Design and Construction of a Rube Goldberg Clock

Technical Capstone Project

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

University of Virginia, Department of Mechanical and Aerospace Engineering

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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.

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Abstract

For our technical design project, the group decided to design and construct a clock incorporating aspects of Rube Goldberg machines. We aimed to incorporate an updated version of the Ferrofluid Clock, an unfinished technical project from years past, as the primary mechanism for displaying time. The Rube Goldberg machine element consisted of moving pinballs and mechanisms designed to keep the system running continuously. The final project was to incorporate mechanical design, electrical engineering, and microcontroller programming. The goal of the project was to develop skills in computer aided design (CAD), rapid prototyping with laser cutting and 3D printing, and project management.

Executive Summary

The goal of the mechanical engineering senior design project was to build a clock that incorporated complex Rube Goldberg mechanisms with moving pinballs at specific points in time. Initially, the technical team planned to improve upon an unfinished senior design project, the ferrofluid clock, and incorporate it into the final design. The magnitude of the required improvements and impracticality of fitting it into the physical size of our design led to an abandonment of that plan and a renewed focus on a different structure for the clock. The initial team of six segmented into two teams of three, teaching us a valuable lesson in project management out of the gate.

Using computer-aided design (CAD) in the program Solidworks, the technical team got to work building the Rube Goldberg clock. The team first prototyped the back gear, flippers, and balldrop, components explored in more detail later in the report. Physics concepts proved to be effective, and were used to design mechanisms to keep the system running perpetually by making use of a combination of motor-types. Throughout the design process, the technical team was forced to overcome numerous roadblocks and manage expectations in order to build a viable product. As the team continued to CAD the full assembly, material constraints began to come into view, particularly with regards to wood and acrylic. The team had to carefully consider how to construct the structure and gear using what would be a large quantity of these materials. Ultimately, the size of the clock was halved to accommodate 0.75-inch balls. The team continued to refine the CAD design, opting to use a CNC machine to cut the wood for the physical structure.

Though the initial goal was to present a finished clock capable of being displayed and continuing operation with minimal maintenance, the team was ultimately forced to present a working structure for the clock to be refined and mechatronics controlled in the future. Many key lessons were learned in the process that strengthened the technical skills of the Rube Goldberg clock team as the project ran its course.

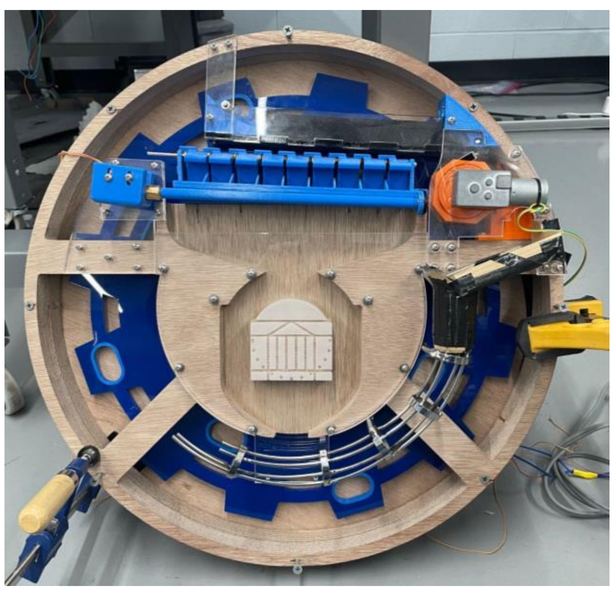

Fig. 1. Final product of the technical project process

Design Chapters

Overview Sections

Below are two sections detailing an overview of the project. An initial proposal outlining ideas from the early stages of the project is provided followed by a brief history of the modeling process.

Initial Proposal

The initial design for the senior design project involved the construction of housing for the reworked ferrofluid clock with two tracks for pinballs surrounding the ferrofluid frame. The design called for two tracks for the pinballs, with one running every 1 minute and the other running every 10 minutes. This allowed for the clock to display both the current time and the passing of longer periods of time.

The ferrofluid clock uses ferrofluid, a liquid that becomes highly magnetized in the presence of a magnetic field. By carefully controlling the magnetic field, the team planned to create the numbers and other necessary components of the clock face using the ferrofluid. The clock required a new design for the mechanism that extends and retracts the permanent magnets used to manipulate the ferrofluid.

The clock was to sit in the center of the structure, with the pinball tracks positioned around the clock and layered in depth for visual effect. The 1-minute track was to begin at the top and deposit pinballs through an exciting wire cage path. The ball was to land in a reservoir at the center of the clock, segmented into nine pockets. After nine balls fill the reservoir, the tenth would pass all of the filled pockets of the reservoir and trigger a plinko-style drop of the other pinballs. The pinballs would be released at regular intervals and follow their respective tracks, with the 1-minute track pinballs representing the passing of each minute and the 10-minute “plinko drop” pinballs representing the passing of each 10-minute interval. The team initially aimed to create an illusion of the pinballs changing the digits of the ferrofluid clock.

In summary, the initial design for the senior design project involved the creation of a ferrofluid clock with two tracks for pinballs, allowing for the display of both the current time and the passing of longer periods of time.

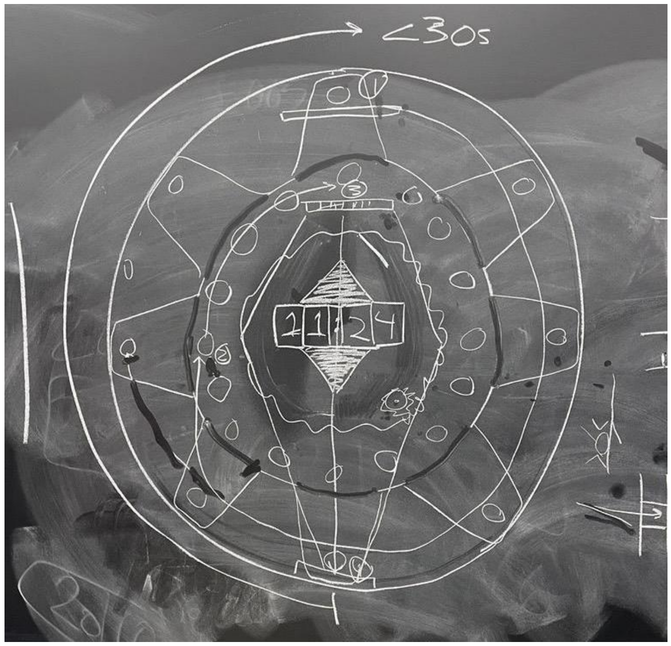

Fig. 2. Illustration of initial proposal for clock design

Modeling History

Once the original concept was established, the team sought to model the individual mechanisms that made up the Rube Goldberg clock. The gear mechanism was modeled with ramps that would force balls out of the gear at a specific location. This would allow transportation of pinballs vertically.

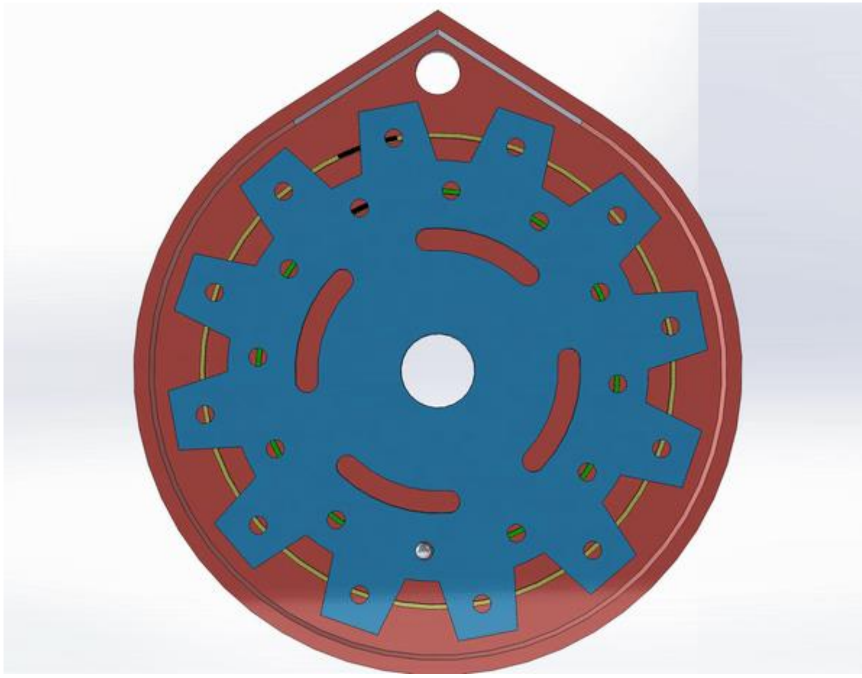

Fig. 3. Pinball within gear transport mechanism

In addition to the gear transport mechanism, the team began to model other Rube Goldberg machine components and tracks. Fig. 3 is an early stage assembly of draft components. It includes the central reservoir, known as the "flipper array," that stores 9 balls and allows the 10th ball through. It also includes a spiral staircase into a wire cage pinball track, and the pick up location for the inner gear holes. At this stage, the team was focused on developing and understanding the individual mechanisms in each component of the clock. The team sought to verify that the physics principles employed would consistently work in reality before going the full distance with their designs. The team had not yet considered how to connect or support the pieces that were currently floating in the models.

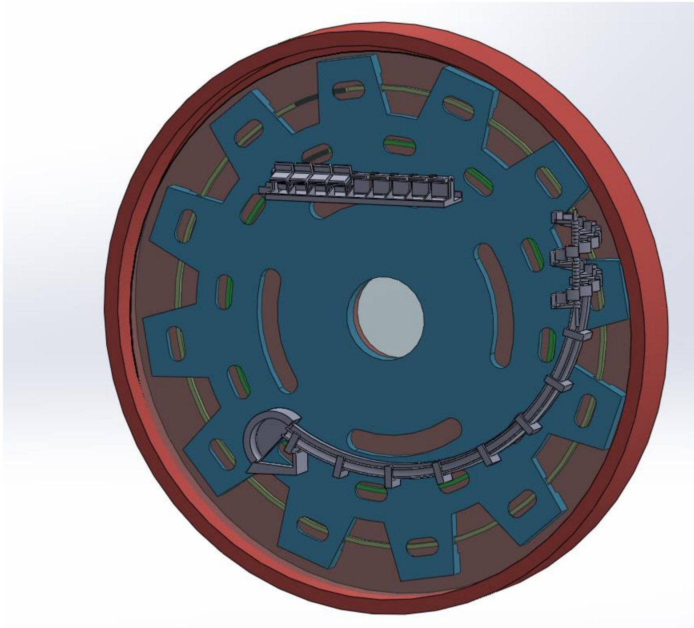

Fig. 4. Early assembly of draft components

The assembly progressed further (Fig. 4) with the addition of a support structure, the top ball reservoir, and the plinko board in the middle. A rotating balldrop was designed to deposit balls from the top reservoir to the minute track. The design began to take a more clear shape, and it was apparent how the various components would need to layer and mesh together for smooth operation.

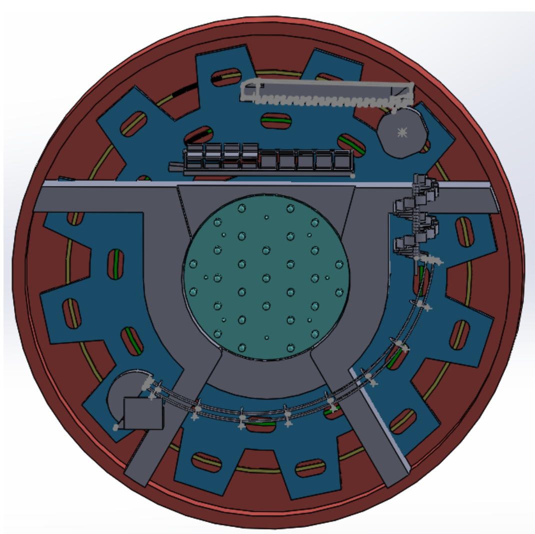

Fig. 5. Assembly with added support

At this stage, the team began to think more about the material cost of the project. It became clear that the cost of the wood for CNC milling into the case of the gear and the gear itself was far too expensive to afford for the current dimensions of the design given the budget at hand. To reduce the material cost, the team decided to shrink the entire design down by half. The central gear's diameter was halved from 36 inches to 18. Although every other component was reduced by half, it was decided that half inch diameter pinballs would be unimpressively small, so instead .75 inch balls were selected. This meant that any component that was sized to the previous ball diameter would have to be reconfigured. It also meant that some components would take up considerably more space than before, as their relative size compared to the case had increased. It was expected that this new size constraint would be difficult to work around, so the team modeled the placement of components within the case more carefully. A funnel for capturing the balls flooding through the plinko board was designed to feed them back into the gear, and a proposed "kick-out" failsafe was drafted for the wire cage track to handle cases where pinballs did not reach the end of the minute segment. These changes are seen in Figure 5.

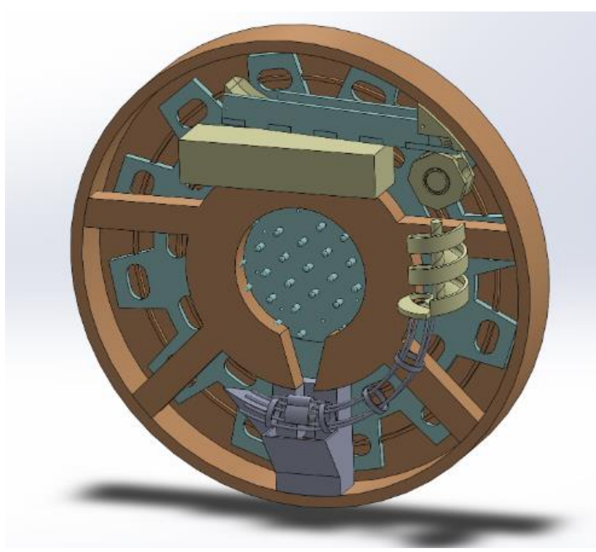

Fig 6. Developed assembly with placeholder for flippers as size was redesigned, new plinko funnel, kick-out failsafe, etc.

Components in Focus

The following section of the design chapters portion of this report will analyze the development of a few of the trickier and more complex components of the design.

Gear in Detail

The design of the gear focused on being able to continuously move pinballs between the one and ten minute tracks. The gear is placed in the center of the clock structure, behind the one and ten minute tracks, and was planned to be made from a durable material such as wood or acrylic. The gear includes two sets of holes: one to carry pinballs from the end of the one-minute track to the 10-minute ball reservoir, and another to carry pinballs from the bottom reservoir back to the beginning of the one-minute track. Along the back of the gear are cut grooves that allow for the pinballs to be pushed out as they pass over wedges attached to the clock frame.

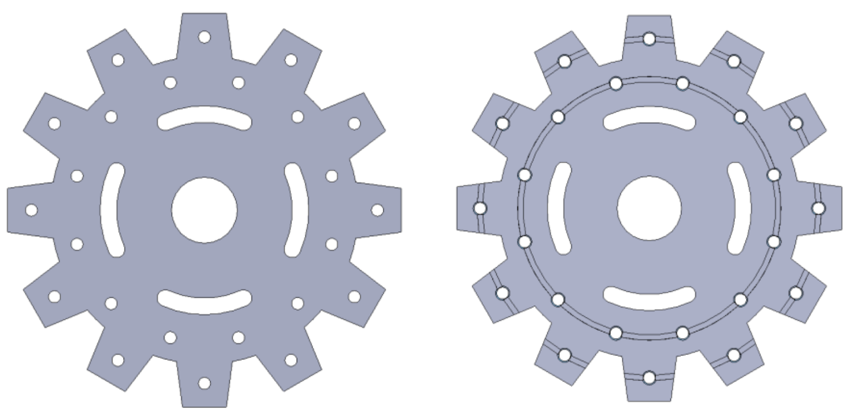

Fig. 7. First design for gear

The initial design of the gear had a maximum radius of 18 inches. Before the next iteration, the holes in the gear were also expanded to allow for leeway in pinball pickup.

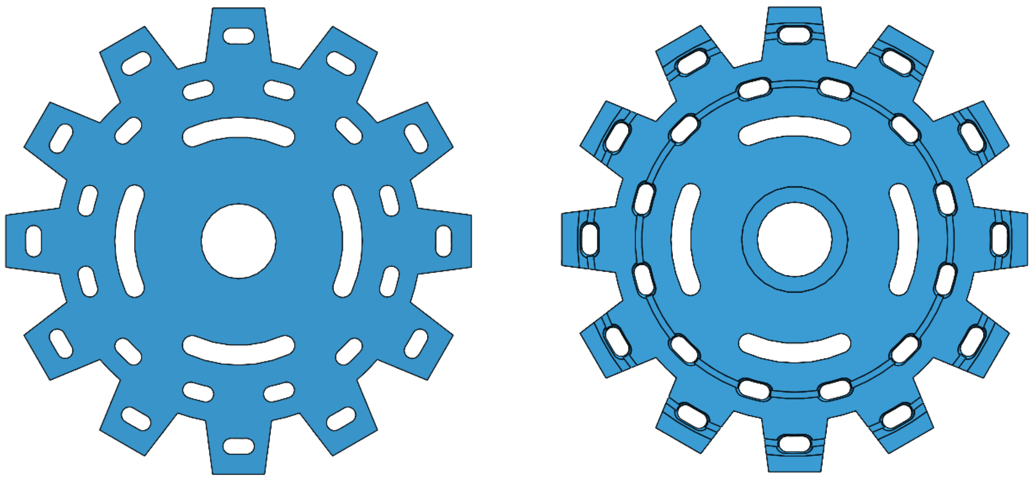

Fig. 8. Second design for gear with expanded holes

To conserve materials and production time, the team opted to reduce the gear to half its original size and use 0.75 inch pinballs rather than 1 inch. The number of holes and aesthetic grooves were also reduced, and rails were added to connect the outer set of holes to prevent the pinballs from dropping out into the frame.

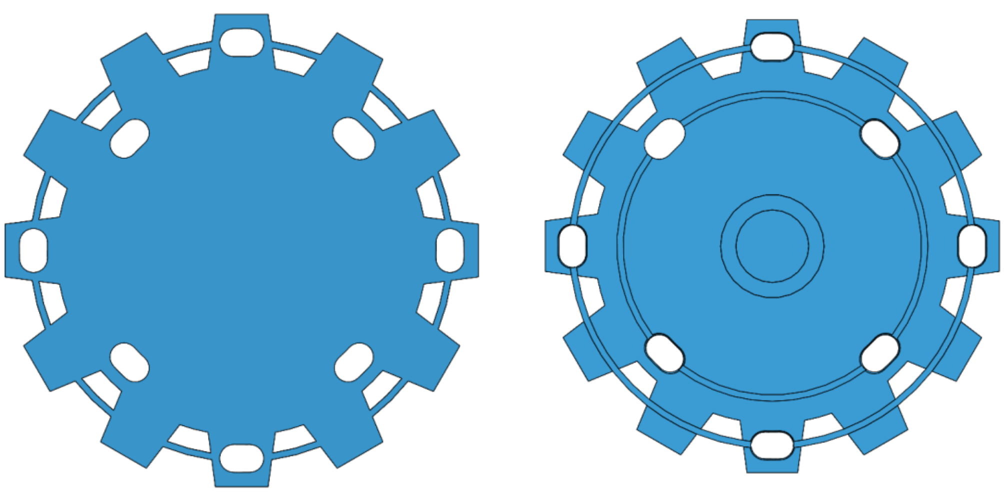

Fig. 9. Final design for gear with connecting rails and fewer holes

3D printed inserts were added to the gear to achieve a slope in each hole, allowing the gear to be laser cut from a single sheet of ¼ inch thick acrylic and the groove to be cut using the

CNC mill. The 3D inserts also contributed to the removal of holes, reducing the amount of material and time needed for production.

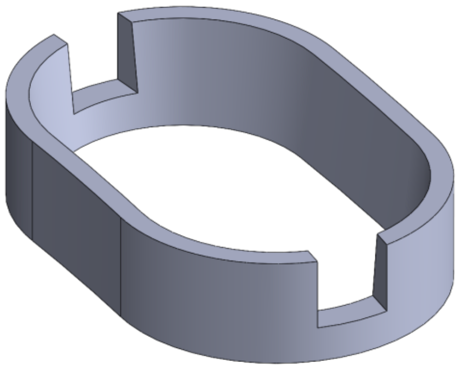 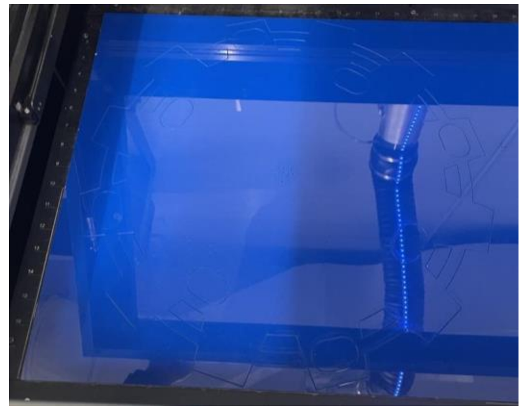

Fig. 10. Gear hole inserts (left) and pre-punched laser cut final gear (right)

For testing, the team ensured clockwise rotation and attached the push-out ramps to test if the balls would be persuaded out of their slots as expected. After filing the ramps to ensure clearance, the following test confirmed the functionality of the gear.

Fig. 11. Final test of gear functionality with pinballs

Support in Detail

The team's plan was to design a support, attached to the outer rim frame, that would sit in front of the gear and serve as the main structure for attaching clock components. The support would also contain the track for the pinballs to fall through after being released from the flipper array. The team planned to machine the wooden support using a CNC mill. The initial design of the supports was created for visualization purposes, giving the team a better understanding of how the finished clock would look and function. The design was not intended to be a final, production-ready version, but rather a starting point that could be refined and improved upon.

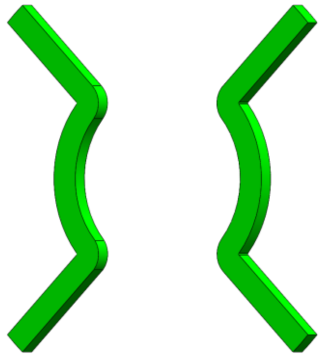

Fig. 12. Initial design for support structure

Once the initial design was complete, the team was able to make more informed decisions about the final design of the supports, such as the shape and placement of the support arms. The next iteration outlines the general shape that was further built off of. Initially, the team explored options about how to pass the ball through the center after being released from the flippers. At this point, the team had desired to use a rotating plinko board that would turn with the gear. The plinko would be a part of the gear, simply protruding through a hole in the support structure.

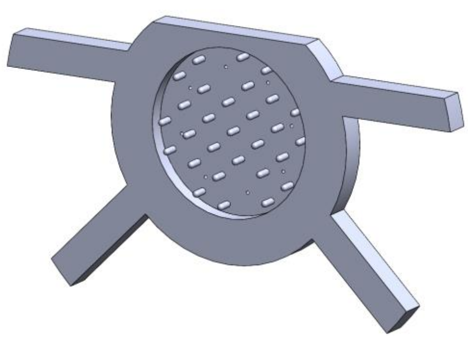

Fig. 13. Redesigned support arms and plinko board

The team was initially thinking about machining metal pegs for the plinko board, but after further consideration ultimately decided to go with a simpler design for the ball cascade, dropping the plinko style altogether. A wooden channel design was settled on that could be directly CNC milled with the rest of the support, saving time and creating a cohesive visual look. A design of the UVA Rotunda was featured to allow the balls to flood around it and cascade down to the bottom reservoir smoothly. This design was easier to implement, and allowed the team to both give the clock a visual centerpiece and avoid added machining. Solidworks was used to create a model of the support and rotunda, which was then used to generate machining instructions for the CNC milling machine. An acrylic cover was then designed to accent the Rotunda and keep the pinballs in the plane of the track as they cascaded.

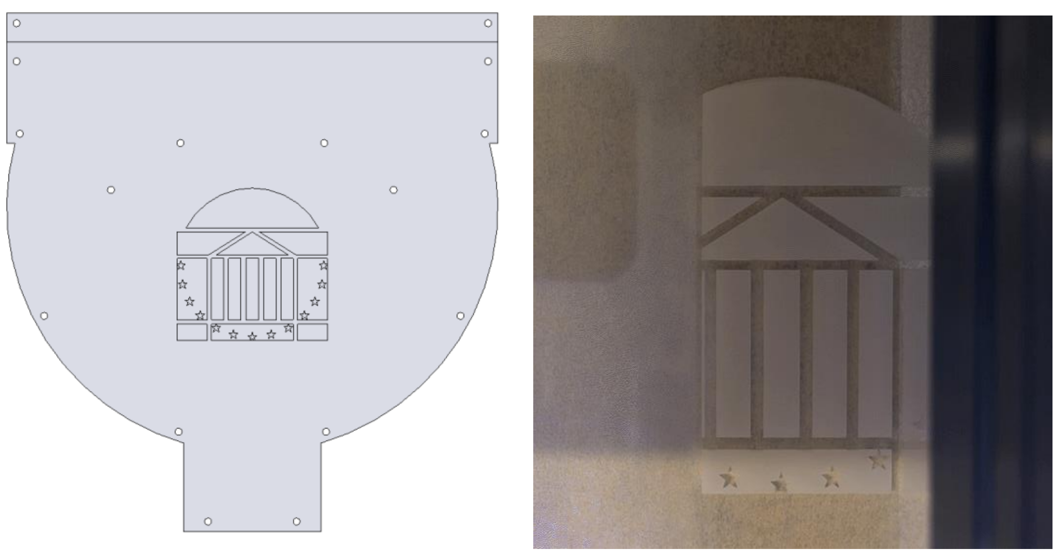

Fig. 14. Final design for acrylic support cover (left) and cover laser cutting process (right)

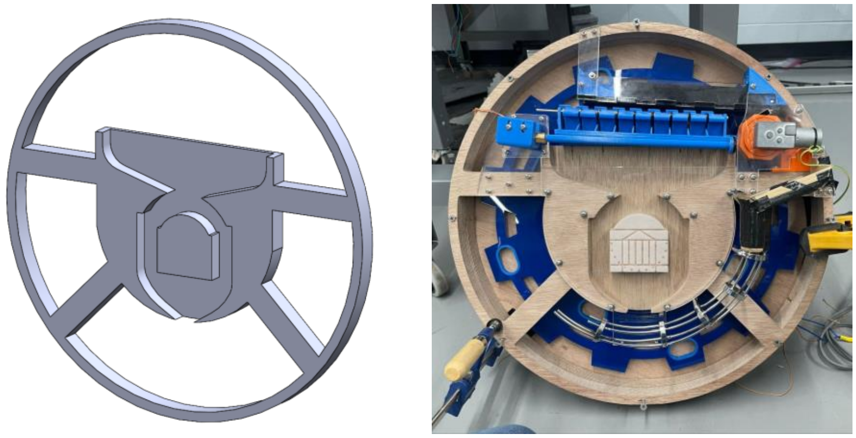

Fig. 15. Final design for support structure with rotunda logo (left) and support structure in context of final build (right)

Balldrop in Detail

The original goal was to design a small 3D-printed part with cups that turn every minute to transfer a pinball from the top reservoir to the one-minute track. The part has a series of four cups, evenly spaced around its central axis and large enough to hold a single pinball. Along the outer edge of the balldrop, the team designed a groove to keep pinballs on the ball drop when the closest hold is occupied. To ensure that part rotates exactly 90 degrees, once every minute, the team planned on having a limit switch follow a track within the ball drop part that was triggered at each stop location. The team implemented this design as the project requirements switched the part to half-size. Holes were added to be used for attaching the motor.

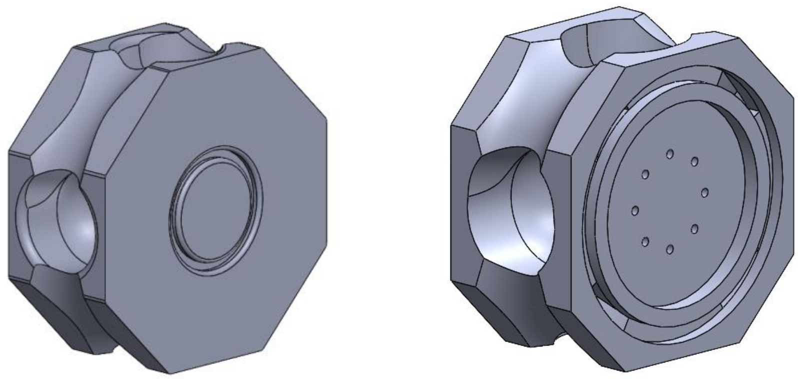

Fig. 16. First design of ball drop (left) and final design of ball drop (right)

However, after the final design of the ball drop was printed, it came to light that the roller of the limit switch would not be able to fit in the groove. This was a result of scaling inconsistencies as the clock changed size in the model. The team opted to then design an insert to eliminate the groove, reworking the limit switch trigger mechanism. This would prevent the reprinting of a sizable part. After gluing the insert, the motor could be attached to the ball drop. The final product is depicted in the next "in detail" section.

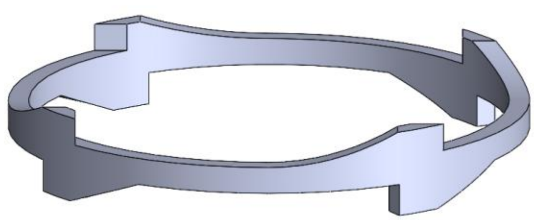

Fig. 17. Ball drop insert for triggering limit switch

Ball Interchange in Detail

The team planned to design a 3D-printed part to change the direction of the pinball's motion after it is released from the ball drop. The interchange is shaped in such a way that it follows the curvature of the frame, fitting with a tight clearance on the support and allowing the pinball to smoothly transition from its initial downward trajectory to the beginning of the one-minute track. The team designed the interchange with consideration of the forces it would need to endure, as it is subject to the impact of the pinballs as they are released from the ball drop.

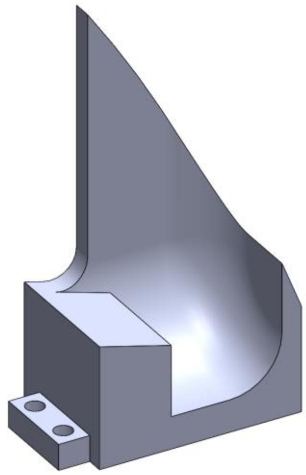

Fig. 18. Ball interchange

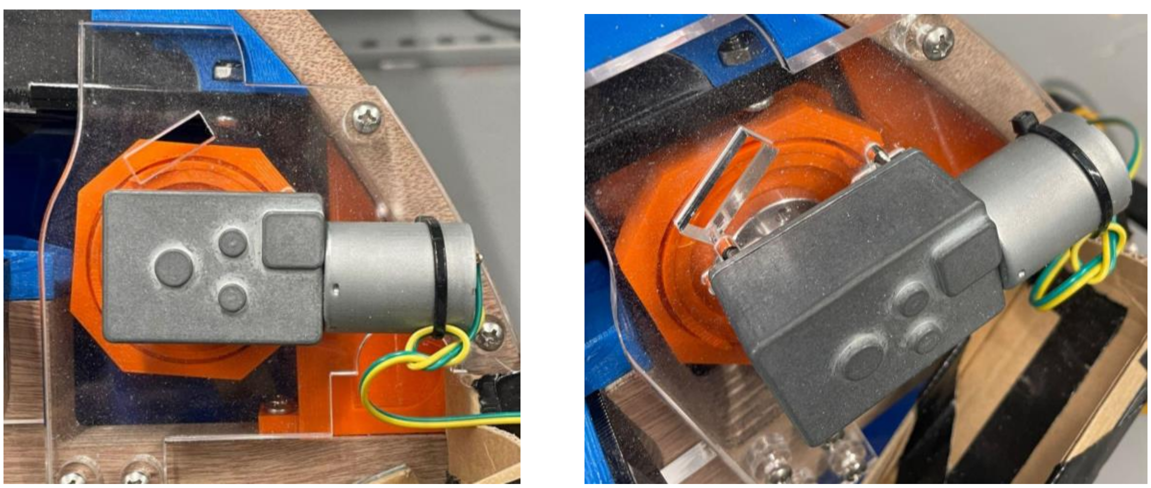

Fig. 19. Ball drop and ball interchange in context of final build

Flipper Array in Detail

A crucial component of the Rube Goldberg clock is the nine-pocket array of flippers at the center that stores balls incrementally until the cascading release at ten minutes down through the wooden channels. It was quickly decided that making use of basic physics to properly “pocket” the balls as they arrived would make for a visually satisfying component while potentially scaling down the amount of mechatronics work needed. A basic proof of concept was designed and printed.

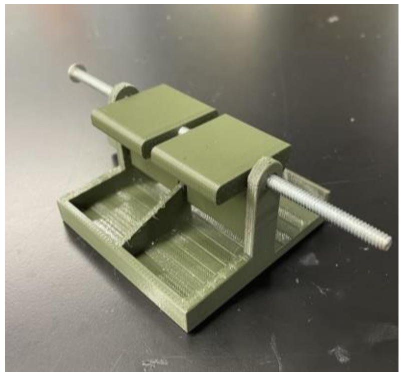

Fig. 20. Flipper array first prototype

The behavior of the flipper assembly is rather simple. A ball is to come rolling in from the far back corner. The main base is sloped both towards the front left wall and the back right exit hole. Due to this sloping of the main base, the entering ball rolls through the gate of a T-shaped flipper and keeps rolling forward until it contacts the front wall. This causes the flipper to rotate. The rotation of the flipper essentially blocks any further balls from entering the pocket, creating a wall in the form of the rotated top plate of the flipper. Thus, when another ball enters the assembly, it shall pass the filled pocket and proceed to the next empty slot. As mentioned, this would continue for nine balls and nine pockets. This “open” and “closed” behavior is depicted in Figure 21 in the context of the final project.

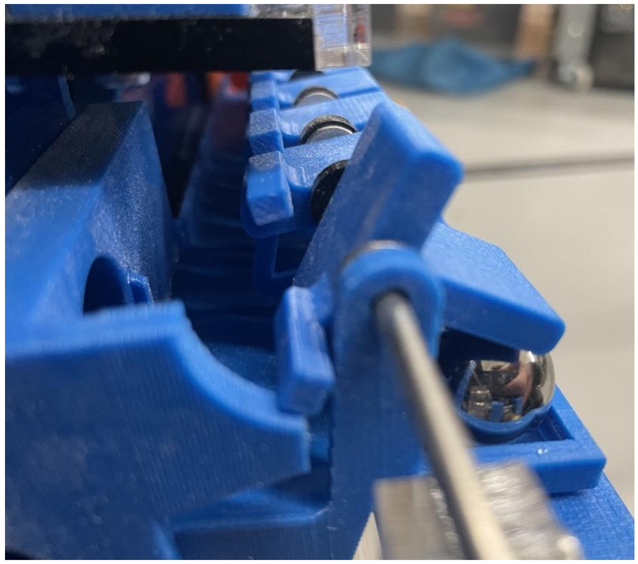

Fig. 21. Open position (back flippers) and closed position (nearest flipper).

A ball entering a pocket “closes off” the pocket and forces the next ball

to travel to the following pocket.

A few flaws were immediately apparent. An attempt to print a cylindrical axle to hold the flippers was foiled by a lack of smoothness and a slight oversizing. Temporarily, a large screw was used, seen above. Additionally, the resolution of the 3D printers used for the technical project dictate that one direction of printing be performed in steps of 0.01 inches. The direction chosen for this prototype caused the ideally smooth rolling surface of the balls to be choppy and rough, as seen in the base of the image above. As such, the refined slopes of the CAD model were not manifested in reality. This contributed to a third problem. The rolling of the balls was a bit unpredictable with this choppiness, and in the case where it would actually pick up *too much* speed, balls could skip an open flipper pocket, ruining the continuity of the design. Lastly, there was some slop in the angular position of the flippers. When a ball would pass a “closed” flipper, it could still rotate the flipper forward slightly. This mitigated the influence of the designed slopes and often caused balls to come to a stop in the middle of the array, which would need to be avoided in creating a reliable final product. A new system was designed and prototyped to solve these various problems.

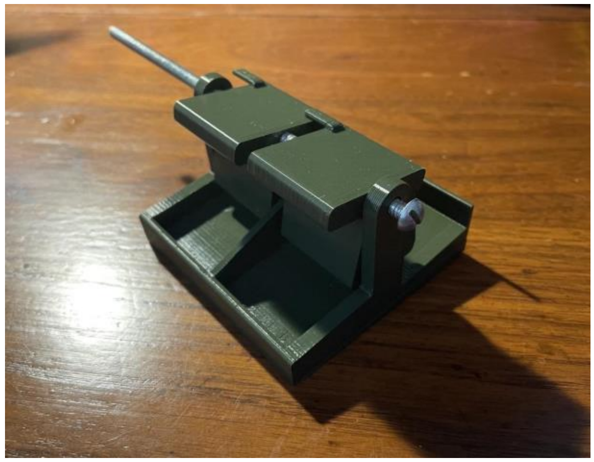

Fig. 22. Refined flipper array

The new assembly fixed all previous problems. Firstly, it was decided that a 0.125 inch diameter metal rod would serve as a smooth and easy rotational axle. Clearances were adjusted and a prototype wire was implemented. To fix the slope resolution problem, the positioning of the part for 3D printing simply needed to be adjusted. The part was oriented in such a way that the 0.01 steps printed along the length of the whole assembly, from side to side, generating extremely smooth slopes whose fine-tuned nature now perfectly brought the balls to the necessary pockets. As for the skipping of pockets, a preventative arm was added to the flippers. With this addition, balls physically could not pass a flipper when in its open state. Lastly, to address the angular slop, a small tab was added on top of the flipper. When the flipper rotates into its closed position, this tab catches the column of plastic that houses the flipper axle. When pinballs further impact the back of the flipper, this tab prevents the flipper from rotating in excess. For flippers beyond the first, the tab catches on the flipper adjacent to it.

Fig. 23. Flipper with new preventative arm and tab (bottom)

With the mechanism perfected and balls filling pockets in an extremely consistent manner, it was time to stretch it into a nine-ball array and determine how balls would be released from the assembly. It was first suggested that balls should exit out of the front of the flippers where a wall was currently present. With difficulties encountered regarding feeding the balls back inwards underneath the assembly to properly fall into the wooden channels, a trapdoor alternative was created and set as the final outcome.

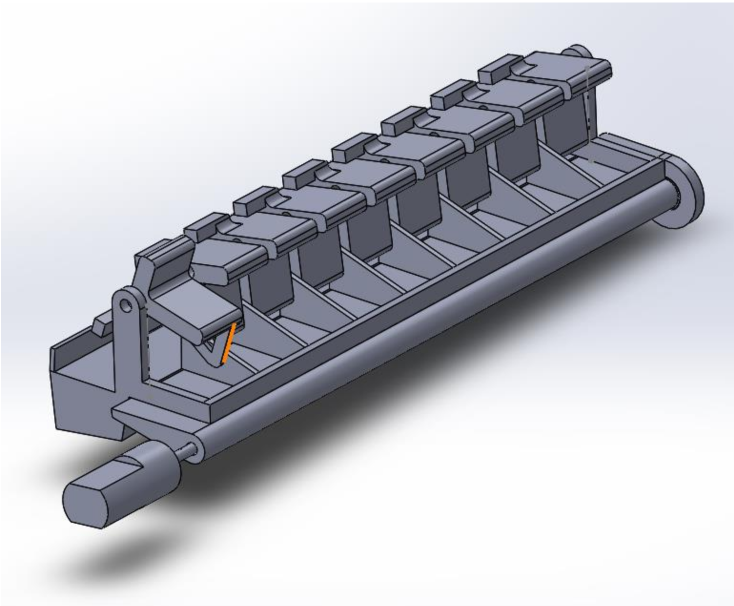

Fig. 24. Final trapdoor assembly with all nine pockets

The trapdoor is mounted upon a long wire axle coupled to a small motor that dictates its rotation. All nine pockets were added in this assembly and an arm was created at the far end to support the long trapdoor axle via a small bearing. The trapdoor would be rotated downward by a motor, modeled above, releasing the waiting nine balls into the wooden channels below. The motor was to be placed within a mount that would brace it against the wooden support structure. The mount was constructed out of acrylic plates with slots for fastening screws that could tighten down upon the motor within the mount using hex nuts. The final version of that motor mount is depicted in Figure 26.

The team next designed the connection from the acrylic gear to this array of flippers. There was extremely limited depth between the two components, so creativity was necessary.

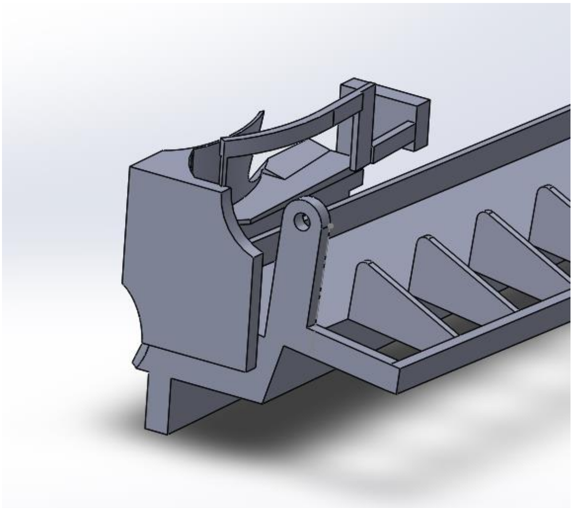

Fig. 25. First iteration of the gear-to-array connection

The first attempt had its benefit, but was ultimately unsuccessful. Many of its components were far too delicate to withstand the wear and tear of continuous pinball impact, such as the thin guardrail at the top. The unique curvatures were also difficult to capture with strong resolution in a 3D print.

The use of this part was eventually foiled not by deeming it unsuccessful but by an unintentional break when the part fell from a work table. In need of a reprint anyway, changes were implemented for bulking up strength. A new system for depositing the balls scrapped the guardrail system and focused on a forcing “tunnel”. Seen in the upper left of Figure 25, a gradually increasing slot guides pinballs out of the acrylic gear in accordance with the finalized push-out ramps. The ball then pops through a hole in the slot and heads onto the sloped base. Mounting plates with screw holes were added to affix the array to the wooden support structure. The tabs on the flippers themselves were bulked up for extra strength, and acrylic spacers were cut and implemented along with washers to make sure all flippers maintained their relative horizontal positions and didn’t get caught on the thin blue dividers below. This final array worked perfectly to guide balls into each pocket in a reliable and visually satisfying fashion.

Fig. 26. Finalized flipper array from above

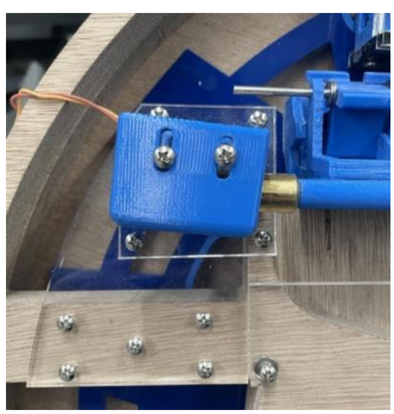

Fig. 27. Motor mount for the trapdoor

Wire Track in Detail

Our initial expectation for the wire track was that it would be welded out of ¼ inch diameter stainless steel wire and segments of stainless steel pipe with an inner diameter that would allow the wires and a ball to fit through it. It was also important to align the wires within the rings of pipe such that a ball could not fall out between any two wires. After the adjustment of ball size from 1.0625 inch to .75 in, we decided to use ⅛ inch diameter wire and correspondingly smaller pipe sections.

Our expectation was that welding would result in a wire track that perfectly fit our specifications, so we designed with large tolerances. We also expected some deviation during the process of rolling straight wire into curved segment of the correct radius. By gradually rolling the wires into tighter and tighter curves while checking against an image with the ideal dimensions, we we able to get reasonably close to our ideal curvature for all four wire pieces. The welding proved difficult and messy as we expected, but ultimately produced a functional wire track that fell within our expectations of error.

Physical Assembly

Physical assembly is the final design chapter. While obstacles sprang up with high frequency, applying designed components in the real world was an engaging and rewarding process. All components mentioned below can be observed in one final figure, Figure 28, that showcases the temporarily finished project. It is a duplicate of Figure 1.

With the aid of Professor Gavin Garner, the wire cage track was welded together using metal rods and cut pieces of a metal tube. The track was affixed to the wooden support frame using slots, making its depth off of the plane slightly malleable. Balls could seamlessly roll down this track in a high-speed and satisfying arc.

The ball interchange was quickly attached to the wooden frame. The balldrop mechanism was then finalized and assembled as explored in the previous design chapter. One obstacle here was the progressive stripping of the motor coupling set screw, making continuous disassembly a challenge. However, a final ideal positioning was reached. The upper ball reservoir was also assembled by cutting various lengths of acrylic and gluing together their staggered tabs. Glue was deemed a fair method of fastening this piece, as disassembly would not be needed.

The finalized flipper array was next mounted upon the wooden frame in a centered position. The flipper axle was set into place with a small amount of excess wire exposed for future trimming or capping.

The trapdoor motor mount was next assembled and affixed, which came with few issues. The trapdoor was aligned under the array and smoothly matched the slopes designed. The intermediate wooden rim that connects the wooden support structure to the back plate was screwed into the support structure at this point. Wood glue was determined to be too permanent a solution, and also a strategy that would take too long to securely "set" given the approaching deadline of the project.

The most difficult part of assembly involved mounting the blue acrylic gear to the wooden back plate and aligning it with the crowded front face. The placement of the push-off pieces needed to be precise to ensure ball motion through the system would not create wear and tear in unforeseen locations. The hurdles encountered during this process are outlined in the Future Work section, as most assembly solutions were temporary fixes that could use a more stable strategy in further progression of the clock. In addition, use of glue for a few key components of this assembly is mentioned in the Future Work section for future designers to determine if a change should be made.

Lastly, a cardboard sloped track connecting the balldrop portion of the clock to the welded wire track was created to allow the technical team to present a greater portion of the minute track than would otherwise have been available to showcase. Below is the final assembly produced for the project presentation. Visually, it is incomplete. Certain track connections, the LEDs for telling time, and a variety of circuitry components were not included in the team's final output simply due to time constraints. What is missing is detailed in Future Work. Despite these apparent holes in what was presented, the team made great strides in capturing the vision and operation of the project. Many components feature extremely sound design that demonstrate the team's abilities and growth in a tangible way.

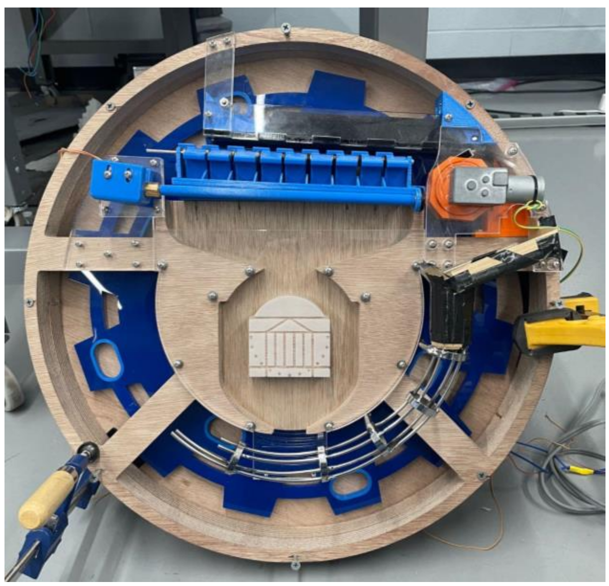

Fig. 28. Final product showcased once more

Future Work

Should the Rube Goldberg clock project be continued, the roadmap towards its completion is clear, though it will likely bring unforeseen obstacles to the table. The first step is fixing current physical issues. In the final hours of project construction, it was noted that the back plate which houses the direct drive AC motor and anchors the large acrylic pick-up gear was a little too close to the two other CNC'd wooden structures and the various components mounted upon them. This was exacerbated by the slop in the AC motor coupling that allows the acrylic gear to slightly tilt back and forth as it rotates. With these issues, the gear often grinds against various surrounding components, including the upper ball reservoir and the flipper array, in a manner that could prove devastating to long-term function. Plus, the type of AC motor purchased tends to switch rotational direction when met with resistance. Thus, collisions with surrounding components often tended to reverse the gear into counterclockwise rotation, breaking the functionality of the clock and its track loops. To solve these problems, it is suggested that some form of spacer be developed between the wooden back plate and the middle-layer wooden rim to prevent grinding and contact between the acrylic gear and frontal components. The depth of this spacer may need to be iteratively fine-tuned to ensure the pinball push-off ramps still reliably persuade pinballs out of the gear and onto the next track. In addition, a more technical shim should be developed and placed under the AC motor coupling to clamp down on gear tilting. With more clearance from the gear to the various track components and a more stable AC motor coupling, the gear should be able to more smoothly pick up and deposit pinballs without placing wear and tear on the system or running the risk of a sudden continuity-breaking change in gear rotational direction.

Two optional fixes for current components involve use of glue instead of fasteners. The push-out ramps that propel pinballs out of the pockets in the acrylic gear are currently glued to the backplate; this was a forced decision in the final hours of construction due to the clearance problems described above. Screw heads simply could not fit to affix the push-out pieces to the backplate without adding yet another location for the gear to grind against external features.

Thus, locations where screws attached to the push-out pieces were knocked off with a handsaw. When the gear clearance problem is rectified, the push-out pieces can be reprinted with their screw holes properly utilized, allowing future interchangeability.

The other location where glue was implemented is the black acrylic “cover” that keeps the bearing that shares a hold on the trapdoor axle in place. There was not enough time nor space to design a feature that could be disassembled with screws; future workers may wish to make this change. Future workers may also wish to trim or cap the excess wire of the flipper axle, left there to allow freedom in future design choices.

Another fix to the current system involves the trapdoor for the flipper array. While the trapdoor can sit in its “closed” position when no pinballs have loaded into its pockets, the motor powering the trapdoor does not have enough internal resistance to maintain this position where around 5 to 6 pinballs take their place on the trapdoor. Consequently, the trapdoor releases those 5 to 6 pinballs down through the wooden channels prematurely. There is a lot of room for creativity in solving this problem. A motor with stronger internal resistance is a possibility. Another pitched solution would be a small solenoid positioned underneath the trapdoor. When sensors indicate that the tenth ball has passed through the flipper array and has arrived at the balldrop, this solenoid could retract, allowing physics to take their course and rotate the trapdoor. With the balls released, the trapdoor motor would only be needed to reset the trapdoor into its closed position. These are just two options for solving this current problem; experimentation is recommended.

With current assembly problems mended, the track system shall be finalized. Two major pieces are needed here. First, a connection between the offramp to the balldrop mechanism and the welded wire cage track is needed. As a placeholder, a cardboard connection was built by the team. In reality, any type of reliable track could be placed here. In initial designs, a 3D-printed track resembling a spiral staircase was designed to transfer the ball from the balldrop to the wire cage in an exciting manner. This idea could be pursued further, or individuals resuming work on the clock could come up with another ideally “fun” and satisfying connection track. The second track piece needed requires a more careful and functional approach. A 3D-printed connection ramp was designed by the technical team to bridge the end of the wire cage track with the location where pinballs would be fed into the pickup gear and transported to the beginning of the flipper array. This piece was printed, but it carried a few issues with it. First and foremost, its screw hole connections to the wooden support system aligned in a slightly askew manner that left a little to be desired structurally and aesthetically. More importantly, the slopes built into the initial “turnaround” ran the risk of feeding a pinball back into the wire cage, breaking the continuity of the clock. The track direction and sloping must be redesigned to more consistently get pinballs back to the gear without a risk of rollback.

With the track finalized, there is an opportunity to add further failsafes ultimately sacrificed by the technical team due to time constraints. Some form of escape hatch at the bottom of the wire cage track, likely operated mechatronically, is necessary in the case of the aforementioned rollback scenario, or in the case of an object such as a spectator’s finger interfering with the motion of pinballs. In general, a clear cover over the entire clock would be a smart decision to prevent any spectator tampering with some of the currently exposed features of the clock such as the gear pinball inserts or the flipper array.

Given that LEDs were initially desired for an every-hour lightshow, future workers may install a variety of LED components here. A central 60-bit LED ring is desired to show the ticking-off of seconds. LEDs lining the rim of the clock could signify the 12 hour positions and the tens place, with the nine-ball array indicating the ones place. There is flexibility here in how future workers desire to tell time.

The major step left to those pursuing future work involves, rather broadly, programming and circuitry. The clock is almost to a complete physical assembly, but the mechatronic interface that operates it has yet to be tackled. The objectives in this realm are best described in list form, and are as follows:

- Add limit switches to the "open" and "closed" positions of the trapdoor to dictate extent of trapdoor rotation.
    - If natural trapdoor opening is implemented as previously described, only a "closed" limit switch would be necessary. A fixture to hold the limit switch with a fastener is likely required.
- Add roller limit switch to prescribed slot in the balldrop motor mount
- Add sensor between final flipper pocket and the balldrop
    - This sensor would detect when the tenth ball has passed all of the flipper pockets, indicating that all nine pockets are loaded and ready to drop.
- Wire these limit switches and the two front-face motors to a central board harnessing a Propellor chip
- Construct code, which must accomplish the following:
    - Run a central "clock" brain
        - Coordinate selected LED's to display this time, trigger every hour in an entertaining manner, etc.
    - Trigger rotation of the balldrop mechanism every minute

        - Harness variables / equations to determine which rotations shall be more than 90 degrees. This must be the case whenever the tenth ball arrives at the left side of the balldrop, as this ball will be transported 180 degrees to continue minute track continuity while the other nine balls drop through the wooden structure. This programming step will also need to run a check with the sensor placed between the flippers and the balldrop to ensure the tenth ball has indeed arrived.
    - Trigger trapdoor rotation and / or solenoid retraction every ten minutes
        - Run same sensor check to ensure all nine balls are in slots first

Lastly, if the project reaches a completed functional state, it is suggested that future workers get creative with theming. Painting, sanding or other fixtures could add visual excitement, professionalism or simply a creative aesthetic to the project. A retro, outer space pinball machine theme was one concept floated by the technical team, but future workers taking over the reins of the clock project should choose whatever they see most fitting and most entertaining for their purposes.

Conclusions

Whether the technical project is resumed by the technical team next semester, picked up by future capstone groups, or left in its current state, the design and construction process resulted in several major takeaways. These are divided into two main categories.

The first major takeaway category focuses on valuable skills honed by the group. Throughout the project timeline, the 3D modeling and Solidworks skills of the technical team were improved upon immensely. Parts featuring unique slopes, sweeps and lofts mandated an improved familiarity with some of the more advanced drawing abilities of the software that will aid the group in any future modeling endeavors. Bringing these designs into reality in constructing the clock also allowed the team to brush up on skills surrounding physical assembly. This is a facet of engineering that had only been exposed to the team in abstract through previous machine elements courses; actually positioning and assembling motors, screws, bearings and other pieces that had been personally designed in a virtual environment was a unique and informative process.

The Rube Goldberg clock was distinct in its incorporation of the principles of physics. While there are certainly opportunities in future work for mechatronically "cheating" with motors and programming, much of the project features components fine-tuned to harness gravity and force distribution in special ways, including the refined grades of the flipper array, the slopes of the gear inserts, or the grooves and channels of the balldrop mechanism. While this technique involved many design iterations, watching gravity do the work through many of the pieces of the project was an exciting final outcome and allowed the technical team to apply some of the fundamental principles explored in early physics and dynamics courses.

Lastly, the clock featured multiple wooden structures created via CNC milling. Gaining exposure to this complicated yet powerful construction tool was a worthwhile endeavor. As mentioned in the design chapters, the process was certainly a bit finicky, but the final outputs contributed greatly to the aesthetic and functionality of the final clock. The team's introduction to this technology will be great to carry forward and expand upon in future projects.

The second major takeaway category for the clock project focuses on lessons learned for prevention of future problems in any design challenge or scenario. Many lessons came as a result of our experiences in the assembly stage. First off, the team noted that the order of assembly of physical components should be a point of careful consideration in all future design endeavors. In a virtual landscape such as Solidworks, it is simple to drop in designed pieces and perfectly mate them where they should go. In reality, the sequence in which components could be added to the wooden support structure mattered greatly. The team often screwed in components to the frame only to find that the component needed to be briefly removed to install another piece of the project whose location had become momentarily inaccessible. This trial-and-error process resulted in lost time and excessive wear on various screw holes. In the future, the team hopes to avoid these errors by more carefully planning the succession of component installations. Alongside this issue, there were a few cases of imperfect clearances. While clearances had been built into all project designs, some tolerances were a bit too close for comfort, resulting in imperfect fits and the grinding of parts. Nearly all of these problems were solved by the addition of washers or by lightly sanding down parts; however, these are inferior solutions to a problem that could have been avoided in design. With this experience, it is clear to the technical team that slightly overshooting predicted tolerances would be a sound strategy for the future. At a minimum, carefully refining the tolerances to a more accurate value in the prototyping stage could prove advantageous.

Two other valuable lessons from this project revolve around saving time. As mentioned in the design chapters, the clock had to be downsized midway through the modeling phase due to material and cost constraints. This change resulted in the loss of valuable time and completed designs as finished pieces were reworked. The technical team pursued a size for the clock that would provide a great visual effect, yet only realized the difficulties of an assembly of that scale later in the game. With this major obstacle in mind, material budgeting and size restrictions to a project should be more mindfully considered at the very start of the design process. This would prevent such a large setback later in the game.

The last lesson is more of a missed opportunity than a lesson learned. Due to the immense amount of time dedicated to modeling and physical fabrication, exposure to the circuitry and programming elements of the clock was rather limited. A few basic wirings were achieved that could make components work when plugged into an outlet or a breadboard, but the project was ultimately rather far from functioning completely on its own electronically. The team ideally would have arrived at this process and broadened practical skills in the programming and circuitry fields, but there simply was not enough breathing room at the end of the project schedule to attempt any of these challenges. This is certainly a regret but presents a large opportunity for future work.

Overall, the technical project offered an ambitious and demanding challenge that allowed the technical team to strengthen their engineering skills in a variety of different ways. While the final product has some holes to fill, it is ultimately a physical output the team can be proud of. The project offered verification of many strengths of the team, including CAD modeling and the incorporation of physics, while offering new lessons in tangible assembly. The project also provided critical learning experiences regarding the consideration of budget and the reality of clearances and tolerances. Uniquely, the project provided a chance to design from scratch and see that work come to fruition, a concept unseen in many previous courses. At its essence, the project yielded growth in the knowledge and abilities of the technical team, along with a chance to showcase wisdom accumulated over several years in an engineering program. The project was an indispensable experience that will carry the team far in future engineering careers and ventures.