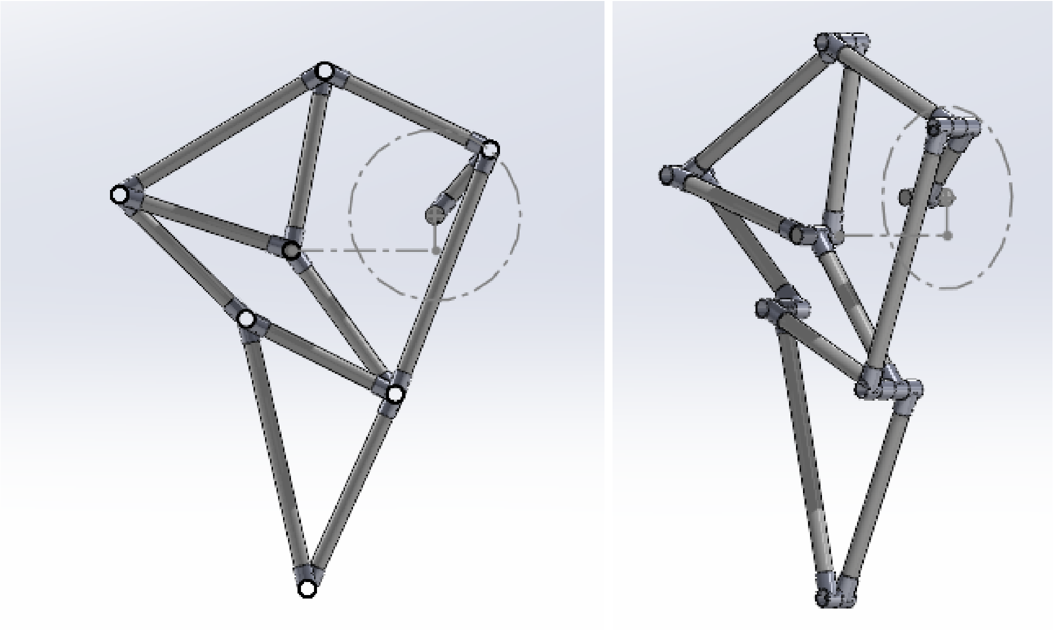


Fig. 8 - Revised Leg Models

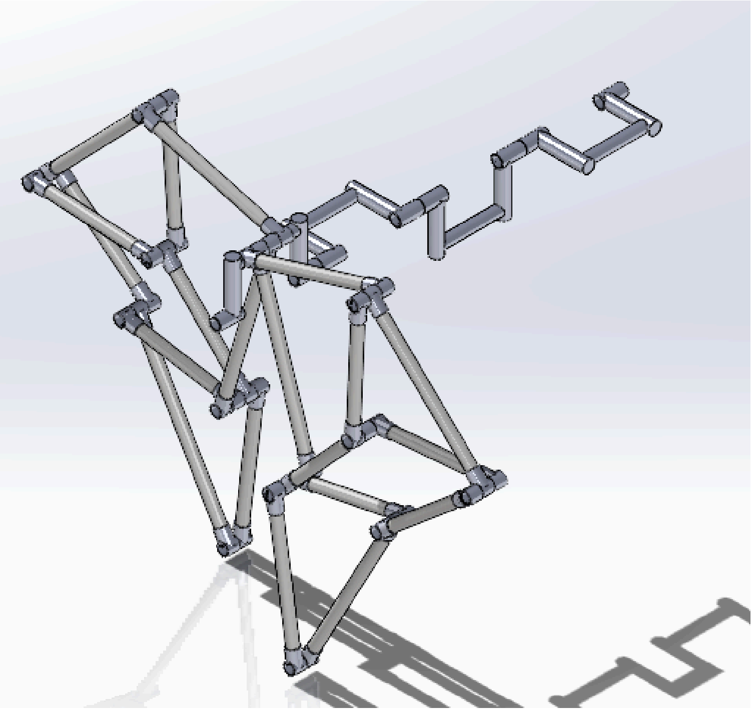


Fig. 9 - Early Model of Leg Pair

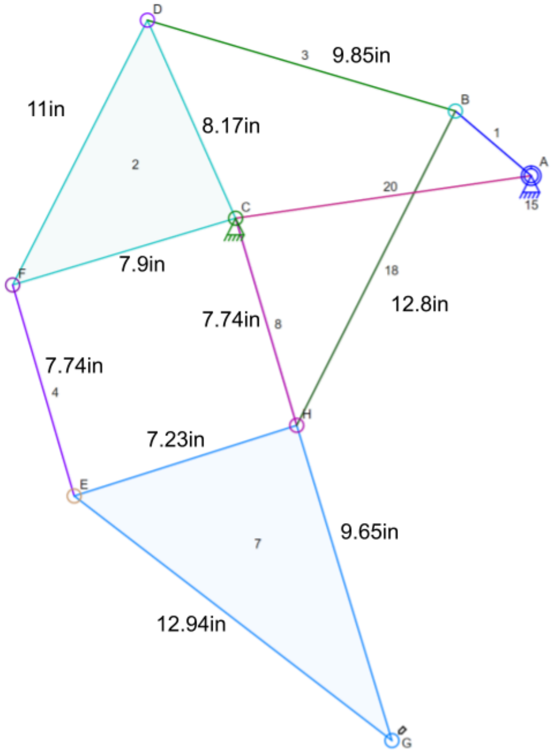


Fig. 10 - Final Dimensions of Legs

Revisions to our initial dimensions found through the estimation process, (not listed), were made after a test leg was made with real materials, and found to be larger than anticipated. This was due to inaccuracies in the size of our modeled components and assumptions made about connections, particularly in the length contributed by the joints used. This test leg can be seen below, (Figure 11).

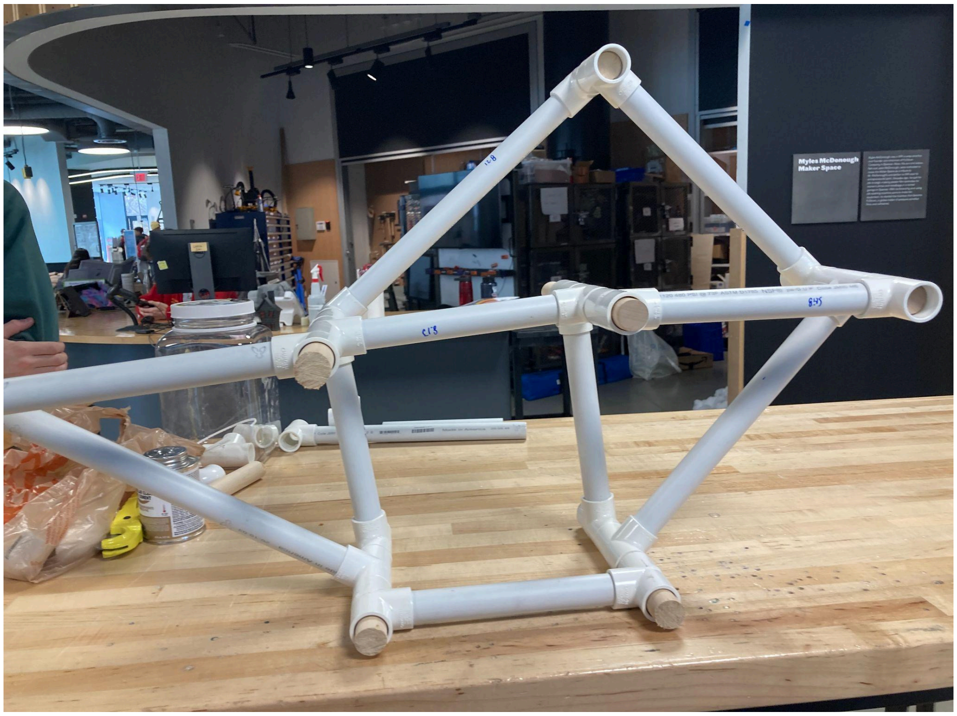


Fig. 11 - Test Leg

Once the matters of width and height were settled, the next task was to determine how many leg pairs to include, which would directly impact the length of our system. For this, the Leg Team settled on the number of 4 pairs, 8 legs in total. This was selected to ensure a minimum of three contact points with the ground at any given time, while also giving ample room to work with for each leg, and limiting complexity for the necessary, but later to be included, crankshaft.

This brings us to the crankshaft, and the frame that would support it. Jansen linkages, by design, have two fixed points, seen as points A and C above, in Figure 10. Point C, for us, was decided to be one bar connecting all 4 legs on a given side, these two bars then being connected to keep at the proper distance apart. Point A, though, would be the main part of the crankshaft itself, with point B being the connection between what would be considered the end of the “leg” and the beginning of the crank. An early Draft of the crankshaft can be found below, (Figure 12).

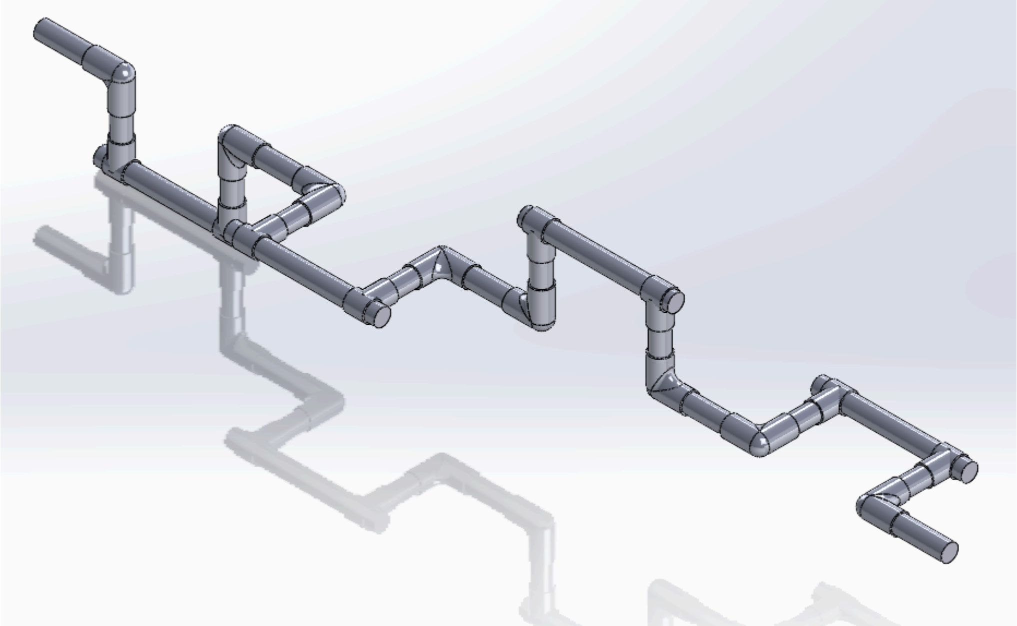


Fig. 12 - Early Draft Model of Crankshaft

When all combined, the legs, crankshaft, and frame was planned to fit together as pictured below, (Figure 13).

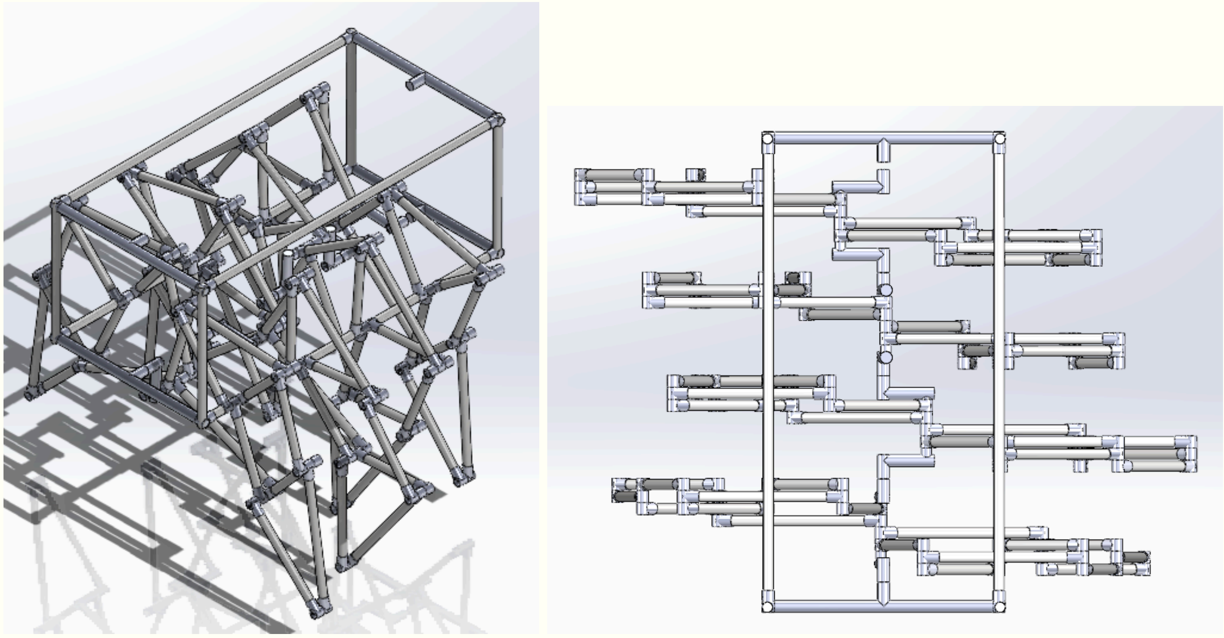


Fig. 13 - Early Draft Model of Leg, Crank, Frame System

## 5.2 Wind Team

The Wind Team subgroup began work by selecting how to make use of wind power. Sails were considered, taking inspiration from the original Stranbeests, but in the end wind turbines were selected due to their ability to directly demonstrate more mechanical concepts. The question was then how to make use of them.

The Wind Team largely focused on two courses of action. The first included one large turbine, rotating about the vertical axis, that would connect to a crankshaft via bevel gears. This turbine would sit on the top of a frame, and allow the sculpture to make use of wind from a many number of directions. A negative of this concept was it added complexity in the likely event the Wind Team wanted to add a gear ratio to aid in the rotation of the crankshaft, possibly requiring the addition of more shafts. A visual of this concept, frame not included, can be found below, (Figure 14).

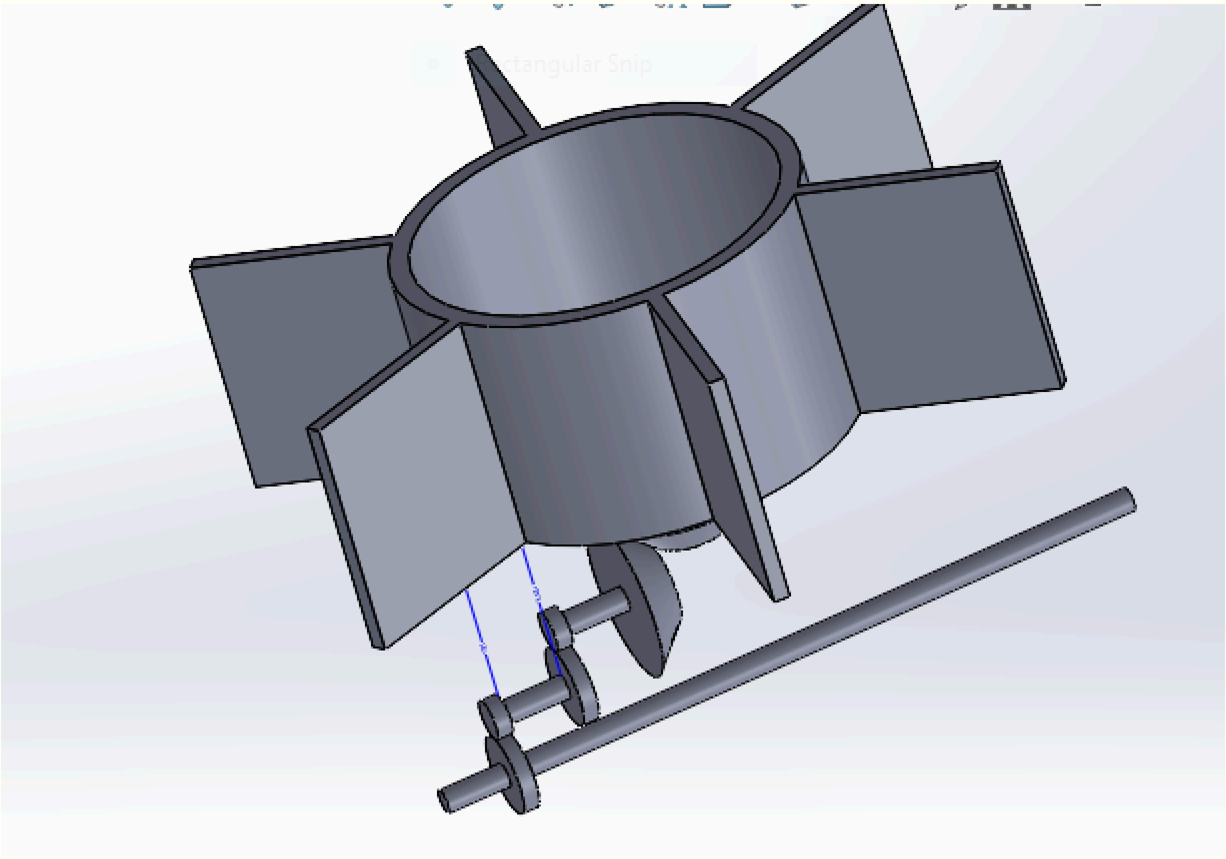


Fig. 14 - Single Vertical Turbine Visualization Model

The second concept, unlike the first, included two, smaller turbines. Each would be fixed to the sides of a frame, and would both be connected to a shaft running parallel with the crankshaft. Spur gears could then be used to bridge between the two shafts, allowing for motion to be translated and for a ratio to be easily implemented. The negative with this concept was that it was dependent on wind blowing perpendicular to the direction the sculpture was set to walk.

Between these two directions, the latter was chosen. The simpler shaft and gear layout outweighed the positives of a multi-directional input. An early draft of this design, combined with the Leg Teams progress at a similar stage, can be found below, in Figure 15.

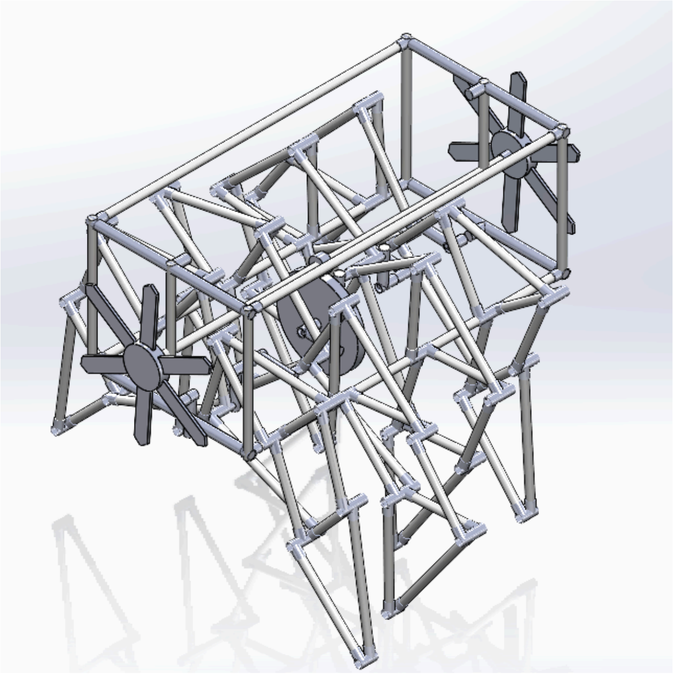


Fig. 15 - Early Combined Model

With this double turbine system, the next area of interest was the gears, and what ratio to include. This was determined using a conservative estimation of the resistance the legs may have to moving, and the average wind speed found on campus.

The average wind speed at WPI is 7.4167 mph (WeatherWorld, 2023). For use in calculations, this is converted to m/s. The force of wind is assumed to act halfway along the turbine blade, and the tangential speed at that point is assumed to be equal to the speed of the wind. This makes the average rotational velocity of the turbine shaft 12.512 rad/s or 119.48 rpm. In order to reach a more desirable crankshaft speed and improve the turbine shaft's ability to turn it, a 1:5 gear ratio was chosen. This makes the crankshaft's rotational velocity 2.502 rad/s or 23.896 rpm. The calculations used in these steps can be found in Appendix E.

## 5.3 Mutual Design Challenges

As each team made further progress in solidifying the concepts and implementations of their areas of interest, it became increasingly important to refocus on creating a unified vision. When determining details for this more fully combined design, there were some challenges that arose. The core of these challenges came in the form of the shafts of each sub assembly, and the connection between them.

To begin with the crankshaft, in consideration of a real, physical shaft, we realized the difficulty in manufacturing a solid structure in the needed shape, nevermind one made of our chosen materials. Due to the many segments and changes in direction, combined with the loading that would be applied, we were worried about the shaft failing. To amend this, but not obstruct leg segments that had to pass through the main axis of the shaft in some places, additional supports were added throughout the frame, rather than single connections at either end. An early iteration of this addition is pictured below, (Figure 16). These supports were revised in later versions to include less angular components. These supports also served to reinforce the structure of the frame overall.

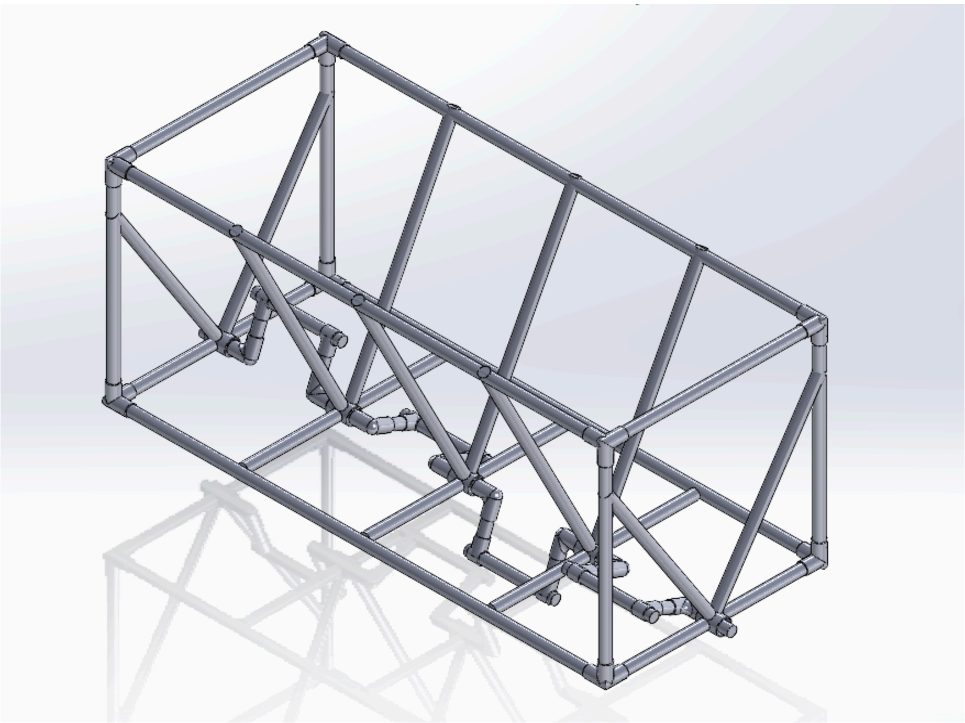


Fig. 16 - Early Draft Model of Crankshaft Supports

Another Challenge, resulting from a combination of space requirements and the encouraged gear ratio, was about the distance between the two parallel shafts. Due to how far away the shafts would have to be, there were no ready made gears to accommodate the distance at the ratio we aimed for. To overcome this, we narrowed our options to two plans.

The first plan, making use of chains, was to use bike gears. These gears would come pre-fit for a bike chain, and, using this chain, we could clear the gap between the shafts. The second plan, making use of on-campus manufacturing methods, was to laser-cut wooden gears, which would allow us to create significantly larger gear than what we could find commercially.

These two options were pursued in parallel, with the intent to gain more information. After reaching out to bike shops in the Worcester area and further thought, we eliminated the bike gear route due to lack of availability, the complications of connecting such gears to our shafts, and the possible need for tensioning. For this reason we moved forward with the wood gear plan, which was accessible and allowed for more customization. With this plan, modeling and cutting parts would be possible on campus, which would allow us flexibility and control over how gears would be attached to the shaft, and allow adaptation in cases where we’d need to accommodate parts of the frame and/or shaft separation.

# 6.0 Detailed Design Description

The design below was created using the collaboration of group members. This design started from creating design parameters and listing requirements. From research and brainstorming we created a leg geometry that would simulate a walking motion. In Figure 17 below is the Solidworks model of the eight legs used in the assembly of our sculpture. The leg assembly below is the final iteration of our Solidworks model. The leg was designed to occupy the least amount of area using our design parameters. The legs would be held together by using wooden dowels that allowed joints to freely articulate. They would be supported from the frame at two points on the legs as outlined in the sections above.

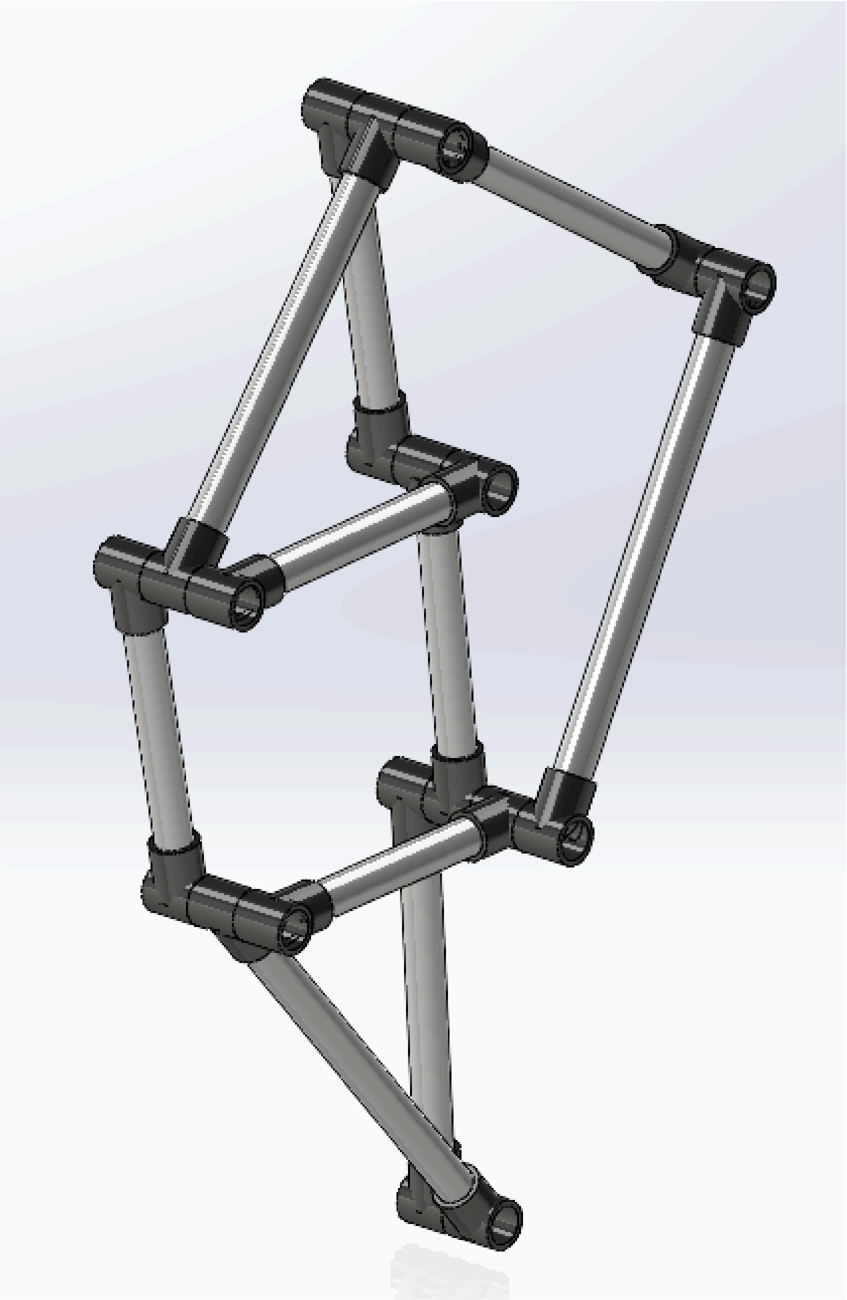


Fig. 17 - 3D Model of Leg

## 6.1 Common Components

In Figure 18 below is a 3D Solidworks model of a modified ¾ in pvc t-joint. A normal T-joint would be around half an inch longer on both sides. We made this decision to cut them short to save space on the full assembly and reduce friction. The more area that comes into contact with our moving assembly would increase friction and require more external power to get moving. A challenge we encountered when designing the legs was the amount of area they occupy. Our team's plan from the beginning of the project was to use the PVC T-joints at full length to reduce the manufacturing time. This was quickly changed to shorten the leg assembly's width while maintaining rigidity. Using readily available materials was our team's course of action to accelerate the design process.

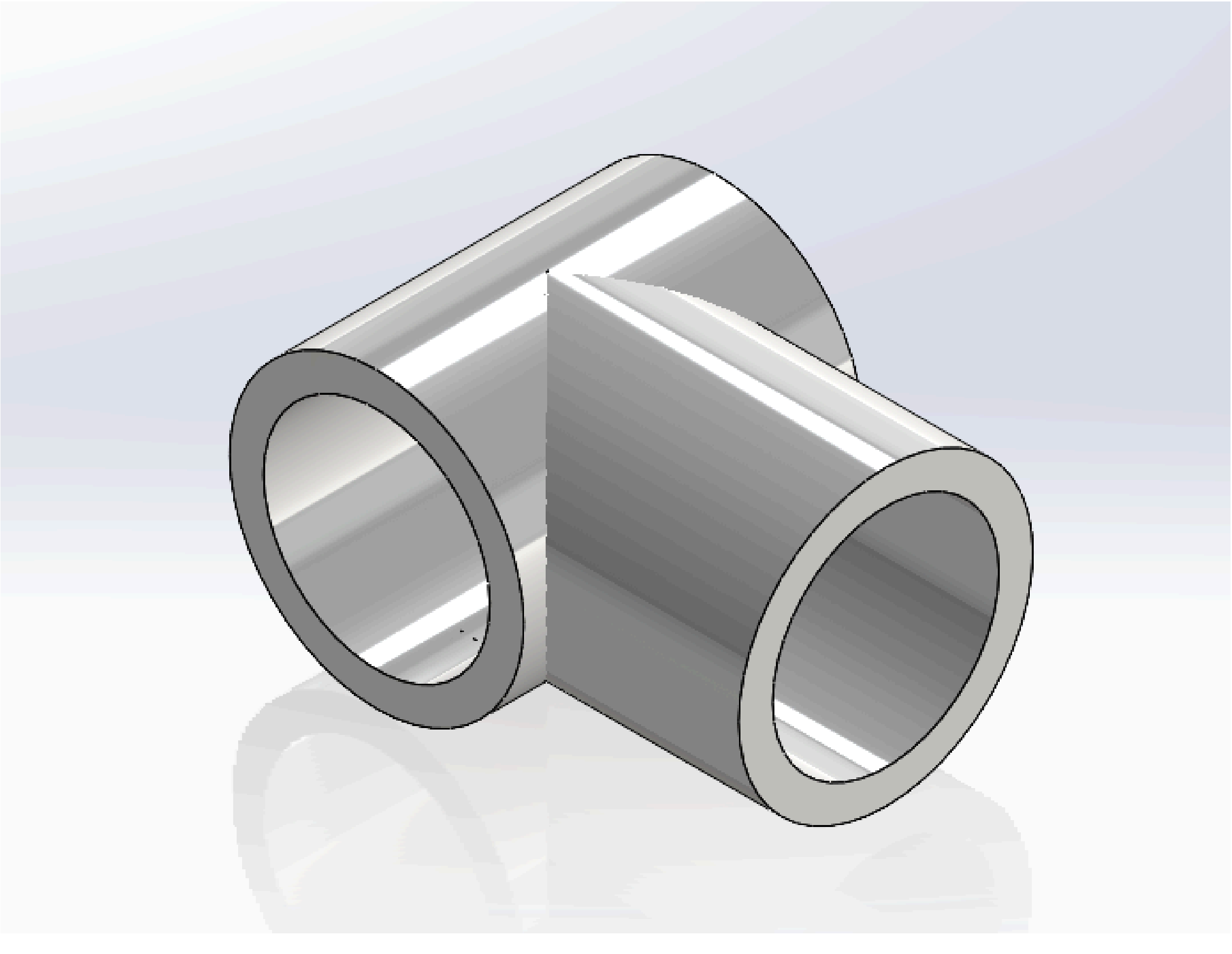


Fig. 18 - Solidworks Model of Modified PVC T-Joint

## 6.2 The Frame

The frame of the assembly would comprise of PVC and wood materials. The team decided to use the same ¾ inch PVC fitting and pipe throughout the assembly. In Figure 19 below is the Solidworks model of the frame on our kinetic sculpture. This design went through multiple iterations to be improved and meet the design parameters. On the bottom lengths of the frame is where the legs would rest and be secure and supported. The frame was necessary and designed to hold all the other components of the assembly securely. During the design phase, the frame was built around all eight legs and the crankshaft. The frame is 50 inches long, 15 inches high, and 18 inches wide. These dimensions help achieve our design requirement of fitting through a door while maintaining enough room for the remaining assembly. Cross supports were designed to increase the structural rigidity and support the crankshaft on the bottom and turbine shaft on the top.

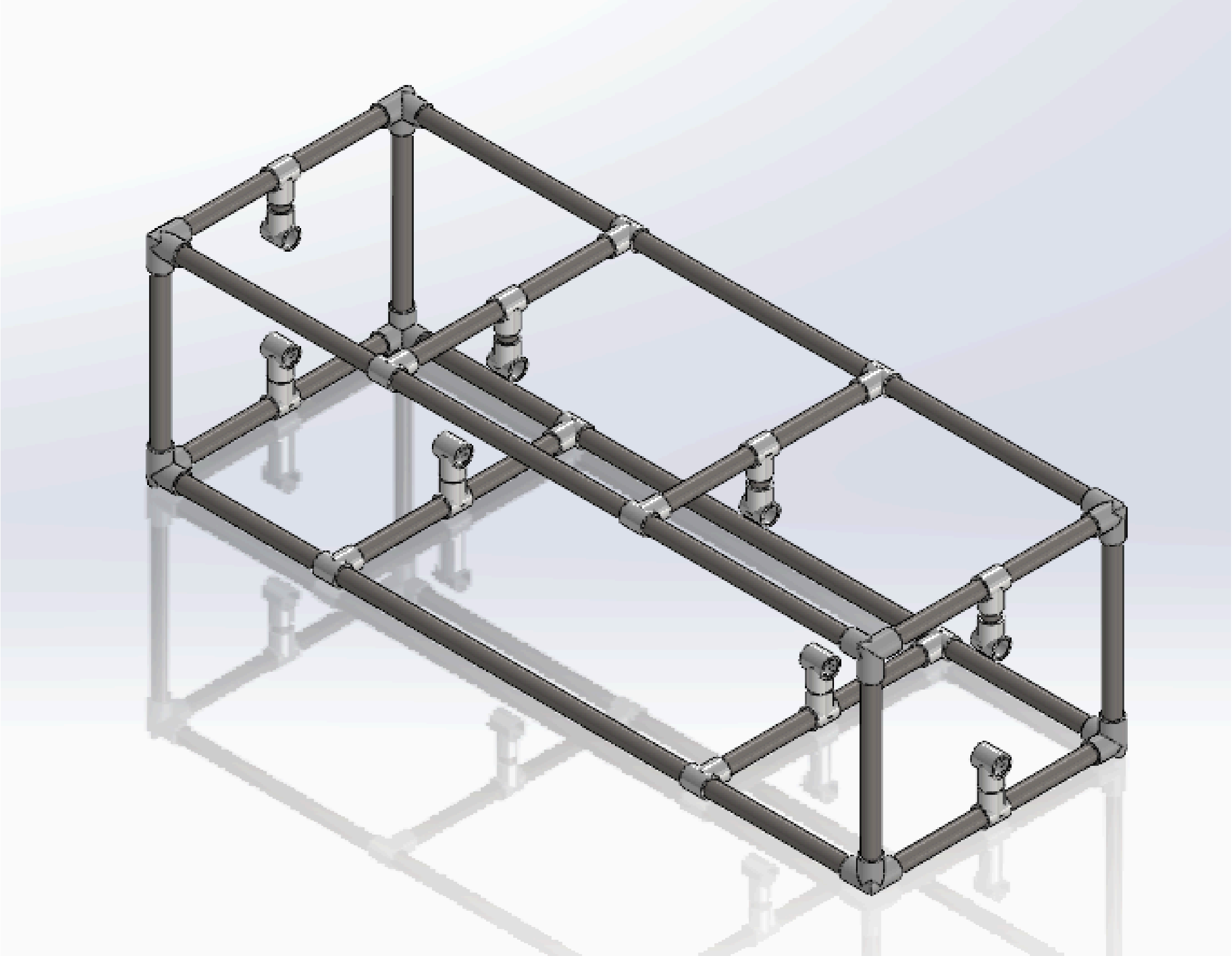


Fig. 19 - Solidworks Model of Frame for Assembly

## 6.3 The Crankshaft

In figure 20 below is the Solidworks model of the crankshaft. This model started with our design parameters for a kinetic sculpture. In order to achieve a walking-like motion for the sculpture we designed a crankshaft that allows the legs to be on different paths therefore making the walking motion less turbulent and instead a smooth and stable platform. The crankshaft has 90 degree offsets in four locations to achieve 360 degrees of travel. The length of the Solidworks model is 53 inches long and a radius of 3.8 inches. The legs were designed to be used in pairs so there are two legs per section of crankshaft. Each leg will be in a different stage of motion while traveling around the crankshaft. It was designed to be easy to modify if changes needed to be made. Our team knew the crankshaft could not support itself because it was not one solid piece but instead many parts. Adding space for supports was a necessity to reduce play and flexing on the overall assembly.

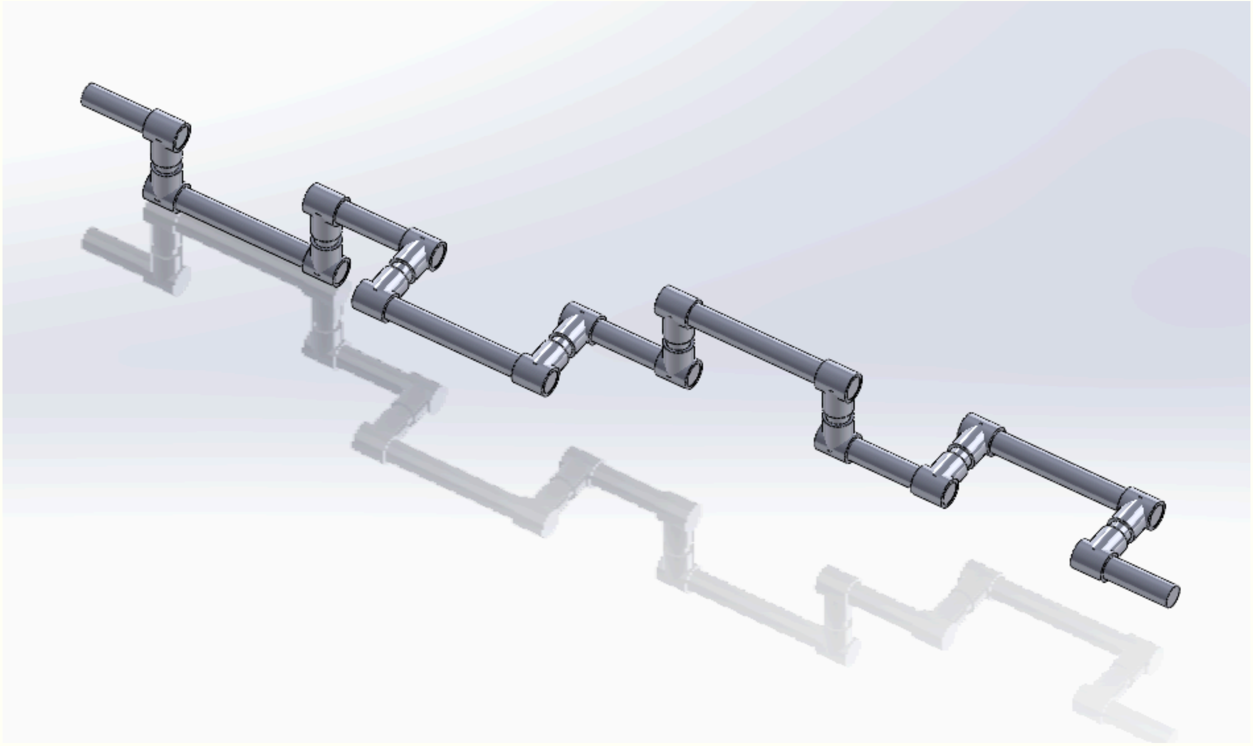


Fig. 20 - Solidworks Model of Crankshaft (Isometric View)

## 6.4 Full Model

Assembling the full model in Solidworks was straightforward and with it we could identify where improvements could be made. In Figures 21-24 below are the full assemblies of our kinetic sculpture in Solidworks. The turbine blades on either side of the model would propel the gears to move the crankshaft for a continuous walking motion. These gears which can be seen in the middle of the assembly were going to rotate the crankshaft which rotates the legs. The full assembly model measures 58 inches long, 37 inches tall. The width of the assembly varies depending on rotation which can range from 47 inches to 35 inches.

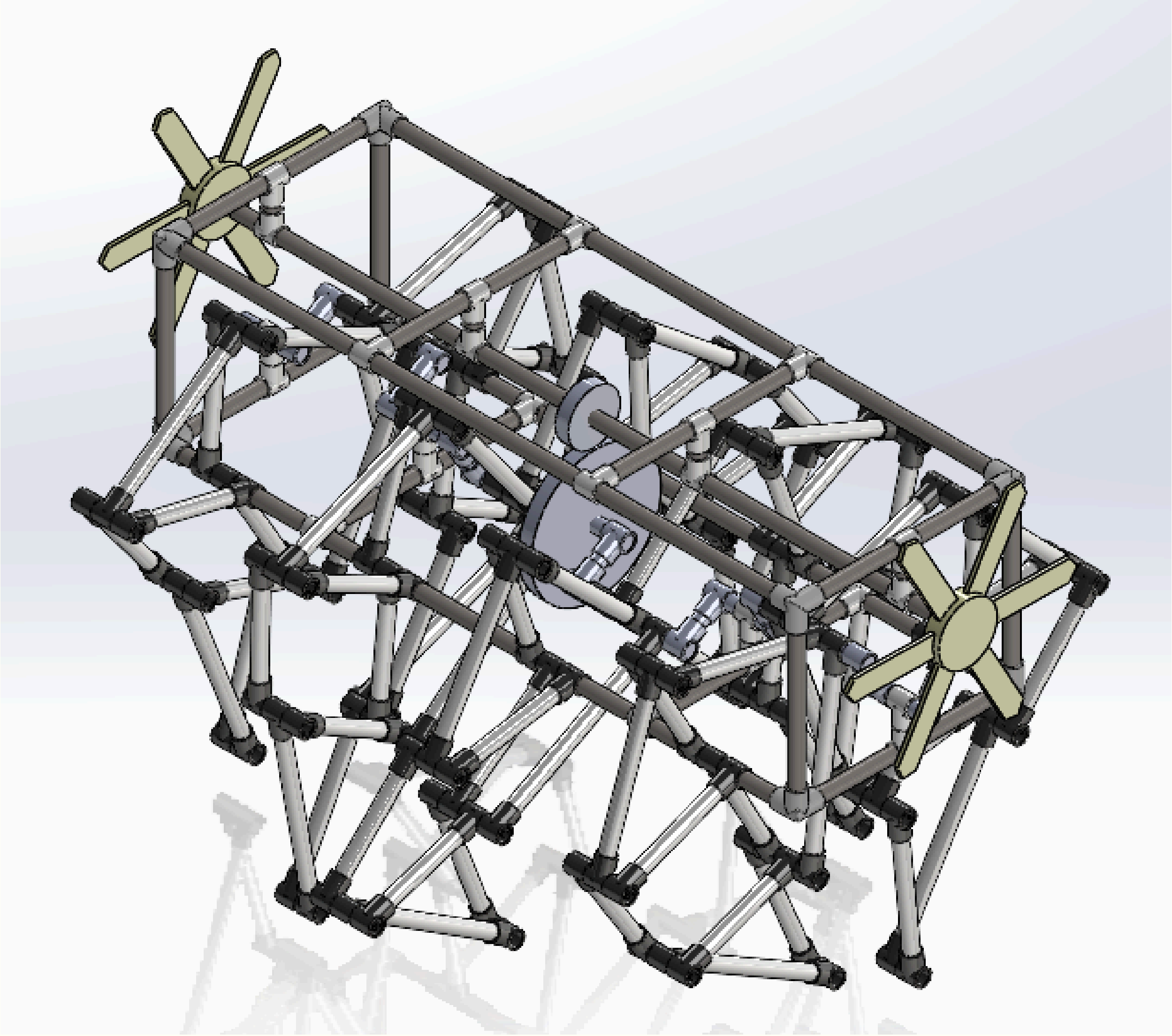


Fig. 21 - Solidworks Full Assembly Model (Isometric View)

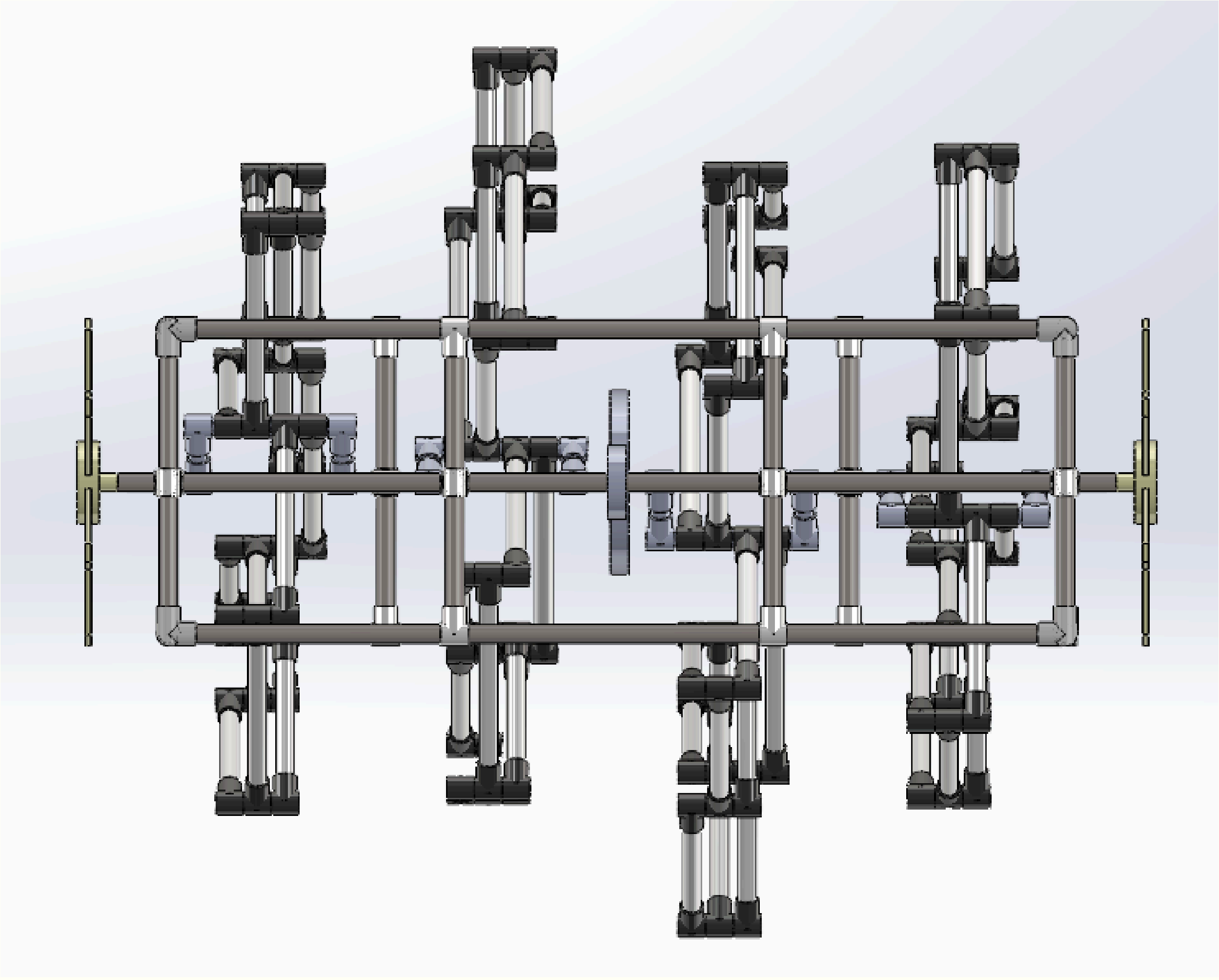


Fig. 22 - Solidworks Full Assembly Model (Top-Plane View)

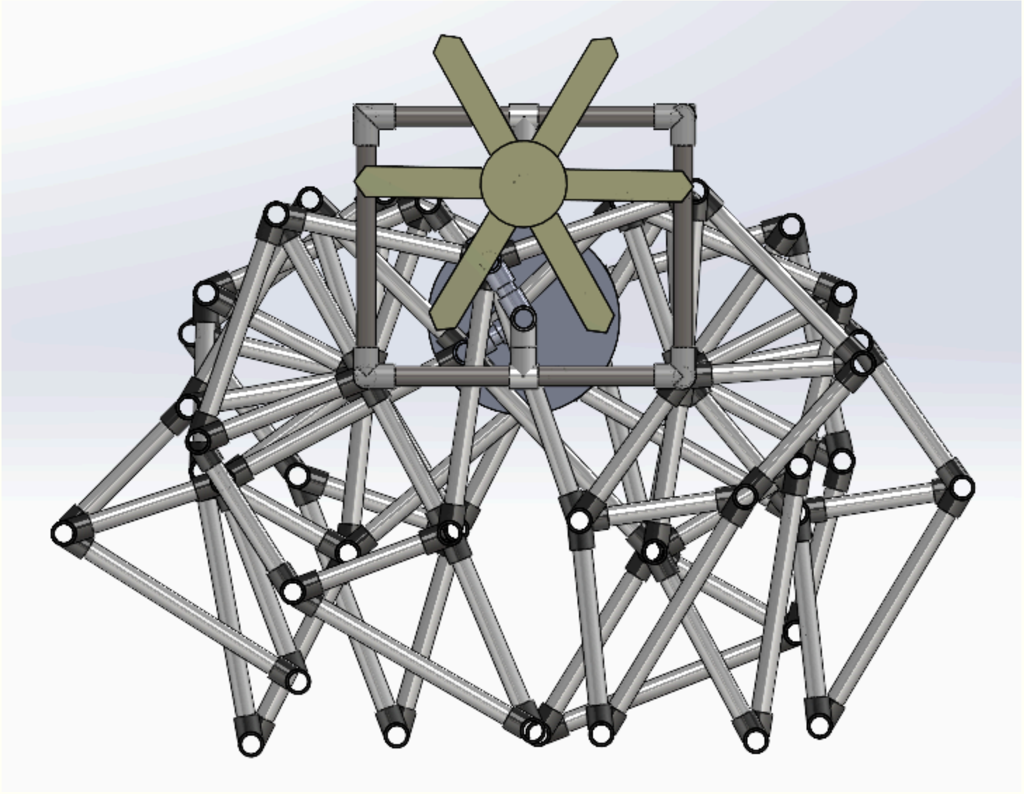


Fig. 23 - Solidworks Full Assembly Model (Right-Plane View)

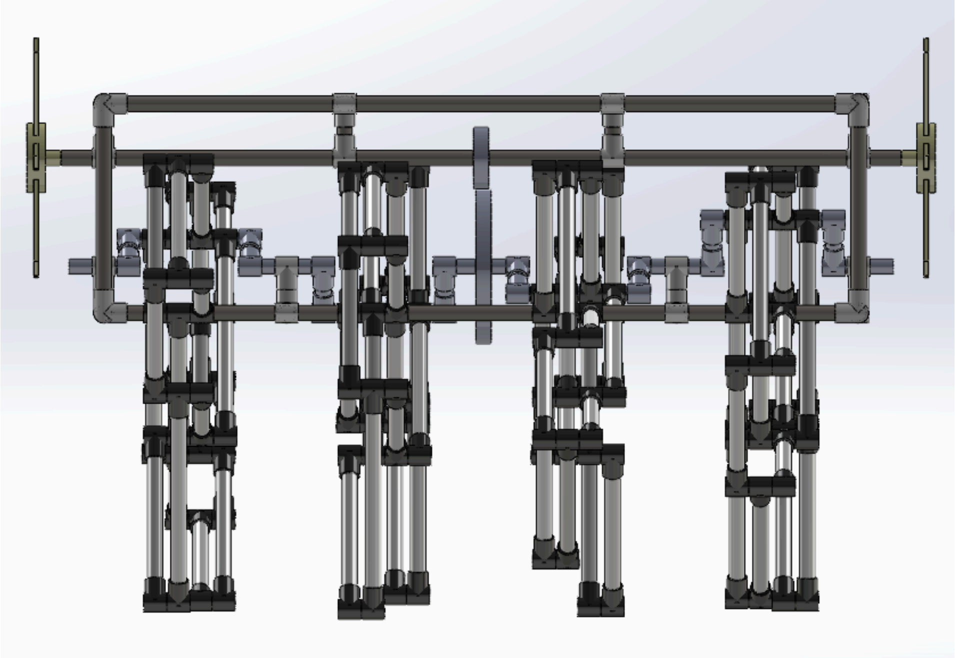


Fig. 24 - Solidworks Full Assembly Model (Front-Plane View)

# 7.0 Manufacturing

We spent the majority of time developing this project on manufacturing and assembling the kinetic sculpture and its components. Components were purchased from the Home Depot as well as through online retailers. The acquisition of these parts included PVC pipe and joints, screws, wooden dowels, PVC cement, wooden gears… Through thorough product research, testing, trial and error, and final re-adjustments, the kinetic sculpture was assembled as shown in Figure 25.

Fig. 25 - View of Kinetic Sculpture Linkages

## 7.1 PVC Links

Based on the CAD model of our linkage, we measured each link and cut it to a specific length to ensure the proper stride of the kinetic sculpture. Using a tape measure, we marked and cut the 10 feet of ¾ inch PVC pipe with a ratcheting pipe cutter as shown in Figure 26. Each leg linkage contains ten links with two cuts per link, totalling 20 cuts per leg and 160 cuts in all. Because we needed to refine the model for more vertical clearance within the linkage leg path, resizing each link was necessary to change the proportions of the linkage. This process was done halfway through cutting the links creating a minor setback to recut all the links.

Fig. 26 - Links (¾ inch PVC Pipe)

PVC “T” joints allowed the individual links of each linkage to rotate about an axis while maintaining connection as shown in Figure 27. These ¾ inch diameter pieces were assembled on both sides of each linkage totalling 20 per leg and 160 for the entire linkage system. Before assembling them onto each link, both sides of the PVC T were cut so they were flush with the diameter of the part which reduced the width of the part, saving space for the linkage system as shown in Figure 28. These were cut using a ratcheting PVC pipe cutter.

Fig. 27 - ¾ inch PVC T

Fig. 28 - Cut ¾ inch PVC T

Incorporating both the PVC Ts and PVC pipe links, two Ts were added to the ends of each link as shown in Figure 29. This is the largest portion of the kinetic sculpture which gives it shape and allows movement of the pieces together. With the wooden dowels cut to size, the linkages were assembled using the Ts to connect each link in the orientation of the walking linkage.

Fig. 29 - Links with ¾ inch PVC Ts

### 7.2 Wooden Dowels

To connect the PVC pieces to each other, ½ inch wooden dowels were placed through the ends of the PVC Ts allowing them to pivot as shown in Figure 30. These were cut down using a hand saw to the width that corresponds with the number of PVC Ts on the specified section, while leaving space for shaft collars to be added on each end of the wooden piece.

Fig. 30 - Wooden Dowel for PVC Rotation

## 7.3 Linkages

Using the PVC pipe, PVC Ts, and wooden dowels, all were assembled using the design of Theo Jansen's linkage. This included 10 individual links, 20 PVC Ts, and 7 wooden dowels per linkage. A fully assembled Jansen linkage moves in a motion that mirrors walking in nature because of the ratio each link is to each other. The one of eight fully assembled linkages is shown below in Figure 31.

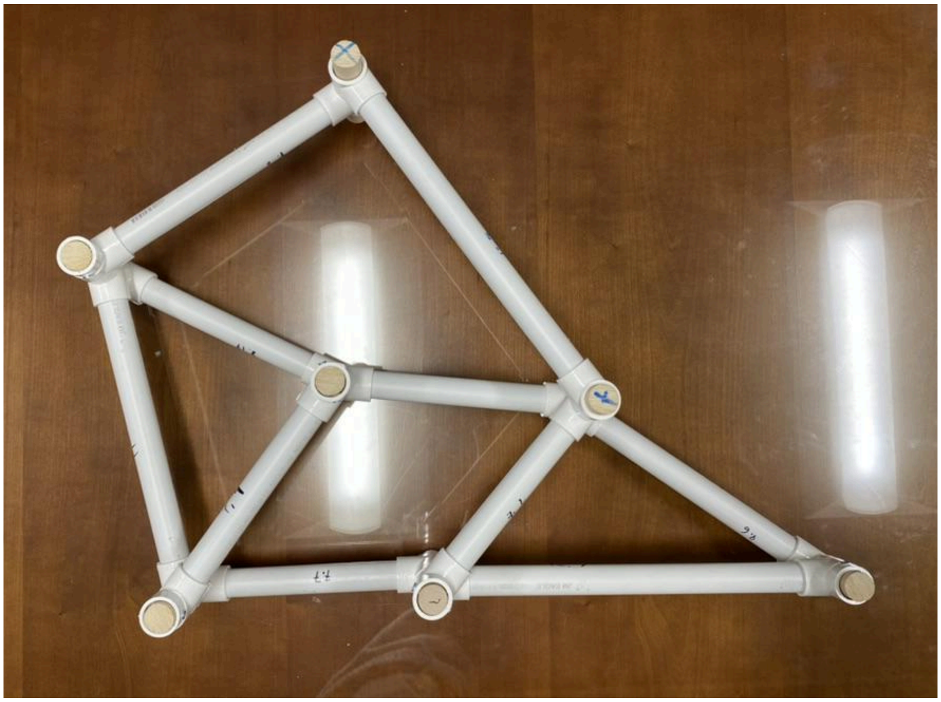


Fig. 31 - Assembled Linkage

## 7.4 Shaft Collars

To keep each of the Ts connected but allow the rotation around the wooden dowel, shaft collars were secured on each end of the dowels as shown in Figure 32. These collars were taken from the otherwise unused scraps of the Ts that were previously cut off. The ¾ inch cylindrical pieces were ½ inch in width and were secured into the wooden dowels with two ½ inch flat headed screws per each collar. The screws were short compared to the dowel because we did not want to risk splitting the wood from screws that were too long or wide. Screws were also on opposite sides of the collar, as shown in Figure 33, to allow for a better securement and so they did not intersect with each other.

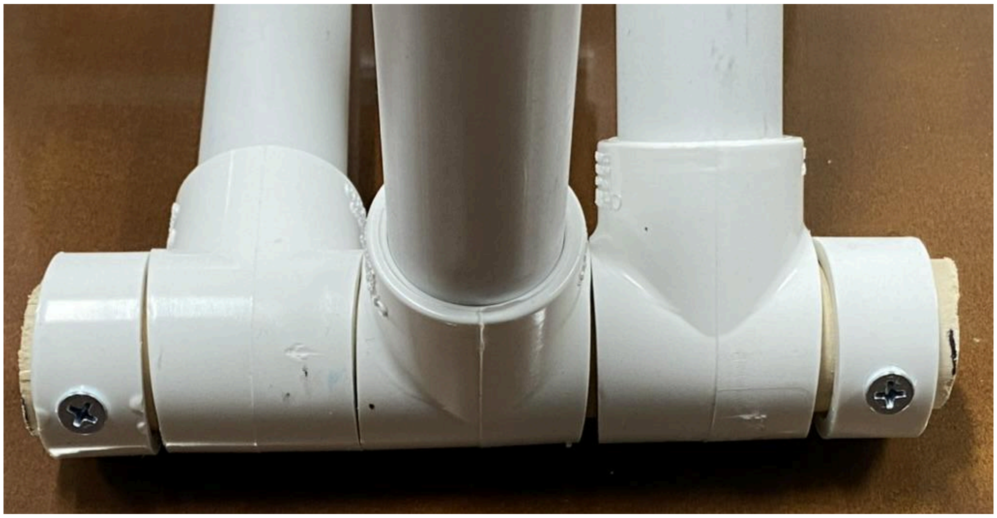


Fig. 32 - Shaft Collars on Dowel

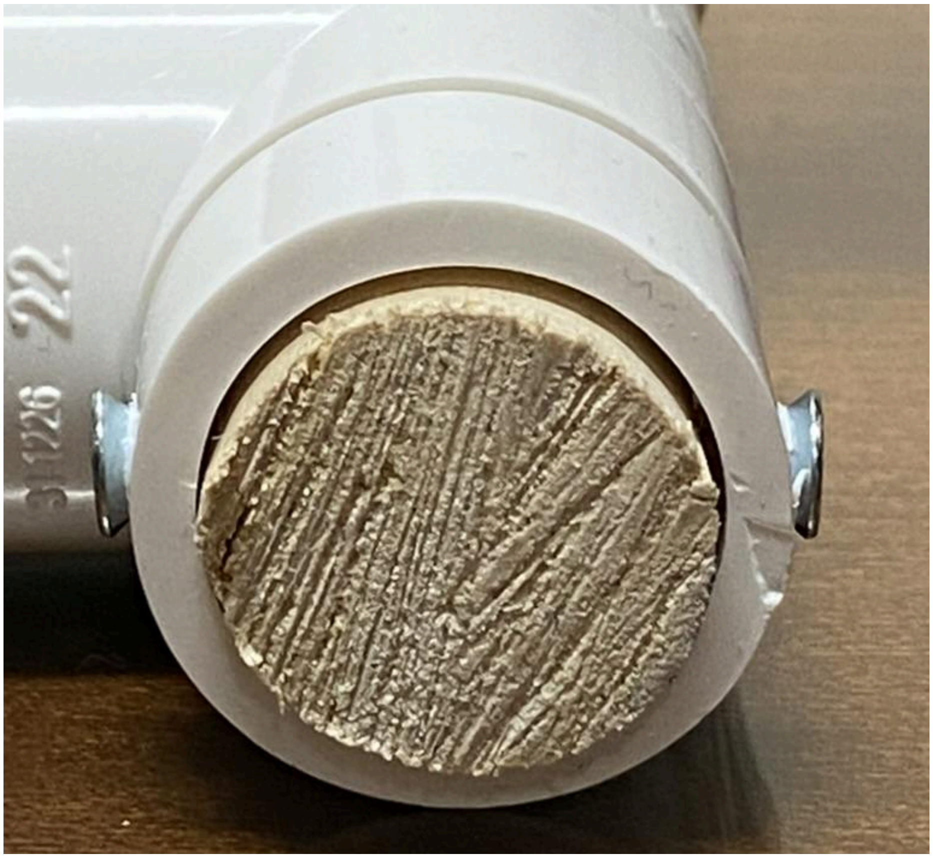


Fig. 33 - Side View of Shaft Collar

One issue with the shaft collars was the amount of additional space they took up. A problem we found was that by having two shaft collars on each end we added additional width and because ample space was needed to prevent components from rubbing against each other, we realized several of the shaft collars were screwed in too closely to the other Ts on the dowel and caused excess friction. We needed to unscrew and rescrew many of the shaft collars because of this which caused the wooden dowels to split.

## 7.5 PVC Cement

After constructing each of the linkages, the PVC components needed to be permanently secured to one another. We used regular clear PVC cement around the ends of each of the links to glue the PVC Ts to the links (PVC pipes), as shown in Figure 34. This process was successful in securing the components to each other, but because this was done after the linkages were put together, it was difficult to ensure the Ts were aligned straight with each other. Because of this, additional friction was found when rotating several of the components.

Fig. 34 - PVC Cement

## 7.6 Frame

Wooden dowels used as the axis for rotation in the linkages were also incorporated into the frame of the kinetic sculpture. The four long edges of the 3-dimensional rectangle, used for the frame, were the 43 inch long wooden dowels (five inches were removed from the original length to fit properly) as shown in Figure 35. These dowels were slightly bigger in diameter because they were less dry and had expanded compared to the original dowels we had. To sand these down to match the diameter so that they could fit smoothly into the ¾ inch Ts, we sanded the circumference of the new dowels. To do this, we used sand paper for the first dowel but quickly switched to a belt sander to speed up the process significantly for the other three. These dowels have structure to the linkages and allowed them to rotate as well, holding the entire kinetic sculpture together.

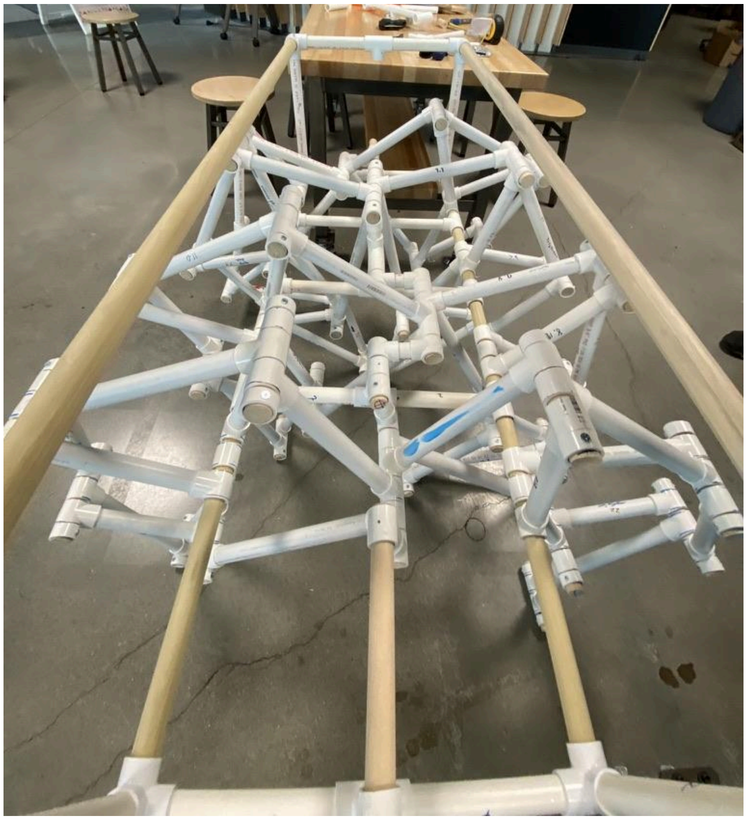


Fig. 35 - Top View of Wooden Dowels in Frame

The rest of the frame included 3-way PVC elbows on each of the corners of the frame to hold the dowels and other PVC pipes into place as shown in Figure 36. These were screwed into place using the same ½ inch flat headed screws used on the shaft collars. Between each set of linkages we added a structural support piece that connected the two bottom frame dowels to give the structure added rigidity and as a place for the crank shaft to connect to for support as well.

Fig. 36 - ¾ inch PVC 3-Way Connector

## 7.7 Crank-Shaft

The crack-shaft of the kinetic sculpture was assembled as the linkages were put onto the frame. This was done using PVC Ts and wooden dowels to off-set the linkage set's rotation from the central-axis by 90 degrees compared to the other linkage sets as shown in Figure 37. This was done to ensure constant contact with the ground while walking. Unlike assembling the linkages, the Ts were directly screwed into the wooden dowels to prevent rotation of the components. This allows for the crank-shaft to rotate the linkages when a torque is applied to it from gears or manually.

Fig. 37 - Top View of Crank-Shaft

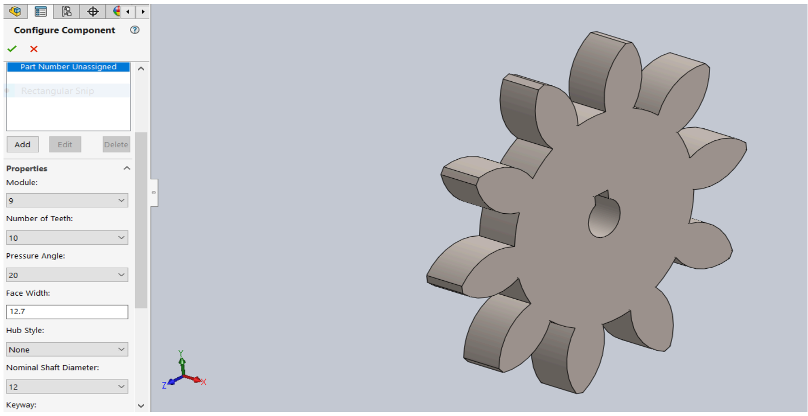
## 7.8 Tractional Feet

For added traction, foam pipe insulation was cut and placed around the portion of the linkage that comes into contact with the ground. These were secured into place with the use of zip ties as shown in Figure 38. The use of these tractional feet at the bottom of the kinetic sculpture allows for travel over a variety of surfaces with less slipping.

Fig. 38 - Zip Ties Securing Foam for Foot Traction

## 7.9 Gears

The gears were modeled in Solidworks using its Toolbox, (Figure 39). Their faces were saved as drawings which were used as the laser-cutting files. We first attempted to cut them into ½” plywood, but the laser-cutter struggled to get through it. Adding more power or more passes caused burning. The final gears were cut from ¼” plywood. The laser-cutter mostly got through it, and the gears were able to be pressed out despite the cut being incomplete in a few places (Figure 40). The original plan was for the each pair of congruent gears to be bound together to act as one thicker gear, but the large gear proved unable to fit within the frame, and the plan changed to have one on each side of the shaft, outside the frame.



Module: 9

Number of Teeth: 10

Pressure Angle: 20

Face Width: 12.7

Hub Style: None

Nominal Shaft Diameter: 12

Keyway:

Fig. 39 - Small Gear Model in SOLIDWORKS

Fig. 40 - Gears Removed from Plank

### 7.10 Turbine

The turbine hub was incompatible with the turbine shaft. The hub was designed to be screwed into the base of a shaft and our shaft was a plain keyed metal one. The diameter of the hub's bolt hole was also far larger than the diameter of the shaft. To rectify this, we designed an adapter. It was modeled in SOLIDWORKS: a simple cylinder with one side containing a hole matching the keyed shaft and the other containing a pilot hole where a screw could fix it to the hub. Two copies of this adapter were 3D printed in PLA, (Figure 41).

Fig. 41 - Printed Adapter

## 8.0 Testing

### 8.1 Leg Testing

In the process of our sculpture's construction, multiple tests were done. Many of these were checks of function, failure, and feasibility. One such test, one of our first, was that of our leg design, a Jansen linkage made out of PVC and wood. Our first test leg, pictured in Figure 42 of section 5.1, revealed not just functionality in our chosen materials, but also oversight in how we modeled and dimensioned our links. This test gave our team the confidence to move forward with the PVC and wood dowel system, and allowed us to refine not just our design, but also how we estimated our sculptures full scale. From this point in the process on, simple checks of leg movement were done as each additional leg was constructed. Other simple tests of feasibility were performed for other structural components, such as for the frame.

Once enough legs were built, an important step was to check the paths of the legs when cranked. This was done using two fully constructed legs attached to a rough model of the eventual frame. The pins that required grounding were done so using spare dowels, the proper distance between these grounded points being maintained by fragments of eventual crankshaft supports, which had the dimensions needed. This setup can be seen in Figure 42, below. Moving the mutually connected dowel simulating a crankshaft connection, traces of the expected walking motion, similar to Figure 3 in section 2.2, were recognizable. This was reassuring in our pursuits to connect the other 3 pairs of legs.

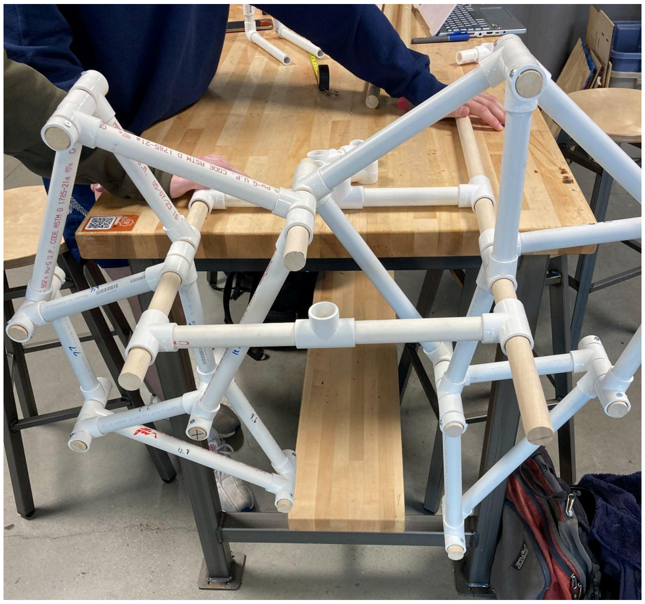


Fig. 42 - Leg Pair Test

Later in the construction process, once the frame, legs, and crankshaft segments were individually prepped and complete, our team's next steps were to test the functionality of the, yet unpowered, full mechanical system. This was done by attempting to crank the crankshaft by hand, and observing any issues that arose. This process was repeated multiple times.

The first set of checks by this process was to ensure everything was functional before the final gluing of the PVC, as it would limit our ability to make changes if problems came up. In this test we noticed some collared pins that were tighter than others, causing unnecessary resistance. Once we had confidence in the parts ability to function as intended, and our method of crankshaft inclusion, we glued all segments. To do this, though, all sections were disassembled and reassembled, bringing us to our second check.

The second run of this process revealed more friction than the first, and catching of the crankshaft on frame sections due to inconsistencies in reassembly. This was rectified by shortening some crankshaft sections and repositioning its supports relative to the frame. Friction in the newly glued leg segments was also noted to be higher in this phase, seemingly due to misalignments in the gluing process. Though noticeable in many links, some T joints were twisted and offset by a noticeable degree. At this point in the year it was no longer feasible to fully disassemble and reassemble the system, so our team decided to move on.

In the interest of testing both the feet functionality of the pipe insulation, as well as the possibility of other means of locomotion, a test was also performed to see if the system, with no gears or fans attached, could move if pushed or pulled. This was inspired by Theo Jansen's original design, which did not make use of fans or gears, instead using more of a sail based system. To test this, our team placed our yet unpowered system on its feet, and attempted to push or pull it, observing if the friction of the feet and the path of the links would result in the turning of our crankshaft.

From these tests we were not able to get the intended motion. From our observations, it seems that the feet did not contribute enough friction with the ground to properly translate the forward or backwards motion of the legs into translation of the crankshaft, not helped by the excessive friction previously mentioned due to gluing misalignments.

## 8.2 Gear Testing

The gears laser cut from the plywood were tested to see how each would interact with the other and functioned as expected. Based on the gears' tooth dimensions and tooth shape, the gears were able to mesh with one another. If implemented onto the frame successfully, the gears would have allowed the shafts to transfer rotational energy.

# 9.0 Conclusions and Recommendations

Throughout the process of designing, manufacturing, and testing the kinetic sculpture, the team observed several issues with the functionality of the project and suggest any future project groups consider the following:

Friction was the largest design barrier the team came across when building the kinetic sculpture as a whole. This barrier came in several ways including friction from the crank-shaft materials, spacing of rotating joints, and misalignment of joints on the individual links. To combat these problems in the future, we recommend several solutions from our learnings on this project.

To reduce one of the largest sources of friction, the crank-shaft material should be altered in future projects. The existing crank-shaft created large amounts of friction between the wood and PVC rubbing during rotation as well as bending from wooden components. A metal crank-shaft would allow smoother rotation of the linkages because of the lower coefficient of friction and the more consistent surface of the metal. Pairing low friction metal bearings in the joints connected to the metal crank-shaft would greatly reduce the largest source of friction the team found and improve overall functionality.

Additionally, we noticed more space was needed between the rotating T joints of the links. Because of this lack of space, Ts were rubbing against each other especially since some Ts were slightly angled due to the inconsistency in the cutting process. If we cut the Ts more consistently and had been given more space between each rotating joint, we would have significantly reduced the friction in linkage joints. Lastly, the misalignment of Ts in links caused more friction than estimated. Because we needed to cement the PVC T joints onto the PVC links while they were already assembled together, this problem caused inconsistencies in making the Ts aligned with its pair on the PVC links. These inconsistencies caused the rotation of links to be tight in some areas because T joints were somewhat twisted, increasing the rubbing of the wooden dowel and PVC in several areas. We would suggest cementing the Ts onto links before assembly while using a process or mechanism to ensure the PVC Ts are aligned on each link.

Similar to the twisting of PVC Ts on the links, the frame of the kinetic sculpture had succumbed to twisting of its own do to the forces being applied. This twisting as shown in Figure

43 created more friction in the components that were designed to move in parallel with each other. To solve this problem, the team suggests future project groups to add additional supports to the frame to prevent the torsional forces from altering the frame and linkage motion.

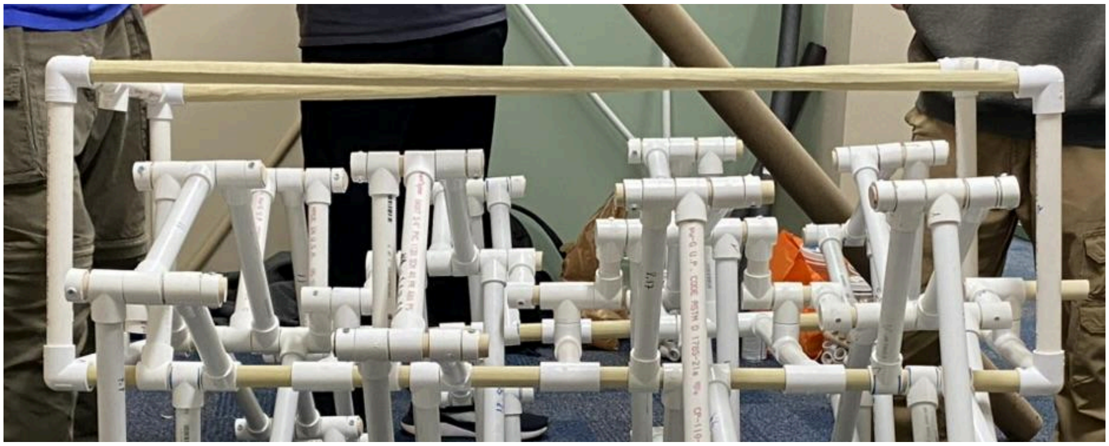


Fig. 43 - Frame Twisting

The turbine shaft and gears were not incorporated into the kinetic sculpture due to time limitations and the failure to foresee designing and manufacturing difficulties. Because of this and the lack of additional prototyping to merge the leg system with the turbine and gear systems, issues arose with gear sizes, gear assembly, gear-frame adaptation, and meshing the gears with the turbine axial system. The team recognizes these problems and would recommend extensive prototyping in the earlier stages of the project development to determine finalized gear sizes, assembly dimensions, materials, and adaptation. With early prototyping and communication of results, the team would find more time to properly decide and implement the gear assembly.

If the project were to be completed again, the team would start by pushing the original time table forward and focusing more on the prototyping phase, rather than research and development phase. This would allow for adequate time to redesign and manufacture specific components and mechanisms on the kinetic sculpture to improve its performance. Additionally, the team would take further steps at reducing friction throughout the mechanisms. This was the most significant factor preventing better performance from the mechanisms. Although the team recognizes areas for improvement in the project process and mechanisms, we were able to complete a kinetic sculpture that will entertain students and allow them to study the mechanisms in use.

# Appendices

## Appendix A: Bibliography

Badawy, Mohamed, et al. “One-Handed Carrying among Elderly and Obese Individuals: A Systematic Review to Identify Research Gaps.” PubMed, U.S. National Library of Medicine, 2018, pubmed.ncbi.nlm.nih.gov/29708048/.

“Beaufort Wind Scale.” National Weather Service, US Dept of Commerce/National Oceanic and Atmospheric Administration/National Weather Service, 2 Sept. 2016, www.weather.gov/mfl/beaufort.

Britannica, The Editors of Encyclopaedia. "kinetic sculpture". Encyclopedia Britannica, 14 Apr. 2018, https://www.britannica.com/art/kinetic-sculpture. Accessed 16 April 2024.

Jansen, Theo. Strandbeest, Theo Jansen, 2022, www.strandbeest.com/.

General Properties of Polyvinyl Chloride Pipe, American Water Works Association, 2002, www.awwa.org/portals/0/files/publications/documents/samples/30023_excerpt.pdf.

hhrhhr. “Theo Jansen’s Strandbeest.” GeoGebra, GeoGebra, 2024, www.geogebra.org/m/xdnnbGZG.

“Kinetic Art.” The Art Story, The Art Story Foundation, 1 May 2018, www.theartstory.org/movement/kinetic-art/.

Li, Mark. “Different Types of Linkages.” Firgelli Automations, Firgelli Automations, 31 Mar. 2023, www.firgelliauto.com/blogs/news/different-type-of-linkages.

Shigley, Joseph E. "The Mechanics of Walking Vehicles." Sept. 1960.

Nansai, Shunsuke, et al. “Dynamic Analysis and Modeling of Jansen Mechanism.” *Www.Sciencedirect.Com*, Department of Advanced Multidisciplinary Engineering, Tokyo Denki University, 13 Nov. 2013, www.sciencedirect.com/science/article/pii/S1877705813017529?via%3Dihub#section-cited-by.

Qamar, Sayyad Zahid, et al. “Integrity Assessment of High-Performance PVC Pipes for Thermal Wells.” Polymers, MDPI, 2023, www.mdpi.com/journal/polymers.

Scheublin, Wouter. “Walking Table.” Walking Table, Scheunlin & Lindeman, 2006, scheublinlindeman.nl/walking-table.html.

Uicker, J. J.; G. R. Pennock; J. E. Shigley (2003). *Theory of Machines and Mechanisms*. New York: Oxford University Press.

“What Is the Shelf Life for Solvent Cement, Primer and Cleaner?” Oatey, Oatly Co., www.oatey.com/faqs-blog-videos-case-studies/blog/what-shelf-life-solvent-cement-primer-and-cleaner. Accessed spring 2024.

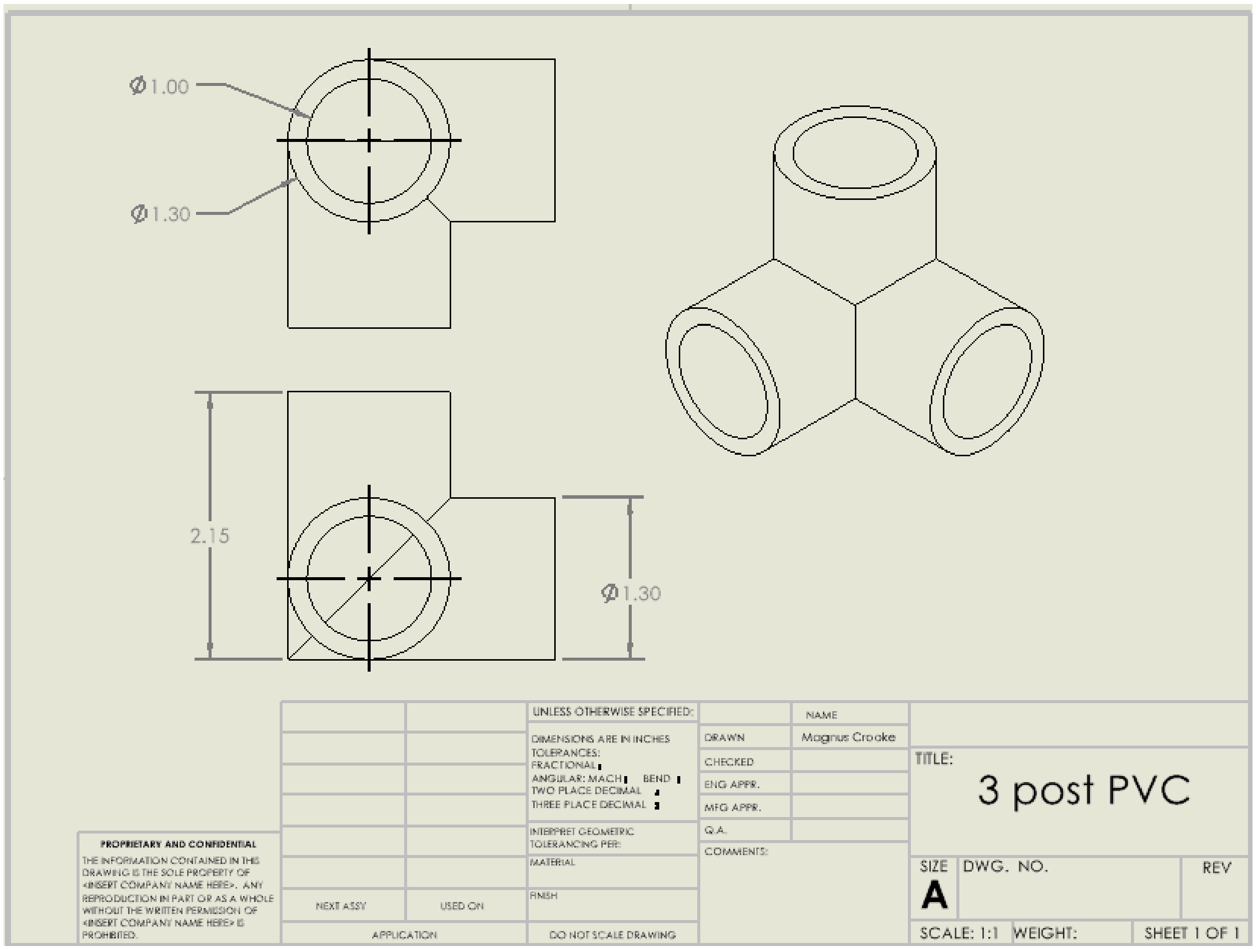
Whittle, A. J., and A. Teo. Resistance of PVC-u and PVC-M to Cyclic Fatigue, Iplex Pipelines Australia Pty Limited, 2018, https://pvc4pipes.com/wp-content/uploads/2018/02/Resistance-of-PVC-U-and-PVC-M-to

-cyclic-fatigue.pdf

"Worcester Polytechnic Institute, Massachusetts Climate Averages." WeatherWorld.Com, Weather World, 2023, www.weatherworld.com/climate-averages/ma/worcester+polytechnic+institute.html.

Yorozu, Ayanori & Nishiguchi, Shu & Yamada, Minoru & Aoyama, Tomoki & Moriguchi, Toshiki & Takahashi, Masaki. (2015). Gait Measurement System for the Multi-Target Stepping Task Using a Laser Range Sensor. Sensors. 10.3390/s150511151.

## Appendix B: Part Drawings



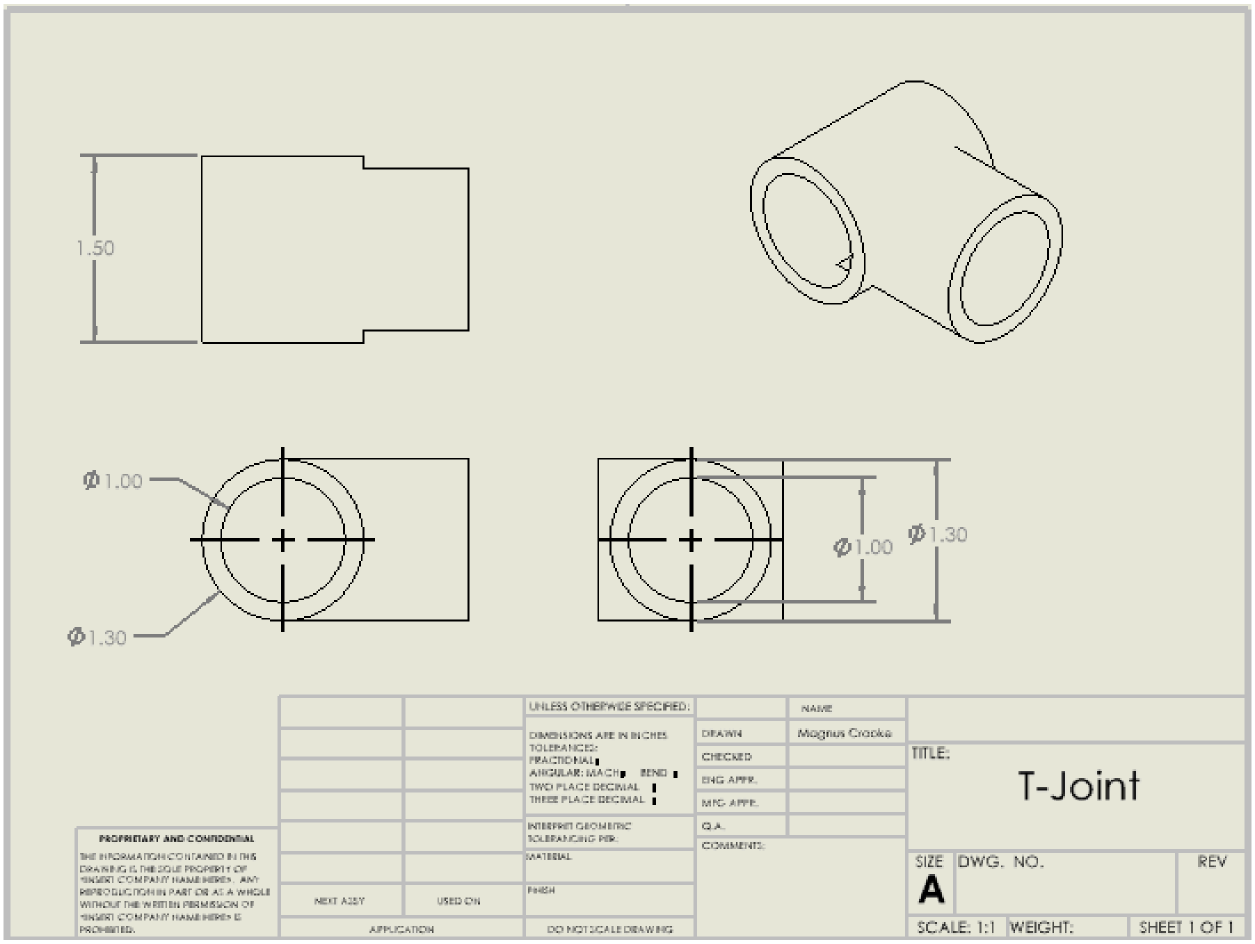
DRAWN Magnus Crooke

TITLE: 3 post PVC

SIZE A

SCALE: 1:1

SHEET 1 OF 1



DRAWN: Magnus Crooke

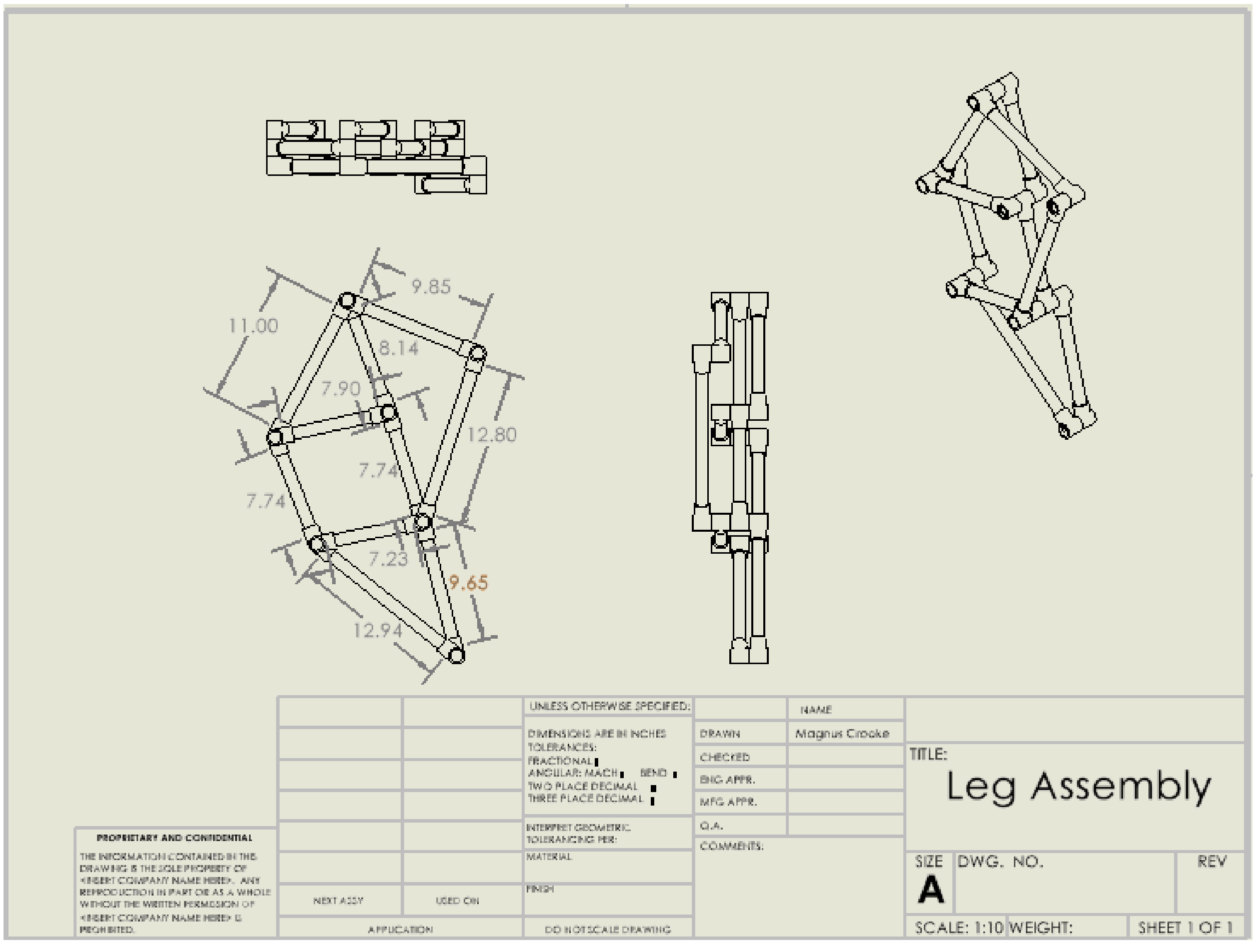
TITLE: T-Joint

SIZE: A

SCALE: 1:1

SHEET 1 OF 1

# Appendix C: Assembly Drawing



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

| | NAME |
|---|---|
| DRAWN | Magnus Crooke |
| CHECKED | |
| ENG APPR. | |
| MFG APPR. | |
| Q.A. | |

COMMENTS:

TITLE:
Leg Assembly

SIZE A
DWG. NO.
REV
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1

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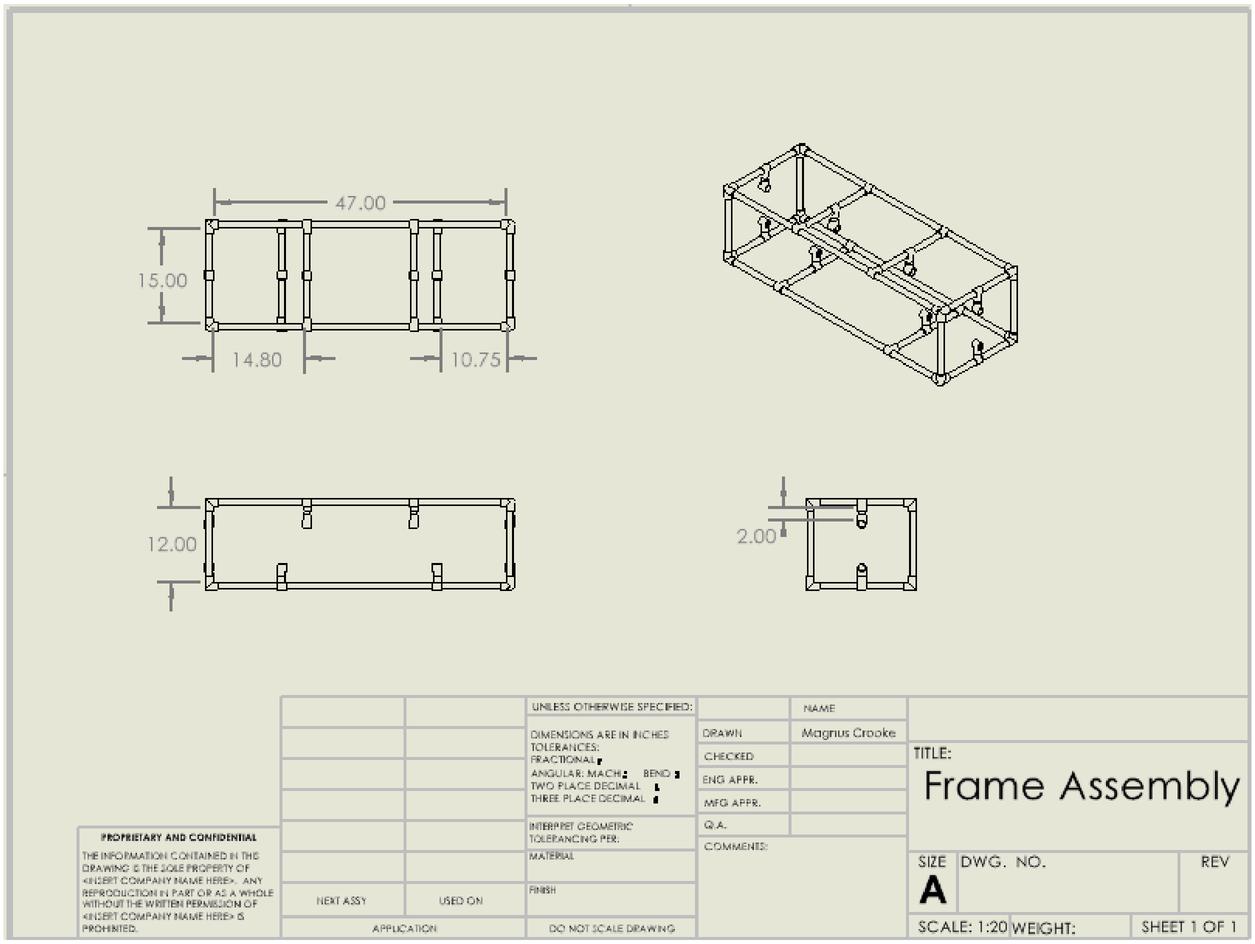

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

**PROPRIETARY AND CONFIDENTIAL**

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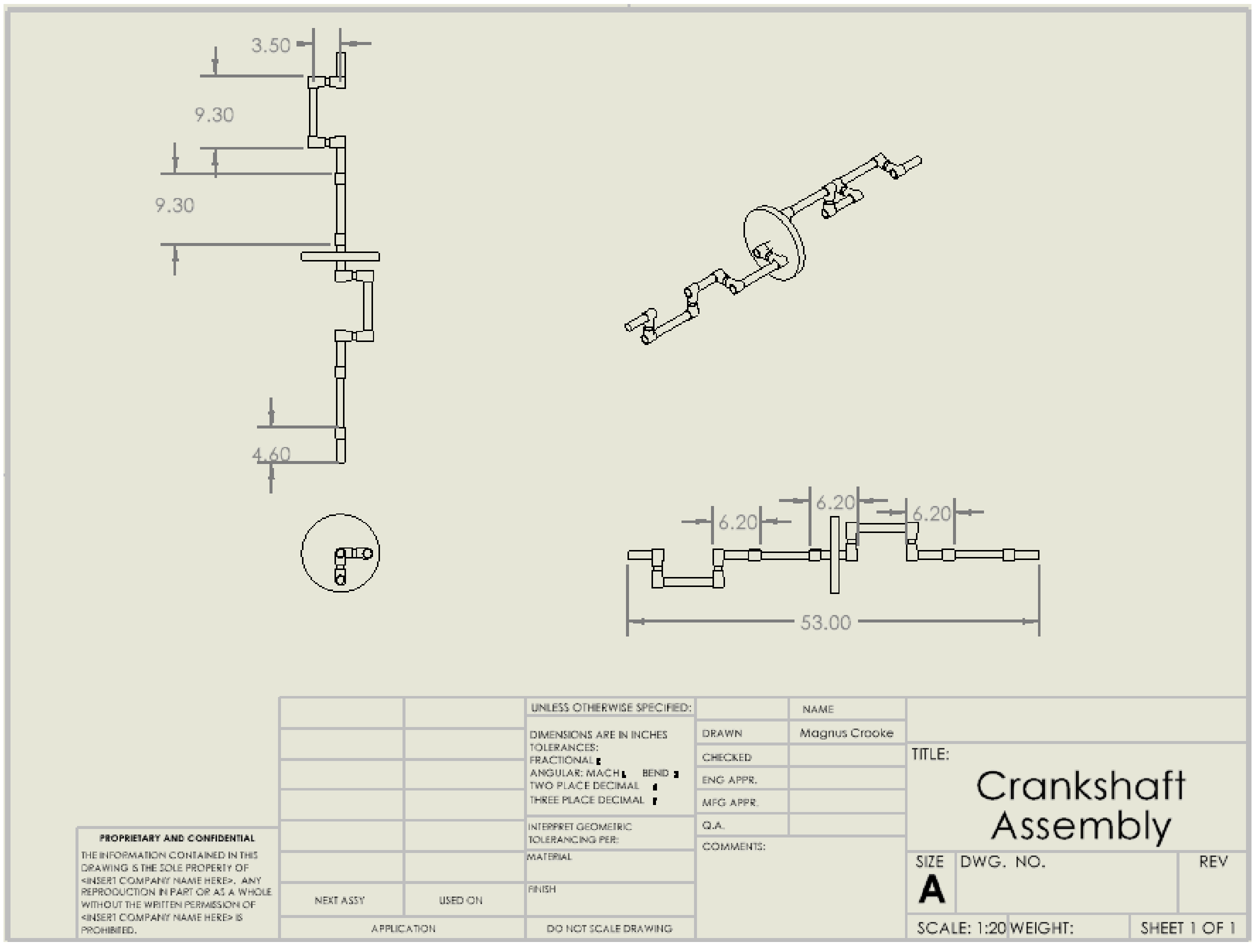
| | NAME |
|---|---|
| DRAWN | Magnus Crooke |
| CHECKED | |
| ENG APPR. | |
| MFG APPR. | |
| Q.A. | |

COMMENTS:

TITLE:
Frame Assembly

SIZE A
DWG. NO.
REV
SCALE: 1:20
WEIGHT:
SHEET 1 OF 1


3.50
9.30
9.30
4.60
6.20
6.20
6.20
53.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL
ANGULAR: MACH BEND
TWO PLACE DECIMAL
THREE PLACE DECIMAL
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DRAWN
Magnus Crooke
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Crankshaft Assembly
SIZE
A
DWG. NO.
REV
SCALE: 1:20
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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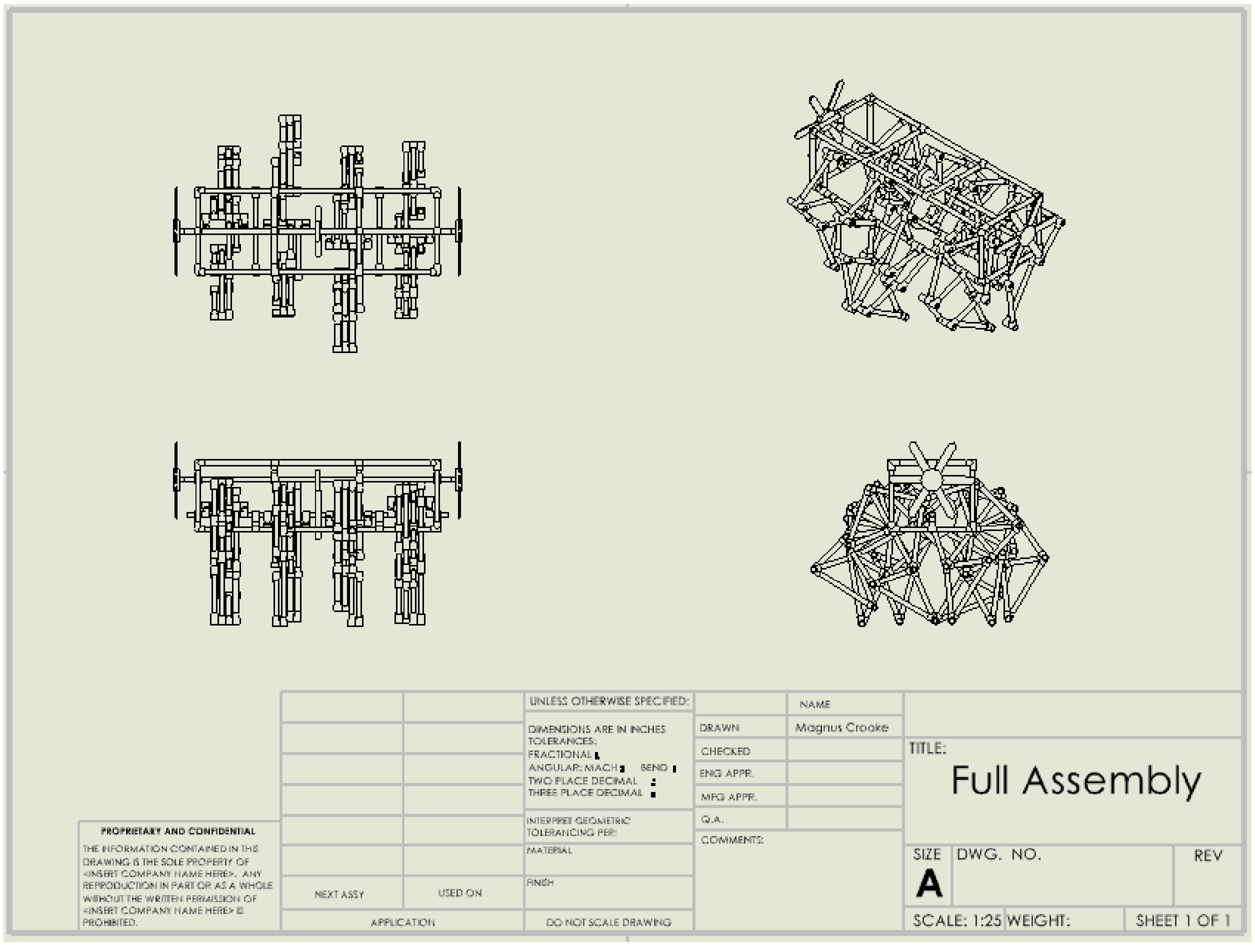

## Appendix D: Authorship Page

| | |
|---|---|
| **1.0 Introduction** | **PJH/LWB** |
| 1.1 Goal Statement | LWB |
| **2.0 Background** | **LWB/PJH** |
| 2.1 Kinetic Sculpture | LWB |
| 2.2 Sources of Inspiration | LWB |
| 2.3 Mechanisms | PJH |
| 2.3 Functional Requirements | LWB |
| **3.0 Design Concepts** | **LWB/GPC** |
| 3.1 Deciding on Concept | LWB |
| **4.0 Synthesis and Analysis** | **LWB/LB** |
| 4.1 Leg Analysis / Proof | LWB |
| 4.2 Material Selection | LB |
| **5.0 Design Selection** | **LWB/WM** |
| 5.1 Leg Team | LWB |
| 5.2 Wind Team | LWB/WM |

## Appendix E: Calculations

7.2167 mph * 0.44706 (m/s)/mph / (0.550m/rad / 2) = 12.512 rad/s

12.512 rad/s * 1 rotation / 2π rad * 60s/m = 119.48 rpm