VIRTUAL RECONSTRUCTION OF JUANELO TURRIANOôS ARTIFICE TO RAISE WATER FROM THE RIVER TAGUS TO TOLEDO

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ABSTRACT

Toledo stands on a steep promontory washed on three sides by the River Tagus. The city experienced a period of splendour and demographic growth during the reign of Charles V or Charles I of Spain (first half of the sixteenth century) when it was the capital of the Spanish Empire. At the time, with the Roman aqueduct and the huge waterwheel built during Islamic domination in ruins, water had to be carried on the backs of donkeys from the river to the distribution tanks 100 metres above.

A number of alternative supply systems, based on the most advanced technology of the times, failed. In 1565, further to a recommendation made by King Philip II, the city commissioned the construction of a water-drawing machine from Giovanni Torriani (Juanelo Turriano), an Italian clockmaker, mathematician and inventor. Originally brought to Spain by the kingôs father, Holy Roman Emperor Charles V, Juanelo accompanied the elder monarch until the time of his death at Yuste.

Turrianoôs mechanical device raised water to the city at atmospheric pressure satisfactorily and uninterruptedly until the mid-seventeenth century, when, for want of upkeep and due to the uncontrolled theft of parts, the city was obliged to revert to donkey power.

This article summarises the research conducted to document and virtually rebuild ñJuaneloôs artificeò and synthesises the theories that still co-exist about the way it operated. In the reconstruction, certain inconsistencies and imprecisions found in the historical record had to be resolved to simulate the operation of the mechanism in accordance with the proposed virtual design. CATIA V5, very powerful modelling software, was used to generate an animated model.

Keywords: historic research, simulation, animation, modelling, CATIA, propagation

Subject category: virtual reality

1. Introduction

This paper synthesises the research conducted to determine what Juanelo Turrianoôs ñartificeò actually looked like and how it supplied Tagus River water to the city of Toledo. The most recent solid modelling and computer animation techniques were deployed to validate the historic hypotheses, recovered and reviewed in a detailed study of prior research on the subject. The inconsistencies and imprecisions detected in earlier drawings had to be rectified to build a virtual system that would operate satisfactorily.

The article first describes the water-drawing devices known up to the early sixteenth century and summarises Juaneloôs biography. That is followed by a chronological discussion of the theories on the design of the device. Lastly, the CAD-based virtual reconstruction of the artifice is briefly introduced.

2. Water-drawing predecessors

Construction of the artifice in Toledo caused an enormous impact, eliciting visits by such notables as Juan de Austria (Charles Vôs bastard son). Until then, nothing of this magnitude had ever been built anywhere in the world, for the highest such structure standing, the Augsburg tower, measured less than 40 metres. According to contemporary descriptions, it used Archimedes screws to draw water. These ñscrewsò are a special type of volumetric machines consisting of a pipe wrapped spirally around a shaft. When the end positioned underwater at a given slant rotates, the water rises inside the pipe and spills out at the other end, located at a higher elevation.

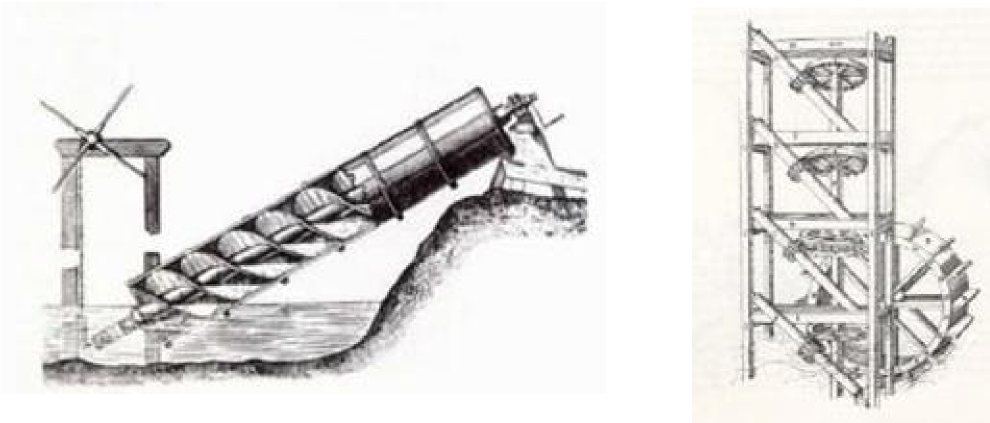

Figure 1: Archimedes screw and cochlea

As the figure shows, the screw was often powered by a wheel to which it was hinged, in turn rotated by canal or river water to generate primary motion. Moreover, if fitted on their outer circumference with scoops or ladles, these wheels could also raise the water themselves as they turned on their axis, which rested on two columns anchored in the riverbed. As they reached the bottom, the scoops would take up water that would then be spilled into a tank when they reached the top. The ñEl Carpioò cranes built in 1561-63 on the banks of the River Guadalquivir that drew water for irrigation for over 300 years constitute an example of such a system. [azuza]

The notion that a stream could induce motion in a wheel subsequently used to raise its water was proposed by Archimedes in the third century BCE, around the same time that Ctesibius, an Alexandrian engineer and mathematician, devised and built a force or plunge pump, described years later by Vitruvius in Book X, Chapter VII of *The Ten Books on Architecture*. In addition to what he called the ñmachine of Ctesibiusò, Vitruvius discussed ñengines for raising waterò in Chapter IV of Book X, where he classified the known elements for drawing water and described their construction. In Chapter V, he wrote about water wheels and water mills, and in Chapter VI he described the construction of a ñwater screwò i.e., an Archimedes screw.

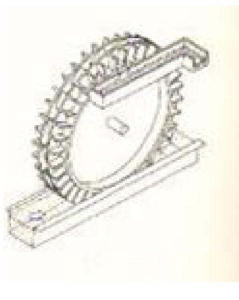

Figure 2: Wheel

According to a number of historians, Juanelo could have used any of these pumps to supply the city of Toledo with water. He was familiar with both suction pumps, in which the water is raised by mere atmospheric pressure, and force pumps, in which it is raised by suction and plunging. Suction pumps could only raise the water 10 metres, whereas force pumping was limited by the strength of the material and, of course, the cost of obtaining materials able to withstand the pressure deriving from the difference in elevation involved.

The following figure is a copy of a drawing for a double cylinder force pump found in Book XIII of *Los veintiún libros de los ingenios y las máquinas* (twenty-one books of engineering and machines), which some authors attribute to Juanelo himself. Note the elements described by Vitruvius in the drawing.

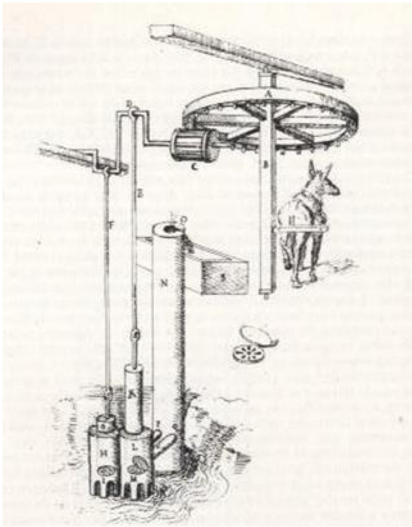

Figure 3: Two-cylinder force pump

Since Juanelo was to finance the construction of his artifice himself and as he did not believe that the materials available would withstand the pressure needed in a pump system to span the difference in elevation between the riverbed and the Alcázar or castle-fortress, he decided to invent a new machine in which the water would be hoisted at atmospheric pressure.

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3. Giovanni Turriano (Juanelo Turriano). Biographical notes

Before going into the work itself, a word is in order about its the author. Giovanni Turriano was born at Cremona, Lombardy, around 1500. In 1530, Emperor Charles V brought him to Spain, where he served as court clockmaker. In the early years he restored Giovanni Dondiôs Astrarium and built his famous astronomical clock, christened ñCristalinoò. He was also a prominent engineer, mathematician and device manufacturer so favoured by Charles V that he formed part of the monarchôs entourage when he retreated to Yuste.

After his fatherôs death, King Philip II, wanting to keep Juanelo in his service, appointed him Master Mathematician who, while ñon loanò to Gregory XIII, participated in the popeôs calendar reform. While in Spain, Juanelo Turriano authored many of the empire's assets: the Tibi Dam in Alicante, the worldôs tallest for nearly 300 years; the bells in El Escorial Monastery, on commission by his friend the architect Juan de Herrera; and any number of mills, moving figurines (dancers, warriors, flying birds) and clocks.

But his most ambitious creation was the hydraulic machine to supply River Tagus water to the city of Toledo. In 1565 he was commissioned by the Marquis of Vasto to permanently hoist ñone thousand six hundred 2-gallon jugs of waterò (around 12 400 litres) daily to the deposits underneath the Alcázar. The works were to be completed in three years. Juanelo honoured his part of the agreement and delivered a mechanism, on schedule, that performed satisfactorily and even improved on the initial forecast, delivering 1 700 jugs daily. The city never paid him, however, with the excuse that the castle-fortress, where the water was deposited, kept it for its exclusive use. After also paying for the upkeep for over six years, a bankrupt Juanelo reached an agreement to build a second artifice to be paid for by the Crown, to which he and his heirsô would hold perpetual title. It was completed in 1581 and although the King paid his debt, the city did not. Unable to pay for upkeep on the device, he was forced to give it up, a circumstance that must have contributed to his death on 13 June 1585.

The complexity of the artifices rendered their conservation difficult. Both were in service for over 40 years, through the mid-seventeenth century, when the first one was dismantled, while the second was kept as a city emblem, in light of the enthusiasm and admiration it had roused the world over. Little by little, however, time and constant theft took their toll, and the remains of the artifices gradually vanished from the city of Toledo altogether.

4. Reconstruction of Juaneloôs artifice

What were these greatly admired machines like? How did they work? Answering those questions when the only record left of the devices themselves is the praise of writers, travellers and others of Juaneloôs contemporaries, with no drawings at all to go by, is a laborious and complex task. Essentially three of the aforementioned documents are of particular interest, along with contemporary inventories taken of the devices, found in major national libraries. The first and perhaps the most important of the three was authored by Ambrosio de Morales, a humanist and friend of Juaneloôs, who did not actually see the devices but only the scale model built by the engineer to convince the people of Toledo that his idea could work. The two theories in place today on the operation of the artifices are based on that text and Moralesôs description of the machines, cited below.

ñ...*The basis of this invention is to attach or hinge flat boards end-to-end and crossing in the middle as described by Roberto Valturio for lifting men. With the whole length so attached, when the first two boards closest to the river move, all the others that rise up to the castle-fortress move slowly and smoothly, as would suit the machine***ô***s perpetuity... But the most ingenious idea is to have hinged to the ends of the moving boards a series of long pipes all made of the same metal which, as they rise and fall with the wood, when they descend one is full and the other empty, and coming together on that side, they remain upright as long as necessary to keep the liquid from spilling out. Thereafter, the pipe that is full rises and pours the liquid into the one that is empty, and the one now empty rises and falls to join up with the full pipe behind it, which also descends to fill it. Therefore, sometimes the two scoops on a pipe are both empty, while the two pipes alongside it each has a full scoop, and alternating in such manner that the one that had a full scoop is emptied completely, and the one that was empty is filled, there always being one pipe with two empty scoops between two full ones...***ò***

Mining engineer Luís de la Escosura y Morrogh was the first author, in 1880, to rise to the challenge of trying to explain how Toledoôs devices worked on the basis of that account. Given that interpreting Moralesôs description with no illustrations whatsoever is no simple feat, Escosura set out to find a drawing that would help him understand the text. In his conclusions he noted the following.

ñ...*what I was unable to achieve with diligence and hard work, I came across coincidentally, when reviewing a very odd book... entitled* Le diverse et artificiose Machine del Capitano Agostino Ramelli. *Chance would have it that I opened the book to a page in Chapter XCV containing a drawing that depicts a machine for raising water, in which I immediately recognised Juanelo***ô***s artifice as described by Morales...***ò** »

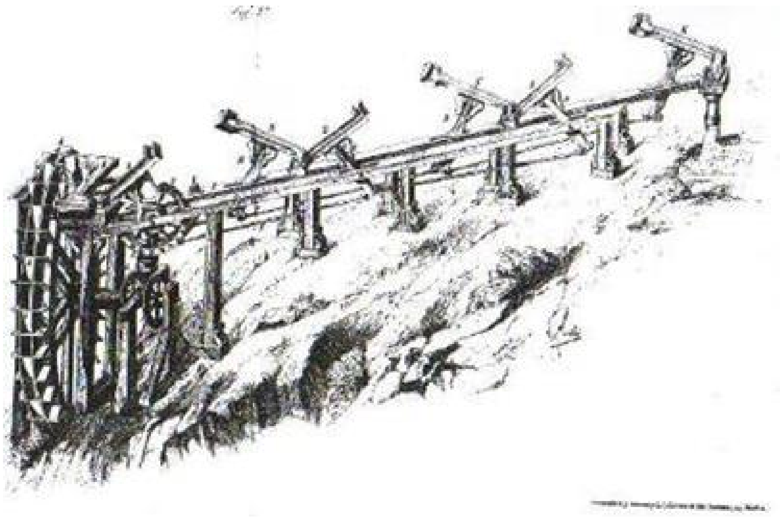

Figure 4: Ramelliõs machine

Figure 4 reproduces the illustration that Escosura identified with Juaneloõs artifice, although acknowledging differences between it and Moralesõs description. Specifically, Juaneloõs friend remarked in a separate paragraph, entitled ñWondrous characteristics of the Aqueductò that ***ñ****the shape of the chain and the copper pipes that initially scooped up the water...****ò*** On those grounds, to complete his theory, Escosura assumed that the water was lifted to a first height by scoops on a chain moved by a water wheel, driven by the flow of the River Tagus itself, and from there to the top it would be lifted by the apparatus proposed by Ramelli, which would supply power only and hence have no scoops. He also replaced Moralesõs boxes and channels with brass scoops and pipes to make the description of motion, pauses and stops more understandable. The last major hurdle facing Escosura was to fit the Valturio scissor ladder mentioned in the description into the device. He concluded that it comprised the ties or stays that conveyed the swaying motion from one set of scoops to the next, which they would replace in Ramelliõs sketch. With that final touch, Luis de la Escosura y Morrogh believed that he had unveiled the mystery surrounding Juaneloõs devices. His hypothesis, in which water from the River Tagus to the castle-fortress would be raised across a continuously sloping slanted plane system, is one of the two theories on the workings of the machines presently in place.

The second was put forward by Ladislao Reti, a reputed technology researcher who, intrigued by the subject, studied Escosuraõs writings as well as texts authored by a German engineer, Theodor Beck who, accepting Escosuraõs theory, developed it somewhat more fully. Assailed by doubts about the accuracy of the reconstruction described in those papers, Reti decided to undertake a more critical study of the operation of the devices and the biography of their creator. The intense search in archives and major libraries that followed quickly revealed that the facts gathered by Escosura hardly represented the entire historical record on the artifice or on Juanelo himself. He presented his findings in a conference delivered in Toledo on 15 June 1967, along with a scale model built by a local craftsman, Juan Luis Peces Ventas, in which all the conclusions he had drawn were materialised as depicted below.

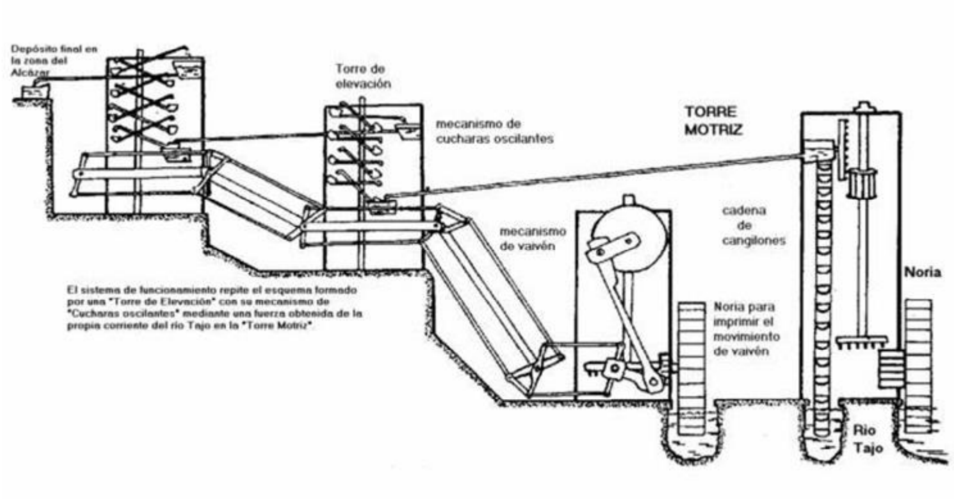

Figure 5: Ladislao Retiôs sketch

According to Reti, the Tagus had a weir that directed the water into two canals housing water wheels that powered the artifice: one moved a series of buckets whose existence on the mechanism was discussed by Escosura, while the other turned the bull wheel that drove the artifice per se. This second stage in the hoisting process lies at the root of the difference between the two theories, for Reti, chose as the model for his deductions not the illustration that had been so helpful to Escosura in solving the puzzle of Toledoôs mechanisms, but the one appearing immediately after it in Ramelliôs book

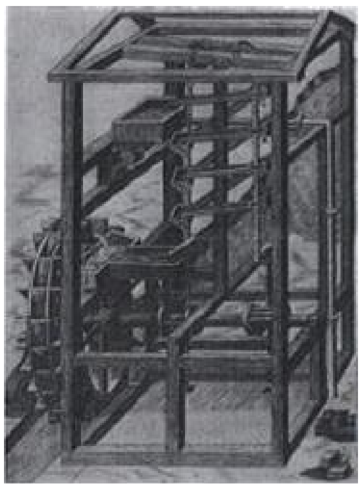

Figure 6: Illustration from Ramelliôs book used by Reti

In Retiôs theory, the artifice was a vertical system, inspired by the bucket-carrying towers in the figure that raised the water by tiers: the water would be raised in the tower with the swaying motion of the buckets and then carried through brass pipes from one tower to the next. Reti backed his idea with contemporary engravings that depicted such a tiered system, a number of sixteenth-century inventories found in libraries, and a key document, according to which the machines operated as he described. The text was written by a contemporary traveller, Sir Kenelm Digby, who saw the artifices in operation, and wrote most significantly: ***ñ****...And thus the two sides of the machine were like two legs that by turns trod the water...****ò***

Retiôs is the theory most widely accepted today, particularly after the appearance of the third most important text on the enigma surrounding Toledoõs machines. That document, whose discovery was reported in 1986 in *Revista de estudios extremeños*, reinforced Retiõs theory, for it describes an artifice that raised water at atmospheric pressure by tiers using bucket-bearing towers to adapt to the uneven terrain. The document also contained the only known drawings whose author actually saw the devices in operation.

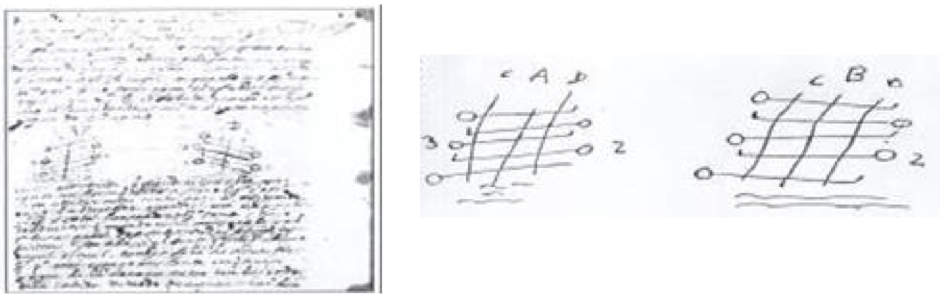

Figure 7: Third manuscript

5. Artifice modelling and computerised animation

In the present study, Juaneloõs artifice was modelled on the grounds of the drawings, furnished by Fundación Juanelo Turriano, that form part of the ñDesign for the partial reproduction of Juaneloõs artificeò drafted by Retiõs disciple and the organisationõs founder, José Antonio García-Diego. The design, which was never implemented, is naturally based on the vertical theory. That solution was chosen here because it is the best known and most widely extended, as well the most fully developed theory, inasmuch as drawings that could be used as a basis for the virtual reconstruction were at hand. The CATIA (release 5) software used for the solid modelling, and more specifically its modules for generating parts and assemblies, is so powerful that the resulting model could even be animated and ñseenò in operation. The greatest obstacles confronted in this endeavour were the many imprecisions and errors in the drawings, whose shortcomings had to be remedied by resorting to other sketches, pictures and even scale models in place today. The intention here is not, by any means, to detract from or find fault with the work performed by García-Diego's team: quite the contrary, for with the state of the art prevailing in graphics in 1975, their drawings could not be verified or the operation of the devices revised as they can today thanks to the simulation and virtual reality tools presently available.

The models for the first and second hoisting stages are depicted separately below.

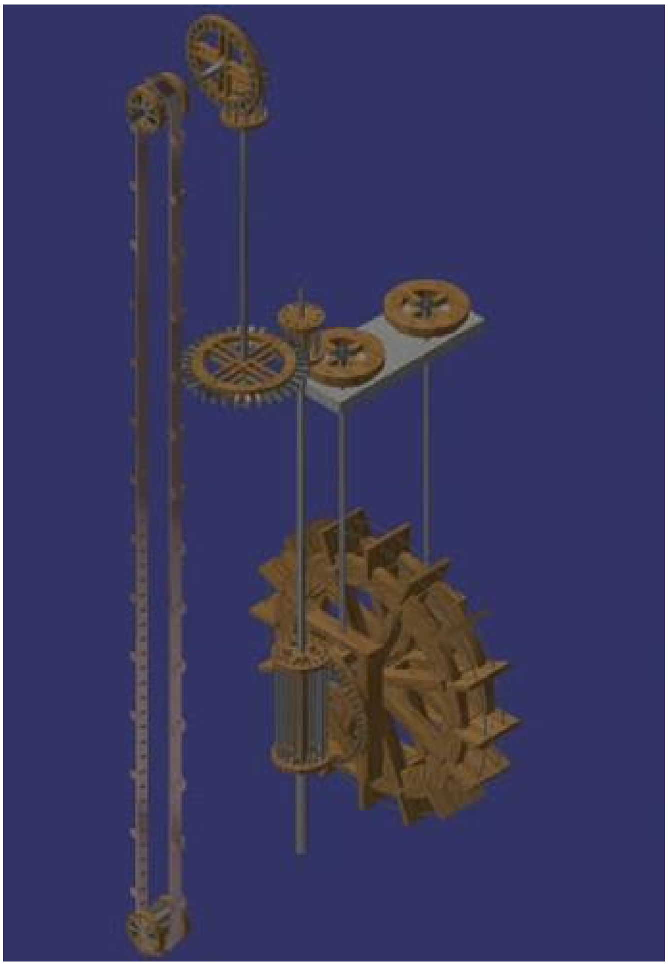

Figure 8: Perspective of the first hoist assembly

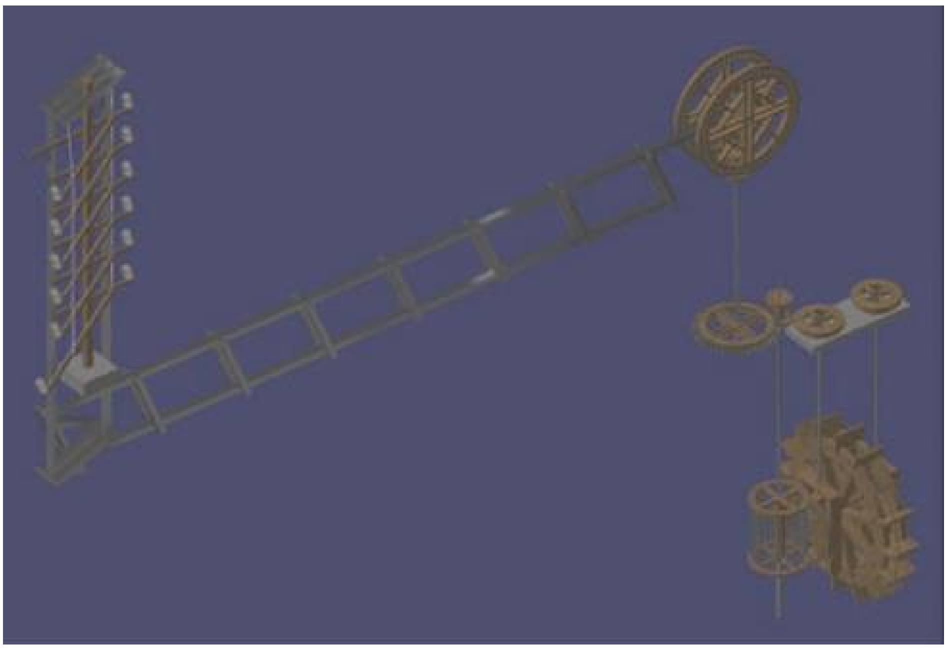

Figure 9: Perspective of the second hoist assemblyn

6. Final comments

Computer simulation and its sequel, virtual reality, can be used in the ñrealò reconstruction of mechanisms, machines and buildings, providing insight into what they were or will be like. The present study drew from these powerful techniques to ñrestoreò what in its day was a bold and innovative device, which even now rouses the curiosity and interest of both engineers and the public at large.

The importance of virtual reality now and in the near future is indisputable, and in fact these techniques form part of what is known as "the language of the twenty-first century". Graphics engineering has much to contribute in this respect and the community of practitioners is morally obliged to seize the opportunity afforded to take the lead in humanityôs scientific progress.

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