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Technology and Autonomous Mechanisms in the Mediterranean: From Ancient Greece to Byzantium

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Abstract – **The paper aims at presenting technology and automation advances in the ancient Greek World, offering evidence that feedback control as a discipline dates back more than twenty five centuries.**

I. INTRODUCTION

The paper objective is to present historical evidence of achievements in science, technology and the making of automation in the ancient Greek world until the era of Byzantium and that the main driving force behind Greek science [16] - [18] has been curiosity and desire for knowledge followed by the study of nature.

When focusing on the discipline of feedback control, James Watt's Flyball Governor (1769) may be considered as one of the earliest feedback control devices of the modern era. As demands on the device grew, the flyball governor was required to work in new operating regions where it was exhibiting undesirable oscillations for unexplained reasons at that time. It was J. C. Maxwell (1868) who first used differential equations to model and explain this phenomenon, and this event marked the beginning of the introduction of mathematical rigor into the study of feedback control devices, together with the work of Routh (1877) and Lyapunov (1890) [5] - [13].

However, the discipline of feedback control has a very long history dating back over twenty centuries. Looking back, one finds that automatic feedback control devices appeared first in the work of Ktesibius (or Ctesibius) of Alexandria (circa 270 B.C.) as reported by Vitruvius (circa 25 A.D.), Heron (or Hero) of Alexandria (circa 60 A.D.) and Philon of Byzantium (circa 230 B.C.). In fact, the first feedback control device on historical record is the water clock of Ktesibius [5], [6].

Indeed, the roots of automation, automated mechanisms, and feedback control are found about 3,000 years ago, and they are centered in the ancient Greek world that developed in the Mediterranean region. A foundation is first provided by sketching the map of the Mediterranean region and the ancient Greek world in terms of science and technology and its major contributors. Details of achievements during each period are then provided followed by accomplishments in automatic control and the transition from the ancient Greek world to the Greco-Roman era and the Byzantium.

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II. CHRONOLOGICAL MAP OF SCIENCE & TECHNOLOGY

It is worth noting that there was an initial phase of imported influences in the development of ancient Greek technology that reached the Greek states from the East (Persia, Babylon and Mesopotamia) and practiced by the Greeks up until the 6th century B.C. It was at the time of Thales of Miletus (circa 585 B.C.), when a very significant change occurred. A new and exclusively Greek activity began to dominate any inherited technology, called science. In subsequent centuries, technology itself became more productive, and technological innovations surfaced through synergies between science and technology. New measuring instruments, geometrical concepts, engineering, mechanics, musical instruments, influenced important application domains like metallurgy, construction projects, architecture, military tactics and machines, among others [16] - [18].

One of the first inventions of the 5th century B.C., not widely known but very important, was the starting mechanism in ancient stadiums, built to prevent untimely starts in races, called 'hysplex' (in Greek *ύσπληξ*), shown in Figure 1. Quoting from [14, pp. 465-472], "The system consisted of two horizontal ropes stretched in front of the waist and the knees of the runners. The ends of the ropes were tied at the peaks of vertical wooden posts implanted in mechanisms near the two ends of the starting threshold. The mechanisms were controlled by the starter, who, standing at the back of the runners, could let at the appropriate moment the ropes to fall down, thus permitting all the runners to start simultaneously" [20].

In terms of chronological accomplishments and breakthroughs, the era of ancient Greek science is divided into four major periods [16], [21]: i) The pre-Socratic period from 600 B.C. to about 400 B.C. ii) 4th century B.C. (400-300) with main representatives Plato, Aristotle, the Epicureans and Stoic philosophers. iii) The Hellenistic (in Greek *Ελληνιστική*) period, 300-100 B.C. with main representatives Euclid, Archimedes, Apollonius. This has been coined as the Golden Era of science and technology. It was the period that followed the death of Alexander the Great, 323 B.C., where Alexander's successors ruled most of

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the so called Old World. During that period more direct interaction took place between the Greek and remnants of older cultures. iv) 100 B.C.–600 A.D., where Greek science was influenced by spiritual and non rational currents that were partially responsible for the rise of Christianity. It was during that period that Greek science passed later on to the Arabs and to the Latin West was epitomized, reorganized and subjected to extensive commentaries.

Mathematics as a discipline was tightly coupled with technological achievements. Mathematics was used not only as a theoretical discipline but also as a tool; mathematics was behind a wide range of applications and the means to engineering designs. It is no coincidence that Thales, Pythagoras, Euclid, Archimedes, and Apollonius were mathematicians at first. Archimedes was the first one to utilize mathematics in a completely mature fashion for the treatment of a physical problem. Furthermore, the tradition of formal mechanical treatises, including theoretical and applied mechanics, as distinct domains from the almost completely theoretical mechanics of Archimedes continued in the 3rd century B.C. by Ktesibius whose work, although lost, is known only through the references of Vitruvius and by Philon of Byzantium. The most comprehensive of the extant mechanical treatises is that of Heron of Alexandria, a recognized mathematician and an excellent mechanic.

III. Ancient Greek Science & Technology

There were three main institutions in the ancient Greek world that contributed to science and technology: Plato's Academy, Aristotle's Lyceum, and The Library of Alexandria. Plato's Academy and Aristotle's Lyceum were focusing more on science; they were very influential institutions operating as Schools or Universities charging tuition, and financially self sustained. The museum and Library of Alexandria established around 300 B.C. exerted long lasting influence over many centuries; it was operating more like a research laboratory than a University and it was financially dependent on the rulers of Egypt [16] - [18], [22].

Among the earliest contributors to ancient Greek science and technology were the members of the Miletian School and particularly Thales of Miletus. The main contributions of the Miletian School were considered to be the distinction between the natural and the supernatural and the introduction of rational criticism and debate. Achievements of the period between Thales and Aristotle were the advances in factual knowledge (anatomy, zoology), the problem formulation (Aristotle's biological problems of reproduction and heredity), the application of mathematics to the understanding of natural phenomena (Pythagoreans and Plato) and the notion of undertaking empirical research (Hippocrates and Aristotle).

Thales is mostly known as the first person who studied geometric objects, circles, lines, triangles. He was the first who thought of the angle as a separate, distinct and autonomous mathematical entity, and he established it as the fourth geometric element complementing the other three, length, surface, volume. Thales' contribution to science is that his work never referred to calculations and results obtained for a specific example or case study (as the Egyptians and the Babylonians did), but rather, it was very general; he is considered to be the first theoretician in the field of mathematics with theorem proving abilities.

Focusing on mechanisms, technological innovation was either related to invention of machines functioning using external means such as, animal or wind power, or related to invention of automatic devices moving by themselves without requiring any human force; such were the inventions of Heron of Alexandria as detailed below.

One of the oldest mechanisms chronicled around 580 B.C., depicting an oil press operated by the weight of stones was found by Fouque in 1879 in Therassia, a small island opposite Thera (Santorini). The only evidence found on an ancient Greek design is on exhibit at the British museum in London.

It is documented that the first major breakthrough contribution to autonomous mechanisms occurred during the era of Pythagoras (who was Thales' student for a few years). It is attributed to the Pythagoreans and in particular to Archytas from the city of Tarantas (in south Italy), known as Archytas the Tarantine (also referred to as Leonardo da Vinci of the ancient world). Archytas was not only the inventor of the number 'one', 1 (the father of 1) in number theory, but he also was the first engineer. By applying a series of geometric notions and observations to the study of structures, links and joints, he created Mechanics (in Greek *Μηχανική*)! Not only he was drawing mechanisms, he was also building them. As such, in 425 B.C. he created the first Unmanned Aerial Vehicle of all times by building a mechanical bird, a pigeon that could fly by moving its wings getting energy from a mechanism in its stomach. This flying machine flew about 200 meters. However, once all energy was used, the pigeon fell, landed, on earth and could not fly, take off, again.

The introduction of catapults changed the art of war. The first catapults appeared in Syracuse, during the time of the tyrant Dionysius the Elder (Dionysius of Syracuse, 430 – 367 B.C.), who created the first ever scientific research center [2]. The widest and most well known use of catapults occurred during the reign of Philip of Macedonia and his son Alexander the Great who perfected the use of catapults to gain advantage in battles against their enemies. Perfection was the elaboration of mathematical formulas that related the size of the catapults' components to the weight of the projectiles or the size of the bolts that were about to shoot by the Alexandrian mechanics [14, pp. 545-548]. Figure 2 illustrates two types of catapult that subverted martial tactics and dominated for many centuries the battlefield; Figure 3 depicts reproduced designs by N. Orfanoudakis of other types of catapults; a catapult used to throw 'Greek fire' and the theoretical design of a portable mechanism to throw 'Greek fire', composed of pipes coupled with a tormentum serving as a power source. Similar mechanisms are shown in Figure 4.

Several inventions are attributed to Archimedes, who, according to Drachmann, was "…the greatest mathematical and engineering genius of ancient times" [14], [23], [24]. He was perhaps the first to use mathematics to solve physical problems. Figure 5 shows Leonardo da Vinci's drawing for the 'architronito', the steam gun invented by Archimedes and its modern reproduction by J. G. Sakas in 1981 [27], and Figure 6 illustrates the endless screw. Other inventions by Archimedes include cranes and solar mirrors. The steam gun created the foundation for the theory of hydrodynamics. Information about the steam gun is due to the Italian Petrarca (1304-1374 A.D.), but it was Leonardo da Vinci who explained its operation and stated that it could through a bullet weighted 1 *τάλαντο* about 1,100 meters away.

Another invention attributed to Archimedes is the water clock, shown in Figure 7 that stood tall more than 4 meters (although there are researchers claiming that it was invented by Heron or Philon, and others). As stated in [24], there are three sources from Vitruvius, Pappos the Alexandrian and an Arabic document that provide evidence regarding this invention by Archimedes, as reproduced by the German scientists Wiedemann and Hauser. It is important to state that it looks like there was progress in this area before Ktesibius invented his water clock (see below) without knowing exactly when it started. But since Archimedes (287-212 B.C.) and Ktesibius (285-222 B.C.) lived almost at the same time, it may be that either Ktesibius improved Archimedes' clock, or the two invented it independently of each other.

The School of Alexandria

During the golden era of the School of Alexandria [22], Greek thought evolved towards what Newton called Natural Philosophy. This turn of Greek thought culminates in the search for observation, measurements, design and construction. The School of Alexandria is directly linked with three Greek engineers of the Hellenistic world: Ktesibius, Philon of Byzantine and Heron of Alexandria who lived in the second century B.C. through the first century A.D. Their contributions influenced western science and technology and their writings were reprinted until the 16th century A.D.

Ktesibius (circa 270 B.C.) was a Greek physicist and inventor, the first great figure of the ancient engineering tradition of the School of Alexandria. The discovery of the elasticity of air is attributed to him, as is the invention of several devices using compressed air, including force pumps and an air powered catapult. His most famous invention, however, was an improvement of the clepsydra (in Greek *κλεψύδρα*), or water clock, in which water dripping at a constant rate raised a float that held a pointer to mark time (the passage of hours). Another notable invention was a 'hydraulis', or water organ, in which air was forced through the organ pipes by the weight of water rather than by falling lead weights [18] - [20]. Unfortunately, Ktesibius' writings have not survived, and his inventions are known only from references by Vitruvius [19] and Heron of Alexandria. Figures 8 to 10 illustrate inventions made by Ktesibius. Ktesibius' water clock, shown in Figure 9, incorporated a feedback mechanism that used a floating device as both a sensor and actuator that kept the water level approximately constant and ensured constant flow of water and so accurate time keeping [5], [6]. This device was so successful that it was still used in Baghdad in 1200 A.D. when the Mongols conquered the city!

Philon of Byzantium (circa 230 B.C.) authored several books (most of which have survived) on levers, water clocks, pneumatic mechanisms and military machines, among others. His major contribution relates to the subject of spur gears (in Greek *οδοντοτοί τροχοί*). The transfer of mechanical power and the multiplying or dividing effect of circular motion machines are based on such gears. Philon's treatise *Pneumatica* is addressing key physical properties of liquids and gases supported by a plethora of experiments. He also had advanced knowledge of metallurgy. Philon explained thoroughly Ktesibius' contention regarding the replacement of animal fibers with thermally treated metal leaves. In essence, Philon advanced further the Alexandrian School's developments in automatic mechanisms started by Ktesibius. The Arabic translation of Philon's *Pneumatica* is a thesaurus of such automatic devices based on properties of air, liquids, fire, floaters and gears. They offer a rich foundation for a new technology, automation. Although he did not complete his work, he laid the groundwork for the European technological developments for the next 1500 years [18].

Eight hundred years of tradition in ancient Greek science and technology culminated with the enormous work of Heron who was a scientist of great breadth. Heron of Alexandria (circa 60 A.D.) taught at the museum of Alexandria and presented in his books

About Pneumatica and *About Automation* (in Greek *Αυτοματοποιητική*) the up until then known knowledge of automation technologies. Among his surviving writings, his book on automation according to historians, lays the foundation of modern automatic control and it is the oldest known document that describes mechanical automatic systems capable of performing programmed movements. [18], [20], [25]. *Αυτοματοποιητική* refers to automatic machines that operate and move without human intervention by capitalizing on properties of steam, liquid and gaseous matter, and involve complex mechanical systems and ingenious programming of movements. Every mechanical device was broken down to its constituent components which, in turn, refer to levers with a basic geometric interpretation. Therefore, a methodology was pursued although the ultimate objective of Heron's books was applications.

Heron's two books, *About Pneumatica*, introduced steam as a major driving force. He did not invent Watt's steam engine, but he presented basic notions such as the lifting and driving force of steam as well as its properties under compression and expansion. These two books are the oldest preserved in their original Greek manuscripts that describe applications of pneumatic and hydraulic control systems; they comprise a systematic collection of machines dating before and during his lifetime. These machines moved with water, air or steam pressure, produced sounds and were intended to decorate public places and to amaze or serve the practical needs of the spectators.

Although in his books he describes a menagerie of mechanical devices, or 'toys' like singing birds, puppets, coin operated machines, a fire engine, and a water organ, his most famous invention is the first steam powered engine, of special significance to the science of automation because he presented automatic means necessary to control steam supply. The device consists of a sphere mounted on a boiler and supported by an axial shaft with two canted nozzles that produce a rotary motion as steam escapes (Greek word *ατμοστρόβιλος*); it constitutes a revolutionary entry into the field of today's automatic control.

Among Heron's inventions are the 'automatic theaters', capable of conducting an entire theatrical performance with automatic portals, changing automatically the stage props, and moving puppets that performed a myth. For these mechanical automata, Heron wrote "A prop is placed on a pylon depicting a theatrical scene with portals that open and close automatically. Therefore, it allows several scenes of a play to be enacted in sequence and the puppets are able to move, act, and speak or produce sounds like live characters. In addition, fires are lit automatically and new puppets appear on the stage until the end of the story".

Heron's book *The Belopoeica* (Engines of War) purports to be based on a work by Ktesibius. His three books on Mechanics (in Greek *Μηχανική*) survived in a somewhat altered Arabic translation. Mechanics is closely based on the work of Archimedes, presenting a wide range of engineering principles, including a theory of motion, a theory of balance, methods of lifting and transporting heavy objects with mechanical devices, and how to calculate the center of gravity for various simple shapes. Both books include Heron's solution to the problem of two mean proportionals, two quantities, x and y that satisfy $a/x = x/y = y/b$, with a, b known. This may be used to solve the problem of constructing a cube with double the volume of a given one.

A catalogue of 60 mechanical devices is attributed to Heron, not mythical but historical and indeed functional, as proven by their modern reproductions. The function of his devices was based on scientific observations of nature. But unlike pure science that involves theoretical understanding of the environment but often lacks immediate implementation, his observations were applied science brought to use. Heron himself, however, explained that some of these devices were not meant to cover any practical use but they were created only for aesthetic pleasure. Heron's devices were explored and reproduced by Romans, Arabs and Byzantines and served as the link that united the Ancient Greek and the European technologies of the Renaissance that marks the beginning of the technological advances of Western Civilization. Figures 11 and 12 illustrate the oil press and a hoisting machine, two of Heron's creations. Figure 13a shows the agiasterion that which supplied an amount of holy water by throwing a coin, Figure 13b the water mechanism for the automatic opening of the gate of a temple, Figure 13c the dioptra, mechanism useful in geodesics, and Figure 13d the armonio, musical instrument operated by air pressure. Figure 14 depicts Heron's steam boiler and Figure 15 the odometer, along with modern reproductions.

Mechanical achievements during those centuries were very significant. The world had one of the greatest geniuses, Archimedes, who devised remarkable weapons to protect his native Syracuse from the Roman invasion and applied his powerful mind to such basic mechanical devices as the screw, the pulley, and the lever. Alexandrian engineers, such as Ktesibius and Heron, invented a wealth of ingenious mechanical contrivances including pumps, wind and hydraulic organs, compressed air engines, and screw cutting machines. They also devised toys and automata that may be regarded as the first successful steam turbine.

Little practical use was found for these inventions, but the Alexandrian school marks an important transition from very simple mechanisms to the more complex devices that properly deserve to be considered machines. In a sense, the School of Alexandria provided a starting point for modern mechanical practice.

IV. Greco-Roman Period & Transition to Byzantium

The Roman Empire became the dominant force in the greater Mediterranean region starting at 100 B.C. The Romans were responsible, through the application and development of available machines, for an important technological transformation: the widespread introduction of rotary motion. This was exemplified in the use of the treadmill for powering cranes and other heavy lifting operations, the introduction of rotary water raising devices for irrigation works (a scoop wheel powered by a treadmill), and the development of the waterwheel as a prime mover. Vitruvius, a Roman engineer gave an account of watermills, and by the end of the Roman era many were in operation.

The Roman Empire was split in two parts around 350 A.D. with Rome being the capital of the Western part and Byzantium, later called Constantinople (today's Istanbul), the capital of the Eastern Roman Empire. The eastern Roman Empire also called Byzantine Empire became distinctly Greek as opposed to its western Roman counterpart. The level of knowledge declined much more rapidly in the Roman west than in the Greek east. Inventions in Byzantium derive from Heron's era as shown in Figure 19 that depicts mechanical animals and birds of the Byzantine throne.

In the West, what survived was mostly contained in handbooks as collections of known facts. Notable examples are Pliny's Natural History (75 A.D.), Aulus Gellius Attic Nights (2nd century A.D.), Slinus' Collection of Remarkable Facts (3rd or 4th century A.D.).

In the East, by contrast, much more of the Greek science was preserved. The tradition of scholarship kept knowledge alive from the ancient scientific texts (through scholarly discussions and the publication of commentaries in addition to original texts) even when the scholarly commentators themselves did not attempt to engage in original scientific research on their own account. Much of what is known today about Greek science is due to this tradition.

By the year 600 A.D. preliminary efforts had already been made to turn part of the Greek corpus of scientific learning into Latin in the West and into Syrian in the East. Greek science was converted first into the Arabic tongue in the 9th and 10th centuries and then once again from Arabic and Greek into Latin in the 12th and 13th centuries. Although the Greek corpus received major additions and modifications at the hands of Arab and Latin authors, it was still essentially the Greek learning that made its way to the Latin west.

After the fall of Alexandria to the Arabs (642 A.D.), knowledge of medicine, biology, astronomy and mathematics spread through the Arab world and from about the middle of the 9th century, the Arabs produced scholars like the astronomer and geometer Thabit ben Qurra and the polymath Al Kindi [18], [26].

V. Discussion and Concluding Remarks

The central objective of this study was to provide justifications and evidence related to technology and autonomous mechanisms in the Mediterranean region and the ancient Greek world. Indeed, it has been shown that the Mediterranean region was the hub from where the foundations of modern western science and technology were laid.

The foundations were very strong based not only on ingenious solutions to specific problems but also drawing from first principles that govern natural phenomena and from powerful mathematical concepts also developed in the same geographical area during the same time frame.

It should not be overlooked that this paper touched only upon mechanisms as mostly related to the discipline of (feedback) control, without even making an attempt to state accomplishments is other areas. However, there is documented evidence and proof of major inventions in areas like Architecture, Metallurgy, Marine Engineering and ship building, Hydraulics and hydraulic projects, construction engineering, music instruments, everyday life, mechanisms using series of bolts and spur gears, to name a few [2], [27].

Therefore, as it has been demonstrated, ancient Greek technology was rather complex but also very dominant and did not lack contributions to society. It is very misleading to claim that Greeks contributed only to philosophy, arts and sciences excluding technology. Perhaps this erroneous statement was partially because of Plato, his fight against Archytas the Tarantine as well as his passion for science and not technology with the meaning of learning how to do or fix something [27].

It is also true that most of such inventions originated in areas away from Athens, but it is the Athenian Philosophers who eventually recognized and supported the need for technology in parallel and in addition to philosophy, arts and sciences. More details may be found in [28].

As evidence and references continue to mount in quantity, it will not be before long that there is a complete picture of what was accomplished and invented during that time. Regardless, those were exciting times indeed!

Acknowledgements: We acknowledge the sources of the schematics and pictures used in this article. They include [2], [5], [14], [23], [24], [27].

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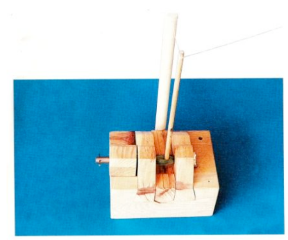

Figure 1. The hysplex, invented in the 5th century B.C.

Figure 2. Catapults used by Philip and Alexander the Great.

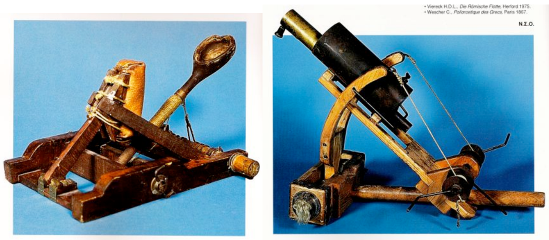

Figure 3. Types of battlefield catapults taken from [27].

Figure 4. Modern reproductions of different catapults and crossbows taken from [27].

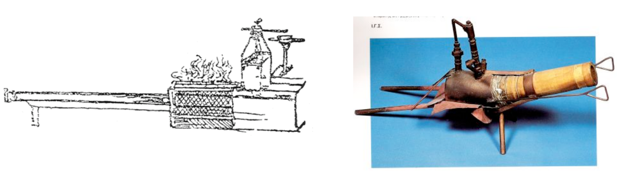

Figure 5. The steam gun invented by Archimedes and its reproduction.

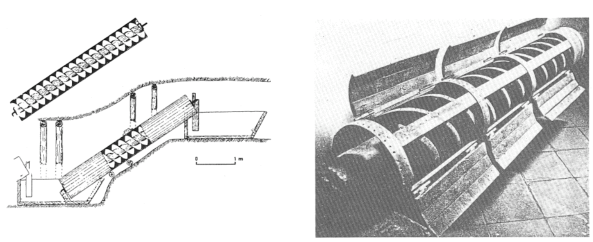

Figure 6. Representation of the endless screw and its modern reconstruction in Liverpool in 1930.

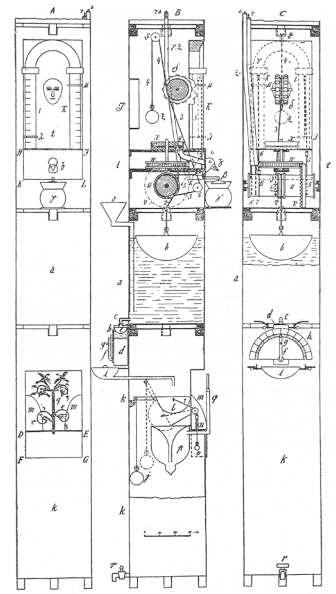

Figure 7. Drawing of the water clock of Archimedes. The façade (A), the cross section (B) and the back view (C).

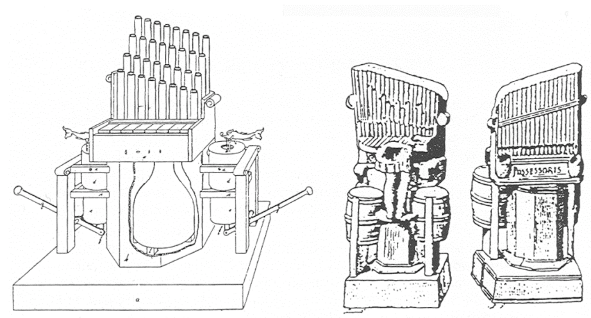

Figure 8. The water musical instrument of Ktesibius, and rare terracotta model.

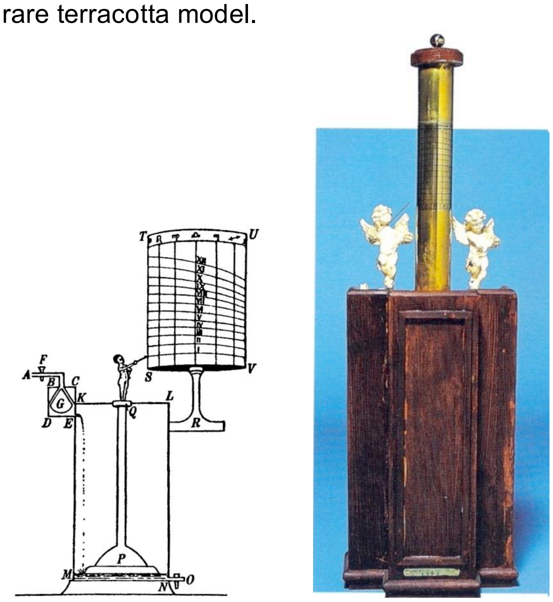

Figure 9. The water clock of Ktesibius and modern reproduction.

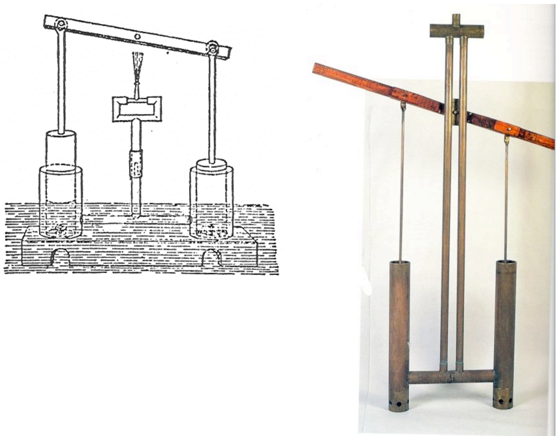

Figure 10. The force pump of Ktesibius and modern reproduction.

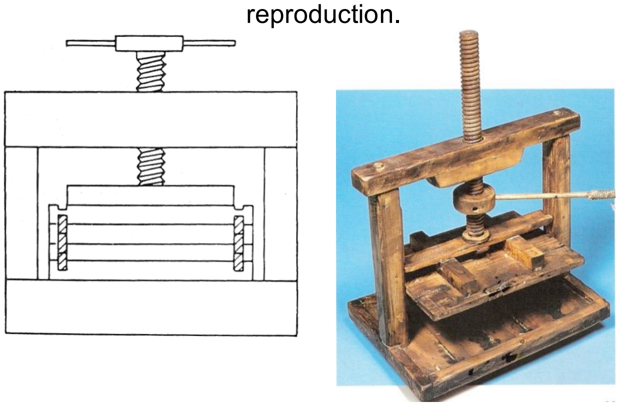

Figure 11. Representation of the oil press and modern reproduction.

Figure 12. The monokolos hoisting machine.

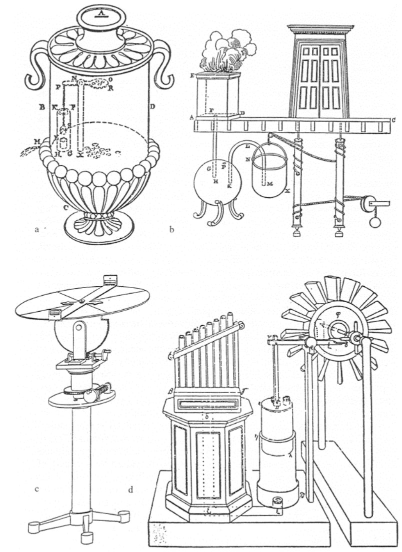

Figure 13. Four inventions by Heron.

Figure 14. Representations of the steam boiler from Heron's writings and physical reconstruction of the device.

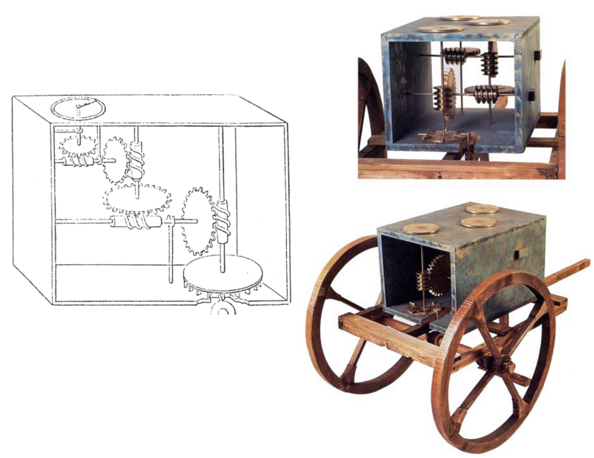

Figure 15. Heron's odometer and reconstructions of the odometer by Woodcraft.