3D Reconstruction of Two Medieval Artifacts by the Engineer Al-Murādī

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Abstract. "The Book of Secrets in the Results of Ideas", usually called "Book of Secrets" is a codex containing drawings and descriptions of thirty-one artifacts attributed to the engineer Alī Ibn Khalaf al-Murādī, who lived in Andalusia in southern Spain at the beginning of the 11th century. This manuscript is one of the first written testimonies that describe medieval mechanisms with complex precision. The aim of this work is to reconstruct and study from a historical and technological point of view two of the ancient artifacts contained in the "Book of Secrets", the "Fortress Demolisher" and the "Magic Well". The "Fortress Demolisher" is a war machine designed to demolish the upper part of the walls or towers and consists of a battering ram mounted on a platform that can be raised several meters above the ground using a scissor mechanism. The "Magic Well" is a mechanism with several pulleys whose purpose is to raise water several meters from the bottom of a well by collecting a small portion of rope. The physical reproduction of the two artifacts was made by 3D printing, using the Fused Deposition Modeling (FDM) technology. Previously, a virtual model and a detailed study of the geometry and operation of the mechanisms have been carried out.

Keywords: History of machines and mechanisms · Digital modelling · 3D printing · Scale reconstruction

1 Introduction

Since its origin, human beings have always wanted to record their passage through history and transmit to next generations how they lived. For this reason, since the invention of writing, all cultures have given great importance to the transmission of their knowledge through the written word.

The evolution of knowledge has led to the evolution of the transmission medium, evolved from oral transmission or basic writing to the variety of multimedia and digital options of today.

In this work, an emerging technology such as 3D printing will be used for the transmission of knowledge, with the aim that the real scale reproduction of ancient mechanisms helps to better understand their operation, and thus understand the most complex modern mechanisms.

M. Ceccarelli and R. López-García (Eds.): HMM 2022, HMMS 40, pp. 84–96, 2022.
https://doi.org/10.1007/978-3-030-98499-1_8

1.1 Written Transmission of Knowledge in Ancient Times

Throughout history, the transmission of the knowledge has always been one of the priority objectives for the development of societies. This knowledge was stored since ancient times in libraries. Perhaps the earliest known library as an organized collection of documents is that of the Assyrian king Ashurbanipal, discovered during excavations in the city of Nineveh. In it, some thirty thousand fragments of clay tablets appeared buried among the remains of the Royal Palace. Later, the libraries of Alexandria, Pergamum, and different Roman libraries were famous. From those times until the advent of the printing press (Johannes Gutenberg, 1440), the fundamental supports for this transmission were tablets, scrolls and codices [1].

The tablet was an element used since ancient times in Rome, which consisted of a rectangular wooden table filled with wax. It was written on it using a wooden or metal punch, called a stylus.

The manuscript scrolls appeared in Egypt and were obtained from the Cyperus papyrus plant, very abundant in Egypt, which was cut into small strips that were later macerated and glued, overlapping the different cut layers to form the final tissue. They were stored in different temples and libraries, in clay pots, wooden boxes or leather cases [2].

The codices are one of the previous formats of the book as we know it today. They are made up of a set of folded and bound papyri or parchments [3]. They were the most used element for manuscript conservation and historical dissemination since the Middle Ages.

1.2 Science and Technology in the Medieval Arab World

The first sciences that attracted the curiosity of the learned Muslims were astronomy and mathematics, since their practical nature led them to dedicate themselves mainly to the exact sciences. Observatories were built in the most important centers of the Islamic empire, highlighting those of Baghdad, Cairo, Córdoba, Toledo and Samarkand. In mathematical sciences, many basic principles of arithmetic, geometry and algebra were discovered by Muslim scholars. In arithmetic, we still use numbers and the counting method invented by the Arabs. The invention of algebra is attributed to the Arabs. Among the most famous authors Al-Khwarizimi stands out, one of the best scientific minds of Islam, who exerted a great influence on mathematical thought throughout the Middle Ages.

The Arabs also made important contributions to physics and chemistry sciences, such as those made in the field of optics by Hassan-Ali-Aitan. In chemistry sciences, they discovered distillation and were the first to use the methods of sublimation, crystallization, coagulation, and cupellation to extract and mix substances.

After mathematics and chemistry, medicine was the science that most attracted Muslims scholars. During the first centuries of the Hegira, it was an integral part of a complete education, so the number of famous doctors and treatises on medicine is considerable. Muslim doctors played a decisive role in Western medical science. For several centuries, the works of Rhases, Ibn-Sina, Abul-Cassis and Ibn-Zohar were the basis of medical studies in all European universities. They also became interested in agronomy because of their interest in traditional herbal medicine.

Possibly the first engineering treatise written by Al-Murādī is from the Taifa era, when great interest in applied science was aroused. This manuscript is the first sample of the western Islamic mechanical tradition, which will be continued in North Africa and Europe, characterized by the use of rough mechanisms and powerful machines compared to the eastern mechanical tradition, which stands out for its delicate mechanisms and controls [4].

1.3 The Book of Secrets

The Book of Secrets (باتك راسأ راكفألا ةجتانلا, kitab al-asrar al'afkar alnnatija), is a codex with a collection of thirty-one artifacts attributed to the engineer Alī Ibn Khalaf al-Murādī, who lived in Andalusia, probably in Córdoba or Granada, at the beginning of the 11th century AD.

In this manuscript, the first written testimonies of medieval mechanisms with complex precision are drawn. The codex has been preserved for centuries in the Biblioteca Medicea Laurenziana in Florence. However, his drawings were not interpreted until the 21st century.

The existence of this manuscript was brought to the fore by the engineer and historian Donald Routledge Hill around 1970 and was not given much attention until after about thirty years. It was then when, thanks to the economic collaboration of the Emir of Qatar Sheikh Hamad bin Khalifa Al Thani, who financially endowed the project. The facsimile reproduction of the manuscript was carried out [5], also its study both from the technological point of view and historiographic, and the reproduction of two of the inventions collected to be exhibited at the Museum of Islamic Art in Doha, in Qatar (Fig. 1).

Fig. 1. Pages from the facsimile edition of the Book of Secrets [5]

Among the thirty-one artifacts described in the codex, there are five automatons in the form of a "little theater", two calendars (one zodiacal and another astronomical), four war machines, two mechanisms to draw water from a well and, above all, there are clocks. The tools most used to create the mechanisms of the artifacts are ropes, pulleys, water tanks and counterweights. The present work has focused on recreating the 23th and 25th artifacts, a war machine called "Fortress Demolisher" and a pulley mechanism of a well called "Magic Well".

2 Description and Digital Modelling

As a previous step to the physical reconstruction of the two aforementioned artifacts it was necessary to carry out a digital modelling of them. CAD software CATIA has been used for digital modelling, which allows the design of the parts, their assembly and the conversion of each part to the STL file format needed for the 3D printing.

The original manuscript of the book of secrets contains numerous drawings and schematics of the artifacts, but they are deteriorated by the passage of time and present quite a few inaccuracies. For this reason, to design the geometry of the different pieces of each artifact, it has been necessary to take as reference the reproductions of the original work made by the engineers of the Leonardo 3 studio [5]. In these reproductions, an interpretation of the original schematics of the codex is made with 3D simulations (Figs. 2 and 3). The simulations show the operation of the artifacts with some clarity, but do not contain detailed drawings or dimensions. For this reason, in order to make a digital model that could later be printed, the design had to be reinterpreted and resized based on these simulations and the little information in the original codex.

Fig. 2. Description, drawings and interpretation of Fortress Demolisher [5].

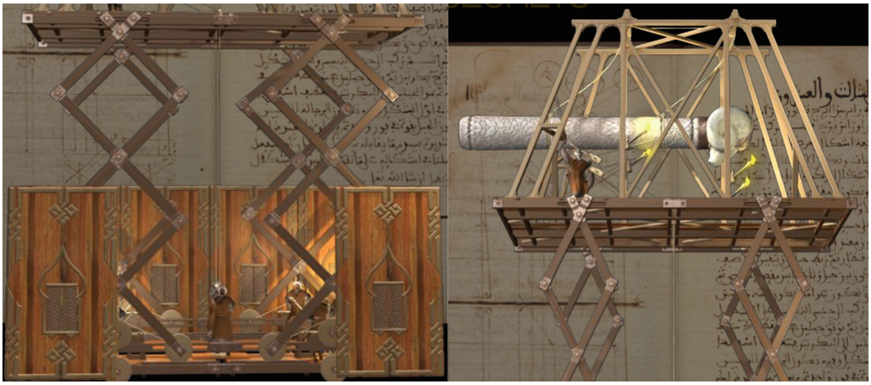
The reproduction scale has been decided based on the limitation imposed by the size of the 3D printer's printing plate, which does not allow a printed part length greater than 200 mm. Therefore, the largest piece has been designed based on this limitation, and the rest of the pieces have been scaled to maintain the geometric proportion.

Fig. 3. Description, drawings and interpretation of Magical Well [5].

2.1 Fortress Demolisher

The Fortress Demolisher is an assault war machine similar to the typical battering ram that was used to destroy the lower parts of the walls or the gates, and to open breaches in the defenses of the enemy. The study device differs from a classic battering ram in that it is mounted on a platform that can be raised several meters high by means of a scissor mechanism in order to be able to knock down the upper part of the enemy fortifications. The original codex defines the use of the mechanism as follows: "*We want to install on top of this tower and to its left a weapon which can demolish the top of a wall or tower*" [5].

Initially, walls hide the platform with the ram. The platform is raised above the walls by the movement of four winches operated by a pair of men each. When picking up the rope with the winches, wheels on rails move and close the scissor mechanism rising the platform. (Fig. 4 (a)). Once the battering ram is positioned at the desired height, it could be moved backward with a system of ropes and pulleys, to then release it and hit the enemy wall with a strong impact (Fig. 4 (b)).

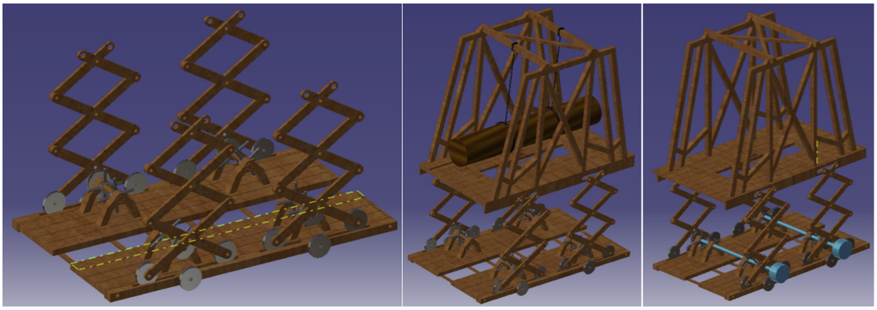


(a) Scissors mechanism (b) Elevated battering ram

Fig. 4. Details of the reproduction of the Fortress Demolisher by Leonardo3 study [5].

As there is not a clear reference to the geometry or elevation height of the Fortress Demolisher scissor mechanism in the Book of Secrets, the height has been deduced from the information in another mechanism in the book with a similar lifting system, the 22th called Mechanical Tower. After interpreting the data from this mechanism, it was deduced that the platform rise from a height of three meters to a height of eleven meters. A design of the scissor mechanism has been made based on these measurements, adapted to the reproduction scale. The rest of the elements have been designed with dimensions proportional to the scissor mechanism.

An attempt has been made to make the reproduction as faithful as possible to the original model (Fig. 5). However, because the design is oriented towards its subsequent 3D printing and manual operating, small modifications have had to be made in order to print and later assemble the parts. For example, to reproduce the movement of the scissor mechanism and that it could be carried out with only two hands, the shafts that move the pulleys have been lengthened to be able to be driven from the outside (Fig. 5 (c)).



(a) Scissors mechanism design (b) Battering ram design (c) Modified shaft

Fig. 5. Digital model of the Fortress Demolisher.

To give greater realism to the designed Fortress Demolisher, its design has been rendered resulting in the image shown in Fig. 6.

2.2 Magic Well

This device is a simple multi-pulley mechanism whose objective is to be able to lift a load several meters collecting a small portion of rope. In this case, the load is a bucket of water into a well. The codex expressly indicates the purpose of the device: "*we want to take water from a well, whose depth is eight meters, collecting only one meter of rope*" [5].

This mechanism is based on the lock-and-board principle. A rope is passed through a pulley and tied to a fixed location. The other end of the rope is attached to the element to be lifted. The pulley is pulled up and a double-acting mechanism is obtained that makes the objects go up by picking up half the rope.

The original manuscript does not mention the anchoring position of the ropes, nor their length, possibly because the exact dimensions did not want to be revealed so that

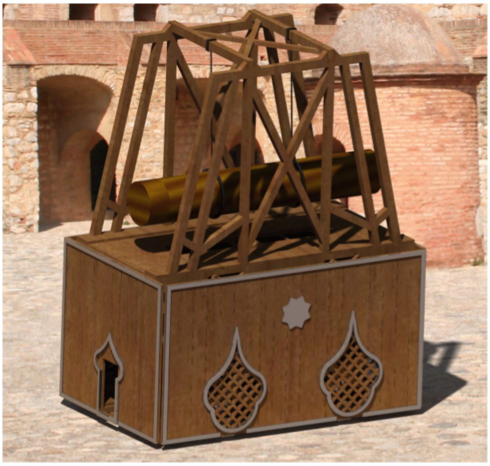


Fig. 6. Digital reproduction of Fortress Demolisher.

the well did not lose its "magical" character. However, the interpretation of the drawings indicates that the length of the strings has a sequence of 1-2-4 to be able to bring the bucket from the bottom of the well to its curb. The general law that governs the operation of this mechanism is based on the distance between the supports of the pulleys and the distance to the bottom. For the device to be effective, the distances between pulleys must be in a geometric ratio of 2 (Fig. 7). With this design, the length of rope to be picked up is reduced, but the lifting force of the water is increased since the force necessary to lift each pulley is twice that of the lower pulley.

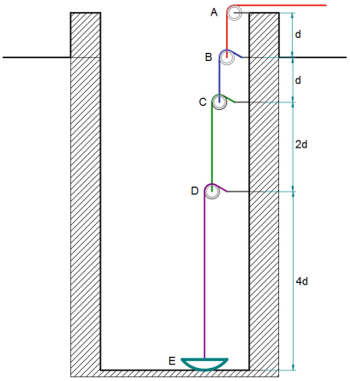


Fig. 7. Geometric relation of the Magic Well.

The dimensions of the pieces of the digital model have been designed by scaling the depth of the well with the maximum dimension available in the printer. All pieces have been scaled according to this ratio. Figure 8 shows the final digital model.

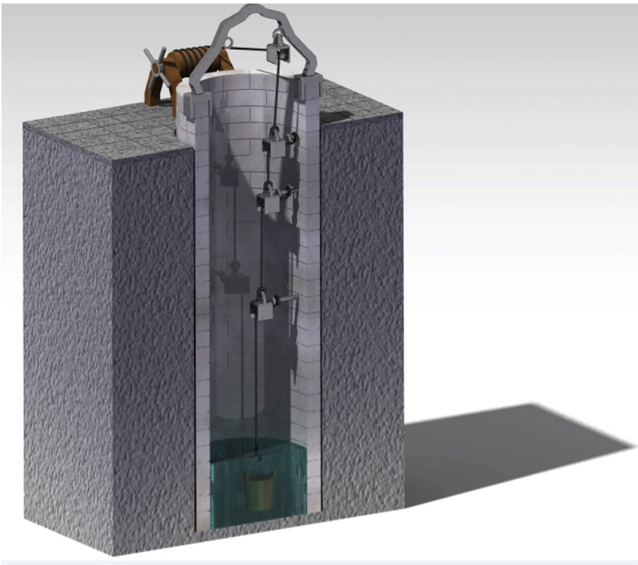


Fig. 8. Digital reproduction of Magic Well.

3 Physical Reconstruction

3.1 3D Printing

Once the digital modelling was done, the two artifacts have been physically reproduced. All the parts of the mechanisms were manufactured with a 3D printer using Fused Deposition Modeling (FDM) technology. FDM technology is based on depositing layers of a molten polymer filament according to a horizontal path followed by an extruder. The polymer is extruded at a temperature close to melting temperature, so it quickly solidifies after being deposited. The overlapping of solid polymer layers allows the generation of three-dimensional structures. The movement of the extruder is what defines the geometry of the printed part. This movement is governed by an alphanumeric code similar to the ISO code used by Computer Numerical Control (CNC) machines [6].

Starting from the digital model made with CATIA software, a discretized STL model can be obtained. This model approximates the surface of the three-dimensional object with a closed triangle mesh. The discretized file is processed with a slicer software that performs horizontal slices of the discretized model. The intersections of the triangular planes with the horizontal planes generate joined straight lines that mark the contour of the part in each plane. The coordinates of these lines are those that the extruder will follow to deposit the molten polymer.

The CURA 3.6 slicer software was used to generate the GCODE text file with the code of the paths and the conditions of the movements. This file is reproducible by the 3D printer to generate the part. This software not only allows the processing of the digital model but also manages its printing by choosing the critical printing parameters such as temperature, printing speed, layer height, wall thickness, filling type and density, etc.

3.2 Materials and Printing Set up

The material used for the printing of the mechanisms parts has been PLA (polylactic acid). The PLA is a biodegradable thermoplastic polymer obtained from cornstarch, and is widely used in molten deposition printing. PLA does not have great mechanical resistance but is widely used for prototype reproduction due to its ease of printing and low cost. To give the reproduction more realism, gray and brown filament spools have been used, which simulate the stone and wood that would be the originally used materials. Table 1 shows the characteristics of the PLA used.

Table 1. Characteristics of PLA filament

Recommended printing temperature	200/220 ºC
Melting temperature	145/160 ºC
Glass transition temperature	56/64 ºC
Density	1,24 g/cm^3
Filament diameter	1,75 mm

An ANET A8 printer has been used for printing, which is a low cost printer with quite good print quality for its price. The printer has a square print surface of 200 mm per side, and a maximum print height of 215 mm. These printing dimensions conditioned the scaling of the printed parts. To reduce vibrations and improve the quality of the finished parts, the original design of the printer has been modified, lightening the weight of the extruder by changing the position of the extrusion motor (Fig. 9).

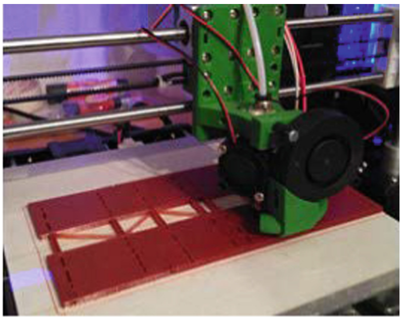


Fig. 9. 3D printing process.

Table 2 shows the value of the main printing parameters.

Table 2. Main printing parameters

Layer height	0,1 mm
Wall thickness	1 mm
Top/bottom layer thickness	1 mm
Infill density	20%
Infill pattern	Triangular mesh
Printing temperature	210 ºC
Print speed	60 mm/s
Infill speed	80 mm/s

3.3 Assembly and Real Scale Reproduction

After printing all the parts, they were assembled to obtain a real scale reproduction of each artifacts. The union between parts were made using a cyanoacrylate adhesive, since its result in the gluing of PLA is very satisfactory. To join the larger fixed parts, a joint system with holes and shafts has been designed, which facilitates assembly and gives greater stability to the reproduction. For the union of the mobile elements, such as those of the scissor mechanism, small shafts were manufactured and inserted between the moving parts. The end of the shafts was flattened by applying heat, acting as a rivet (Fig. 10).

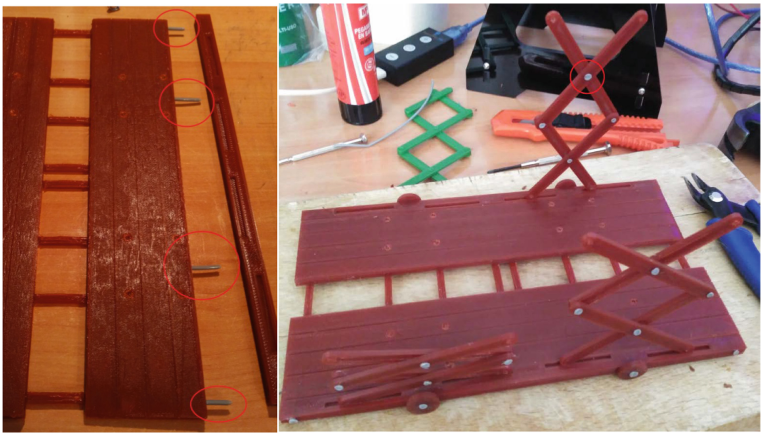


Fig. 10. Detail of the assembly of the joints

To ensure the correct operation of the fortress demolition lifting mechanism, the eight trestles that house the shafts for manual lifting had to be aligned and adjusted (Fig. 11).

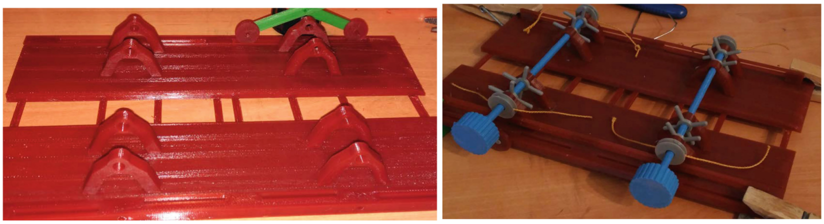


Fig. 11. Lifting mechanism shaft alignment

The only difficulty in assembling the Magic Well is determining the length of the strings. Before the printing of his pieces, a physical simulation was made with a wooden slat and four eyebolts to which the rope was attached. The length of the rope was varied until reaching the solution that was closest to reality (Fig. 12). Due to their small size, the pulleys could not be printed to the same scale as the well. Pulleys with a larger scale have been used to be able to give it a real movement.

Fig. 12. Rope length test

Figure 13 shows the results of the two reproductions.

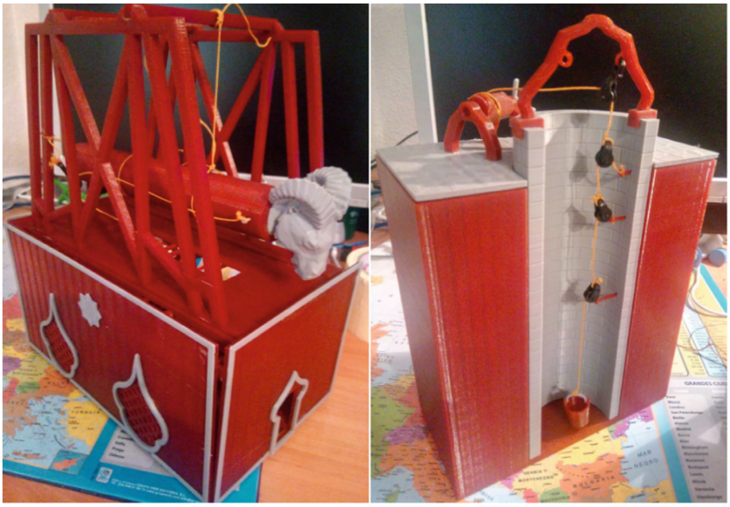


Fig. 13. Real scale reproduction of the two medieval artifacts

4 Conclusions

As a result of this work, the digital modelling and physical reconstruction of two medieval artifacts, the "Fortress Demolisher" and the "Magic Well" have been obtained. Digital modelling allows to study in detail the geometry of artifacts and to subject them to mechanical analysis using engineering software. The physical reconstruction allows to study its movement and operation in a more visual and didactic way.

The use of new technologies allows us to take another step in the transmission of knowledge. Nowadays knowledge is not only transmitted through printed writing, but it is mostly done digitally in written, graphic or audiovisual form.

The use of 3D printing in the reproduction of machinery or mechanisms, manages to go from digital information to a real three-dimensional scale model, quickly and economically. This physical reproduction allows a more direct interaction with the reproduced artifact. This can help to better understand the functioning of the mechanisms that compose it, which is a great help for students, especially in the field of mechanical engineering.

The study of historical machines allows us to deepen our knowledge of the most elementary mechanisms and better understand the evolution that has been followed up to the most complex mechanism designs.

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