The Hoist of the Aerial Rigging of the Mystery of Elche

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Abstract. In the town of Elche, during the 14th and 15th of August and without significant interruption since the last third of the XVth century, festivities are held in honor of its patron saint, the Virgin of the Assumption. This theatrical performance was declared Intangible World Heritage in 2001. The representation of the final days, death, assumption into heaven and coronation of the Virgin Mary is the highlight of the performance that takes place inside the temple of the Basilica of Saint Mary. This representation, unique in the world, is performed in song after converting the whole of the interior of the temple into a huge stage, with its corresponding rigging fitted with composite machinery, a double hoist, which allows lowering and raising to a height of 27 m. The aerial devices are occupied by singers, sometimes as many as five, reaching a weight of up to 600 daN, and even the simultaneous maintenance of two of the devices in the air. The lifting machines installed have undergone various modifications over time. The last of these was undertaken by the architect, Marcos Evangelio, in 1760 and, except for maintenance repairs required over the years and, despite a fire at the church in February 1936, they remain in a similar state to how the architect designed them. Studying them allows us to assess the mechanical assembly in general as very primitive technology, but which, after being used and perfected over the centuries, has allowed it to reach a high degree of precision and efficiency. This paper shows the main mechanical characteristics of the hoist, which is 300 years old.

Keywords: Historic winch · World Heritage · Mechanical lifting devices

1 Introduction

In the town of Elche, during the 14th and 15th August, and without significant interruption since the last third of the XVth century, festivities are held in honour of its patron saint, the Virgin of the Assumption. The representation of the final days, death, assumption into heaven and coronation of the Virgin Mary, is the highlight of the performance that takes place inside the temple of the Basilica of Saint Mary. This theatrical work has outlived others of its kind that were celebrated in the Christian world centuries ago, despite the clauses established by the Council of Trent that banned them inside temples. It was protected by a papal decree granted in 1632 by Pope Urban VII and the extraordinary thing about this event is that the performances have lasted until the

M. Ceccarelli and R. López-García (Eds.): HMM 2022, HMMS 40, pp. 149–159, 2022.
https://doi.org/10.1007/978-3-030-98499-1_13

present day -and during five centuries- and have only been interrupted by cases of force majeure (wars, epidemics, etc.). This representation, unique in the world, is performed in song after converting the whole of the interior of the temple into a huge stage, with its corresponding rigging fitted with composite machinery, a double hoist, which allows lowering and raising to a height of 27 m. The aerial devices are occupied by singers, sometimes as many as five, reaching a weight of up to 600 daN, and even, as we can see in Fig. 1 (a), the simultaneous maintenance of two of the devices in the air. Therefore, this extraordinary set will consist of two parts: one at ground level, known as the lower rigging, and another -the aerial one-, known as the upper rigging or sky in the dome, the two spaces being connected by means of three aerial devices—la Mangrana, el Araceli and the Santísima Trinidad. As the main component—see Fig. 2 (b)—there is a hoist responsible for moving the aerial devices between the two rigs, separated by a height of more than 24 m and a platform, by way of a balcony, which extends from the inner walls of the drum towards its centre and allows easy and convenient access to the aerial devices.

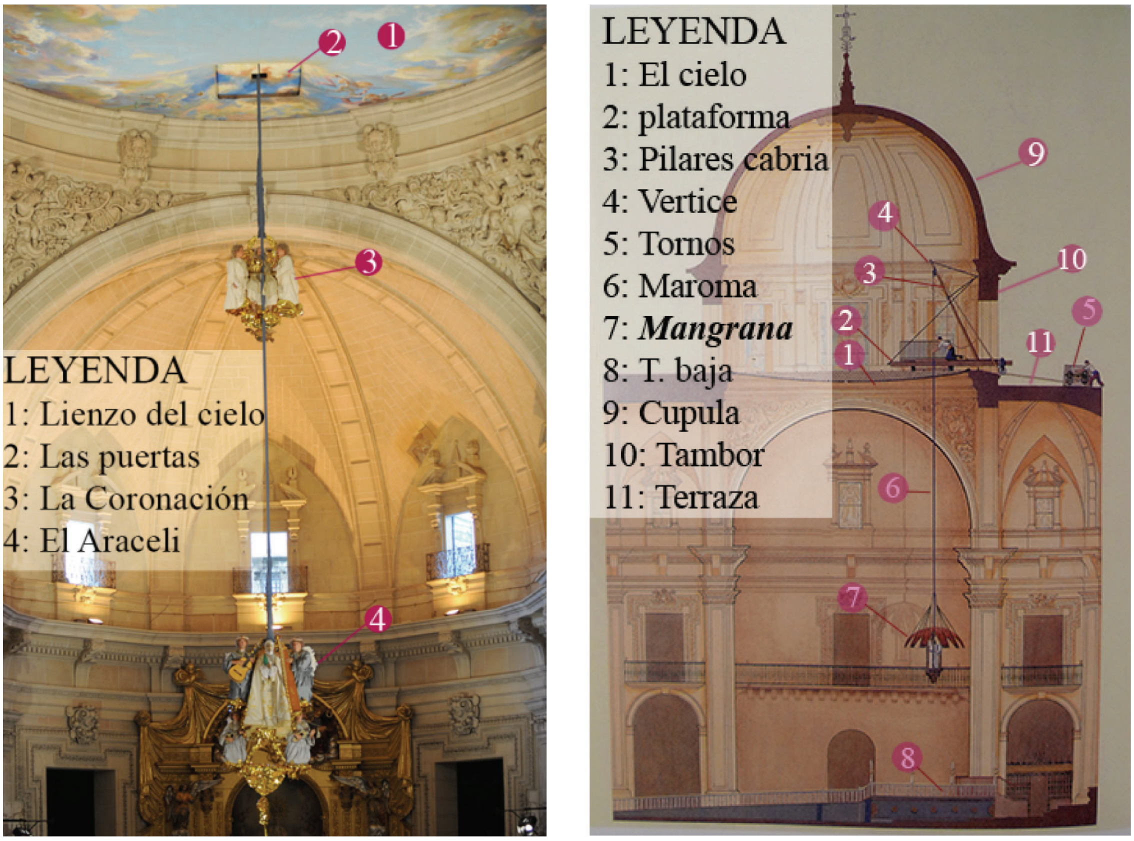
The lifting machines installed have undergone various modifications over time. The last of these was undertaken by the architect, Marcos Evangelio, in 1760 and, except for maintenance repairs required over the years and, despite a fire at the church in February 1936, they remain in a similar state to how the architect designed them. Studying them allows us to assess the mechanical assembly in general as very primitive technology, but which, after being used and perfected over the centuries, has allowed it to reach a high degree of precision and efficiency.

2 The Aerial Rigging

The different elements that make up all the necessary machinery for the representation of the Mystery have already been commented on, below its parts and mode of operation are described, for this let us observe Fig. 1(b) where a longitudinal section of the temple and the disposition of this.

As can be seen in Figs. 1 (a) and 1 (b), next to the machinery and as an essential element, is a circular canvas covering the base of the dome, the part that is visible to the audience decorated with blue-coloured paintings, clouds and musical angels; in the script of the play, it represents the sky. In the part located below the working platform, there is a square opening covered by two sliding doors, which open to allow the aerial elements to pass through. From the lower terrace to the canvas of the sky there are 27 m of height.

It works as follows: the ropes start from their respective reels and by means of pulleys known as “de remonte” (lifting pulleys)—see Fig. 2-b (n° 2)—they change their trajectory from horizontal to oblique. After reaching the existing pulleys at the vertex formed by the pillars—see Fig. 2 (a)—they turn 214° to reach a vertical position. Their ends, under the pulleys and on the platform, are attached to the apparatus, remaining suspended and ready for its occupants to get on. When the time comes for the apparatus to enter the stage, the doors open and allow it to pass through. The winch releases or recovers rope from its reel and the apparatus descends or ascends—see Fig. 1 (b).



(a) LEGEND
1. Canvas of the sky
2. The doors
3. The Coronation
4. El Araceli

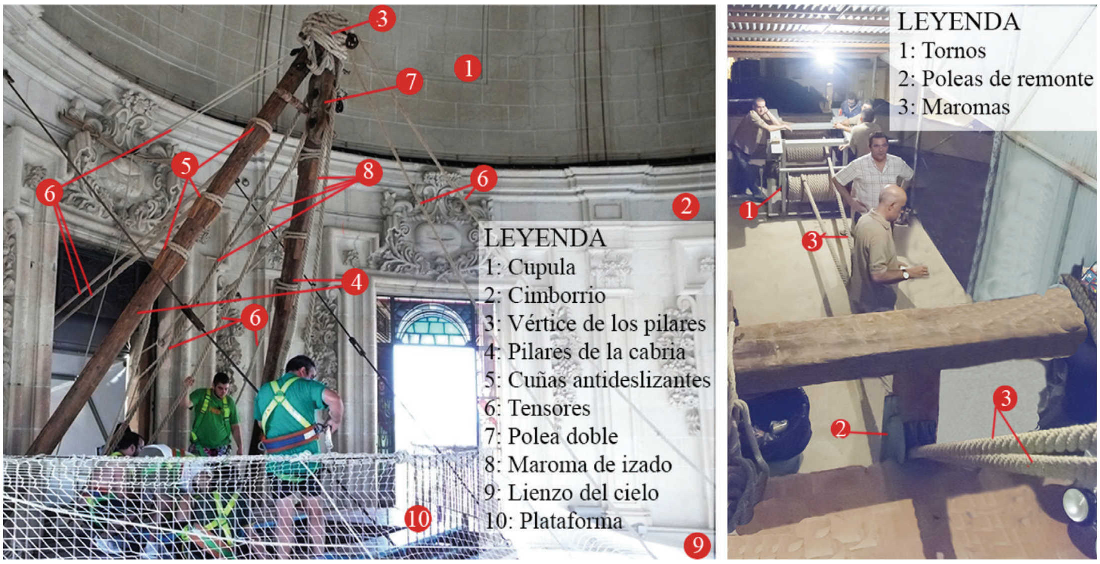
(b) LEGEND
1. The sky
2. Platform
3. Pillars, hoist
4. Vertex
5. Winches
6. Rope
7. ***Mangrana***
8. Lower terrace
9. Dome
10. Drum
11. Terrace

Fig. 1. A composite figure of a snapshot of the performance with two devices in the air and above, part of the canvas of the sky with their doors referenced as (a) and the longitudinal section of the temple with the arrangement of their main parts referenced as (b) [5].

3 The Hoist of the Aerial Rigging

Consisting of two pillars assembled at an acute angle, joined together at their apex and resting on the main ring, they are inclined towards the interior of the temple. A set of eight braces hold them in position, which is regulated by the length given to them. Two manually operated winches with parallel axes, each equipped with gear reduction systems, located on the terrace and separated from the pillars, are responsible for providing the force to lower and raise the devices; a force that is transmitted by means of thick hemp ropes guided by the pillars—see Figs. 1 (b) and 2 (b).

The whole assembly has, as a common support, the part of the building in which they are located: the terrace of the presbytery and the interior of the dome on the fourth floor of the basilica. These are sufficiently rigid to transmit the forces between the different members of the machine, and support the loads required, without any relative movement between their parts.



(a) LEGEND

1. Cupola
2. Dome
3. Vertex of the pillars
4. Pillars of the hoist
5. Non-slip wedges
6. Tensors
7. Double pulley
8. Lifting rope
9. Canvas of the sky
10. Platform

(b) LEGEND

1. Winches
2. Lifting pulleys
3. Ropes

Fig. 2. Showing the hoist with its components and its location within the dome referenced as (a) and the path followed by the ropes after leaving the winches referenced as (b).

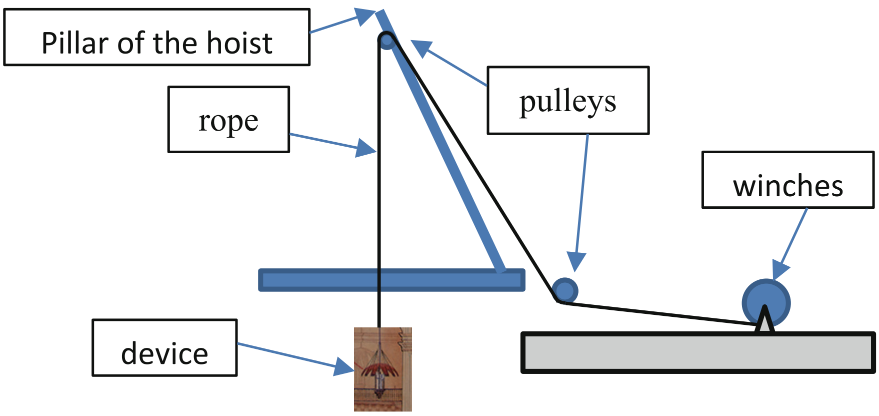


Fig. 3. Mechanical schemes of operation

3.1 The Pillars

As can be seen in Fig. 2 (a), two 6.46 m long masts form the beams of the hoist. At the tops of the two masts, there is a truncated cone-shaped cap which, as well as reinforcing the wood, holds the assembled parts together. It is customary to cover the metallic joint system of the vertex, with what would once have been its fastening system and formed by a tie with ropes, which is what can be seen in the image. Next to and below it, the two pillars are threaded by a steel bar that is responsible for holding the set of pulleys. Along the length of each mast, there are three groups of wedges, attached to it and separated from each other, which prevent the tethers from slipping downwards.

3.2 The Ropes

Twelve ropes of different diameters and lengths complement the pillars, except those used for the lifting equipment, all of which are made from industrial hemp (Cannabis sativa) and have traditionally been the only material used. Recently, those used for lifting, which are hidden from view, have been reinforced with synthetic fibres.

The ropes that function as tensors are made up of eight ropes tied at one end to different points of the beam and, at the other, to as many firm points distributed both on the inside and outside of the dome (Fig. 2a (6)). This is done symmetrically. The seventh is made from the vertex to a ring anchored to the upper part of the lintel of the window by means of a tackle that allows its inclination to be regulated. Finally, the eighth is made by means of a pulley attached to the vertex and a rope that starts and ends on the opposite side of the drum where the pillars are mounted. This counteracts the pull on the vertex caused by the lifting ropes and the opposition caused by the passive forces on the vertex pulleys.

The lifting ropes are the thickest and strongest of the whole rigging. They are corked in such a way that they have been reduced to a third of the length of the ropes, which gives them an optimum resistance value, with an apparent external diameter of 52 mm. Under these conditions, for hemp, a working load of 1912 daN and a breaking strength of 10000 daN, are estimated. With regard to the core, made of synthetic material, the data provided by the manufacturer is for the rope section given a breaking strength of 8000 daN, which gives a total breaking load for the rope of 18000 daN, a figure which, of course, is conditional on the state of the hemp.

3.3 The Pulleys

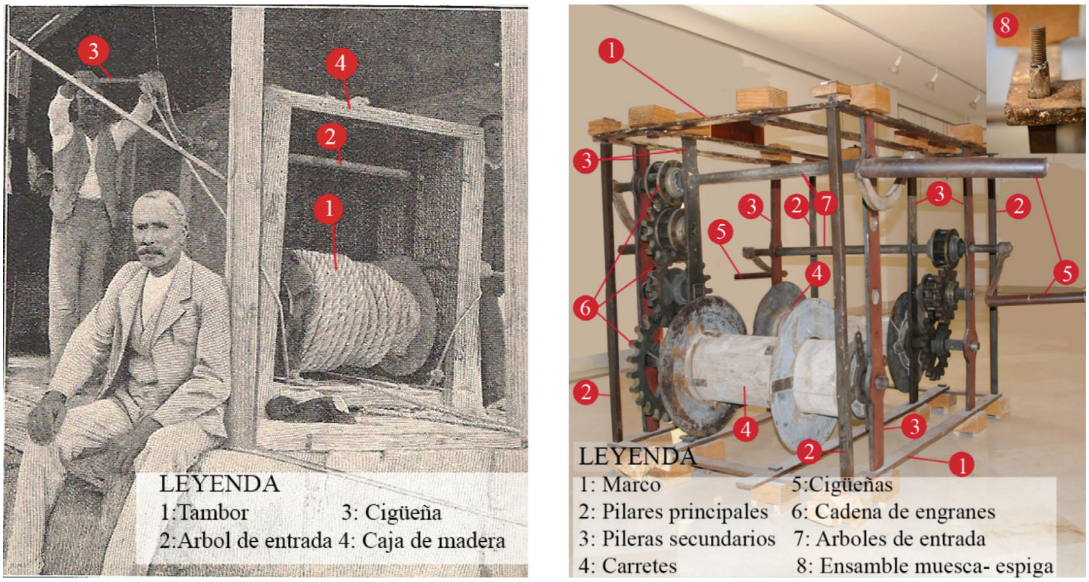
The pulleys are an indispensable complement to the ropes; fourteen of them are used in the hoist. The main ones are the two sets used to guide the lifting ropes from the winch to the apparatus: the lifting pulleys (Fig. 2b-2) and the vertex pulleys (Fig. 2a-7). The first two, which are located on the sill of the window that connects the inside of the drum to the terrace where the winch is located, consist of two bronze eye pulleys mounted in parallel with a shaft and a common steel frame (Fig. 2b-2). Those at the vertex are particularly unique, being a pair of pulleys, made of wood, mounted on top of each other, the one with the largest diameter on top intended for heavier apparatus, and both in the same frame, also made of wood and all reinforced with forged steel (Fig. 2a-7).

3.4 The Winches

The force applied to the ropes has always been with manually operated winches. The current ones entered into service in 1971 and replaced others with similar dynamic characteristics, which entered into service in 1761. After they were removed, they were moved to the Casa de la Festa, where they can be seen today. Comparing the two machines, we understand that it would be appropriate to present the hoist with the old winches given their special singularity.

The first image we have of them is the one in Fig. 3 (a) corresponding to the year 1899, Fig. 4 (b) shows its current state and corresponds to the result of a restoration that was carried out so that it could be exhibited in the aforementioned Casa de la Festa.

We can see in Fig. 4 (b) that these are two independent winches, different from each other and mounted on a common frame made from profiles of forged steel. This set was accompanied, as can be seen in Fig. 3 (a), by a wooden box that contained it and which had, among others, the following characteristics: its shafts are parallel horizontally, they are manually operated with two input cranks per winch and the multiplication of the force is provided by two chains of gears and this chain means that the number of gears is the main differentiating element between the winches, one having three pairs and the other, two.



(a) LEGEND
1. Drum 3. Crank
2. Input shaft 4. Wooden box

(b) LEGEND
1. Frame 5. Cranks
2. Main pillars 6. Gear chain
3. Secondary pillars 7. Input shafts
4. Reels 8. Notch-tenon assembly

Fig. 4. Showing the hoist with its components and its location within the dome referenced as (a) and the path followed by the ropes after leaving the winches referenced as (b) [5].

They are mounted opposite each other on the frame, with the output drums at the same height, the gear trains positioned on opposite sides and the two cranks corresponding to the chain with the highest number of gears positioned higher than the others.

Until 1971, the whole assembly was anchored to the terrace of the basilica and positioned in such a way that its axes of rotation were orthogonal to the trajectory of the ropes. In this location, the winch with the chain with the highest number of gears, the most powerful one, was located at the part furthest from the dome and which we will consider as the rear part throughout this paper. As for the least powerful, the smallest and intended to lift the Santísima Trinidad, it is located, according to the reference taken, at the front.

Originally, the frame consisted of a metallic structure reinforced on the outside with a wooden box. After the box was burnt in the 1936 basilica fire, what has survived is the internal part. Due to the poor condition it was left in after being dismantled at the terrace of the basilica, prior to being exhibited, some parts had to be reconstructed, which is why, today, many of them are not the originals, which are easy to identify as they are made of laminated steel.

In order to describe it, we will consider that it has a main part, made up of two rectangular frames, one located at the base and the other at the top, their vertices joined together by four vertical columns. This main part is joined by accessory parts such as: two longitudinal crossbars in each frame, formed by rectangular plates identical to that of the frame, and also has two sets of three secondary columns formed by plates that are the support points to the shafts. To this end, at their resting point, the plates, while maintaining their thickness, produce a widening so that the hole for the bearing does not weaken the column. At the outer limits, the assembly resembles the geometric figure formed by the twelve edges of a straight parallelepiped or orthohedron with external measurements of: 1,556 mm long, 1,095 mm wide and 1,199 mm high.

The different parts that make up the structure, except for the frames, which are fastened with rivets, are joined using the system known in carpentry as notch-tenon—see detail in Fig. 4 (b)—on the upper right-hand side. Notches were made in each frame, four at the vertices and two on each side; the ones at the vertices being square and the rest, rectangular. The ends of both the main and secondary pillars, end in a tenon and, as an extension to it, has a threaded bolt to hold and support the wood of the box that encloses it. After tightening the nut to the bolt, the frame and the wood of the box would be securely fastened. The two remaining pillars are fastened using the same system as the four crossbars attached to the frames.

As we have just seen, the metallic part of the frame is entirely made up of parts arranged vertically and horizontally, without the presence of struts, cross braces, braces or crosspieces capable of triangulating the structure, a function that was assigned to the parts of the wooden box.

The groups of secondary pillars are arranged with their broad faces parallel to each other; each group having one pillar contained in the plane of each of the side faces of the orthohedron. The distance that remains from the axes of each group with respect to the plane of the rear part is 227 mm for the first and 1,177 mm for the second. The central pillar of the first group is separated from the left side faces by a distance of 426 mm, the second being separated by the same distance, but from the right side plane. Each of these pillars is attached in the same way as the side pillars, but on each of the crossbeams arranged in the upper and lower frames.

All the bearings are friction bearings and are attached to the secondary pillars. They are flanged bushings, made of bronze, on which the different shafts of the winch rest. Originally, the bushings of the hub were square on the outside and the flange was circular. After being repaired, some of them were replaced with bushings with a circular outer section.

The shafts start from a forged square section and have rods, both front and transverse, for both winches, which are roughly the same. The input shafts have a length of 1,546 mm and a square section at their ends, intended for coupling the cranks. On the output side, those supporting the drums have a maximum length of 1,122 mm and those corresponding to the intermediary gears of the kinematic chains have a maximum length of 300 mm.

As for the cranks, they consist of a main bar with a rectangular cross-section in the form of an arch. The length of the arch cord that forms the profile is 350 mm for the two corresponding to the small winch and 450 mm for the large one. All four have a square tube at the end intended to be attached to the shaft which coincides with the square shape given to the four ends of the two input shafts. At the opposite end, the one intended to be gripped by the hands of the operators, the plate was bent into a right angle. This end was forged into a cylindrical shape. These days, this cylinder has a steel tube on the outside that rotates concentrically on the forged cylinder.

The drums, both of which are the same, are where the ropes are wound. Attached to the shaft that supports them is the wooden matrix that forms a revolving cylinder on which the ropes are wound. To contain them within the cylinder, two circular crowns are fastened to it, the planes that contain them being parallel to each other and perpendicular to the axis of the cylinder. Due to the arrangement of the gear train of the small winch, only two thirds of its total length can be used on the drum of the large winch, which means it requires greater effort. The torque is provided by the force from the kinematic gear chain applied to the last gear, which is attached to the drum shaft.

The transmission of forces between each input shaft and its corresponding output shaft is effected by means of two ordinary straight gear trains located between each of the central columns and the corresponding one on the outside; to the left of the output drum in the large one and to the right in the small one.

The gears, formed from cast bronze, have turned side faces and the teeth, which are fitted by hand, are of the oblique, or so-called double point, type. The pinions are all lantern, and the head of the other gears describe the curve that results from tracing the envelope of the positions of the roller when its centre travels through the positions of its profile—see detail of Fig. 5 (a).

For the large winch, the kinematic chain is made up of three lower pairs and four members; the first is attached to the input shaft and the last to the output drum and the two intermediate ones, are attached to two shafts which rest on the central and outer column of the frame and are held in place by friction bearings housed in holes made in the columns.

The input shaft is fitted with a lantern pinion made up of eight rounds of steel attached to bronze crowns. It engages with a 14-tooth cast bronze sprocket that is closest to the outside and to this wheel, an 8-tooth cage pinion identical to that of the input shaft. The wheel and the pinion were attached to the shaft by inserting the shaft through the square holes made in them and tightening them together.

The second shaft, similar to the one described above, is located further down and its position is reversed. The wheel, which has 18 teeth, is at the same distance as the previous pinion so that the mesh between them is perfect. The pinion is in the right position to engage with the 24-tooth wheel attached to the output shaft.

The chain ratio is therefore 8/14 for the first pair, 8/18 for the second and 8/24 for the third, which means a total gear ratio of 1/0.0847; in other words, for every 11.8125 turns of the cranks, the drum does one turn. The module is slightly variable for the different gears, being roughly 18, the lanterns are all the same, with a primitive diameter of 140 mm and a pitch of 55.4 mm. Regarding the wheels, there is a primitive diameter of 447 mm with a circumferential pitch of 55 mm for the 18 teeth; a primitive diameter of 245.8 mm and a circumferential pitch of 64.4 mm for the one with 14 teeth. The thickness of the wheels is 28 mm and the geometry of its teeth is of the so-called point type, in which the point has been replaced by a cylinder [1]. They are made of cast bronze, with the teeth filed down and the faces turned.

As for the small winch, the kinematic chain comprises two lower pairs and three members with similar characteristics to the chain of the large winch. The location of the chain in this machine is to the right of the drum and the ratios for the pairs are 8/14 for the first one and 8/18 for the second, which means a total transmission ratio of 1/0.253968; in other words, for every 3.9375 turns of the cranks, the drum does one turn.

Regarding the large winch, in the case of having the drum width limited to 464 mm, a width that has always been used since the date it was installed in 1761, even without the delimiting disc as can be seen in the first photographs we have of it, the force on the handles from each of its operators varies from a minimum of 8.78 daN, corresponding to the turns of the third layer, to a maximum of 10.72 daN, corresponding to the turns that are placed on the fourth layer and the torque required in the input shaft for the first situation is 16.17 daN-m, and a maximum value of 19.74 daN-m.

If the large winch were to work with the full width of its drum, with a width of nearly 700 mm, with only two layers of rope and only two riggers, the values would be between 12.94 daN for the minimum and 14.66 daN for the maximum, and for the first situation, the input shaft required a torque of 11.90 daN-m and a maximum of 13.60 daN-m.

These days, and with the new winches, the time it takes to raise el Araceli is 7 min, 48 s, to travel a distance of 27 m at a speed of 0.05756 m/s.

With regard to the work carried out by the riggers during the lifting of el Araceli, when the whole drum is not used, a workload value of 270 kJ is obtained and the power developed by each rigger would be 144.22 W. Under these conditions, the efficiency of the winch would be 0.58.

(a) (b)

Fig. 5. Figure composed of the 1761 winch gears referenced as (a) and a gearing system, from the same era as the previous one, comprising a wooden wheel with wooden teeth and a lantern with steel cylinders attached to wooden discs reinforced with steel straps and attached to a wooden shaft and belonging to a windmill from the Cartagena countryside referenced as (b).

If the whole drum were used, with only two layers of rope, and two riggers, the workload would be 247.2 kJ and the power developed by each rigger would be 263.55 W. Under these conditions, the efficiency of the winch would be 0.59.

In order to evaluate the power supplied by a single rigger, we have consulted a specialised book on the subject [2] and it establishes average power values by age groups in different sports. It gives values for different sports and ages, and they are quite a lot higher than this figure. They did not have to be athletes, were generally young people, so we understand them to be figures, for both strength and power, so that, with only two people, the most arduous operation involved in the Mystery of Elche could have been carried out.

4 Conclusions

The most striking thing about the machine is, of course, the absence of design criteria, an aspect typical of constructions prior to the XIXth century, and the next is that the date of construction does not correspond to the high level of technology with which it was built. This leads us to understand that the machine is ahead of its time and, above all, in relation to the geographical place where it appears: the town of Elche in the year 1761 And what is so striking about it for us to say this? Quite simply, the technology of the metallic gears and their manufacturing process.

As for the construction process for the frame, there is nothing special about it, given that they are forged pieces with a better or worse finish that, in each case, depended on the skill of the blacksmith who made them, and, with regard to the shafts, the situation is similar to that of the frame, although whoever made them must have taken much more care given the straightness required and the tolerance in their measurements.

However, for the construction of the gears, the truncated cone-shaped parts that reinforce their position on the shaft and the shaft rods, not only was special care required on the part of the blacksmith, but, above all, it was essential to have special machining equipment that was certainly not available in the town of Elche or in the surrounding area. The gears were cast, the teeth were then adjusted manually and the sides of the discs along with the cone-shaped trunks that reinforce their position, were finished by means of a turning process—see Fig. 5 (a).

The technology that was being developed around the town of Elche was very different to that used in the construction of the winches and we can see this in the wind and water flour mills of the Cartagena countryside, where the designers of the winches came from, and which underwent a period of expansion and reached its maximum splendour in this same era [3].

Cartagena, after being named the headquarters of the Maritime Department of the Mediterranean in 1728, under the new Bourbon dynasty, must have been one of the places in Spain, and, above all, in these parts of its geography, with the greatest concentration of technology at that time. After its nomination, the region underwent, among other things, significant demographic growth, and with it, the need to feed its new inhabitants, as well as the occupants of the king’s galleys [4]. It was traditional in those parts to grind wheat using windmills and given the growth of the population, in keeping with tradition, the number of these wind machines increased. This increased need brought about a growth of up to a total of 81 mills in the area.

A flour mill has a chain of gears that transmits the force from the sails to the grinding wheel, or via water extraction, and the mills of that era have a frame, which is the building itself, with wooden parts reinforced with steel and gears formed with wooden parts, also reinforced with steel—see Fig. 5 (b). It was not until well into the XIXth century that flour mills began to be constructed with parts of steel.

In light of all this, the question arises: where was the winch built? As a hypothesis, we can point to places where, at this time and much earlier, this technology was already in use. For example, in cathedral bell towers, where at the end of the XIVth century, as in the case of Wells cathedral in England, which are on display at the London Science Museum, similar mechanisms were already being used to operate the chimes and to support the corresponding weights.

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