Design of a 3D Printable Time Simulating Solar System Model

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ABSTRACT

The previous paper presented at the 2016 FCRAR discussed the research topic of creating time simulating solar system models. This paper is an overview of the work done over the passed year in solar system model creation and the potential future work in STEM education. The use of designed tools to assist with relating abstract ideas to reality is now a possibility with the use of the modern manufacturing method of 3D printing. A 3D printed solar system model was designed and printed. Research was conducted to relate the history of mechanical engineering and the solar system to STEM education through the use of the solar system model. The inner four planets' natural orbital periods with respect to Earth were modeled in SolidWorks and then fabricated using 3D printing. A 3D printable mechanical time simulating solar system model used in science, technology, engineering, and mathematics (STEM) could assist with the user's understanding of the history of science, planetary orbital mechanics, gearing ratios, 3D printing, and systematically constructing a project using instructions. This paper describes the design of a 3D printable time simulating solar system model and how its construction could be used to teach the history of mechanical engineering and the abstract idea of the solar system. The combination of these two ideas could inspire users to learn, pursue coursework and, eventually, a career in a STEM field.

Keywords: STEM Education, Solar System, 3D printing

1. INTRODUCTION

The development of the solar system model started with the idea of a project around space science, mechanical systems, 3D printing, and a possibility to make something original on the subject of solar system models. This proposal was published at the FCRAR in 2016 [1] and a master's thesis was completed on the topic [2]. Researching the history and functions of mechanical clocks was a significant area of focus which allowed the project to work as designed. The project had two main research focus points, the first being designing a functional solar system model, the second being how 3D printable systems can be built and function as designed. Tolerances played a large role in the parts meshing properly; more work can be done on the trends and charting of 3D printed tolerances. By expanding the goals of the project to include more than building the solar system, a STEM education focus with the history of science became a large area that allowed for significant research. Beyond the completion of the project build, a background of where the solar system model came from allowed for a STEM education application. Looking into the background of where a heliocentric system originated led to a journey of the birth of mechanical engineering through the study of the night sky and Sir Isaac Newton's laws of motion. The impact of the work could be seen as a view of where the field of mechanical engineering originated, the study of the planets, and how continuing that study is relevant to current engineers and scientists as well as for STEM education as space programs are planning to send humans to Mars and beyond.

2. THE SOLAR SYSTEM

The development of a solar system model required research into mechanical systems that were developed to teach the solar system from the past. There were three main mechanical teaching systems that dominated the science of astronomy until the invention of the telescope in the early 17th century [3]. These three tools allowed for predicting the orbits of moon and planets, telling the time by using the Sun and the date, and teaching visually how the dates are based on the equinoxes, perihelion, and aphelion of the Earth's orbit.

1. **Celestial Globes:** Ptolemy, an authority on the solar system during the 2nd century AD Alexandria, created a celestial globe to teach astronomy [3]. The device can be seen in Figure 1a. This mechanical system was the first proposed mechanical calculator for astronomy capable of making complex spherical triangle calculations of the stars by using physical representation rather than 2D drawn or painted images of the night sky[3].

2. **Astrolabes:** The astrolabe is a mechanical calculator that is similar to a celestial globe in its calculations, but different physically as it uses numbers and dials to display the results as shown in Figure 1b. Astrolabes were used by astronomers and navigators to determine local time using latitude and Sun or planetary positions [3]. The written theories and uses of the astrolabe are accredited to Hipparchus. Although he did not invent the astrolabe, his work in astronomy contributed

(a) Celestial Globe [4]

(b) Astrolabe [5]

(c) Armillary Sphere [6]

Figure 1: Three typical astronomical devices used before mechanical clocks were developed [3]

greatly to understanding the calculations made possible by using the device.

3. **Armillary Spheres:** Armillary spheres were popular among medieval scholars from the 13th century to the 17th century [3]. They are similar to celestial spheres in appearance but focus on the Earth as the center body rather than on the surrounding outer sphere of stars, like that of the celestial sphere. The armillary sphere shows the ecliptic, the tropics of capricorn and cancer, the axial tilt, and many other complications depending on the armillary sphere creator. There are two type of spheres: the Ptolemaic armillary sphere and the Copernican armillary sphere, the former being geocentric and the latter being heliocentric.

These mechanisms track the motion of the planets relative to Earth. They accurately describe the predictable motion of the planets no matter if they are geocentric or heliocentric systems. Figure 2 shows the contrasting views of the solar system models. Since the view of the planets from Earth could interpret the planetary motions as shown in Figures 2a and 2b, it should not be a trivial task to understand the abstract idea of planetary motion. The construction of the solar system model could potentially allow for this idea to bring curiosity and conversation around the history associated with the abstract idea of a heliocentric system.

3. THE SOLAR SYSTEM MODEL

The design of the solar system model was driven by the study of mechanical solar system models from *Geared to the Stars* [3] as well as from mechanical devices as shown in Figure 1.

There were three design questions being asked:

1. Can gear ratios similar to the orbital ratios of the planets be determined within resolution restraints of the 3D printer?
2. Once discovered, can a large, functioning gear train system be 3D printed based on the results?
3. Can features be added to the gear train system once it is functioning?

Table 1: Orbital periods from the NASA website [7]

	Mercury	Venus	Earth	Mars
Orbital Period	0.241	0.615	1	1.88

Table 3: The gear ratio error

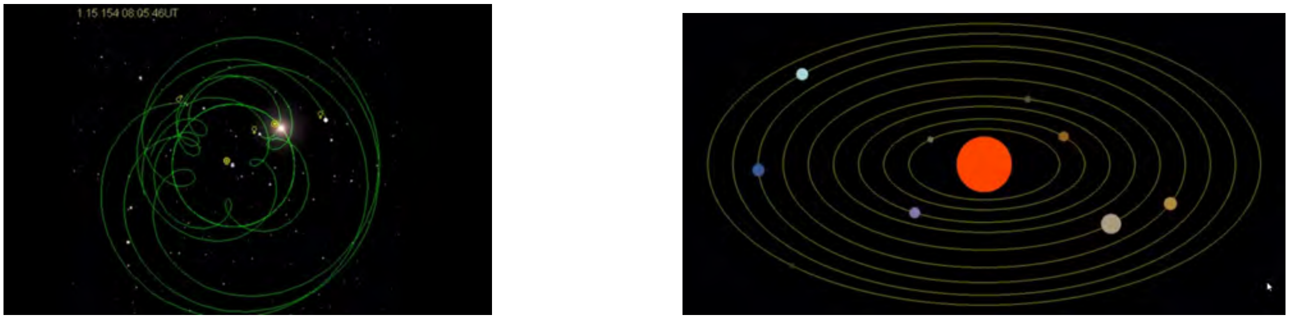
	Goal Ratio	Actual Ratio	Error (%)
Mercury	0.241	0.24064	0.1494
Venus	0.615	0.61497	0.0043
Earth	1	1	0
Mars	1.88	1.88888	0.4723

3.1 Planetary Ratios

The first design question relies on the naturally occurring planetary ratios for the inner four planets. In order to create an accurate representation of the inner four planets, the designed gear ratios between them must be accurate to their actual rotational ratios. Table 1 shows the planetary ratios from NASA's website [7]. These ratios were the basis of synthesizing a 3D printable series of gears to achieve similar numbers. Table 2 shows the developed algorithm to arrive at the desired gear ratio. The driving number of 22 teeth for the Earth stayed consistent as the systematic path was followed to achieve the desired NASA planetary gear ratios as shown in Table 2 and to complete the first design question.

The mathematics behind determining an effective gear ratio uses the principle of working from the goal and finding a suitable gear ratio near an integer. Since there are limitations when working with integer gear teeth, this approach allowed for a minimal amount of error despite the additive manufacturing method used. The following equation describes how the gear ratio is calculated.

$$\prod_{i=1}^{n} \frac{driven}{driver}_{i} \dots \frac{driven}{driver}_{n} = ratio \qquad (1)$$



(a) The geocentric model (b) The heliocentric model

Figure 2: The geocentric and heliocentric models of the solar system

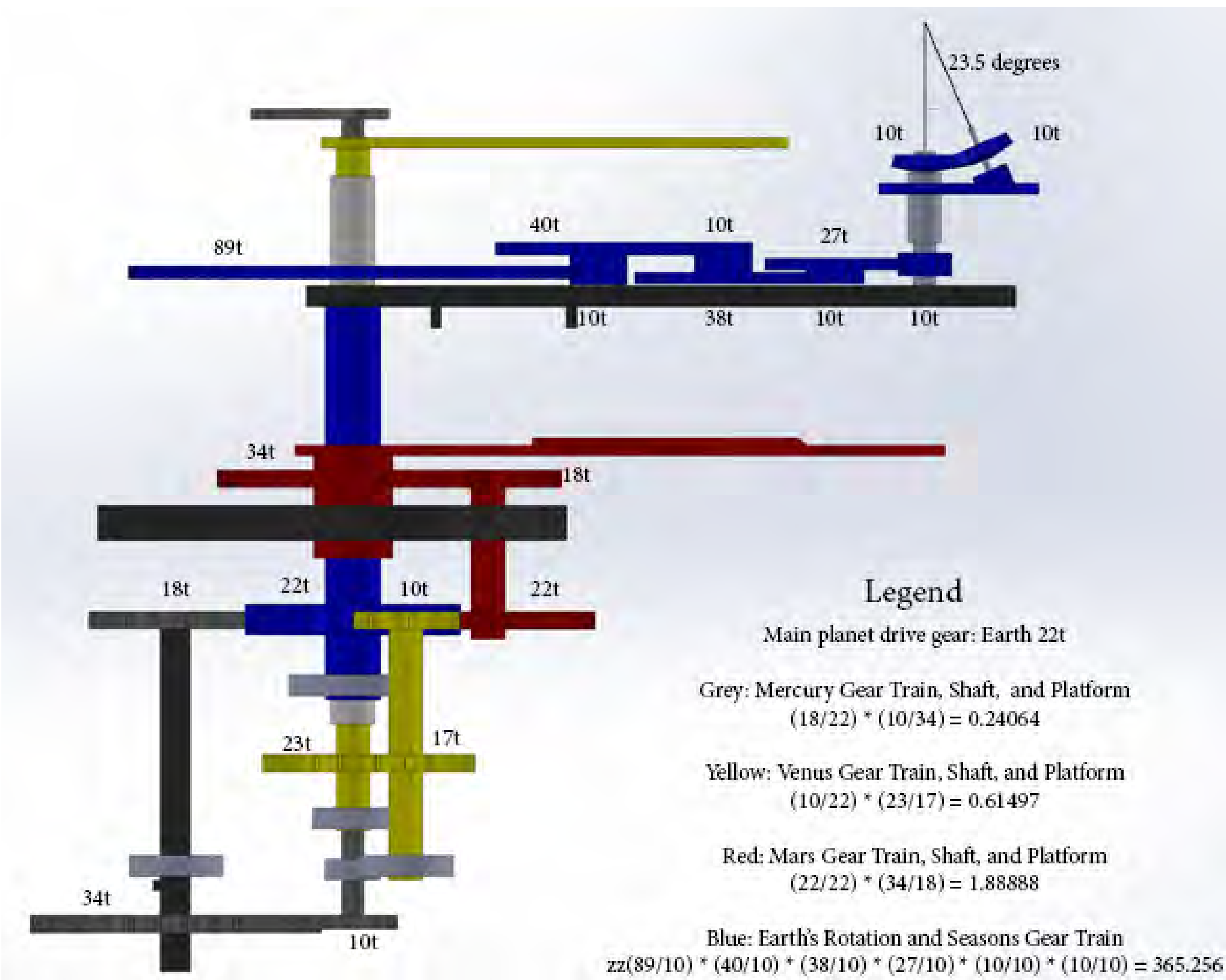


Figure 3: The gears, their teeth numbers, and how the gear train system is connected

Figure 4: The parts used to create a full build are shown

Table 2: The method of calculating the gear teeth numbers in the gear trains

Gear Ratio Solution					Formula			
Goal:	1.88			Mechanical Period	Goal:	1.88		
Driver	Driven	Driver	Driven					
Earth	Mars	Pinion	Gear		Earth	Mars	Pinion	pinion
22	22	18.0851063829787	34	1.88888888888889	22	22	=(22*34)/(1.88*22)	34
	Final:	18				Final:	18	
Goal:	0.615				Goal:	0.615		
Earth	Venus	Pinion	Gear		Earth	Venus	Pinion	gear
22	10	16.99926	23	0.614973262032086	22	10	=(10*23)/(0.615*22)	23
	Final:	17				Final:	17	
Goal:	0.241				Goal:	0.241		
Earth	Mercury	Pinion	Gear		Earth	Mercury	Pinion	gear
22	18	33.949	10	0.240641711229947	22	18	=(18*10)/(0.241*22)	10
	Final:	34				Final:	34	

The Venus gear train calculation will be shown as an example. The velocity ratio of the planets with respect to Earth is the goal of the gear train. By keeping the error to a minimum, the gear trains will closely mimic the actual movement of the planets with respect to Earth.

Example

Ratio of Earth to Venus's orbital period: 0.615
Goal = find driver gear teeth number on second gear/pinion portion as shown in Equation 1:

$$\frac{10}{22} * \frac{24}{goal} = 0.615 \tag{2}$$

Rearranging the above equation leads to a solution to the goal:

$$\frac{10}{22} * \frac{24}{0.615} = goal = 17.738 \tag{3}$$

As can be seen, the determined number is near not near an integer solution. Rounding up to 18 would produce a significant error in the goal period ratio of 0.615. The driven gear tooth amount is changed from 24 to 23:

$$\frac{10}{22} * \frac{23}{0.615} = goal = 16.999 \tag{4}$$

The value found is near an integer value, albeit not perfect, but near for the purposes of this integer based solar system model. This iterative process of finding a near integer was used to create the gear trains for all of the planets as shown in Table 2. The error created from the Venus gear train ratio is shown below:

$$\frac{NASA\ period\ value - approximate\ value}{NASA\ period\ value} * 100 = error$$

$$\frac{0.615 - 0.614973}{0.615} * 100 = 0.0043\ \%\ error \tag{5}$$

A summary of the error of each of the ratios can be found in Table 3.

3.2 Gear Trains

To answer the second research question, more than a 3D CAD model was required to test the functionality of the gear trains.

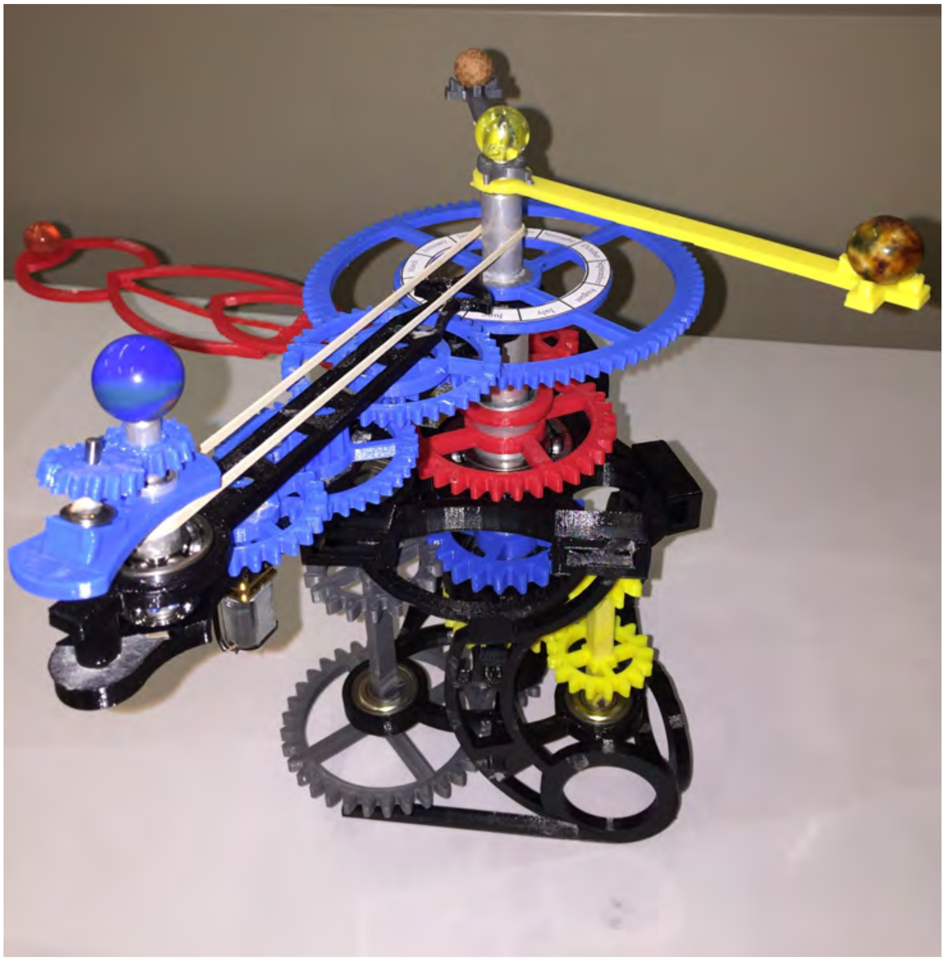


Figure 5: The fully built 3D printed solar system model

Figure 3 shows the layout of the gear trains. The system consists of four gear trains working together to move the planets around the Sun. There is one primary driving gear called Earth_22t. This gear simultaneously drives the three other planetary gear trains: Mercury, Venus, and Mars. This method of supporting the gears through 3D printed shafts and bearings allowed for the second research about 3D printing a functioning system question to be answered.

3.3 Features

The solar system model has two features that allow it to give additional planetary data. A feature is an added subsystem to the gear trains that gives additional meaning to the overall output. The main output of the system is the orbital rotations of the inner four planets. The two additional subsystems are the day rotation and the seasonal tilt of the Earth. The Earth rotation can be seen in the upper right corner of Figure 3. In order to achieve the 365.25 gear ratio of the Earth rotation per year, a similar technique shown in Table 2 was used to determine the gear train teeth values.

The second feature was the addition of the season tilt of the Earth. Earth is tilted 23.5 degrees as it orbits about the Sun. This tilt is always facing the same direction; it does not always face the Sun. The feature necessary to achieve this required a one to one ratio between the Earth's rotation and the center shaft. This would allow the tilt to maintain its position as it orbits about the Sun. The top right section of Figure 3 shows the platform and the concentric tubes which are then connected via belt. The implementation of these two features solved the final design question about adding features to the solar system model.

3.4 Printing and Assembly

The solar system model was printed using PLA filament and standardized settings across all parts on a Wanhao Duplicator 4 3D printer. The purpose was to make the parts printable on any hobby level 3D printer. No tools are required for assembly as all of the parts are pressure fitted. Assembly instructions have been created but are too long to be included in the context of this paper.

4. USE IN STEM EDUCATION

The solar system model has been developed and is able to be 3D printed and pieced together into a functioning model. The next step is to develop a curriculum combining the history of engineering and science along with the fabrication of the solar system model. Connecting the planetary orbital periods, history, and a modern manufacturing technique into one curriculum could give students an interest in building and learning as the course offers hands on experience which is a notable technique to stimulate curiosity [8].

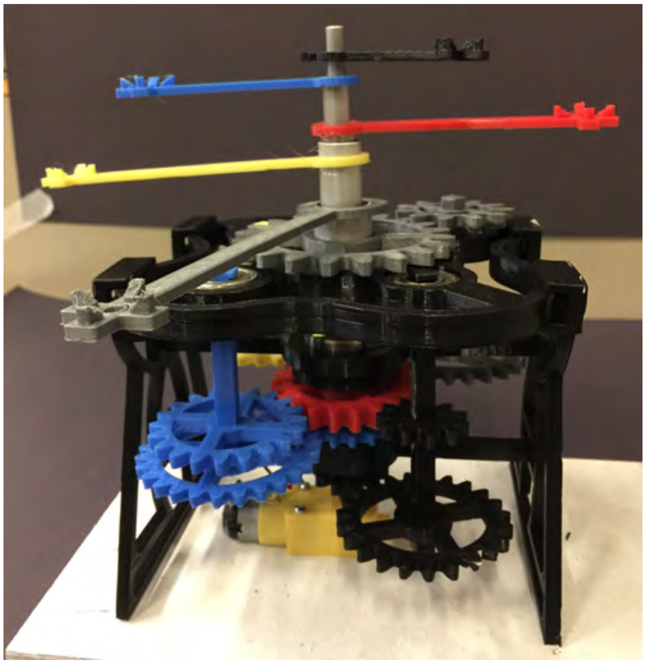


Figure 6: The KOI-500 solar system

Using 3D printing to develop historic experiments for students to handle and learn from could be an effective method of developing and holding interest in STEM fields [8].

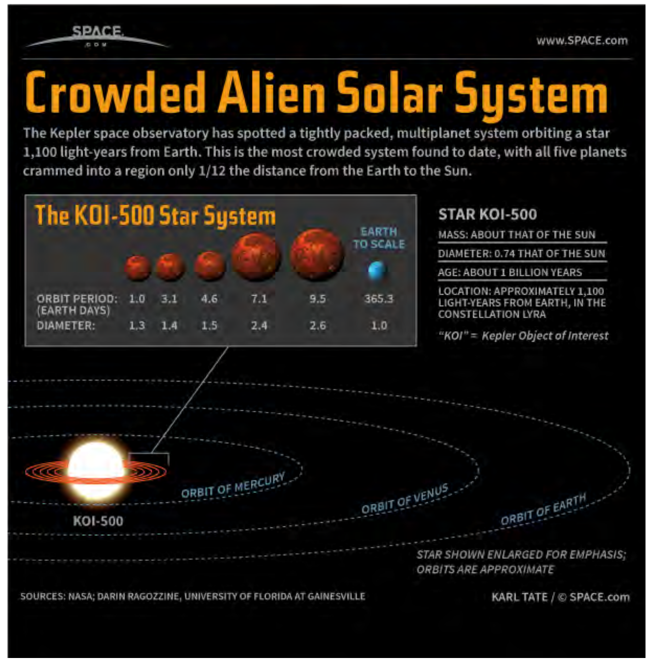


Figure 7: Facts and ratios of the KOI-500 solar system Source: http://www.space.com/18075-tiny-alien-solar-system-koi-500-planets-infographic.html

5. OTHER SOLAR SYSTEMS

5.1 KOI-500

The solar system KOI-500 was designed, modeled, and fabricated for the use of a physics student to describe the motion of the planets as shown in Figure 6. Figure 7 shows the ratios that were used to derive the gear trains necessary to design the solar system model.

5.2 TRAPPIST-1

TRAPPIST-1 is a solar system discovered by NASA that has 7 earth-like planets. These seven planets are all in the habitable zone about its sun. Figure 8 shows the ratios of the planetary orbits. The model is currently being designed. The status is shown in Figure 9.

Figure 8: Facts and ratios of the TRAPPIST-1 solar system. Source: https://en.wikipedia.org/wiki/TRAPPIST-1

6. FUTURE WORK

This paper discussed the development techniques required to make a 3D printable solar system model. Techniques to create gear trains that move relative to one another at a specified rate were developed and proven to work effectively. Future work could be to develop even more solar systems using this same technique to give physicists the ability to showcase their work with respect to the orbital mechanics of their solar system of study. The systematic process could be repeated to create the desired solar system as shown in the three examples.

The technique to determine a gear teeth number for the specified ratio is not optimized. A program could be developed to determine the most optimal integer value to achieve the goal ratio. This work is currently being developed.

Figure 9: The current status of the TRAPPIST-1 model design

A tolerance table for additive manufacturing could be developed specifically for radial tubing in 3D printed parts. This would be useful for creating pressure fitted gearing on radial tubing. Specifically for this project, it would be useful for fitting the gears onto the tubing as well as for fitting the bearings into their holders. The heating and cooling of the PLA material used in 3D printing causes variances from the designed part based on the thickness, diameter, and width of the outer diameter of the structure. A graph of tolerances reference sheet could lead to a strategic method to prototyping pressure fitted radial parts.

The future work for STEM education would be to test teaching and presentation methods of the solar system model. As this paper discussed the development and background of the solar system model, the next step is to present the model to groups of students and teachers and record their understanding and interest. Systematically discovering the strong and weak points of the presentation would allow for a concise, interactive, and interesting presentation to be developed and performed to promote STEM education.

7. CONCLUSION

This paper discussed the background of solar system models, heliocentric and geocentric systems, and the development of a 3D printed solar system model with features. As mentioned previously, there is work to be done to further develop the design process for gear ratio systems. The background of the solar system is linked to the history of mechanical engineering through Newton's laws of motion and gravity which were developed through planetary studies. This STEM education focused work gives an opportunity for students and teachers to learn about 3D printing, the solar system, and the history of engineering and science. To find videos and updates to the 3D printable time simulating solar system model visit the RASSL website at: http://research.fit.edu/rassl/

References

[1] Moffett M, Larochelle P, *Time Simulating Solar System Models* FCRAR Conference 2016 May 12-13, 2016, Florida International University, Miami, FL, USA

[2] Mark B. Moffett, *“Design of a 3D Printable Mechanical Time Simulating Solar System Model For Use in STEM Education"*, master's thesis, Florida Institute of Technology, 2017

[3] *Geared to the Stars*, Henry C. King 1979. Toronto Press

[4] Mechanical celestial globe made by Eberhard Baldewein in 1574 in Kassel, Germany. Photograph: Istituto e Museo di Storia della Scienza

[5] Astrolabe of Jean Fusoris (fr), made in Paris, 1400

[6] Armillary sphere in monastery of "El Escorial", San Lorenzo del Escorial, Madrid, Spain. Constructed by Antonio Santucci; date of construction circa 1582

[7] NASA, Dr. David R. Williams http://nssdc.gsfc.nasa.gov/planetary/factsheet/planet_table_ratio.html [Online; accessed: 20-January-2017]

[8] Michaelis, J.E., & Nathan, M.J. (2015, June). *The four-phase interest development in engineering survey.* American Society of Engineering Education (ASEE 2015) Education Research Methods (ERM) Division. Seattle, WA.