The Abaclock

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Abstract

Despite the numerous hours involved studying mechanical engineering, there are very few opportunities for University of Virginia undergraduates to demonstrate their knowledge and skills. Lab and course work provide adequate experience when it comes to the theoretical practice of mechanical engineering through simulations and closed experiments. However, such methods of learning often disregard real life variables such as feasibility, reliability, and practicality. Shifting from theoretical studies to real-life problem solving, the senior design project requires students to learn from inevitable, temporary failure. This technical project will rely on skills learned in the UVA mechanical engineering curriculum while also providing an opportunity for us to grow those skills through our own design iterations.

Introduction

Project Summary

The object of this project is to create a mechanical wall clock in the form of an abacus. This clock will integrate mechanical and electronic systems that both demonstrate the practical skills of undergraduate mechanical engineers at the University of Virginia while paying homage to the origins of numerical methods. An abacus is a computing tool used for the four arithmetic operations (addition, subtraction, multiplication, and division). The abacus does not require pen or paper, works for any base number system, and such technology has over 2000 years of documented use. Just as an abacus performs under any base counting system, this clock will perform through the combination of mechanical, computer, and electrical engineering systems in order to physically display the time of day in the form of numbers on an abacus.

Project Goals

As stated in the abstract, a major part of the senior design project is learning and growing from failure. Throughout the scope of the project, unforeseen issues occurred with each prototype that had to be addressed following prototypes. While various prototypes existed during this project, we still shared an overall goal before constructing a single facet of the project. Goals of the Abaclock not specific to each iteration of the clock will be discussed here.

Before delving into design and function considerations of the clock it is important to define the actual motivation behind the clock itself. During brainstorming sessions prior to forming design team groups, professor Garner highlighted that clocks always serve a purpose. Stick a clock anywhere, and its ability of communicating the time will benefit those who interact with it. Given the considerable amount of clocks already attempted in years prior by former UVA students, our team wanted to build a creative clock that expressed time like nothing before. This expression was ultimately chosen to be the expression of an abacus. Having an automated abacus clock with moving beads, untouched by any visible motors excited us. A fun part of engineering and creative projects is having viewers have to critically think about how the product is actually operating. Knowing that this clock would provide that experience to its viewers and users, our Abaclock team was confident in the project idea and was ready to start the creation process.

Functionality

Having decided to create a clock that tells time in the form of an abacus, our team then defined how exactly an abacus could tell time. For each digit of the time in digital format (HH:MM), there would be one column of an abacus to represent that digit. For example, if the time was 01:07, the clock would look like this:

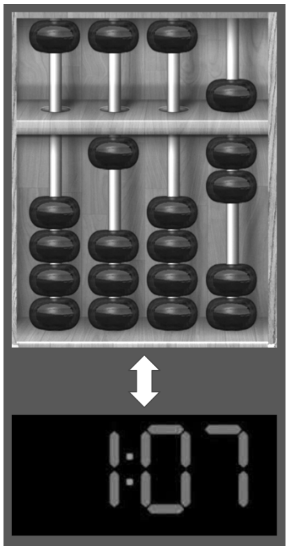

Figure 1: Conversion of four column abacus to four digit clock

The first column represents a zero (leading zero) followed by: one, zero, and seven. When the time changes to 01:08, the clock will automatically move the next bead in order to display an eight instead of a seven. Given this format of displaying the time, the clock will consist of beads that travel vertically along linear guide rails. In order to make the clock visually appealing, our team agreed the final design would look nice if the entire clock resembled the Rotunda. Figure 2 shows a rough sketch of the layout.

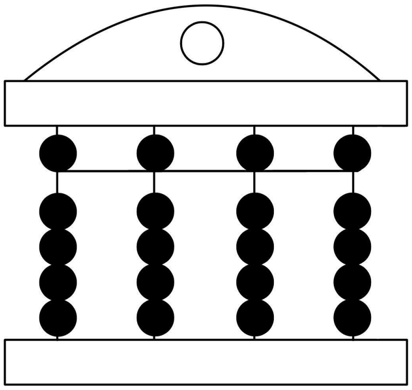

Figure 2: First sketch of the Abaclock with Rotunda top and bottom base design

Design Chapters

Design Brainstorming

Before diving into Prototype 1, our team took time to discuss potential methods of getting the beads to move vertically up and down the guide rails without any visible motors. By having the digits displayed vertically, the beads will be combatting gravity at all times. To move the beads vertically without any visible motors, the most obvious way of grabbing and lifting magnets would be to use magnets. The attractive force from a magnet on a movable Z-axis would be able to hold or “grab” the beads, even through an opaque layer of acrylic. Other ideas were far less rational, whether it was using an internal motor on each bead (20 in total), using lead screws and wireless controllers to toggle the beads’ ability to move up and down, or even an overly intricate pulley system embedded inside a hollow rod. None of these ideas sounded more practical than magnets, which allowed us to press on with magnet-centered brainstorming.

It would be easy to “combat gravity” if each bead could be controlled by a rack and pinion or a worm of gear. However, that would require a motor for all 20 beads. With our budget in mind, we had also to synthesize a method of moving the beads that would require far less motors.

The design of the clock will consist of beads that travel along linear guide rails. The beads will be 3D printed and will have pockets for the magnets as shown in Figure 3. The beads will be the only part of the clock visible in order to add to the mysterious aspect of the clock. An opaque sheet of acrylic will separate the beads from the mechanisms that move them.

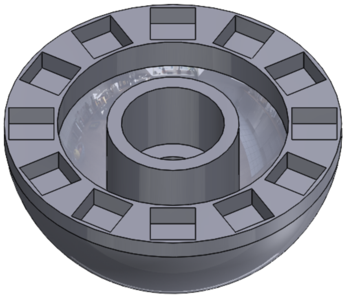

Figure 3: First Abacus bead design with small magnet housings

For each column of beads, a stepper motor and lead screw system will move a linear actuator up and down. The actuator will engage and retract some type of magnet that will use its magnetic field to interact with magnets in the beads. The magnetic force combined with the force of friction will allow the lead screw system to move the beads while being hidden behind the acrylic sheet.

<u>Prototype One</u>

The first prototype designed consisted of an electromagnet on a stepper motor and lead screw to lift a 3D printed bead embedded with permanent magnets. The original bead design is depicted in Figure 3. The idea behind this design was to have the electromagnet controlled by an H-bridge. It would magnetize pieces of ferromagnetic material embedded in the acrylic wall behind the abacus beads. The electromagnet on the motor would lift the embedded beads and attach them to the ferromagnetic material that was previously magnetized. To drop the beads, the H bridge would switch directions in turn switching the polarity of the electromagnet and the polarity of the embedded ferromagnetic material in the acrylic backplate. The poles of the material and the bead would then be the same, so that they would repel each other and the bead would drop. A picture of our first prototype can be seen in Figure 4 below.

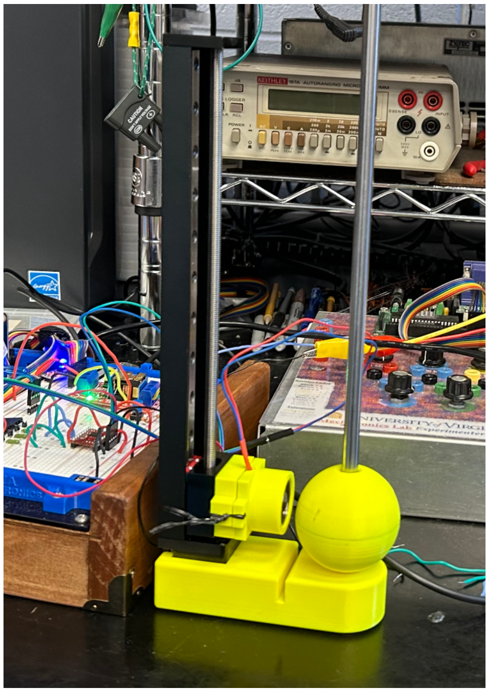

Figure 4: First prototype featuring one bead and electromagnet

After a few initial tests, we quickly learned it would not work, as the electromagnet being used was far too weak to lift anything near the weight of a 2 inch diameter plastic bead. Further, the design of many readily available electromagnets on the market were not conducive to this specific purpose. The magnets in our price range were designed to maximize the surface area of the magnetic field produced instead of the distance away from the magnet. This meant that in order to use electromagnets, the one needed would be much too large to lift with a simple stepper motor system. Taking lessons learned from this prototype, we decided a large permanent magnet would have to be used to lift the beads instead of the electromagnet.

Prototype Two

Because we changed the design to be based on permanent magnets rather than electromagnets, we could no longer use our original idea of embedding ferromagnetic material into the backplate of the abacus to hold lifted beads. The only way this would still be possible would require the permanent magnet to rotate directions which we decided was unnecessarily complicated. Therefore, our new design involved adding a linear actuator (MPJA motor) to move the permanent magnet towards and away from the beads. This would allow the magnet to have the strength to lift up the bead and also lose strength allowing the beads to fall. The CAD model for the MPJA motor can be seen in Figure 5 below.

Figure 5: CAD model of MPJA motor

For this design, we used a stepper motor with lead screw to move the MPJA motor up and down. The stepper motor we used did not have a guide rail attached like in the previous prototype. Therefore we used a linear guide rod to achieve the vertical motion of the motor. In order to attach the MPJA motor to the system, we designed a 3D printed motor mount to attach to the lead screw and guide rod. Another change we made in this prototype involved the bead design. Instead of using numerous small magnets in each bead, we designed beads that could hold two larger magnets in order to increase the strength of the magnetic field. Because the magnets were stronger, we did not have to worry about the magnets being misaligned as they would always orient themselves so that the larger raising magnet and bead magnet faced each other. For the base on this prototype, we designed a top and bottom plate that could be cut from acrylic with mounting holes for the guide rods and stepper motor. This allowed us to keep the set distances without the magnetic force pulling the parts too close together. A four column assembly of this prototype can be seen in Figure 6 below.

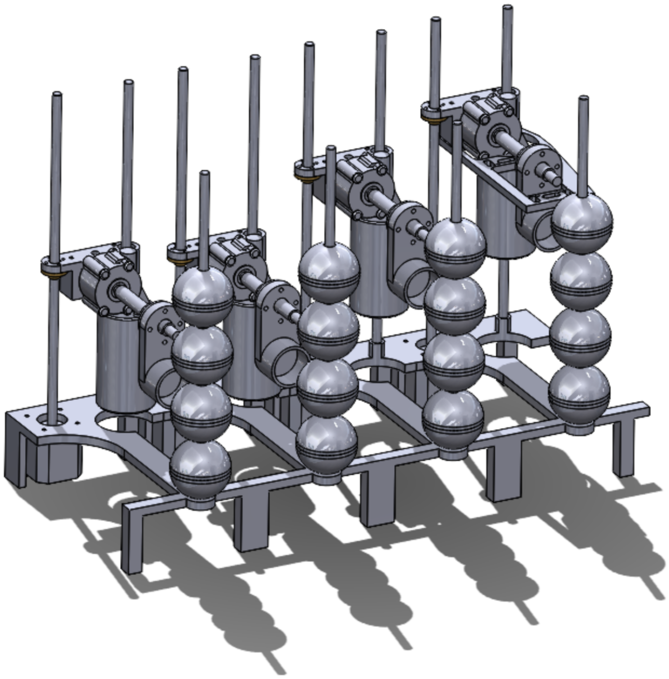

Figure 6: Four column assembly of Prototype 2

Prototype Three

For this prototype we utilized many of the same components from the last design while altering a few in order to improve their design. One of the main changes we made was our design for the top bead in each column. In an abacus, the top bead is separated by a divider and represents the number 5. However, with our current design the stepper magnet system was used to hold the beads in place. For the abacus to function properly, the top bead would need to be held in place separately while the bottom four beads are moved around. Therefore we had to figure out a mechanism to hold the top bead in place without relying on the stepper system. Our design for the top bead mechanism involved incorporating 4 magnets into the top half of the top bead that would be attracted to four magnets at the top of the guide rod. This would allow the bead to be held in place on its own without being permanently attached. The top bead CAD model can be seen below in Figure 7.

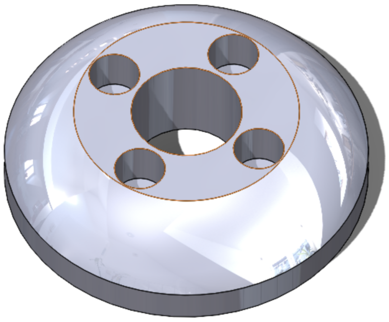

Figure 7 : CAD model of top half of top bead

Another change we made in this prototype involved the rest of the beads as well. Because there was no new movement mechanism to move the top bead, we were restricted on space on the lead screw. To combat this issue, we decided to shrink the vertical size of all the beads. Instead of being perfect spheres, they are more ellipse shaped. The new bead design can be seen in Figure 8 below along with the CAD model of a single column assembly in Figure 9.

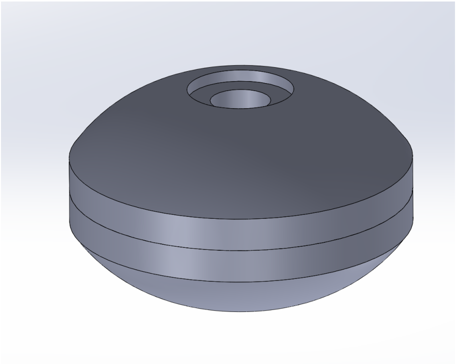

Figure 8: Shortened bead design

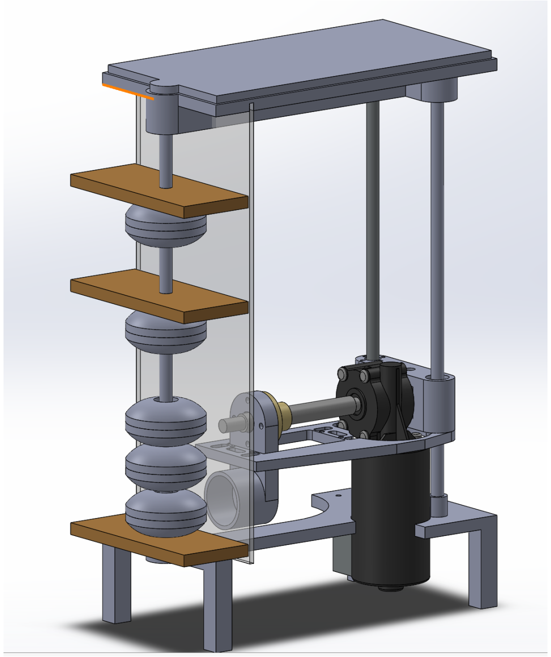

Figure 9: Single column assembly of Prototype 3

Final Design

The SolidWorks Assembly for the final one column prototype is depicted in Figure 10. It consists of a hollow steel C frame with 4 accompanying 3D printed ABS plastic base pieces. The back base holds both the guide rail and stepper motor. The stepper motor is elevated to increase the usable length of the lead screw because it is so much shorter than the guide rail. The MPJA motor is mounted on both the lead screw and guide rail with a thicker 3D printed guide for the magnet and magnet holder. The guide has two limit switches embedded on the front and back to control how far the magnet can travel. A limit switch is also embedded on the top of the stepper motor housing which stops the motor at the bottom of the frame and aligns it with the very bottom bead.

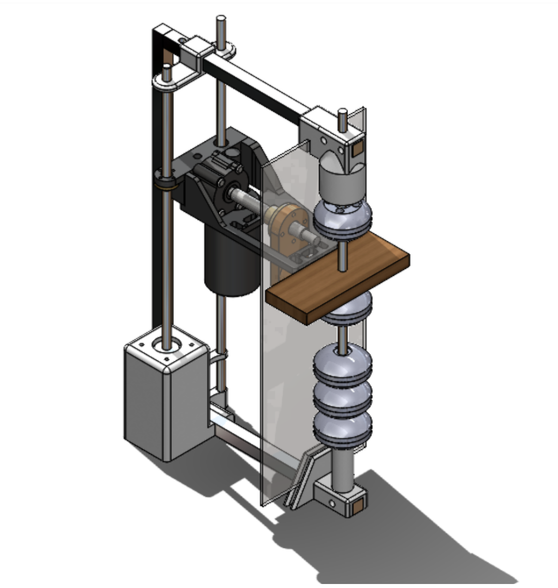

Figure 10: Final CAD model of the one column Abaclock design

The bead halves each have housings for two larger magnets and two smaller cylindrical magnets as seen in Figure 11. The larger magnets line up with the retracting magnet controlled by the MPJA motor. The smaller magnets in the bead halves align with themselves and keep the bead together without adhesive. The very bottom two beads contain .5 in x .5 in larger magnets so as to give enough magnetic force to allow all four beads to be lifted at the same time. The next two top beads contain a stack of 10-12 .5 in x .04 in magnets. These thinner, weaker magnets allowed for us to alter the amount used and reduce weight on the top beads, but had just enough magnetic force to allow both to be lifted at the same time. If the thinner magnets were used on the bottom two beads, the stack would never be lifted because the magnetic force would be too weak. On the other hand, if all four beads used the .5 in x .5 in magnets, the weight of the larger magnets and force of competing magnetic fields would be too strong and the stack wouldn't lift either. This balancing act of magnetism and weight was something the team experimented with for a long time.

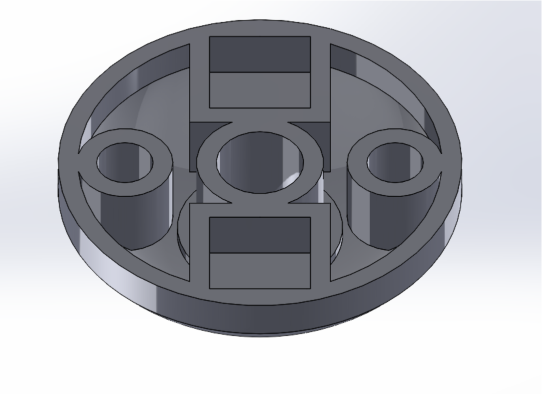

Figure 11: Final shelled CAD model of the abacus bead halves

The very top half of the top bead also has four embedded small magnets in order to be able to attach to the front top base piece as well. Recalling back to the introduction on the abacus, the top bead either stays resting on the ledge or up at the very top of the frame to represent five or zero, respectively. So, to keep the top bead floating to represent zero while the motor moves to count from one to four with the bottom four beads, the top half of the top bead attaches to the bottom of the front base base piece. This bead half design is shown in Figure 12.

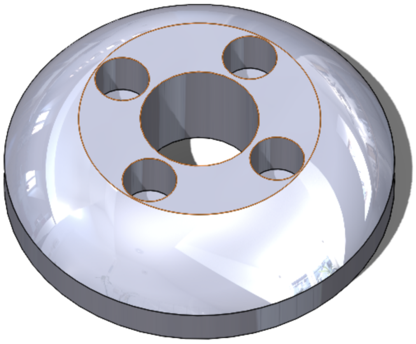

Figure 12: CAD model of the top half of the top bead with small magnet housings

Programming

We used the Propeller 2 microcontroller to operate the final prototype, programmed in the Spin 2 language, due to our familiarity with it from our previous coursework. This allowed us to quickly iterate the code, and for everyone in the group to contribute when diagnosing issues. The final prototype design operates in three phases: 1) initialization, where the microcontroller pins responsible for running various motors and limit switches are specified and activated, 2) reset, where the column makes sure that it is displaying the proper starting number, 3) and operation, where the Abaclock column begins keeping track of time.

Initialization

For each column, seven pins are declared in the constants section of the code. Two pins control the direction the MPJA motor rotates, two pins control the stepper motor rotation, two pins control the microstep size the stepper motor operates at, and one pin controls the homing limit switch for the vertical motion of the assembly. In the initialization phase, the pins controlling the MPJA motor rotation are set as smartpins which enable a sawtooth signal generation when set to high. Then the two pins responsible for setting the microstep size are both set to high, which corresponds to a 1/16 microstep size using the MP6500 microstepper driver. Lastly, the pin connected to the vertical limit switch is set as an input to allow the microcontroller to register when the assembly has reached the bottom of its travel.

Reset

The final prototype column only uses open loop control, and does not know whether the column is set to the proper number at the time it is turned on. For this reason, it goes through a reset routine that sets itself to display zero, then to display whatever initial number was specified in the constants section of the code. To begin, the MPJA motor retracts the permanent magnet to avoid dragging any beads by accident, then the stepper motor moves the assembly down until the limit switch is triggered. Once this occurs, the code sets this position to be the home position, and measures all travel distances from this point. Since the bottom four beads in each column reset to zero when not held by the permanent magnet, the only bead that needs to be reset is the top bead. For this reason, after homing, the stepper motor raises the MPJA motor, and makes sure that the upper bead is in the up position to represent zero. After this, the stepper motor homes itself again. The last step to the reset phase is where the column moves to display the initial number specified by the user in the constants section of the code, after which it begins keeping time.

Operation

The purpose of a clock is to accurately display the time, so even while in motion, the clock must be keeping time. To accomplish this, we took advantage of the Propeller 2's parallel processors to execute code simultaneously. After completing the reset phase, one of the Propeller 2's parallel processors, a cog, runs a timer method, which does nothing for sixty seconds, but after a minute, sets a variable, minutePassed equal to 1. Meanwhile, the Main method is still operating, but will not progress while minutePassed equals 0. Once minutePassed equals 1, the Main method continues, minutePassed is set to equal zero, and the MinuteOnes method runs which changes the number displayed on the column to the next one in the sequence, from 0 to 9, upon which point it goes back to 0. This allows the column to begin changing digits immediately once a minute has elapsed, and based on testing exhibits no time loss.

Electronics

Selecting the Propeller 2 microcontroller for this project also allowed us to use the mechatronics lab kits from MAE 4710 to quickly iterate and adjust circuitry for this project. To control each column, three circuits were utilized: 1) microstepper driver circuitry, 2) bottom limit switch circuitry, and 3) the H-bridge circuit for controlling the MPJA motor. We will focus our discussion on the latter two circuits, as the microstepper driver circuitry uses a common MP6500 stepper driver that can be wired according to documentation easily found online.

Limit Switch Circuit

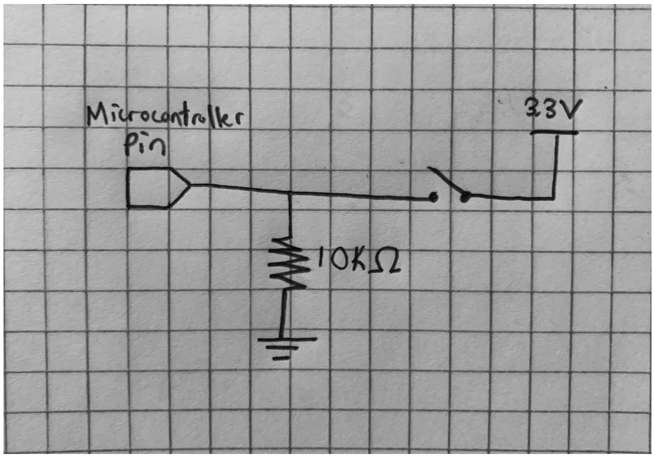

Figure 13: Circuit diagram of limit switch used to sense when the MPJA motor has reached the bottom of its travel

The limit switch circuitry as shown in Figure 13 is also relatively trivial. It consists of a switch with the common connected to 3.3 V, and the normally open contact connected to a pin on the Propeller 2 microcontroller. Additionally, a 10kΩ resistor functions as a pulldown resistor to prevent the pin from reaching a floating state. When the limit switch is closed, the microcontroller registers the now positive voltage, detecting when the extension assembly has reached its lowest position.

H-Bridge Circuit

The same system outlined in Figure 13 could have been used to register when the permanent magnet was either fully extended or retracted, but to avoid damaging the assembly due to uploading incorrect code, we opted to incorporate limit switches directly into the circuit as shown in Figure 14.

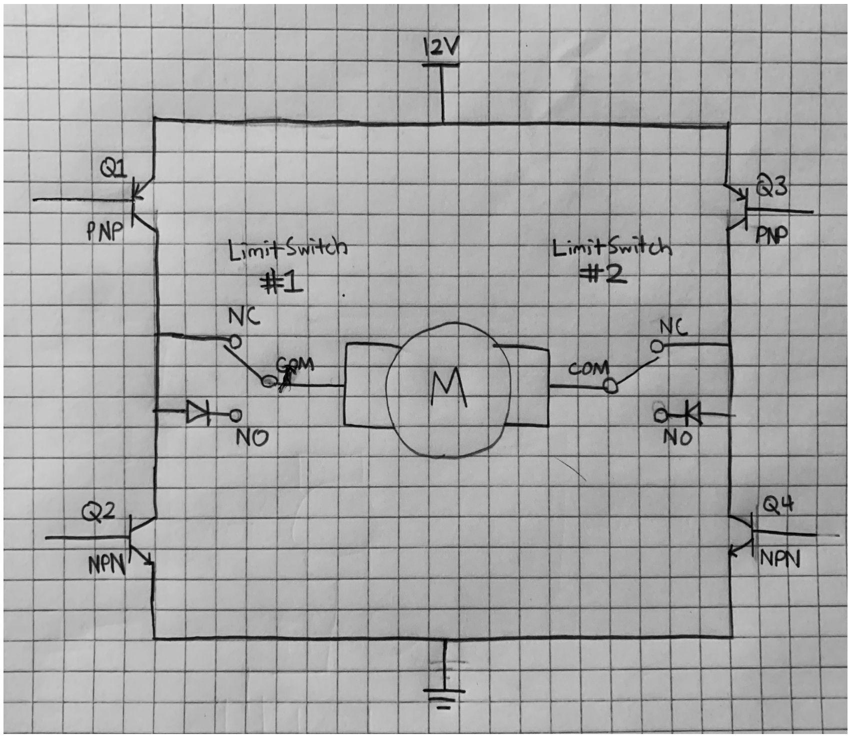

Figure 14: H-bridge circuit with integrated limit switches

The circuit shown in Figure 14 resembles a normal h-bridge in that it turns on different transistors (Q1, Q2, Q3, and Q4) to change the direction the motor rotates, but has a few key additions. The limit switches in the circuit are placed in the path of the extending and retracting permanent magnet, so that when the motor reaches either extreme, the NO contacts are connected. An example of what this would appear like can be seen in Figure 15.

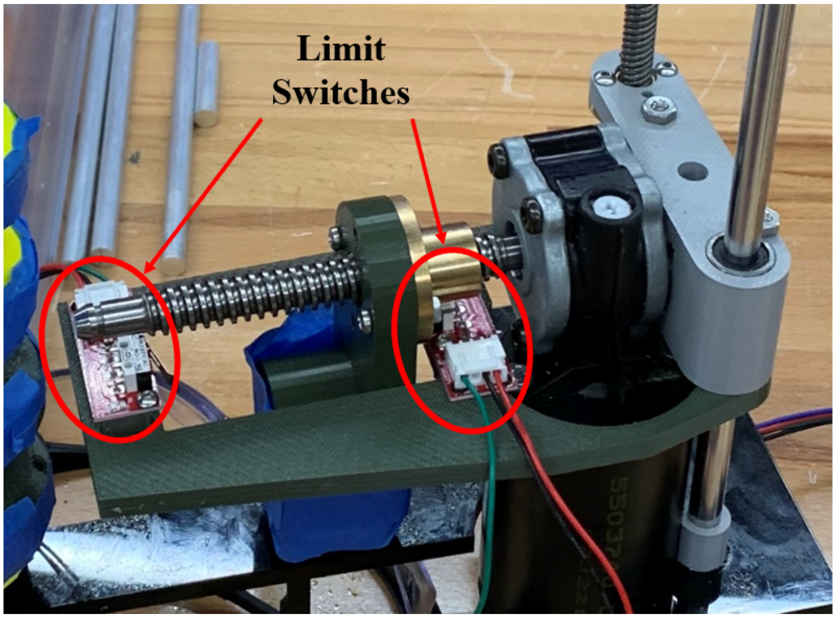

Figure 15: MPJA motor extension and retraction system with limit switches in travel path highlighted

The diodes connected to the NO contacts prevent current flow, and as such when the limit switches are pressed it is impossible for the motor to continue rotating in the same direction since there is no path from 12V to ground. However, when the rotation direction is swapped via the H-bridge circuit, the diode allows current to pass in the opposite direction. The motor begins to rotate in the opposite direction, and the limit switch returns to being NC. Once the permanent magnet reaches the opposite end of the travel, the same system stops the motor from rotating any further, while still allowing reversal.

This system was quite advantageous early on as when testing the extension and retraction we did not have to develop code to detect when the magnet had reached the end of its travel. However, it is very important to make sure that the limit switches correspond to the correct limits of travel. Wiring them backwards resulted in a prototype guide rail being destroyed as the MPJA motor continued to rotate and put too much stress on the part.

Future Work

The work on The Abaclock has only just begun. Attempting to build and test an entire system that has never been done before in only one semester has left the team thinking of all of the future work to be done, with hope that this idea will fully come to fruition one day. The first piece is to finish the three accompanying columns to the abacus so the system can accurately tell time.

The next pieces of future work have to do with refining our final design to increase functionality and reliability for future iterations. Firstly, the design can be modified to allow for another limit switch to be added at the top of the column along the top base piece that comes into contact with the motor mount when it is raised. This would have similar functionality as the bottom limit switch that sits above the stepper motor which provides feedback to the motor and magnet system, allowing it to accurately count steps and prevent it from running into the bottom of the system if something goes wrong. Adding a limit switch to the top will allow for more feedback and prevent loss of steps which is an issue the team experienced a lot at the end of the project. Additionally, a sensor system can be implemented that would track the bead movements. Right now, the system is just assuming all of the beads are in the correct positions and has no self correction functionality if it fails to pick up the necessary beads. Sensors would allow for more accuracy in the bead positions and corrections if errors are made. Finally, limiting the amount of magnetic material used in the system would be a good tweak to future iterations. The magnetic fields of the beads were impossible to simulate due the steel rods and body of the design. Including more aluminum, wood, or ABS plastic into the design would benefit the predictability of the beads and increase ease of use.

Additionally, future work could be done to enhance the aesthetics of the Abaclock. Firstly, using smaller form factor motors to extend and retract the permanent magnet would be beneficial. The lead screw on the current motor is very long, which forces the whole system to be much deeper than would be feasible to hang on a wall. The motor itself hangs 5 inches below the magnet system, and causes the base to be much thicker than required. Shrinking these dimensions would lead to a much more aesthetically pleasing and less bulky final product. Furthermore, adding the envisioned backplate in between the beads and motor system would finalize the original vision. A thin sheet of acrylic was used to separate these two parts of the Abaclock, but the material was far too flexible and warped when the magnet was extended. A backplate made out of aluminum could be used in place of acrylic, and finally add the factor of mystery envisioned for the first iterations of this design. Finally, our original design included the top and bottom of the abacus to mimic the dome and stairs of the rotunda, with the rods and beads of the abacus portraying the columns. Adding this aspect could bring another unique aspect to this unconventional clock.

The use of these four abacus columns as a clock is only the beginning of what this design could do. In altering the code and adding an interface, a calculator could be made as another interactive art form. The implementation of bead sensors would be important for this idea, as the user could input numbers or move the beads accordingly, input an arithmetic operation, and the system would then produce the answer on the four columns. The four columns of the Abaclock could also be used as a calendar, to express days and months (MM/DD), and change every day without upkeep. This variation would be much more similar to the original Abaclock functionality and take less modification of the code and interface.

Conclusion

In this technical project, multiple prototypes of the abaclock were produced. Our group used Solidworks, 3D printing, acrylic laser cutting, and our problem-solving intuition to address issues with each new prototype. However, we often encountered new problems while trying to fix old ones. Professor Garner emphasized that engineering is not about solving problems, but rather about breaking big problems into smaller ones that can be more easily managed. After a rigorous and sometimes frustrating process of prototyping the abaclock, we finally understood this perspective firsthand.

Although we did not achieve all of the goals we set out in the introduction of this technical report, we consider this project to be a success. Through our mistakes and failures, we learned more about engineering than we could have from any class. In addition to improving our skills in CAD, design, and manufacturing, we also developed valuable non-technical skills such as project management, teamwork, and a heightened intuition for real-world practicality. The experience we gained from trying to create the abaclock within a one-semester time constraint is just as important as the final product itself. If given the opportunity to do this project again or to work on a different technical project, we would use the skills we learned in this capstone course to tackle the challenge more effectively.