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Ctesibius, Vitruvius and Leonardo: A Digital Reconstruction of the Water Clockwork Timeline

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Abstract. Over the centuries several physical models of Leonardo's machines have been reconstructed to solve a fascinating question: visionary and prophetic intuitions or real projects corroborated by analytical studies on their actual possibilities of use? Taking advantage of an interdisciplinary approach and exploiting the potential of digital design, this paper presents the reconstruction of one of the most complex machines represented by Leonardo and first by Ctesibius and Vitruvius: the water clockwork. Starting from the analytical study of Leonardo's drawings, the workflow proposal leads to a digital reconstruction of this machine, made available through an Augmented Reality mobile app developed for the exhibition *Leonardo e Vitruvio. Oltre il Cerchio e il Quadrato.* A digital solution to share this remarkable Cultural Heritage, making the complex language of Leonardo's drawings accessible to a wider audience.

Keywords: Leonardo · Water clock · Digital reconstruction · Augmented Reality

1 Introduction

Over the centuries several physical models of Leonardo's machines have been reconstructed starting from his drawings. The limits of these reproductions can be exceeded by new digital versions able to simulate their functioning and to easily compare different possible settings, helping understand Leonardo's intention: designing visionary and prophetic intuitions or real projects corroborated by analytical studies on their actual possibilities of use?

Transforming this extraordinary heritage into a 3D digital database also turns "hard to read" images into something that can be enjoyed by a wider audience. Virtual Reality (VR) can generate thus new forms of communication, promoting Cultural Heritage (CH) fruition in spectacular ways, both evocative and didactic. Therefore, it means more than simply elaborate scientifically validated digital twins, but generating a new educational

M. Ceccarelli and R. López-García (Eds.): HMM 2022, HMMS 40, pp. 134–145, 2022.
https://doi.org/10.1007/978-3-030-98499-1_12

repertory, bringing Leonardo's machines from physical to digital reality. A solution that opens up new opportunities in designing museum and knowledge paths, making Leonardo's mechanics easily accessible to a wider audience thanks to digital solutions.

From this perspective, the 500th anniversary of Leonardo's death represented a starting point, with great exhibitions and scientific projects based on digital technologies. This paper fits into this scenario presenting part of the scientific research carried out for *Leonardo e Vitruvio. Oltre il cerchio e il quadrato* [1], an exhibition that took place in Fano (Italy) aiming to explore the connection between Leonardo and Vitruvius, the closest ancient author to the Tuscan genius as expression of a multiform and encyclopaedic wisdom. A bond that goes beyond the well-known subject of the *Vitruvian man* and that was explored focusing on the field of mechanics and measurement. Disciplines to which Vitruvius dedicates the *Book IX* and the *Book X* of the *De Architectura*, two essential books to the history of Machines and Mechanics. The *Book IX* describes the water clock of Ctesibius whereas the *Book X* the construction of a ballista and an odometer. Three machines to which Leonardo devote the greatest attention and which mention a deep connection with Vitruvius, highlighted in three sheets of the *Codex Atlanticus* exhibited in Fano [2, 3]. This paper is specifically focused on the water clock, Fig. 1, describing its reconstruction hypothesis and AR fruition, an effective replicable solution also to disseminate other machines history and functioning.

2 Water Clocks in Antiquity

The hourglass was called by the ancient Greeks κλεψύδρα (klepsýdra) which means "water thief" since the passage of time was measured by the constant flow of water in or out of a vessel.

The oldest hourglass of which there is physical evidence dates back to c. 1417–1379 B.C., during the reign of Amenhotep III where it was used in the Temple of Amen-Re at Karnak. The oldest documentation of the hourglass is the tomb inscription of the 16th century B.C. Egyptian court official Amenemhet, which identifies him as its inventor.

In Greece the use of the hourglass was introduced in 325 B.C.: a vessel had a hole in its side near the base through which the water was drained slowly and evenly out of the container; the level of the water gave an idea of the time elapsed. However, this "clock" was not accurate because the water pressure decreased as the liquid level dropped, making the flow progressively slower.

In the first half of the third century B.C. Ctesibius of Alexandria transformed this apparatus into a water clock, that is into a real measuring instrument, thanks to various devices that were described many centuries later by Vitruvius.

The main novel idea was to keep constant the pressure at the exit hole, allowing the water to flow from a vase in which the water level was kept constant as well. Thus, the flow of water, which depends on the pressure, became constant too. Ctesibius was also the first to describe the use of a float to indicate the level of water in the basin and to operate the ring: both these elements, as well as the constant level of the head of water, are present in Leonardo's machine.

Ctesibius also turned the water clock into an automaton, able to take into account the variable duration of the hours at the different periods of the year; in fact the ancient

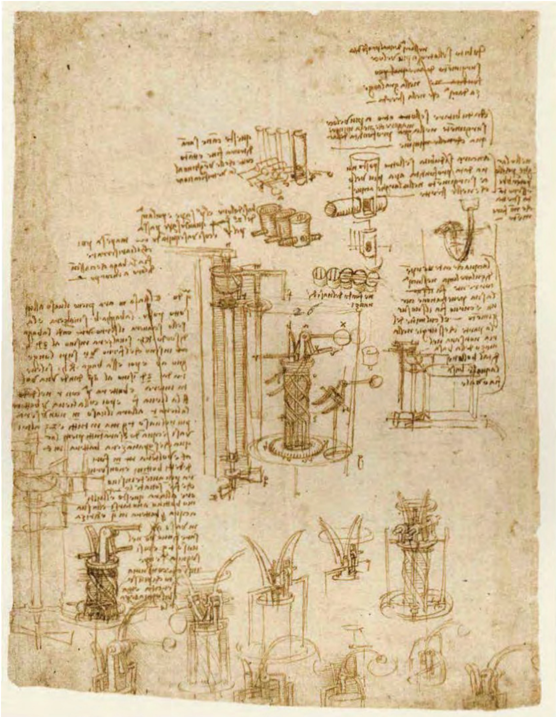


Fig. 1. Codex Atlanticus, f. 943r, around 1508–1510, pen-and-ink, 259 × 196 mm, Milan, Veneranda Biblioteca Ambrosiana

Greeks and Romans had twelve hours from sunrise to sunset and since summer days are longer than winter days, summer hours were longer than winter hours.

Going into the details of the clock, Fig. 2, a constant flow of water pours into a vessel, inside which there is a float that holds an indicator: as the float rises, the indicator slides along a graduated cylinder, pointing to the current hour for the day. When the vessel is filled up, a siphon flushes down the water which in turn rotates a wheel divided into six spokes: a series of gears connects such wheel to the graduated cylinder, so that it completes a full rotation in 365 days, showing day by day the correct time.

Based on Ctesibius' concept, various mechanisms have been conceived in the following centuries. A notable example is the Tower of Winds, Fig. 3, which is located in the Agora of Athens: it was constructed by Andronicus Kyrrhestes of Macedonia during the Roman period in the second quarter of the first century B.C.

Built of marble and octagonal in shape, it is 43 feet (13 m) tall. In its interior, time was determined by a water clock, driven by water coming down from the Acropolis.

In the first century B.C. Vitruvius in book IX of De Architectura describes the first precision hourglasses designed by great Greek mathematicians of the past, such as Ctesibius. In the book, Ctesibius' water clock or clepsydra, is described as the first to have a regulator that would maintain a constant head of water in the effluent part of the clock in order to improve the accuracy.

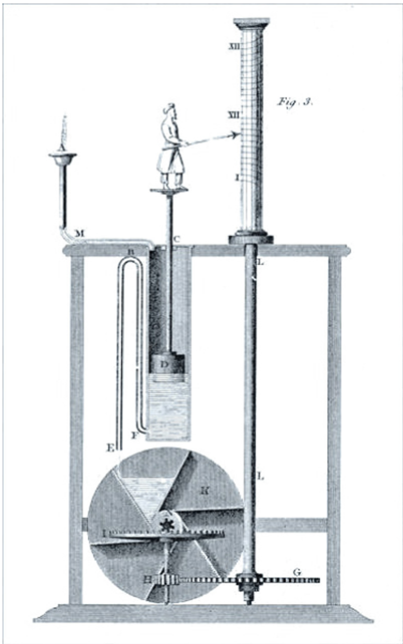


Fig. 2. An early 19th-century illustration of Ctesibius's clepsydra by John Farey, Jr. (1791–1851)

During Renaissance many artists showed a strong interest in ancient scholars and turned to the work of Vitruvius about architecture and painting techniques. Leonardo, however, was also interested in ancient technological world therefore drew on Vitruvius' work on issues related to hydraulics, machines, measurement instruments, materials, and so on [4–6].

Leonardo developed his studies on hourglasses during his service with Charles of Amboise, French governor of the state of Milan: at that time the treatise of Vitruvius was already printed but hardly accessible, moreover it was written in Latin and without illustrations.

The only attempt to represent Ctesibius's water clock in figures could be found in Roberto Valturio's De re militari. Some key features of the hourglasses described by Vitruvius have been reinterpreted by Leonardo in an original way, such as how to obtain a uniform flow of water.

After the fall of the Roman Empire, the tradition of water clocks was preserved by the Arabs with an entire book of these devices written by Al-Jazari in the thirteenth century with the "Book of Knowledge of Ingenious Mechanical Devices".

3 Leonardo's Bell Ringer

The water clock has been the subject of many studies by Leonardo, which led to different conceptual solutions, therefore it appears in various sheets of the Codex Atlanticus and in the Windsor collection.

Fig. 3. The Tower of the Winds

Folio 943 recto of CA, which was on display in the Fano Exhibition, contains many sketches used by Leonardo to assess different viable alternatives, so that it is possible to follow his entire line of thoughts during the redesign of Ctesibius' machine as described by Vitruvius.

The final design of Leonardo is sketched in the central part of the folio and is partly reproduced in Fig. 1: a description written in Leonardo's classic mirror handwriting appears in the upper left-hand side of the sheet. It is a very complex machine and the precise working flow is not yet understood in all details, also because it was probably only sketched. The scientist drew different concepts for the main components of the clock, at least as many in another part of the sheet not shown in the figure. An informed review on the studies of Leonardo upon this complex mechanism can be found in [7] while Rosheim [8] managed to build a prototype of the water clock.

Leonardo conceives an hourglass supplied by a canal which continuously pours water into a container hinged to the frame. The container can rotate to fill one after the other 24 vessels (called "bottini") representing the hours of the day: only one of them is shown in the drawing. At the end of the day all the containers are full and can be emptied.

The indexing motion of the container is actuated by the central body of each vessel, which is a complex mechanism shown with details in Fig. 4: key elements of its functioning are the helical guides that wind around the central column and two floats; one of them is spherical while the other is toroidal and is called "baga" by Leonardo.

When the vessel is filled with water to its maximum level, the spherical float rises and triggers the release mechanism that frees the horizontal bar: such bar is the upper part of a metal body passing through the central column with helical guides and is connected to a stop for the lower float. The baga can now rise up following the guides which impose a motion that is rectilinear for the first part and then helicoidal. This helical motion causes the horizontal rod to beat against two levers that rotate the container to feed the subsequent vessels; the same mechanism opens up a valve that flushes down the water of the vessel.

In addition, fork levers have been added, perhaps as counterweights, to make sure that the spherical float can lower again.

The Vitruvian mechanism, so ingeniously reinterpreted by Leonardo, would be so precise and automatic that it would never need to be tuned or reloaded. On top of the entire mechanism, Leonardo imagined installing a large bell beating the number of chimes corresponding to the hour of the day. This should be either a living being that would simply observe how many tubes were full, or some sort of automaton, almost a robot.

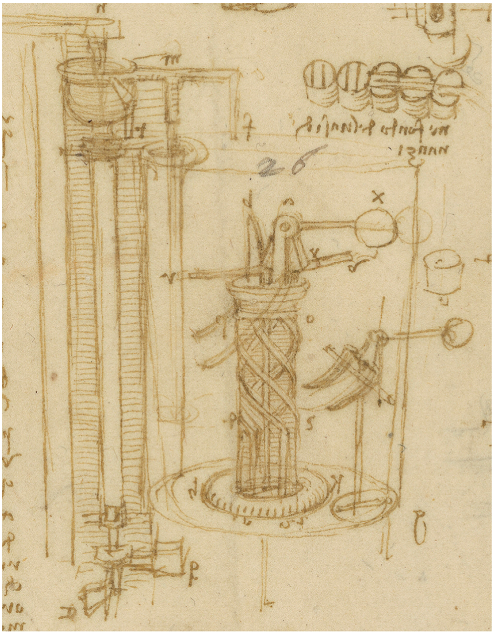


Fig. 4. Water clock sketch according to the original description by Vitruvius

4 Digital Mock-Up

The digital reconstruction of the water clock and the related animations allowed the Authors to experiment the feasibility of the concept and the Exhibition's visitors to understand its complex functioning; a sample animation can be accessed on the internet at the web address: https://www.youtube.com/watch?v=2omu1jSofUU&ab_channel=MeccanicadelleMacchine%40UnivPM.

The virtual prototype realized by the Authors allowed to assess that the mechanisms of Leonardo's clockwork and its workflow are sound despite the fact that he never realized a physical prototype. However, some issues coming from the actual realization of the clock can be pictured by the perspective of modern technology. Rosheim in [8] managed to build a small-scale clock facing many technical challenges never mentioned by Leonardo. Such issues mainly involved the materials and the surfaces finishings, which strongly affected the forces mutually exerted by the components.

Let's take the baga as an example: its material affects both the upwards and the downwards strokes. In fact, such component should be light enough to float and at the same time heavy enough to drag the whole mechanism while going back to its home position; solid wood can be an option in such sense.

Moreover, the ability of the baga to move along its helical guide depends on the quality of the surfaces in contact: the friction developed by the bodies could easily jam the whole mechanism. Such hypothesis is more than reasonable, especially if we think that the contact among two bodies (the baga and its helix) takes place under water where the use of a lubricant is virtually impossible. Moreover, the physical properties of the wood change when underwater, thus making the sliding of the components even more difficult.

This section is a brief explanation of the digital mockup that was animated during the Exhibition and was able to interact with the visitors. Figure 5 shows one of the 24 vessels, connected by pipes to transport water from one to the other. Each vessel has a complex mechanism that drives the filling and flushing of the water from the container and is composed by the following main parts.

4.1 Hours Basin and Water Supply System

The water flow fills the upper vase coming from the top left and comes out through the side duct to fill the hours vessel. When the latter has filled up, and therefore an hour has passed by, a mechanism (explained later on) rotates the water supply duct, which then feeds the next vessel. At the same time, a valve on the bottom flushes the water down. The stroke of the hour is marked by the ringing of a bell, not shown in the sheet exposed at the Exhibition.

4.2 Float Release Mechanism

When the water level in the hours vessel reaches the spherical float located in the upper part of the drawing, the float rises due to Archimedes' buoyant force and therefore it tilts the circular sector, which finally unlocks the small horizontal rod.

4.3 Central Column (Valve/Actuator)

While the water is filling the hours vessel, the toroidal float placed at the bottom receives an upward thrust but cannot rise since, being integral with the central shaft and the horizontal rod, it is blocked at the upper end by the circular sector previously described. When the water reaches the level necessary to free the central shaft, the horizontal rod, pushed by the lower float, starts rising upwards. The components of the central column have a shape such that during the rise the motion is initially straight but from a certain point onwards it becomes helicoidal, as there is also a rotation of the block around the vertical axis. In the final phase of the movement the small horizontal rod gets in contact with the adduction duct and makes it rotate of a certain angle, so that it goes to feed the aside basin of the following hour. The rotation of this duct also opens the drain valve, flushing the container (Fig. 6).

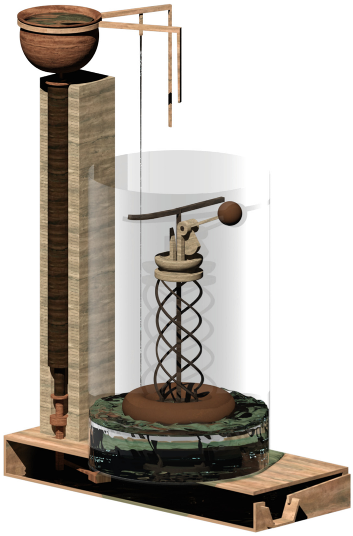


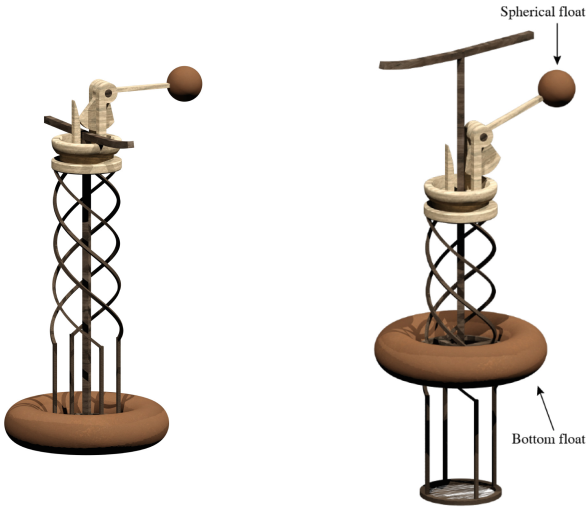
Fig. 5. Rendering of the interactive model of the water clock

5 Digital Technologies for Cultural Heritage Experience

Cultural Heritage (CH) is defined as set of elements which, for historical, cultural or aesthetic importance, are of public interest, representing a community and its cultural wealth. CH is therefore, by its very definition, of great interest to the public, who must be allowed to enjoy it in a proper way.

In order to achieve this goal, it is necessary to go beyond a static relationship between CH and its user. Overcoming the need for a rational systematization of CH expressed by the Museum Institution of late eighteenth-century, new needs are emerging today: to stimulate a dynamic and interactive perception of CH, developing a process of continuous learning is just one of the challenges to be faced shifting the attention of Museum Institution from the object to the observer.

The physical presence of CH is no longer enough to spread culture, it is necessary to build a relationship between the work of art and its observer, to know its contents,



(a) (b)

Fig. 6. Details of the central column commanding the filling/flushing of water through the hours vessel; the bottom float is locked in (a) and it is released and rising in (b)

its techniques, its expressive and aesthetic meaning [9]. From an educational point of view, works of art are carried out in a complete way only when it successfully reaches its recipients, that is, when the communicative act implicit in it is completed [10].

In this scenario the use of technology as an intermediary between CH and the user, as a tool of transition from passive contemplation to a new dynamic fruition, represents an effective solution [11–14]. It must be considered that the users who enjoy CH are the same who use the screen of a PC, tablet or smartphone as privileged "window" to the world every day. Therefore, these tools have to convey cultural contents, making also CH a daily presence.

However, making fruition "technological" is not enough, technology must be used in a conscious way, avoiding, as often happens, to aim more at entertainment than education. These two components must be balanced in a learning by playing approach to involve users, designing cultural and multimedia operations that solicit connections [15, 16].

This strategy makes the technological medium and their potential benefits effective. Digital tools allow us to customize CH experience and therefore to communicate it, placing it at the user level thanks to different depths of contents and linguistic register.

The awareness of the effectiveness of smartphones and tablets for CH experience has led to a wide use of these devices. Several museums offer apps containing sections on the masterpieces preserved in their galleries or offering the possibility of virtual visits. These experiences show how the use of new media improves the fruition CH, encouraging its diffusion to a wider audience and even at a higher quality level. From new thematic paths to the enhancement of single works of art, from the 3D reconstruction of existing museums to the setting up of only virtual ones, different technological solutions can be exploited for CH fruition. In any case, a user-centered fruition that makes CH more accessible by improving its perception must be the goal, regardless of whether enhancing the vision of the real object (Augmented Reality), combining real and virtual (Mixed Reality) or creating a completely virtual environment and interaction (Virtual Reality).

6 LeonARdo: An AR App for Leonardo's Machines

The AR mobile app developed for Leonardo's water clock and the other drawings exhibited in Fano allows to integrate original drawing, one of major expressions of human inventiveness, with their digital 3D reconstruction. It has been developed for Android OS using the Unity game engine. To be used as a target, the images of the original drawings were uploaded on the Vuforia platform, where they have been analysed identifying their features to be recognized when the app is running the camera of user's device. Once the quality of the image has been validated, a dataset was automatically downloaded, providing all necessary for target recognition. This dataset and all the other elements for the

Fig. 7. User Interface. After selecting the language (1), the camera is activated. Automatically detecting the depicted machine on the framed drawing, the app generates the 3D model (3). The user is then allowed to activate the mechanisms and access in-depth folders about the representation (4), with the possibility to explore its HD digital reproduction (5). Further insights about the machine, its sub-assemblies (6) and history, are also available.

development of the App were imported into the Unity environment: the image-target and the dataset from Vuforia, the ARcamera that simulates the camera of the user's device, the 3D models of Leonardo's machines with related materials and an illumination and shadows system to make their visualization more real. Finally, the app was built after scaling and positioning the 3D models to make them appear from the original drawing as they were generated by the lines on the paper.

Concerning the user interface, it was designed to offer an immediate fruition of the contents. Once the app is open, users only have to frame one of Leonardo's drawings that was previously uploaded as target, making the corresponding 3D model appear on the screen. Once the model has been visualized, it can be investigated independently from the drawing, its components can be observed, and the functioning of the machine can be simulated. It is also possible to access a section about the original drawing, with textual information and high-resolution image, and one about the choices made for the digital reconstruction analysed from the mechanical point of view, Fig. 7.

7 Conclusions

The exhibition held in Fano has shown that is desirable to generate a digital heritage of Leonardo's inventions able exploits the possibilities granted by digital technologies for new forms of investigation, fruition, narration and understanding. A digital approach solves problems related to the complexity of the original drawings and it helps to better understand the delicate step from the concept to the representation. The physical models of Leonardo's machines are in fact not able to fully describe this passage, not allowing variations or simulations that digital reconstructions enable.

Coupling digital design and digital fruition also allowed to define methods and best practices for the transition from the cognitive model to the communicative one, generating a dynamic interaction with drawings that are by their very nature static representations. The AR application was, in fact, designed to return those drawings in the form of the artist's thought, recreating a suggestion able to penetrate the mind of the greatest genius who ever lived.

Acknowledgments. The Authors wish to acknowledge the Municipality of Fano, sponsoring institution of the Exhibition *Leonardo e Vitruvio – Oltre il Cerchio e il Quadrato.*

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