Chapter 21
Application of Reverse Engineering to Implement 3D Designs of Ancient Mechanisms

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Abstract In this work reverse engineering has been applied. To carry out this process, some plans and videos are used to make the mechanism in 3D. The Juanelo Turriano mechanism, which served to raise water in the city of Toledo, has been taken as a reference for the application of this work. This work is based on a video provided by the Juanelo Turriano Foundation in which the complete mechanism can be seen. To carry out the work, all the parts of which the mechanism is composed have been identified in the first place in order to be able to carry out the final assembly and be a functional mechanism. With this type of work, imagination is greatly developed since there are some pieces that have to be designed in a functional way that cannot be seen in this case in the video.

Keywords Reverse engineering · Mechanisms · Juanelo Turriano

21.1 Introduction

As for mechanisms for water supply in ancient times, the deposits in the southwest of the peninsula are notable, such as: the ten wheels of Sâo Domingos (Portugal), or

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other broken ones found in the mines of Tharsis (Huelva). Of these, not all of them are preserved, but rather they are exhibited in different museums in fractions: in the Musée des Arts et Métiers in Paris, almost 1/4 of a Sunday wheel from 1864 and 1/5 of a broken one in the Museum of Transport in Glasgow since 1867. The latter may belong to the Tharsis mines, however, its location cannot be confirmed due to the limited and confusing documentation found [1–5].

The Renaissance was a stage of great success in the evolution, development and dissemination of hydraulic machines due, in large part, to the influence of creativity that characterizes this historical period. This fact is reflected in inventions such as Leonardo Da Vinci's (1452–1519) centrifugal pump, whose dissemination throughout Western Europe in the mid-15th century is due to the invention of the printing press. In turn, the work was disclosed: "Kunstliche Abris allerhand Wasser" by Jacobus Strada in which there are different engravings such as; "hydraulic machine for spout fountain", or "Noria with draft animal" and also, the manuscript by Francisco Lobato from Medina in which he speaks of the "regolfo mill" [6, 7].

It is interesting to highlight several majestic inventions in this historical stage, however, the analysis focuses on the one that will give meaning to this document and which is discussed more extensively in the following sections. Juanelo Turriano is the creator of various machines that stood out in the European Renaissance due to their complexity and the use that was made of them. Many of his works have been recognized, while others have fallen into oblivion, such as the Artificio by Juanelo Turriano in Toledo. This majestic mechanism managed to raise the water of the Tagus River ninety meters in a journey of just three hundred and six meters. This was built for the first time in 1569 and later modified in 1581, achieving a flow of seventeen. Unfortunately, no explicit document describing this contraption has reached our days, mainly due to the creator's intention to safeguard the secrecy of the contraption's operation and numerous economic inconveniences that he found in its implementation [8–11].

21.2 Metholody

Juanelo Turriano or Janello Torriani was originally from Cremona and his date of birth was between 1500 and 1511, the earliest being the most accepted by most studies. He was born from a humble family that from an early age rubbed shoulders with illustrious characters from his environment who formed him throughout his life. Giorgio Fondulo, physicist, doctor, philosopher, connoisseur of Greek and Hebrew, mathematician and astrologer, marked Turriano's life by being his first teacher and later one of his illustrious friends [12].

The case study of this document lies in the city of Toledo and the passage of the Tagus River through it. Despite the benefit generated by this natural asset, Toledo is considered a mostly continental city, located far from the marine influence and at a medium–high elevation, being in turn shielded between its mountains, with elevations of 1000–1400 m protecting to the city of strong winds. The object of study of this work falls on the structure that revolutionized hydraulic architecture, the ingenious device of Juanelo Turriano. This section focuses on explaining the operation and purpose of this machine, whose parts will be treated in more detail in the following points. This document will explain the artifice, distinguishing it into four independent mechanisms, which, when joined together, would form the complete structure, perfectly fulfilling its objective. All the information is based on the “3D Animation of the Artifice of Juanelo Turriano” carried out by the Juanelo Turriano de Toledo association.

The mechanism had a fortress at the level of the river, where the initial drive subassemblies were located, forming a subassembly of geared wheels with water load and a subassembly of geared wheels without water load.

The first was in charge of raising the water by means of a chain provided with buckets activated by means of a reduction gear set of geared wheels. And the second, activated a tie-rod and forcing mechanism by means of an identical group of geared wheels. This ended in a wheel with a single tooth that was responsible for transforming the rectilinear circular movement of the wheels into a rectilinear oscillating one. The braces and forcing bars (Fig. 21.1) consisted of a number of bars joined together by means of pins that allowed the transmission of a rectilinear movement, overcoming irregularities in the course of the transmission of movement.

The last subset consists of a tower of oscillating buckets (Fig. 21.2) that collect water from a tank and raise it, passing it from one to another and achieving successive increases in elevation.

The motor of these towers are the braces and forcing forces that describe a horizontal rectilinear movement in the lower part, which is then transformed into another vertical rectilinear one by means of a mechanism located below. In this way, the oscillating movement of the buckets that will make the fluid rise is achieved. The braces are also responsible for connecting the different towers that will be activated in the same way as explained above.

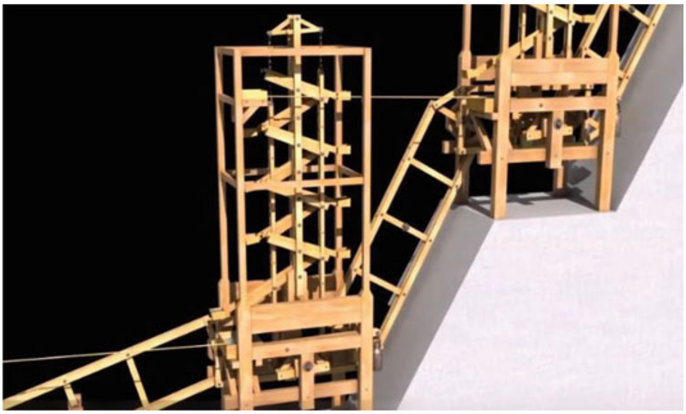


Fig. 21.1 Tie rod and forcing mechanism

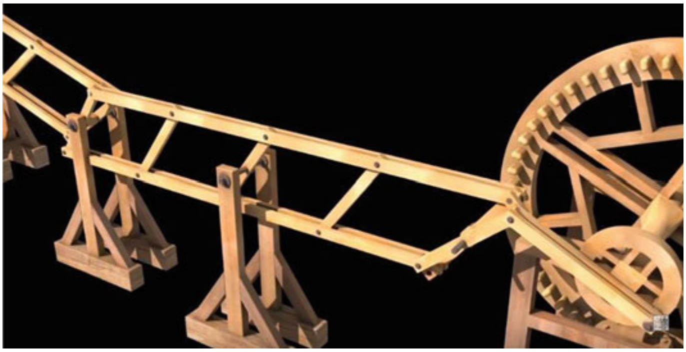


Fig. 21.2 Oscillating bucket towers

Therefore, the didactic methodology consists of analyzing the mechanism's information source, based on animation videos (as is the case), plans, sketches, diagrams, annotations, etc., in order to model a specific 3D design with capabilities scalable features. There are numerous old mechanisms, as is the case of the Juanelo mechanisms, which despite having information from various sources and nature, have not been fully adapted to new design and 3D printing technologies in educational environments. With this proposed methodology, the student starts with training in 3D design and in the fundamentals of machines and mechanisms. With this, he develops analytical skills in the functioning of mechanisms, synthesizing the key elements in functional models. Despite the complexity of the Juanelo mechanism as a whole, the choice of the Juanelo mechanism responds to its historical importance, and the large number of more simple elements that make it up, giving further study to the operation of mechanisms subdivided into different phases of operation.

21.3 Results

Based on the designs and methodology described in the previous section, a geometric, structural and mechanical analysis is proposed that results in the 3D design of the different components of the Juanelo Turriano mechanism. These are shown in detail in Table 21.1.

Figure 21.3 shows the complete mechanism once all the parts in Table 21.1 have been designed.

The bucket tower is the most important mechanism of this set since it fulfills the main objective for which this infrastructure is built, to raise the water of the river. The tower houses inside some slats with buckets at their ends that will take care of the rise of water. These perform a vertical movement through braces attached to them by pins. In turn, the straps are attached to a triangle-shaped piece at the top and another

Table 21.1 3D design of the different components of the Juanelo Turriano mechanism

Mechanism	Operation	Design
Wheel 5	Initial wheel: It is responsible for starting the transmission mechanism being driven by the flow of the river at a speed of approximately 3 m/s	
Wheel 4	Wheel 1st stage: It is connected to the initial wheel through its axis and, consequently, transmits the angular velocity of the first wheel to the next, achieve a decrease of speed thanks to the difference in the number of teeth between the two	
Wheel 3.2	2nd stage wheel: Receives the movement of wheel 4 positioned horizontally and transforms it into a vertical turning movement, thus managing to transmit this angular velocity to the next wheel through a vertical axis that connects them	
Wheel 3.1	2nd stage wheel: It is exactly the same as the wheel that precedes it and transmits the speed that arrives through the vertical cross axis to the next wheel of the mechanism	

(continued)

Table 21.1 (continued)

Mechanism	Operation	Design
Wheel 2.2	3rd stage wheel: Positioned horizontally, it receives the movement of wheel 2.2 and transmits it to the next one through a vertical cross axis that connects them	
Wheel 2.1	3rd stage wheel: It rotates with the angular speed of wheel 2.2 and transmits it to wheel 1 making its vertical cylinders collide with the teeth of the opposite	
Wheel 1	4th stage wheel: This wheel is responsible for transmitting the rotational movement to the output wheel	
Wheel 0	Output wheel: It consists of a wheel that contains a single tooth that will transmit the movement generated by the set of wheels to the bar mechanism, transforming the circular movement into rectilinear movement	

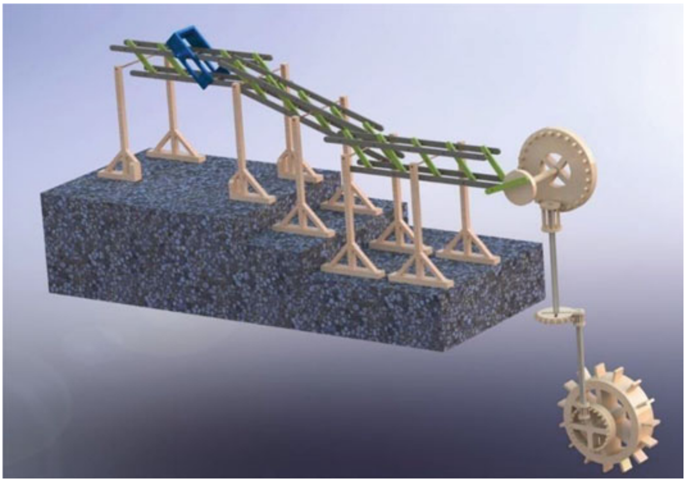


Fig. 21.3 3D model of the tie rod and forcing mechanism

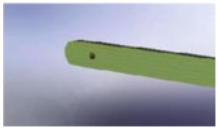
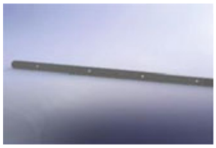
of the same nature at the bottom. They will be defined more precisely in Table 21.2, where the corresponding 3D design is also shown.

Figure 21.4 shows the complete mechanism once all the parts in Table 21.2 have been designed.

21.4 Conclusions

In this work, the practical application of reverse engineering to ancient mechanisms with the use of modern digital tools has been demonstrated. In this case, applying the methodology designed to the Juanelo Turriano mechanism, which served to raise water in the city of Toledo centuries ago, a structural and mechanical analysis of the available sources has been carried out, including plans and videos of foundations on the mechanism. With this, detailed 3D designs of each of the parts of the mechanism assembly have been developed, in such a way that designs with greater capacity for dynamic analysis and capable of being able to develop scale implementation studies are proposed.

Table 21.2 3D design of the bucket tower of the Juanelo Turriano mechanism

Mechanism	Operation	Design
Connecting bar	This element fulfills the function of joining the driving wheel with the tie rod and forcing mechanism, and in turn joins the different sets of bars between them	
Guide bar	It consists of an extensive wooden bar that, joined laterally to a counterpart by connecting bars, transmits the oscillating movement while maintaining parallelism between them	
Pins	These are cylindrical pieces whose mission is to serve as a joining element for the different bars, being inserted through their holes The pin in the image is the longest in the mechanism, however, different sizes are available depending on the distance between the elements to be joined	
Supports	They are those that fix and limit the slenderness of the mechanism and the angle that the bars will form with respect to the ground We find two types: Supports with symmetrical reinforcements and trimmed supports. The cut supports are due to the impossibility of using the usual ones due to lack of space	 
Driving part	This 1060 alloy piece is connected to the center of the tie rod and forcing mechanism by means of pins and is the motor of the bucket tower. It achieves this by dragging a piece that activates the tower when it rotates with the movement provided by the bar mechanism	

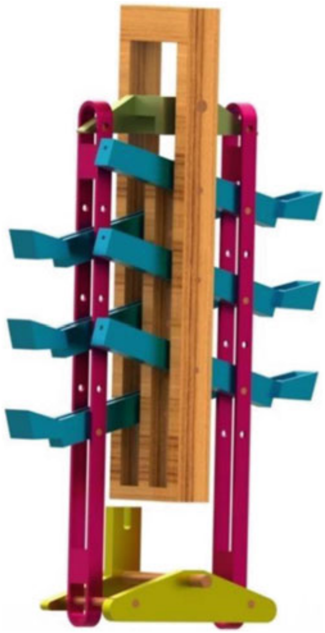


Fig. 21.4 Complete 3D design of the swinging bucket tower

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