Design and Construction of a Robotic Hourglass Clock: The Sands of Time

University of Virginia, School of Engineering and Applied Science

Department of Mechanical and Aerospace Engineering

MAE 4610 and MAE 4620

Fall Semester 2018

Advised by Professor Gavin T. Garner

Team Members:
Jackson Collins
Stuart Forrester
Merrick Furman
Carlton Higby
Oliver Sørensen

Table of Contents

Introduction

The goal of this capstone design course was to produce a piece of kinetic art to decorate the hallway of the Mechanical Engineering building. After initial brainstorming, the team decided on several different items that were essential to include in the design. The first and most import was a visible mechanism that was creating (or pretending to create) the motion, followed by the inclusion of light-emitting diodes (LEDs), and the showcasing of modern manufacturing techniques. With these in mind, the team proceeded to brainstorm what project could include all of those design features. After watching a number of videos on kinetic art installations, the initial project proposal was for a 3D map of the Mechanical Engineering building that would consist of hundreds of pegs actuated by linear actuators or a water pressure system. This research led to the conclusion that it would not be financially possible to build this style of art. Upon further conversation with Professor Garner, the team was introduced to the idea of building a clock made out of sand timers to indicate the different intervals on the clock. This idea resonated with all members of the capstone team, as it would easily include all of the team's personal design requirements and could result in increased recognition for UVA. It was decided that the clock would have a rotating hour hand which would extend every 5 minutes and rotate an enclosure with a 5 minute sand-timer inside. Each of these enclosures would be backlit by a panel of LEDs to help identify which enclosure was actively "timing". At this time it was decided the clock would be entitled "The Sands of Time" based on the poem *A Psalm of Life* by Henry Wadsworth Longfellow. On top of sprucing up the Mechanical Engineering hallway, there were plans to build a second installation with different background artwork to place in the Virginia Science Museum's Forge to inspire makers and increase attraction to UVA Engineering.

There were a number of constraints that needed to be taken into consideration in the design of The Sands of Time. The most obvious was budget, but the team was told to not lose sleep over this since there is significantly more funding available if it was needed. A location to hang the clock was also considered, and after scouting several locations for potential visibility, power, and noise restrictions, the blue wall outside the Lounge was settled on. This would give the clock the most visibility and not restrict the amount of motor noise it could output, but did create several challenges, namely the method of mounting The Sands of Time to the wall and the sourcing of a power outlet. Design was also constrained by the materials which could be used, as the team wanted to manufacture as much of the clock as possible in-house to minimize time and cost. The Sands of Time will have to be sturdy enough to withstand years of timekeeping on a wall frequently leaned against and the potential for repeated contact from intrigued, museum-going children. Finally, The Sands of Time needed to be beautiful, so some materials were chosen simply for their aesthetic qualities, despite the occasional increase in manufacturing difficulty. Some constraints that were also considered to a lesser extent were weight, noise output, and power draw. All of these requirements were kept in mind as we were designing The Sands of Time, and they all provided their own challenges in mitigating.

Background

Prior Work

Prior to designing and building The Sands of Time, the capstone design team looked back towards projects that had been previously completed in the Mechanical Engineering Department for inspiration. A common reference was the gear clock above the water fountain that was built by the Gizmologists. The elements of the clock that inspired parts of The Sands of Time were the use of large gears in both a timekeeping and aesthetic capacity. Another element borrowed from the Gizmologists' design was the use of the DS3234 Real Time Clock chip to maintain accurate time. Aside from direct adoption of elements of prior work, much of the mechatronic design instrumentation and code has been adapted from Professor Garner's Mechatronics course. This includes the methods used to interface with the absolute encoders as well as DC brush motors, via Serial Peripheral Interface and H-Bridge chips, respectively. Another facet of the project that was previously developed is the LED driver, developed by Professor Garner, used to individually address each of the LEDs in the rings surrounding each hourglass. Although many of the methods used in this project have been implemented into previous projects or coursework, it is the synthesis of all of the elements that inevitably make the design of The Sands of Time unique.

Impact of Kinetic Art

Rare is the product in modern society that an engineer has designed without consideration of form factor or aesthetics. The field of aesthetics is a nebulous subject that requires a firm definition to fully explore its importance within engineering. As Rolf A. Faste (1995) notes, while often reduced to surface beauty, aesthetics is more accurately defined as the overall feeling and quality associated with an object (p. 5). Lack of beauty or elegance alone in a creation can stifle the success of even the most well-designed, problem-eliminating creation, but a bad overall feeling to a design spells doom for a product. In a similar fashion, the functional ability of even the most rigorous students improves within a stimulating, aesthetically pleasing environment, as Lizzio et. al found in their study of randomly selected university students (2002).

This project aims to beautify the currently drab Mechanical and Aerospace Engineering building of UVA through installation of this kinetic art piece. These pieces will hopefully serve not only to liven up the hub of learning for mechanical and aerospace engineering students, but also to inspire future students through a visually stimulating and evocative display of mechanical design in action. Because of its unique structure and method of communicating the time, it should make those who witness it curious about the methods and design structure operating the clock. The placement of the piece within the science museum will ideally inspire young people to learn more about mechanical design and educate themselves in the topics that are the foundation of our project's operation. The team is undertaking this design project with the intention that the final product will receive a wide audience to view it. In either the Science Museum of Virginia or the Mechanical and Aerospace Engineering Building, there will be a high volume of foot traffic moving past the time display daily.

The kinetic art pieces will also serve as important case studies in the value of aesthetics over functionality; while functionality is certainly important to almost every engineered design, the true value this capstone team hopes to illustrate through these pieces is the necessity of an aesthetically appealing design in tandem with functionality.

Planning

The first several weeks of the capstone design portion of the class were spent carefully planning the project. After moving away from the initial 3D peg-map idea and settling on the hourglass clock per Professor Garners suggestion, team Time dove into extreme design brainstorming and began to plan the bones of the project. The clock needed to have 12, 5-minute timers which would dictate the general size of the structure since the timers were going to be 4.5 inches tall and would need some sort of assembly to house them. After discussing several iterations of ways to house the timers, lazy susan bearings were decided on as the mechanism for rotation-- these would be the largest dimension of each assembly. From there, a way to mount the timer in each assembly was sought, and a center mounted shaft with a clip around the neck of the timer and simply pinching the timer between two sheets of acrylic and potentially fastening them with glue or clamps at the top and bottom were discussed. Obscuring any of the timer with a clamp was a concern, and the team did not like the manufacturing time of a 3D printed shaft, so moved towards the pinching mechanism. This mechanism would not be finalized until a prototype was built as it was impossible to tell until then if some sort of adhesive or clamp on the top and bottom would be necessary.

To indicate the hour on the clock, a rotating arm with a mechanical extension to reach each timer was designed. It was unclear, however, how the arm would rotate the assemblies or if it would rotate them at all. There was some discussion of placing a motor on each assembly so we could avoid the mess of properly meshing gears or having to apply a large torque from the front face of the clock. After further research into this and contemplation the difficulty of running power to each of these motors, as well as coordinating their motion with the extension of the arm, the team concluded it would be easier to use one motor on the end of the arm to rotate each of the assemblies.

A large amount of time was spent studying the aesthetics of The Sands of Time, a process that would not be completed until final assembly, as well as judging the ability of users to interpret The Sands of Time. This primarily took the form of deciding how to indicate minute increments. Since a sand timer's volume is not linearly related with time, it can be difficult for a passerby to interpret what time it is to the minute. To fix this, the team discussed cutting roman numerals into the backplate which would illuminate to indicate the minute, but decided there was no good way to incorporate 4 numerals (since you don't use a zero) into the design. This would also draw attention away from the sand timers, and might defeat the purpose of having sand timers at all. Therefore, the team settled indicating discrete minutes with a specific pattern of

LEDs when each assembly is activated. In order to create a robust system of LEDs and an accurate way to turn each of the assemblies to keep time, absolute encoders were placed on each of the assemblies as well as the arm, so that at any given time the propeller chip could know where each timer is in its rotation and where the arm is on the clock.

In addition to the planning of the actual clock, some time needed to be spent deciding where in the Mechanical Engineering Building the clock could be placed. After scouting several positions for access to power, noise constraints, and general visibility and safety, the blue wall outside of the Lounge was settled on as the ideal location for The Sands of Time because it would be most visible and have fewer people bumping into it than the adjacent cinder-block walls. This wall would prove to be a challenge to mount The Sands of Time to, as it is drywall with metal studs, and there is not a convenient power outlet which would need to be added by a licensed electrician.

The basic outline of our project was now settled, and the dimensions and materials for each component needed to be decided upon. This would present the team with a host of new challenges as it attempted to reconcile aesthetics with manufacturability and cost, each of which will be presented in the design section below.

Budgeting

The budget for this project was originally set at $1200, but as the design was created it was clear this would not be enough, particularly if the clock was built to the standards which Professor Garner wanted. These stringent standards, including the use of a dozen non-contacting absolute encoders and marine grade plywood, were believed to be essential to The Sands of Time's longevity in the hallway, and more importantly if it was going to survive in the Virginia

Science Museum. Upon further consideration of Professor Garner, it was determined that the budget could be increased from the initial projections, and the upper limit was removed on the condition that The Sands of Time be built to Garner's standards. Each time a purchase needed to be made, it was simply approved by Professor Garner. Because an upper limit was not provided, and because duplicates of parts were ordered to be used on a second clock, detailed record of expenditures were not kept. However, a final bill of materials with cost for the original clock is included at the bottom of this technical paper.

Design

Artistic Design

The artistic vision of The Sands of Time was carefully planned as it is intended partially to beautify the Mechanical engineering building hallway, and it was felt that the more attractive it was the better it would showcase a UVA engineer's multifaceted talents. A number of backplate designs were brainstormed, including using the classic "Virginia V", the V-Sabres, and the Rotunda. After modelling the various art types in Solidworks, the Rotunda was settled on as the centerpiece of the design because it complemented the circular nature of the clock and the square shape of the arm resembled the columns.

Much consideration was also given to the material choices and their aesthetic qualities. We wanted The Sands of Time to have a coherent theme of antiquity as represented mainly by the sand timers, which are filled with a metallic looking copper color of sand. Therefore, earth tones were used as the primary color palette, and the hourglass assembly gears were to made out of aluminum to match the bearings (and for structural integrity). Blue-tinted, clear acrylic was to be used for the front compression plate of each assembly as it revealed the aluminum beneath but also highlighted the copper sand within the timers. In order to have the hourglasses stand out against the wooden backplate, a dark stain was chosen for the lighter wood so the brighter aluminum would pop.

For construction of the arm, both artistic and mechanical factors were considered. Aluminum was chosen to construct the primary channels of the arm due to its structural integrity, but also to keep the coloring consistent with the timer assemblies. Since it is a kinetic art piece, the faceplate of the arm was built out of clear, scratch resistant acrylic in order to expose the inner mechanisms. This transparent design was intended to inspire engineers walking past, and is particularly important to the design of the version that may go in the Virginia Science Museum. Within the arm, there were limited options artistically as most of the parts, including the linear guide rails, rack and pinion, and motors had no color options. The brass rack could have been painted to match the color of the aluminum parts around it, but it was left as natural polished brass since the paint would eventually fade and look incomplete. The last design choice inside the arm was to use neutrally colored wires for the limit switches so they did not stand out against the rest of the arm and draw the eye away from the timer assemblies and arm mechanism as the focus of The Sands of Time.

Mechanical Design

The mechanical design of The Sands of Time was no small undertaking, and was carefully coordinated in line with the capstone class goal of learning machine design. For each design choice made, extensive thought was put into multiple options before a final design was decided on. That is not to say the “final” designs were without error, and through prototyping mistakes were often found and small adjustments were made. This is of course a valuable design experience and is to be expected with any undertaking in the field of engineering.

The primary mechanical aspect that needed to be designed was the motion of the arm and how exactly it would rotate the timer assemblies, and the system was divided into three subsystems: one to rotate the timer assemblies, one to extend the arm, and one to rotate the arm.

To extend the arm, a number of different ideas were proposed, including the use of a spring loaded pulley system to retract and extend the arm, and a timing belt to turn a gear at the end of the arm that would rotate the assemblies. These both presented their own set of problems, however, including the potential for fatigue failure of the pulleys and cables over time, as well as the inexactness of a spring system. The use of a lead screw and carriage system was also considered, but the speed of this motion was deemed to slow and we felt there would not be enough space in the arm to accommodate a lead screw and carriage. After another round of brainstorming, this team decided to use a linear guide rail system powered by a rack and pinion due to its space saving capacity and relative exactness. The downsides to this system are that they can be relatively noisy, and gear teeth can wear down over time, but the team hoped to avoid these problems by using a high quality rack and pinion from McMaster-Carr. To extend the arm, the pinion would be mounted with a set screw collar to the shaft of a 15 rpm worm gear DC Brush motor that would be powered off of a 12 volt supply. The extending portion of the arm is situated on two high-end linear guide rails with minimal friction that allow for smooth extension. These rails use carriages that contain a ring of ball bearings that rotate throughout the body and create smooth motion. At the end of the extending portion of the arm is a second 15 rpm DC brush motor that has a single gear attached with a set screw collar that will be used to turn the timer assemblies.

Rotating the arm to each time was a significant design challenge. The arm was to be made out of aluminum, though the prototype was done in laser cut acrylic, which would prove to have implications in later design. The arm was mounted on a 4-inch diameter lazy susan bearing, which was chosen over a sturdier, but several-hundred-dollar more expensive face-mounted bearing of the same size for the price point. On the backside of the clock, the screws from the arm that passed through the rotating portion of the bearing would be mounted to a central gear that would be driven by another motor. This gear was cut from .25" aluminum and would be driven by a half-sized driving gear attached to a rear-mounted 7 rpm worm gear motor, generating an overall rotation speed of 3.5 rpm. Also meshed with the arm gear is another gear of the same size which is rotating an encode, so that the arm position is known at all times. This was necessary because the main arm gear would have electrical wiring coming through a hole in its center.

A number of challenges in the mechanical design presented themselves throughout the process. Once the arm prototype was built, the motor driving the primary rotation struggled to lift the arm from the 6 o'clock position as it could not generate enough torque. This challenge was overcome by using a slower, higher torque motor, by gearing down the drivetrain to create more torque, and by adding a brass counterweight to the rear of the arm. While all of these measures were not necessary to get the prototype to function, the final arm was to be made out of aluminum which is more dense than acrylic, so the counterweight was added for good measure.

Another struggle was balancing a desire to keep the profile of the arm low so that it does not present a hazard to people walking past, but also to provide enough room to fit a gear at the end that could be used to turn the timer assemblies. The general guideline decided on was to minimize wasted space, and keep the arm as slim as possible, but this caused a number of problems since there were often unaccounted for offsets needed to fit the heads of screws and wires, so the arm had to be enlarged or redesigned several time to accommodate all of the necessary components. Since the dimensions of the motor and length of its shaft were unalterable, the end gear was manufactured to be twice the thickness of the gear on the timer assemblies so that there was less precision necessary in the placement of the end gear.

Electrical Design

The electrical design of the arm would prove to be one of the most frustrating parts of the prototyping progress. The primary challenge of this portion is the powering of the motor used to rotate the end gear since it is sliding along rails. Because of this motion, wires could not be used since they would need to lengthen and shorten depending on where the arm was. For this reason, the team decided to use hardened steel linear guide rails which could be electrified. Short wires were attached to washers which were seated on the screws that attached the rails to the arm, and the other ends were attached to the motor. This way the motor and wires remained stationary with respect to the carriages carrying the arm, and would not need to lengthen and shorten. Unfortunately, the electrification of the rails would also electrify the aluminum frame of the arm, and significant changes had to be made to the body of the arm, including the milling of channels in the sides of the arm that could contain an acrylic “seat” for the rails to prevent them touching the sides, and the use of 3D printed plugs in the screw holes that would keep the screws from contacting the frame.

Another challenge was keeping the wires that were powering the extension motor and the limit switches from getting tangled with the rotation of the arm. A simple solution was the inclusion of a premade 12-input slipring, which is an assembly of 12 input and output wires connecting by rotating graphite brushes. The slipring spins with the arm and maintains contact between the wires, allowing the wires on the rear of The Sands of Time that attach to the circuit board to remain stationary as the clock operates.

Each of the timer assemblies has a 93 LED disc made of concentric rings attached to the back. These use the WS2812B protocol to communicate, and have their data in and out terminals wired in series. Each ring draws around 2.5 amps of current at full power, however, so the clock is designed with 4 sets of 3 discs wired in parallel. This way the maximum current going through any wire does not exceed its melting capacity, and that no rings can be burned out by the following ring drawing too much power. The LEDs use a 5V 18A external power supply, so when all turned on could exceed the maximum amperage. For this reason, a 15A fuse was included between the power supply and the circuit board and LEDs so there is no risk of a fire if the LEDs were to encounter and error and all come on full bright at once. When the LEDs do accidentally come on full bright in error, they tend to reset the propeller chip which reverts them back to the EEPROM code fast enough to avoid anything burning out.

Final Design

After iterating through many previous designs and considering a multitude of artistic, engineering, planning and budgetary constraints, a final design was composed in SolidWorks so that manufacturing and assembly could begin. The first element of the design to be completed was the hourglass enclosure assembly, pictured below.

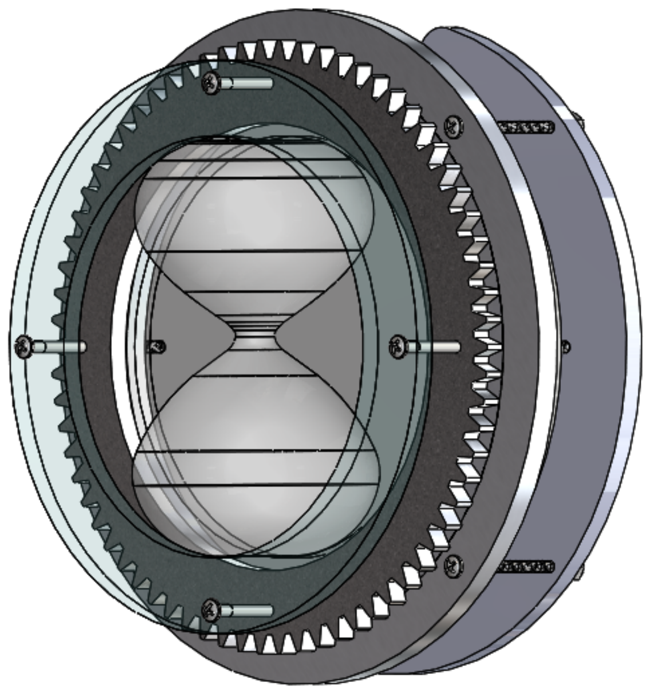

Figure 1: Hourglass Enclosure Assembly

The final iteration of this part of the design largely resembles the early prototypes that were developed. This is due in part to the large amount of time that was spent designing the hourglass enclosure prototype. The clamping ring mechanism and opaque diffusive backplate are key elements of the design, along with the large aluminum gear and bearing to allow for the LED light to pass through. Though it may appear simple in design, there are many small nuances to the design that improve its aesthetics but resulted in manufacturing and assembly challenges.

The next phase of the design that was finalized was the robotic hour hand that is used to interact with the hourglass enclosures and also acts as the clock's hour hand. A number of small changes were added to the final arm from the prototype, including the addition of a brass counterweight, internal limit switches, and the final, smaller linear guide rails. The final arm design, as shown below, will have a brass pointer added to make the arm look more like an hour hand.

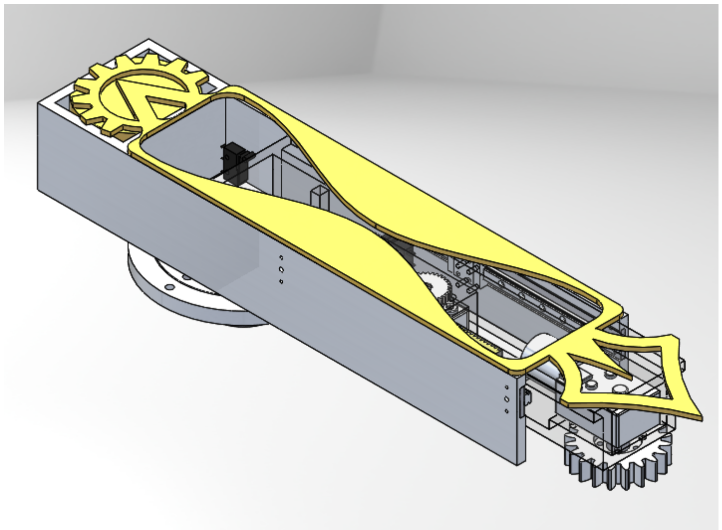

Figure 2: Hour Hand and Robotic Arm Assembly

After completing the design of the smaller, more detailed subassemblies, attention was turned to the overall structure of the clock. The main design considerations that were implemented were the aesthetics elements discussed above, as well as a low profile mounting structure to reduce the distance that the clock would extend from the wall. The final SolidWorks design is shown below, incorporating the previous subassemblies into a the final deliverable.

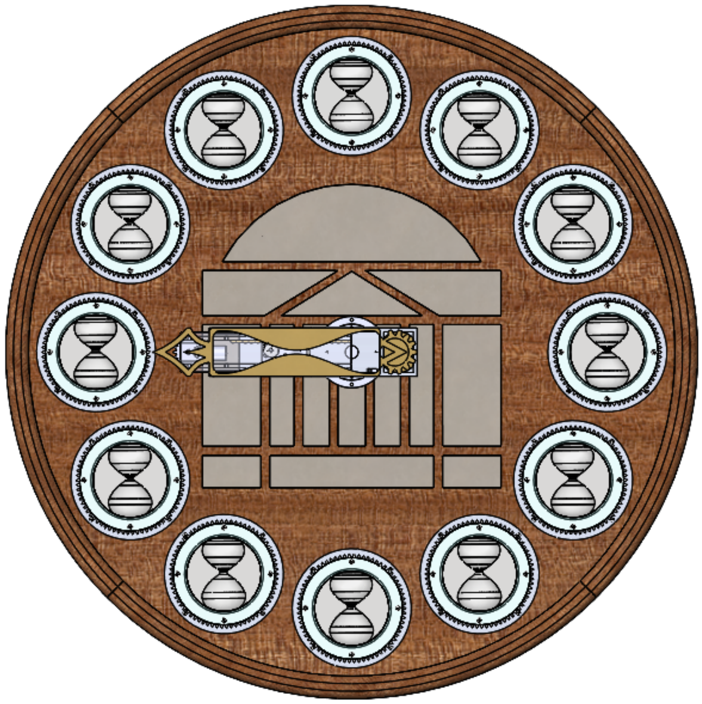

Figure 3: Final, Complete Clock Assembly, Incorporating Hourglass Assemblies and Robotic Arm

Prototyping

The first element of The Sands of Time design that we prototyped was the hourglass subassembly that represents individual clock numerals. For this prototype, we used materials and manufacturing techniques that minimized construction time, without too much consideration for long term mechanical strength or material aesthetics. There were a couple main areas that we wanted to test with the first prototype: overall mechanical design and LED pattern and functionality.

Hourglass Subassembly - Prototyping

Within the mechanical design the main things that we wanted to test were the hourglass clamping mechanism and overall ease of assembly. The main concerns going into testing were that the hourglass would not fall out of the clamping rings when tightened and that the gear would be able to be meshed with consistently. After testing, it was determined that the proposed clamping mechanism was usable; however, some problems arose with the potential gear meshing, specifically the inconsistency in gear placement and the clampings rings and gear teeth overlapping. To resolve the first issue, we decided to move the gear from flush to the front clamping ring to flush to the back clamping ring. This allowed us to have more control over the position of gear as it no longer depended on the diameter of the hourglass, a more variable dimension than the thicknesses of the bearings and clamping rings. The pitch diameter of the gear was also increased to ensure that the root diameter of the gear would be larger than the outer diameter of the clamping rings. This prevents the teeth of the meshing gear from contacting the clamping ring even if the height of the two gears meshing is slightly varied. In addition to these mechanical flaws, a number of electrical and software issues were tested with this prototype.

In terms of LEDs and coding, the main goals for this prototype were to see if the LED driver, provided by Professor Garner, could be properly implemented to produce LED output and to try to receive rotational position data from the encoder. The encoder programming proved to be fairly simple, as the encoders used in The Sands of Time are the same as ones used previously by the group in Professor Garner's Mechatronics course. The only issue encountered with the encoders was that between different encoders there is no common mechanical zero point, eg. the physical rotation of the D-shaped shaft relative to the zero position is different across encoders. In order to fix this, two courses of solutions were considered, one path software-based and the other mechanical. After considering the benefits of both avenues, it was determined that a software solution would prove too complex and prone to errors. The full extent of the mechanical solution is described in the Engineering Solutions section above.

The LEDs tested in this prototype proved to have proved mostly successful, with one major design flaw that was uncovered. Running the LED panels at full power while enclosed in the hourglass assembly caused the the panels to overheat and stop working. Our team discussed and tested two alternatives in design that led to much more successful operation of the LEDs over long periods of time. The first and most obvious solution to the overheating problem was to reduce the intensity of the LEDs while in operation. This increased their time of use indefinitely, and no problems have been observed since. Another solution was also implemented: the use more of conductive backplates, made of aluminum, in order to sink more heat away from the LEDs. This first prototype of the hourglass assembly showed the team a lot about the designs and the improvements that could be made, but it was not the only prototype constructed.

Robotic Arm - Prototyping

The clock arm for The Sands of Time went through many design iteration and was subject to multiple prototypes. The goals of the arm prototypes were multifold, to gauge sizing for aesthetic purposes and to test functionality through dynamic integration with the hourglass assembly prototype. The first attempt to prototype the arm ended up being entirely for aesthetic purposes. Although it was intended to be functional, the motor requirements changed soon after the first arm was cut on the laser cutter. We did learn that the physical scaling of the arm was appropriate relative to the final size of The Sands of Time. The second prototype was designed and built to be a more functional robotic arm. This iteration fully integrated motors, linear bearings, and gear systems to create the linear extension and hourglass rotation that will be used in the final design. There were multiple facets of the prototype that we considered to be successful, namely its functionality and form factor, but there were also some issues that led to learning opportunities. The rack and pinion extension system proved to work, but was held back as the gears were cut on the laser cutter and the kerf of the laser was not taken into account, causing an imperfect meshing between the gears. There was also a need for increased clearance between components to provide smoother motion. Lastly, for this prototype the limit switches were simply glued on top of the arm's outside channel. For the final design the necessary extension distance was calculated, and the limit switches were spaced accordingly. Overall, this proved to be a successful prototype, giving us a better idea of what to improve moving forward.

Circuitry Layout and Software

With regards to the circuitry design, there are a few primary circuit components to consider. The coding involved in running the clock is divided into five main sections based on the physical components with which it interacts. The overall circuit was designed to interface with the Propellor chip shown in the center of Figures 5 and 6. Each circuit component on the board represents an output or input being transferred to or from a physical component on the clock, controlled by pins on the propellor which are distinctly made output or inputs. By reading incoming signals on the input pins, the propellor is able to manipulate and monitor data about the positions and statuses of different clock components. The propellor can also send information on the output pins to change the states of the electronic components on the clock. The language used to interpret these input and output signals is called SPIN, a microprocessor language developed by Parallax and unique to the Propellor chip.

Starting at the top left, pins P0-P3 are used to interface with a Dallas Semiconductor DS3234 real time clock chip. Once the time has been set, the chip is able to maintain the time with extreme accuracy through use of a temperature-compensated crystal oscillator. The time data is then transferred into the Propellor's pin P2 using the Serial Peripheral Interface (SPI), a form of communication that transfers discrete bits of data one by one into the Propellor.

```
PUB GetTime  | i       ''Refresh time[0] through time[6] values
  outa[CCS]~
  repeat 8         'Set starting address to be $00=seconds
    outa[CCLK]~~
    outa[CSO]:=0
    outa[CCLK]~
  repeat i from 0 to 6
    repeat 8
      outa[CCLK]~~
      time[i]:=time[i]<<1+ina[CSI]
      outa[CCLK]~
  outa[CCS]~~
```

Figure 4: Circuit Diagram for full control of motors, LEDs, encoders, and clock chip

SPI is demonstrated in Figure 6. When the method is first run, the chip select pin is set low to turn on the clock chip. Next, eight zeros are shifted in to the clock by triggering the clock pin high then low eight times and setting the output pin so that the first data bit read will be in the seconds place. The relevant clock data is contained within six sets of eight-bit data. To interpret this correctly, the bits are shifted in one at a time with a clock pin high (outa[CCLK]~~), reading the current bit (ina[CSI]), then sending the clock pin low (outa[CCLK]~). This process repeats eight times to the first array of time data, then repeats eight more times on the next array of time data until all six relevant lines of clock data have been read. The clock chip is then shut off until the GetTime method is run again to read the time data from the clock chip. By performing this operation many times a second, the Propellor chip can constantly and reliably track the current time.

The next three pins are used to read the encoder data, which describe the rotational positions of all 12 hourglasses as well as the rotational position of the mechanical arm. Similar to the clock, this data is transferred into the propellor via SPI; however, one key difference is in order to simplify the incoming data stream and to reduce the required number of pins, the encoders were wired in a daisy-chain configuration, This means that all 13 encoders share a common clock and chip select pin that controls the movement of data all at once. Each bit of data is then transferred from one encoder to the next until the data reaches the propellor chip. Since each encoder outputs 16 bits of position and status data, the encoder output read on pin P6 must be read in 16 bit divisions to read the correct position information from the desired encoder. This can be thought of as similar to the aforementioned six arrays of time data, where in this case, there are just 13 arrays of encoder positions. One difficulty that the encoders impose on the coding is the jump from 0 to 1023. The encoders 10 bits of position data means that there are 1024 discrete positions in one full revolution of an encoder. For ease of assembly and the option of replacing the encoders in the future, this team decided to insert the encoders so that the 0 position is directly upwards. This, however, leads to difficulty in determining the position and making logical decisions when the arm is around the 12 o'clock position. Using the limitations on encoder resolution, the code was written such that the arm takes the shortest path to the hourglass that needs to be turned. The arm then stops once it has surpassed the position denoting a certain hour. Detecting whether the arm has passed a position, however, becomes much trickier if the arm is passing over the 12 o'clock position. For example, take the case of 1:55, where the clock arm is moving from 1 o'clock's position of 938 across zero to 11 o'clock's position of 85. Such a counterclockwise rotation means that the encoder's position is increasing, but the code cannot check if the hour hand's position is greater than 85, since its starting position of 937 is initially and immediately greater than 85. This discontinuity also creates difficulty when starting from. The resolution of the gears relative to the encoder's positioning means that there is about 10 positions of uncertainty in the hour hand's position. This means that when the arm is currently located at 12, it's not clear whether the arm encoder will be reading it's position as 0 or as 1023, two positions that are right next to each other but yet 1023 positions apart. This circular nature of the encoders' positioning meant that the code had to be structured with several special cases for what movements the clock should take when the arm had to interact with the cross over from 0 to 1023. This problem was not as prevalent in the rotation of the hourglass encoders, since those fixtures can rotate in either direction, with little specificity in the exact orientation of the hourglass besides the two vertical positions

Pin P15 sends out the serial data that instructs a liquid crystal display (LCD) allowing users to easily set the time without needing to understand the software interface. This code makes use of a built-in parallax driver to simplify the serial bit transfer operations. Pins P17 through P21 receive the input from a five-direction joystick. This joystick's input is read by the propellor chip to allow the user to input the time shown on the LCD to reset the time of the clock chip, and thus the clock. The code for the joystick uses conditional logic to read the high or low state of each pin. Depending on what the current value selected on the LCD is, different inputs on the joystick change the desired value for setting the clock.

Pin P16 shifts out data serially into each of the 12 LED discs. The discs were also wired in a daisy-chain fashion so that the data instructing each LED to light up is passed out of the Propellor chip and through each individual LED. The code for controlling the LED's was simplified by using a WS2812B RGB LED driver developed by Gavin Garner. The code developed by this capstone team focuses on repeatedly incrementing brightnesses, colors, and LED locations to create different effects across the 12 discs. Since the LED's are daisy-chained in series, the Propellor chip effectively outputs the data as if the 12 LEDs were one long ring of 1116 LEDs rather than 12 rings of 92. This requires special consideration in the code, since turning on LED disc 7 requires that those instructions first pass through the LEDs of discs 0 through 6.

Pins P23 through P27 all control the direction and speed of the motors. Each motor has two pins that go into a DRV8801 DC Motor Driver, which allows both the direction and speed of the motor to be easily controlled via code. The upper pin, of each driver shown in Figures 6 and 7, Pins P23, P25, P27. controls the direction of an H-bridge circuit in the motor driver, determining the direction of current flow through the motor, and thus, what direction the motor rotates. The lower pin determines the speed of the motor by sending the pin a pulse width modulation (PWM) signal. This is a technique that uses code to rapidly switch the pin state, which can only be fully on or fully off, to simulate the pin being a partially on. For example, a 50% duty cycle PWM signal, or a signal that switches on and off at equal intervals, would simulate the motor being powered at 50% and thus, run the motor at half speed.

The Propellor chip is powered off of 5 volts. This voltage is then stepped down by a regulator to 3.3 volts, which is used to power every other logic chip on the board. The three motor drivers, shown on the right of Figures 4 and 5, receive a 12 volt input that powers the motors themselves. All chips on the board share a common ground that the voltages used are all the same relative to each other.

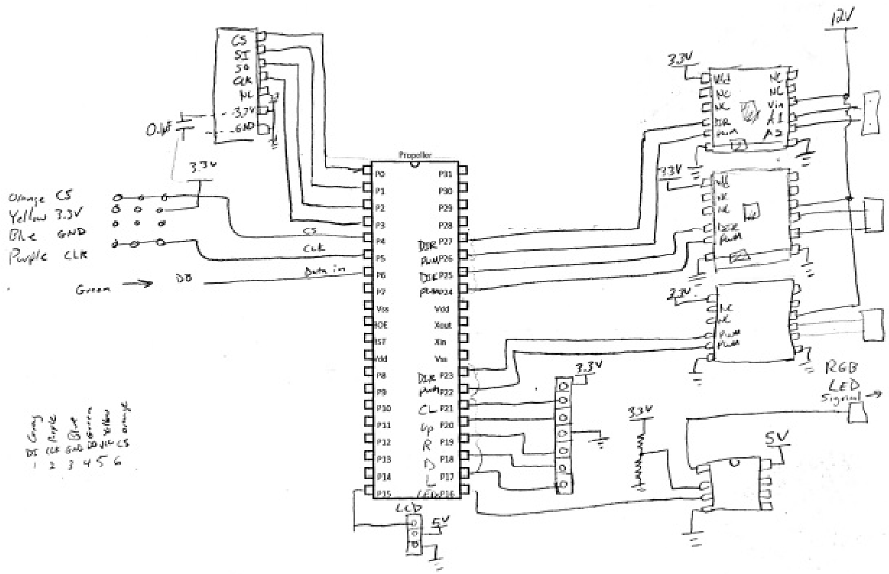

Figure 5: Circuit Diagram for full control of motors, LEDs, encoders, and clock chip

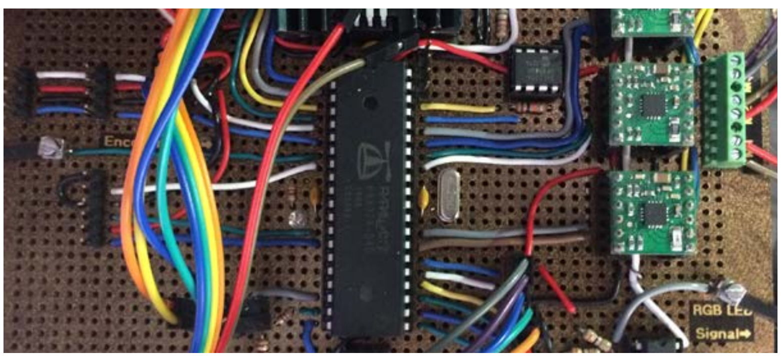

Figure 6: Perfboard used to solder full microcontroller circuit

Manufacturing

One of the largest undertakings of the entire project was its extensive manufacturing process. The challenges partially stemmed from having to build and assemble twelve hourglass assemblies, each of which contained roughly 40 to 50 components, including screws and nuts. Another major manufacturing challenge was the fabrication of the wooden clock backplate. Although we only had to build one backplate, the design was very complex, requiring every screw hole to connect all twelve hourglasses and the robotic arm. In total the backplate took about 10 - 15 hours to manufacture, taking into account CNc cutting the two clock halves and all the support pieces. The manufacturing process for individual components of The Sands of Time is broken down into two subsections: traditional and advanced manufacturing, the latter utilizing CNC driven machines to accurately produce parts.

Within the category of advanced manufacturing, our team used a variety of different machines that operate through a similar process: taking in computer determined coordinates and moving a cutting tool along a path to produce a finished part. The construction of The Sands of Time used multiple advanced manufacturing techniques, including: a laser cutter, water jet, CNC router, and 3D printer, each of which have their own set up, procedure, and beneficial qualities that made them appropriate to use in certain scenarios. The following section will walk through the use and benefits of each advanced manufacturing technique used to make The Sands of Time.

PLS6.75 Laser Cutter

For this project the PLS6.75 laser cutter from Universal Laser Systems was used for all cutting of cast acrylic parts. This accounted for multiple components within the final product, including the clamping rings, LED diffusers, and encoder mounts, as well as a large majority of the parts within the hourglass assemblies and arm prototypes. Acrylic was chosen for its ease of manufacturing with the laser cutter and its relatively low cost. Of the CNC advanced manufacturing processes used to make The Sands of Time, laser cutting was by far the simplest and most time efficient to use. After designing a part in Solidworks, two dimensional DXF files were exported. After relocating to the computer connected to the laser cutter, the DXF files were then imported into the graphic design program CorelDraw to prepare the cutting lines for the laser cutter. From CorelDraw the file was printed to the PLS software to initiate the cut. Settings based on material type and thickness were determined and then the cutting procedure could begin. A full operating procedure can be found in the laser cutter instruction manual located in the MILL, authored by Professor Garner and some of his previous students.

For this project, the laser cutter was the most useful CNC manufacturing system, due to its quick turnaround time from design to manufacture and integration into The Sands of Time. It also allowed for quick and easy prototyping which allowed better design visualization and testing early on in the semester.

OMAX Maxiem 1515 Waterjet Cutter

The capabilities of the water jet are very similar to those of the laser cutter, in the sense that they both cut 2D profiles out of stock materials of varying thickness, again using DXF files. The main difference occurs in the types of material that can be cut; we used the water jet solely to cut aluminum. The water jet we used is located at Lacy Hall which hosts the machine shop for the School of Engineering and Applied Science. In order to cut the aluminum with the water jet, we consulted Sebring Smith at Lacy Hall for his expertise and guidance.

In preparing the DXF files to be cut, multiple of them had to be combined into one larger DXF file so that they could be appropriately spaced out onto the sheet of aluminum that was to be cut. This was accomplished using OMAX IntelliMAX Layout, a software package unique to the brand of water jet cutter located at Lacy Hall. An example of the largest cut is shown below, and was cut out of a ¼” 4’x4’ sheet of 6061 Aluminum.

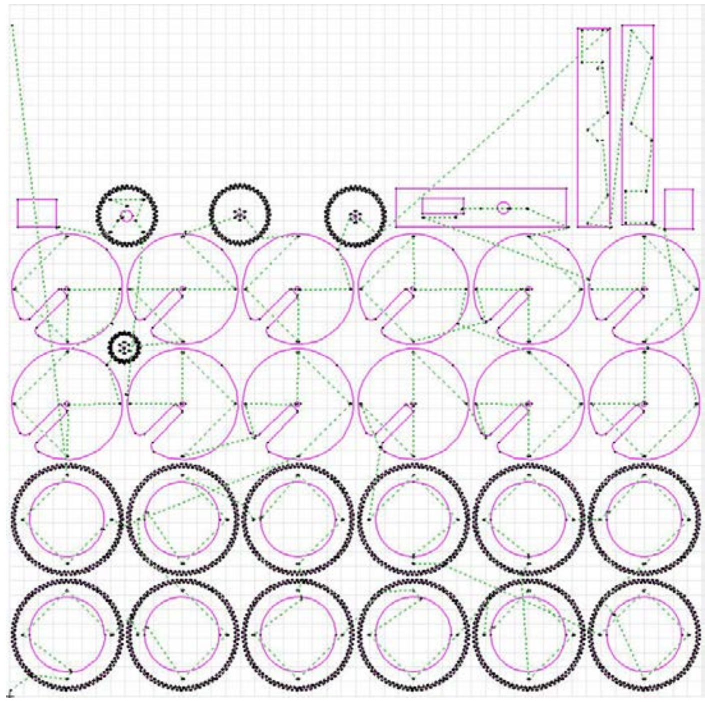

Figure 7: Water Jet Layout for 4’x4’ sheet of aluminum

Two other cutting operations also had to be made, one out of mirrored ⅛” aluminum and one out a smaller ½” aluminum bar.

Once the DXF files were finalized, including lines traversing between each closed contour, the files could be exported to the IntelliMAX Make software. During the export process, the kerf of the water jet was taken into account by deciding which side of each line the stream of water and garnet, was to cut. In the Make package, the machine origin was lined up with the workpiece coordinate system. The Make software was also used to drive the water jet during cutting. A major impact on the water jet manufacturing process was the need to refill the garnet abrasive dust supply to ensure successful cuts.

Over the three pieces of aluminum required to be cut, the entire water jetting process took about five hours of just machining, not accounting for the many hours needed to appropriately layout the toolpaths and determine the kerf placement. Overall it was deemed necessary to put in this much time because the capabilities of the water jet cannot be matched by other machines in terms of the complex shapes that it can cut out. The use of the water jet in this application proved to be one of the defining features of The Sands of Time, due to the aesthetic components that were able to be manufactured. Manufacturing gears with the water jet also saved a lot of money, because milled gears are quite expensive, especially for the size requirements that The Sands of Time had.

ShopBot PRSalpha CNC Router

In comparison to the laser cutter and water jet, the ShopBot PRSalpha CNC Router has a greater degree of freedom in its abilities to machine materials. Whereas the laser cutter and water jet are limited to cutting 2D profiles out of material sheets, the CNC Router can cut into the material across a range of z-axis values while still operating in the x-y plane. This is achieved through mounting a cutting bit that rotates at high velocity onto an electrically motorized three-dimensional movement carriage. Thus the CNC Router is capable of drilling screw holes directly into the material as well as physically machining away material it drills into. For the manufacturing purposes of the team's project, the CNC Router was primarily utilized to cut out the clock's backplate, support beams, and spacers from three four foot by three foot sheets of marine grade plywood. The ShopBot PRSalpha CNC Router used is located in the MILL in the basement of the Mechanical Engineering Building. Marine grade plywood was required for use in the CNC Router, as it has the correct material strength to ensure that CNC machining done on it does not splinter the wood's surface finish. It also provided a nice surface finish when stained. After designing a part in SolidWorks to be cut out from wood, toolpaths were created in SolidWorks using the AutoCad plugin, HSMWorks. The resulting toolpaths are shown below.

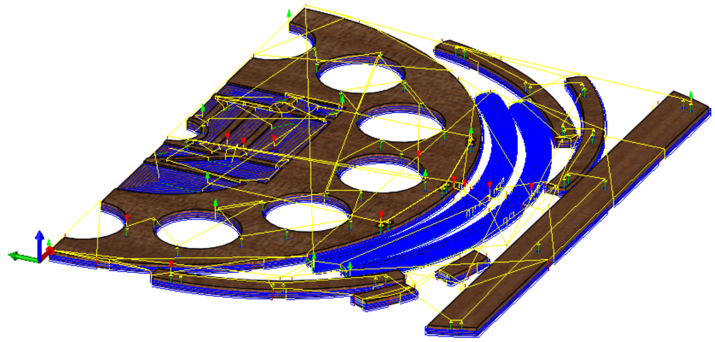

Figure 8: CNC Router Toolpaths for Wooden Components

After generating the toolpaths, the resulting G-Code was loaded onto the ShopBot's computer and G-Code interpreter, which gives the machine instructions on where to cut. After mounting the workpiece and setting the coordinate system, all that is left to do is to change cutting bits and run the appropriate G-Code for each bit, stopping to change the bit whenever required. At this time there is not an automatic tool changer for the Shopbot, but hopefully one will be designed and implemented soon. Although the ShopBot CNC was instrumental to the success of the manufacturing of The Sands of Time, the main downside to its use is the large amount of time that is required for both developing toolpaths and actually running the machine to cut out the workpiece. That said, the features the ShopBot introduced would not have been easier or even possible to achieve using another machine, so the long time commitment was deemed necessary for this project.

Dimension uPrint 3D Printer

The Dimension uPrint 3D Printer is the most different from the other three forms of CNC advanced manufacturing. Instead of cutting in just two dimensions, the 3D printer extrudes plastic in two dimensional layers repeatedly to produce three dimensional parts. Although the printer was only used for a few parts within The Sands of Time, its ability to make essentially any three dimensional shape is useful. To use the 3D printer, an STL file needed to be exported from each SolidWorks model to be printed. Once exported, the STL was brought into CatalystEX 4.5, a software package that allows one to choose the layer height, infill, and print orientation of the specific 3D prints. For the purposes of The Sands of Time, all final assembly pieces were printed as solids to improve strength at the cost of extended printing time.

Assembly

After all parts where manufactured, the assembly of The Sands of Times could start. During assembly several issues were discovered, but these could be solved along the way. By the start of assembling the aluminum parts, it was discovered, that when the parts were waterjetted, the parts had several incorrect dimensions. This is likely due to incorrect calibration for the kerf of the water jet machine when laying out the DXF files in the software. To solve this, a number of holes required redrilling and all of the polished aluminum rotunda pieces needed to be sanded down in order to fit the debosses left by the ShopBot CNC machine.

When the arm was designed, the linear guide rails was gonna be used as an electric connection, for the motor that turns the hourglasses. But after assembling the arm, it was discovered that the whole arm would be electrified by this since there wasn’t any insulator between the steel guide rails and the aluminum the arm is manufactured from.

To assemble the acrylic and aluminum parts for the arm, it was needed to drill and tap many of the holes after water jetting and laser cutting. This is due to the both machines producing two dimensional pieces that needed to be fastened together, so out of plane holes needed to be drilled and tapped to connect the individual pieces. Although this was expected during the design phase, it proved to be more time consuming than expected.

The backplate was made in two parts in the CNC, these would have to be connected at the flat edges of the plates. Dowels and glue would be used for this. To make sure the drilled holes for the dowels was placed at the same place, a 3D printed part was designed. This would place the holes at the same distance from the big surface every time. The Rotunda logo in the middle was waterjetted from polished aluminum. But since the dimension was wrong, it was needed to either make the rooms for the pieces in the wood bigger or sand down the aluminum pieces. It was chosen to make the aluminum pieces smaller by using the sanding machine. This was chosen since the result of either methods would look the same and the sanding of the aluminum pieces could be done on the sanding machine and not by hand.

The hourglass assemblies are assembled by bolting the two hourglass clamps/rings and the gear to the front of the inside ring in the bearing. Behind the bearing a diffuser plate was mounted to inside ring of the bearing. The outer ring is fixed to the wooden plate by T-nuts on the backside. These bolts are sticking out on the back so it is possible to mount a heat sink plate on which the LEDs and the encoder is mounted. The encoder is connected to the diffuser plate by mounts that is glued to the diffuser plate. For glueing the encoder mounts a jig was laser cutted, to make sure that the mount be in the center of the diffuser plate.

The spacers and the supporting beams a screwed in from the back, into a T-nut which is on the front face of the plate. The outside ring which covers the T-nuts that holds the spacers and supporting beams on the back is stained a little darker and is then glued to the front face of the clock. The T-nut under the outside ring enable the back to come of the back without the ring has to come of.

Challenges

During assembly of The Sands of Times, challenges occurred. The bearings for the hourglasses had a low quality and was leaking the grease onto the wood. This stains from the grease got hidden when the wooden plate was stained dark. This was solved by removing the original grease in the bearings and the use teflon grease in the bearings instead. The low quality of the bearings could also been seen as there was play in the bearings.

The bolts that was used to mount the bearings to the wood, was smaller than the holes in the bearings. This means that it was difficult centering the bearings and if the bearing would not be centered, the encoder shaft would not fit in the encoder mount. It was therefore time consuming to place all the bearings to make everything fit together, so the encoders would fit in all 12 hourglass assemblies.

To make the diffuser plates have the same distance from the hourglass in all assemblies, a lock nut was screwed to all the bolts with the same distance from the bearing. This took a long time, since the space, where they were to be mounted, was very limited. A solution to this would be to use aluminum spacers between the diffuser plate and the bearing.

In the design on Solidworks, it was preferred to electrify the guide rails to power the motor which turns the hourglasses. During the assembly it was discovered this was not possible since this would electrify the whole aluminum arm. A solution was not made during this assembly, because the group did not have time to figure out, how to insulate the guide rails from the arm.

There were also a number of mistakes that led to parts being hard to replace. Namely, the LED discs cannot be removed without taking of the entire heat sink and encoder mount, which can lead to difficulty during reattachment and the potential loss of the encoder’s mechanical zero. In order to replace a bearing, the whole hourglass assembly including the two acrylic mounts and the aluminum gear need to be take off, since the gear obscures the heads of the screws in the stationary part of the bearing. The gear had to be this size, however, to allow for the smooth meshing of the gears without the potential for the arm running into the acrylic.

With all of these mistakes in mind, the design and manufacture of the second version of this clock will be significantly more streamlined and informed. As with all engineering, the more prototypes that are done the easier the final design will be, and The Sands of Time will work as a fantastic prototype for future constructions of these timekeepers.

Successes

To contrast the many difficulties and setbacks endured over the course of this project, there have also been a number of elements of The Sands of Time that have been deemed successes. Primarily, the clock works, which is a stark contrast to the other projects from this section of machine design. While it does have some operational flaws, and while there was no time to electrify the guide rails, neatly wire the back, and properly enclose the arm, the heart of the design goal--to design a kinetic art clock--was completed. The Sands of Time was also nearly finished on time, is structurally sound, included all of the features initially laid out in the brainstorming phase, and is eye-catching and accurate.

The Sands of Time is also exceedingly beautiful, and though some mechanical touch ups are needed, it could sit in any building at UVA and stun passerbys. This was the greatest accomplishment of the semester, weaving mechanical design with elegance into a sleek final package, and this team was very proud of that. This success can be attributed to a number of factors, including chance and the luck of getting a nice wood grain or having the appropriate stain, but mostly it was due to brainstorming. An exorbitant amount of time was spent at the beginning of the semester planning the artistic qualities of this piece, and those values were not lost on any of the group members throughout the process. It was this continual focus on aesthetics that made The Sands of Time into the beautiful timekeeper it is.

Conclusion

The design of The Sands of Time was no easy task, but it was a successful endeavor. While there were plenty of setbacks, each of which was eventually overcome, that is to be expected from any engineering undertaking this large. The team learned the value of brainstorming, the benefit of prototyping, and gained a general spacial awareness for mechanical systems and modelling. While the project did fall into several traps, including feature creep and prototyping too late, they were overcome and did not hinder the project significantly. They taught very important lessons in design, however, and the team benefitted from suffering through them.

The Sands of Time is nearly complete, and with a few hours of time will be ready to hang on the wall of the Mechanical Engineering Building for years to come. This is a great success for a capstone design team, and it was a fantastic feeling to have a team which wanted to work on the project, that didn't feel obligated to descend into the basement to work but rather wanted to. The team came a long way from our initial ideas and understanding of the project, and that is evident in the beauty and genius of The Sands of Time.

References

Faste, R. A. (1995). The role of aesthetics in engineering. *Journal of the Society of Mechanical Engineers*, *98*(916), 204–206. https://doi.org/10.1299/jsmemag.98.916_204

Lizzio, A., Wilson, K., & Simons, R. (2002). University students' perceptions of the learning environment and academic outcomes: Implications for theory and practice. *Studies in Higher Education*, *27*(1), 27–52. https://doi.org/10.1080/03075070120099359

Appendices

Total Budget

Item	Price	Needed	In Stock	Extras Ordered	Total Cost
Marine Grade Plywood (4' x 3' x 3/4")	$125.71	2	0	0	$251.42
Lazy Susan Bearing (8")	$17.99	12	0	1	$233.87
Lazy Susan Bearing (4.5")	$9.95	1	0	1	$19.90
5-Minute Sand Timers	$9.99	12	0	4	$159.84
Slip Ring	$24.43	1	0	0	$24.43
Linear Guide Rail (180 mm)	$73.80	2	0	0	$147.60
Linear Guide Rail Carriage	$102.30	2	0	0	$204.60
Bourns EMS22A30 Absolute Encoders	$35.15	13	13	0	$0.00
Fluorescent Blue Acrylic (1/4")	$20.92	8	0	0	$167.36
White Acrylic (1/8")	$14.27	4	0	0	$57.08
Tee Nut Inserts (100)	$9.50	1	0	0	$9.50
Bolts (2")	$10.41	1	0	0	$10.41
Bolts (3")	$11.01	1	0	0	$11.01
Size 6 Nylon Insert Nuts	$7.10	1	0	3	$28.40
Brass Metal Gear Rack	$33.73	1	0	0	$33.73
Round Bore Metal Gear with Set Screw	$22.20	1	0	0	$22.20
Polished Aluminum (.125" x 2' x 2')	$129.92	1	0	0	$129.92
1/4-20 3.5" Screws (50)	$13.58	1	0	0	$13.58
1/4-20 T-Nuts (100)	$10.20	1	0	0	$10.20
DC Brush Motor (7 RPM)	$34.99	1	0	0	$34.99
DC Brush Motor (15 RPM)	$34.99	2	2	0	$0.00
18-8 Stainless Steel Pan Head Screw (1/2", 100)	$4.45	1	0	0	$4.45
6061 Aluminum (1/2" x 2-1/2" x 6")	$8.28	1	0	0	$8.28
8mm Shaft Mounting Hub	$7.95	1	0	0	$7.95
LED Ring	$24.99	12	3	5	$349.86
6061 Aluminum (1/2" x 4' x 4')	$400.00	1	1	0	$0.00
Total					$1,940.58

Parts Lists

Hourglass Enclosure Subassembly

Part Name	Number in Assembly	Manufacturing Method, Distributor
Acrylic Clamping Ring	2	Laser Cutter, McMaster-Carr
Lazy Susan Bearing	1	VXB.com
5 Minute Hourglass	1	Amazon
Acrylic LED Diffuser	1	Laser Cutter, McMaster-Carr
Aluminum LED Heat Sink	1	Water Jet, Lacy Hall Stock
LED Ring	1	Amazon
Absolute Encoder	1	Mechatronics Lab Stock, Bourns
Aluminum Gear	1	Water Jet, Lacy Hall Stock
Acrylic Encoder Hub	2	Laser Cutter, McMaster-Carr
6-32 3” Screws	4	McMaster-Carr
6-32 2” Screws	4	McMaster-Carr
6-32 Nylon Insert Nuts	12	McMaster-Carr
6-32 Machine Nuts	12	McMaster-Carr

Hour Hand, Robotic Arm Subassembly

Part Name	**Number in Assembly**	**Manufacturing Method, Distributor**
Acrylic Inner Channel	1	Laser Cutter, McMaster-Carr
DC Brush Motor	2	Mechatronics Lab Stock
Aluminum Outer Channel	1	Water Jet, Lacy Hall Stock
Acrylic Motor Shield	1	Laser Cutter, McMaster-Carr
Aluminum HG Rotation Gear	1	Water Jet, McMaster-Carr
Lazy Susan Bearing	2	Amazon
12 Wire Slip Ring	1	Amazon
Linear Guide Rail	2	McMaster-Carr
Linear Guide Carriage	2	McMaster-Carr
Brass Gear Rack	1	McMaster-Carr
Stainless Steel Pinion Gear	1	McMaster-Carr
SPDT Limit Switch	2	Mechatronics Lab Stock
Gear Mounting Hub	1	Mechatronics Lab Stock, Pololu
Brass Counterweight	1	Milling, Machine Shop Stock
6-32 ⅜” Screws	20	Mechatronics Lab Stock
M3 Screws	8	Mechatronics Lab Stock
2-56 ½” Screws	8	Mechatronics Lab Stock

Overall Clock Assembly

Part Name	Number in Assembly	Manufacturing Method, Distributor
Wood Clock Backplate	1	ShopBot CNC Router, McMaster-Carr
Wood Spacer Rings	6	ShopBot CNC Router, McMaster-Carr
Wood Face Rings	4	ShopBot CNC Router, McMaster-Carr
Wood Back Support Beam	3	ShopBot CNC Router, McMaster-Carr
Hourglass Enclosures	12	See Above
Robotic Arm Assembly	1	See Above
Absolute Encoder	1	Mechatronics Lab Stock, Bourns
Aluminum Motor Gear	1	Water Jet, Lacy Hall Stock
Aluminum Encoder Gear	1	Water Jet, Lacy Hall Stock
Aluminum Bearing Gear	1	Water Jet, Lacy Hall Stock
DC Brush Motor, 15 RPM	1	Amazon
Motor Mounting Hub	1	Mechatronics Lab Stock
6-32 Screws, Varied Lengths	12	Mechatronics Lab Stock
6-32 Tee Nuts	60	McMaster-Carr
¼ - 20 Screws	12	McMaster-Carr
¼ -20 Tee Nuts	12	McMaster-Carr

* Full parts list still in progress

Full Code