Digital Experience of the Work of Vitruvius and Leonardo

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Abstract. On the celebrations for the 500th year since Leonardo da Vinci’s death, the city of Fano (I) organized an exhibition on the works of Leonardo to put in evidence the influence of the previous studies of Vitruvius, who left in Fano remarkable signs of his talent. Among the original drawings that were shown, some sheets showed the design of three machines originally described by Vitruvius and then re-interpreted by Leonardo: the water clockwork, the ballista and the odometer. The Authors realized a digital reconstruction of such works, with the aim to let the visitors of the exhibition understand the operation of the machines but also to study the differences in the concepts, to explore their feasibility and to assess their possible performance.

1. Introduction
The Roman architect and military engineer Marcus Vitruvius Pollio around 30-15 b.C. wrote the famous “De architectura” dedicated to his patron, the emperor Caesar Augustus [1]: it is a ten books treatise meant as a guide for realizing projects such as buildings, military camps, facilities, instruments and machines.

For many centuries Vitruvius’s work had been forgotten, but in the early 1400s it was one of the many pieces of classical writing unveiled by Renaissance and Leonardo da Vinci was very interested to his studies, as appears in many writings [2]. Leonardo embraced the work of Vitruvius in both his art and his science and the most famous expression of this connection is the well-known drawing of the Vitruvian Man. As a matter of fact, most Renaissance scholars and artists were interested in Vitruvius’ studies about architecture and painting techniques but Leonardo, on the other hand, drew on Vitruvius’ work on issues related to hydraulics, machines, measurement instruments, materials, and so on.

On the celebrations for the 500th year since Leonardo’s death, the city of Fano (where Vitruvius left important signs of his talent) organized an exhibition on the work of Leonardo to put in evidence the influence of the previous studies of Vitruvius. Among the original drawings that were exposed, some sheets showed the design of three machines originally described by Vitruvius and then re-interpreted by Leonardo: the Water Clockwork, the Giant Crossbow and the Odometer.

The Authors realized a digital reconstruction of the works by Leonardo and Vitruvius, with the aim to let the visitors understand the operation of the machines but also to study the differences in the concepts, to explore their feasibility and to assess the possible performance [3].

2. The Virtual Machines of Leonardo
Many physical models of the complex Leonardo’s machines have been built over the centuries but today’s tools of digital representation provide alternative and probably more effective ways to explore the work of the great scientist. They allow to critically simulate the configuration and the operation of such machines, trying to penetrate Leonardo’s intention in the act of their design, i.e. to assess whether they
were simple visionary and prophetic intuitions or real projects corroborated by analytical studies on their actual functioning and possibility of use.

Being able to transform this extraordinary design heritage into a three-dimensional digital form allows today to place "difficult" images in a wide scenario of use available to a wider audience. The new augmented and immersive virtual reality scenarios allow, within the digital supply chain, to create new forms of communication of Leonardo's designs and his machines, thus promoting their knowledge and use in spectacular, suggestive, and didactic ways. It is not a matter of generating simple digital copies or scientifically validated 3D models but of creating a new communicative and interpretative repertoire never made possible before and today allowed by the rapid evolution of digital systems. This generates new opportunities in designing new museum and knowledge paths of Leonardo's mechanics, therefore increasing its diffusion and dissemination through the reproducibility of digital solutions.

Of course, these reconstruction processes must always be grounded on scientific rigor but it may not be sufficient: by considering the precision that can now be achieved in the digital representation of details that may have escaped the control of the author himself, this rigorousness must always be strongly supported by very deep degrees of knowledge of the design on the one hand (therefore of the scenario of Leonardo) and the mechanical components on the other. This requires an interdisciplinary approach that leads to composing different skills in the organization of these exhibitions and events: after all, a sort of re-composition of the multifaceted Leonardo's wisdom [4].

But there is another aspect that enhances the three-dimensional digital reading and reproduction of Leonardo's drawings. Leonardo has an extraordinary drawing ability in representing in a few square millimeters of paper details that often only under the microscope emerge in their incredible precision and completeness. This is particularly true for the design of the machines, in which these details play an important role in their understanding and reconstruction, such as in gearings. The digital representation allows to overcome the limits of the scales of the paper layout, always allowing to draw in 1:1 scale without any constraint linked to the physical medium, thus being able to go to the maximum definition of the three-dimensional representation of the most minute of details.

**Figure 1.** A visitor exploiting the digital mock-up of the giant crossbow at the image wall
The Fano Exhibition explored a little studied but evident link between Leonardo and Vitruvius, perhaps the author of antiquity closest to the Tuscan genius at least as an expression of a multiform and encyclopedic wisdom, touching for the first time the field of mechanics and measurement. Two disciplines to which Vitruvius dedicated two books that actually started the history of mechanics: the IX and the X book of “De Architectura”. In Book IX Vitruvius describes the hydraulic clock of Ctesibius while in Book X he explains how to design ballistae and to realize an odometer. Three of the machines to which Leonardo paid the greatest attention and that tell us about an effective and deep relationship with Vitruvius, highlighted in three sheets of the Codex Atlanticus displayed in the Fano exhibition.

3. The Water Clockwork

3.1. Description
Leonardo’s water clock is one of his famous automata projects, probably the last and the most developed one [5]. Leonardo has collected centuries of writing and technology in his drawings, taking inspiration from the works of Heron of Alexandria, Vitruvius and above all Ctesibius. 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. The clock dates back to around 1510, a period in which Leonardo lent his services to Charles II d’Amboise in Milan: it consisted of 24 containers that were filled in succession by running water, every hour of the day, and was able to ring a bell that beat the corresponding number of chimes.

Folio 943 recto of CA, which was on display and is partly reproduced in Fig. 2, shows at the center the key mechanism for operating the water clock: its mechanical structure is rather complex, but the digital reconstruction and the related animation allowed to understand its functioning.

Figure 2. Drawing of the water clockwork, also known as bell ringer, in folio 943r of the Codex Atlanticus. It can be noted that the side notes are mirrored, as usual by Leonardo. 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.
3.2. Mechanical structure

The entire machine was composed of 24 basins, identical to the one shown in Fig. 3, connected by pipes to transport water from one to the other. Each basin has a complex mechanism that drives the filling and flushing of the water from the container and is composed by the following main parts.

- **Hours basin and water supply system (Fig. 3)**
  The water flow fills the upper vase coming from the top left and comes out through the side duct to fill the hours basin. 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 basin. At the same time, a valve on the bottom opens the basin, which is flushed. The stroke of the hour is marked by the ringing of a bell, not shown in the sheet shown here.

- **Float release mechanism (Fig. 4)**
  When the water level in the hours basin reaches the spherical float located in the upper part of the drawing, it rises due to Archimedes’ buoyant force and therefore tilts the circular sector, which finally unlocks the small horizontal rod.

- **Central column (valve/actuator) (Fig. 4)**
  While the water is filling the hours basin, the 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.

![Figure 3](image1.png) Rendering of the interactive model of the water clock, exploited through the Stark image wall

![Figure 4](image2.png) Details of the central column commanding the filling/flushing of water through the hours container
3.3. *Ancient waterclocks by Ctesibius, Vitruvius and Leonardo*

The water hourglass dates back to Pharaonic Egypt: it was a container with a small hole in the bottom that was filled with water. The level of the water gave an idea of the time elapsed. Ctesibius transformed this apparatus into a water clock, that is into a real measuring instrument, thanks to various devices that were described 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.

4. *The Giant Crossbow*

4.1. *Description*

The crossbow is a throwing weapon of very ancient origins, designed independently in Greece and China to increase the power and range of the bow. Then the Greeks devised the ballista, which gives the initial speed to the projectile through a torsional spring made by pulling ropes wrapped around two cylinders. Vitruvius in the "*De Architectura*" describes a brilliant outline scheme for the design of the ballista while between 1485 and 1492 Leonardo da Vinci conceived two giant crossbows (probably to impress Ludovico Sforza) that differ slightly for the tensioning system of the bow.

The crossbow drawn by Leonardo in folio 147 verso of the Codex Atlanticus, see fig. 5, was shown in the exhibition and a digital reconstruction illustrated its operation through an image wall that allowed the visitor to interact with the model.

![Design of the giant crossbow in folio 147v of the Codex Atlanticus: it is the final drawing of an unfinished project and was never built. Another famous version of the crossbow is drawn in folio 149r-b](image)

4.2. *Mechanical structure*

The crossbow was very big and was meant to be pulled by horses or oxen; it did not provide means of adjusting the tilt but stopping on an inclined plane. The digital mock-up is shown in Fig. 6-7: it is composed by the following main parts.

- **Cart.** The body of the crossbow is 22 m long and 1.5 m high, has a weight of about 4 tons and must support the bow that weighs almost as much. This element was conceived as a carriage with 3 axles that support the weight of the crossbow by means of 6 wheels with a diameter of almost 2 m.
• Tensioning system. A large wheel with handles is rotated by one or more people; it is keyed on the shaft of a worm screw whose rotation causes the translation of the nut; this is connected to a disk that holds the string when it is stretched while a release mechanism (lock) makes the string snap at the appropriate time.

• Bow. The bow was made up of 39 separate parts of thin wood. It consists of a bundle of two sheets of different length and variable section (leaf springs): this choice allows the material to be exploited optimally while reducing the weight of the system. When the crossbow is charged, the deformation of the bow and of the string allows to store a great potential energy, which is then transformed into kinetic energy of the projectile at the end of the launch phase.

4.3. The designs of Vitruvius and Leonardo

Vitruvius describes the project of a ballista, a launching machine slightly different from the crossbow since the speed of the projectile derives from the conversion of the elastic torsional energy of two skeins of ropes. As a matter of fact, Leonardo took also inspiration by the treatise on military engineering by Roberto Valturio (around 1450) and describes only functionally a large war machine, while Vitruvius provides real project guidelines that allow the rapid construction of ballistas of different sizes in case of war [6].

Moreover, if a crossbow is designed with a narrower shaft and a tapered bolt, which adjusts the nocking of arrows, it greatly improves the airflow of the bow and the drag on arrows; this allows the crossbow to operate much more efficiently and have a more precise aim. These ideas were present in Leonardo's design and originated with Leonardo alone [7].

The mathematics that Leonardo used for the design of his crossbow were far advanced despite having some now known inaccuracies with today's current knowledge of geometry and design principles. Nonetheless, Leonardo was "the first modern engineer to attempt to apply the geometrical mathematics of the laws of motion to the design of machines" [8]. The other mathematical marvel that is noted in Leonardo's design of the crossbow is the proportional techniques that he utilized in every aspect of the design. As a matter of fact, Leonardo scaled the descriptions by Valturio up to giant dimensions to invoke fear and panic in its enemies, convinced that the laws of geometry and proportions allow to scale the performance too, in open controversy with the believes of Vitruvius [9].

Figure 6. Digital model of the giant crossbow: exploded view of the main sub-assemblies
5. The Odometer

5.1. Description
The odometer (from the Greek ὁδός hodós, road, and μέτρον métron, measure) is an instrument used for measuring the distance travelled by a vehicle. His invention is attributed to Archimedes of Syracuse (287-212 B.C.), but first appeared in the "De Architectura" by Marcus Vitruvius Pollio. Between 1500 and 1504 also Leonardo da Vinci dealt with the design of the odometer and drew a version in which the instrument was mounted on a carriage and driven by the rotation of the rear wheels. The drawing appears on folio 1 recto of the Codex Atlanticus preserved in the Veneranda Ambrosiana Library in Milan and has been visible in the exhibition, see Fig. 8: the digital reconstruction allowed to understand its functioning, also by appreciating the role of the smallest components.

5.2. Mechanical structure
The first concept of Leonardo, shown on the right of Fig. 8, was based on the meshing of a one-tooth gear, practically impossible to realize, while the second concept, shown on the left, exploits a worm-gear mechanism, known since the age of Archimedes. The digital mock-up is shown in Figs. 9-10 and is composed by the following main parts.

- Frame. The odometer is mounted on a two wheels frame; it is carried by a horse and is rather bulky: it is 4 meters long and higher than 2 meters.
- Axle and wheel. The wheels have a circumference of 10 arms: therefore the odometer has travelled a Florentine mile, which corresponds to 3,000 arms, when the wheels have completed 300 turns. On the axle of the wheels there is a short section of thread that mates with a pin wheel mounted on a longitudinal shaft: for each revolution of the axle this wheel...
shifts one peg. Since this wheel has 300 pegs, when it has rotated one turn the odometer has travelled 3,000 arms, or 1 mile.

- Longitudinal shaft and display wheel of the travelled distance. The rear end of the longitudinal shaft is connected, by means of a worm screw coupling, with a pin wheel: this is integral with a lancet which displays the number of shaft revolutions and therefore the number of miles travelled.

- Longitudinal shaft and wheel for counting the travelled distance. The longitudinal shaft is also connected with a wheel placed at the front end of the machine; the end of the shaft has a tooth which mates with a series of circumferentially fixed pegs on the wheel: at each complete rotation of the shaft, which corresponds to the distance of 1 mile, the tooth shifts the wheel of a peg. The wheel has a hole, which houses a pebble, in correspondence of each peg; the lower face of the wheel is in contact with a fixed drum which has just one hole: in this way when the odometer has travelled one mile a pebble falls into the container, allowing to measure the number of miles travelled during the day.

![Figure 9. Rendering of the interactive model of the odometer (some parts have been left out or crossed for sake of clarity)](image9)

![Figure 10. Details of the frame wheels mounted on the axle and the meshing of the single-thread worm-gear](image10)

5.3. The odometers of Vitruvius and Leonardo
The drawing on the right of Fig. 8 faithfully represents what Vitruvius described in "De Architectura", while the drawing on the left represents Leonardo's view which retains the same principle of operation and differs from the previous one only for some marginal aspects.

The most significant difference lies in the fact that Vitruvius couples a toothed wheel with a single tooth and a toothed wheel with 400 teeth, which is difficult to achieve in practice: in its place Leonardo uses a more elegant coupling with a worm screw, more compact and effective [10].

Moreover the effectivity of the two projects obviously relies on the units of distance measurement in force at the time. The Vitruvius odometer measures the Roman mile, equal to 1,000 steps, that is about 1,482 m: this is obtained through 400 rotations of the wheel in contact with the ground, which has a circumference of 12.5 feet; Leonardo's odometer measures the Florentine mile, which is 3,000 arms or about 1,751 m: in this case the mile is marked by 300 rotations of the wheels of the cart, which have a circumference of 10 arms. Finally the two "engineers" use different approximations for the value of the constant π: Vitruvius assumes a value equal to 3.125 while Leonardo uses (3 + 1/7), closer to the real value, therefore obtaining more precise measurements.
6. Acknowledgment

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7. Conclusions

The work developed for the Fano Exhibition “Leonardo e Vitruvio: oltre il cerchio ed il quadrato” has exploited the new instruments of digital technology to put in evidence the vivid and intense link between Leonardo da Vinci and Marcus Vitruvius Pollio, two scholars and scientists who lived more than 1,500 years apart but that were fascinated by the same subjects, a connection still little explored up to date.

The exhibition let the visitors understand the discoveries and inventions by the two giants of the past through different Virtual Reality, Augmented Reality and Mixed Reality tools and instruments that really provided an immersive experience. The present paper tried to explain that the digital Leonardo is not a copy of the analogue Leonardo but a new form of knowledge, reading, interpretation and communication. A new Leonardo here, a forerunner and prophetic scholar that begins to amaze once again precisely in the age of digital reproducibility of the work of art.

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