Time Simulating Solar System Models

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ABSTRACT

Mechanical representations of the solar system have been around for thousands of years. The human fascination with the night sky has been recorded in every culture as far back as documented time. This paper proposes a method for motivating STEM through the development of two orrery systems both of which have unique characteristics that provide their own teaching methods to students and adults about how the solar system functions. An orrery is a mechanical solar system. This paper details the technical development of a classical orrery and a modern orrery that can be used to teach and simulate the solar system. The classical orrery will have one degree of freedom and feature gear trains for the orbit simulation motion while the modern orrery will have ten degrees of freedom and feature programmed actuators for the orbit simulation motion. These contrasting designs mixed with the curiosity of planetary motion creates a STEM learning experience for both the builders and the observers of these simulated solar systems.

Keywords: Solar System, Orrery, Simulator, STEM, Time

1. INTRODUCTION

The motion of planets has fascinated humans since they have been able to look at the night sky. Since five planets are visible with the naked eye, (Mercury, Venus, Mars, Jupiter, and Saturn) people have been telling stories and named them after their gods. The earliest known planetary calculator is the Antikythera Mechanism, which was found off the coast of Antikythera in 1900, radiocarbon dating gave it an origin of 210-40 BC[1]. The Antikythera Mechanism is an analog computer capable of predicting astronomical movements based off of planetary observations over time. This planetary calendar functions as a way to track the planet's past motion as well as predict their future motion[1]. Similar to the Antikythera Mechanism, mechanical orrery's are analog visual representations of the solar system that have been around since the Charles Boyle, the 4th Earl of Orrery commissioned the first creation of the device in 1704[4]. Since this time they have been developed into accurate representations of our solar system. Over time, however, they have become mere curiosities of ancient astronomy. The mechanical development of the gear ratios and gears along with the proper calibration of the system is not a trivial task, and like mechanical watches, has fallen into the realm of enthusiasts and hobbyists. The mechanical orreries in use today are expensive clocks that happen to have planetary motions on top of them. Popular planetariums in the US do not have active orreries that give accurate representations of the planets in a physical sense. The proposed work involves the design of two 3D printed orrery systems that can be used to promote STEM learning through planetary and time curiousity.

Figure 1. The Antikythera Mechanism is a two sided analog computer filled with complex gearing mechanisms that calculate and display planetary motions on the dials.[1]

1.1 Classical Orrery

The first aspect of the work is to design and machine a 3D printable classical mechanical orrery complete with the gear train systems of the inner four planets and their moons (Mars, Venus, Earth, Mars) that functions as a solar system clock, displaying the current inner planet orbits moving in real time. The orbital periods of gear trains depend on their ratio to orbit of the Earth. This one degree of freedom property of the mechanism restricts it to linear movement through time.

Figure 2. An example of a contemporary classical 1 degree of freedom orrery. Rather than using dials to display the location of the planets, an orrery is a physical representation of the solar system.[7]

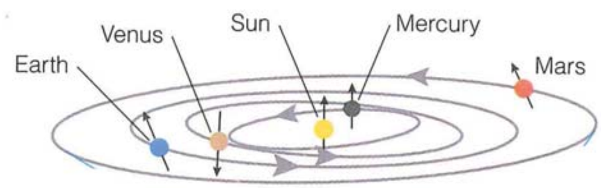

Figure 3. The planets and their orbits in their planar configuration as they orbit the sun.[3]

1.2 Modern Orrery

The second aspect of the work is to develop a solar system made of independent actuator driven planets that are calibrated by a ratio algorithm embedded into the system and controlled from a smartphone or tablet. The increase from 1 degree of freedom to 10 degrees of freedom allows for rapid, nonlinear movement through simulated time. Using the controls, the user will be able to jump to any place in time by selecting a given year to visit. Moon phase prediction, planetary visibility, and an outside view of how the planets are moving at any point in history and the future is now possible. These mechanisms will give insight into how the planets are rotating around the sun and where we fit in the past, present, and future, in our solar system as time continues to unfurl.

2. CLASSICAL ORRERY

The first step to recreating the solar system is understanding the orbital planes and periods of the planets. The planets orbit the sun in a planar fashion as shown in Fig.3. The degree of tilt of each planet relative to Earth can be found in Table 1. Note that the scale of the planet size, the distance between the planets and the sun, and the shown tilt is not to scale. The actual large distances relative to the sizes of the planets make a one to one visual comparison difficult.

Table 1. Orbit of planets around the sun normalized about Earth

Planet	Orbital Period (Earth years)	Moon Orbital Period (Earth years)	Orbital Inclination (deg)
Mercury	0.241	No moon	7
Venus	0.615	No moon	3.39
Earth	1	0.0748	0
Mars	1.88	0.31891 and 1.26244 [8]	1.85

The calculations involved for simulating the solar system require facts about the motion of the planets. NASA has made planetary facts based on years of data and successful interplanetary missions available to the public[6]. Table 1 shows the ratios describing the true motion of the inner four planets.

As shown in Table 1, the orbital periods are relative to Earth's orbit around the sun. This data can be designed into a mechanical gear train system that will be used as a visual aid and clock to understand the motion of the planets. The classical orrery project uses one degree of freedom to simulate the orbital paths of the inner terrestrial planets, Mercury, Venus, Earth, Earth's moon, Mars, and Mars' two moons.

2.1 Initial Work

The classical orrery is made up of mechanical gear trains that conform to the known ratios shown in Table 1. The problem with building an exact ratio system is managing the size of the gears and the obtainable ratios. A goal of this project is to 3D print the gears so the gear tooth sizing is restrained to the print resolution of a typical 3D printer.

The classical orrery is made up of four orbital systems around the sun, with two of the systems having their own orbiting bodies. Earth will have its moon and Mars will have its two moons, Phobos and Deimos. Since the ratios are all normalized about the Earth's orbit around the sun, recreating the Earth's orbit will be the one degree of freedom of the system. The orbital period of the Earth is the crucial calibration point of the project as all of the other planets are driven off this main system. Shown below are the current ratios used in Fig.4 for Earth's orbit around the sun and the moon's orbit around the Earth obtainable with typical helical gear trains.

$$\frac{73}{10} * \frac{20}{10} * \frac{20}{10} * \frac{10}{4} * \frac{25}{5} = 365 \quad \frac{Earth\ days}{Earth\ year} \tag{1}$$

The actual sidereal Earth days per year is 365.256[6].

$$\frac{73}{10} * \frac{30}{10} * \frac{20}{16} = 27.375 \quad \frac{Moon\ orbits}{Earth\ year} \tag{2}$$

The actual moon orbits per year is 27.3217 [6].

This gear train allows for 365 rotations of the Earth as it performs one orbit around the sun. Fig. 4 is a SolidWorks[5] representation of the above gear ratio. The current gear train is not practical due to gear sizing and layout practicalities, but is meant as one gear train of the first edition draft of the proposed classical orrery.

2.2 Future Work

With the primary degree of freedom for the gear train systems established, connecting the other 3 planet systems

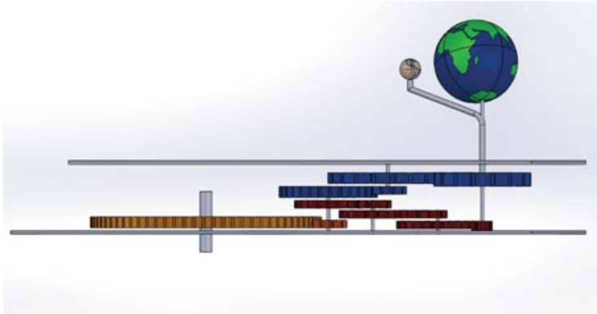

Figure 4. A side view of the first build of an Earth and moon orrery. The Earth gear train, shown in red, has 365 rotations per 1 Earth orbit around the sun. The moon gear train, shown in blue, provides 27.375 rotations about the Earth as the Earth orbits 1 time around the sun. The large orange gear center represents the sun location.

to this gear train is the next step. The design of the other three gear trains is the future work for the completion of the classical orrery design.

The whole system is driven by one actuator or alternatively, a hand crank for off-line operation. The main drive motor will turn the Earth system in its 1:1 rotation about the sun. The remaining 3 systems will branch off of the main drive shaft at their respective ratios, causing their systems to orbit the sun in accordance with the confirmed NASA planetary observations[6][8].

3. MODERN ORRERY

The nature of long, 3D printed gear trains causes friction, variance in performance, and other manufactured deviations which cause inaccuracies over time. A modernized orrery with electronically programmed rotation and orbit ratios with 10 degrees of freedom controlled by independent actuators will allow for non-linear time travel simulation and planetary movement exploration. This modern orrery will move with the accuracy of digital actuators which is inherently superior to a 3D printed gear train. It lacks the novelty of gear trains, but is replaced with the accuracy and control that the gear trains do not possess. When traveling back in time, the actuators can rapidly achieve their location in space at a given time independent of one another whereas the gear train is a fixed system and must travel linearly through the years in time to obtain the accurate planetary configuration for a given year, month, and day.

A programmable solar system controlled by actuators offers an accuracy that allows for time travel by the user via control from an app on a smart phone or tablet. Using a stacked configuration of actuators that can be aligned in the center for a shared axis of rotation grants added degrees of freedom for the rotation of the planets and moons.

Having complete control over every rotational body allows for a system that is as accurate as the quality of actuators installed in the orrery. The known planetary ratios can be reliably followed to the exact specifications programmed into the system. A solar system simulator with the freedom to move rapidly through time allows students to understand both how the planets move in the solar system and also how the predictable nature of the planetary motion has mesmerized humans since the dawn of time.

Table 2. Distance of Planets to Sun in AUs

Planet	Distance to Sun (AUs)
Mercury	0.4
Venus	0.7
Earth	1
Mars	1.6

4. PLANETS

Despite the large distances between the planets, the orreries will be scaled to Astronomical Units (AU, 1 AU = the distance from the Earth to the sun) The planets will follow the Titius-Bode Law of planetary distances [2]. Using this ratio, the planets will appear at distances according to Table 2. Scaling the AU down to more manageable lengths will allow for the orreries to have accurate distances between the planets while still being a palpable size.

4.1 Earth

The Earth on the modern orrery will be designed to give a complete visual of lunar cycles, day and night transitions, and seasonal changes all while giving the location of the user on Earth. A GPS system installed on the modern orrery will indicate the location of the user on the Earth using an inner 2R robot arm to point at the location from inside the Earth. The multi-layered Earth model will have a tinted side and a clear side that mimics the transition from day to night.

The systemized Earth model will be a larger scaled model than that of the rest of the planets. Due to the nature of the scaling of planets and their distances, the models will not be scaled to size. The Earth is given emphasis so the user might gain insight to their location on earth relative to the planets they see in the night sky.

4.2 Mars

Given the popularity and interest of achieving life human colonies on Mars, an accurate model of Mars will be created with statically indicated locations of past missions shown on the planet. Day and night will be shown, similar to the earth model, and the curious movement of the faster-than-rotation-of-a-day moon and the more regular movement moon will be shown in their proper orbits around Mars.

4.3 Graphical Simulation

Given the different orbital periods of Earth and Mars, launches to the planet are made at specific times in order to follow the shortest path to the planet. The physical visual representation of the planetary orbits will allow for launch simulations to be performed on the tablet or smartphone at user defined times. Launch trajectories will be simple examples of trajectory tracking, not taking into account the complexities of the real solar system, but a simple simulation of a generalized mission. Although the proposed simulation is a software program, it can be used in congruence with the physical modern orrery to give the user an accurate representation of the planet configuration as a launch occurs.

4.4 Venus

Venus will be a basic setup of a spherical globe rotating on its proper axis, on its proper orbit. Multiple missions were executed in the 1970's and 1980's by NASA (Pioneer) and the Soviet Union (Veneras) to obtain data about Venus[2]. The location of the Soviet Union lander Veneras 9 will be marked on the planet's surface.

4.5 Mercury

Mercury will be an orbiting body with a 3:2 spin to orbit ratio around the sun[2]. A sunrise every 176 days is an interesting fact of the planet that the modern orrery will be able to display.

5. FUTURE WORK

The expanded design and manufacture of the classical orrery, the design and manufacture of the modern orrery orbit system, the design and manufacture of the planets, and the app development are the key features to be completed for this research project.

6. STEM CONNECTION

The technical aspects of this project lead to a number of science, technology, engineering, and mathematics applications in young people and adults alike. An affordable, 3D printable solar system offers an educational experience in both building either orrery and using it as an exploration tool. The misconceptions of space sciences are prevalent when dealing with difficult to visualize scales as found in [9]. A hands-on manipulation experience will allow students and adults to grasp and understand the solar system in which all humans inhabit.

7. SUMMARY

Through the design and development of two orreries with unique properties, this research project will provide to the science community a new way of viewing the solar system. The 3D printed classical orrery will be a testament to the one degree of freedom humans experience, locked in time. The modern orrery utilizes 10 degrees of freedom, allowing for rapid movement through simulated time and space as the user chooses where to go from the use of a custom tablet or smartphone app. The finished project will lead to a better understanding of the solar system for those that encounter the classical and modern orreries.

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