Mechanical Engineering Devices in the America Colonization

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Abstract. Due to the scientific gap between America and Europe at the XVI century, the first Europeans' settlements in the new world had to face different technological issues. Besides to expose the scientific and technological situation, this paper shows two singular mechanical wits representative of the technical advances introduced in America to overcome different problems. Firstly, a pump based on an alternative movement system through crankshafts and pistons used against the continuous flooding suffered in the Ciudad de México valley. Although this system did not solve the problem (it was solved in the XIX century), it was essential to the continuous depletion of water. Secondly, a port crane that due to its capabilities to handle cannons, military devices and constructive materials, was useful during Lima fortification in the XVII century.

Keywords: Port crane · Hydraulic pump · Reverse engineering · Industrial heritage

1 Introduction

The technological and scientific advances in Europe during the XV and XVI centuries were critical for the development of agriculture, metallurgy, warfare and naval transport [1]. Each improvement feedbacked the others and all together were boosted by the trade routes in the Mediterranean Sea as well as the opening of routes between East and West, and finally with the New World.

During the evolution of the aforementioned techniques, the printing press played an important role increasing the possibility of expanding the wealth of existing knowledge to extraordinary levels in a society that already had a large amount of graphic production.

Innovations in agricultural technology were unevenly lodged in Europe. These advances include the use of better water mills to drain the land, the use of drying techniques and obtaining a balance between crops and animals, with a method consisting of cultivating a specific part of the land to feed the animals, which in turn fertilized the land. The insertion in Europe of new crops from America and Asia, required new engineering knowledge, both to drain the land and to set up new farms.

From the middle of the XV century, Germany laid the foundations for the mining exploitation and subsequent metal processing, this by improving mining techniques,

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since at that time Germany had some of the richest mines. During the first half of the XVI century, a growing transfer of mining and metallurgical technology took place in two directions: in America, to exploit the silver mines of Potosí and Mexico, and in Central Europe [1].

Other metallurgical procedures were undergoing improvements, such as the melting of metals, contributing to later advances in Chemistry by providing experience on chemistry empirically, since to use this science was necessary to have an exhaustive and precise control of the metals and non-metals that intervene in it.

Following the above discussion, in the XV and XVI centuries, the Spanish settlement of colonies in America required an important scientific and technological effort to solve many technical issues [2]. Regarding the approaches implemented, it is noteworthy the lack of historical references that help to value and appreciate the engineering quality of these solutions.

Secrecy and vertical knowledge based on petitions from vassals to the king was the preferer way for scientific documentation in the Spanish empire [3]. This approach did not reduce scientific creation, but it has contributed to hide the large number of technical advances and scientific developments achieved by Spanish and Native Americans.

This work explains how a reverse engineering procedure [4, 5] can provide virtual prototypes of lost mechanical systems: a pump used to drain the Ciudad de México valley and a port crane used in the port of Lima. Despite of the difficulties raised by the secrecy pointed out above, the use of engineering methods supported by current CAD and numerical simulation tools can improve our knowledge about these ancient technical wits.

Regarding the manuscript structure, Sect. 2 describes the pump and the crane devices in the spotlight. Section 3 and 3.1 respectively explore the existing information about the pump and the crane, describe the recovering procedure applied, and show the resulting virtual mockups. Finally, the main conclusions are drawn in Sect. 4.

2 A Draining Wit

In 1521 the Spanish settled Mexico City in the 9 square kilometer area formerly known as Tenochtitlan. Unfortunately, the city is located in a valley that suffers continuous floods.

According to the writings [6], on October 14, 1555, the Cabildo (the responsible for the municipality's government) requested a solution to the water problem. Viceroy Velasco ordered rebuild the stones works destroyed in the past, but that solution did not solve the problem.

In the absence of short-term solutions, the viceroy proposed changing the location of the city, to which Madrid replied that it would cost more to build the capital from scratch than to solve the flooding problem. Therefore, it was needed to find a quick and effective way of drainage to continue facing the problem of the works. This task was designated to the German engineer Enrico Martínez, who had the ingenious idea of draining the valley by drilling it to leakage the formed lagoons' water.

After successive and unsuccessful attempts to continue with his initial idea, Enrico Martínez was accused of negligence and taken to prison. However, he was finally released to participate in the project again because of his experience. When Enrico Martínez died in 1630, Fray Andrés de San Miguel, a Spaniard living in Mexico, accepted the challenge. He had excellent knowledge of hydraulics and knew the previous solutions and works to be improved.

The viceroy, faced desperate by the flooded capital situation, ordered the Cabildo to promote a drainage system and boosted the project with 24 machines and the necessary men and animals for continuously evacuating water in strategic points of the city. The work promoted by the Viceroy took advantage of the open-pit excavations carried out by Enrico Martínez. However, the initial project, focusing on the surrounding lagoons, was never finished due to the continuous government changes and the non-continuity of the works.

The continuous extraction of water from the subsoil during the colonial period was critical compared to the failed project for controlling the lakes' water through channels. Thus it is interesting the recovery and technological analysis of a hydraulic pump used for draining water.

2.1 Description of the Pump

According to Fray Andrés de San Miguel, who was present at the drainage work in Mexico City during the viceroyalty, the hydraulic pump understudy, illustrated in Fig. 1, was used to drain water in Mexico City.

The hydraulic pump consists of two supporting pillars, two carriage-type wheels for manual movement, one wooden structure for the cylinder block, one lantern transmission mechanism, a very long crankshaft, eight connecting rods, eight cylinders contained in the same block, a system of valves operated by pressure difference, a system of conduits for evacuating water and a set of water outlet pipes.

The system, most likely based on the technical knowledge from Europe, works as follows (Fig. 1 and 2):

1. The movement of two donkeys runs a vertical wooden axis. The lantern mechanism transmits the axis circular movement to the crankshaft, which is mapped into an alternative movement.
2. The crankshaft moves the connecting rods, which generate a continuous reciprocating movement in the cylinders housed in the block, creating pressure differences in the cylinders, opening the suction valves, and closing the non-return valves, water entering the odd-numbered cylinders. At the same time, the pairs eject and vice versa in a continuous movement.
3. The water leaves the cylinder block through a system of tubes that leads it to a vertical tube which evacuates it to the desired drainage point.

2.2 Reverse Engineering: Pump Reconstruction

One of the main issues in obtaining a detailed design of an ancient device is dealing with and studying the current information and archeological remains. The starting point for the pump system under study was a drawing of Fray Andrés de San Miguel (Fig. 1). That illustration provided the information to identify the bill of materials and the main

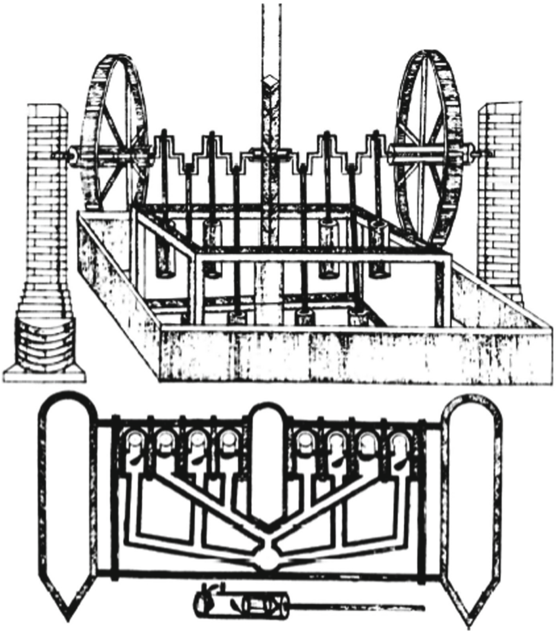

Fig. 1. Scheme of the hydraulic machine under study used for draining water [7].

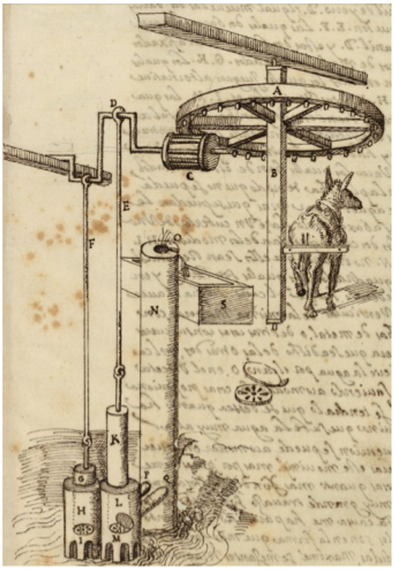

Fig. 2. Two-cylinder force pump from "*The twenty-one books*" [8].

dimensions of the system elements. It stands to reason considering that the parts were drawn to preserve the relation among component sizes. Besides, the bricks corresponding to the structure that supports the ends of the crankshaft are the reference used to scale parts dimensions. From a specific bibliography, the bricks used for purposes similar to that of the machine were about 45 mm thick.

Fray Andrés de San Miguel focused on the pump wit, but he did not care about how to power the system, and it is only known that it was blood-actuated. The approach considered in this work is based on the Ctsibio pump. It is operated in the same way as "*The Twenty-One Books*" suction machine (Fig. 2). Due to the enormous power requirement given its dimensions and the fact that it consists of 8 cylinders, most likely, the pump was animal-run by at least two donkeys which fit well with the symmetrical nature of the system.

To size the lantern gears that run the pump through the crankshaft, and to figure of flow rate, it is needed an estimation of the animal power $\dot{W}_{\text{Animal}}$, an estimation of the gear performance η_{Gear} as well as the input-output pressure difference ΔP, flow rate of water Q, and the performance of the pump system η_{Pump}.

The power provided by the two donkeys $\dot{W}_{\text{Animal}}$ depends on their average speed v when moving a specific load F; both data were obtained from specific bibliography (v ~ 1 km/h for $F = 1960$ N [9]). Taking into account the η_{Gear} (that for a lantern gears is usually considered equal to 0.5), the crankshaft received this power:

$$\dot{W}_{\text{Crankshaft}} = \dot{W}_{\text{Animal}} \cdot \eta_{\text{Gear}} = 2 \cdot v \cdot F \cdot \eta_{\text{Gear}}. \tag{1}$$

On the other hand, the power needed to suction water is:

$$\dot{W}_{\text{Pump}} = \Delta P \cdot Q \cdot \eta_{\text{Pump}}. \tag{2}$$

The relation of Eq. 1 and 2 and the hypothesis: $\eta_{\text{Pump}} = 0.6$, ΔP ~ 1 atm provide a way to estimate the flow rate Q. The flow obtained is 47.39 l/s. This value could not be obtained manually in any way.

Once known the pump volume, the flow rate, and the transmission rate (relation among crankshaft and animal rotational speeds r ~ 2.1), it is possible to size the lantern gears. Once the calculations have been made, it is possible to obtain a detailed 3D model of the system and simulate its movement (Fig. 3).

3 A Port Crane

Callao is and was in the past the largest port in Peru. Formerly, it was an indigenous fishing village called "*Piti Piti*," and its use as a pier and place of reception and departure of ships predated the formation of the city of Lima founded by Francisco Pizarro.

The first name it received was "*Puerto de la Mar*," and commerce was its primary use. Proof of this is the Cabildo license to construct a warehouse on March 6, 1537, to store the merchandise produced by the port's commercial activity [10]. Antonio de Herrera's work, "*Descripción de las Indias Orientales*", mentions the existence of a custom house and its large capacity and activity.

The above commercial placed the port in the spotlight of other nations, which attacked it several times during the 16th and 17th centuries. As a result, the port had to be fortified,

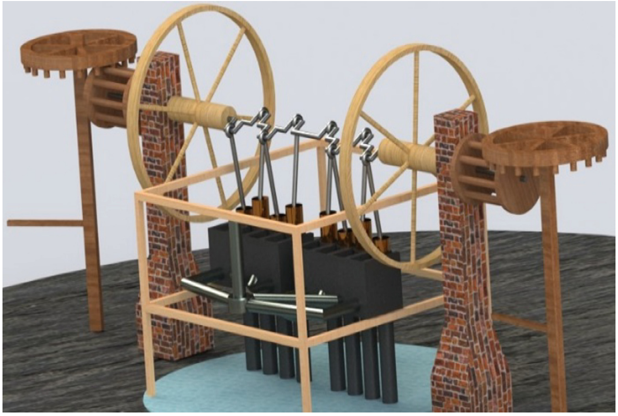

Fig. 3. Virtual mock-up of the pump understudy.

creating the first defensive structures under the mandate of Viceroy Francisco de Toledo in 1570.

Viceroy Juan de Mendoza y Luna built a platform in 1615 which had a defensive artillery system separated into three fortifications, whose shooters had a view over the entire bay. Given the danger of the continuous enemy expeditions in the South Sea, the port was walled in 1640 over the existing base. Callao became a fortified city port.

It is worth mentioning that the Callao pier was designed to avoid the cumbersome loading and unloading of the ships through unstable boats that usually overturned due to the load during the journey to the beach.

Port cranes were installed on the piers to load and unload military material, merchandise, and other heavy construction elements from boats. There is evidence of several testimonies of the first large crane installed: "Port cranes were placed that served to unload and load merchandise. They were rotating and moved by men who stepped on large wheels, and sometimes they also had multiplications based on pulleys and hoists… As a safety measure, they used ratchets [11].

Port crane design would be based on a technical manual such as "*The twenty-one books*" [8]. In this book, Juanelo Turriano described a crane to lift loads, which could turn on itself and had a treadwheel. It meets all the characteristics described in the testimonials and has a perfect geometry for port use, given its simplicity and the mechanical advantage it undoubtedly provides. Therefore, the builders of the system understudy could use the schemes portrayed in Juanelo Turriano to manufacture the crane. Years after its implementation, the crane was changed for improved solutions, which appeared in the "*Album de construcción naval del Marqués de la Victoria*" [12].

3.1 Port Crane Description

The port crane consists of treadwheel, treadwheel support structure, pillar with a coupled pulley, pillar structure for rotation, support the weight of the people who rotate it and finally stabilize the column to avoid buckling and unwanted horizontal displacements that would cause instability. Pillars are buried in a compacted land as the foundations of the houses of the time.

According to "*The Twenty-one Books*," which was the basis of the technique that probably travels to the new world, it is a construction crane, but it was used as a port crane by extending its size and reinforcing the structure for permanent use. It was installed around the year 1707, according to the testimonies.

The system works as follows:

1. Men walk inside the treadwheel made of wood and power its rotation producing a thrust torque.
2. The rotation of the wheel wraps the crane rope in the drum attached to its axis. This rotation tightens the rope raising the load connected to it.
3. The vertical movement provided by the treadwheel combined with the rotation of the leading crane pillar allows complex movements as required in port loading-unloading activities. Workers can push the timbers attached to the pillar or move the load by hand to achieve the desired lateral movement.

   The pillar ends in a large metal bolt supported on its base, thanks to it is possible the rotation and at the same time prevents horizontal displacements. This mechanical

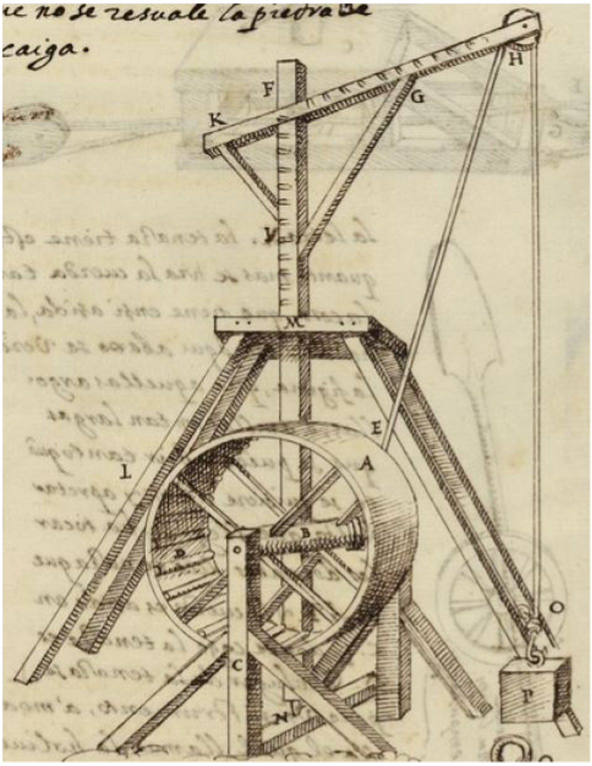

Fig. 4. Crane from "*The twenty-one books*" [8].

approach, lubricated with animal or vegetable grease, gives stability against buckling, limits lateral displacements, and reduces the bending of the pillar base.

4. Once the load is lifted and turned until it rests on the land side, the men are told to stop walking since the rope's tension is lost. Very thick logs were used as a ratchet if, for some reason, the wheel had to be stopped, supporting it between the internal logs of the wheel and the base log.

3.2 Reverse Engineering: Crane Reconstruction

The starting point to dimension the crane elements is the definition of the treadwheel size. It should be large enough that a man can walk comfortably inside it. Once this wheel is defined, the rest of the crane elements (Fig. 4) can be proportionally dimensioned and drawn using AutoCAD software. Considering an average man height of 1.70 m, it stands to reason taking a wheel radius of 3 m, which leaves more than 1 m between the wheel axis and the worker's heads.

It is necessary to establish the number of men needed to run the crane to analyze how it works. An energy balance provides the equations to estimate this number of workers. Taking into account the scheme portrayed in Fig. 5, the torque provided by N men that push the radius R wheel with a force E is equal to the torque transmitted to the radius r drum that winds the rope connected to the load F:

$$N \cdot R \cdot E = r \cdot F. \tag{3}$$

Regarding the maximum weight to lift for this crane, since it was installed a few years after 1700, the heaviest constructive or military element composed of a single piece would be a 24-pound cannon, used by the Spanish navy to defend fortifications from XVI to XIX century. Its weight was $F = 2500$ kg in total, of which almost 500 were part of the gun carriage.

It is interesting to calculate the mechanical advantage produced by the system or the factor that multiplies the force provided to overcome the resistance. Known r and R values:

$$F = R/r \cdot E \rightarrow F = 6.207 \cdot E. \tag{4}$$

Considering that an average man weighs $E \sim 70$ kg and Eq. (5), the number of workers needed to lift the maximum load is 6.

Dimensions and power input have been determined. The following step concerns analyzing the crane structure to verify that it can withstand the stresses to which it is subjected in operating conditions.

It is important to note that all the crane elements are mahogany wooden since it is a large tree to obtain the necessary pieces. Its wood is robust and is very abundant in the forests of Lima.

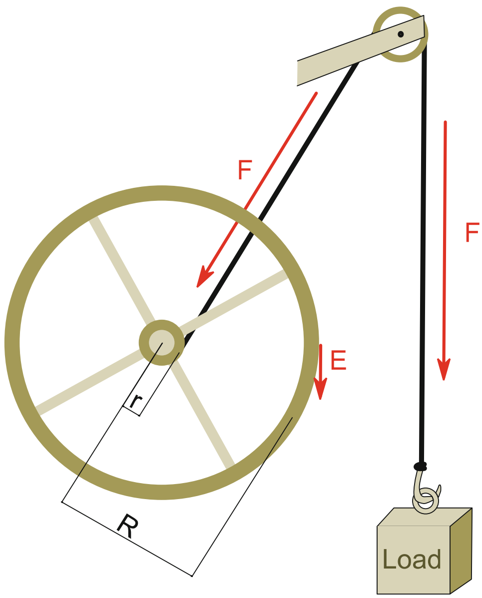

Fig. 5. Forces scheme for the crane system.

Finite element analysis of the pillar (Fig. 6).

The pillar rotates on itself, and it is connected to the load $F = 2500$ kg through a pulley. The joints are considered rigid since the woods are very well joined with each other. After conducting a static analysis by finite elements in the software Solidworks, the pillar that supports the load shows that it fully complies with the Ultimate Limit State for resistance. Being its maximum tension 22.13 MPa, 26.55% that of the material (83.35 MPa). So its service condition is safe and it possible to lift heavier loads with more than 6 workers. It is worth mentioning that the timber on the left has no structural function, so it is confirmed that it was used to rotate the crane.

Finite element analysis of the pillar base (Fig. 7).

The pillar supports are semi-buried and completely fixed to it. A force of 6867 N is applied on the upper face, the equivalent of having ten people weighing 70 kg simultaneously on the platform, an exaggerated figure but which serves to check the structure for resistance with more security.

As shown in Fig. 7, the base does not reach even 1 MPa, and the elastic limit is 83.35 MPa since its supports are very robust and there are four so that ten people for it does not suppose anything. This robustness is to stabilize the pillar that goes inside and allow the crane to rotate safely.

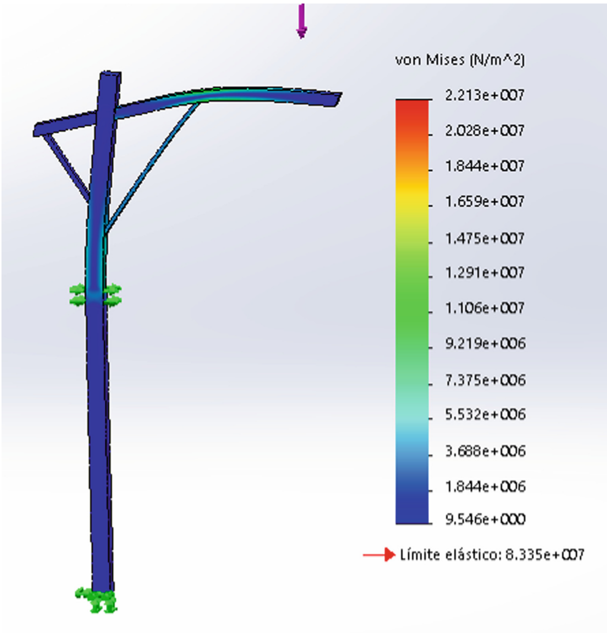

Fig. 6. Von Mises stress in the crane pillar.

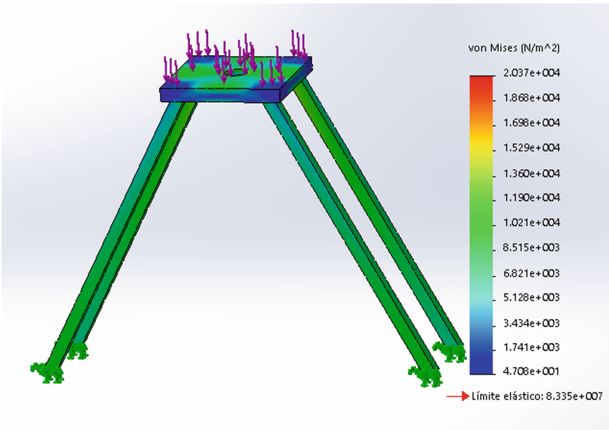

Fig. 7. Von Mises stress in the crane base structure.

Finite element analysis of the tread wheel support (Fig. 8).

From the volume and density of the treadwheel, its weight can be estimated at 12580.98 kg. A load of half the wheel's weight is applied to each hole that supports the wheel so that 6290 kg corresponds to each support, the equivalent of 61709 N per support. On the other hand, the supports are partially buried and wholly fixed to the ground as if they were cemented.

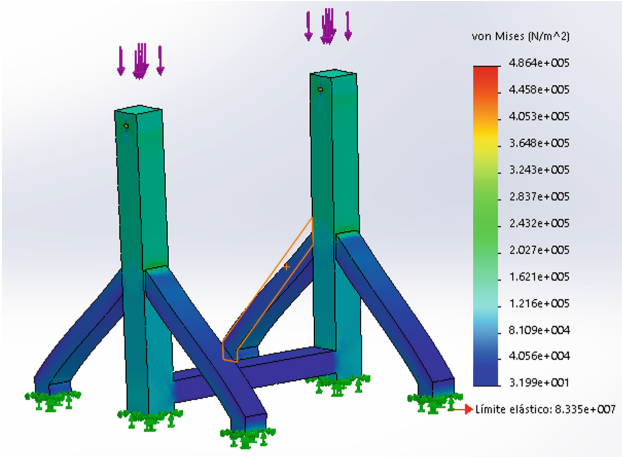

Fig. 8. Von Mises stress in the wheel support.

As a result of applying the conditions described above, it is observed how the maximum stress is reached in the joints with the diagonal supports, with a value of 0.4 MPa, far from the elastic limit, since this structure is oversized like the whole assembly in general with woods of great section and resistance.

It is observed that the crossbar inserted in the middle does not fulfill a structural function since the supports are embedded. Indeed, it was designed this way to compensate for possible movements of the supports due to the terrain, thus maintaining the structure's integrity with greater security against possible imposed displacements.

Fig. 9. Virtual mock-up of the port crane.

Once proven structurally viable and its whole operation has been determined, it is possible to make a complete 3D model and simulate its movement Fig. 9.

4 Conclusions

This work relives through virtual prototypes, built using reverse engineering, two mechanical wits used in the new world Spanish settlements from XVI to XVIII centuries. Specifically, this study focuses on a hydraulic pump used to drain water in the valley of Ciudad de México and a port crane installed in Callao's port (Peru). From limited historical information, the geometrical design, the engineering analysis, and numerical simulations fill the gaps found in the available information helping to accomplish a detailed CAD 3D model that can be simulated or printed.

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