AL-JAZARI (1136–1206)

Lotfi Romdhane and Saïd Zeghloul

Abstract Ismail Al-Jazari, Arab inventor who is remembered for his design of water-raising machines and many unusual clocks and automata. His book entitled: “Book of Knowledge of Ingenious Mechanical Devices” presents a whole range of devices and machines, with a multiplicity of purposes.

From all the presented machines, two are most remarkable: his famous elephant clock, which was by far the most sophisticated clock at that time and his invention of a water pump using a crank-slider-like system, which was the first known machine to use a crank.

Biographical Notes

Al-Jazari is by far the most famous mechanical engineer of the pre-medieval era. His name is

“الشيخ رئيس العمل بديع الزمان أبو العز إبن إسماعيل إبن الرزاز الجزري”,

“Al-Shaykh Rais Al-Amal Badii Al-Zaman Abu Al-Izz Ibn Ismail Ibn Al-Razzaz Al-Jazari”.

This long name is actually a combination of his title and his real name. The first three titles “Al-Shaykh Rais Al-Amal” indicate that he was a notorious chief engineer, “Badii Al-Zaman” the best of all times, “Abu El-Izz” the well respected, “Ibn Ismail” sun of Ismail (his father), “Ibn Al-Razzaz” his grandfather, and “Al-Jazari”

L. Romdhane (✉)
Laboratoire de Génie Mécanique, Ecole Nationale d’Ingénieurs de Sousse,
Technopole Sousse 4054, Tunisia
e-mail: lotfi.romdhane@gmail.com

S. Zeghloul
Université de Poitiers, Laboratoire de Mécanique des Solides,
CNRS UMR 6610, Boulevard Marie et Pierre Curie, Téléport 2,
BP 30179, 86962, Futuroscope Chasseneuil Cedex, France
e-mail: said.zeghloul@lms.univ-poitiers.fr

M. Ceccarelli (ed.), *Distinguished Figures in Mechanism and Machine Science: Their Contributions and Legacies, Part 2*, History of Mechanism and Machine Science 7,
DOI 10.1007/978-90-481-2346-9_1,

Fig. 1 Al-Jazari

indicates that his family came from Al-Jazira, which is the region in northern Syria and Iraq between the two rivers Tigre and Euphrates (Fig. 1).

He lived most of his life away from his homeland in Diyar Bikr in Upper Mesopotamia, which is in present-day southern Turkey. He was in the service of three consecutive Artuqid rulers: Nur al-Din Muhammad ibn Arslan (1174–1185), Qutb al-Din Sukman ibn Muhammad (1185–1200) and Nasir al-Din Mahmud ibn Muhammad (1200–1222). The only known information about his life is that given in his book. He completed writing his book in early 1206 and it took him 7 years to complete it. He recorded that when he started writing his book he had more than 25 years of experience in building machines. Hence, historians concluded that he started his active life in around 1175. Several aspects of his life made him different: the first one is that in the contrary of most scientists (علماء oulama in Arabic) at that era of Islamic civilization, he was interested only in inventing and building machines. Indeed, most of the scientists of that time were pluri-disciplinary, in the sense understood nowadays. Some of the most famous scientists, like Al-Farabi, Ibnou-Sina (Avicenna), Al-Khawarizmi, to name a few, were excelling in several disciplines going from poetry to theology to philosophy to science to medicine. Al-Jazari, however, was a true mechanical engineer and he excelled in his job as a chief engineer in the court of the Artuqid rulers.

His Work

Al-Jazari finished his single contribution in 1206. His book is entitled: الجامع بين العلم والعمل النافع في صناعة الحيل i.e., “Al Jamaa byna al ilm wal amal ennafii fi sinaat al hiyal”, which was translated in several ways (Fig. 2).

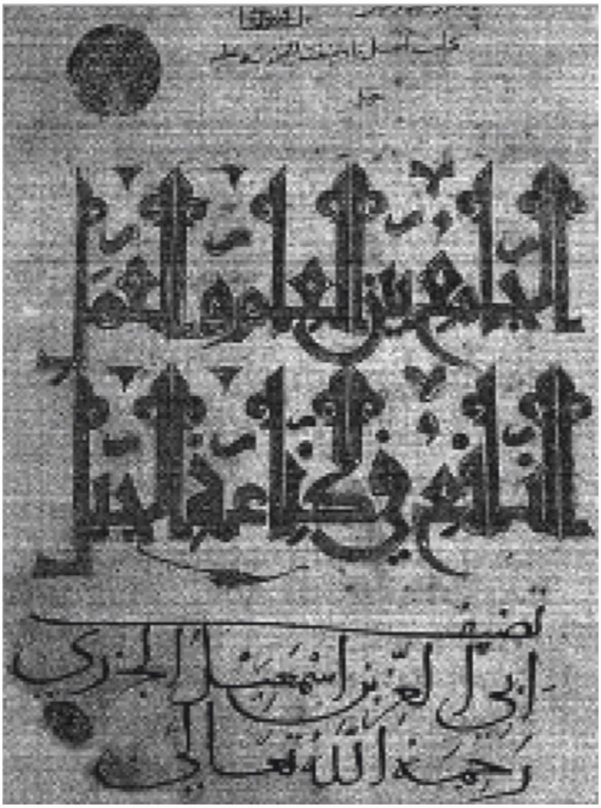

Fig. 2 First page of Al-Jazari's book (The Topkapi Palace Museum, Istanbul, N° A 3472)

The first attempt to translate this book was by Wiedmann and Hawser, who translated parts of it into German in the first quarter of the twentieth century (Hill 1998). The most known translation of this book, however, is by Hill and is entitled "The Book of Knowledge of Ingenious Mechanical Devices" (Hill 1974). Others preferred translating it as "A Compendium on the Theory and Practice of the Mechanical Arts" (Al-Hassan 1976). Some sources refer to the same book simply as "Automata" (Chapius and Droz 1958). All these attempts tried to capture the meaning of this long and very eloquent title. If we analyze the key words of the title we can find the word "ilm علم ", which means science or knowledge in its broadest sense. "amal ennafii العمل النافع" can be translated as the useful work or power, but from the meaning of the whole title, it is probably intended for practice or the practical aspect of design or simply engineering. Al-Jazari tried by allying science and practice to design machines called here "hiyal الحيل", which is the plural of «hyla حيلة » meaning an artifact or a tricky way to get something done.

Al-Jazari's book presents a whole range of devices and machines, with a multiplicity of purposes. What is interesting to note is the considerable degree of engineering skill required to manufacture these devices, and the use of delicate mechanisms and sensitive control systems. In this respect, Al-Jazari can be called a true design engineer more than a scientist. Dimargonas, in his recent book on mechanical design (Dimargonas 2001) said: "…thus, Al-Jazari's work is really a study in systematic machine design!"

Al-Jazari's book is divided in six types (أنواع Anwaa, which is the plural of Nawâ نوع type in Arabic) totaling 50 different devices (أشكال Ashkal, plural for Shakl شكل: : geometric form in Arabic):

- Ten different Clocks
- Ten designs of Automata vessels dispensing wine and water for drinking sessions
- Ten designs of Water dispensers for ritual ablution (oudhou الوضوء in Arabic) and bloodletting devices
- Ten fountains and musical automata
- Five different designs of water raising machines
- Five miscellaneous machines like instruments for measuring spheres and locks

From all the presented machines, two are most remarkable: his famous elephant clock, which wasby far the most sophisticated clock at that time, and his inventions of a water pump using a crank-slider-like system. Even though, only a few of his inventions can be classified as utilitarian machines, Al-Jazari still departed from his predecessors when he presented these inventions. Indeed, despite him living in the court of his ruler, he was also listening to the needs of the people. The fifth chapter of his book presents five different, useful inventions mainly to raise water for irrigation and domestic purposes. This attitude was unusual at that time since most of the scientists (*Oulama* علماء) were at the service of the caliphs and their concern is mostly motivated by responding to the need of these rulers. Moreover, in writing his book, he tried to use simple Arabic and to clarify as much as he can the way his machines work and he even gave precise information on how to build the different parts of these machines. At that time, this way of writing was unusual, since most of the scientists (*Oulama* علماء) were more interested in impressing their peers by writing their books using a sophisticated language hardly understandable by common people, hence limited to the elite.

The rest of his book, but an important part of it, presents another type of engineering that is different from the utilitarian technology described in the fifth chapter. This type of technology is usually called "fine technology", since its distinguishing features derived from the use of delicate mechanisms and controls. Some of these devices had obvious practical uses: water clocks were used in astronomical observations and were also erected in public places. Others gave amusement and aesthetic pleasure to the members of royal circles, which led him to invent the first programmable humanoid robot in 1206. Al-Jazari's robot was a boat with four automatic musicians that floated on a lake to entertain guests at royal drinking parties (Margaret 2006; Franchi and Güzeldere 2005). Some of these devices functioned as curiosities.

Review of his Main Work on Mechanism Design

To show the ingenuity of the proposed designs, we will be mainly interested in water-raising machines, some of which are original and can still be seen in several contemporary machines. By far the most important contribution of Al-Jazari to mechanism design is the crank-slider system and his use in a machine. This first description of a crank-slider mechanism came 300 years before Western Engineers, e.g., Francesco di Giorgio Martini and Leonardo Da Vinci, who used the crank-slider-type mechanism in the fifteenth century (Al-Hassan 1976). Ramelli also used the crank-connecting rod in a pump in his book of 1588 (Teach and Ferguson 1994).

We also present some of his inventions in designing clocks. To show the ingenuity of Al-Jazari who, according to several historians (Ören 2001), laid down the foundation of automatic mechanical control as perceived today.

It is also interesting to note that the degree of precision in the description of his devices allowed people with no background in mechanics, to understand how these machines should work.

Water Raising Machines

Throughout history, the supply of water for domestic and irrigation purposes has always been a vital consideration. Earlier designs can be found since the antiquity. The water-raising technology was of great benefit to the people of that time and it also laid the foundation for the machinery of irrigation and the machine design, in general.

Despite being at the service of the Artuqid rulers, Al-Jazari was sensitive to the needs of the common people and he proposed in his book five different designs of water raising machines. These machines are intended to help people in everyday life and to alleviate some of their burden. Two different machines, which are mostly an improvement of the most ancient water raising machine, called the "Shaduf", are first presented. This type of machine lies on a lever system with a counterweight at one end to help fill a bucket, attached at the other end, and lifting it. This system is still in use nowadays in some Middle Eastern countries.

Al-Jazari suggested the use of a hollow tube as a lever instead of the beam and a scoop at the end instead of a bucket, so when it is raised the water can flow inside it to the irrigation system. This system made raising water easier and faster.

Al-Jazari's third machine was an improvement of the "Saqiya". The classical design of the "*Saqiya*" is an animal-powered mechanism of two perpendicular wooden gears. An animal is harnessed to the vertical axis of the horizontal wheel. The second gear is driving a vertical wheel with clay pots attached to its circumference (pots-wheel). As the vertical pots-wheel rotates, the pots are dipped into the water one by one. As each pot reaches the top, its water pours into a wooden sluice.

The first idea of Al-Jazari is to take advantage of the power of the water, in the form of a flow, and to use it to drive the system. He presents his invention (Fig. 3) where he does not eliminate completely animals from the driving system but rather he designs a complementary system to help the animal. Hence, depending on the flow of the water, the system can be fully autonomous, but if the flow is not enough (during the dry season, for example) the animal can still drive the system. This way of thinking drove most of the Al-Jazari's inventions.

The second idea of Al-Jazari is to use a pots-chain instead of a wheel with pots as it was known at that time (Fig. 3). The chain-like system solution allowed the use of the "Saqiya" in places like wells, where the classical design could not be used due to the limited space. Moreover, the proposed design can be adapted easily for different heights by simply changing the length of the chain.

Therefore, Al-Jazari improved the well-known design of "Saqiya" in two ways: the first one was by adding a water wheel to help driving the system in an autonomous way, and the second one was by replacing the wheel with pots, in the classical design, by a chain-like system containing the pots.

The way this machine was sketched is also very interesting. Al-Jazari tried to make his drawing as clear as possible by trying to show the 3D aspect of the

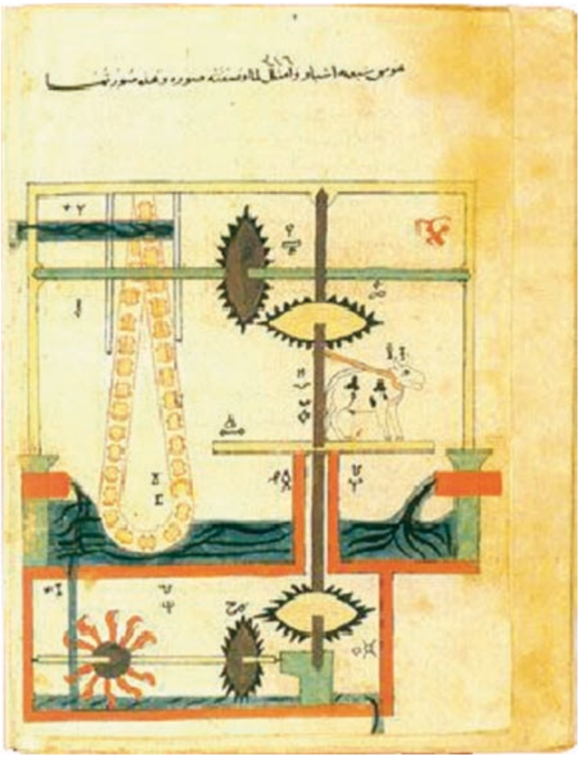

Fig. 3 Al-Jazari's water-powered Saqiya chain device (The Topkapi Palace Museum, Istanbul, N° A 3472)

machine. Indeed, one can notice that the gears, which are circular, are drawn as some sort of ellipses. Depending on the direction of the great axis of the ellipse, one can know the plane containing the gear. For example in Fig. 3 the gears with the vertical axis are drawn with “ellipses” with horizontal great axes and similarly for the horizontal axes gears. Moreover, the chain-like system of pots is represented skewed to show that it is contained in the vertical plane perpendicular to the one of the drawing, but still shows enough details. This representation is, indeed, one first attempt to use projection to represent 3D systems. Al-Jazari also used also letters and some special symbols to help him in the description of the system in very much the same way as in patents today.

The fourth machine used a flume beam (a hollow beam or a tube) and was animal powered. The tube oscillates back and forth thanks to a couple of gears driven by an animal and a crank-slider system. The scoop at the end of the tube is filled with water when it is at its lowest position and when it is raised, the water can flow inside the tube to the irrigation system. The idea of the tube here is very similar to the one used in the first two machines (Shadhuf). This shows how Al-Jazari is using modular designs and then improving on them each time, which attests to his practical sense of optimizing the design process. What is original, however, in this invention is his idea of converting a continuously rotating motion to an oscillating one using an inversion of the crank-slider mechanism. Several historians (Hill 1998; Bertrand 1969) considered this design as the first one to use a crank-slider mechanism in a machine. Indeed, even though the adopted solution is probably not the best, according to our contemporary knowledge, this design opened a whole era for more complex machines going up to the steam engine and the internal combustion engines. The idea of having a pin-in-a-slot type joint will be used again in his fifth invention (Fig. 4).

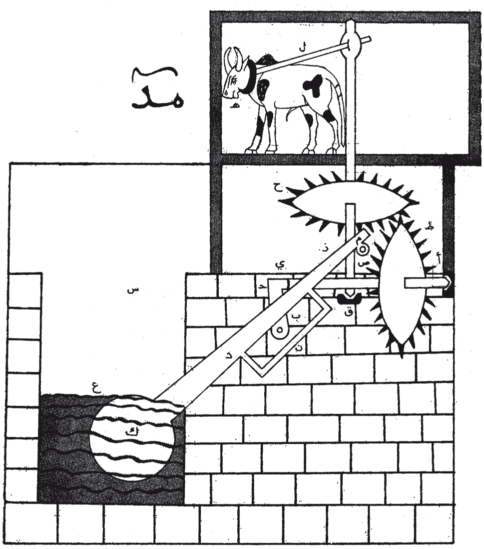

Fig. 4 Fourth water raising machine by Al-Jazari from Al-Jazari’s manuscript

The fifth machine, presented by Al-Jazari, took this idea of converting different types of motion further by proposing what we nowadays call a piston pump. The translation motion of the piston is obtained by transforming a continuously rotating motion through a tricky system of gears and links.

This machine, a twin-cylinder, water-driven pump, represents the first attempt to use suction and discharge to lift water to a certain height. Up until that time (twelfth century), all the water-raising machines relied on filling some type of container and lifting it to empty it at the desired height. The machine proposed by Al-Jazari went away from this solution to try to force water through a pipe, which allowed him to lift water to heights never reached before with a relatively small-size machine. This invention contains the most features of relevance for the development of mechanical design, and is very similar to contemporary pumps (Fig. 5).

Three main novelties can be noted in this design. The first one, and probably the most important, is the use of eccentricity to convert the continuously rotating

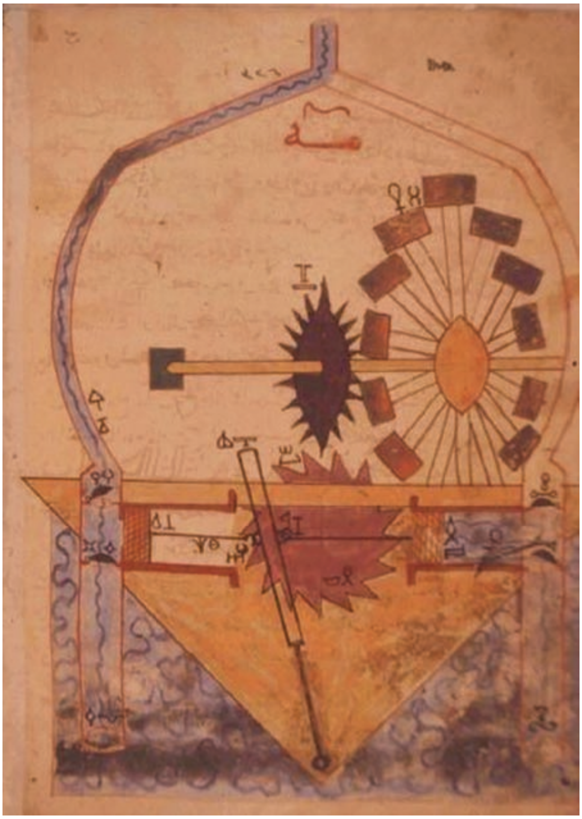

Fig. 5 The reciprocating pump from Al-Jazari's manuscript (Topkapi Palace Museum Library, Ahmet III 3472)

motion to an oscillating motion. Moreover, through a pin-in-slot type joint, Al-Jazari succeeded in getting the necessary reciprocating motion of the pistons.

The second novel aspect in this machine is the use of valves as a means to allow the suction and the discharge process in the reciprocating pump. Several contemporary machines are still using this design in controlling the suction and the discharge phases (steam engine, internal combustion engine, piston pumps…). All the historians agree that this invention was not known before by any of his predecessors.

The last aspect is the use of a large water wheel to make the system completely autonomous. Some historians mentioned that Al-Jazari also used animals to drive this machine, mainly during the drought seasons where the level of the water is low.

Clocks

Al-Jazari also mentioned many amusing, yet practical, devices, including several unusual clocks which were much more elaborate than those developed before. They were sometimes driven by weights. As the weight fell, it encountered resistance from a float riding in a water tank. Others involved a bucket that tipped over when filled with water, hitting a ratchet that moved the clock ahead (Fig. 6).

a

b

Translation: (a vertical pole) located between the two basins is used to sustain the horizontal tube in the middle. On top of the tube at the middle a funnel and the two ends of the tube are opened. At the bottom side of the tube, a small tube emerges from it and extends until it reaches the bucket. Also it gets out of the tube another small tube and it extends until it reaches the bucket. And I represent all in the figure.

Fig. 6 (**a**) Water clock by Al-Jazari (Süleymaniye library, Istanbul, Turkey), (**b**) translation of the text

Water clocks

This water clock uses two tipping buckets that are filled alternatively, making the horizontal tube tip from one side to the other. The flow of water is therefore switching from one tank to the other after a fixed period of time required to fill one bucket. A similar design was proposed by Al-Jazari as a musical instrument. The flow of water in the tank chases the air inside it and forces it to go through a whistle (Nadarajan 2007; Hill 1974).

The interesting idea in this design is the use of the small tubes to fill the two buckets. The oscillation of the tube triggers a system (not represented) to indicate the time at constant intervals. This clock can work as long as the water is flowing.

Candle Clocks

Al-Jazari also describes candle clocks which all worked in a similar manner. Each design specified a large candle with a uniform cross-section and known weight. The candle was installed inside a metal sheath, to which a cap was fitted. The cap had a hole in the centre, around which was an indentation on the upper side. The candle, whose rate of burning was known, had its wick going through the hole. The bottom of the candle rested in a shallow dish that had a ring on its side and was connected through pulleys to a counterweight. As the candle burned away, the weight pushed it upward at a constant speed. The automata are operated from the dish at the bottom of the candle by letting a small sphere drop in a container, which is suspended to the arm of the robot. Under the weight of the ball, the arm of the robot lowers, indicating the hour. The container descends until it hits the floor, which makes it to tip and to let the ball out (Fig. 7).

A second design is presented in Fig. 8, where the scribe sitting on the left is rotating as the candle goes up. A set of pulleys and a cable with a counterweight allows the transmission of the motion between the candle and the scribe. The tip of his pen indicates the hours and the minutes, which are engraved on a circular scale. The set of spheres on the right is made such that one sphere drops from the falcon's beak at the top of each hour.

Weight Clocks

The most famous of Al-Jazari's clocks is his three-meter-high elephant clock. Using weights dropped from its top at regular intervals, an intricate mechanism is triggered.

The clock features a perforated submersible bowl, a device that is at the heart of the clock mechanism. The small orifice in the submersible bowl is carefully

a

b

Translation:
The candle is attached by two strings through two pulleys to a weight. As the candle burns away it gets lighter and it lifts off under the effect of the weight, which lets one small ball to drop in a container suspended by a string to the arm of the robot. Under the weight of the ball, the arm of the robot lowers, indicating the hour. The container tips when it gets in contact with the floor and the ball rolls out of the mouth of the bird.

Fig. 7 (**a**) Candle clock of Al-Jazari (Smithsonian Institute), (**b**) translation of the text

Fig. 8 A candle clock from Al-Jazari's manuscript

calibrated to produce the correct rates of flow. This rate of flow determines the time at which the clock strikes at hourly intervals. As the bowl fills with water, it sinks and a set of pulleys and a cable with a counterweight allows the transmission of the motion to the scribe sitting on the back of the elephant. The tip of his pen indicates the hours and the minutes, which are engraved on a circular scale. When the bowl reaches the bottom, it releases a ball from the castle, which falls onto a channel mechanism that rotates a dial to reveal the time. The ball then travels to the falcon's beak and is then dropped into the mouth of a snake, which then swings due to the weight of the ball and drops the ball into a vase. The motion of the snake pulls on the bowl and empties it. The ball then disappears into the elephant's body and it activates the Mahout sitting on the head of the elephant to strike the cymbals. The snake swings back to his original position due a counterweight. At this time, the bowl is again floating and it starts to sink and the whole process repeats itself as long there are balls on top of the elephant (Fig. 9).

Fig. 9 Elephant clock (NY Metropolitan Museum)

Miscellaneous

Other chapters of Al-Jazari's work describe fountains and musical automata which are of interest mainly because the flow of water in them alternated from one large tank to another at hourly or half-hourly intervals. Several ingenious devices for hydraulic switching were used to achieve this operation (Rosheim 1994). These revolutionary machines owed him the title of the father of robotics (Chapius and Droz 1958; Nocks 2007).

One of Al-Jazari's machines was a boat with four automatic musicians that floated on a lake to entertain guests at royal drinking parties. It had two drummers, a harpist and a flautist (Fig. 10). The heart of the mechanism is a rotating cylindrical beam with pegs (cams) protruding from it. These just bump into little levers that operate the percussion. The point of the model is to demonstrate that the drummer can be made to play different rhythms and different drum patterns if the pegs are moved around (Fig. 11) (Ören 2001). Al-Jazari is also an inspiration for a musical robot live-coding system bearing his name, and his work is acknowledged in several contemporary books on robotics and mechanical design (Ceccarelli 2004; Dimargonas 2001).

Al-Jazari also noted a number of practical joke devices in his manuscript. Some were trick drinking vessels that appeared to contain water but could not be emptied. Others looked empty but produced water when tipped over.

In producing these not-so-useful inventions, Al-Jazari was typical of his age.

Fig. 10 Musical Automata from Al-Jazari's manuscript

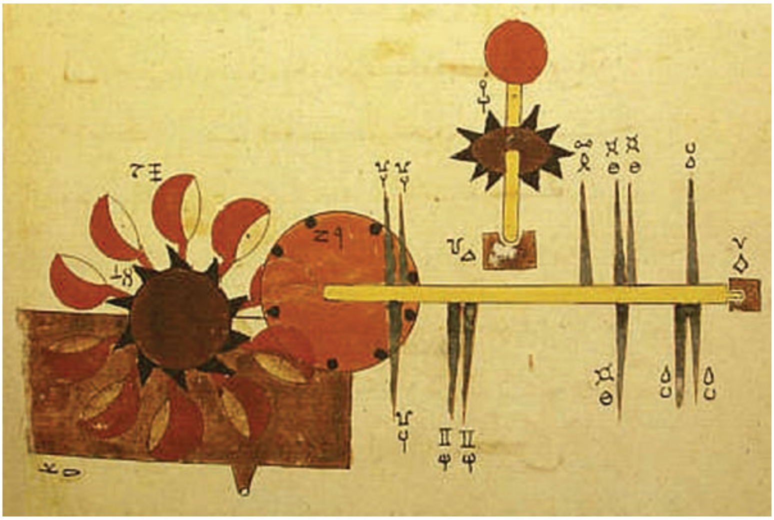

Fig. 11 Cam mechanism from Al-Jazari's manuscript

On the Circulation of his Work

Many copies of this book are conserved in a number of museums worldwide such as Top Kapi in Istanbul, and the Museum of Fine Arts in Boston, the museum of the Louvre in France and Oxford's Bodleian Library (Hill 1998).

British engineer Donald Hill, who has a special interest in Arab technology, writes: "It is impossible to over-emphasize the importance of Al-Jazari's work in the history of engineering; it provides a wealth of instructions for design, manufacture and assembly of machines" (Hill 1974).

About al-Jazari's book, Sarton says that "this treatise is the most elaborate of its kind and may be considered the climax of this line of Moslem achievement" (Sarton 1975).

Al-Jazari's book was translated into English by Hill (1974). It is a complete translation of his work, using mainly MS Graves 27 at the Bodleian Library, Oxford, UK (Hill 1998).

It is worth mentioning that the written Arabic heritage in mechanical technology began with the Banu Musa book, written in the nineth century. Banu Musa described a hundred ingenious devices. They have made contributions to technological refinements and new applications. However, Saliba (2007) compared the work of Al-Jazari and the work of Banu Musa and he concluded: ".... when their works (Banu Musa) are compared to the work of Al-Jazari, we note a remarkable maturity in the latter's work that is nowhere to be found in the works of Banu Musa. With Al-Jazari, we begin to notice discussions regarding the real function of mechanical devices, and real appreciation of their significance as tools that did not only fulfill daily functions for the society but that they were also tools that could demonstrate the way in which the natural physical principles worked" (Saliba 2007).

Many of the ideas employed in the construction of ingenious devices were useful in the later development of mechanical technology and they had a tremendous influence on the history of the mechanical design of machines. His utilitarian inventions were also used in the entire Arab world at that time and spread all the way to Spain. It is believed that the most likely location for the transfer of information between the East and the West was Spain where Muslims and Christians coexisted for eight centuries (Cigola and Gallozzi 2000; Cigola 2006). On the other hand, with the Crusades, the West met the East and the transfer of scientific and technical knowledge from the Eastern world was accentuated.

We can also note that Al-Jazari introduced several individual components like conical valves and locks. Conical valves appeared later in Leonard da Vinci's book (1495) and as a float-controlled regulator for steam boilers in England in 1784 (Mayer 1970).

Al-Jazari developed techniques to build his machines such as casting in closed mold boxes, which reappeared in Europe in 1500 (Smith 1968; Baer 1984).

In his book, Rosheim (2006) mentioned the book of Al-Jazari as one of the sources that might have influenced Leonardo da Vinci in building some of his clocks. This information was also reported in (Needham 1965) in his study on the influence of China and the Medieval Arabic civilization on the West.

Taqi Eddin, in the sixteenth century, also proposed a six-cylinder pump most likely inspired from the pump, which was invented by Al-Jazari 300 years before (Al-Hassan 1976).

Al-Jazari's third water-raising machine allowed lifting water higher by simply increasing the length of the chain and without drastic changes in the whole design. However, with classical designs of the "*Saqiya*", increasing the height requires changing the whole wheel for one having greater diameter, which is a much more difficult task.

One such machine was located on the River Yazid in Damascus (thirteenth century) (Fig. 12) and is thought to have supplied the water needs of a nearby hospital.

Several prototypes of Al-Jazari's machines have been built recently. During the Islam Festival in England in 1976, three of Al-Jazari's machines were shown. The first one was a monumental water clock, which is now exhibited in Asten in the Netherlands. Other prototypes can be seen in Frankfurt, Germany and in Aleppo, Syria. A full-scale prototype can also be seen in a mall in Dubai (Fig. 13) and a very elaborate simulation of the same system can be found on the web (Fig. 14).

In addition to the elaborate explanations and illustrations, Al Jaziri's book has an artistic and a historical value. All illustrations in the book are in color and they have great artistic merit. Historians believe that great artists lived at the court of the Artuqids who helped Al-Jazari in illustrating his book. These illustrations were also used by historians to study the clothing styles of men and women in Diyar Bikr in the thirteenth century (Akurgal and Hilber 1980; Raby 1985; Turner 1996).

Fig. 12 Vestige from a Saqiya in Damascus, Syria http://www.flickr.com/photos/damascene/80436428/

Fig. 13 Al-Jazari's clock at Dubai's Ibn Battuta Mall

Fig. 14 Simulation of the elephant clock (http://communication.ucsd.edu/aaytes/transliteracies/cezeri2.htm)

Modern Interpretation of Main Contributions

His inventions of water-raising machines have been in use since the thirteenth century. Indeed, the idea of having a chain of pots, in building the Saqiya, is still used nowadays in some Middle Eastern countries. Figure 15 shows a recent sketch of a Saqiya and the built system in the south of Egypt. We can notice that the use of two cogwheels with different diameters, as shown in Fig. 15, was not proposed by Al-Jazari.

In all his machines, Al-Jazari uses only cogwheels with identical diameters; hence we can conclude that gears are used in order to transmit movement between perpendicular axes rather than as a speed multiplier.

The fourth raising machine proposed by Al-Jazari (Fig. 4) is the first one made of only rigid bodies. The kinematic diagram of this machine is shown in Fig. 16. The dimensions are chosen as close as possible to the ones proposed in the manuscript. In Fig. 16a, we can see the lowest position of the tube where the bucket is being filled with water, and in Fig. 16b we have the second extreme position of the tube being emptied in the irrigation system. Figure 17 shows a planar kinematic

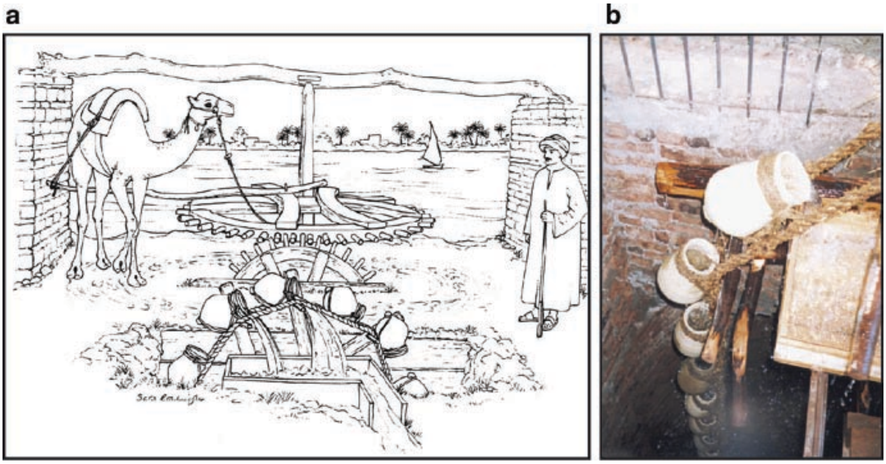

Fig. 15 (**a**) A recent sketch of a Saqiya as proposed by Al-Jazari, built in the south of Egypt, (**b**) the built system (http://www.saqiya-luxor.com/)

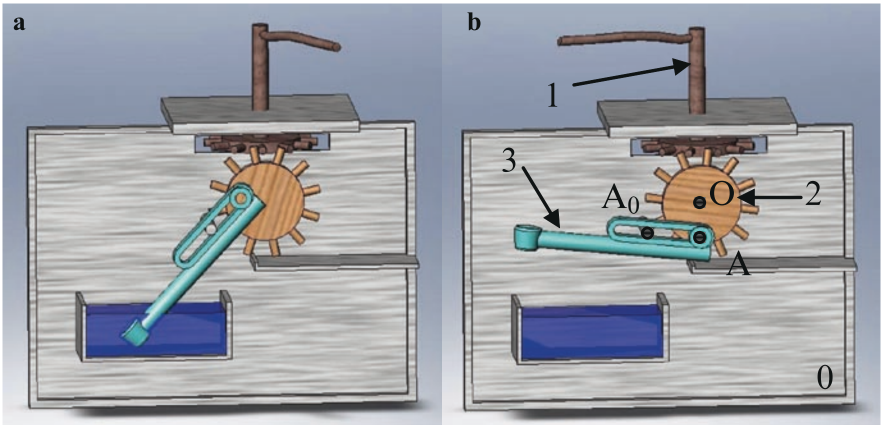

Fig. 16 a 3D CAD model of Al-Jazari's fourt water raising machine. (**a**) Lower position, (**b**) upper position

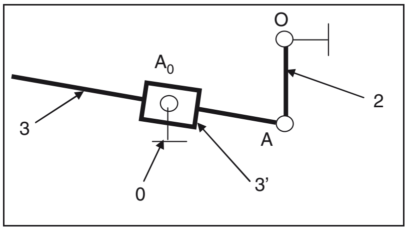

Fig. 17 A planar kinematic diagram of Al-Jazari's water-raising machine

diagram of the proposed machine. The pin-in-a-slot joint was replaced by two lower kinematic pairs. Therefore, the proposed mechanism is an inversion of the well-known crank-slider mechanism. Indeed, most historians agree that this is the first use of a crank-slider system in a machine and is probably the first use of the pin-in-a-slot joint also (Al-Hassan 1976; Teach and Ferguson 1994; Hill 1998; Bertrand 1969).

The drawback of this machine is its limited height to which it can lift water. This limitation inspired Al-Jazari to move away from the classical solution of raising the water and to invent the pumping solution. His fifth machine (Fig. 5) is a twin cylinder pump where the crank and the pin-in-a-slot joint are again used to build this system. Figure 18 shows a 3D CAD model of the system. The planar mechanism made of bodies 0-2-3-4 is the one transforming the continuous rotation into a reciprocating motion of the pistons (4). Figure 19a shows a kinematic diagram of the mechanism when the joint in B is modeled by a hinge joint.

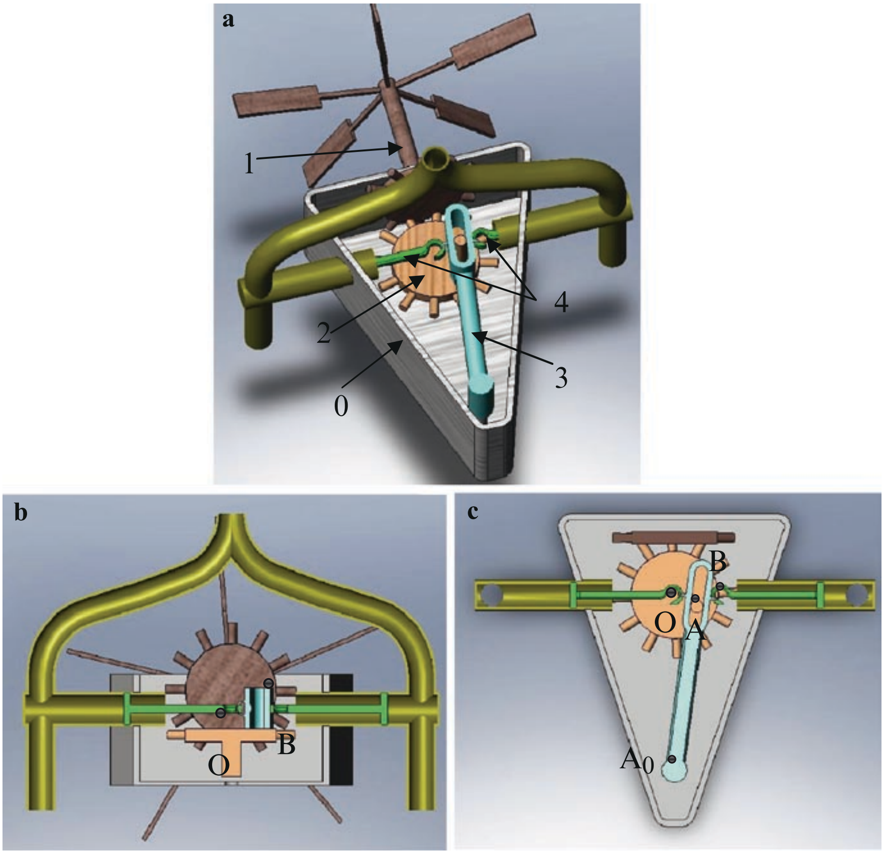

Fig. 18 (**a**) 3D CAD model of Al-Jazari's pump, (**b**) a vertical cut, (**c**) an horizontal cut

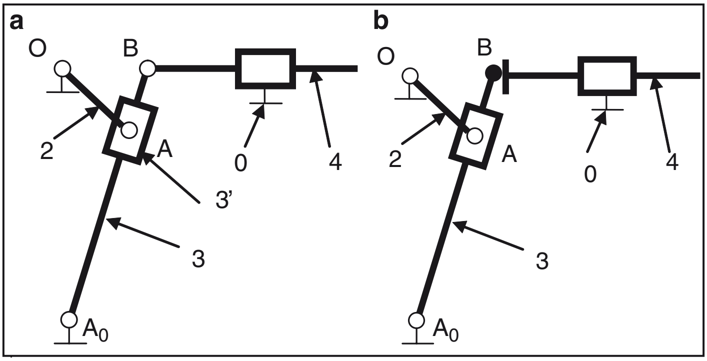

Fig. 19 A planar kinematic diagram of Al-Jazari's pump. (**a**) A hinged solution, (**b**) the adopted solution

One can see that the mobility of the system is 0 and no motion is allowed in this case. Al-Jazari was aware of this problem and proposed a unilateral joint made of a revolute joint but with an exaggerated clearance (Fig. 19). Therefore, this can be modeled by a point contact joint as shown in Fig. 19b. This practical solution allowed the system to work despite the existence of a backlash when inversing the direction of the motion of the pistons. Since the input speed is not important, the behavior of the system was deemed satisfactory by Al-Jazari. Nowadays, this mechanism has a connecting rod to allow the correct functioning.

This type of mechanisms is not far from a design point of view, from mechanisms taught at engineering schools nowadays, and its similarity with the quick-return mechanism is striking.

Acknowledgement The authors wish to thank Samir Lahouar for his help in drawing some of the presented models.

References

Al-986 AY (1976) Taqi Eddin and Arabic Mechanical Engineering. Institute for the History of Arabic Science, Aleppo University, Aleppo

Al-Hassan AY, Hill DR (1986) Islamic technology – an illustrated guide. Cambridge University Press, Cambridge

Al-Jazari, *The Book of Knowledge of Ingenious Mechanical Devices: Kitáb fí ma'rifat al-hiyal al-handasiyya*, translated by P. Hill (1973), Springer Science.

Akurgal E, Hilber L (1980) The art and architecture of turkey. Rizzoli, New York

Baer E (1984) Metalwork in medieval islamic art. State University of New York Press, Albany, NY

Bertrand G (1969) A history of technology and invention, progress through the ages, ed. Maurice Daumas, vol I. Crown, New York

Bunch BH, Hellemans A (1993) The timetables of technology: a chronology of the most important people. Simon & Schuster, New York

Ceccarelli M (2004) Fundamentals of mechanics of robotic manipulation (intelligent systems, control and automation: science and engineering). Springer, New York
Chapius A, Droz E (1958) Automota: a historical and technological study. Neuchatel: Editions du Griffon, France
Cigola M (2006) Greek and Muslim automata: influence of Greek knowledge in medieval Islamic science. In: Proceedings of the 2nd International Conference on Ancient Greek Technology, Athens, 2006
Cigola M, Gallozzi A (2000) Drawings of automata in middle age. In: Ceccarelli M (ed) Proceedings International Symposium on History of Machines and Mechanisms, Cassino, Italy, 11–13 May 2000
Dimargonas AD (2001) Machine design: a CAD approach. Wiley-IEEE, New York, p 14
Franchi S, Güzeldere G (2005) Mechanical bodies, computational minds. MIT Press, Boston, MA
Hill DR (1998) Studies in medieval Islamic technology [Texte imprimé]: from Philo to Al-Jazari – from Alexandria to Diyar Bakr. David A. King, Aldershot (GB)
Losano Mario G (2003) Automi d’Oriente. “Ingegnosi meccanismi” arabi del XIII secolo. Medusa Edizioni, Italy
Margaret A (2006) Mind as machine: a history of cognitive science. Oxford University Press, Oxford
Mayer O (1970) The origins of feedback control. MIT Press, Cambridge
Nadarajan G (2007) Islamic automation: a reading of Al-Jazari’s the book of knowledge of ingenious mechanical devices (1206). MediaArtHistories/MIT Press, Cambridge, MA), pp 163–178
Needham J (1965) Science and civilization in china, Vol IV-2. Cambridge University Press, London, pp 435–481
Nocks L (2007) The Robot: the life story of a technology. Greenwood, West Port, CT
Ören (2001) Advances in computer and information sciences: from Abacus to Holonic agents. Special Issue on Artificial Intelligence of Elektrik (Turkish Journal of Electrical Engineering and Computer Sciences – Published by TUBITAK – Turkish Science and Technical Council), 9:1, 63–70, T.I. 2001
Raby AJ (ed) (1985) The art of Syria and the Jazira. Oxford University Press, Oxford
Rosheim ME (1994) Robot evolution: the development of anthrobotics. Wiley-IEEE, New York
Rosheim ME (2006) Leonardo’s Lost Robots. Springer-Verlag, Berlin, p 117
Saliba G (2007) Islamic science and the making of the European. MIT Press, Boston, MA
Sarton G (1975) Introduction to the history of science, vol II. Krieger, New York
Seo MH, HaHn Y, Lee J, Nam M (2000) Clock-work mechanisms of the automatic striking cepsydra Jagyungnu. In: Ceccarelli M (ed) Proceedings International Symposium on History of Machines and Mechanisms, Cassino, Italy, 11–13 May 2000
Smith CS (1968) The early history of casting moulds and the science of solidification. In: Mullins WW, Shaw MC (eds) Metal transformations. Gordon & Breach, New York
Teach GM, Ferguson ES (1994) The various and ingenious machines of Agostino Ramelli. Dover, New York
Turner HR (1997) Science in medieval Islam: an illustrated introduction. University of Texas Press, Austin
Turner J (1996) The Grove Dictionary of art. Oxford University Press, New York, p 322
Ungerer A (1930) Horloges monumentales. Edition des archives alsaciennes d’histoire de l’art, Strasbourg
http://communication.ucsd.edu/aaytes/transliteracies/cezeri2.htm
http://en.wikipedia.org/wiki/Al-Jazari
http://www.history-science-technology.com/Notes/Notes%203.htm
http://news.independent.co.uk/world/science_technology/article350594.ece
http://www.muslimheritage.com/day_life/default.cfm?ArticleID=188&Oldpage=1
http://www.muslimheritage.com/topics/default.cfm?ArticleID=466
http://www.pawfal.org/index.php?page=AlJazari
http://www.shef.ac.uk/marcoms/eview/articles58/robot.html
http://www.knowledgehunter.info/wiki/Robot