Motion of the Spheres: Constructing a Compact Mechatronic Orrery

A Technical Report submitted to the Department of Mechanical 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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1. Problem Statement

1.1 Statement of Purpose

Human beings have been fascinated with the heavens for much of our history, with the earliest known orrery dating back to around 200 B.C. (Marchant, 2015). The orrery is a mechanical device that replicates the movement of the solar system on a miniature scale, using a series of gears to regulate the speed of each body. The goal of an orrery is for the ratio of all movements to be accurate, and to show where celestial bodies will be relative to one another at a given point in time. However, the traditional orrery model is limited in how far in the past or future it can model the solar system, due to the fact that the whole system is controlled by a single mechanical crank. In order to look at the planetary configuration of a distant date, the crank must be turned many, many times. An example of an antique orrery can be seen below in Figure 1.

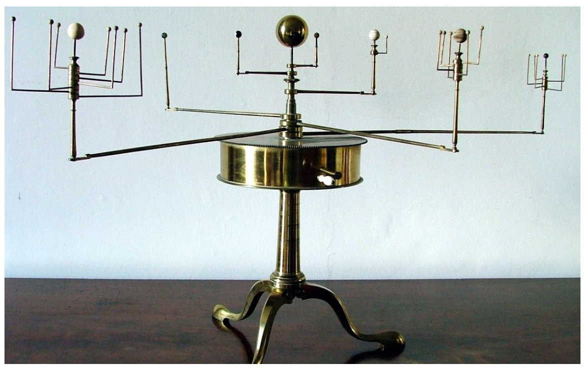

Figure 1. Traditional mechanical orrery (Williams, 2016)

Nowadays, virtual planetariums are much more common. These computer programs allow the user to look up the position of planets using the convenience of a graphical user interface and the click of a mouse. However, in transferring to this digital medium, the mechanical wonder of the orrery is lost.

Our goal was to create something in the middle: a physical orrery model that uses electrical and computer elements to act as a reference tool with the speed of a virtual model. The rationale for doing so was as follows:

1. To reinvent something of interest
2. To demonstrate the feasibility of a physical design in an increasingly virtual world
3. To create a piece of kinetic art that might spark the imaginations of future engineers
4. To develop our design skills, our communication skills, and our ability to work as a team

Furthermore, from inception to final presentation, we had two months to create a finished product, so this was also an exercise in working against a tight deadline.

1.2 Tools We Focus On

Computer-aided design, or CAD, is the process of using various kinds of software to produce a drawing, model, or diagram of a system. In our case, we used a 3D modeling software called SolidWorks, which allows the user to create virtual models of three-dimensional objects, combine these parts into more complicated assemblies, and simulate the behavior of these parts under different loading conditions. These virtual parts can be easily redesigned to adapt to new concerns and changing design constraints, making CAD an invaluable tool for rapid prototyping. The parts designed in CAD can be incredibly complex and precise, meaning that SolidWorks and other softwares like it are excellent for creating new, never-before-seen designs.

3D printing is an additive manufacturing process. Machine design traditionally uses subtractive design, such as cutting and milling away pieces of material, or casting, where molten material is poured into a mold and allowed to cool. Additive manufacturing involves the gradual building-up of a part or system. The computer breaks down a 3D model into thin layers via a process known as "slicing," after which point the printer places layer after layer of material in the same fashion as a traditional ink printer, only these layers are thick enough that they gradually build up into a 3D shape. This allows for the creation of more complex shapes than either subtractive manufacturing or casting. The 3D printers we used had two print heads, one which printed the permanent material, and one which printed a support material that could be easily broken away or dissolved in a mildly alkaline bath. If desired, this process could be used to create parts that are nested inside of one another. 3D printing, though it takes a number of hours to create a small part, is still a relatively rapid process, allowing engineers to quickly produce and iterate prototypes.

Laser cutting is a rapid subtractive manufacturing process that allows us to create thin parts from acrylic sheets. By creating .dxf files in SolidWorks and then transferring them to a program called CorrelDraw, we were able to define areas that the laser cutter was to cut, etch, or raster. While this was excellent for creating decorative pieces, the acrylic-cutting process was also useful for when we needed thin, flat parts with precise borders, such as for creating large, low-stress gears.

Though not as significant, some milling, cutting, tapping, and welding of aluminum and steel was done by our team and our professor to create the finished product. These parts were used where 3D printed parts would be unnecessary, mostly as straight shafts.

1.3 Design Goals

We had a few major design goals. Each goal was chosen to be something ambitious and challenging, yet feasible for the time and money we were given.

1. The Earth and Moon would rotate around the Sun
2. The Moon would rotate around the Earth
3. The Earth would rotate about a tilted axis
4. The Earth would also spin on another motor to keep the tilt of the Earth's axis in

the correct position as it rotated around the Sun

The 4 goals above were designed to work with 2 different modes: cinematic and snap-to-date. The cinematic mode was designed to work as a constant motion of the Earth and Moon around the Sun. The Earth-Moon combination would rotate around the Sun faster so that the model could actually be seen moving. The actual orbit of Earth around the Sun is very slow, so we decided to have the Earth orbit at a faster speed in our model. The snap-to-date mode was designed for a user to input a date of their choosing and the model would go straight to the respective position.

The final overarching goal for this project was to accomplish all of the above tasks while maintaining a visually appealing system. We wanted to exercise artistic license with this project to create something accurate, visually stimulating, and completely unique.

2. Development of Design

2.1 Mechanical

We began by splitting the motion of our orrery into two systems that could be designed separately: the mechanism for showing the earth's orbit and the mechanism for showing the Moon's orbit and the Earth's rotation and tilt. The Earth-Moon system is the more complex of the two systems, so design of this was prioritized.

We wanted to create a system where the parts could rotate independent of each other. Each of us sat down and attempted to create a solution to this first problem. We considered the idea of a sort of "clamshell" shaft that could be clamped around an internal shaft, secured in its position by grooves. This design solved our first requirement: finding a way to have the Moon move around the Earth.

After analyzing that design, we realized we could cut the middle part of the inner shaft out of the design, thus turning the inner shaft into two separate shafts (see Figure 2). We added an angled "zig-zag" to the lower shaft, so the Earth could be mounted at the proper angle of 23.5 degrees. Our plan at this point was to have each of the three shaft sections control a different aspect of movement: the upper shaft would be mounted directly to the rotation ring, allowing the Earth-Moon system to orbit around the Sun, the mid-shaft would control the orbit of the Moon around the Earth, and the lower shaft would control the orientation of the Earth's axis, ensuring that it always points towards our equivalent of the North Star (or, in the case of distant years, it allows for the Earth's axis to slowly precess to a different point). We also intended to mount another motor onto the end of the lower shaft, which would control the Earth's rotation around its axis.

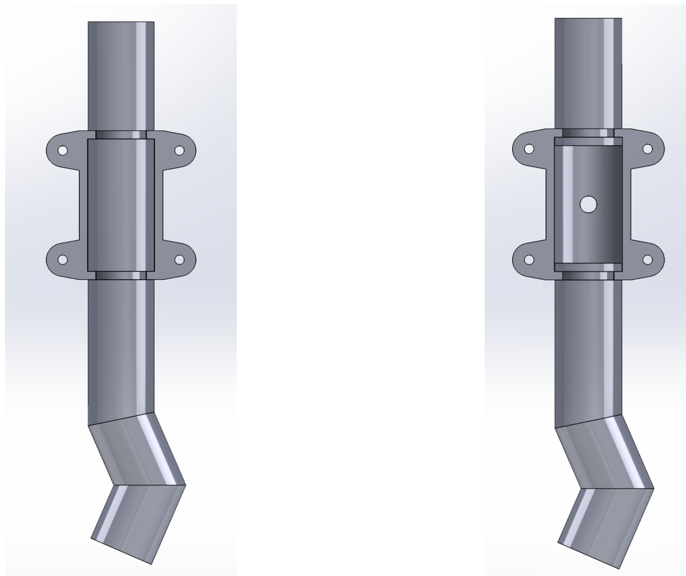

Figure 2. The internal shaft as a solid piece with half of the outer shaft clamped into its slots (left) and the internal shaft as two independently-moving pieces, held together by the outer shaft (right).

After that, we developed the design into a longer, multi-segment shaft; the multiple parts are for ease of assembly, as we were concerned about threading electronics through one long piece. We also added a ring to hang the Moon from, which was connected via two arms to holes in the mid-section shaft. Our hope was to eventually connect a gear and motor system to one of the ring's arms, allowing us to adjust its angle, as the Moon orbits the Earth at an angle and this tilt is what is responsible for the timing of lunar eclipses. While the ring was aesthetically interesting to us, we ultimately scrapped it due to the potential its large operating envelope had for interfering with other parts. The long, thin arms were also prone to heavy deflection, causing the ring to sag considerably.

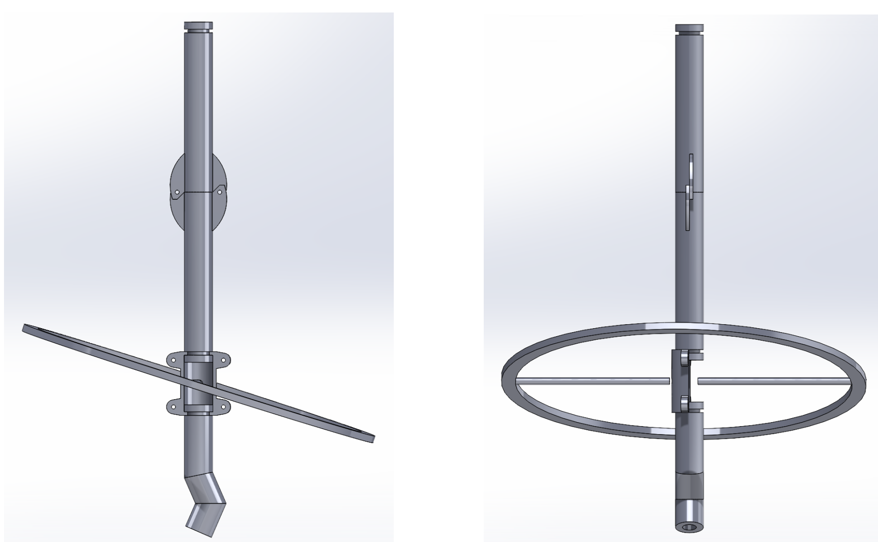

Figure 3. CAD of our first prototype, which used a ring to handle the lunar position

Due to deformation and difficulty of assembly being an issue with our first prototype, our following design was built to be more durable. We replaced the ring with an arm, which could attach to the mid-shaft through shorter, thicker pegs (see Figure 4). This solved the sagging problem, and the narrow arm took up less space at any given time while still reaching out to the correct position. We also broke the lower shaft into two separate parts, again for ease of assembly. We developed a clamp that would allow us to mount the assembly to a horizontal surface. Most importantly, the design switched from the parts sliding in slots to the parts sliding on ball bearings. As seen below in Figure 5, these ball bearings were incorporated via small plastic parts we dubbed “clamp rings,” which would attach to the ends of our thinner shafts via screws. The mid-shaft could then clamp around the ball bearings, holding the entire assembly together. This made the strength of the mid-shaft especially important, as it was responsible for keeping the bearings positioned and aligned.

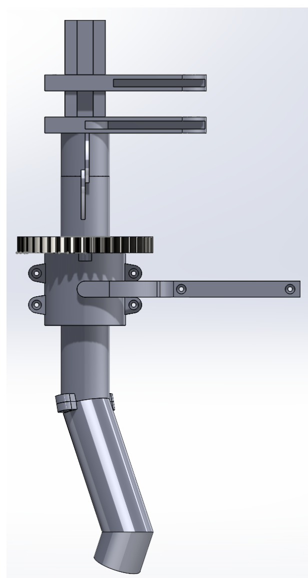

Figure 4. CAD of our second prototype, which emphasized durability and strength

Our next step was to incorporate housings for the motors and a place to put the inductive proximity sensors that we use to home the machine. As seen in Figure 5, we built an arm onto the top shaft which would hold one motor, and added an attachment to the bottom shaft that would hold a second motor. A hold for a third motor exists in the top shaft in Figure 5, but it was not accessible to wire due to a lack of opening in the shaft. This design had a very significant flaw that we didn’t consider: the plastic housings were a thermal insulator, causing the motors contained in them to heat up, and the plastic itself was prone to melting at high temperatures. Our final design would need a way to let the electronics “breathe,” not to mention we still didn’t have a mechanism designed for controlling the position of the Earth’s axis. We also didn’t decide upon how we would handle the Earth’s orbit around the Sun until very late in the project; that mechanism wasn’t given priority, because it would involve only one degree of freedom, as opposed to the three our Earth-Moon assembly required.

We also changed the length of the lower shaft's tilted sections several times, until we found a measurement that positioned the center of the Earth under the axis of rotation for the concentric shafts. This would keep the Earth at equal distance from the Sun, regardless of the angle of the lower shaft.

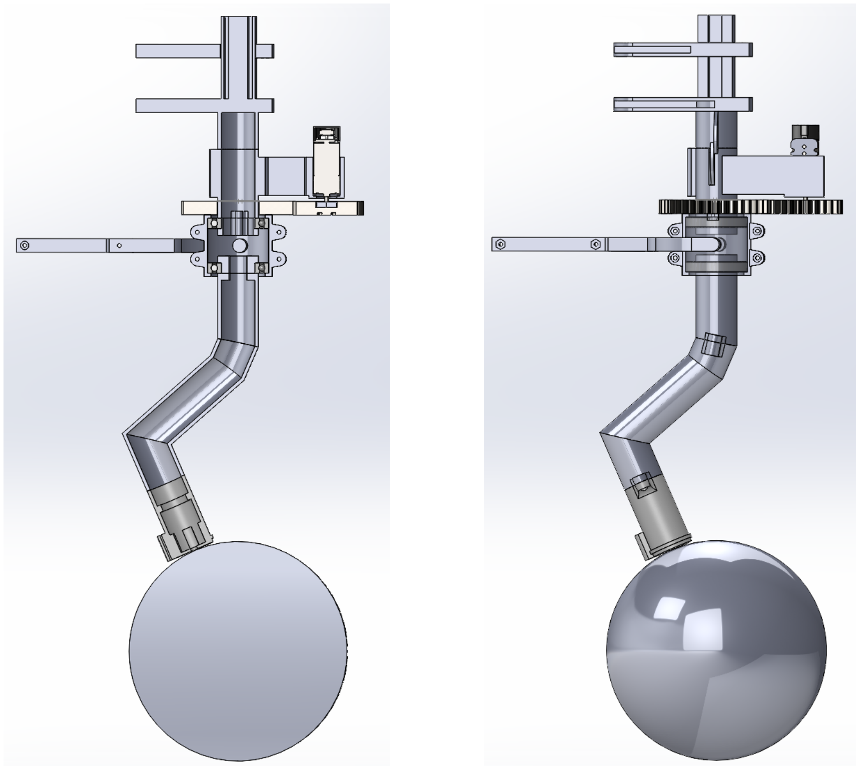

Figure 5. Cross-section (left) and side view (right) of our third prototype. The globe is a placeholder in the images and not included in the physical model.

While iterating upon the Earth-Moon system design, we discussed a few possibilities for actuating and supporting the Earth's orbit around the Sun. First, we considered the use of a planetary gear system in which the sun gear drives three planet gears, and one of the planet gears has the Earth-Moon assembly suspended down from it. We ultimately scrapped this idea because we wanted to try and stay away from planetary gear systems, as incorporating these seemed to not really innovate upon traditional orreries. The second approach we considered was to have the Earth-Moon system cantilevered out from the center of rotation and supported by a large lazy susan bearing. This was later modified to include two lazy susan bearings. A rough sketch of this idea is shown below in Figure 6. The third approach we considered was having the Earth-Moon system suspended down from a track. This track would essentially be a make-shift lazy susan bearing connected to a gear that is driven by a motor mounted to another external gear (see Figure 7). We ultimately decided to pursue a cantilever system as this would simplify the mechanical design and manufacturing of the Earth orbit.

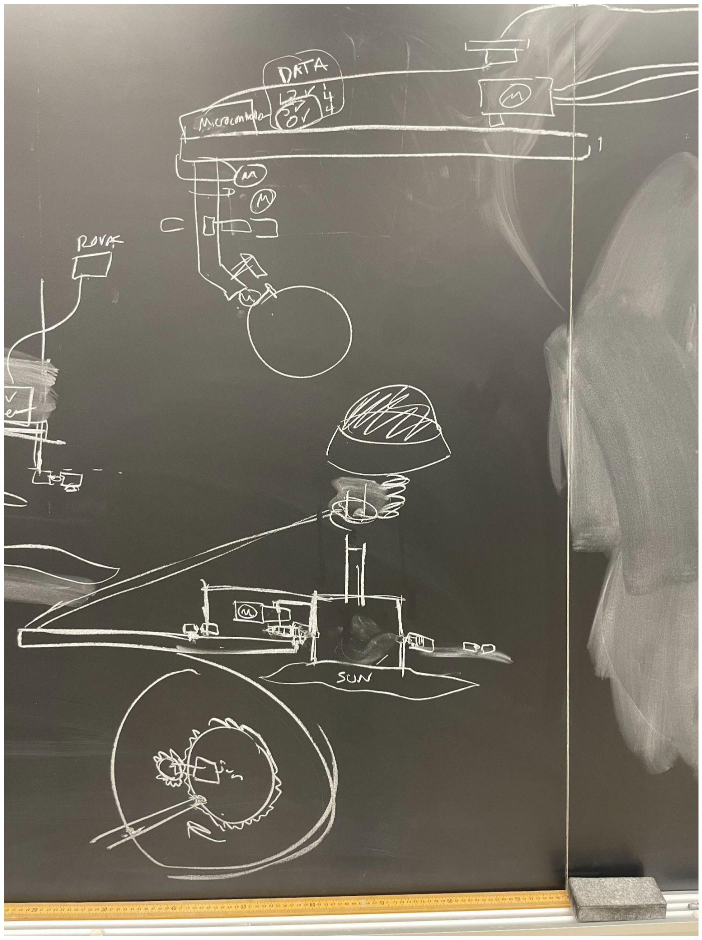

Figure 6. Preliminary sketch of the cantilever Earth orbit system.

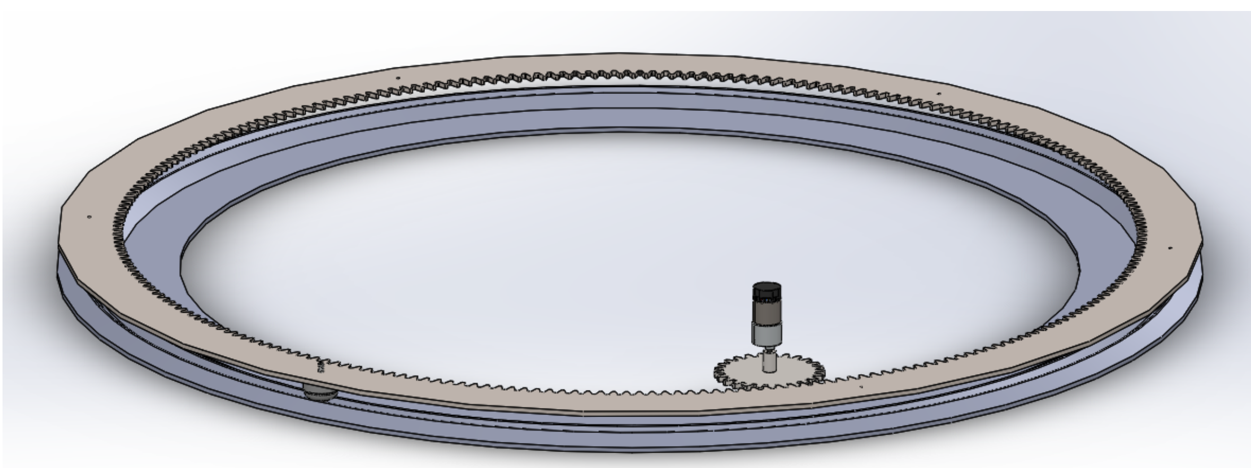

Figure 7. SolidWorks assembly of the track approach for the Earth orbit.

2.2 Electrical

When designing the electrical components for the orrery system, we had to consider the actuation of all the degrees of freedom. For instance, the system would have to rotate the Earth about its axis and move the Moon around the Earth. It would also have to move the Earth-Moon assembly around the Sun. If this whole assembly was moving around the Sun, the Earth's tilt on its axis would stay in a locked position relative to the assembly, which wouldn't be an accurate representation of the motion of the Earth around the Sun. Thus, the Earth's axis would need to self-correct in order to stay aligned with the North Star. Given this, we have four degrees of freedom within our system that all need to be driven by their own motor.

Next came the discussion of what type of motor should be used for the system. It was first thought to use stepper motors for the actuation of the elements in the system. Stepper motors would be useful in maintaining a strong holding position and would be easy to control, especially with the use of a micro-stepper driver chip. However, stepper motors are heavy, not extremely fast, and are susceptible to missing steps if too high of a load is applied. The lack of feedback that stepper motors have would prove troublesome for the type of system we wanted to create. A stepper motor operating on relative positioning that misses steps would result in a position that does not correspond to the input date. Instead of stepper motors, we decided to use DC brush motors with quadrature encoders because of their ability to provide feedback and maintain high resolution positions. These types of motors were also able to give the necessary amount of torque and speed that we desired for the system. They would be controlled using a Propeller 2 microcontroller, programmed with the Spin2 language to send pulse width modulation signals to an H-bridge motor driver. Using an H-bridge would be optimal because it would give us the ability to change the direction of rotation of the motor easily. We would also be able to control the duty cycle of the motors, determining the size of the pulses by multiplying the difference between the actual position and target position by a proportional gain constant.

In order to move our motors to exact positions that correspond to the input date, they must know their absolute position. Since quadrature encoders only provide position relative to when they are turned on, an external homing system is needed to provide the motors with their absolute position. There were a few methods considered for homing each motor to a designated position in the assembly. The first method used was an infrared sensor that would detect changes in position from a given surface. This would work, but in order for the system to be more accurate, we decided to use an inductive proximity sensor. This type of sensor would be able to detect a small piece of ferromagnetic material (metal) through a change in an inductor's magnetic field. This change in magnetic field would activate a transistor, allowing a change in voltage to be recorded. The inductive sensors used an NPN transistor, sending a 12 volt high signal out with no detection. When metal was detected, the transistor would close, making a low signal coming from the transistor as all the voltage would be able to flow to ground. Because a voltage of 12 V would be constantly received by the microcontroller, a voltage divider was created to step down the voltage to 3 V when high. This protects the microcontroller. We used a trim pot to find the resistor values that reduced the sensor output to a safe level.

Because of the mechanical design developed for the Earth-Moon assembly, a slip ring would have to be used for the motor and sensor that would rotate the Earth on its axis. The slip ring would allow for wires to be rotated 360 degrees without becoming twisted. It was important to take note of the amperage that the wires in the slip ring will carry due to the current threshold stated by the manufacturer. The slip ring works by maintaining connection of wires through the use of a copper plate. The wires graze the copper plate on one side of the ring while wires on the opposite side have a similar connection to the other side of the plate. Thus, if an excessive amount of amperage is sent through the slip ring, the copper and the wire will spot weld themselves together, destroying the slip ring. We then had to find a slip ring that would be able to handle the load of current required for the system.

Initially, we were going to use 4 of the same type of DC gear motor, one for each degree of freedom of the assembly. However, there was concern that the motor that would rotate the Earth-Moon assembly about the Sun would not be able to transmit enough torque to the system to effectively move the system to specified positions. Because of this concern, we decided to use a high torque DC worm gear motor with a quadrature encoder. This way we could still maintain the precise positions using an encoder, and we would now have the strength to efficiently move the Earth-Moon assembly.

2.3 Computation and Data Reading/Writing

In order to create an orrery that would accurately model the movements and positions of the Earth and Moon at any given time between 1500 and 2500 AD, we needed accurate data on the positions of the Earth-Moon system around the Sun, the Moon around the Earth, the axial tilt of the Earth, and the Earth's rotation. Our initial plan was to find a method of either calculating the required positional data whenever a user inputs a date and time into our system or precalculating this positional data and storing it in a database that a Propellor chip would be able to pull from. Taking the advice of our advisor, Professor Garner, we decided to pursue the route of pre-calculating and storing the positions. This would allow us to use the more reliable Propellor 1 or 2 chip without requiring the chip to perform complicated calculations or requiring a Raspberry Pi to conduct these calculations. This would greatly improve the reliability of our system

The first idea we had to collect the needed data was to find a preexisting online source for this data. We were not able to find a website with all of the relevant data so we had to be more creative. We identified a few online calculators that would determine the phase of the Moon and Earth's rotation for any inputted date and time. In order to access this data, we would need to create a bot or web-scraping script that could access the website and iteratively plug in date and time values and consolidate these values into a spreadsheet. Because of the difficulty in creating a program to do this, we decided to not go down this route. An additional consideration behind this choice was that this data was not directly usable and would have needed to be processed to convert Moon phase and Earth rotational data into actual positions of these celestial bodies.

The second idea of how to collect the needed data was to precompute the required data. Due to the complexity of orbital mechanics, it would be difficult to ensure that accuracy was maintained across the 1000 year span. In order to create data that is absolute rather than relative to the particular positions of all bodies in our mechatronic system, we would need to use sidereal time. Sidereal time is a timescale used by astronomers that is based on the Earth's rotation with respect to apparently fixed stars which represent the International Celestial Reference Frame. From the Earth, these stars appear to be fixed and can therefore be used as a positional reference for each body in the orrery. This would allow positions to be considered absolute with respect to this reference frame rather than being purely relational. Algorithms for calculating sidereal time require the use of Julian day number, which is the number of days since noon UT on January 1, 4713 BC. One benefit of the Julian day system is that there are no irregularities in the Julian calendar such as leap years, different days in different months. One algorithm that was considered was one provided by Subsystems (2017). Essentially, this method would work by converting any target date into its Julian day number. A reference Julian day number which fell on a new Moon would be found. This reference Julian day number would be subtracted from the target Julian day number and divided by ~29.58, which is the length of the lunar month to determine the number of orbits the Moon has undertaken since the reference Julian day number. The remainder would then be divided by 29.58, which would produce the fraction of the lunar month that a given date and time is in, which can then be multiplied by 360 to determine the angle of the Moon around the Earth, with 0 representing the new Moon. The downside of this approach is that it loses a lot of accuracy over time as the length of the lunar month varies and changes over long time scales. Therefore, this approach was dropped in favor of alternatives that could be relied upon to not only provide accurate positions for the Moon but also the capability of accurately modeling or at least knowing when solar eclipses occur, as this was one idea we had for a capability of this system.

3. Final Concept

3.1 Mechanical

Our final prototype underwent considerable redesign before its production. First, we replaced the lower shaft with an aluminum piece. This had the dual benefit of strengthening the part and saving a little on 3D printer material. However, because we could no longer design the shaft to have connections to our clamp ring, we had to affix a hub to the end of the aluminum via some epoxy; this is one of the few places in our design where we used any kind of adhesive. This hub had a hole in it through which wires could pass. At the other end of the aluminum shaft, we attached a small block that held both the Earth-rotation motor and the inductive sensor.

The new clamp ring connecting to the lower hub was elongated compared to its original design, with a cutout in it to allow for the placement of a slip ring. This slip ring would allow for the wires connected to the Earth-rotation motor to turn with the lower shaft, without twisting the wires that ran up through the rest of the shaft. The position of the Earth's axis is controlled by a second motor offset from the central axis, which is connected with a gear that meshes to another gear in the upper shaft (as seen in Figure 8, right). This gear is connected to the slip ring through a series of plastic linkages and metal rods. The wires of the slip ring are able to pass through an opening in these linkages and rod to emerge through the top of the upper shaft.

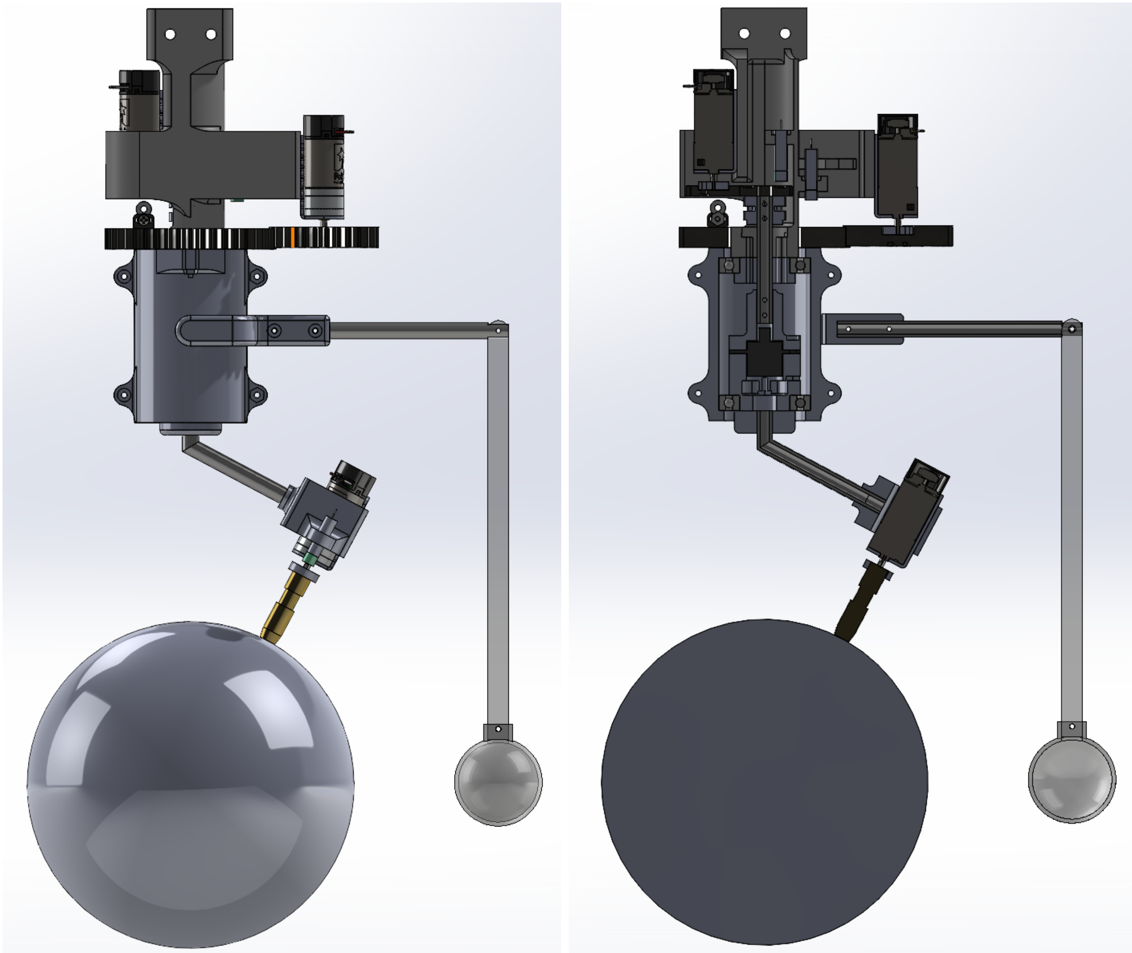

Figure 8. Side view of final Earth-Moon system assembly (left) and cross-section of final Earth-Moon system assembly (right).

We ultimately decided to go with the cantilever arm approach for the Earth's orbit, utilizing two lazy susan bearings (8" outer diameter and 24" outer diameter) to support the arm that holds the Earth-Moon system. The inner track of each lazy susan has four ¼"-20 tapped holes. Four ¼"-20 bolts connect the inner track of the 8" lazy susan to 0.5" steel square tubing welded into an X shape. Four ¼"-20 male-female standoffs and four ¼"-20 bolts connect the inner track of the 24" lazy susan to another X-shaped support. The two steel X's were connected by a 0.5" steel shaft welded at the center. This shaft extends below the supports and will serve as a mounting point for the sun. The shaft will also have a hollow slip ring affixed to it to power the electronics for the Earth-Moon assembly. The steel X frames remain stationary and support the entire system (see Figure 9). The outer track of each lazy susan is connected to an 80-20 Aluminum T-slotted arm by a ¼"-20 bolt that threads into T-slotted framing (see Figure 10).

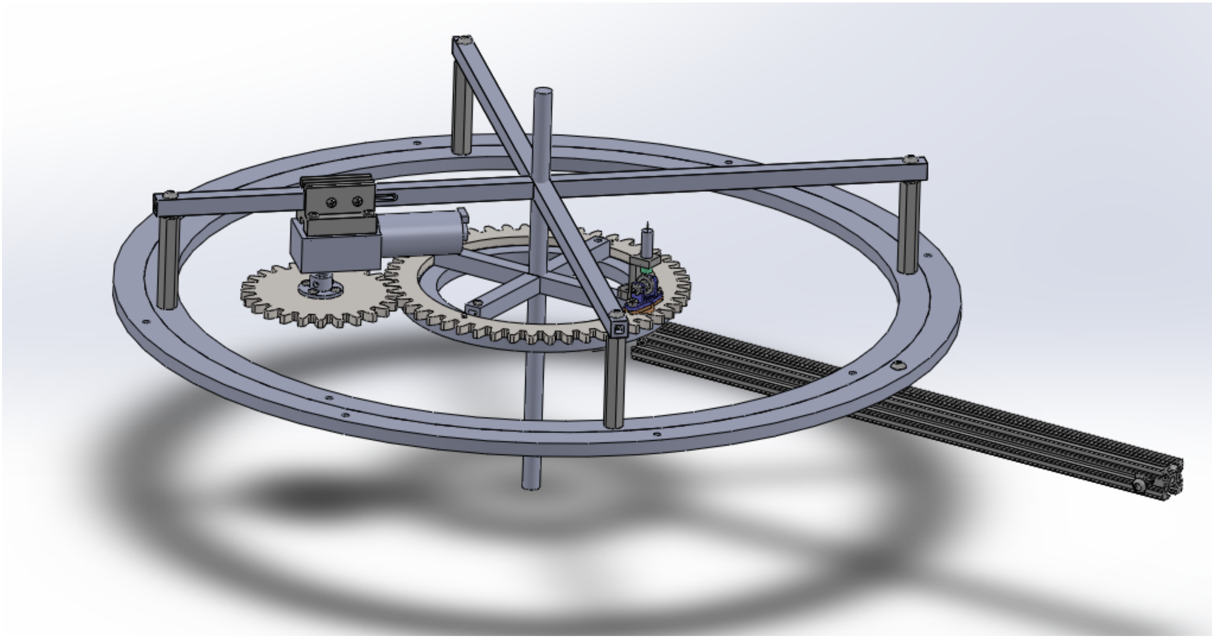

Figure 9. Final Earth orbit assembly in SolidWorks.

Figure 10. Close-up of the connection between the outer track of the lazy susan and the 80-20 aluminum arm.

The Earth's orbit is actuated by a motor that is offset from the center of rotation and mounted to a gear which meshes with another hollow gear (see Figure 11). This hollow gear is connected to the outer track of the 8" lazy susan by 6-32 screws. The motor is mounted to the X frame of 24" lazy susan by a 3D printed part. A slot in the X frame allows for the motor to be placed in a position in which the gears properly mesh. Four M4 0.7 mm screws connect the motor 3D printed mount.

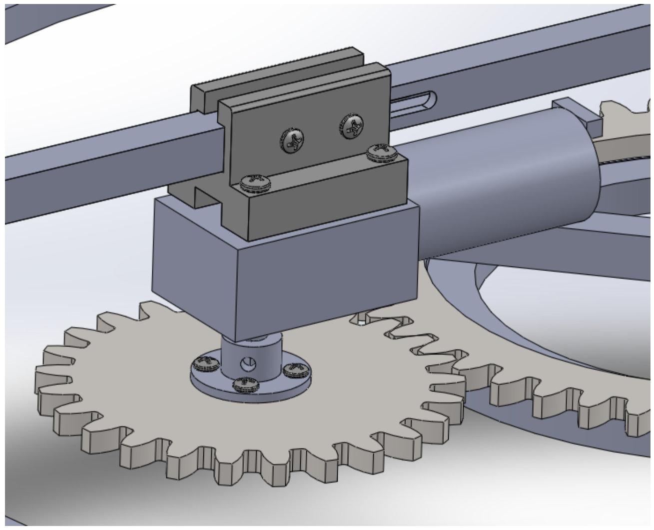

Figure 11. Added slots to the X-frame and a 3D printed motor mount to allow adjustability and ensure proper meshing of the gears.

The Earth orbit system and Earth-Moon system are combined together below in figures 12 and 13 to show the entire orrery assembly. These systems were unable to be combined for the final physical model because the 24” lazy susan and hollow slip ring were never delivered (see Figure 14).

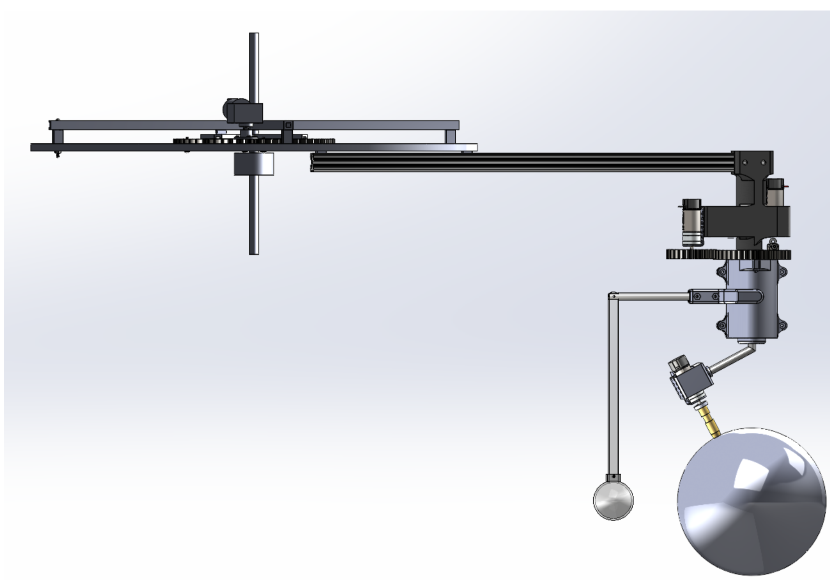

Figure 12. Side view of the entire system.

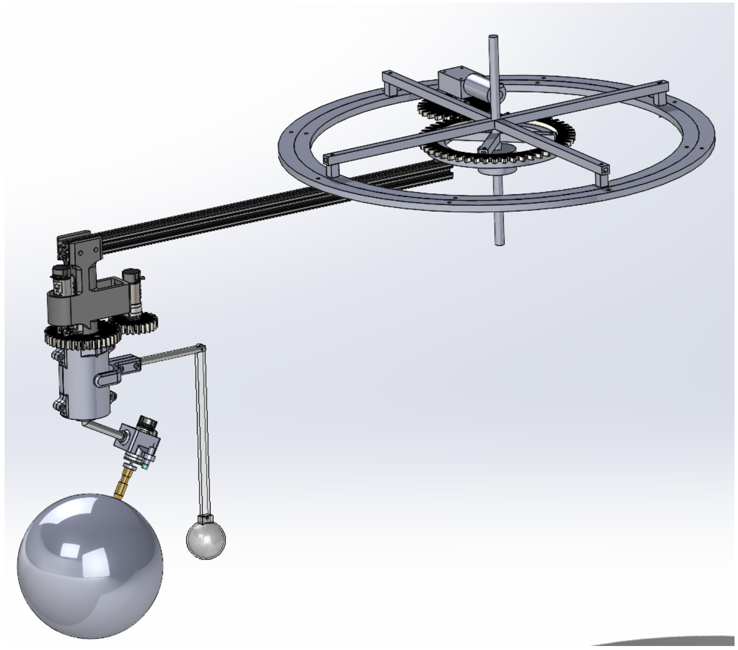

Figure 13. Perspective view of the entire system.

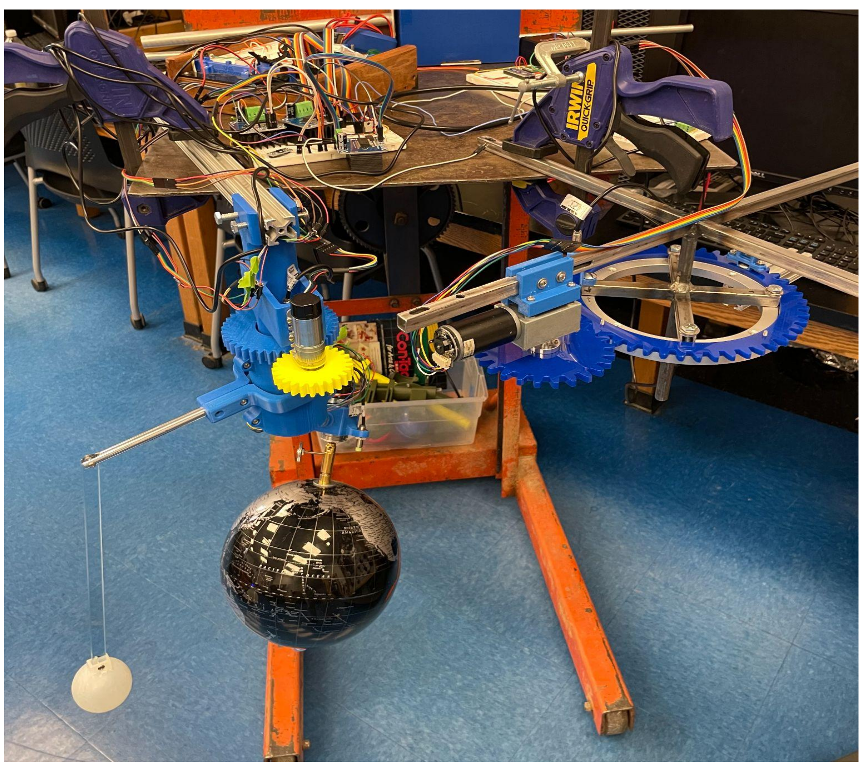

Figure 14. Final physical assembly. Moon-Earth system on the left and Earth orbit system on the right. Note that the 24” lazy susan bearing and hollow 0.5” shaft diameter slip ring were both never delivered. Therefore, we couldn’t cantilever the Earth-Moon system as seen in the SolidWorks assembly.

Another important piece of our mechanical design was our homing procedures. All motors without a direct feedback loop (absolute encoder) lose positional accuracy over time. To combat this problem and keep the positions of our motors up to date, we will send all of our motors to a known position every time our system is turned on. This process is called homing, and it ensures that our motors are truly at their expected position before they move to target positions. As explained earlier in section 2.2, we are using NPN inductive proximity sensors to home our motors. Our specific homing procedure requires a piece of metal to pass within 2 mm of the sensors. We have four motors but only successfully homed three of them. The homing apparatus for the Earth axial correction motor was too small and caused interference so we were never able to home this motor.

The first motor we homed was the central arm-driving motor. We based the homing on the small lazy susan. To do this, we first 3D printed an apparatus that will hold a washer in an adjustable location and mounted it on top of the laser cut gear. This system is made up of two 3D parts which are shown in orange and blue in Figure 15 below. These pieces fit around the bolt that mounts the 80-20 arm and they are connected together with screws. Then, we 3D printed a sensor hold that mounts to the fixed inner ring of the lazy susan using a bolt that connects the X-frame to the lazy susan. The piece reaches out and over the laser cut gear where it holds the proximity sensor. With this system, we can make slight adjustments to the position of the washer and sensor in three directions to ensure that our system is correctly aligned.The apparatus on the laser cut gear will precess around until the washer hits the stationary homing sensor and alerts our microcontroller that it has reached its home position. See Figure 15 below for a SolidWorks model of the system.

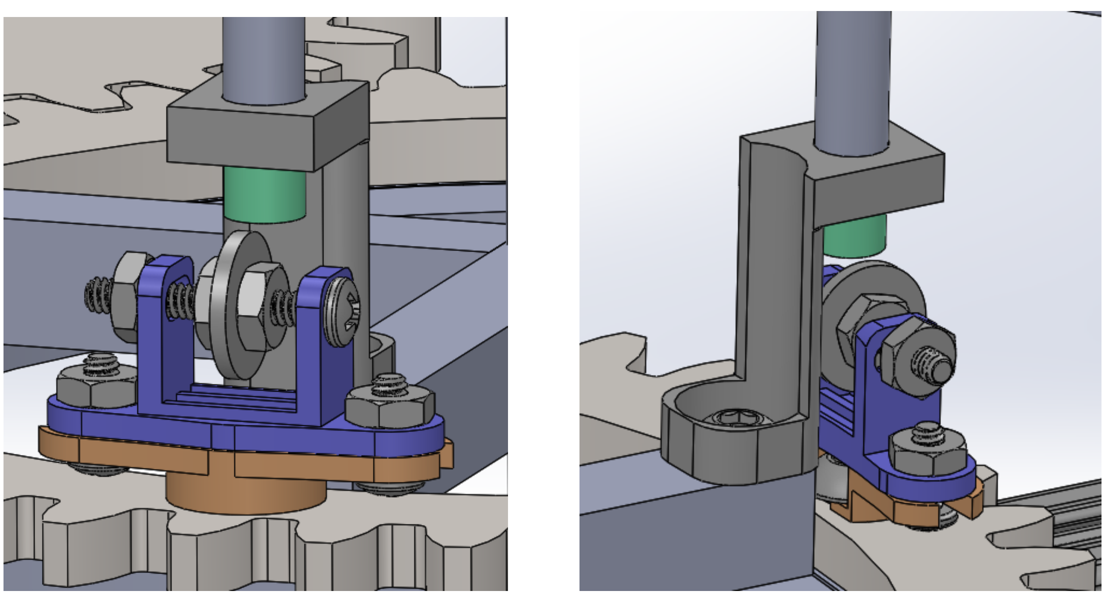

Figure 15. Central driving motor homing apparatus. The blue and orange parts as well as the gray zigzag shaped piece are 3D printed. The green-tipped piece is the inductive proximity sensor. The blue piece has slots to move the washer towards/away from the sensor hold. The washer can move along the screw it is on by moving the nuts that secure it. The proximity sensor can move up and down using the hex nuts that accompany it.

The next motor we homed was the lunar arm motor. This system will home a 3D printed gear to an inductive proximity sensor that is fixed to a 3D printed shaft. 3D printers can easily produce complex geometries, so the hardware mount was designed on top of the gears and the hold for the proximity sensor is printed onto the shafts. Similar to the last homing mount, the washer and sensor have three degrees of freedom to ensure that this homing system always works. See Figure 16 below for a SolidWorks model of the apparatus.

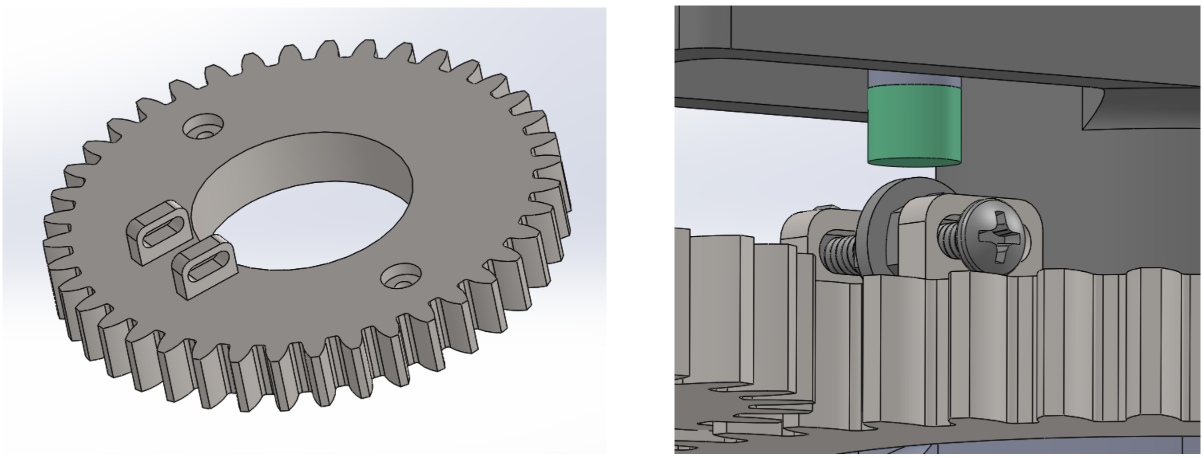

Figure 16. Lunar arm gear with hardware mount (left) and lunar arm motor homing apparatus (right). The slots on the gear allow the washer to move towards/away from the sensor hold. The washer can move along the screw it is on by moving the nuts that secure it. The proximity sensor can move up and down using the hex nuts that accompany it.

The final motor that needed to be homed was the motor that spins the Earth about its axis. This motor is fixed in place with a 3D printed part, so the hold for the proximity sensor is built into that part. A screw is extended out from the driven shaft, and along this screw a washer is secured by a nut. The driven shaft and the attached screw spin around until the washer trips the inductive proximity sensor. See Figure 17 below for a SolidWorks model of the system.

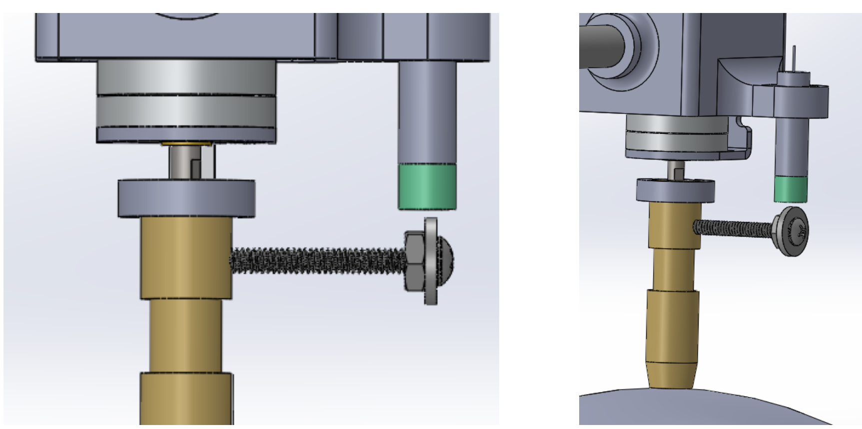

Figure 17. Earth spin motor homing apparatus. The proximity sensor can move up and down using the hex nuts that accompany it. The washer

can move along the screw that it sits on by moving the nut that fixes it. The screw holding the washer comes from a shaft directly below the motor, so freedom in that direction is unimportant.

3.2 Electrical

Our final orrery design made use of the following electrical components:

- Propeller 1 (P1) Microcontroller (1)
- Propeller 2 (P2) Microcontroller (1)
- Pololu 25 mm 12V High-Power 1:34 DC Brush Metal Gearmotor With Integrated 48 Counts Per Revolution (CPR) Quadrature Encoder (3)
- GW4058-31ZY12V High-Torque 1:522 DC Brush Worm Gear Motor With Integrated Hall Drive (Quadrature Encoder) (1)
- Inductive proximity sensor 12 mm Diameter (4)
- 12 Wire 2A Slip Ring* (1)
- Hollow 0.5” Shaft Diameter 6 Wire 10A Slip Ring (1) (didn’t arrive)
- BTS7960 43A H-bridge Double High Power Motor Driver (4)

* This was meant to be a 12 wire 5A slip ring in case the motor stalled, resulting in 5A of current surging through the slip ring. However, there was miscommunication within the design process, resulting in 3D printed parts that were designed to fit a 12 wire 2A slip ring of smaller length.

The Propeller 1 controls the user interface and the Earth orbit motor (GW4058-31ZY12V) and its inductive proximity homing sensor (see Figure 18). The Propeller 2 controls the Moon orbit motor (25D Pololu), Earth rotation motor (25D Pololu), Earth axial correction motor (25D Pololu) and their respective inductive proximity homing sensors (see Figure 19). The user interface was never developed due to time constraints, so it will not be pictured. Data transfer from serial flash memory to the P1 and P2 wasn’t fully developed, so it wasn’t integrated into the final electronics. Further explanation of this can be found in the next section. Detailed circuit diagrams and pictures of the physical circuits can be seen in the figures below.

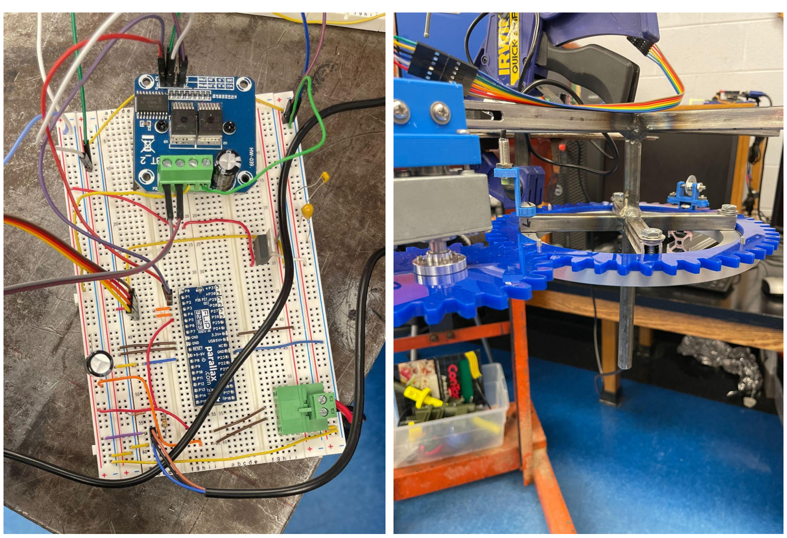

Figure 18. Electrical wiring of the Earth orbit system (left) and the shaft where the hollow slip ring would have gone (right)

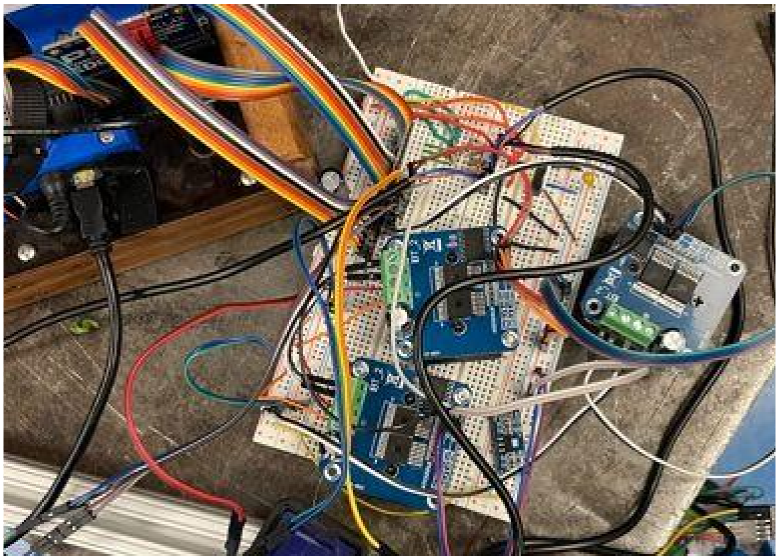

Figure 19. Electrical wiring of the Earth-Moon system. Note that an MEB powers the Propeller 2 microcontroller, and ribbon cables connect P2 pins onto the breadboard.

The Earth rotation motor and proximity sensor must be wired to the slip ring within the assembly (Figure 20). The slip ring has twelve wires distributed in the following manner:

- ➢ Motor Power: 2 wires
- ➢ Motor GND: 3 wires
- ➢ Encoder Power: 1 wire
- ➢ Encoder GND: 1 wire
- ➢ Encoder Output A: 1 wire
- ➢ Encoder Output B: 1 wire
- ➢ Sensor Power: 1 wire
- ➢ Sensor GND: 1 wire
- ➢ Sensor Output: 1 wire

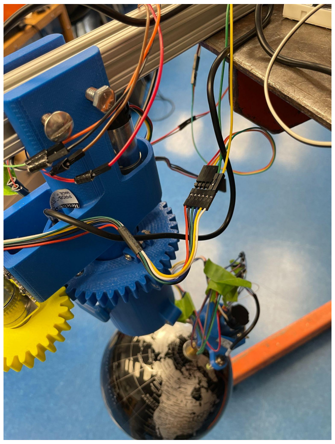

Figure 20. Electrical wiring of the Earth-Moon system with the Earth rotation motor and sensor wired through the slip ring.

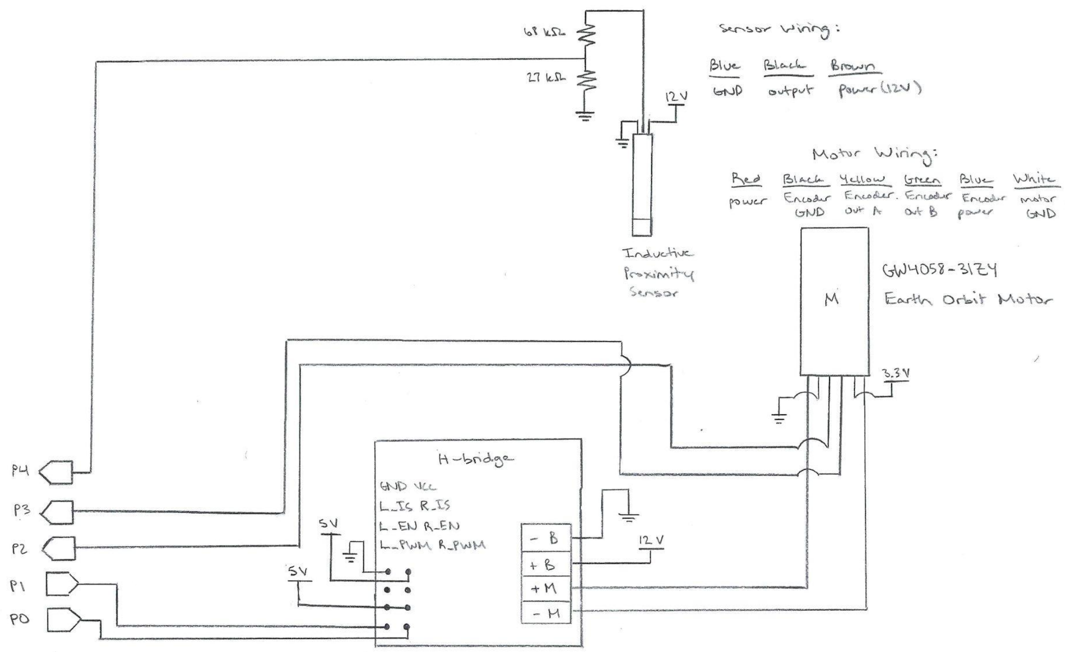

Figure 21. Circuit diagram of the Earth orbit motor wiring with the H-bridge, sensor, and P1 pins.

The Earth rotation motor, Moon orbit motor, and axial correction motor all have the same wiring with the H-bridge and sensor except that they are interfaced with the Propellor 2 microcontroller (see Figure 21 above), and have a slightly different wiring code and pin placement (see Tables I and II below.

Table I

Pololu Motor Wire Code

Wire Color:	Red	Black	Green	Blue	Yellow	White
Description:	Power	Motor GND	Encoder GND	Encoder Power	Encoder Output A	Encoder Output B

Table II

Earth-Moon System Pin Placement

Motor	*R_PWM*	*L_PWM*	*Encoder A*	*Encoder B*	*Sensor*
Earth Rotation	20*	21*	22*	23*	11

Moon Orbit	16*	17*	18*	19*	10
Axial Correction	24*	25*	26*	27*	12

* indicates that the pin is using smartpin capabilities. This is only available on the P2 and is used in this case to create PWM signals and read the encoder output.

3.3 Computation and Data Reading/Writing

There were a few considerations that were especially important as the code to create the database was developed. First, the homing positions of each motor was of particular importance as it defined the basis upon which the data held meaning. Additionally, the fact that the Earth-Moon system was rotated around the Earth meant that the homing positions could all be made so that they were between the Earth and the Sun. This simplified the data processing requirements for each motor position because data on the Moon's position between the Earth and the Sun could easily be used to extrapolate relevant data without needing to engage with more complex topics such as Sidereal Time.

The database used in this project was created through a mix of pulling publicly available online information and then computing missing date/time values. The script took two manually created .txt files representing each recorded eclipse and quarter Moon phase between 1500 and 2500 in 100 year increments, processed the data, and then created two .csv files with each set of processed values in terms of motor positions in degrees scaled between 0-255. The reason that the degrees are scaled between 0-255 instead of 0-360 is to reduce the number of bits required to store that data from 9 to 8 bits, meaning that each motor position can be stored in the database in one byte which simplifies the data storage and retrieval process, as bytes would not need to be combined since each motor position is one byte.

In order to create a database of Earth rotational data, data on every annular and total eclipse was collected, with missing dates and times linearly interpolated. First, data was manually copied into .txt files from the "NASA GODDARD SPACE FLIGHT CENTER ECLIPSE WEBSITE" which displayed the "Calendar Date", "Time of Greatest Eclipse", "Eclipse Type", "Longitude", and many other characteristics of every solar eclipse between the year of 1500 and 2500 AD (National Aeronautics and Space Administration, 2010). A Python script was created to process these .txt files in order to delete any eclipses that were not annular or total in order to only use data from eclipses where the Moon was directly between the Earth and the Sun, as well as being on the same plane as the Earth's orbit around the Sun. The Python script also ignored all data points that were not "Calendar Date", "Time of Greatest Eclipse", "Eclipse Type", or "Longitude". Using the "Calendar Date", "Time", and "Longitude" as known reference points, where the Earth, at a certain Longitude, was directly facing the Sun, the Python script then calculated the difference in time between each successive known reference point, while factoring in leap years and leap centuries. This difference in time along with the Longitude data points were then used to linearly interpolate the longitude at each hour between 1500 and 2500 AD that directly faced the Sun. The Longitude (out of 360) was then converted into motor positions with 255 ~1.412 degree increments (totals 360 degrees), taking the Prime Meridian to be zero degrees. The motor position was then converted into hexadecimal and stored in a .csv file. On each line in the .csv file, the first data point was made up of the year, day of the year, and hour of the day, each in binary and then concatenated together into one value. This value would be used as the data point address within the database. The second value would be the motor position in one hexadecimal.

In order to create a database of the positions of the Moon around the Earth, data on every new Moon, first quarter Moon, full Moon, and third quarter Moon was collected, with missing dates and times linearly interpolated. First, data was manually copied into .txt files from Astro.com, which displayed each instance of the new Moon, first quarter Moon, full Moon, and third quarter Moon, with the year, month, and day and unknown variable, time, and symbol representing each of these four phases of the Moon between 1500 and 2500 AD (Astrodienst, 2020). A Python script was created to process these .txt files by pulling each date and time, ignoring any unknown variables, and pulling each symbol representing the Moon phase. Each Moon phase symbol, which was associated with a date and time, was then converted into degrees out of 255 (~1.412 degree increments) with 0 degrees representing the New Moon, 63 (~89 degrees) representing the First Quarter, 127 (~179 degrees) representing the Full Moon, and 191 (~270 degrees) representing the Third Quarter Moon. Using the calendar date, time, and Moon phase in degrees as known reference points of the position of the Moon with respect to it being between the Earth and Sun, the Python script then calculated the difference in time between each successive known reference point while factoring in leap years and leap centuries. This difference in time along with the Moon positional data points were then used to linearly interpolate the Moon's position at each hour between 1500 and 2500 AD. This motor position was then converted into hexadecimal and stored into a csv file. On each line in the .csv file, the first data point was made up of the year, day of the year, and hour of the day each in binary and then concatenated together into one value. This value would be used as the data point address within the database. The second value would be the motor position in one hexadecimal.

After each .csv file was created, they were then combined using the Panda Python plug-in into a new .csv file with two hexadecimal motor position values per line. Each line represented each successive hour from 1500-2500 AD. This .csv file was then manually converted with Excel into a tab delimited .txt file.

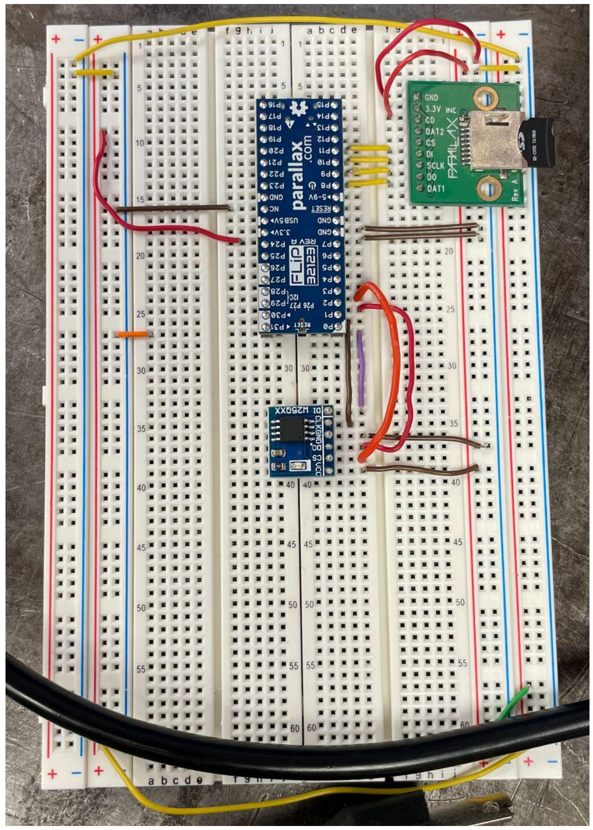

Figure 22. Circuit used to transfer data from SD card to Serial Flash Memory chip

Our Data Reading and Writing circuit as shown in Figure 22 was made up of the following components:

- ➢ Propeller 1 (P1) Microcontroller (1)
- ➢ SD card (1)
- ➢ Parallax Micro SD Adapter Kit 32312 (1)
- ➢ W25Q64JV Serial Flash Memory Chip (1)

The SD card was first connected to the computer. The motor positional data was stored on the computer in a Tab Deliminated .txt file. This .txt file was then transferred onto the SD card, which was then connected to the circuit shown in Figure 22 using a Parallax Micro SD Adapter Kit 32312. The Propellor 1 chip was loaded with a Spin1 script from a usb connected computer. The Propellor 1 chip then used this script to read data from the SD card and then wrote this data onto the W25Q64JV Serial Flash Memory Chip through the use of 4 pin SPI.

The Spin1 code was built off of the foundations laid by the following Spin1 scripts:

- ➢ PST_Driver.Spin (Gavin Garner and Michael Myers, 2008)
- ➢ SD Card to W25Q64 Data Transfer v3.Spin (Gavin Garner, 2022)
- ➢ SD-MMC_FATEngine.spin (Kwabena W, Agyeman, 2011)

➢ Write_To_Memory_Chip_W25Q64_v7.spin (Gavin Garner, 2022)

"PST_Driver.Spin" provided a way to create a debug screen using the Propellor 1 Chip, which was useful in the development of the final code used in this project. "SD Card to W25Q64 Data Transfer v3" was the primary script that was modified for the final code for this project. This program calls "SD-MMC_FATEnginer.spin," which allows for SPI between the Propellor 1 chip and the SD card, along with reading and writing capabilities. Using this, the .txt file on the SD card was read and the hexadecimal representations of the motor position degrees were converted into binary using the "ASCIItoBinary" method in "SD Card to W25Q64 Data Transfer v3". A new page was opened in the Serial Flash memory chip, and a 256 byte group of motor positions was written into the page, with even byte indexes referring to Lunar Motor Positions and odd byte indexes referring to Earth-Rotational Motor Positions.

3.4 Meshmixer and the Moon 3D Print

Another unique part of this project is the 3D printed Moon model. We wanted a Moon that was as technically accurate as possible while also being aesthetically pleasing. We found an STL file of the Moon on the open source digital design sharing website Thingiverse (Dexter_New_Materials, 2015). This file used topographical data from NASA to create an extremely realistic model of the Moon's surface.

Once we had the file for the Moon, we needed a way to attach it to the acrylic hanger that suspends the Moon from the lunar arm. We designed a connector in SolidWorks that would be attached to the Moon and would allow a bolt to pass through it. This is the small rectangular extrusion above the Moon as seen below in Figure 23. We then saved this file as an STL so it could later be combined with the Moon.

As mentioned earlier, the 3D model of the Moon was an STL file which means the part's geometry was defined by thousands of small precisely-positioned triangles also known as a mesh. In order to edit this mesh, we used Autodesk's Meshmixer tool. Meshmixer is a software that allows a designer to easily edit triangular meshes in a wide variety of ways. The first operation we performed was scaling the Moon. To make our orrery as accurate as possible, we wanted the relative size of our Earth and Moon models to be the same as the true Earth-Moon diametral proportion. Since we had already chosen an Earth model that was 8 inches in diameter, we needed a Moon that was 2.18 inches in diameter. Using Meshmixer's "Scale" operation, we were easily able to make the Moon model exactly 2.18 inches in diameter. Next we needed to hollow out the Moon to save 3D printing material and decrease weight. In Meshmixer, we created a 1.98 inch diameter sphere and positioned it in the middle of the Moon. We used the "Boolean Difference" operation to cut away this sphere and leave a hollow Moon with a uniform thickness of 0.1 inches. Lastly, we needed to combine the Moon with the connector piece designed in SolidWorks. We imported the connector and used the "Remesh" command to smooth its mesh and make it compatible with that of the Moon. Then we positioned the connector in the correct spot and used the "Boolean Union" operation to merge these two bodies into one. The final model in Meshmixer can be seen below in Figure 23 (left).

Once we had an accurately sized hollow Moon with an attached connector, we sent the new STL file to a software package called Preform to prepare the 3D print. Preform sliced the given STL file into the layers that the 3D printer will sequentially build. This software also automatically defines the location of support material which ensures that the full geometry of a part can be built from the bottom up. The support structure generated by Preform can be seen below in Figure 23 (center). Once this slicing was complete, we uploaded the file to a Formlabs Form 2 resin 3D printer. 16 hours after it began, the 3D print was finished. It was taken off the print bed, washed in isopropyl alcohol, and cured in a heated ultraviolet chamber. Finally, the support material was removed and our 3D printed Moon model was complete as seen below in Figure 23 (right).

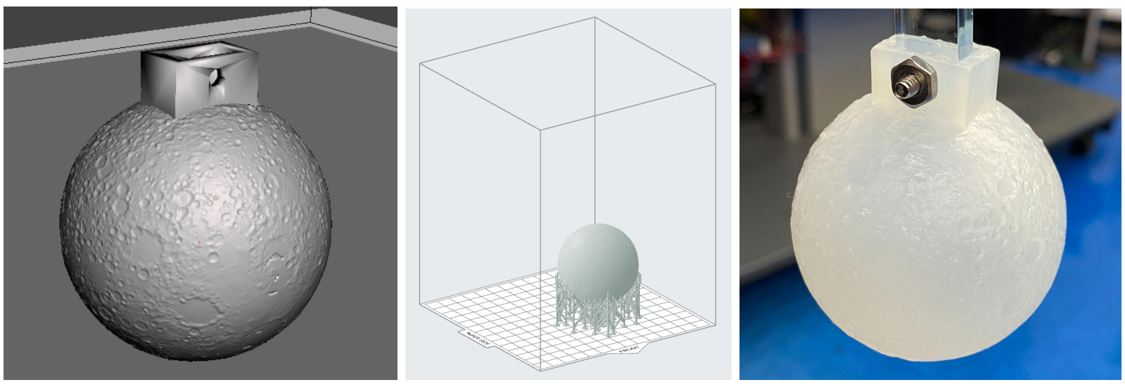

Figure 23. Moon model in Meshmixer (left), Moon model and support structure in Preform (center), 3D printed resin Moon (right)

4. Conclusions and Future Work

There were many things that went well in this project and many that didn't. We were unable to fully assemble the physical model because the 24" lazy susan bearing and hollow slip ring weren't delivered. This required us to keep the two systems separate, demonstrating their functionality independent of each other. We were able to successfully demonstrate the homing of the Earth in its orbit, the Earth's rotation, and the Moon's rotation. The motors were then able to move to set target positions. Many things we had planned were not incorporated into our final physical model. An outline of future work to be done on the orrery will be given in the following subsection.

4.1 Future Work

<u>Completing the Assembly:</u>

As it stands, there are a few more mechanical things to accomplish before the system described above is complete. First, we need to receive the large lazy susan, drill four 0.2 inch diameter holes on the inner ring, tap those four holes with ¼"-20 threads, and drill one 0.26 inch diameter hole on the outer ring. Then the inner ring can be connected to the X-frame with the threaded male-female standoffs that we already have, and the outer ring can be connected to the 80-20 arm with a ¼"-20 bolt. We also need to receive the hollow slip ring that sits in the middle of the assembly and wire that. Once we have these few things sorted out we can bring together the full orrery assembly.

Homing the Earth Correction Motor:

Unfortunately, our plan for homing the Earth correction motor did not pan out. We tried to put a homing mount on the gear driven by this motor, but it was just too small and caused interference as it rotated. To robustly complete this design, we need to be able to home this motor. This means we will have to somehow put a piece of metal on the driven gear and redesign the motor mount and concentric shaft to allow easier access to the proximity sensor. There are a number of ways that this can be executed, so picking one method and implementing it is a necessary future task.

User Interface:

An important facet of our design that did not come to fruition was the user interface. Our plan was to have a system that a user could input a date into. The date would be processed and the motors would move to reflect the accurate position of the Earth and Moon at the given date. We had envisioned block numbers representing the date that could be changed with knobs and confirmed by the press of a button. Building this is a necessary step towards completing our original design concept.

Completing Database System:

An essential aspect of our system is that it would be able to accurately model the movement of the Earth-Moon system around the Sun, the Moon's orbit around the Earth, and the Earth's rotation. A database was created with the positions of the Moon in its Orbit and the Earth's rotation. The ability to write this database onto a SPI Flash Memory Chip was proven, but the SPI Flash Memory Chip was not large enough to store all of the data which. Therefore we require either a larger chip, several chips that can be accessed by the microcontrollers, or a combination of the two. Additionally, the ability to call specific addresses for each required motor position was not proven or completed due to running out of time. Furthermore, in order to reduce the memory requirements on the database and allow for each motor position to be stored using only one byte, conversion from the degree-based positions of the Earth's rotation and the Moon around the Earth into encoder counts would need to be done in the microcontroller after it pulls the degree data from the database. However, the math required would be quite trivial only needing to multiply each degree-based data point by a number in the thousands place which is defined by the two motor gear trains.

Creating Auxillary Microprocessor Motor Postional Data Code:

A database was created that could be used by the microprocessors within the system to contrtol the rotation of the Earth as well as the Moon's positions around the Earth. In order to determine the position of the Earth-Moon System in its orbit around the Sun at any given time, the Microprocessor would have to use relatively simple code to take the day of the year, divide it by 365, and then multiply this by 360* to determine the degree position that the Earth-Moon

System would be around the Sun. This code has not yet been written or tested. Additionally, the code to determine the orientation of the axis of the Earth as facing the North Star would work by adjusting its orientation 1:1 to the movement of the Earth-Moon System around the Sun to compensate with the change in axial direction that will come with the Earth-Moon system movement. This code has also not been written or tested.

Mounting the Sun:

One thing that we did not plan or accomplish is mounting the Sun. From the beginning we wanted a more artistic Sun rather than another sphere. We had a Sun manufactured out of glass by Kevin Knight which can be seen below in Figure 24. However, we did not get to talk to Mr. Knight and plan how this piece will be mounted. Determining the best way to accomplish this and executing it is certainly a necessary step in the future of the project.

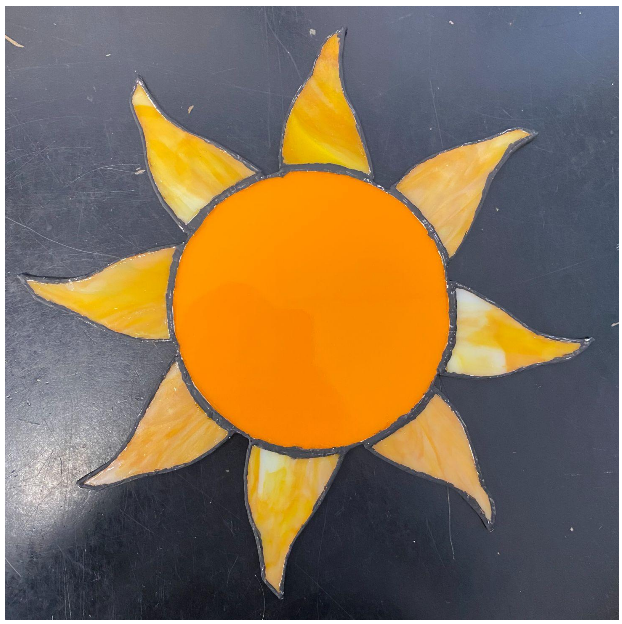

Figure 24. Glass Sun created by Kevin Knight. For reference, a circle that approximately connects all of the outer tips is about 12 inches in diameter. In the future, this will be mounted to the central shaft and suspended down to be on the same plane as the Earth and Moon.

Adding a Lighting Source:

It would be beneficial to add a lighting source that points towards the extended Earth-Moon system. We think that mounting the light to the 80-20 arm would work well because the light would be kept focused on the Earth. If the light is held steady on the same plane as the Earth and Moon, then viewers can be shown sunrises, sunsets, and Moon phases. This is an important next step in maximizing the education benefit of our orrery.

Adding an LED to the Moon:

One small improvement that could be easily implemented is adding a small LED inside the 3D printed Moon. This would help to illuminate the detailed textures on the surface of the

Moon. To accomplish this, very thin wires would need to be run from the Moon, up the acrylic Moon holder, along the lunar arm, and connected to a slip ring. We would likely use a hollow slip ring for this, allowing the wires from the slip ring connected to the lower shaft to pass through its middle. This would be a nice finishing touch to make our orrery even more aesthetically pleasing.

Adding the Moon Tilt Function:

As previously mentioned, we wanted our Moon to orbit the Earth at an angle, and we included a removable arm in our design to allow for that possibility. Right now, the arm is locked in position, and the angle cannot be adjusted. Even if we were to tilt the Moon, the orbit would not have the shape of a tilted disk like it's supposed to. In the future, the design would need to incorporate another motor (possibly another offset-motor-and-gear setup like what we've used for the rest of the design) to move the Moon arm up and down. This movement would require its own programming as well. The wires for this motor would connect to the same slip ring as the Moon LED.

Mounting the System to the Ceiling:

Our orrery was designed to be displayed in the circular alcove in the ceiling near the entrance to room 216 and 217 in the Mechanical Engineering Building. When our system is fully put together, the stationary metal X-frame can be mounted to something in the ceiling. We would also need to access the building power and connect that to our system. Currently, we do not know how either of these tasks would be accomplished, but getting this done is an important step in bringing this project to fulfillment.

Adding Additional Planets:

Adding more planets would be a big step in making our orrery exceptional. This would require at least one more motor and arm per planet. Additionally, if the chosen planets are further away from the Sun than the Earth, we would need to mount the orrery somewhere else because currently the Sun-Earth-Moon system fits perfectly its intended location. Nonetheless, expanding this system to include more planets would be challenging but extremely valuable to our orrery.

4.2 Reflection

Designing, prototyping, and manufacturing this orrery proved to be a challenge that helped the entirety of our team grow and become better engineers. We have become quite proficient in SolidWorks, 3D printing, laser-cutting, and tapping. In addition to this, we have become more familiar with the difficulty of manufacturing metal parts with appropriate tolerances. We found that slots are very useful for assembling parts with lower tolerances. We have also learned a great deal about motor control, sensing, microcontrollers, digital memory and electrical wiring. This orrery was an incredibly ambitious project. We knew from the start that it would be difficult to incorporate everything we wanted given our time frame and budget. Despite not being able to incorporate all the features we envisioned, producing a physical model that came together and moved in the manner we intended is something that we are very proud of.

5. Acknowledgements

- ➢ Thank you to Professor Gavin Garner for your many contributions to our projects. Professor Garner helped our group from the very beginning by giving us great ideas and helping us with both machining and welding for our project.
- ➢ Thank you to Mechanical and Aerospace Engineering Department faculty member Kevin Knight for creating a beautiful glass Sun for us.
- ➢ Thank you to Clemons Library staff member Ammon Shepherd for letting us use his resin 3D printer for our Moon model.

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