# Wales: A Water-Based Physical Motion Rectifier

Group 4: Puzzled

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# Project Description

Four engineers were hired by their local problem solving firm, Mechanical Motion Consolidated, to create a system that takes in a non-constant unidirectional rotary motion and converts it into a constant velocity unidirectional rotational output. The system must be assembled onto and off of a 8” by 8” aluminum breadboard in under 5 minutes. The system must connect to a supplied input motor shaft. It must also have a gear on the input motor shaft that meshes with the supplied encoder gear. The system must have a way to measure the input and output rotational speeds with respect to time. The output rotational speed must rotate a disc with a diameter between 1” and 3”. The system will be tested at 3 frequencies: 1Hz, 0.5 Hz, and 0.25 Hz. The system must reach steady state in less than 10 seconds. The parts of the system must not spin in excess.

# Determining a Solution

The engineers began by brainstorming subassemblies that could counteract the variable speed provided by the motor, resulting in a constant output. The potential solutions used magnetic coupling, a centrifugal governor, and a centrifugal pump. For each design, a sketch and a systems diagram were made to understand how the solution would work.

## Magnetic Coupling System

For magnetic coupling, three magnets would be fixed onto two circular disks. One of these disks would be pinned to a gear that meshes with the motor gear. The other disk would be attached to an axle fixed onto the optical breadboard, likely with cylindrical bearing supports. When connected to power, the motor would spin the disk attached to the gear, thereby spinning the disk fixed onto the axle by way of magnetic coupling. On the other end of the shaft, there would be a flywheel that increases the moment of inertia of the rod, thus making it harder to accelerate or decelerate. This would prevent acceleration or deceleration from the motor gear from significantly impacting the axle, because the magnetic gears would decouple. This design was eliminated because it wasn't reliable. The magnetic gears would likely jolt when coupling or decoupling, and acceleration or deceleration of the output could still occur. A sketch of the proposed magnetic coupling system can be seen below in Figure 1.

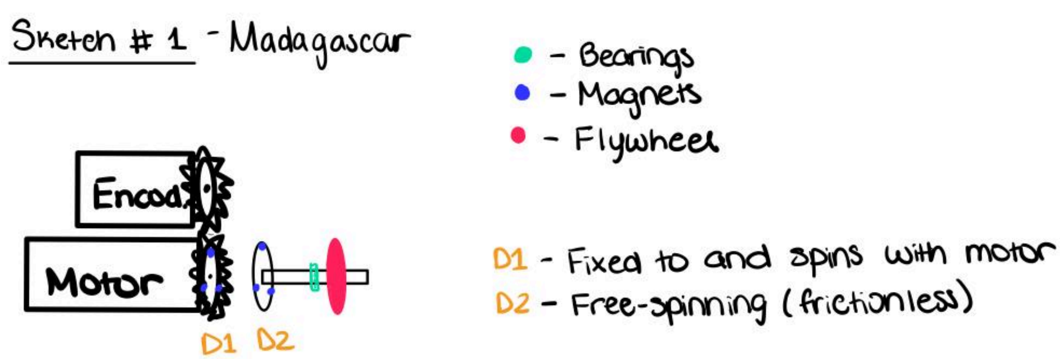


**Figure 1: Magnetic Coupling System Sketch**

## Centrifugal Governor System

The centrifugal governor system would have a motor gear meshed with the encoder gear and a second gear that would spin a shaft. The shaft would rotate bevel gear 1. Bevel gear 2 would mesh with the first rotating the axis of rotation by 90 degrees. Bevel gear 2 would be connected to a centrifugal governor, a device with two arms that raise when the system accelerates. The ends of the arms have masses that result in an increase of the inertia centrifugal governor when the arms raise, causing a deceleration. Furthermore, a propeller would be attached to the centrifugal governor and would lower into a reservoir of water when the governor's arms opened, causing further deceleration. Bevel gear 2 would mesh with bevel gear 3, rotating a shaft and output disk. Below, in Figure 2, is a sketch of the centrifugal governor system.

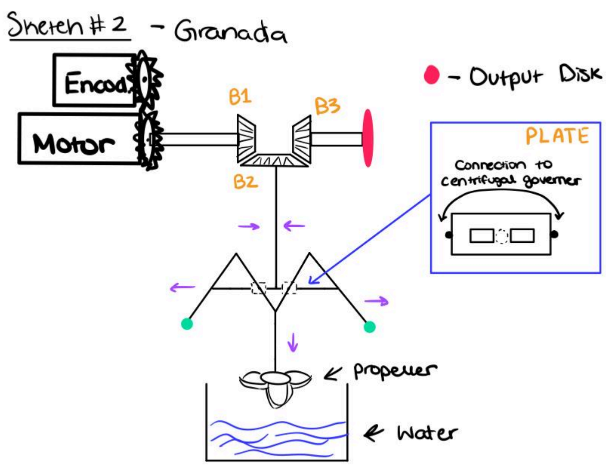


**Figure 2: Centrifugal Governor System Sketch**

## Water Wheel System

The water wheel system would have a shaft that joins two gears, one meshed with the motor gear, the other enclosed in a pump. This pump would be located in a reservoir full of water. This reservoir would be fixed onto the breadboard by pegs hugging two corners. When connected to power, the motor would indirectly spin the gear enclosed by the pump, pushing water from the bottom reservoir up into the top reservoir through a tube. Two supports extending upward from the reservoir would support another shaft with a waterwheel and output disk fixed onto it. Once the top reservoir, held by a fixed vertical support, fills, it would release water onto the water wheel, causing the shaft to rotate. The output speed would be measured through the fixed disk. A sketch of the system is shown below in Figure 3.

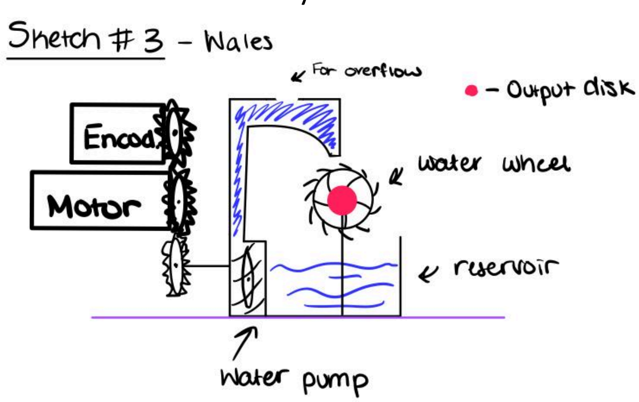


**Figure 3: Water Wheel System Sketch**

# Ideation Conclusion

After the three potential solutions were well understood, a decision matrix was made to determine the most viable solution. The decision matrix can be found below in Table 1. The design criteria considered were reaching steady state within ten seconds, quick assembly, constant output, feasibility, and safety. These design criteria were selected to fulfill the design requirements as specified by Mechanical Motion Consolidated. Feasibility was added as a design criterion because it was important for the system to be able to be built within a relatively short time frame, approximately two months. The higher the weight, the more important the design criterion. Each solution was rated 1, 3, or 7 for each criterion, with 1 being the worst and 7 being the best. The water wheel solution was clearly ranked the highest; therefore, the engineers moved forward with the water wheel solution.

| Design Criteria | Weight | Centrifugal Governor | Water Wheel | Magnetic Coupling |
|---|---|---|---|---|
| Steady State in 10 Secs | 2 | 3 | 7 | 1 |
| Assembly Time | 1 | 3 | 3 | 3 |
| Constant Rotation | 5 | 3 | 7 | 1 |
| Feasibility | 4 | 3 | 3 | 7 |
| Safety | 3 | 3 | 7 | 3 |
| Total | | 45 | 85 | 47 |
| Ranking | | 3 | 1 | 2 |

**Table 1: Decision Matrix for the Three Potential Solutions**

# Rapid Prototype

After the water wheel solution was chosen, the engineers created a prototype of the water wheel system using scrap 3D printed parts, rubber bands, K'NEX pieces, etc. Each part was identified, named, and labeled on the prototype. The prototype is shown below in Figure 4.

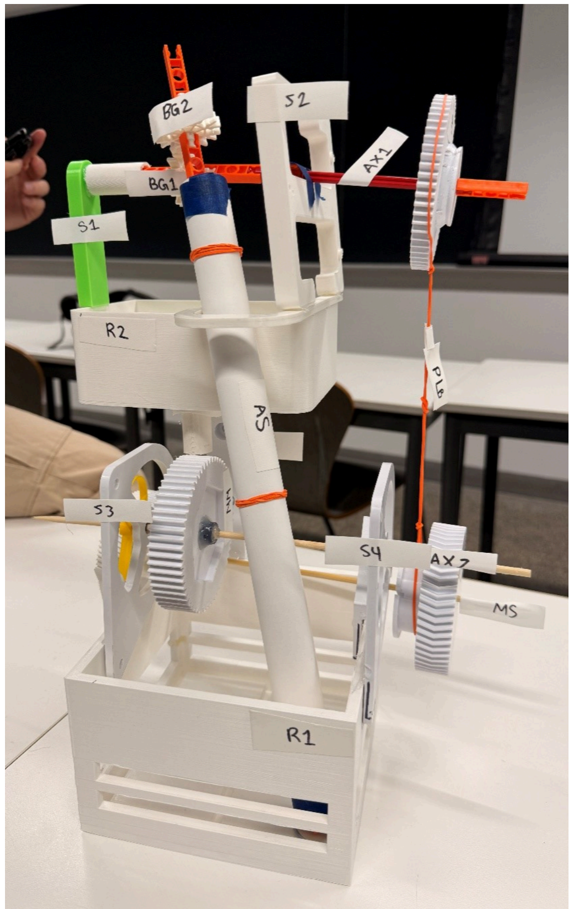


**Figure 4: Water Wheel Prototype**

# Pulley Subsystem

After the parts of the system were known, the engineers began to design the pulley subsystem. The pulley subsystem included a motor gear, pulley gear, and 8mm shaft supports. The power transfers from the provided input, a motor shaft, to a motor gear and tracking gear, which are connected to each other. The motor gear then transfers the force to a rubber band which moves the force to a pulley gear. The power transfers from the pulley gear to the 8mm axle through the clamping force of an M3 screw. Static forces are transferred from the 8mm axle to the mounts and optical breadboard. The power transfer is displayed in Figure 5 below.

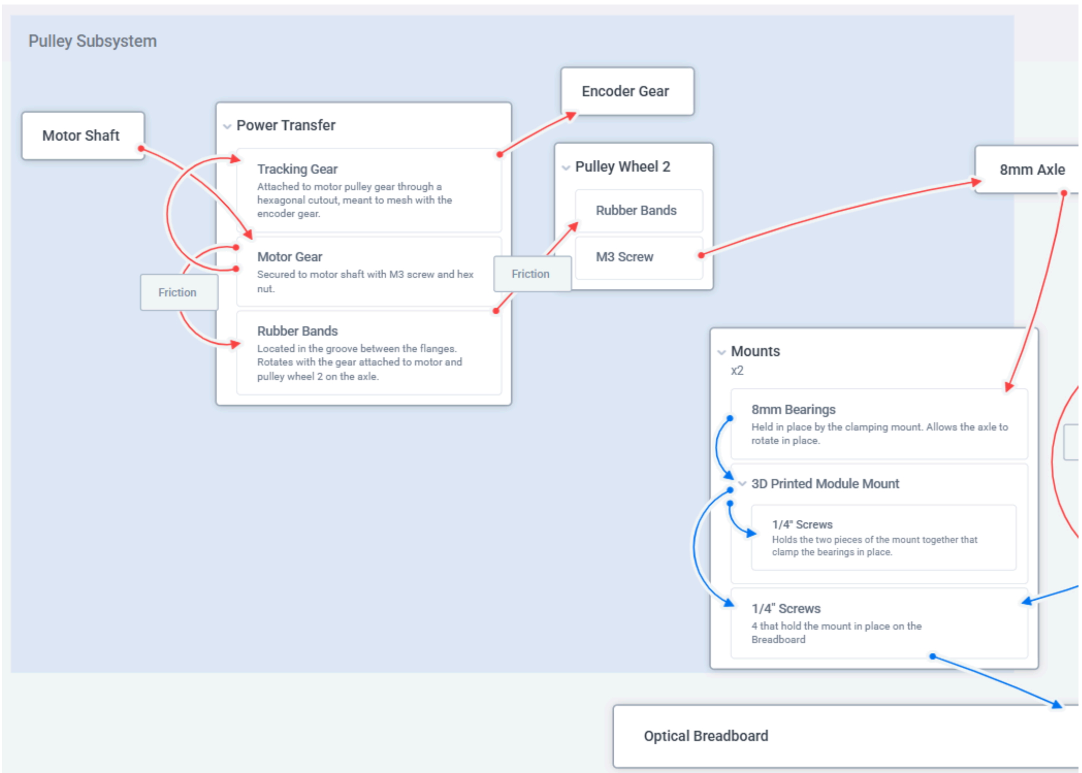


**Figure 5: Pulley Subsystem Systems Diagram**

## Motor Gear Iterations

The initial motor gear featured a hexagonal section, as seen in Figure 5, to hold a gear to mesh with the encoder gear. The motor gear featured a recessed center to guide a rubber band. This motor gear had significant issues with the rubber band slipping towards the side and jamming the motor. To resolve this, we tried various other gear geometries to prevent slipping.

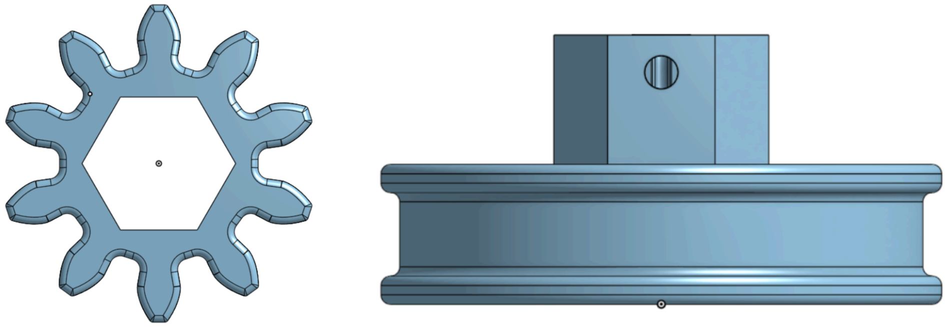

**Figure 6: Initial motor gear (right) and encoder gear coupling (left)**

One iteration features a ribbed surface to induce more friction and keep the rubber band from slipping. However, through testing, this did not help. The gaps between the ribs might have been too small (0.8 mm) to provide proper resistance to slippage.

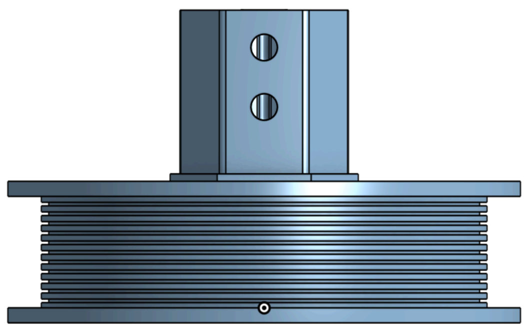

**Figure 7: Ribbed surface motor gear**

Another iteration features a concave surface to try centering the rubber band. However, through testing, the rubber band still slips towards the outside edge.

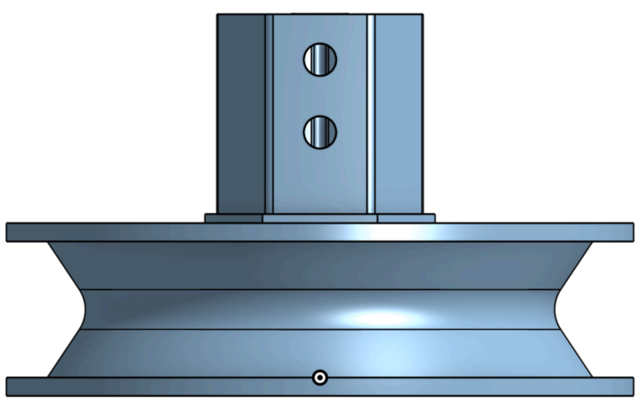

**Figure 8: Concave motor gear**

In the end, the configuration that worked was a crowned pulley surface on both the pulley on the 8mm shaft and the motor gear. This way, the rubber band stayed centered on both surfaces.

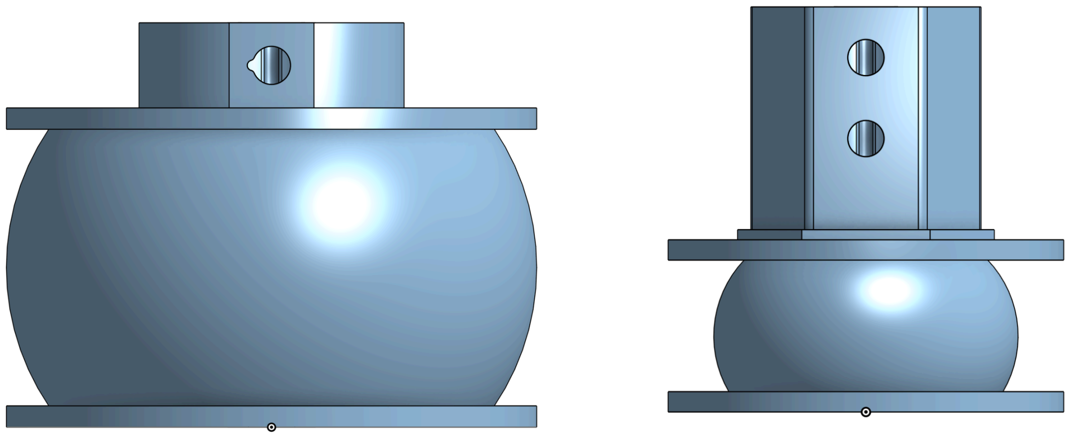

**Figure 9: Crowned pulley gear (left) and motor gear (right)**

Additionally, a smaller radius on the motor gear allowed for the rubber band to stay centered better. This change was to increase the gear ratio from 7/15 to 5/3 between the driving motor gear and driven pulley gear for the archimedes screw to spin slower.

## 8mm Shaft Supports

The initial 8mm shaft support made use of a clamp design on the 8mm bearings. However, this design allowed for the bearings to slide in and out of the clamp, causing the 8mm shaft to slip and fall out of the clamp.

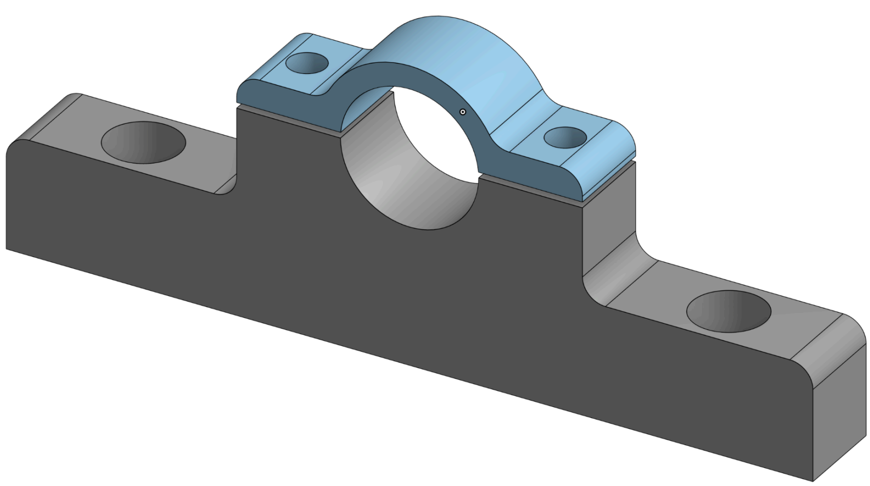

**Figure 10: Initial 8mm shaft clamp**

The second iteration of the 8mm shaft supports are elevated and have an inner lip so that the bearings do not slide side to side. Ultimately, we used a slight variation of the elevated support design with a narrower top to prevent the rubber band from catching and jamming.

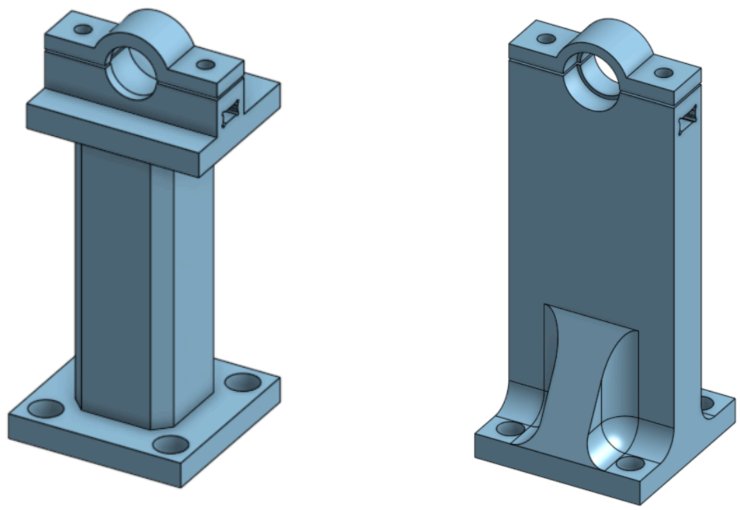

**Figure 11: Revised 8mm supports to account of bearing slipping and an elevated 8mm shaft**

Our final iteration uses several spacer modules in combination of laser cut acrylic bridge pieces to add rigidity and elevate the 8mm shaft to the height of the archimedes screw. This rigidity helped mitigate the vibrations caused by internal resistance of the bevel gears.

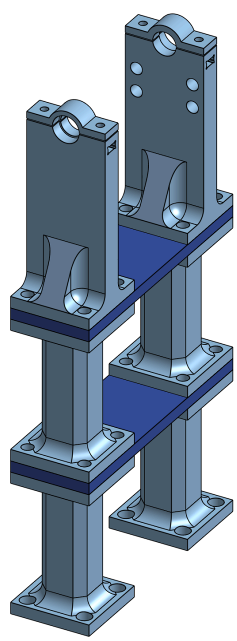

**Figure 12: Final iteration of 8mm shaft support**

# Bevel Gear Subsystem

The bevel gear and archimedes screw subsystem was the second to be designed. The power transfers from the 8mm axle to a bevel gear through an M3 screw. The bevel gear then meshes with a second bevel gear, which rotates the Archimedes screw. The Archimedes screw is held by bearings in a support. Static forces are transferred from the support to the 8mm axle mounts from the pulley subsystem before transferring to the optical breadboard. The power transfers are shown below in Figure 13.

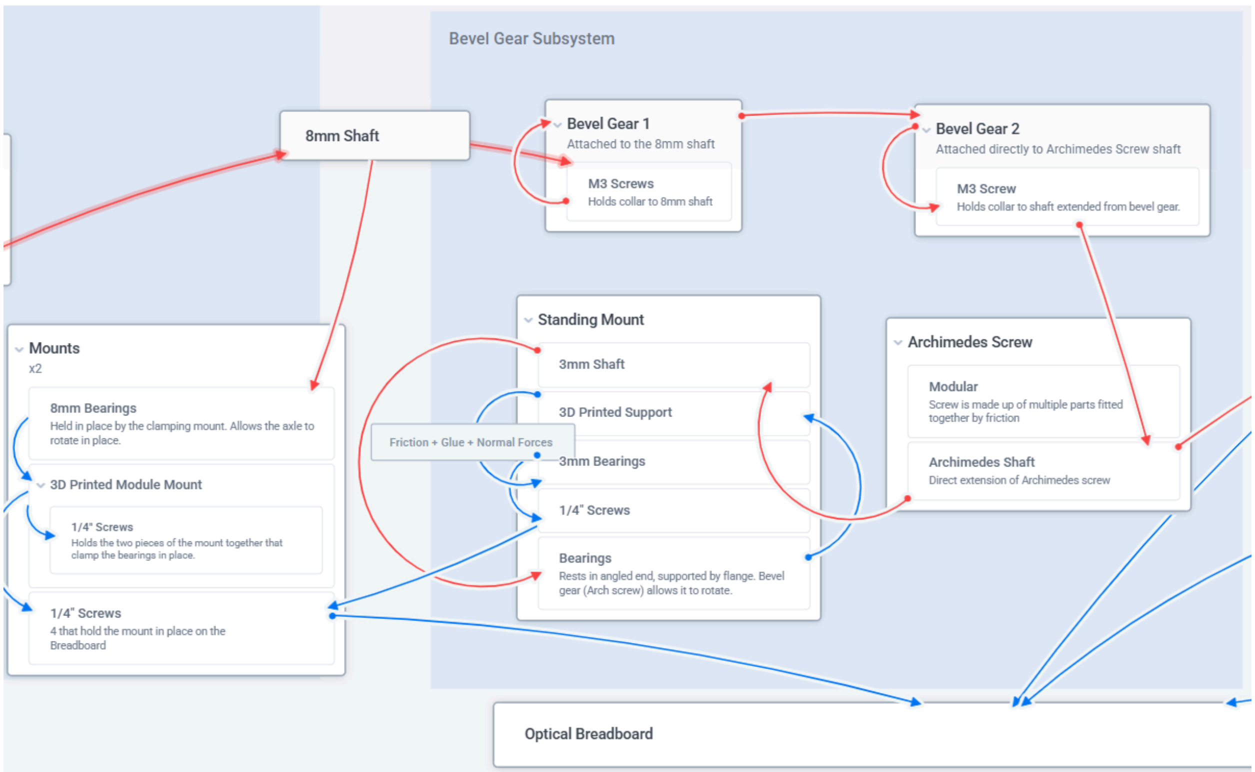


**Figure 13: Bevel Gear Subsystem Systems Diagram**

## Bevel Gear

To change the direction of rotation from the pulley subsystem to the angled archimedes screw, a bevel gear system was used. The bevel gear geometry features a module of 3 mm with 20 teeth at an angle of 45 degrees.

The bevel gear on the 8 mm shaft features a set screw to lock it onto the shaft and a flange to contact only the inner race of the 8mm bearing to not introduce friction.

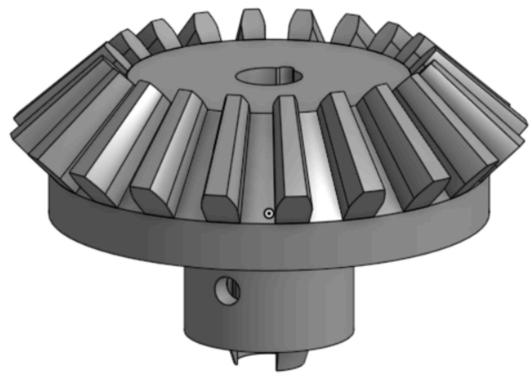

**Figure 14: 8mm shaft bevel gear**

The bevel gear connecting to the Archimedes screw has a symmetric set screw for securing it to a 3mm shaft, along with an additional symmetric set screw mount to attach it to the Archimedes screw shaft.

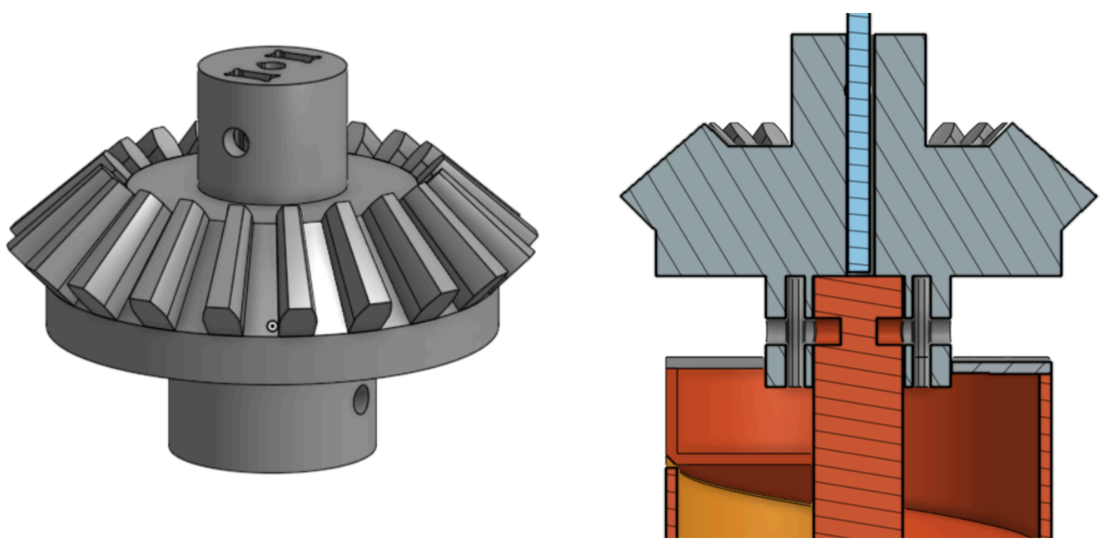

**Figure 15: Archimedes screw bevel gear with cross-sectional view showing the 3mm shaft connection and the Archimedes screw interface.**

## Angled Bevel Gear Support

The first iteration of the bevel gear support was a proof of concept that holds the shaft of the bevel gear at a 45 degree angle. This only supported the shaft at one point which caused the shaft to wobble significantly while in motion.

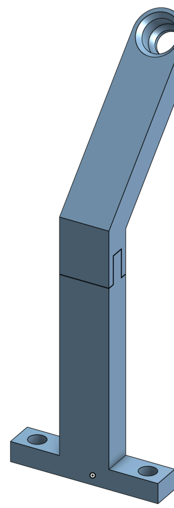

**Figure 16: First draft of bevel gear support**

These issues were all addressed in the second iteration of the bevel gear support. Now, the bevel gear is connected via a 3mm shaft that is held in place at two points with bearings. This is connected to the 8mm shaft support to keep a fixed distance between the two bevel gears so that they mesh properly. This part needed to be very strong to resist any vibrations coming from the bevel gears meshing so the arms are reinforced with fillets and chamfers.

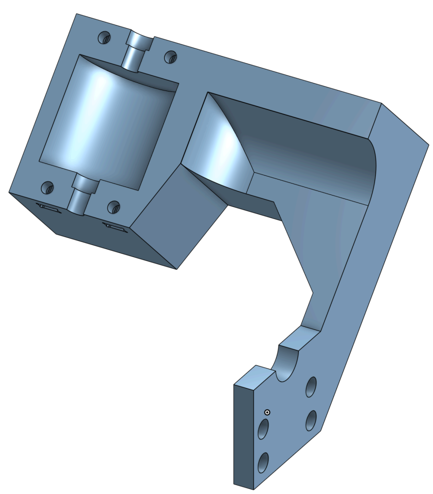

**Figure 17: Consolidated angled bevel gear support**

The final design was revised to be angled at 55 degrees instead of 45 degrees due to limitations in the space allotted on the optical breadboard.

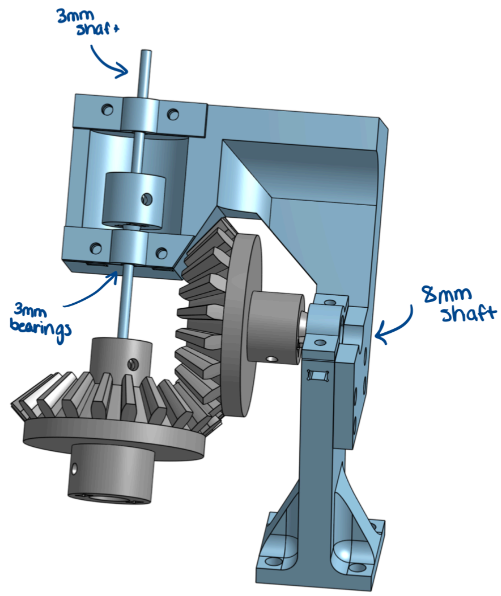


**Figure 18: Final bevel gear subsystem**

## Archimedes Screw Iterations

The first Archimedes Screw is a proof of concept to see whether or not the design can be 3D printed and if it can pump water. Through testing, the design worked but was too small to transfer sufficient amounts of water which resulted in further iterations. For the second iteration, the screw radius and wall height was increased to allow for a higher volume of water transported per revolution.

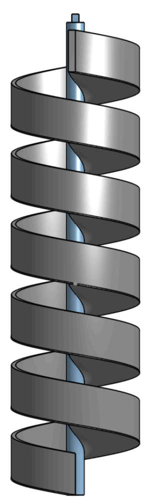

**Figure 19: Second iteration of archimedes screw**

For the third iteration, the screw was split into modules connected via square pegs due to height limitations on the 3d printer. These modules include a top and bottom that connect to the bevel gear and archimedes screw mount respectively.

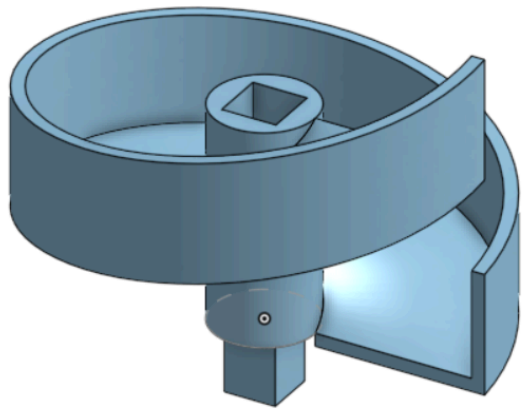

**Figure 20: Modular archimedes screw**

Through testing, it was found that water tended to spray out from the gaps in between the archimedes screw threads. This resulted in a final iteration where the gaps will be fully enclosed by the outer wall, leaving a gap of 0.2 mm of tolerance in between the modules.

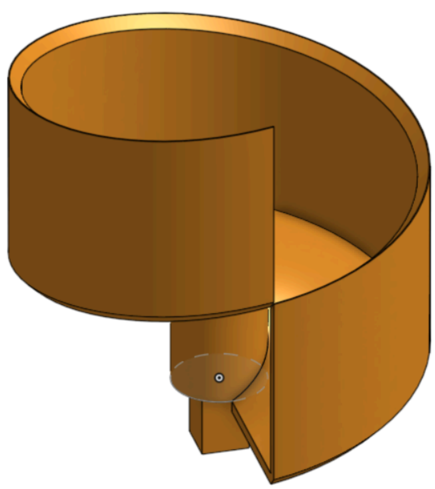

**Figure 21: Fully enclosed archimedes screw**

## Archimedes Screw Support

During testing of the archimedes screw, it was found that the shaft was not stiff enough and not aligned perfectly, so as it wobbled substantially as it spun. This was addressed with a lower mount consisting of a 3d printed bracket and a laser cut acrylic piece. This mount flexed slightly as the system ran but reduced the vibrations and wobble significantly.

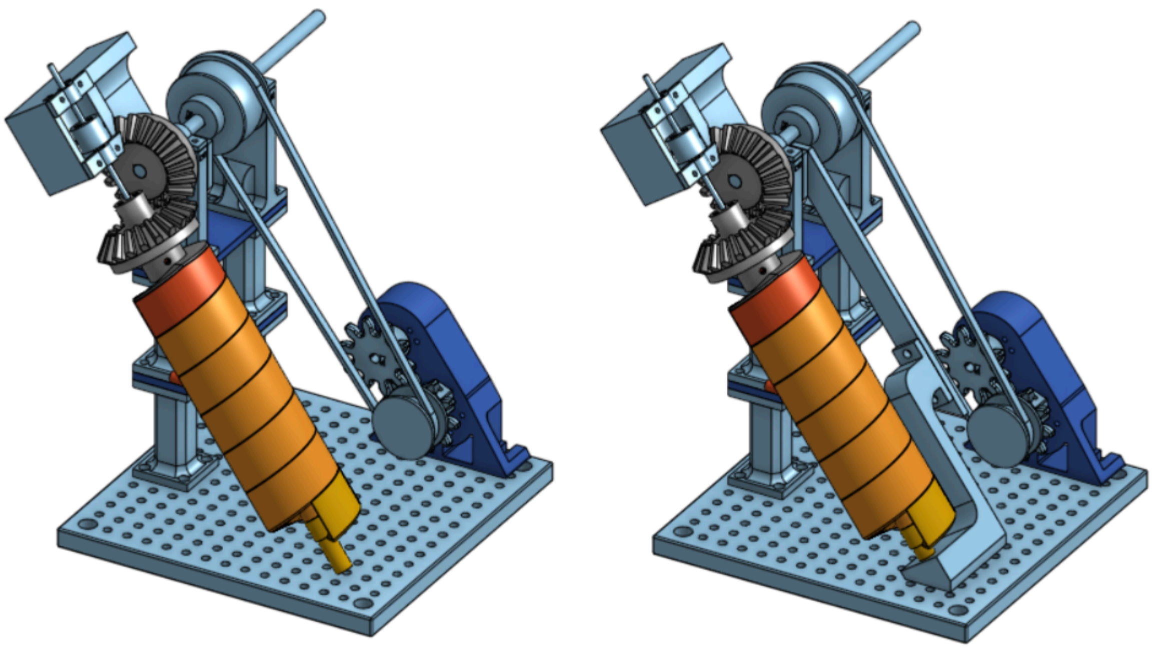

**Figure 22: Archimedes screw with (right) and without (left) lower support**

# Water Subsystem

The water subsystem consists of a bottom reservoir, upper reservoir, upper reservoir support, water wheel, water wheel support, and output disk. The Archimedes screw from the bevel gear subsystem lifts water from the bottom reservoir to the upper reservoir. The water travels through an output tube to a water wheel, transferring power to the water wheel. The water wheel rotates a 5mm shaft through the clamping force of an M3 screw. The shaft then spins an output disk which is used to measure the output of the system. There are static forces holding the bottom reservoir, upper reservoir, and water wheel supports in place, all of which transfer force to the optical breadboard. The power transfer is shown below in Figure 23.

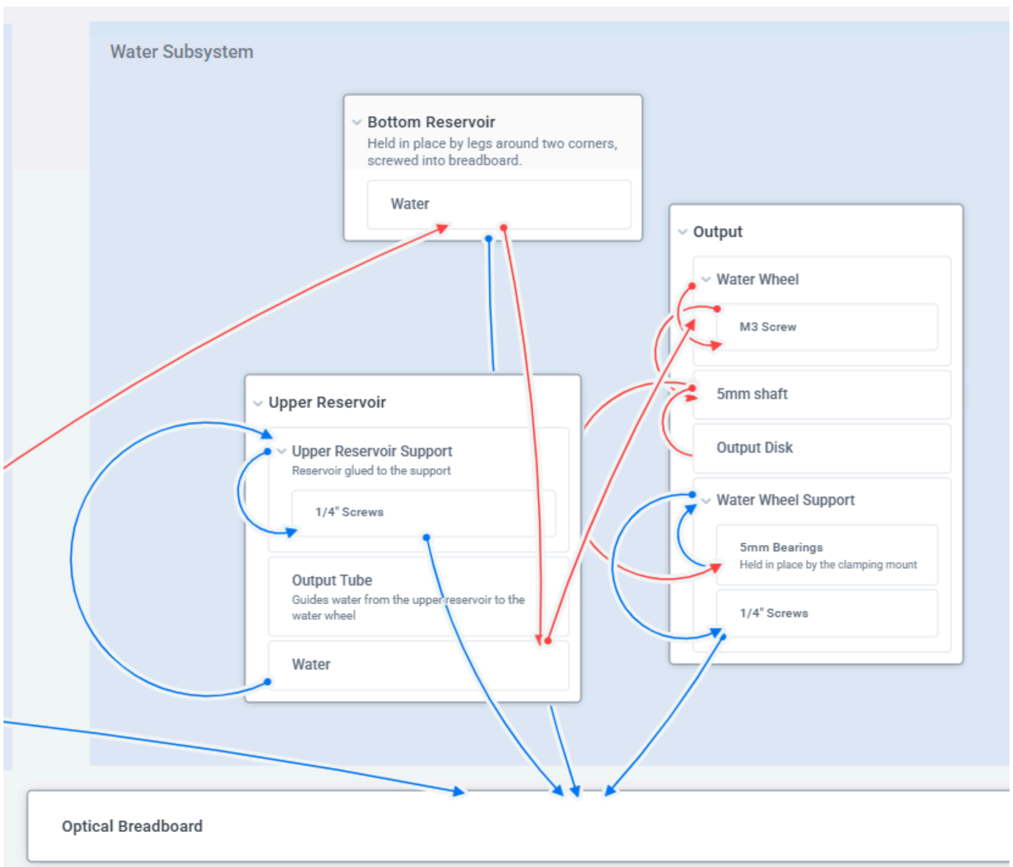


**Figure 23: Water Subsystem Systems Diagram**

## Reservoirs

The reservoirs were sourced from Muji and then the heights were shortened by sawing the upper edges off to fit within the spaces allocated for them. The bottom reservoir had no other modifications. The upper reservoir had a ¼” hole drilled into the side to hold an output tube to guide the water to the water wheel to spin the output. The engineers noticed that water only flowed at a constant rate out of the tube when the water level was high enough. This was because surface tension prevented the water from exiting the tube when there was not enough pressure in the reservoir. A second larger hole was drilled at the top of the side to drain excess water pumping into the upper reservoir. This second hole was drilled after testing the rate at which water was pumped into the upper reservoir. It was drilled at a level such that the water would flow out of the lower tube at a constant rate. The second hole had to be drilled large enough so that surface tension did not prevent water from exiting the reservoir through the hole.

Furthermore, when water exited through the tube to the water wheel, water tension caused water to cling to the tube and drip off the bottom of the upper reservoir, getting water on the breadboard. To prevent water from getting on the breadboard, a small acrylic rectangle was laser cut and glued to the bottom of the upper reservoir, sloping into the bottom reservoir to guide the water back into a reservoir.

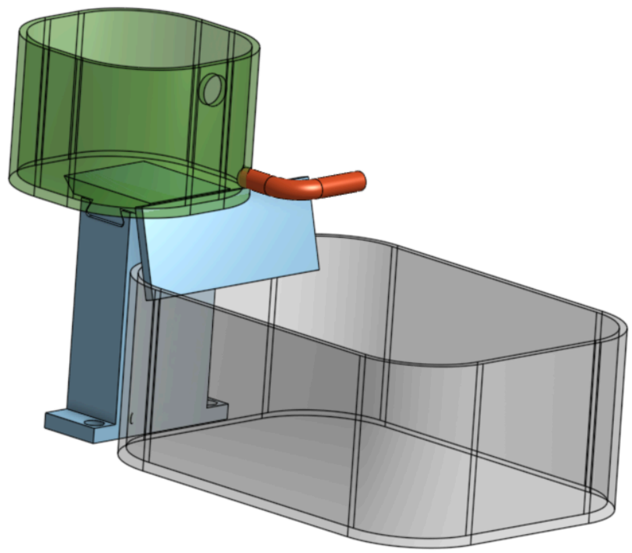

**Figure 24: Reservoirs with the upper reservoir support and output tube.**

## Upper Reservoir Support

The upper reservoir was designed for the ease of removal. Its positioning relative to the water wheel depended on the point at which the torque caused by the water flow would be maximized. So, it was made with a rail and slot system, with the rail glued to the bottom of the reservoir, allowing for the adjustment of its position. This design helped prevent waste that would've come about from multiple iterations to get the ideal position and made cleanup easier.

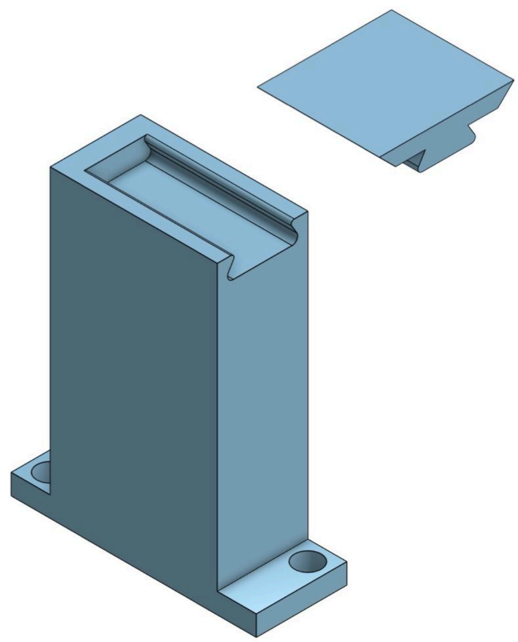

**Figure 25: Upper reservoir support and bottom rail.**

## Water Wheel

The design of the water wheel was pulled from online cad models and fitted to our needs. The first image was the original design found online which was refined to get the correct size and spacing of the fins. The designs also had to be adapted to fit within the area left by the structure of the pulley and bevel gear system.

**Figure 26: Initial Water Wheel**

Below is the final design for the water wheel. It contains 9 fins for water compartments, it is made to fit around a 5mm shaft with a 25mm radius.

**Figure 27: Final Water Wheel**

## Water Wheel Support

The first iteration of the water wheel support was based on the design for the final 8mm shaft support. The 8mm shaft support design was altered to fit bearings for a 5mm shaft and have two connected points on one support to allow the shaft to be held sturdy by only one support. The final iteration of the water wheel support was to make it possible for it to be placed closer to the main reservoir without interfering with the rubber band. This way the 5mm shaft did not have to extend as far for the water wheel to be over the main reservoir.

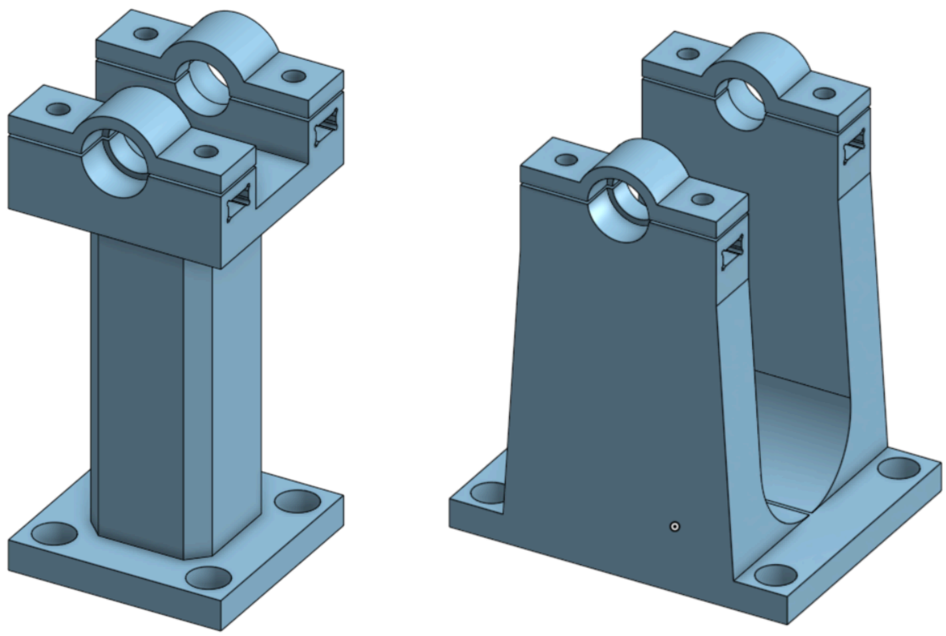

**Figure 28: First (left) and final (right) iterations of the 5mm shaft support**

# Analysis of Design

The final design utilizes a pulley to drive the bevel gears. The pulley consists of a rubber band stretched over 2 pulley gears of different radii, 30 mm and 50 mm for the driving motor gear and driven pulley gear respectively. This pulley system drives an archimedes screw via a set of bevel gears. The bevel gears are orientated such that their axis of rotations are perpendicular to each other but one of them is angled 55 degrees off the horizontal to connect to the archimedes screw. The archimedes screw transfers water from the lower reservoir to the upper reservoir through rotational motion. Every time the archimedes screw turns, each thread is filled with water and moved up by 1 thread, eventually making its way to the upper reservoir. This upper reservoir will release water through a ⅛" inner diameter tubing onto a water wheel to spin it. The objective of this design is to isolate the energy source from an unconstant motor into a stable source of potential energy in the upper reservoir, with the water wheel driving the output gear.

<u>Bill of Materials</u>

| Subsystem | Component | Quantity | Cost | Description |
|---|---|---|---|---|
| **Pulley System** | Shaft Support | 4 | 3d print | Vertial Supports for the shaft connecting to the pulley |
| | Support Strut | 2 | Lasercut | Horizontal plates connecting modules for support |
| | Bearing Mount | 2 | 3d print | Vertial Supports with a fitted bearing location |
| | Bearing Mount Clamp | 2 | 3d print | Clamps to hold bearing in place |
| | 8mm shaft | 1 | Provided | Shaft through bearing that the pulley sits on |
| | 8mm Pulley Wheel | 1 | 3d print | Pulley wheel that spins shaft |
| | Rubber Band | 1 | Provided | Pulley rope |
| | Motor Pulley | 1 | 3d print | Pulley wheel spun by motor |
| | Motor Gear | 1 | Provided | Gear to mesh with encoder gear |
| | Bearing | 2 | Provided | Allows shaft to spin smoothly |
| | 3mm fastener | 7 | Provided | Holds parts in place |
| | 5mm fastener | 12 | Provided | Holds parts in place |
| | 3mm nut | 7 | Provided | Clamping with fastener |
| **Bevel Gear System** | Bevel Gear | 2 | 3d print | Changes rotational angle |
| | Archimedes Top | 1 | 3d print | Top screw of archimedes screw |
| | Archimedes Mod | 5 | 3d print | intermediate screw |
| | Archimedes Bottom | 1 | 3d print | bottom screw |
| | Bevel Support | 1 | 3d print | giant block used to support second bevel gear |
| | 3mm shaft | 1 | Provided | Attaches to bevel gear allowing it to spin |
| | 3mm Collar | 1 | 3d print | Holds the bevel at a predefined position |
| | Support lower | 1 | 3d print | Supports archimedes screw to reduce wobble |
| | Support upper | 1 | 3d print | Supports archimedes screw to reduce wobble |
| | 3mm fastener | 6 | Provided | Holds parts in place |
| | 3mm nut | 6 | Provided | Clamping with fastener |
| | Bearings | 2 | Provided | Allows shaft to spin smoothly |
| | 3mm clamps | 2 | 3d print | Clamps to hold bearing in place |

| | | | | |
|---|---|---|---|---|
| **Water Subsystem** | Lower Resevior | 1 | 1.99 | Larger holds most of the water |
| | Upper Resevior | 1 | 2.99 | Smaller transfer point for archimedes screw |
| | Water wheel | 1 | 3d print | What makes the whole thing work |
| | Water wheel support | 2 | 3d print | Supports to hold the shaft the whater wheel is on |
| | Output disk | 1 | 3d print | used for tracker |
| | 5mm shaft | 1 | Provided | Shaft the water wheel is on |
| | 3mm clamps | 2 | Provided | Holds bearings in place |
| | 3mm fastener | 9 | Provided | Holds parts in place |
| | 3mm nut | 9 | Provided | Clamping with fastener |
| | Pipe | 1 | Provided | Funnels water |
| | Resevior Support | 1 | 3d print | Raises resevior to desired height |
| | Support Slider | 1 | 3d print | Sliding plate to adjust location of resevior |
| | Collar | 2 | 3d print | Holds the shaft in the proper place |
| | Bearings | 2 | 3d print | Allows shaft to spin smoothly |

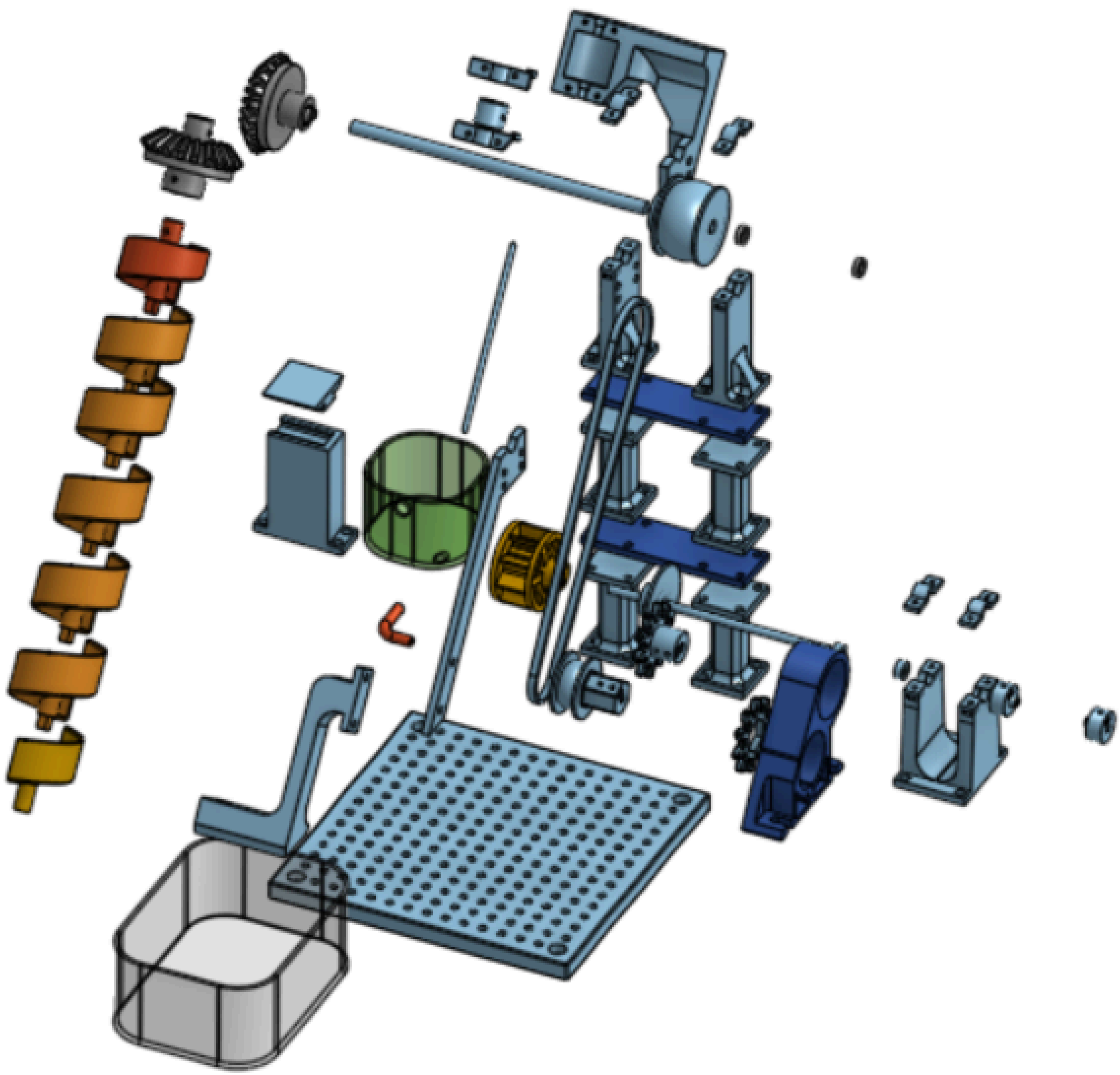

**Figure 27: Exploded view of assembly**

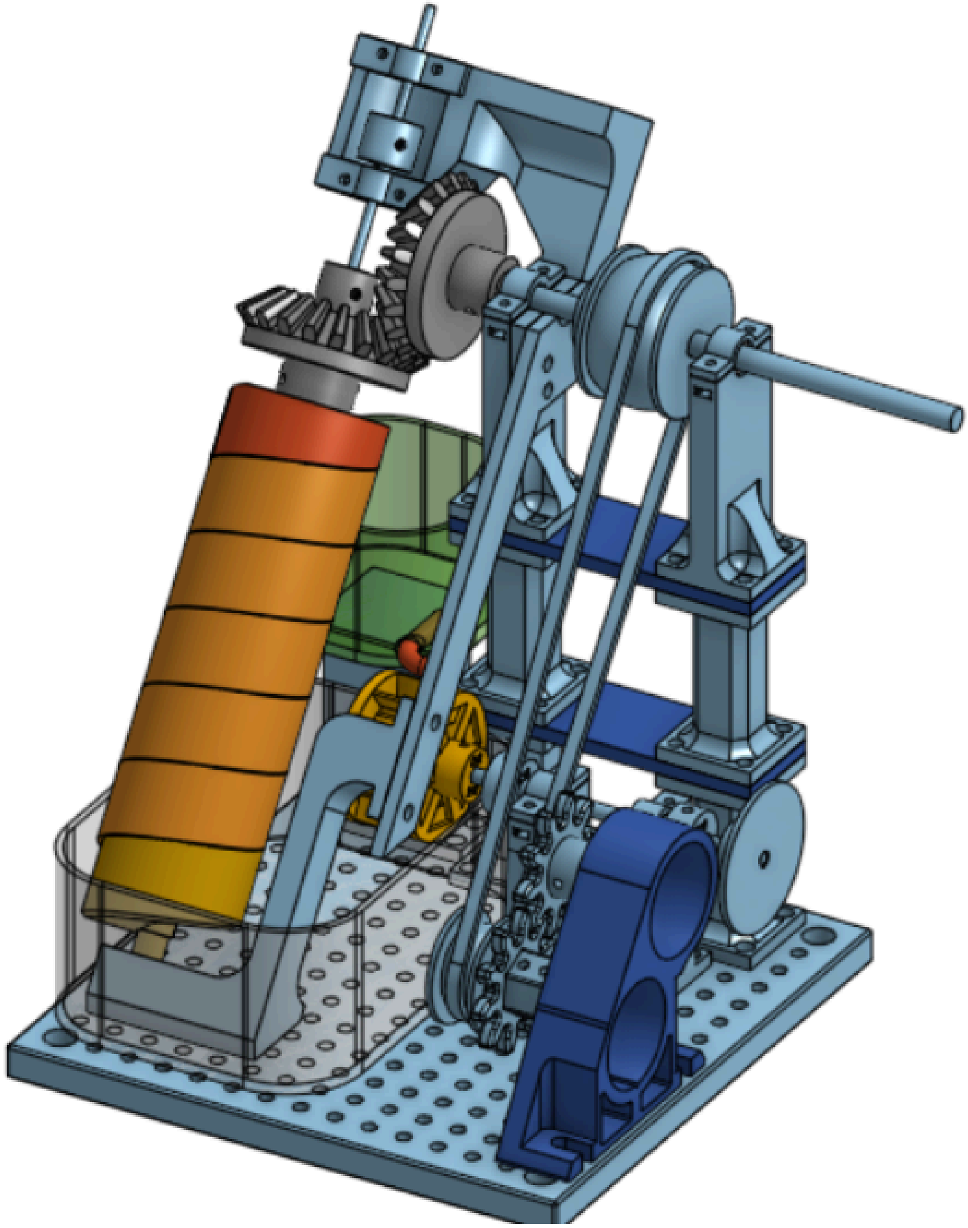

**Figure 28: Regular view of assembly**

# Outcome Analysis

The graphs below contain data collected with the tracker app when running the rectifier at 7.5V for the input gear angular velocity, output gear angle, and output gear angular velocity. Due to the orientation of the axes the output gears have a negative angle and angular velocity, in this analysis only the magnitude is considered. Since the system is decoupled both input and outputs can be measured at the same time with the machine running.

Starting with the angular velocity (Fig 30) of the input gear it forms a sinusoidal curve with a maximum of 26.4 radians per second and a minimum of 16.16 radians per second. Thus the amplitude of the input angular velocity is 5.12 radians per second. Then looking at the angular velocity for the output gear (Fig 32) the data is messier, however finding the maximum and minimum to be 9.37 and 4.20 radians per second respectively indicates that the rectifier is working. Since the amplitude of the output is 2.58 which is approximately half the amplitude of the input gear it shows the rectifier brought the output closer to a constant speed.

Next, comparing the input gear's accumulated angle to the output gear's accumulated angle there is a clear qualitative difference. Firstly, figure 29 was obtained by numerically integrating the angular velocity with respect to time, in this case time steps of 0.01 seconds were used meaning that a good approximation of theta was obtained. In figure 29 the input gear's slope is not quite constant which can be seen clearly between t=50 and t=100. Examining figure 31 for the angle of the output gear the slope appears to be constant which is supported by the $R^2$ value being 1.00. While both graphs have similarly high $R^2$ values for a linear trend line the input gear shows deviation while the output does not.

An issue that hindered this design was cohesion and adhesion of water molecules. Water is a polar molecule which means one side of it is slightly positively charged while the other side is negatively charged, because of this water molecules tend to stick to each other (cohesion) and other molecules (adhesion) such as the container walls. As our design relied upon water flowing water would build up above the outlet and not flow through since the forces of cohesion and adhesion were stronger than the pressures pushing water through causing the flow to become unsteady as water would build up and release cyclically rather than flow steadily.

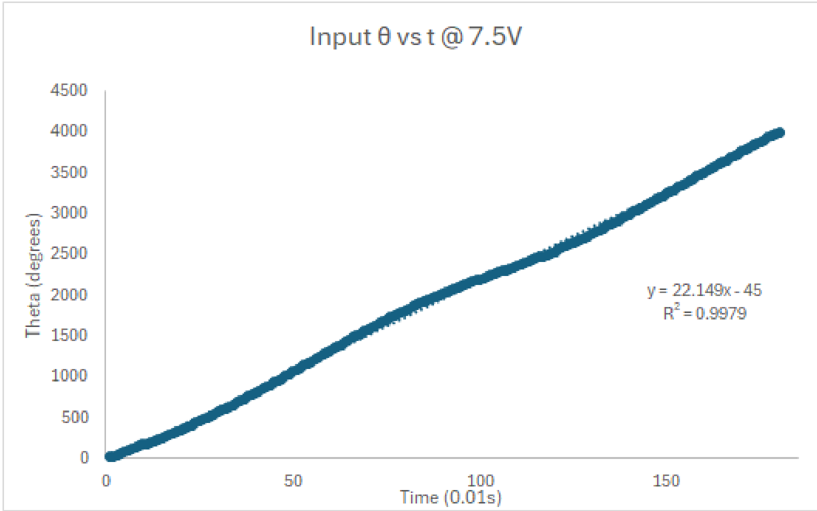


**Figure 29: Input gear angle vs time**

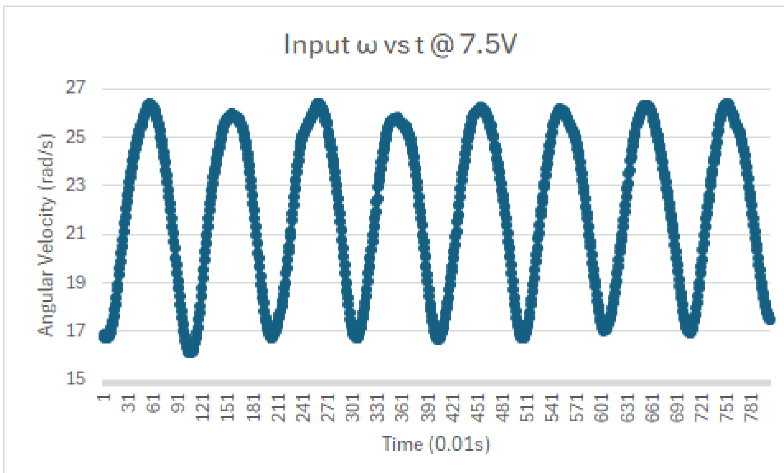


**Figure 30: Input gear angular velocity vs time**

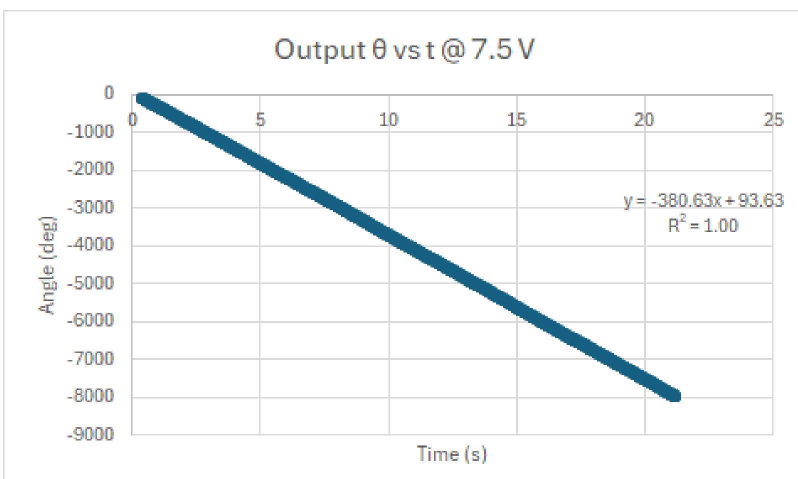


**Figure 31: Output gear angle vs time**

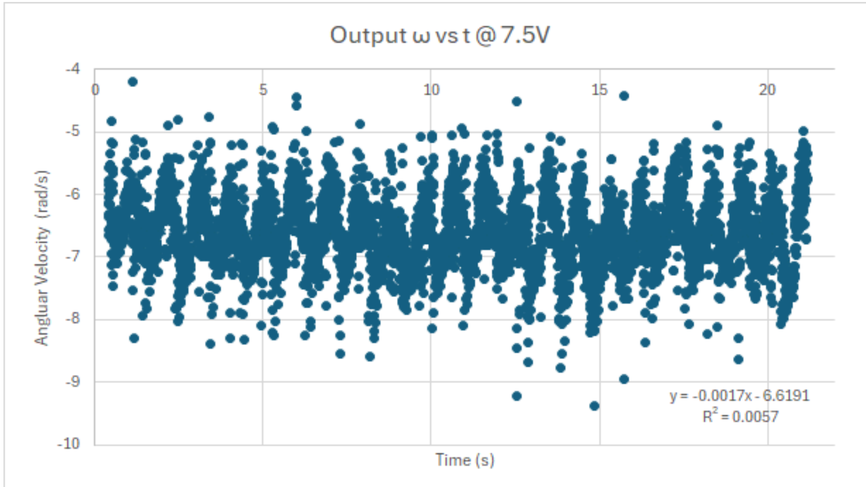


**Figure 32: Output gear angular velocity vs time**

# Future Work

The current design addressed the goal of pumping water via the archimedes screw to a good degree of success. However during testing, it was found that even with a constant source of water flowing down from the upper reservoir, the output wheel is still not rotating with constant velocity.

There are several revisions that can be done to the water wheel design. Surface tension is causing water to cling to the bucket walls instead of exiting cleanly, which drags down the wheel's speed. The buckets are also overly deep, which is good for capacity, but bad for torque, because water that lands near the hub instead of the rim applies almost no torque. To reduce surface tension, the 3D print can be post-processed with sandpaper to smoothen the surfaces, or resin printing can be considered as well. Another revision would be to reduce the depth of the buckets. However, a balance between bucket depth and number of buckets will need to be determined experimentally to not reduce the amount of torque applied onto the wheel.

These modifications should improve wheel efficiency by accommodating misaligned inflows and directing water discharge so that adhesion does not increase the wheel's effective moment of inertia.

# Conclusion

The processes the engineers went through throughout the design process provided numerous lessons. As one of the engineers first ever engineering tasks, systems thinking was a relatively new concept. They learned to think through the design before beginning any physical construction. They also learned to understand the function of every aspect of the system to eliminate unnecessary parts and keep the system as functional as possible. The power transfer from beginning to end of the system was understood and allowed the engineers to further understand their design. This task was the first time the engineers heavily used and designed extensively for 3D printers. They learned iterative design throughout the process, with different parts needing improvements either due to print quality, 3D printing limitations, or to be adapted based on other components. Furthermore, the engineers learned to apply their knowledge of mechanics in a way they had not before. Since the assignment required the use of mechanical components alone, the engineers had to consider fluid forces, friction, and moment of inertia. The placement of the holes on the upper reservoir was to minimize surface tension as the water flowed through. The pulley motor gear was extended slightly past the encoder gear to minimize the friction, and the size of the water wheel was decided based on its moment of inertia.

In the end, the engineers built a system that regulates the variability of rotational input, though it never reached a constant output. They iteratively designed and improved the system until the deadline. Steady communication ensured proper division of tasks and efficiency among the team. However, there was a large amount of wasted material throughout the process. A number of iterations were made within each subassembly that required numerous prints and were used for very briefly before the design was altered again. The design required many screws to hold together supports, so rust became an issue as water was incorporated into testing. Overall, the engineers' successes and setbacks gave the opportunity to understand the iterative design process and the nonlinear path to design and manufacturing.

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