Design and Construction of a Ferrofluid Kinetic Art Clock

A Technical Report submitted to the Department of Mechanical Engineering

Presented to the Faculty of the School of Engineering and Applied Science

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In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Will Pfister

Fall, 2022

Technical Project Team Members

Trenton Bilyeu
Julian Dixon

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Gavin Garner, Department of Mechanical and Aerospace Engineering

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Technical Capstone Project

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Abstract

As a capstone design project, the group decided to improve upon the existing ferrofluid clock while adding our own creative elements to it. We looked to update the existing 3D printed mechanism with something more reliable. To add to the clock, we aimed to design a Rube Goldberg inspired display that would have certain events every time the clock changed. This project included aspects of programming, electrical engineering, as well as mechanical engineering. It also helped to develop real world skills such as problem solving, prototyping, computer aided design (CAD), 3D printing and laser cutting.

Executive Summary

The idea for the Rube Goldberg display was something that consisted of pinballs and rails for them to roll along corresponding to specific time intervals. A ball would be released from a reservoir every minute, roll along a track, and land in a different reservoir. After ten minutes, when nine balls have been collected in the second reservoir, a tenth ball would trigger a mechanism to release all of the balls at once. The entire display would be circular with the ferrofluid clock sitting in the center and balls moving around it. However, material and cost constraints led to a considerable reduction in size, to the point where the ferrofluid clock would not fit inside.

The ferrofluid clock had been nearly completed by the previous team that worked on it; however, it still had several major issues that warranted another semester of work. The ferrofluid clock initially used servo motors, linkages, and 3D printed guide rails to move permanent magnets towards vials of magnetic ferrofluid. This configuration was unreliable and had too much friction to function properly; the linkages and guide rails were ultimately replaced with a rack and pinion mechanism. The other main focus of the ferrofluid clock was the enclosure; the existing enclosure was wooden and very bulky; a completely new enclosure was made out of acrylic.

Fig. 1: A very rough sketch of the team's original vision for the Rube Goldberg ferrofluid clock where the ferrofluid clock sits in the center of the Rube Goldberg display.

While the end goal of this capstone project was to integrate the ferrofluid clock into the Rube Goldberg display, the actual construction of both of these components was almost entirely independent; therefore, the team split into two sub-teams to complete each part. Three members worked on creating the Rube Goldberg display from scratch while the remaining three redesigned and improved the existing ferrofluid clock. This report is focused on the process of revamping the ferrofluid clock.

Prototyping

Existing Design

The existing mechanism was promising but had several key issues preventing the clock from operating consistently and reliably. The basic configuration of the clock included four digits, each with seven independently controlled segments. Each segment contained a off-the-shelf RC servo motor, a strong neodymium bar magnet and a complex rotational to linear linkage and 3D printed guide rail that connected the magnet and servo motor. By moving each magnet closer and further away from a vial of ferrofluid material, the clock was able to display each Arabic numeral from zero through nine. The largest issue with the previous design was the rotational to linear motion linkage. It would often bind as the magnet was being moved along a 3D printed guide rail and the linkage resulted in additional off-axis forces on the magnet. In addition the servo motor was at a mechanical disadvantage since its load arm was longer than its effort arm. As a result, the team decided a complete redesign was necessary.

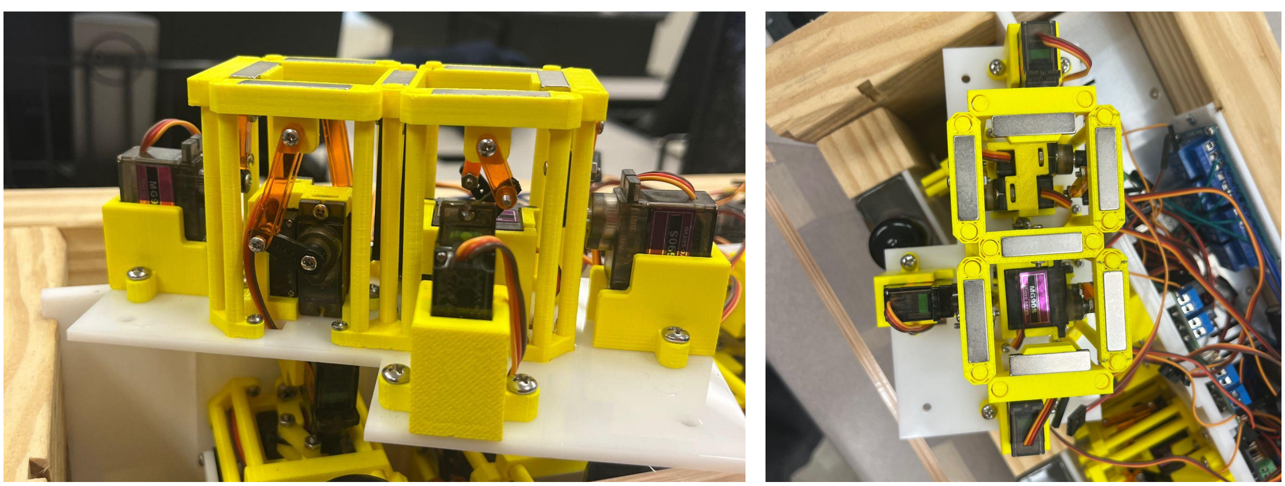

Fig. 2: Side view (left) and front view (right) of a single original clock digit

Prototype 1 - Electromagnets

The team first explored and experimented with electromagnets that would independently turn on and off for each segment of the digit. This would have presented multiple advantages, one being there would be much fewer potential failure points as much of the mechanical interfaces would have been removed. However, after constructing several prototypes with varying wire gauge, core type, and number of windings, we were unable to produce a successful prototype that could produce and maintain a magnetic field strong enough to attract the ferrofluid adequately. Due to size constraints, we were only able to produce electromagnets with 500-800 windings, a relatively low packing factor, around an iron core. In order to produce an adequate magnetic field we had to increase the current running through the winding. This produced a significant amount of heat that dramatically reduced the magnetic field. Calculating excess latent heat, size limitations and the short nature of this capstone, we concluded that our prototypes of electromagnetics were not feasible for the clock. We do believe it could be a solution worth exploring given more research into electromagnet design.

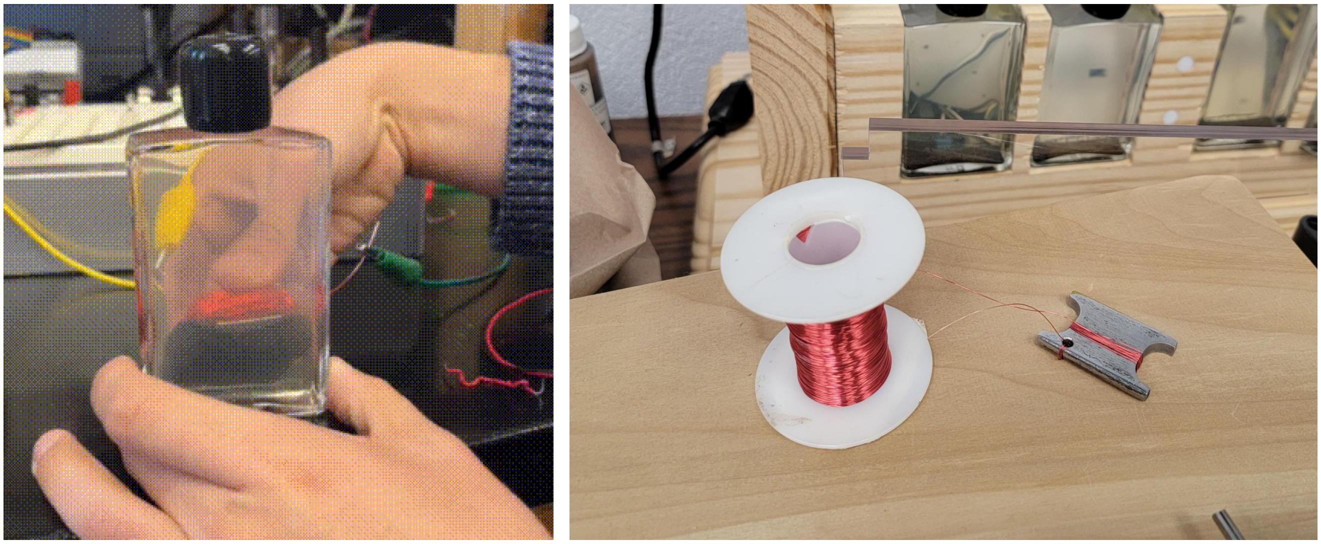

Fig. 3: Example electromagnet prototype (right) and the prototype in action (left) attracting ferrofluid.

Prototype 2 - Vane Display

The team briefly considered using a type of 7-segment display called a vane display. A vane display works by rotating each segment 90 degrees through electromagnets or electric motors. This would solve the problem of the rotational to linear movement linkage as all movement would be solely rotational.

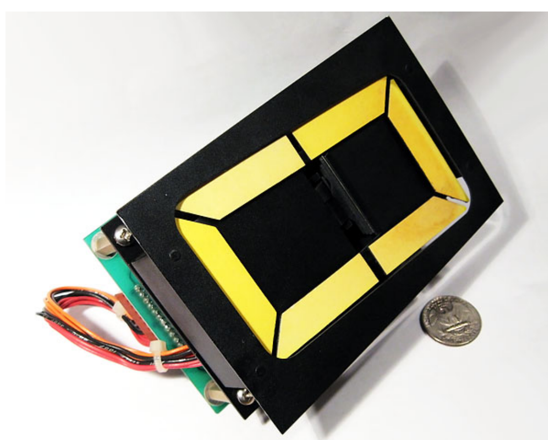

Fig. 4: A 7-segment vane display. The middle segment is flipped back so that only the others are visible, representing the number zero.

However after experimentation, we concluded that it was unable to adequately move the permanent magnets far enough away from the ferrofluid to prevent attraction in the off position.

Prototype 3 - Rack and Pinion

The last mechanism the team explored was a linear rack and pinion actuator. This mechanism presented many advantages: it was sturdy, its motion could be finely tuned, and it allowed us to reuse the existing servo motors. The rack and pinion system consisted of three separate pieces cut from acrylic; the rack, the pinion, and the back plate. The back plate had two holes for screws that would both secure the rack in place and restrict its movement to a linear motion. In this system the back plate would snap onto the RC servo motor, then the pinion would be pushed directly onto the servo motor output shaft via friction. Finally, the rack was screwed into the back plate. The rack also included a mounting hole so that the existing magnet mounting brackets could be bolted to the rack. Once the team constructed a functional prototype, the rack and pinion mechanism was determined to be much more reliable than any of the other systems we had considered. Even after investigating three completely different solutions, deciding which mechanism to pursue proved to be much simpler than perfecting the chosen mechanism.

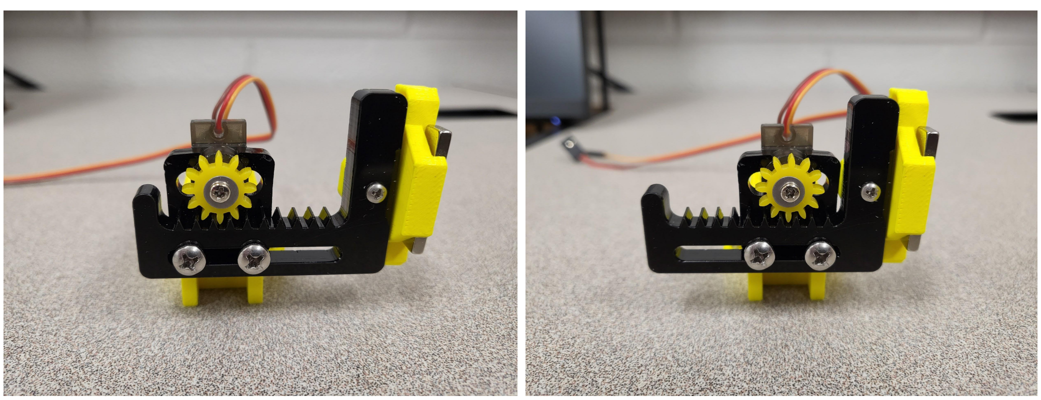

Fig. 5: The team's first functional rack and pinion prototype in the extended (left) and retracted (right) positions.

Before this mechanism could even be tested, the servo had to be set to a known position so that the rack could be attached accordingly. If the rack were to be mounted improperly it could clash with the pinion and risk damaging the servo motor. At this stage of the project we were using a Parallax P2 chip to test the motors, and we did not know what PWM signals corresponded to what servo motor positions; therefore, we had to test this through trial and error. The existing code was written to a Parallax P1 chip, which uses a slightly different language and different PWM values. Once we progressed enough to implement our prototype into the existing infrastructure, we had to repeat the trial and error process of discovering the correct PWM values.

```
con _clkfreq = 300_000_000
  CW=400, center=1000, CCW=1800
```

```
'Servo positions
  RetractL  = 480
  ExtendR = RetractL
  RetractR  = 240
  ExtendL  = RetractR
  ServoMid  =  (480+240)/2
```

Fig. 6: PWM values for the servo motors in spin1 (top) and spin2 (bottom). The P1 chip is coded in spin1 and the P2 chip uses spin2.

The first major issue with construction, and a commonly recurring one, was sizing the parts correctly. Previous projects throughout this course made us familiar with the laser cutter's kerf, i.e. the discrepancy between the nominal size of a hole and the actual size caused by the thickness of the laser beam. Regardless, the back plate and pinion needed to be very accurately fitted. Several iterations of each were produced before a good fit was found that was tight, but did not require excessive force to assemble. The tolerancing of the rack did not need to be as precise.

There were several aspects of this prototype that were less consequential for function, but were still important for the longevity of the clock. One of these aspects was the thickness of the acrylic. We had two thicknesses available to choose from: an eighth and a quarter of an inch. Our original instinct was to go with the eighth inch acrylic to use as little space as possible; however, this led to many issues. The back plate was too thin to tap threads into effectively and would often break during assembly, and we feared that the rack and pinion could move out of alignment too easily. Therefore, all three acrylic components of the rack and pinion system were ultimately cut from quarter inch acrylic. Another cause for concern was the repeated grinding of the rack against the screws. After many cycles of extending and retracting, it was evident that the guiding screws were leaving deep scratches on the rack. Our solution was to order nylon spacers from McMaster Carr to act like contact roller bearings. However, due to cost constraints we had to order quarter inch spacers instead of spacers that were three sixteenths inches in length. Nominally this makes sense, but realistically the spacers were slightly longer than the width of the acrylic; this prevented the heads of the screws from pressing tightly enough against the rack and allowed the rack to wiggle undesirably. This was problematic since the servo motors would all be mounted in very close proximity.

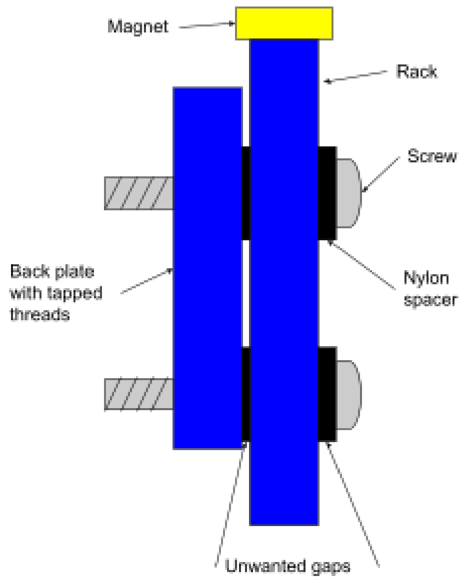

Fig. 7: Depiction of rack screwed onto the back plate with the spacers included. The spacer is too large to allow the head of the screw to contact the rack, resulting in unwanted play.

While it was helpful to be able to reuse the existing magnet mounting brackets, they had holes for the original 3D printed guide rails (as seen above in Fig. 2) that were unnecessarily taking up valuable space. Instead of printing all new brackets, we were able to use nippers to manually cut them down. However, the brackets that corresponded to the top and bottom segments of each digit were shaped differently than the rest; these ones needed to be reprinted.

Manufacturing

Equipment

Most of the needed parts were made using the laser cutter because it allowed us to rapidly produce prototypes and make small adjustments when needed, while also being capable of mass producing duplicate parts quickly. The biggest issue with the laser cutter was the constant demand for it towards the end of the course. This resulted in delays in the manufacturing process as we had to wait for other groups to cut the parts they needed. One mechanical issue that occurred with the laser cutter was when cutting larger parts, it would sometimes not penetrate all the way through the acrylic towards the end of the cut. This made the manufacturing of larger parts more difficult as they would sometimes require a second pass of the laser. Mostly everything that was not made on the laser cutter was manufactured via 3D printers. Like the laser cutter, this allowed us to mass produce necessary parts. Similar still was the huge demand from the rest of the class. 3D printers were rarely available later in the semester as other teams began using them more. The biggest drawback of using 3D printing is the time it takes to complete prints. The 3D printer takes significantly longer than the laser cutter to complete a part, but they both allow for the easy mass production of parts and iterative design as they are both relatively cheap and easy to use.

Electronics and Programming

We were able to use most of the previous group's electronics. The group went through and tested each servo motor to ensure that they could still move across their full range of motion, and most of the servo motors were still good. All of them seemed to work after the initial test, but by the end of the course we had to replace three motors. We also kept most, but not all, of the LED lights. There were four strips of LED lights that were connected via solid core wires along with two individual lights that served as the colon between the minute and hour sides of the clock. The team decided to replace the solid core wires with more reliable and flexible braided core wires. Unfortunately, upon resoldering the LEDs the team realized that the colon LEDs would not fit through the slots in the new mirrored acrylic plate; this forced us to remove the colon LEDs altogether. The team also replaced the existing power supply, but this decision was more out of preference and convenience than necessity. The existing power supply was capable of putting out 30A at 12V, which is far more than this clock needs. We instead stepped down to a 6A 6V power supply that worked just as well.

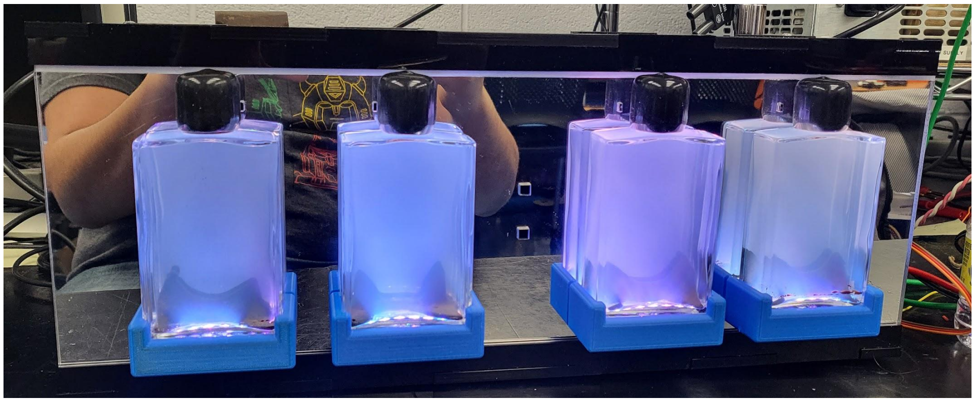

Fig. 8: Front view of the final ferrofluid clock with LEDs on and servo motors retracted. There are two square holes in between the middle two vials where the colon LEDs would have been, but including them would have made the entire LED strip impossible to remove.

Another electronic component that we were able to keep was an LCD screen used for setting the date and time. The screen was mounted onto a sheet of acrylic and accompanied by a 5-position switch and a double pole double throw (DPDT) switch. The DPDT switch was only connected to one input and one output terminal and it controlled whether the clock was operating normally or if the time was being reset. If set to “normal” then the screen would be off and the clock would display the time normally. When flipped to “set” the LCD screen would display the current date and time along with a blinking cursor. The user could then use the 5-position switch to move through the different settings and adjust them as needed. Once the user finishes setting the time they would flip the DPDT switch back to “normal” and the time would update. The team did not have to change any of the code associated with the LCD screen or setting the time; we did, however, have to cut a new acrylic plate for the screen and the switches and mount them on a new plate. Removal from the existing plate was extra difficult since the DPDT switch had been glued in place and we did not have access to any spare switches. The team had to repeatedly douse the area in an uncuring solution and scrape away the dissolved adhesive with a flathead screwdriver. At one point in this process a member accidentally applied too much force to the acrylic with the screwdriver and the switch exploded into all of its base components. Once the member freed the rest of the switch from the adhesive they had to reassemble all of the tiny components of the switch.

Assembly

Enclosure, wiring, serviceability, compactness, servos being dumb and cheap

The existing wooden enclosure for the clock was bulky, unsightly and did not fully meet the standards expected in a final product. The team determined that a complete redesign of the enclosure was needed. The main goals of this redesign were to create an elegant, compact, functional and serverable enclosure. The choice of housing the clock in laser cut acrylic was selected due to the ease and speed of manufacturing.

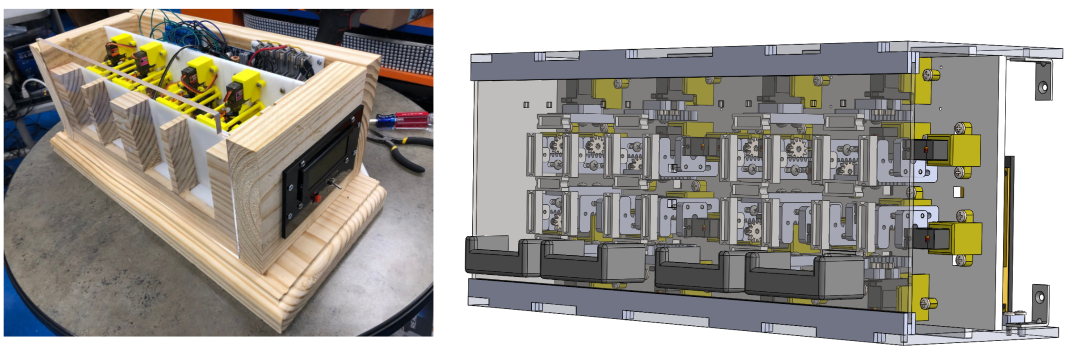

Fig. 9: Original wooden clock housing (left) and SolidWorks model of new housing (right) at similar angles. Neither of these images show the vials of ferrofluid installed in the clocks.

The team was able to completely model the clock containing all its sub-assemblies within a computer aided design (CAD) software called Solidworks. The most difficult portion of this process was finding an arrangement of the motors that was compact enough to align the magnets with the vials of ferrofluid while being spaced out enough that there was no interference with the rack and pinion mechanisms. This was made more complicated when accounting for the kerf of the laser cutter. There were a few instances where the ideal model made in solidworks was unable to match what was produced in reality due to these tolerancing issues. The best solution the group found was to use mounts that held the motors in a vertical position. This gave the rack and pinion the necessary clearance at the bottom of its movement.

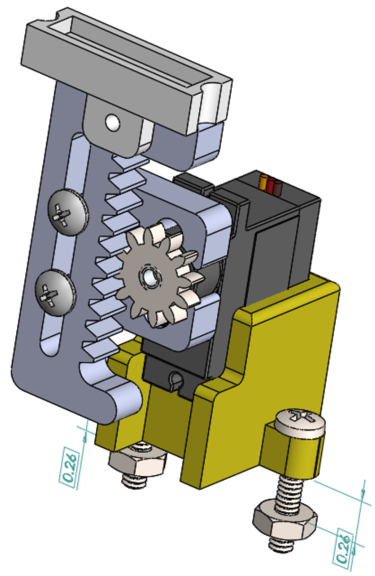

Fig. 10: SolidWorks model of the rack and pinion assembly in a vertical motor mount.

Another key factor in the redesign of the clock was to increase the ease and accessibility to service broken components in the future. Knowing in advance that the probability of failure of individual components, specifically the servo motors, was quite likely, we designed the whole clock to be relatively accessible and modular. The front plate can slide off and the sides of the clock are left open to increase accessibility. We also spent the time to look at where each individual screw was placed and ensured that it was still relatively easy to access when the full assembly was completed. The only use of glue on the clock was to assemble the main structure, otherwise all components were attached with screws and 3D printed brackets.

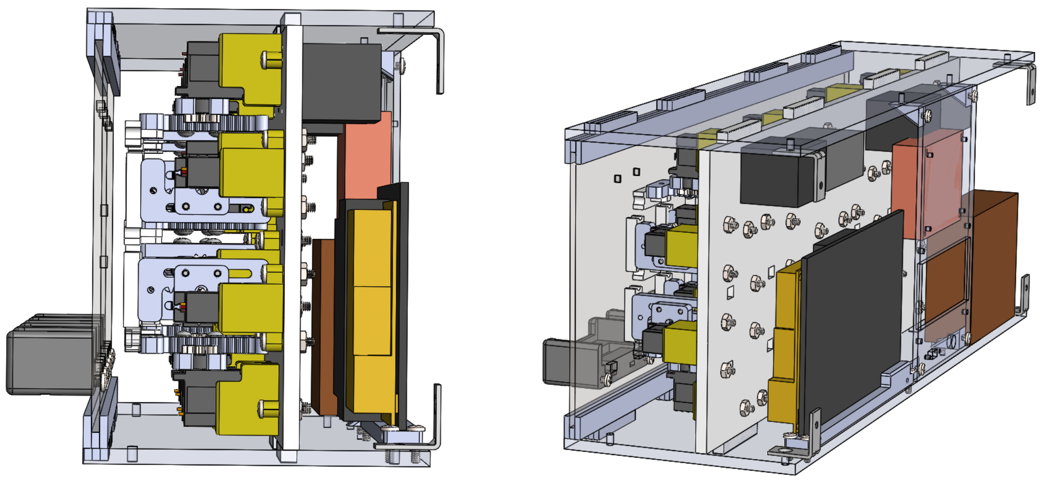

Fig. 11: Side (left) and isometric (right) views of the clock back section in SolidWorks. It is open and was made with accessibility in mind.

Once prototyping was finished and we were ready to begin mass producing parts and assembling all of the rack and pinion mechanisms, the group discovered that some important dimensions of the servo motors were not consistent. This resulted in two variations of the acrylic backplate and pinions to accommodate the difference in sizes. While these were relatively easy fixes, they still provided a challenge as the group had to determine the proper dimensions and figure out how many of each variation were required.

Future Work

Some changes and improvements will be required to allow the clock to run consistently. The first and most important is that the mechanism must be properly coded to pull the fluid from the bottom of the vials to display the correct digits. Had there been more time, this likely would have been achieved but we simply ran out of time to perfect the programming. Secondly, the enclosure can become more permanent. As the design stands, the front plate can be slid on and off the face of the clock. Some end plates or screws on the inside of the face can be implemented to make this a more permanent fixture and eliminate the risk of the plate sliding off and potentially breaking the vials. In addition a redesign of the vial system, including thinner custom made viles and replacing the suspended fluid could help improve the appearance and functionality of the clock. Another area worth considering further research in is potentially conducting more development into implementing electromagnets or motors design for a high duty cycle environment.

Conclusion

This project, to many of us, was the first time we were given funding to create a physical product. This served as a massive learning experience as we were introduced to the problems that occur during the design process and managing a budget. We were able to continually learn and adapt throughout this process as design requirements changed, and we found out what was feasible and what was not given time and budget constraints. While the final product may not have been a complete success; we were successfully able to replace the old mechanism with something that should be more reliable once the bugs are fixed. The old enclosure was also replaced with a much more visually appealing acrylic case. The physical product however is only part of the major outcomes from this class. The skills gained throughout this process will be invaluable in the future as we were able to get firsthand experience with tools that are commonly found across engineering disciplines. Not only physical skills such as CAD, 3D printing and laser cutting were gained but also soft skills such as teamwork, communication and project management. Through taking this course, we should all be more prepared for the future.