2022 STAGE MACHINE DESIGN COMPETITION

DESIGN PROPOSAL

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INTRODUCTION

For this project, the team from the University of Arizona will design and implement a mechanism to control a "crazy clock" for the hypothetical production of *All in the Timing*. For this competition, the team will design and fabricate a prototype according to the requirements listed below, and we will present our finished model in early May, to a panel of judges. After reviewing the competition parameters, our team has developed the following project goals and constraints.

1. PROJECT REQUIREMENTS

1.1. Operational Requirements

- The clock will have three hands: second hand, minute hand, and hour hand.
- The three clock hands must rotate on separate axes with specific angular velocities in relation to each other.
- There are two (2) specified movements for the clock hands which will be referred to as Movement 1 and Movement 2.
    - For Movement 1
        - The second hand must rotate at 180 revolutions per minute (RPM) clockwise (CW).
        - The minute hand must rotate at 3 RPM CW.
        - The hour hand must rotate at 0.25 RPM CW.
    - For Movement 2
        - The second hand must rotate at 60 RPM counterclockwise (CCW).
        - The minute hand must rotate at 3 RPM CW.
        - The hour hand must rotate at 0.5 RPM CCW.
- Only one (1) actuator may be used to drive the three (3) clock hands.
- The mechanical systems must be "as quiet as possible."

1.2. Physical Requirements

- The clock will have a circular face with a radius of 1-foot.
- Any mechanical systems must be hidden behind the 1-foot radius circular face of the clock.
- The team is not responsible for matching the artwork in the provided design documents (see APPENDIX A).
- The clock will have three hands (second, minute, and hour) made of ⅛" plywood which will be on three separate axes. See Appendix A.
- Taking the center of the clock face as (0,0) with +x-axis to the right and +y-axis upward, the second hand will be located at (4", 5"), the minute hand will be located at (-7 ¼", -2"), and the hour hand will be located at (7", -7").

1.3. Competition Requirements

- A working prototype of the design must be presented in front of judges to test the effectiveness of the design.
- Movement 1 and Movement 2 will each operate for one (1) minute during testing of the prototype.
    - Up to 15A 110-120VAC power will be available during testing.

  - 100 PSI air pressure will be available during testing available by 1/4” tube or quick-connect - must request by May 1, 2022.
- During the testing of the prototype, each team will have a total of twenty (20) minutes in which to perform Movement 1 and Movement 2 and make any necessary adjustments between the two movements.
- A design document must be submitted along with the prototype which includes:
  - the proposal,
  - detail design materials (estimates, parts lists, technical drawings, appropriate mathematical/engineering analyses, etc.),
  - as-built drawings of the prototype,
  - documentation of actual costs,
  - any relevant safety and/or operation manuals,
  - assessment of successes/failures of the design,
  - and assessment of successes/failures of the team.

2. DESIGN RESEARCH

We became aware of this competition as we were exploring concepts related to gearing and angular motion in our graduate level physics class. This project represents an excellent way to continue this work by providing us a practical application for our work on designing systems with rotational motion. We first researched the physics and mechanics behind the way normal mechanical clocks operate. We looked at the various components in a typical clock system, including the rotational motion input (such as a motor or weights), the shaft design, the gearing used in the system, and the housing for the system. We then continued our work by researching how to modify these components to suit this theatrical application, as outlined in the following sections.

2.1. Kinematics

2.1.1. Velocity Ratio

An essential part of this project is understanding the physics involved in rotational motion. Because there are specific requirements on the rotational velocities of the clock hands, we must understand how to control this type of motion. An important concept in the design of systems with rotational motion is the relationship between velocity ratios and gear ratios. To control the required rotational velocities of the three clock hands, we will utilize the velocity ratio (VR) equation (Eq. 2.1).

$$VR = \frac{speed_{out}}{speed_{in}} = \frac{size_{in}}{size_{out}} \tag{2.1}$$

In this equation, $size_{in}$ and $size_{out}$ could be the gear tooth number, wheel radius, wheel diameter, or another size value convenient for the situation. Likewise, $speed_{in}$ and $speed_{out}$ could be the most convenient unit of speed, whether that is in radians, degrees, or rotations. Using the velocity ratio equation allows us to determine the necessary gear or wheel sizes for the input and output gear/wheel based on the required speeds for the input and output shafts. Because the velocity ratio is a unitless value, this gives us more freedom when using it because the velocity ratio for a mating gear/wheel pair will always be the same; the sizes and speeds must change in relation to one another.

2.1.2. Compound Gear Train

Using a velocity ratio, we will determine the necessary gear ratios from an input shaft to an output shaft. However, because the design parameters create instances when the gear ratio is too large to practically accommodate a direct gear reduction, such as a gear ratio of 1:60 from the second hand to the minute hand in Movement 1, we see the need for a system that incorporates the use of compound gears. Rather than using one large gear with a 30in diameter and one smaller gear with a 0.5in diameter, we can utilize a compound gear train to break the ratio into between two or more gears. This allows us the freedom to break the gear ratio from 1:60 into one at 1:6 and one at 1:10, which is equivalent to 1:60. Figure 2.1 below shows an example of a compound gear train.

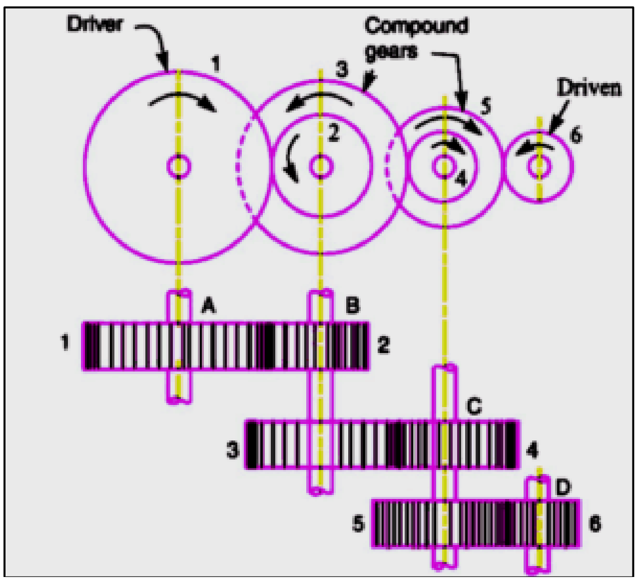

Figure 2.1. *Example of compound gear train which is a concept that we will utilize in our design. [1]*

2.1.3. Idler Gear

The idler gear is an important design concept that allows us to explore efficient ways to change the direction of a gear without changing the output rotational velocity (in relation to the input rotational velocity), as illustrated below in Figure 2.2. An idler gear sits in line with both the driving gear and the driven gear as opposed to being on the same shaft as the driving gear and in line with the driven gear. This allows the gear to have no effect on the rotational velocity of the gears but does change the direction, making the driving gear and the driven gear rotate in the same direction. Because there are directional changes involved when changing from Movement 1 to Movement 2, the idea of including idler gears in our design became an important focal point in the design of our system.

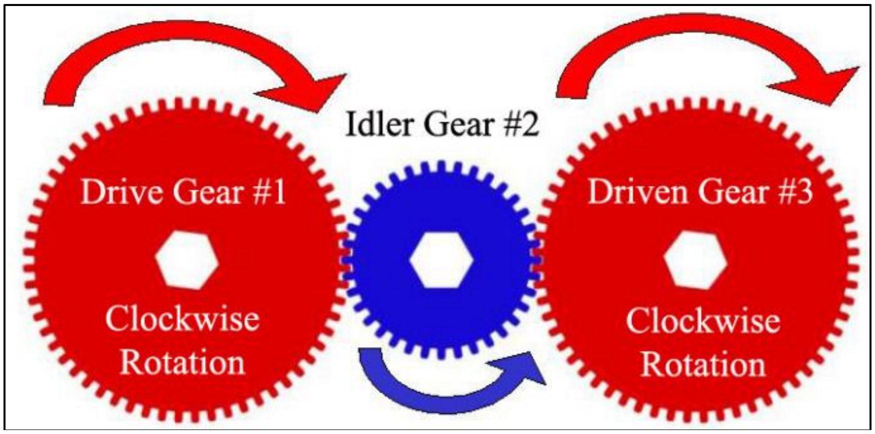

Figure 2.2. *An example of an idler gear used to change the direction of the driven gear. [2]*

2.2. Drive System

2.2.1. Gears

Initially, our team investigated using gears to transfer rotational motion and power from our input shaft to the three shafts with the clock hands, believing gearing would be a simple solution to give us control over the speeds of each hand. However, given the dimensional constraints of the clock face and the asymmetric positioning of the clock hands, we moved away from a purely gear-based design.

Figure 2.3 below shows an early version of our gear-based design. This design achieved the necessary velocity ratios, within the stated constraints of the hand placement, but we ultimately determined this to be an overly complicated solution, requiring up to 17 different shafts for just the first movement.

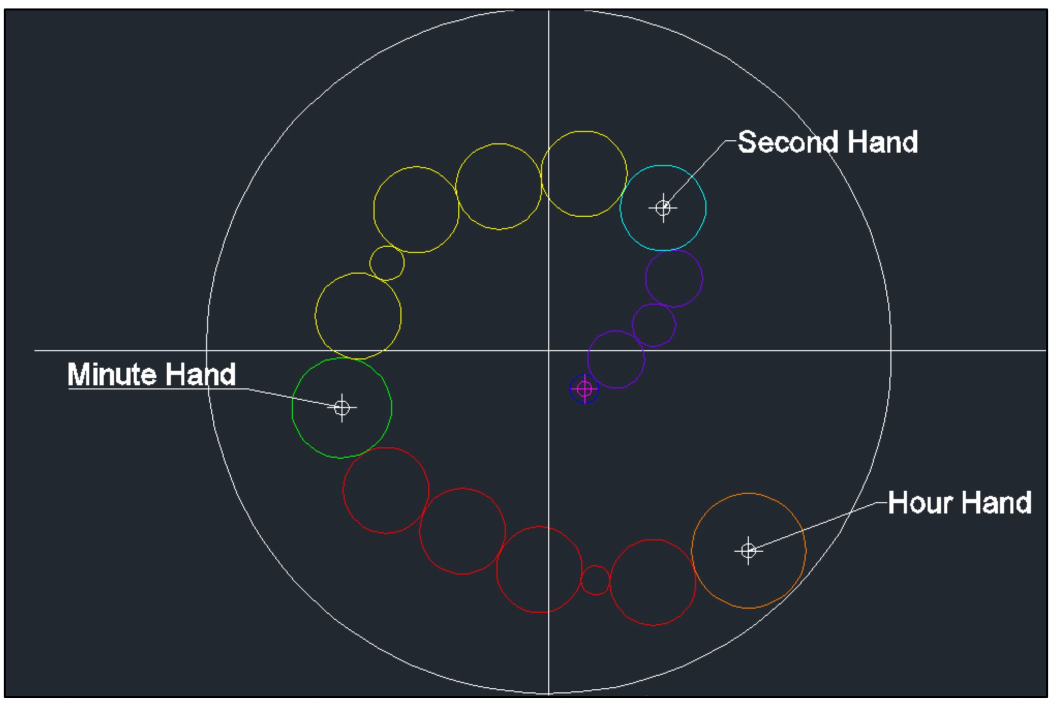

Figure 2.3. *An initial design concept using only gears in the system.*

2.2.2. Friction Drive

We then considered the use of friction drives to limit the complexity of the system. Specifically, when considering how to employ the idler gear during the shift from movement one to movement two, we foresaw an issue related to the meshing of the alternate gear train into the existing system. We thought the use of a friction drive would allow us to eliminate the potential risks that a purely gear-based system created. However, while considering this new approach, we developed a design that allows us to eliminate the need to switch gears altogether.

2.2.3. Belt Drive

In our next design iteration, we explored the idea of using belt drives instead of gearing. We determined that using a belt system would provide us more freedom when positioning the compound gears in relation to the specified placement of the clock hands. This conceptual leap proved to be an important step in our design process because it allowed us more freedom and opened new design paths for us to explore as we began considering the mechanics involved in changing between movement one and movement two.

Figure 2.4, shown below, is an example of one of our initial design solutions for Movement 1 using the belt drive model. In this design paradigm, we gained more flexibility in the placement of the intermediate drive wheels between the input shaft and the clock hands as well as in the design of the speed ratio and directional changing system.

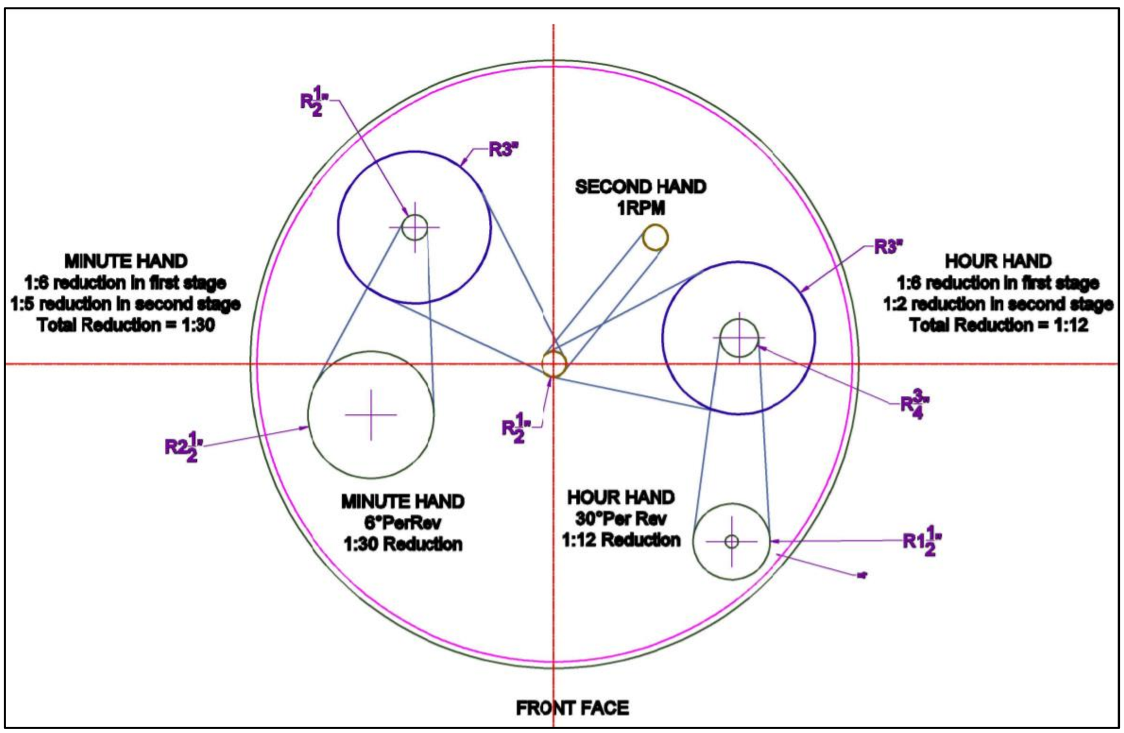

Figure 2.4. *An initial design concept using only belt drives in the system.*

2.3. Switching Mechanism

We had several ideas for a mechanism which we will use to switch from Movement 1 to Movement 2, which we call the "Switching Mechanism." Outlined below are two of the methods we explored in developing the Switching Mechanism.

2.3.1. Sliding Gears

The first method that we explored to design the Switching Mechanism was a set of two driving gears (one for Movement 1 and one for Movement 2) that would slide along an axis and could be engaged or disengaged from the driven gear depending on whether it was Movement 1 or Movement 2. Below is a drawing of the system with hypothetical ratios chosen shown in for Movement 1 (Figure 2.5) and Movement 2 (Figure 2.6).

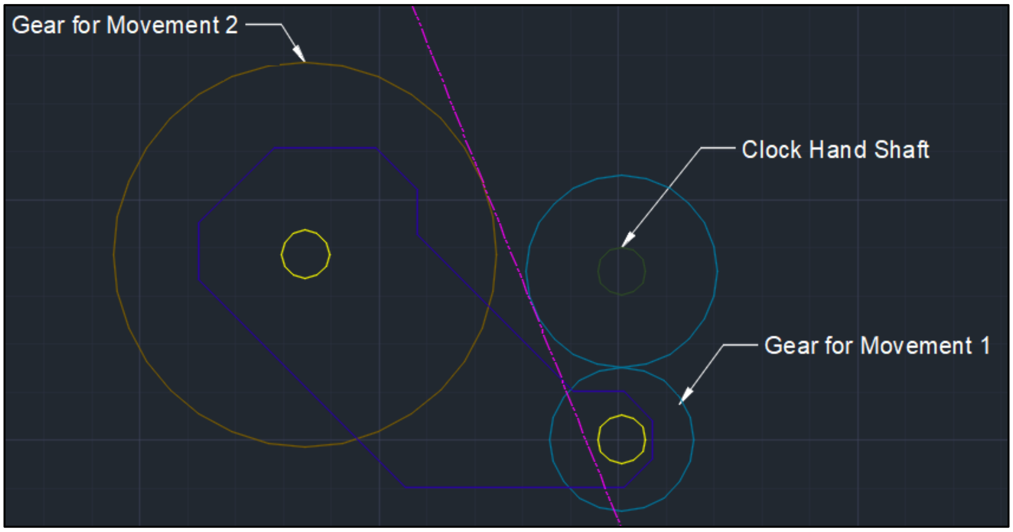

Figure 2.5. *Location for Movement 1 of switching mechanism using sliding gears.*

Figure 2.6. *Location for Movement 2 of switching mechanism using sliding gears.*

This method was successful in allowing us to visualize the switch from one movement to the next. However, this is an overly complicated solution, requiring us to design and implement a system that allows the shafts to slide along a tangential axis. We also identified sizing issues in the shift between Movement 1 to Movement 2, adding another unnecessary level of complexity.

2.3.2. Concurrent Systems

We then explored creating two separate systems specific to each movement, in which the system can be engaged or disengaged to produce the desired motion. The change in direction is achieved by utilizing a removable pin on the input belt drive for both systems. Figure 2.7 shows an example of the drive wheel design with the removable pin to control which system is engaged. The disengaged system will not affect the movement of the clock hands, thus only one system will be active at any point. Figure 2.8 shows an example of the two concurrent systems using belt drives and gearing.

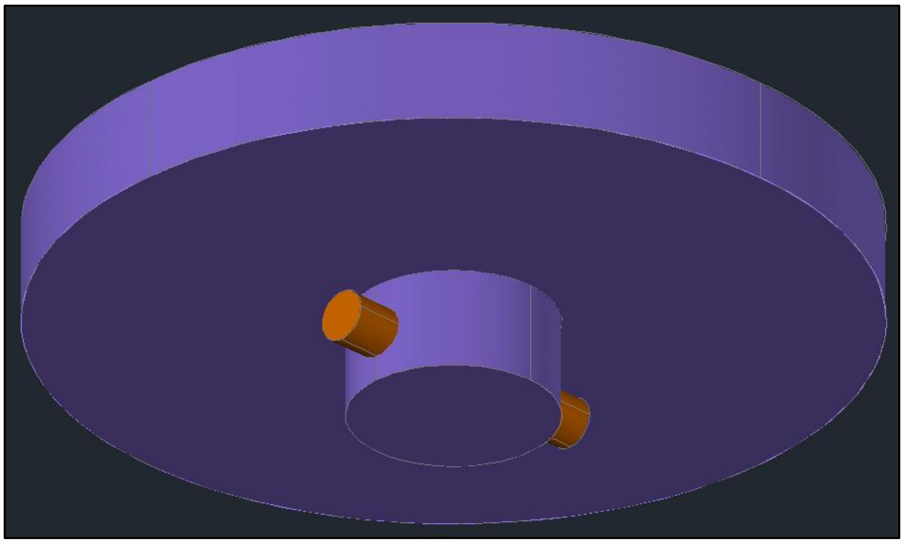

Figure 2.7. *3D model of gear and belt drive wheel design (purple) with a removable pin (orange) which can be used to engage or disengage the gear/wheel, allowing the wheels to spin freely or engage on a shaft (not shown), thus driving the rest of the system.*

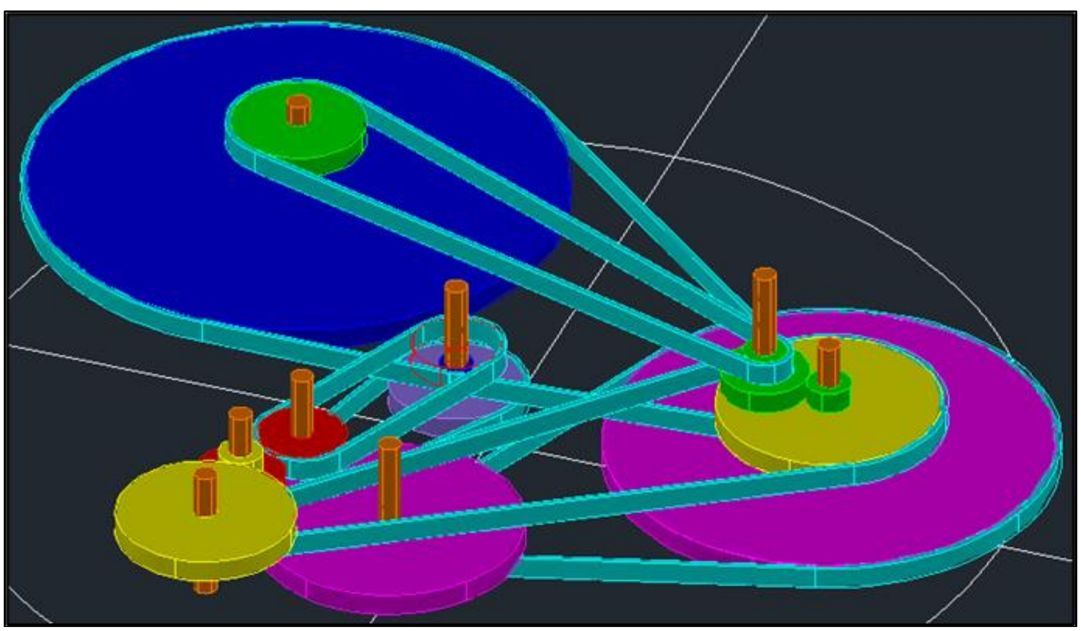

Figure 2.8. *The first design iteration of the concurrent system using gears and belt drives.*

3. DESIGN CONCLUSIONS

After researching and examining the different design solutions outlined above, we have chosen what concepts to include as we move forward with simplicity of the system, practical design, and manufacturability as our governing values. The following sections outline our choices to pull together our design concepts into a cohesive unit and our justifications for those choices. Further, we also outline our fabrication plan for the various system components.

3.1. Mechanical Design

3.1.1. Input Motor

For our drive system, we have chosen to use an electric motor as our input actuator to maintain consistent speed for the 1-minute duration of the clock movements. We will be choosing a motor based on the following criteria:

1. Ability to accurately control and measure the rotational velocity of the output shaft.
2. Ability to maintain consistent velocity throughout rotation with no accelerations or decelerations.
3. Rotational velocity output in the range of 1-3 RPM.
4. Powered by 120V AC power or powered by battery.

3.1.2. Drive System

For the drive system, the team has chosen to use a combination of both belt drives as well as gears. We found that by using belt drives in our design, we had more freedom with placing the shafts of the clock hands in their required locations. Because the placement of the clock hands is a primary design requirement, being able to accurately place these was an important part of our design process.

We found that we could also utilize gearing in select locations to control the directions in which our shafts are turning.

3.1.3. Switching Mechanism

To switch from Movement 1 to Movement 2, we will pursue the design which we call a concurrent system, in which both systems (one for Movement 1 and one for Movement 2) exist at the same time, but only one is engaged and active at any time. This design solution gives us the ability to switch between movements quickly and efficiently by only removing and adding a few pins to engage one system and disengage the other. Figure 3.1 shows a version of the concurrent system which we will be implementing in our design.

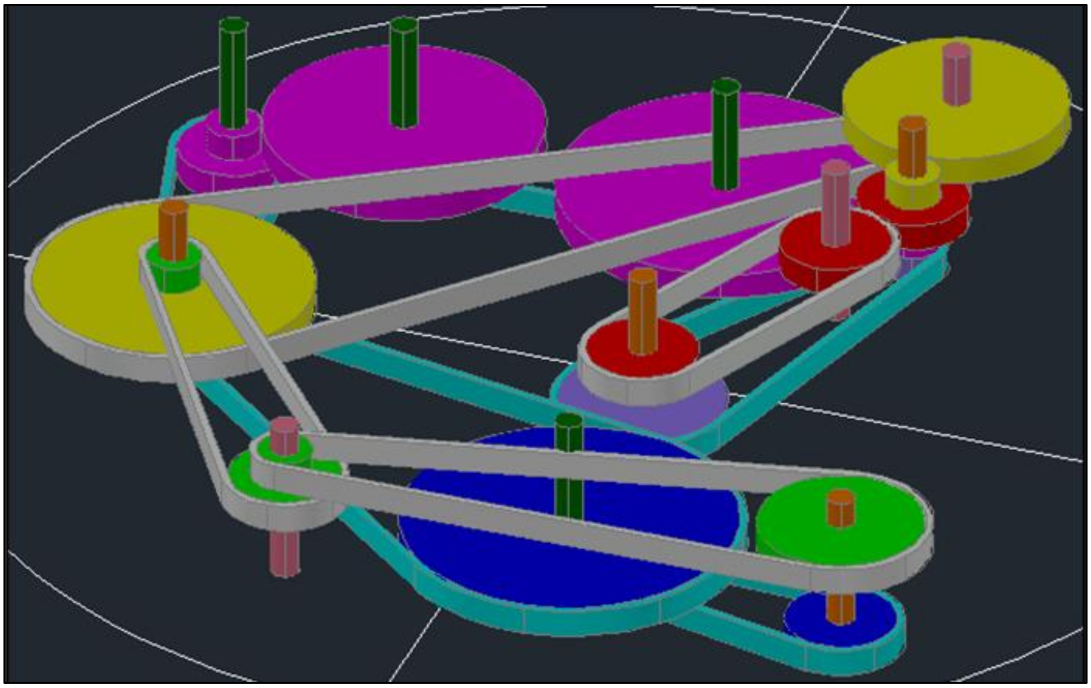

Figure 3.1. *The second iteration of our switching mechanism which we call the concurrent system using gears and belt drives.*

3.2. Fabrication

3.2.1. Gears and Belt Drive Wheels

To fabricate accurate gears that are accurate to our design needs, we will be utilizing additive manufacturing methods based on our custom gear designs. This will give us the freedom to determine the gear design that we need (teeth, diameter) and eliminate a constraint of only using pre-made gears. We will be designing our gears based on the required velocity ratios and then utilizing the gear design module in Autodesk Inventor to create three-dimensional models of the gears (Figure 3.2) and convert the models into .stl files for fabrication on a 3D printer.

Similarly, we will also be utilizing Inventor to design the belt drive wheels used in our system (Figure 3.3). Then, from the 3D objects designed with Inventor, we will fabricate them using a 3D printer. However, the design for the drive wheels will be based on the required velocity ratios only as the defining factor of the belt drive wheels is the wheel diameter. By fabricating our own gears, we will be able to add custom features to the design such as the addition of a removable pin to engage the required shaft.

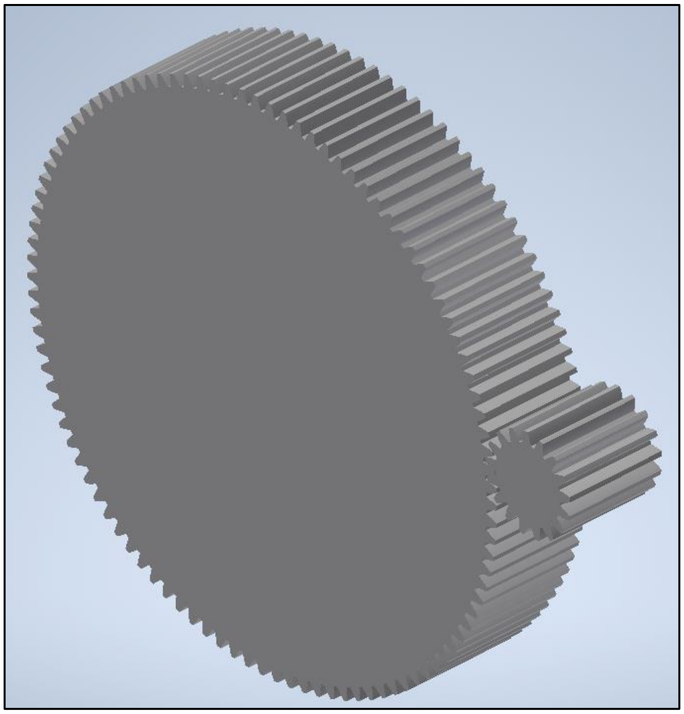

Figure 3.2. *Sample gear 3D models using gear module in Autodesk Inventor by inputting velocity ratio and gear diameter.*

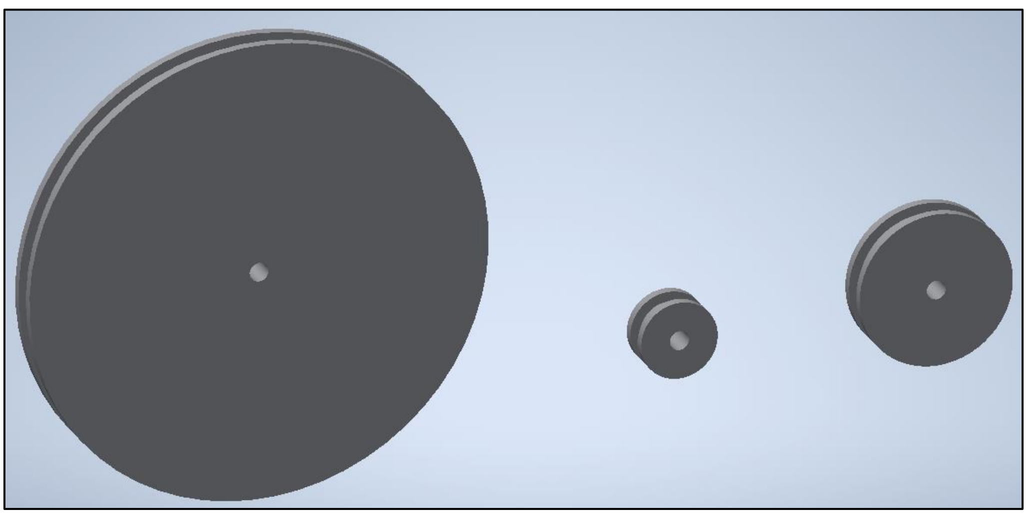

Figure 3.3. *Sample belt drive wheel 3D models using Autodesk Inventor.*

3.2.2. Support Structure

We will be fabricating a custom support for the system by designing two plates (one for the front and one for the back) with specified holes for the shafts. As with the drive wheels and gears, we will be fabricating this with 3D printing. The support for the shafts will also act as a housing for the system and as a safety mechanism to ensure that nothing will get tangled in the system while it is operating. The support will house the shafts, the drive belts and wheels, the gearing, and the electric motor for the system.

3.2.3. Clock Face

We will be using a laser cutter to fabricate the clock face and the clock hands. Using a laser cutter will provide us with the precision we need to cut out a perfect circle for the face of the clock out of plywood. Further, we will also be able to accurately replicate the hands of the clock using the laser cutter as it provides high precision cutting.

APPENDICES

Appendix A: Clock Face Schematics

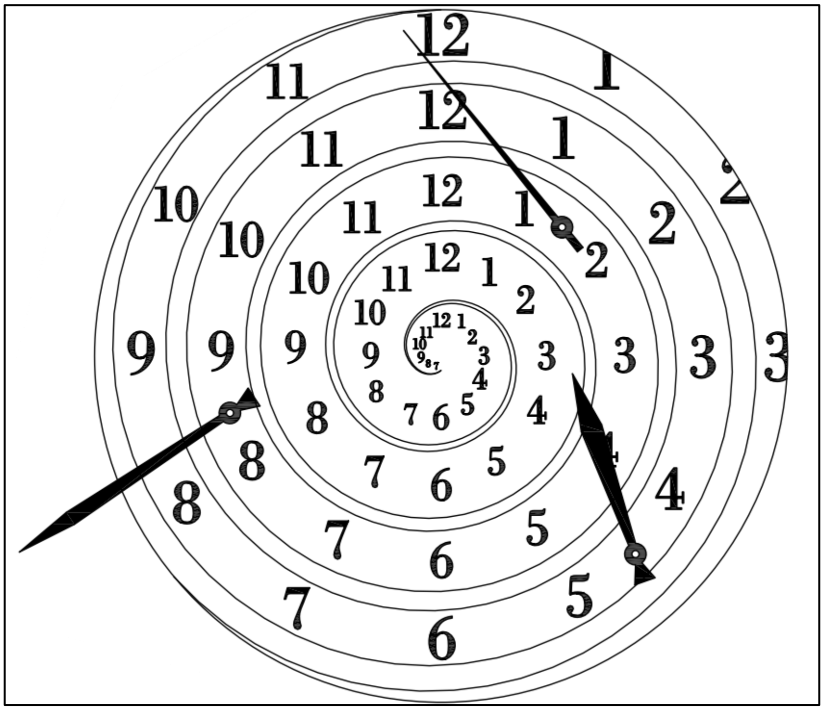

Figure A.1. *The front face of the clock (as seen from the audience) showing the artwork that will appear on the clock. Note: this artwork is not a requirement for this competition.*

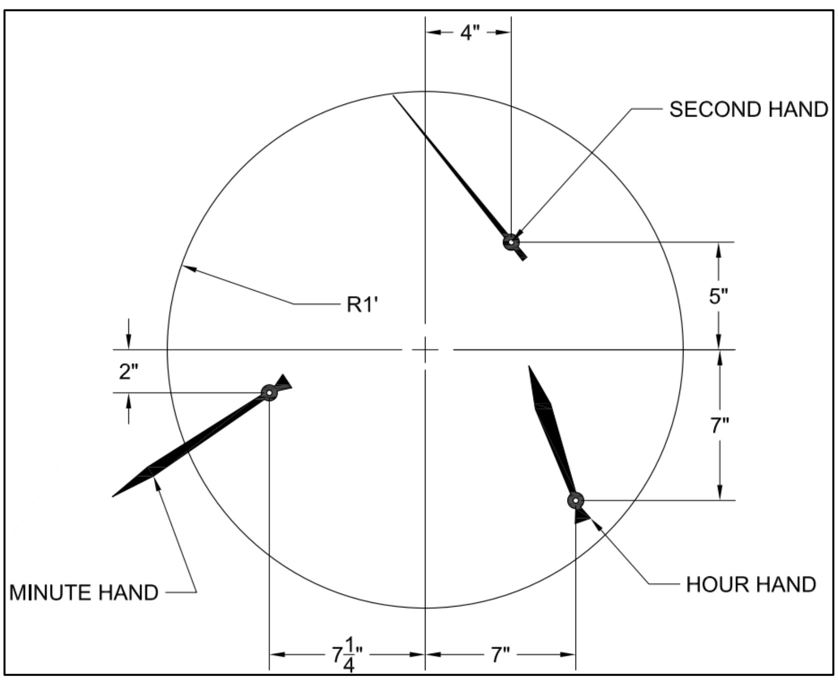

Figure A.2. *The front face of the clock (as seen from the audience) showing the exact placement of the clock hands.*

Appendix B: Table of Figures

BIBLIOGRAPHY

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[3] Martell, Eric C., and Verda Beth Martell. *The Physics of Theatre: Mechanics*. CreateSpace Independent Publishing Platform, 2016.