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Ancient Machines: What Engineering Students Can Learn from Them?

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Ronald Saus is an Alumni of Robert Morris University. Ronald graduated Cum Laude in 2019 with a degree in Manufacturing Engineering. As part of his education at Robert Morris, he reverse engineered the ancient Greek Ropebot to design and build a working example.

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Abstract

Ancient engineers were envisioning all sorts of machines including mechanically programmed ones and building them. This study presents recent efforts of the author and his fellow faculty in employing ancient machines in the engineering and other curricula. A variety of means were employed including an honors thesis, an extra credit project in an engineering course as well as an internal project that replaced the internship requirement for a Robert Morris University (RMU) student: i) A double-degree mechanical and manufacturing engineering student studied the innerworkings of the Antikythera mechanism to replicate its operation in a powered LEGO system for her honor's thesis. ii) A manufacturing engineering student reverse engineered the ancient Greek Ropebot which can be programmed with a rope. This work was treated as an extra credit project in a robotics and automation course. iii) A mechanical engineering student was supplied with a kit of Leonardo Da Vinci's Self-Propelling Cart (a.k.a. Automobile) for assembly and analysis. The student was also asked to review the literature in existence for similar mechanisms. This effort was employed for earning credit to satisfy the internship requirement during the Pandemic. The work mentioned in this paper utilized a variety of different approaches simultaneously, including analysis and synthesis, understanding of mechanics and astrophysics, mechanical movement via automata, as well as computer-aided design (CAD), computer-aided engineering (CAE), 3D scanning and printing areas. The students were already exposed to machine design/mechanisms, mechanization and fixed (hard) automation concepts prior to being involved in these projects. This paper concludes with the lessons learned from such effort and future work including possible efforts in expanding this into a larger audience, such as for secondary education beyond Rube Goldberg challenges.

Background

History of Machines and Automata

Machines are comprised of mechanisms designed to perform movements to accomplish repetitive, complex, or demanding tasks for humans. A mechanism is an abstract representation of a machine. Machines and mechanisms have been an important part of human history and development, including applications in science, life-style and culture, warfare, and construction [1]. Even though ancient Sumerian and Egyptian cultures are known to be the drivers of the humanity's development, recent discovery of Göbekli Tepe, an almost 12,000-year-old Neolithic megalith site in Southeastern Turkey, has proven that human civilization is much older than once thought [2]. Early Egyptian engineers lacked the wheel and the pulley, but had the inclined plane, the lever, and the log roller in their tool set and were able to build a pyramid like Cheops, with a height of 146 m and a slope of 51° (almost a 48-story high building) employing 2.6 million stone blocks weighing 2 to 60 tons [1].

Besides building great structures, ancient engineers were also envisioning all sorts of machines including mechanically programmed ones and building them. We may never know if some of these really existed, like Talos [3], a mechanical bronze colossus patrolling the shores of the island of Crete, throwing boulders at invaders, but we are sure of the existence of machines like Antikythera mechanism, or Archimedes' (287 – 212 BC) machines such as the Screw, a water pump to drain water from ships or aid in irrigation, and the Claw, a crane of sorts used in defending walls of Syracuse in ancient Sicily against the Romans. The Antikythera mechanism, an ingenious mechanical computer dating from 100 BC, is a device consisting of more than 30 bronze gears whose aim was to predict astronomical positions of celestial bodies and events up to 19 years in advance for setting the dates of the Panhellenic games [1]. Even though we are today fascinated with machines like the Antikythera mechanism as we try to unlock its remaining mysteries, we also appreciate the contributions of other machines and their developers to today's contemporary engineering.

In known history, humans also employed mechanical movement for entertainment, as they emulated the movements of living beings in automata, first being credited to Hero(n) of Alexandria (10 – 70 AD). Following section summarizes noteworthy milestones of automata development in history:

- The early automata used water flow, heat, and gravity as their actuators, and some were rather sophisticated. Hero(n) of Alexandria described a fully-automated puppet theatre enacting an entire tragedy, through a combination of displaced grain as well as its mechanical components: axles, levers, pulleys and wheels [3]. As the influence of Greece declined in early centuries AD, the Western cultures entered a millennium where skills of automaton-making were lost along with other scientific knowledge [4]. During that millennium, the mechanical arts were preserved by the Byzantium Empire and Arab world. In 850 AD, three Banu Musa brothers (Ahmad, Muhammad, and Hasan) of Persian origin working at the House of Wisdom in Baghdad, Iraq published the Book of Ingenious Devices comprising close to 100 mechanisms, including automata such as a water-driven organ [3], [5].
- In the 13th Century, there was a renewed interest in the Western world towards automata. [3] The Count of Artois at the château of Hesdin, located in northern France, commissioned a cluster of mechanized beasts and humanoids interacting with his guests by scolding them and soaking them with water. Around the same time, medieval scholars like Roger Bacon were rumored to have created a bronze head answering questions. The popularity of mechanical humanoids continued through the Renaissance, with hydraulic, spring-powered, and clockwork automata. In 1495, Leonardo da Vinci designed an automaton, a medieval armored knight, after studying human anatomy. His design allowed a realistic action of sitting, movement of the arms, jaw, and, and neck based on the working model developed by the researchers afterwards. The design relied on weights and pulleys [1][3]. In addition to his automata, Leonardo's creations included an aerial screw (a design for a helicopter), a crank mechanism for making screws, the self-propelling cart (Automobile – Figure 1), the hydraulic pump, the submarine, the battle chariot, and ball bearings to name a few.
- Over time, Descartes's view of living things as complex machines resulted in a hype about automata in Europe between the 17th to early 19th centuries (Figure 2) [3]. Master mechanical artisans/engineers built fine examples of art-imitating-life, such as Jacques de Vaucanson's 1739 Digesting Duck. With more than 400 moving parts in each wing and internal rubber tubing, the duck appeared to eat, drink, and defecate. The intelligent

design of the duck involved ejecting prefabricated pellets from a hidden compartment to generate the effect of defecation. A few decades later in 1770, inventor Wolfgang von Kempelen's infamous chess-playing Mechanical Turk was revealed. Decades later in 1857, an article revealed that the Turk was being operated by a person hidden inside the set-up. Until then, no one was able to out figure how all that magic happened. Pierre Jacquet-Droz is considered the greatest automata designer in the history due to three of his masterpieces:

Figure 1. A CAD model of Da Vinci's self-propelling cart (Automobile)

the Writer (Scribe), the Musician, and the Draftsman (1768 – 1774). The Musician consists of more than 2000 pieces and is able to play songs while looking down on the keyboard, rocking her chest as if it is breathing and even bowing at the end of her performance. The Draftsman is also made from a similar number of pieces as the Musician and can execute 4 drawings including the portrait of Luis XV. The most complex of the three creations is the Writer (Scribe). It is composed of more than 6000 pieces and is fluent in two languages: French and English [1].

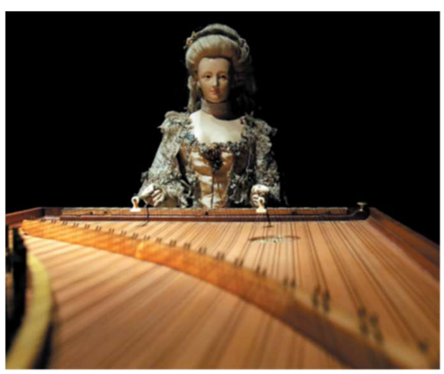

Figure 2. German cabinet-maker David Roentgen's 18th Century automaton of Marie Antoinette with a table-top zither it plays [3]

As the machines developed over a couple of millennia impacting our engineering and consequently lives today, the automata gave a rise to the robotics field.

Literature Review

The lead author conducted a literature review using the phrase, ancient machines, in ASEE Peer publications database, yielding a very small number of works focusing on ancient machines in engineering curriculum. Following section includes a summary of this effort, also including any ancient engineering content other than the machines:

- In their article titled, A Course in the History of Ancient Engineering, Tan and Tan, talk about a course "for expanding students' knowledge of how ancient engineering has shaped human history and in return, how people have shaped engineering and technology." The course was developed as a General Education Curriculum (GEC) course for the Engineering Education Innovation Center (EEIC) at the Ohio State University and includes "such topics as our ancient engineers, stone and hafted tools, the quest for fire, ancient arts, primordial farms, early water-raising devices, the engineering of clayware, early metallurgy, simple machines, military engineering, mechanical and water engineering, and time measurement." The course is offered to engineering and non-engineering students, with a prerequisite of English 1110, First Year Writing or equivalent. At the end of the semester, students submit textual conceptual reports, 3D graphical images, and physical projects which are manually made or 3D printed simulating an ancient device of their choice [6].
- In his paper, A Non-Traditional and Multi-Disciplinary Approach to Teaching Mechanisms and More, the lead author, Sirinterlikci, described an Honors course he developed at Ohio Northern University [7]. It was intended to give students a cross-disciplinary learning experience while dealing with integration of art, engineering theory, and fabrication elements. The approach utilized various means of teaching mechanisms, consequently addressing various types of learners. These means, presented in the following sequence, were:

    1. Study of theory of machines including kinematics and dynamics
    2. Observation of working mechanisms and computer animations
    3. Reverse engineering of mechanisms found in animated toys
    4. Assembly and successful operation of commercially available automata kits (Figures 3 a and b)
    5. An open-ended design project where a group of students had to design and build automata (Figures 4 a, b, and c).

    During the course, students learned the theory governing mechanisms and their uses in the real-world. The students followed a practical path to learn about joint, element, and mechanism types as well as functions of joints and elements, and mechanism as a whole. Following the sequence given above did allow each student to build a knowledge base leading to the open-ended design project assignment. Groups of two to three students designed and presented various mechanisms that included eccentric and lobed cams, ordinary cranks/crank sliders, and some bar linkage mechanisms. During the projects, groups were also exposed to concepts such as materials and process selection, tolerances, clearances and assembly, fasteners, adhesives and joining. NC (Numerically Controlled) laser cutter hardware allowed students to cut and engrave various types of materials with minimal design effort in AutoCAD or Corel Draw. Sirinterlikci also employed animatronics in teaching product (toy) development [8]. Part of his work included teaching mechanisms (automata) utilized in animatronic robots and toys.

- In her article, Storytelling with Machines: Innovative Approach of Developing Creative Mindset and Teaching About Mechanisms Through Stories, Joshi presents an undergraduate technical elective [9] she designed for the James Madison University, which is very similar to Sirinterlikci's approach that took place 20 years earlier [7]. According to Joshi, the objective of her course was to teach students about mechanical elements along with the context of storytelling. This approach allowed students to develop a creative mindset. The students learned about the basic elements of mechanical systems while focusing on the underlying physical principles including elements such as linkages, cams, and gears. "The students

Figure 3. Paper based automata models employed in the Sirinterlikci's honors course [7]

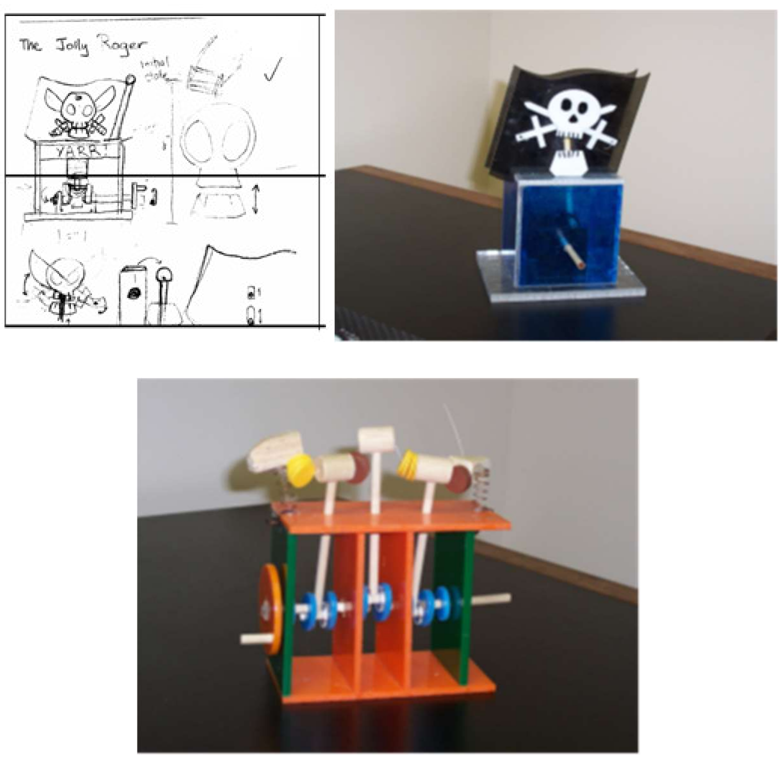

Figure 4. Student projects from the Sirinterlikci's honors course a, b. in-progress c. completed [7]

also investigated the mechanics of storytelling, and explored the historical and creative relationship between automation and narrative. Through hands-on projects, students designed and fabricated basic machines that give life to stories of their own design." [9]

- A team from the Ohio State University, presented the article, Educational Application of Virtual Reality (VR) in Graphical Simulation of the Construction Process of Chinese Dougong, a complex structure of interlocking brackets and associated construction processes [10]. The basis of the VR environment used in their study is a comprehensive, complete, and accurate 3D graphical database of Chinese Dougong where students can examine the structures and construction processes via multiple means: "1) static images, such as 3D models, multi-view engineering drawings, exploded views, and illustrations; 2) dynamic videos, such as animation clips of assembly procedures; and 3) VR interactivity, such as simulations constructing and deconstructing the virtual Dougong models within the VR environment." All of the information and data were compiled and integrated into a knowledge-based system labeled as the Intelligent Dougong System with Virtual Reality (IDSVR), a multimedia learning platform designed to introduce the subject via different dimensions. The same team from the Ohio State University also expanded this approach to other similar structures.

Case Studies

Antikythera Mechanism

A double-degree mechanical and manufacturing Robert Morris University (RMU) engineering student studied the innerworkings of the Antikythera mechanism to replicate its operation in a powered LEGO system for her honor's thesis while working with a Mathematics Professor (Dr. Andris Niedra) [11]. The build was accomplished in less than 10 meetings due to help from the LEGO Club of RMU being involved. The mechanism was built based on the instructions obtained from the Rebrickable's website [12]. The team working on the mechanism calibrated and motorized the design (Figure 5). However, they did not include the two dials of the original design (Callipic and Olympiad dial) in the set-up as seen in Figure 6 below showing its user interface. Students who worked on the project had to study the mechanical design of the model, including the gear ratios and their astronomical representations.

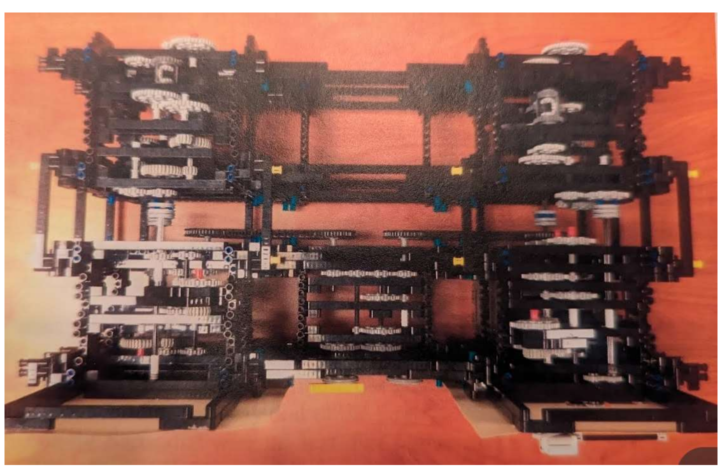

Figure 5. LEGO assemblies for the Antikythera mechanism replica [11]

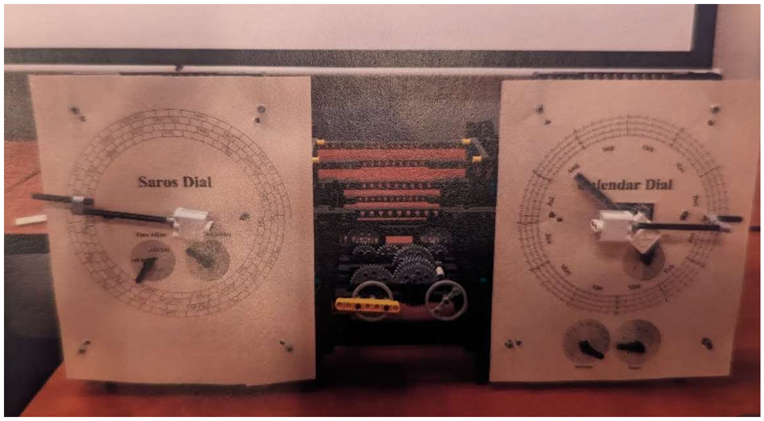

Figure 6. Dials of the Antikythera mechanism replica [12]

Following reflections were given at the conclusion of the student's thesis by the student: *"Various researchers made replicas of the Antikythera mechanism working with the existing fragments of the device and their understanding of the ancient Greek knowledge"*. Andrew Carol [13] later made a working LEGO model, which was more complex and less accurate than the original model, but was made available to the others. *"One of the most impressive aspects of the original model is its accuracy and sophistication. Creative gear combinations and mechanisms were used to control the output displays with a relatively small number of gears and other internal parts. While creating a model with LEGO parts is a notable achievement, it would be the next step to be able to recreate the same mechanism in a way that is not just available to others, but also accurate and less complex"*

The authors can relate this case study to multiple ABET Student Outcomes [14] as listed below:

(1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics - Students involved in a study like this need to understand laws of astrophysics as well as machine elements/design as they try to reverse engineer a mechanical computer by tying the components mentioned above together.
(6) an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions – Students need to experiment with and optimize (adjust) their builds.
(7) an ability to acquire and apply new knowledge as needed, using appropriate learning strategies – Students need to learn or refresh on laws of astrophysics and astronomy.

I Ropebot

An RMU manufacturing engineering student reverse engineered the ancient Greek Ropebot which can be programmed with a rope. This work was treated as an extra credit project in a Robotics and Automation course.

- The working model of the Ropebot was mimicked in CAD (Inventor Software) from its existing drawings available (Figure 7) [15], its parts were 3D printed (Figure 8a) and assembled (Figure 8b) with addition of some components such as bearings and a rope. Weights and pulleys were used in driving the robot.

- After the completion of the assembly, the student experimented with changing the rope wrapping patterns to change the program of the robot, or namely its movement.

Figure 7. Ancient Greek Ropebot [15]

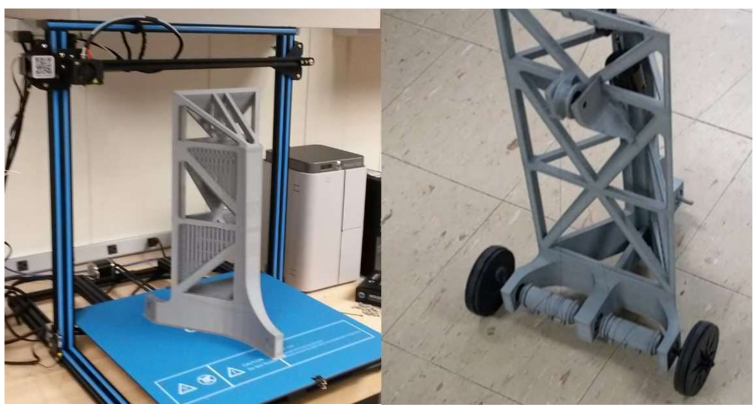

Figure 8 a. 3D printing the Ropebot components b. Completed assembly of the Ropebot

Following reflections were given by the student involved*: "During the reverse engineering process of the ancient Greek Ropebot, I was able to digitize a conceptual design of the I Ropebot. From there, I was able to use the digitized design as a digital twin of the Ropebot, allowing me to simulate some of the movements of the programing cam on the Ropebot. With this information, I was able to redesign some elements of the Ropebot before making a physical model of it using 3D printing. Overall, I was able to learn how to use CAD programs to influence and test my design, along with prototyping techniques (like 3D printing) that allowed me to test my conceptual design in the real-world environment. "*

The authors can relate this case study to multiple ABET Student Outcomes [14] as listed below:

(1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics - Students involved in a study like

this need to know laws of mechanics as they try to reverse engineer and rebuild a robot that is mechanically programmed.
(6) an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions – Students need to experiment with and optimize (adjust) their builds.

Besides the outcomes mentioned above, the engineering students involved will gain experiences in CAD and 3D printing areas with exposure to modern engineering tools, as required by the ABET Curriculum criterion.

Leonardo Da Vinci's Self-Propelling Cart (a.k.a. Automobile)

An RMU mechanical engineering student was supplied with a kit of Leonardo Da Vinci's Self-Propelling Cart (a.k.a. Automobile) for analysis (Figure 9). The student was also asked to review the literature in existence for similar mechanisms including a mechanism that is the subject of the other case study (I Ropebot) listed in this section. This effort was employed for earning credit to satisfy the student's internship requirement during the Pandemic, requiring delivery of a Word document as a final report, a PowerPoint (final) presentation, and a journal of work summary/ log of work hours.

- After assembling the kit (Figure 10), the student experimented with the working model to understand its innerworkings, and compared the model to the original design since the model assembled has small number of simplifications. Students in this program are taught use of mechanization and three forms of automation: fixed (hard), programmable, and flexible in their Robotics and Automation elective. With this exercise, student was exposed to an early use of mechanization to generate a self-driving vehicle, the mechanism carrying its own control logic without any access to electricity or controls.
- After understanding the mechanism, the student completed the literature review including the I Ropebot, an ancient Greek robot covered above.

Figure 9. ITALERI's model kit of the Da Vinci's Self-Propelled Cart

Figure 10. Different views of the assembled Self-Propelled Cart model

At the completion of the experience, the student had an interesting observation: *"Both of these robots (Da Vinci's Self-Propelled Cart and the I Ropebot), though different in purpose and design on many fronts, there is one major part that is in a form identical and is a very interesting note. The two different robots, as previously stated, use a point to point style programming to make the desired movements. This point to point style programming is common today similar to a way to program the FANUC robots used in our labs*". He also noted that *"without these two robots, today's robotics would potentially be very different, and the simple mechanics helped push the norms of those times"*.

The authors can relate this case study to multiple ABET Student Outcomes [14] as listed below:

> (1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics - Students involved in a study like this need to be competent in mechanisms/automata as they try to rebuild a robot that is mechanically programmed. This case includes a design that is more complicated than the previous one.
> (6) an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions – Students need to experiment with and optimize (adjust) their builds.

Conclusions and Future Work

The work mentioned in this paper required a variety of different approaches simultaneously, including analysis and synthesis, understanding of mechanics and astrophysics, mechanical movement via automata, knowledge of and skills in computer-aided design (CAD), computer-aided engineering (CAE), 3D scanning and printing areas. The students were already exposed to machine design/mechanisms, mechanization and fixed (hard) automation concepts prior to being involved in these projects. Besides getting students engaged in the activities or areas listed above, study of ancient machines also enables engineering students to have a better understanding of history and other cultures, contributing to the overall development of the student.

The lead author recommends use of honors courses or theses over technical electives in including this type of content/approach in engineering curricula. He also supports giving students extra credit assignments for a similar objective. These recommendations come from the idea of not inducing additional burden on already tight engineering curricula due to pressures of credit reductions coming from university administrations or accreditation requirements taking up space. In terms of the student evaluations, ABET student outcomes 1, 6, and 7 were found relevant to the projects mentioned in the case studies. Since each case study is officially associated with a single student, no outcomes analysis was conducted. Students also gained additional experience in CAD and 3D printing tools as a part of the ABET Curriculum criterion, requiring student learning of modern engineering tools. Multiple students, the honor's student and RMU LEGO Club members, involved in the LEGO Antikythera project were also exposed to 3D scanning of historical artifacts.

The authors support the idea of organizing ancient machine competitions in expanding this into a larger audience, including secondary education beyond Rube Goldberg challenges.

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