The Holistic Documentation of Movable Cultural Heritage Objects - The Case of the Antikythera Mechanism

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Abstract. The Antikythera Mechanism is the oldest extant complex geared device, and an amazing example of an early analogue computer. It was built approximately 2150 years ago. The device was operated manually by a user, who would set a date on a dial. All necessary calculations were made using a set of gears (at least 39), while the results were displayed on several scientific scales. The Mechanism was used to calculate the diurnal and annual motion of the Sun, the Moon and probably the planets among the stars. It implemented the astronomical knowledge of ancient Greeks about the motion of these celestial bodies with astonishing accuracy, taking into account the anomalous orbit of the Moon using a system of eccentric gears. It could also predict eclipses of the Sun and the Moon from the Saros period, which was found in one of its scales. It calculated the dates of the major crown games that took place in ancient Greece (e.g. the Olympic Games). Finally, it was accompanied by an extended User's Manual. More than 20 references to astronomical mechanisms can be found in classical literature from 50 BC to 500 AD. In this study, the first approach for a holistic documentation of the Antikythera Mechanism is presented.

Keywords: Cultural Heritage · Holistic documentation · Antikythera Mechanism · Gears · Ancient Astronomy · Ancient Technology

1 Introduction

The Antikythera Mechanism is a highly complex object, and since it was found in 1900 has been the subject of many extensive studies. It is one of the oldest extant geared devices and was an astronomical "computer" used for the calculation of the diurnal and annual motion of the Sun, the Moon and potentially the planets, as well as for calculating the dates of the Olympic Games. From the extensive studies [1–4], we have a huge amount of data and as such this is an excellent case study for proposing an approach for the holistic documentation of cultural heritage objects. This paper is made up of two constituent parts, the first outlines an approach for how the Mechanism can be holistically documented

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within a conceptual data model, and the second outlines some of the data that is necessary to be collected and recorded in order to holistically document the asset. Both of these sections have data representational of what is available, from the physical object and the relevant contextual information (modern, ancient, astronomical, geographical). An integral part of this being classed as a success story comes from ensuring that both the digitization process (i.e. the use of x-ray tomography and Polynomial Texture Mapping (PTM) Dome technology) and the documentation process, including how the data is represented and mapped in a digital format, are done to a high quality by engaging with the complexity of all of these factors.

2 Identifying Necessary Data for the Holistic Documentation of Movable Archaeological Findings

Cultural Heritage (CH) objects are distinguished between tangible and intangible as well as movable or immovable. One of the most iconic and complicated museum object is the Antikythera Mechanism. The Mechanism proves that the Greek engineers of the Hellenistic period were far more advanced in the design and manufacture of geared devices than the surviving written sources imply.

The digital holistic documentation of movable objects, like the Antikythera Mechanism must include: all possible data regarding the physical object, including the 3D geometry, the materials of its construction, the ancient context including intangible elements such as, its purpose, utility, handling and operation, its geographical and chronological origin and the modern excavation and analysis data. Based on the information gathered, the identification of the scientific and technological knowledge necessary for the design and construction of such a complex device should be recorded. Simultaneously, a review and documentation of the existing knowledge regarding the mechanism during the period of its construction should be completed. Furthermore, accurate digital and physical representations of the original discovery must be created, as well as, the complete reconstructed functional copies of the object.

In the following paragraphs a representation of all the data necessary for a holistic documentation of the Mechanism are presented. The more detailed explanation of this data and the subsequent discoveries regarding the Mechanism will be presented in Sect. 3. These data are available in digital form and can be easily introduced into an integrated digital environment with corresponding interfaces, so as to create a digital holistic recording of the Mechanism.

A conceptual model of data for the holistic documentation of the Antikythera Mechanism was created, dividing up into the categories of different types of data needed in order to holistically record a CH object. The initial stages of the model, from "*Tangible*" through to "*Mechanism*" follow the general taxonomic system under construction in the *MNEMOSYNE* project [30], and categorises the Mechanism within the classes of "*Movable*", "*Instruments and Manufacture*", "*Astronomy*" and "*Mechanism*" which indicates the type of the object (Fig. 1). From this point we start to represent the data needed to record each tangible facet ("*Elements*") of the physical object and its intangible information ("*Context*") – both historical and modern - which will be explained further in *Sect.* 3.

Within this conceptualization, the data is separated out into contextual information, which includes information relating to the "*Ancient*" and "*Modern*" contexts – including, its production, use, deposition, excavation and post excavation studies, as well as relating information regarding the "*Geographical*" and "*Astronomical*" data, which provides important explanations and knowledge, that enhance our understanding regarding the need for and the use of such an object. The other main category is "*Fragments*", which refers to the information related to the physical object. It is important to highlight, that the Antikythera Mechanism is a particularly complicated object; many elements of the structure have been proposed but no physical remnants have been found – for example some of the gears, much of the frame etc. Additionally, the mechanism has been found in a calcified fragmentary form with large portions remaining undiscovered, thus, many of the links between elements have been proposed through extensive studies using the application of high level technologies such as x-ray tomography and model building.

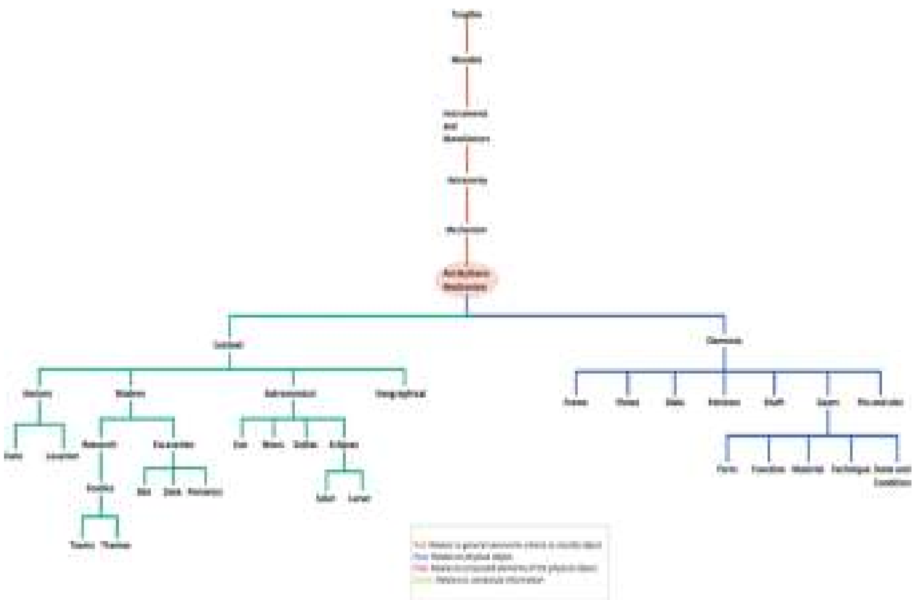

Fig. 1. Conceptualisation of "holistic" documentation regarding the Antikythera Mechanism.

The collected information was carefully consolidated to support contextual knowledge redistribution and preventive conservation of historic assets through heritage significance awareness. Holistic recording of the context of the mechanism revealed a series of important categories (Fig. 2). The categories of data types are connected by solid lines, whilst values and object related data are represented by dotted lines, to differentiate between the different aspects of the model (the categories versus the value based data). Firstly, the modern context including the excavation, related objects from the wreck, conservation, storage and related research projects related to the mechanism. Stages of data acquisition and processing leading to the production of digital and physical reconstructions of the mechanism are shown in Fig. 7. The figure highlights the sheer quantity and variety of data (and data formats) involved in the digitization process of documenting such a complex object; from cutting-edge technologies of x-ray tomography, through to the necessary manipulation of the multi-layered data sets handled within sufficiently detailed point clouds. Secondly, the ancient context, including the manufacture, use and deposition. Thirdly, the astronomical context, revolving around lunar and solar occurrences and astronomical knowledge that was woven into the manufacture and use of the object. Finally, the geographical context, which is also integral for understanding the ancient context of the object. The mechanism was calibrated to work optimally between 33.3–37.0° latitude, which falls in the mid-Mediterranean range, and is consistent with Rhodes; a possible manufacturing site [16]. Recording and studying related information from a broad range of areas (from physical objects from the same context, to astronomical research), have been integral for piecing together the knowledge regarding and the story of the object, so recording all of this related information within the same system is extremely important. Figure 2 shows the overall taxonomy of the context (i.e., the intangible information). Figures 3, 4, 5 and 6 present the detailed taxonomy of the branches associated with the context, which show the various data and metadata individually related to the discovery, research and history of the asset, as well as its astronomical uses and geographical information.

Figure 8 shows the overall taxonomy of the elements (i.e. the tangible information) that compose the mechanism. Figures 9, 10, 11 and 12 present the detailed taxonomy of the branches associated with these elements, which show the various data and metadata individually related to the frame, dials, pointers, shafts and gears. The elements in blue have been physically found (or identified within tomography images) and the elements in pink have been proposed by the various research teams, but have not been physically found.

The main criteria that are modelled here, or are expected to be modelled within the next period are:

- Form – referring to the physical form of the object (i.e. the number of teeth on the gears),
- Material – all data relating to the material and chemical composition of the object, considering the impact of the seawater and the conservation process on each element.
- Function – referring to the purpose and use of the element. An additional consideration here, taking into account the complexity of the object, is how each of the elements (existing or proposed) connect together and their combined output.
- Technique – ideally this would refer to each aspect of the "technique" aspects, this is a term that can be applied as an addendum to function, as in the technique for which the elements work together to perform an action, but can also be a term to cover the methods of how each element was manufactured and the mechanism constructed.
- State/Condition – data relating to the preservation and conservation of the element.
- Location/Context – data relating to where it was found/alongside what, this maybe used to indicate which, in this case, elements connected/functioned together, as well as in which fragment they were found.

It is important to clarify that each of these criteria, whilst initially modelled independently, will be interlinked where necessary and they will be further enriched with the

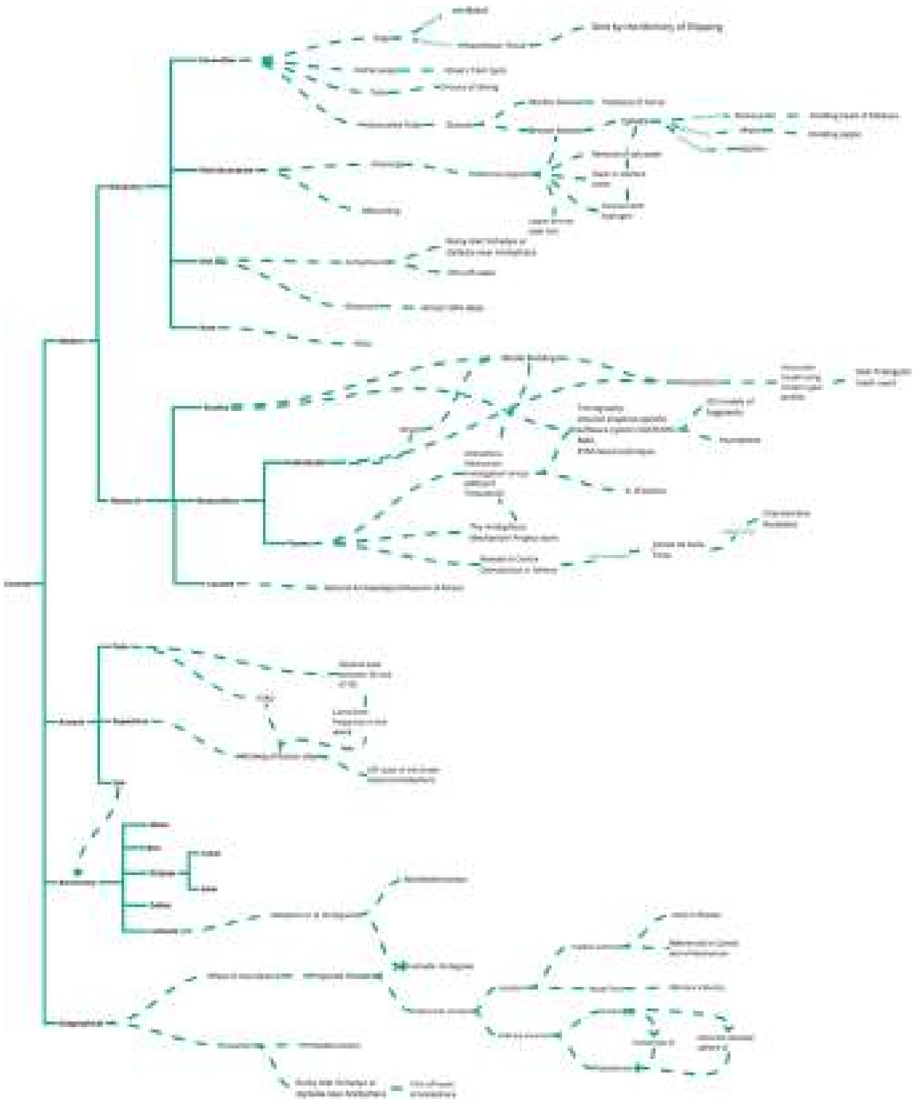

Fig. 2. Conceptualisation of data regarding the contextual information of the Antikythera Mechanism. The expansion of these branches is shown in Fig. 3, 4, 5 and 6.

contextual information. It should be highlighted that the mechanism consists of many small parts of equal importance working in synchronization.

As can be seen in the example of Antikythera Mechanism, within the category of elements, each constituent part is separated out into form type, i.e. gear, pointer, plates, dials, shaft, pin and slot mechanism and frame and this is then subdivided into the actual or proposed element, i.e. a specific gear. From this stage, the data represented is extracted from the various studies outlined throughout Sect. 3 of this paper, some of

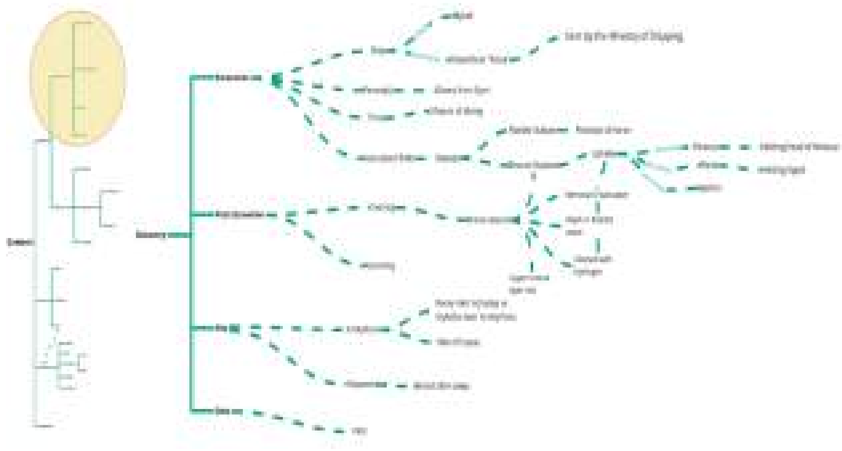

Fig. 3. Context taxonomy: "Discovery" branch.

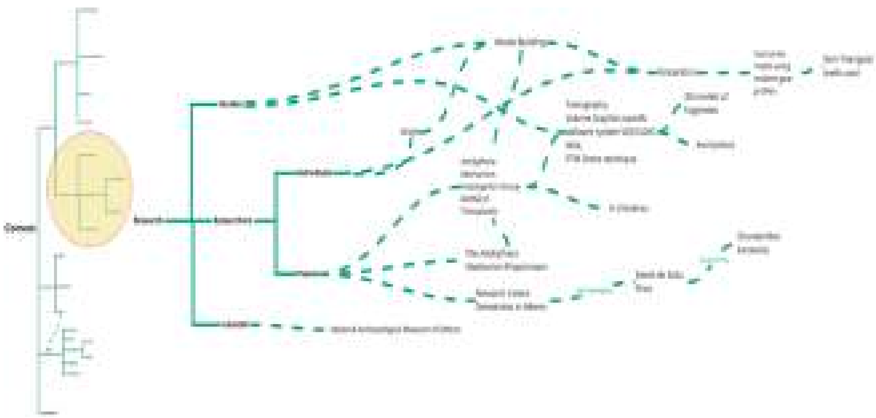

Fig. 4. Context taxonomy: "Research" branch.

which is contradictory or at least come to different conclusions, which is often the case among different study groups and technological advancement. A key example of this is the number of teeth on a gear, which have been postulated upon by a number of different researchers. However, this variable research is part of the holistic process and feeds into and supports the holistic documentation of the object.

Empirical evidence suggests that digitization concerns have overgrown technical issues of conversion and often expand to cover the management of collections, mediation and representation of cultural heritage in the digital environment, economics of digital repositories, business models, quality and sustainability of digitization initiatives etc. This type of interrelating categorizations was meant to form an all-inclusive functional data model, consistent with role-based online analytical processing (OLAP)

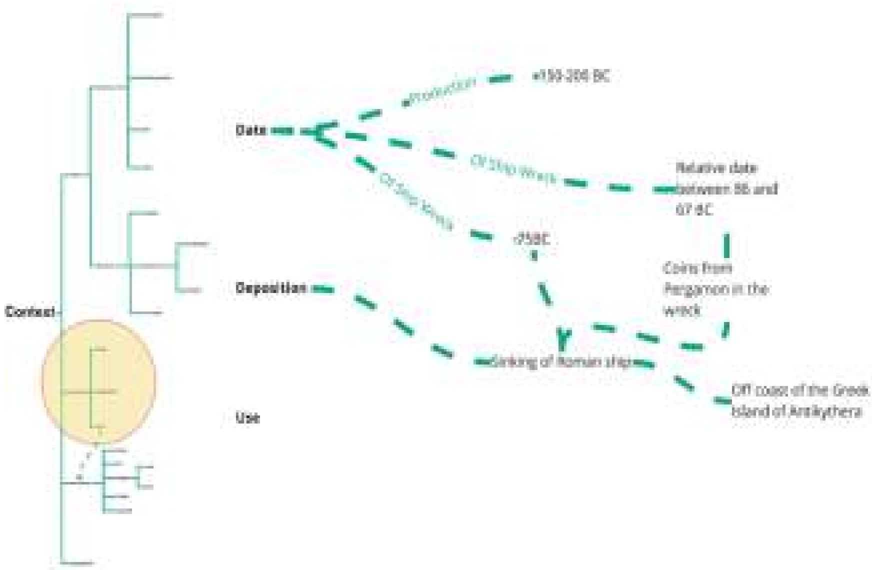

Fig. 5. Context taxonomy: "Ancient" branch.

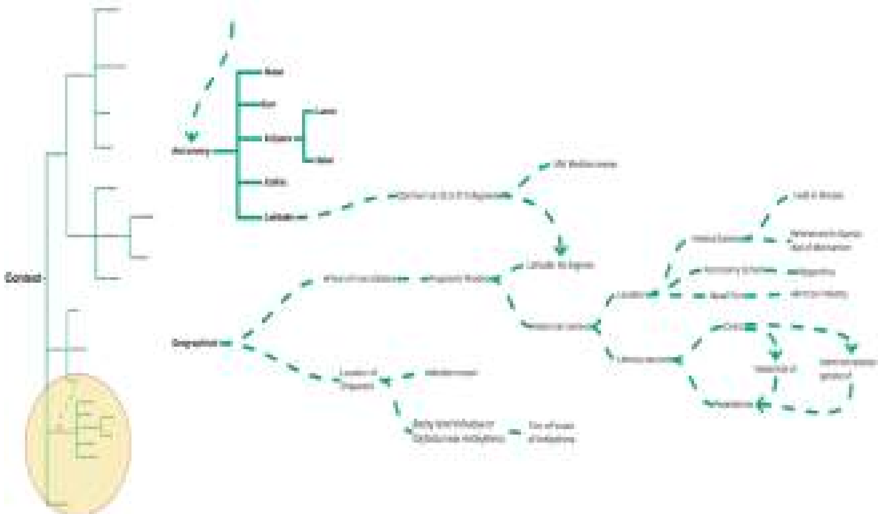

Fig. 6. Context taxonomy: "Astronomy" and "Geographical" branches.

operations. This means they could easily serve as a benchmark for integrated visualizations built in powerful dashboard design software packages that come with visual analytics capabilities; thus, enable specific users to conduct ad hoc queries (and filter on-demand), with little or no programming skill. One very interesting application is the

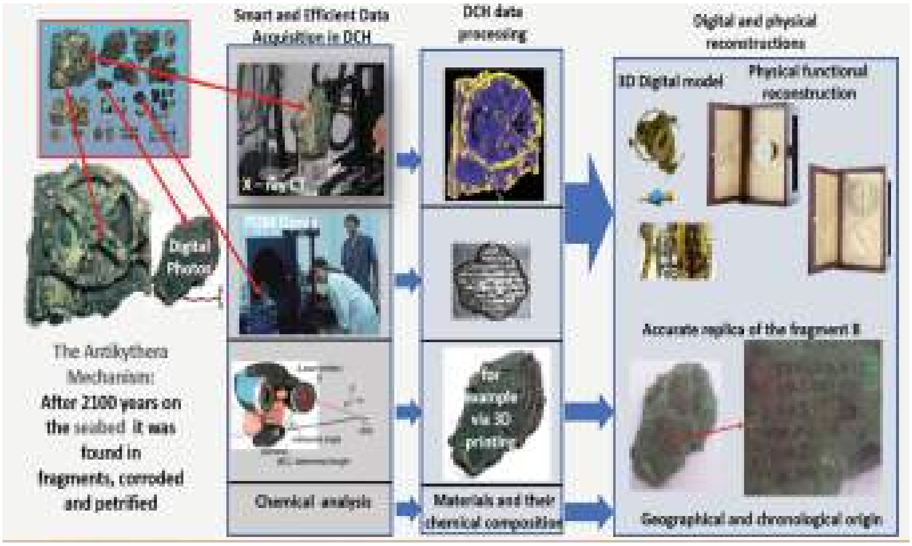

Fig. 7. Data acquisition to reconstruction workflow for the Antikythera Mechanism.

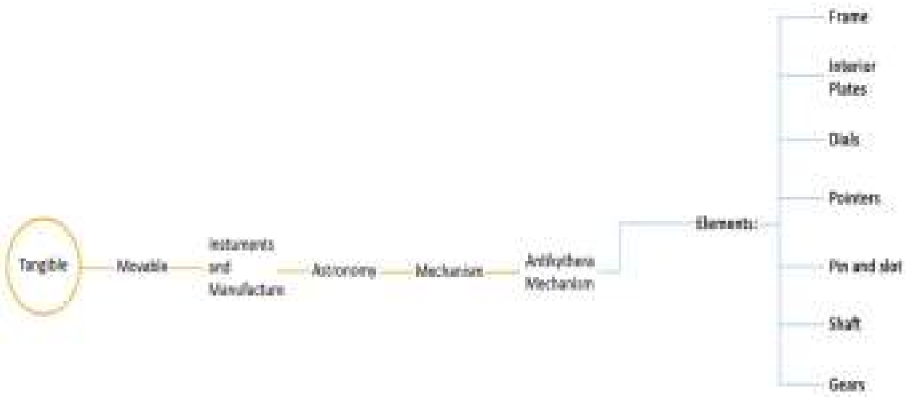

Fig. 8. Elements taxonomy branches for the Antikythera Mechanism.

ability to recursively traverse a dimension hierarchy and print-out aggregations at the actual browsed location. For example, providing grounds for an engineering specialist to select individual shafts and inspect the corresponding engaged gears (Figs. 13 and 14). As can be seen in these figures, the items listed in the hierarchy (left-hand side) are taken directly from the elements of the asset's taxonomy, which are shown on the right-hand side of Figs. 13 and 14. The selected individual shafts and their corresponding engaged gears, coloured in blue, are visually distinguishable.

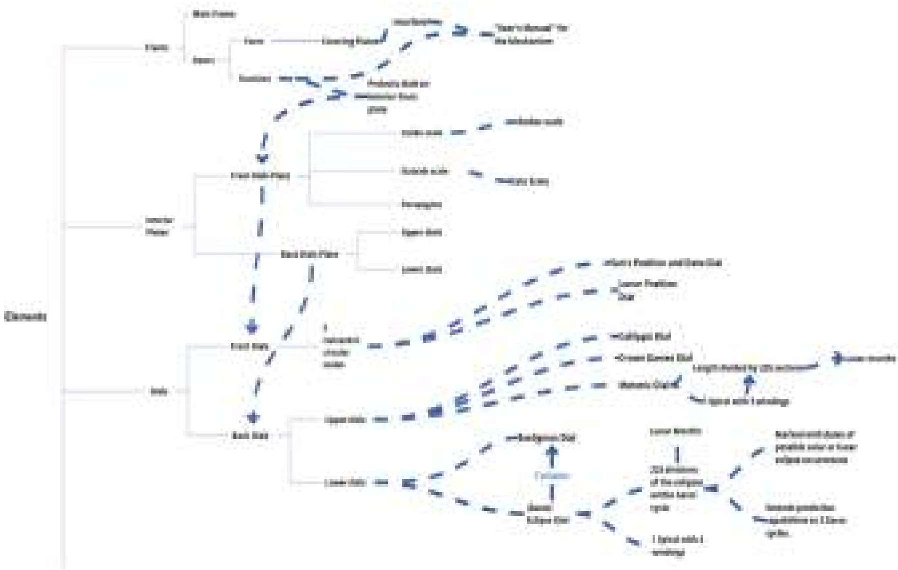

Fig. 9. Elements taxonomy: "Frame", "Plates" and "Dials" branches.

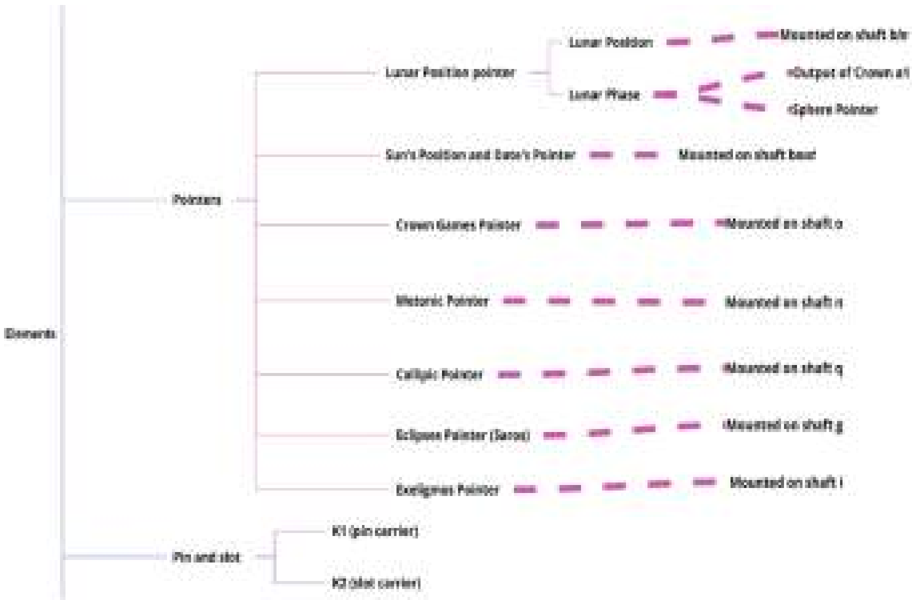

Fig. 10. Elements taxonomy: "Pointers" branch.

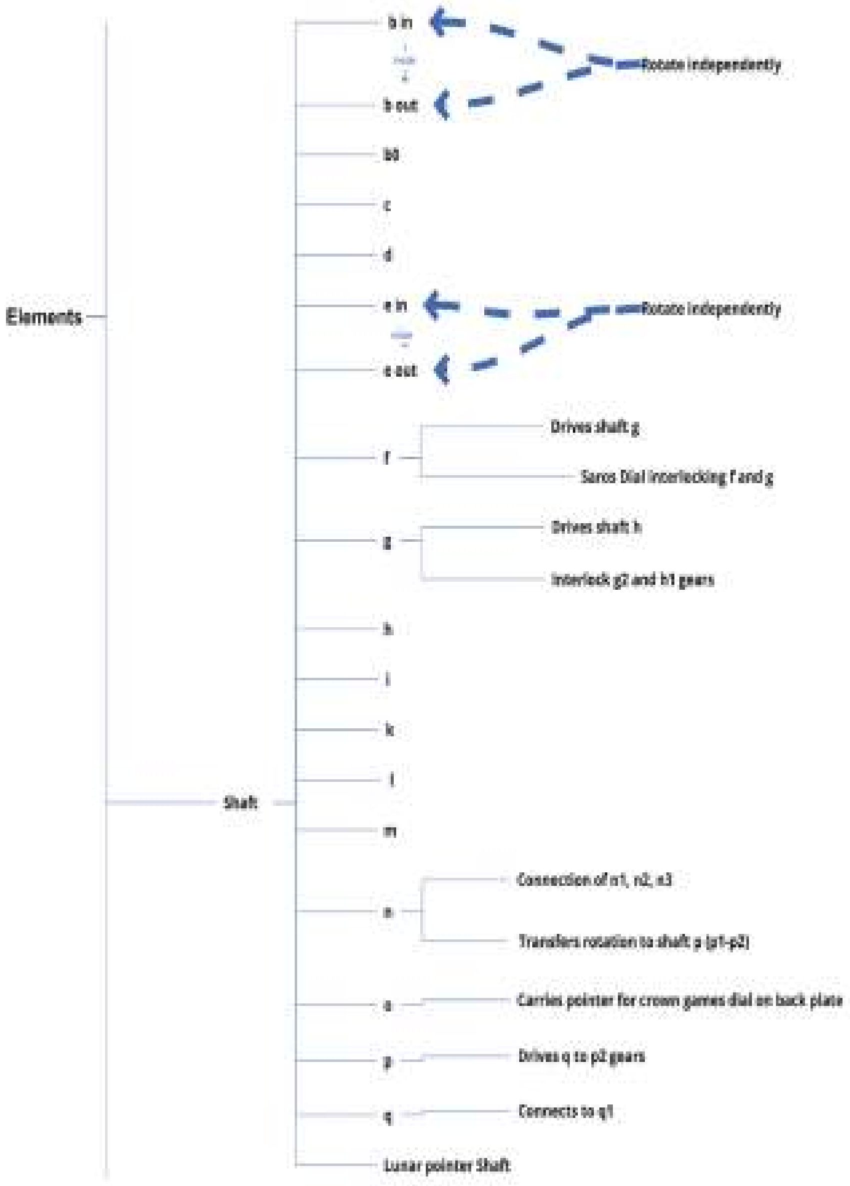

Fig. 11. Elements taxonomy: “Shafts” branch.

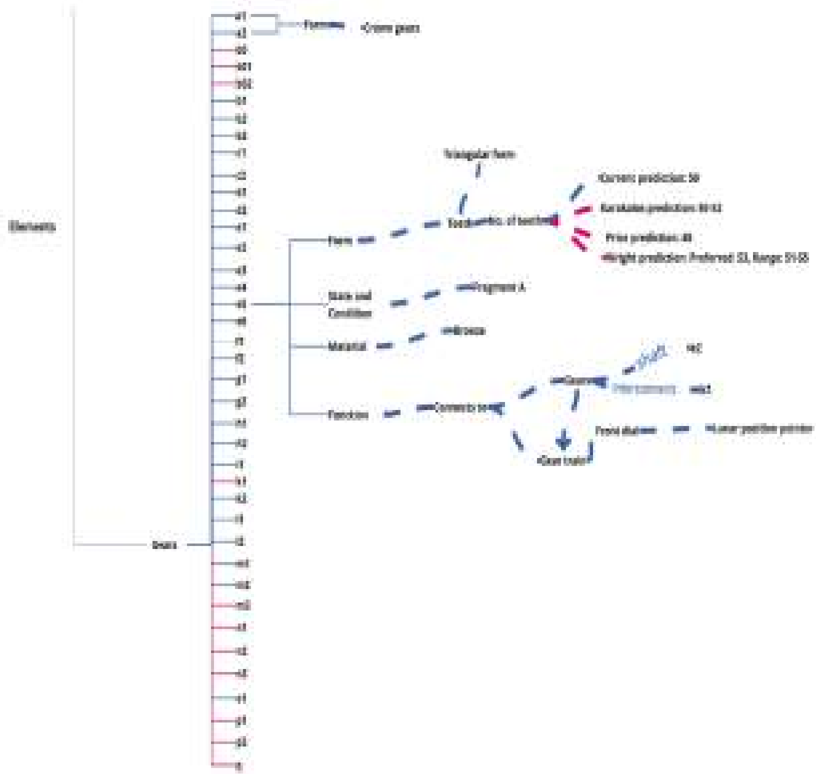

Fig. 12. Elements taxonomy: "Gears" branch.

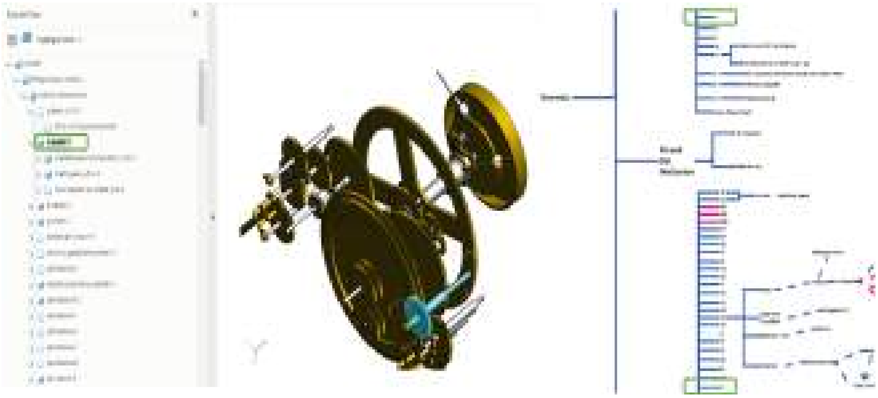

Fig. 13. Antikythera Mechanism. Shaft "i" and gear "i1".

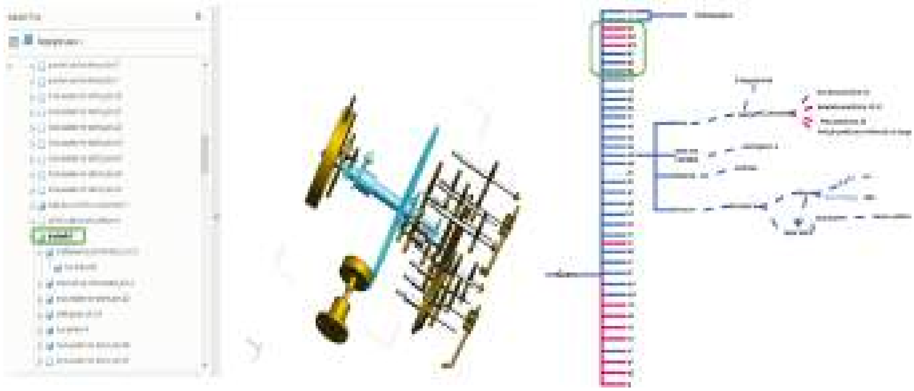

Fig. 14. Antikythera Mechanism. Shaft "b" and gears "b01", "b02", "b1", "b2", "b3".

3 The Existing Data for the Holistic Documentation of the Antikythera Mechanism

3.1 The Antikythera Shipwreck and the Discovery of the Mechanism

In 75 BC a large Roman ship sailed between the mainland of Greece and Crete. The boat sank off the shores off the small Greek Island Antikythera. The ship was loaded with works of art and other precious artifacts. Two thousand years later, during Easter in 1900 AD sponge-divers from the Greek Island of Symi, accidentally discovered the ancient shipwreck off the coast of Antikythera. The underwater excavation began at the end of November 1900 and a few months later important findings were recovered, such as the famous Antikythera Ephebe [4] (Fig. 15). Most of these findings are now exhibited at the National Archaeological Museum of Athens [4]. Coins from Pergamon were also retrieved, which gave the wreck a relative date between 86 and 67 BC [5].

Fig. 15. The Antikythera Shipwreck and the underwater excavation.

Amongst the findings, a strange bulk of material that was broken, worn and calcified, with signs of the presence of bronze was found (Fig. 16) [4]. In the first publication of the Antikythera shipwreck [6] the existence of the Mechanism was mentioned with the suggestion that it was an astronomical instrument. Through investigation, the Antikythera Mechanism, had the potential to change the knowledge we had so far on the technological skills of ancient Greeks.

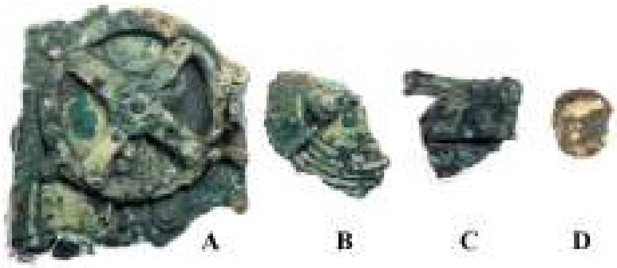

Fig. 16. The biggest fragments of the Antikythera Mechanism [4].

3.2 The Investigation of the Antikythera Mechanism

The first scholar, who studied the function of the Mechanism extensively, was Derek de Solla-Price, with the help of Charalambos Karakalos from the Research Centre Demokritos in Athens. He worked for more than 30 years and eventually published an extensive account, "Gears from the Greeks" [7]. He declared that "the Antikythera Mechanism is the oldest proof of scientific technology that survives today and completely changes our view of ancient Greek Technology".

After de Solla-Price, research was undertaken by Michael Wright and Alan Bromley. Unfortunately, Alan Bromley died in 2002. However, Michael Wright published a series of papers, where he postulated that the back dials of the Mechanism were spirals and that the upper dial was built to follow the draconic lunar month. He also elaborated on the pin and slot mechanism (see Sect. 3.2.1.1) and proved its epicyclic function [8]. Additionally, he made strides towards creating a reconstruction of the Mechanism and he produced superb bronze replicas.

In 2001, Mike Edmunds and Tony Freeth (Cardiff University), Xenophon Moussas and Yanis Bitsakis (University of Athens) and John Seiradakis (University of Thessaloniki) created the "Antikythera Mechanism Research Group". They received a grant from the Leverhulme Foundation, U.K. and the permission to undertake a new investigation from the Ministry of Culture of Greece. After the permission was granted, Eleni Magkou and Mary Zafeiropoulou (National Archaeological Museum) and Agamemnon Tselikas (Cultural Foundation of the National Bank of Greece) joined the team, which was soon supported by an international team of astronomers, archaeologists, mathematicians, physicists, chemists, computer engineers, mechanical engineers, epigraphologists and papyrologists.

In September 2005, they undertook a major new investigation of the Antikythera Mechanism, using an innovative and state of the art high power micro-focusing x-ray tomography, specially constructed by X-Tek Systems [9] (Fig. 17, left) and the Hewlett Packard, USA, PTM Dome technique [10] (Fig. 17, right). In November 2006 the results of the investigation were announced during an international conference in Athens and published in the international journal Nature [11]. This technique allowed the acquisition of three-dimensional images of the fragments of the ancient mechanism. The images were examined to reveal internal details of gearing and inscriptions that had hidden due to the preservation state of the fragments which remained underwater for more than 2000 years and the previous lack of the necessary technology to access this information.

All inscriptions are written in Greek. A new font (True type fonts) was developed at the Aristotle University of Thessaloniki, in order to reproduce the fine art letters.

Realizing the importance of the Antikythera Mechanism, one of the largest active groups of researchers was formed in the Aristotle University of Thessaloniki (AUTH) of Greece, which they have worked to produce numerous publications on the analysis and reconstruction of the mechanism [12–16].

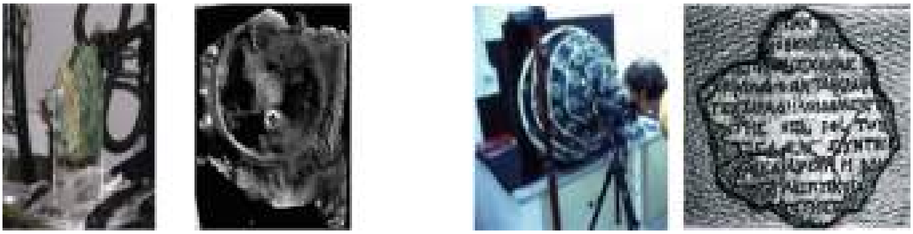

Fig. 17 X-ray tomography (left) and PTM Dome technique (right) applied for the study of the Antikythera Mechanism.

3.2.1 Investigation Results

3.2.1.1 Description of the Antikythera Mechanism [2–4, 11, 12, 14–16]

The Antikythera Mechanism is relatively small, approximately 30 cm × 20 cm × 10 cm in size, which was found in poor preservation state, consisting of 82 fragments that have been studied together to reveal the information and data that will be discussed within the following sections (Fig. 18). The largest seven fragments are named with the letters A, to G and the smallest fragments are referred to as numbers 1–75.

Construction's Materials of the Mechanism

The material used to reconstruct the various parts of the Mechanism, except for its wooden mounting box, is bronze, a copper - tin alloy. In the period from 1970 to 1974, chemical analysis was performed to determine the chemical composition of the metal alloy used in the manufacture of the Mechanism. The chemical analysis was performed by a spectroscopic method. Two small fragments of the Mechanism were studied. The chemical analysis showed that the fragments were made of bronze, with a tin content of about 5% [4]. Newer analyzes by Panagiotis Mitropoulos in 2018 revealed three alloys, the main components of which are copper, tin and lead [4]. The shares of copper tin and lead varied. It can be assumed that the individual parts of the mechanism consist of copper alloys of different composition [25].

Structural Elements

Gears

The gears found in the Antikythera Mechanism are the earliest known to resemble the shape and design of modern gears. Their triangular teeth were designed to transmit angular motion, not power. Detailed studies of the fragments of the Mechanism revealed that it had at least 39 gears, 29 of which have been identified in the largest of the calcified

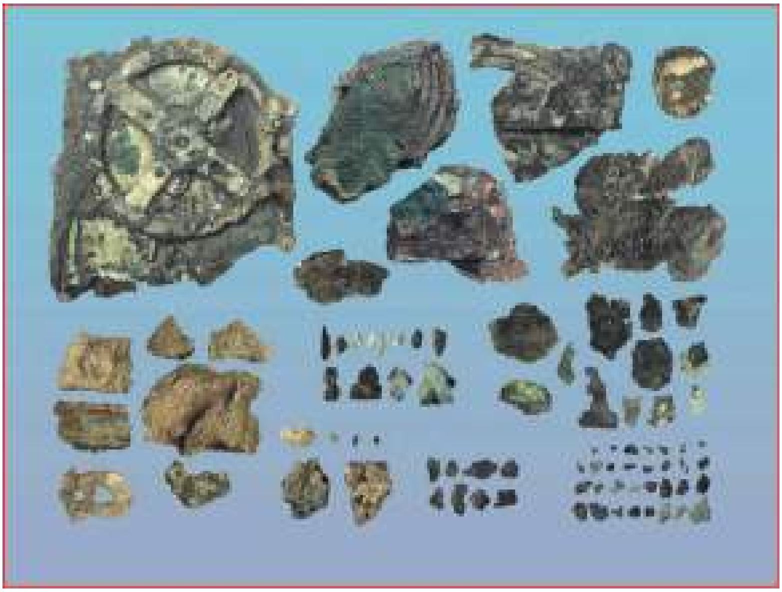

Fig. 18. Fragments of the Antikythera Mechanism from the National Archaeological Museum of Athens.

fragments - 28 in Fragment A and 1 in Fragment C. The existence of ten more gears has been determined taking into account astronomical calculations [11, 12, 20, 21]. A functional diagram of the gear trains is presented in Fig. 19. The gear pairs are displayed with the driving gear first (to the left), except for the triple where gear b_2 drives the two other gears, c_1 and l_1.

The Antikythera Mechanism incorporated also 2 crown gears as well as 19 shafts and axles with complex geometry. Two pairs of them are concentric, which means that one of the two shafts passes through the other. The two shafts are rotating independently. Moreover, there is an axis, which has two eccentric cylindrical bearing points for two gears. At various locations, mainly inside the Mechanism, there were also various components that supported the shafts and other parts of the device to make the construction robust and functional.

Pin-and-Slot Mechanism

In the pin-and-slot mechanism (Fig. 20), the axial distance of the rotation's axis of the two gears is to approximately 1.1 mm. The lower gear has a pin that engages with a slot on the upper gear, forcing it to rotate. The epicyclical movement of the upper gear tracked the motion of the Moon in the sky with great accuracy [18, 19].

Dials and Inscriptions

The Antikythera Mechanism was a complicated instrument. By using x-ray microfocusing tomography, inscriptions that have not been read for more than 2000 years were revealed. Approximately 3500 letters and symbols have been deciphered so far.

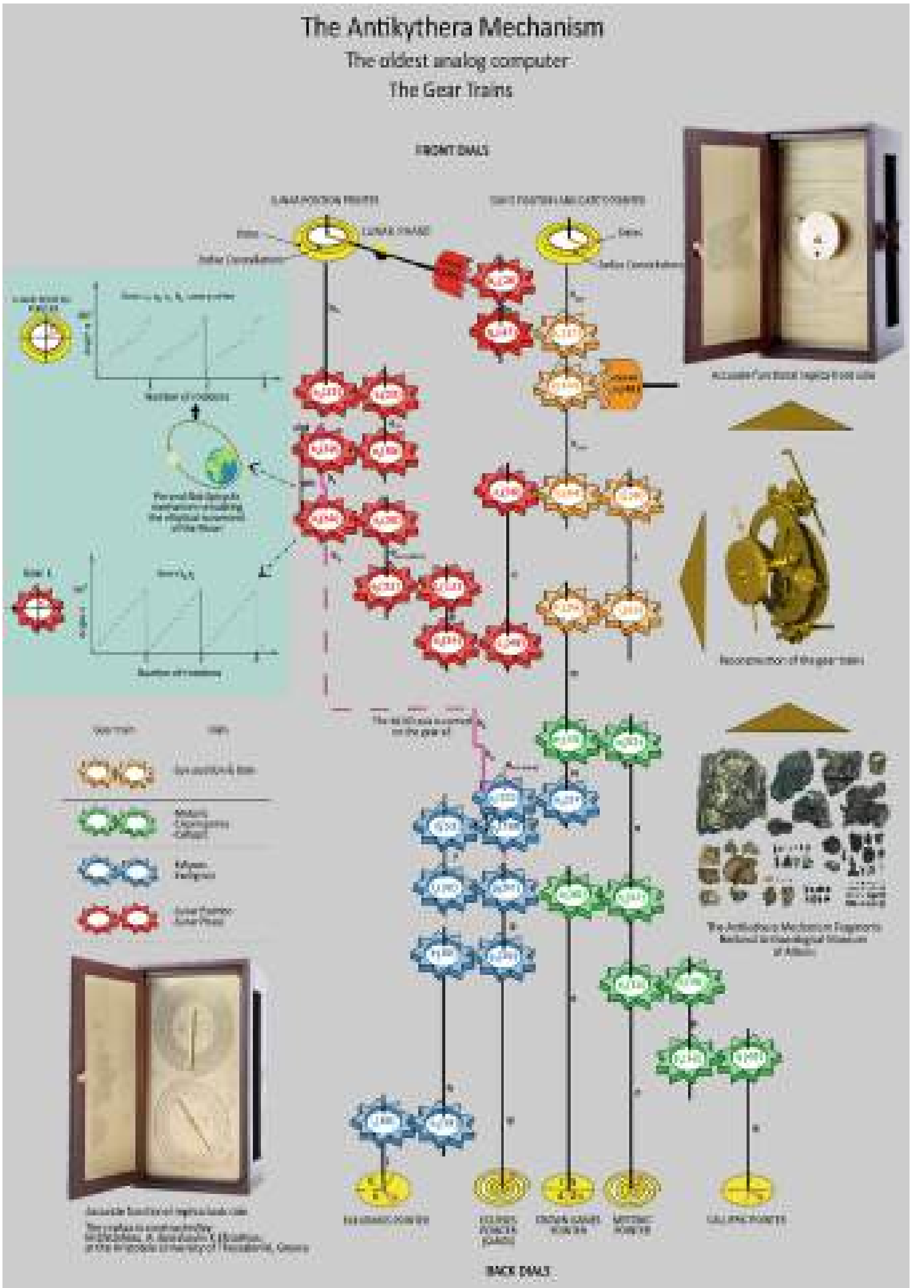

Fig. 19. Gear trains of the Antikythera Mechanism.

Fig. 20. The pin-and-slot mechanism [20].

There meaning fall into three broad categories: astronomical inscriptions, geographical inscriptions and technical inscriptions. Several astronomical terms have been read referring to the Sun, the Moon, the ecliptic, the Metonic and Saros cycles and other astronomical phenomena. The word “ΣΤΗΡΙΓΜΟΣ” (stationary point) is mentioned several times, likely referring to planetary stationary points.

The Mechanism had 7 pointers, which provided 8 indications in the scales of the Mechanism (the pointer of the Moon gives two indications). It had three main dials, one at the front side with two concentric scales, and two at the back in the form of spirals. On the front side (Fig. 21, left), there were two concentric circular scales. The outer scale had 365 subdivisions the days of the year. The inner scale had 360 subdivisions and the names of the 12 zodiac constellations. The date scale had the shape of a ring (Fig. 21) which was removable. Behind this date ring, there were 365 holes, and the ring was secured at one of the holes using a pin. Every four years, the operator was able to remove the ring and move it by one hole, to take leap years into account.

A very careful analysis of the gears’ co-action revealed their use in calculating to a high level of accuracy, the position of the Sun and the Moon on the zodiac (the zone that contains the zodiac constellations). This position was shown by the pointers of the front dials. Similarly, a crown gear drove a black and white coloured spherule, showing the current phase of the Moon.

On the back side of the Mechanism (Fig. 21, right) there were two spiral scales. The upper spiral consists of 5 windings, with its total length divided in 235 sections. Using this dial, the user could read the position of the Moon within the Metonic cycle of 19 tropical years, which is almost equal to 235 synodic (lunar) months. The Metonic cycle is almost equal to the least common multiple of the tropical year (365.2422 days) and the synodic month (29.5306 days). The difference between the two periods (of 19 tropical years and 235 synodic months) is only 2 h. This knowledge allowed the calculation of the exact day a full Moon would occur, which is a very useful knowledge for agricultural or nautical activities 2000 years ago, when no electricity was available. The accuracy of the position of the Moon was achieved by a pin-and-slot mechanism [8, 17] that reconstructed Hipparchus’ first anomaly of the Moon’s motion (due to its elliptical orbit around the Earth).

This anomaly is, in fact, Kepler’s 2nd law.

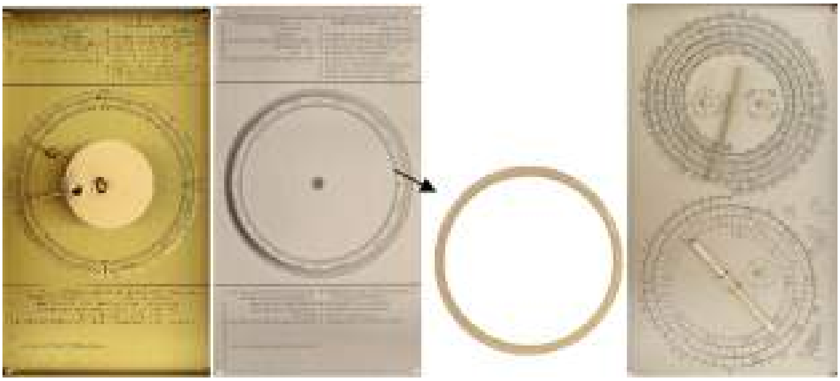

Fig. 21. The front side with the removable date scale ring and the back side.

Calippos 100 years later corrected Methons calendric system. Every 4 periods of Meton, i.e., every 76 years, one day needed to be removed. The Callippic pointer of the subsidiary dial within the upper back spiral of the Antikythera Mechanism indicated when the correction must take place.

A subsidiary dial within the upper back spiral of the Antikythera Mechanism displayed the celebration date of the ancient Panhellenic crown games. On the circumference of the dial the words Olympia, Pythia, Isthmia, Nemea and Naa have been deciphered. In each quadrant of the interior, the four years Olympic cycle are indicated. All these games were crown games, with winners being rewarded with olive branch crowns.

The lower back dial is a Saros eclipse-prediction dial, arranged as a four-turn spiral. This dial contained the 223-month eclipse Saros cycle (of approximately 6585.3213 days, or nearly 18 years and 11 1/3 days). 223 lunar months (one Saros cycle) after an eclipse, the Sun, Earth, and Moon return to approximately the same relative geometry, and a new, nearly identical, eclipse cycle begins. The Saros cycle was marked with the dates (month, day, and hour) when a possible solar or lunar eclipse would occur. The markings were engraved with symbols (“H” – HΛIOΣ – Sun and “Σ” – ΣEΛHNH – Moon, etc.), The fact that both letters, “H” and “Σ”, appear simultaneously in some glyphs, most probably means that the glyphs represent predictions of future eclipses and not records of past eclipses.

A subsidiary Exeligmos dial, within the Saros dial, extended the eclipse prediction capabilities to three Saros cycles, indicating that 8 and 16 h should be added respectively in the second and third Saros cycles to the eclipse times indicated by the inscriptions.

The most impressive part of the Mechanism is related to the moon phases and the moon’s movement anomaly. In the seventeenth century, Johannes Kepler, in relation to the sun and moon movements, claimed that the “holy circular motion was not circular" and suggested that it was an ellipse orbit (first and second law of Kepler). Inside the Mechanism, a gear system is identified, that simulates this motion with a high-level of accuracy.

The display of this movement was achieved by the use of two eccentric gears (Fig. 20), taking into account the moon's movement anomaly caused by its eccentric orbit around the Earth, was achieved by the use of two eccentric gears (Fig. 20).

The Fragment D of the Mechanism

The latest outcomes of the AUTH team are related to the investigation of fragment D. In all modern studies of the Mechanism, fragment D is considered as a lone fragment and does not exist in any constructed model of the Mechanism. After a long-term study, it was determined that Fragment D is indeed part of the mechanical arrangement that calculates the equation of time [2].

3.2.1.2 The Antikythera Mechanism, from Physical to Digital 3D Representations

Starting in 1998 by M. Roumeliotis [26], to date many animations and simulations of the Mechanism have been created, which can be searched online.

Regarding physical models, from 1900 until today, many scientists have involved with a reconstruction of the Mechanism. In 1928 Admiral I. Theofanidis with the contribution of E. Zinner, R.T. Gunther and W. Hartner, listed the visible gears and circles from the back side of the Mechanism and they characterized the Mechanism as an astrolabe. Admiral Theofanidis achieved to read 350 letters of the inscriptions and was the first who tried to make a replica model of the Mechanism [4, 20].

De Solla Price studied the Mechanism from 1950 until 1974. First, he analyzed the constructed materials. Under the supervision of De Solla Price, Robert J. Deroski was constructed in 1975 two replicas of the Mechanism as a proposal for the possible function of the device [4, 20]. Afterwards various manufacturers reproduced Price's models with few functional deviations, such as the models of J. Gleave in 2000 and D. Kriaris in 1999 and 2007 [4, 20].

In 1985, A. Bromley has continued the research of Price including his remarks. At his first attempt he cooperated with F. Percival and a replica of the Mechanism was constructed Five years later in 1990, he cooperated with M. Wright, and they used x-ray Linear Motion Tomography in order to define the array of the gears into space. This method didn't achieve the desired results. M. Wright claimed that the Mechanism could predict the movements of the Sun, the Moon and of five planets [19]. In 2005, he constructed a model using approximately 40 gears [8].

In 2008, the Aristotle's University of Thessaloniki began to develop models of the ancient Mechanism [11–13]. In 2011 five accurate and functional models were constructed (Fig. 22). From then until now many updated accurate and functional replicas in scale 1:1 as well as in scale 3:1 are constructed and are exhibit in various museums and other institutions worldwide [20, 28, 29].

The AUTH used complicated digitization processes, such as, using three - dimensional images obtained from the x-ray tomography, the PTM Dome techniques and using the Volume Graphics specific software system VGSTUDIO MAX [22], to develop 3D digital models of the four basic fragments (Fig. 16). Using the same data, the whole Mechanism was digitally recreated. In Fig. 23 and Fig. 24 illustrates the 3D digital reconstructions of the gear trains and the whole functional Mechanism is presented.

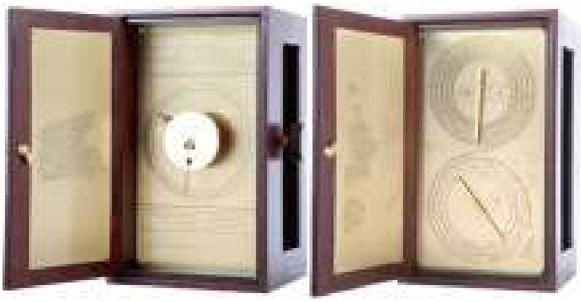

Fig. 22. Accurate and functional model of the Mechanism scale 1:1 (AUTH 2011).

Fig. 23. 3D digital reconstruction of the Mechanism [20].

Figure 24 illustrates how the front side of the Mechanism (left) and the gear system (right) was designed based on components revealed from the x-ray tomography images.

Fig. 24. Mechanical parts localized in the tomographies and corresponding designed elements.

3.2.1.3 Importance, Purpose, Utility, Operation, and Handling of the Mechanism

3.2.1.3.1 Importance and Purpose of the Mechanism

Taking into account the theoretical and technological knowledge required for the construction of the Mechanism, it can easily be ranked amongst the Wonders of Ancient World [2].

The Antikythera Mechanism was the first surviving geared analogue computer in history. The next extant geared device is a Byzantine clock calendar, which was built in the 5th or sixth century, and the next mechanical calculators were built more than 800 years later. Other examples of a similar complexity to the Antikythera Mechanism came much later, with at the beginning of the thirteenth century the astronomical indicator of Wallingford, 50 years later (1348–1364) the astronomical clock of Dondi, and in 1410 the Prague astronomical clock were developed. Later in the seventeenth century, the calculator of Schickard (Kepler's collaborator) and the Pascaline of the great French scientist Pascal were built. The Antikythera Mechanism inspires manufacturers to date as for example the design of the years dial of the Atmos millennium clock [23] and the mechanical computer of the spacecraft "Automaton Rover" [24].

3.2.1.3.2 Utility, Operation, Handling and prediction's Accuracy

The main use of the Antikythera Mechanism was to calculate the exact position of the Sun, the Moon, the phases of the Moon and the lunar or solar eclipses and possibly the position of the planets in the sky. Additionally, besides the predictions of astronomical events, the Mechanism could determine dates related to religious, social and agricultural rituals and events.

As previously discussed the subsidiary dial on the upper back spiral of the Antikythera Mechanism displayed the dates of the Olympic Games, which were held during the first full Moon after the summer solstice. The Mechanism could accurately calculate this date as well as the date for the Panhellenic crown games of Isthmia (Corinth), Nemea (Nemea), Pythia (Delphi), Naa (Dodona) (Fig. 25) [21].

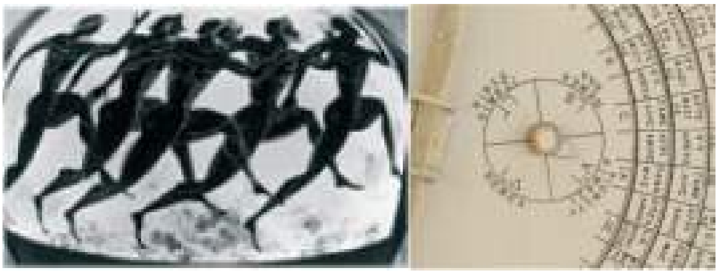

Fig. 25. The subsidiary dial displayed the dates of the Panhellenic crown games.

In Fig. 26 the Parapegma of the Mechanism is shown [16]. The Parapegmas were essentially calendars of astronomical and meteorological events, which were widely used in ancient Greece. The astronomical events referred in the Parapegmas are events that associate the sunrise and sunset of stars or constellations with the sunrise or sunset. For many years, seasons, with their different climatic conditions, were an important unit of time as they played a crucial role in people's lives. Over time, however, it was found that the start date of each season, could not be determined with the usage of classic calendars, based on lunar months. Therefore, people turned to stable natural phenomena, to define the seasons. Some of these phenomena were the rising or sinking of some stars. These phenomena appear every year at a fixed date in the sky. The occurrence of these events once during a solar year has contributed to use them in order to organize practical-social activities such as agriculture and navigation [16]. Hesiod mentions that the harvesting period is the season when the constellation of Pleiades appears for the first time in the sky, and the time of plowing is the time after the temporary disappearance of the Pleiades. The grape harvest must take place when Arcturus appears in the sky for the first time. Such phenomena and the date on which they will occur, are predicted using the Parapegma on the Mechanism [16].

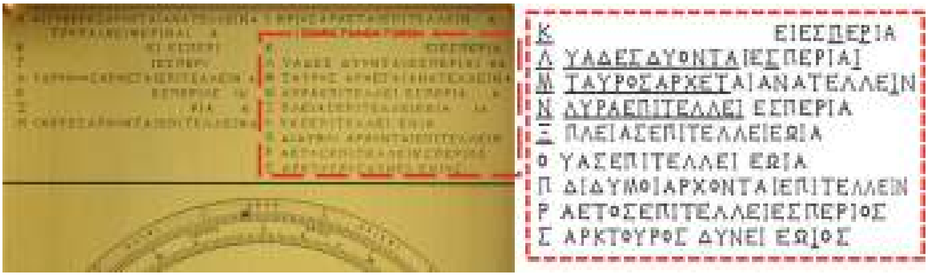

Fig. 26. The Parapegma of the Mechanism.

The rotation of any of the gears or any of the pointers gives movement simultaneously to all other gears and subsequently cases the seven pointers to move, which shows the various astronomical phenomena in the related mathematical scales. Based on an analysis of the applied torque of the operator when handling the Mechanism, and the necessity of a precise positioning of the pointers, e.g. the Sun/Date pointer on the front of the Mechanism, the most probable scenario for the handling of the Antikythera Mechanism is the rotation of the Moon pointer [2]. The operator, by rotating the moon pointer and choosing a date, can determine the astronomical phenomena that may occur on that day. Respectively, by choosing an astronomical phenomenon it can be observed on which date it will happen.

Regarding the accuracy of the predition, it is mentioned that, from the construction of the Mechanism to date, the position of the constellations in the sky shifted approximately 30°, which corresponds to one zodiac constellation. To find out the accuracy of the Mechanism's predictions for the present era, in the model shown in Fig. 27 we have captured on the front of the Mechanism, the current positions on the scales of dates and zodiacs. On the front side of the Mechanism, the indications of the pointers of the sun and the moon during the operation of the Mechanism, for the 15 June 2011 are shown. Based on current estimates for June 15, 2011, the predictions were: Sun in the Taurus Constellation, Moon in the Sagittarius Constellation, Full Moon, and a Lunar eclipse at 23:00. The corresponding displays on the front side of the Mechanism for this date are exactly the same (see Fig. 27): Sun in Taurus, Moon in Sagittarius Constellation and Full Moon. Thus, a moon eclipse was possible.

Observing the pointer of the eclipses on the back side of the Mechanism for this date (Fig. 28), a lunar eclipse would likely occur.

Regarding the moon eclipse, the Mechanism showed: a) Eclipses pointer: Σ (Σελήνη = Moon), $\Theta = 9$ and b) Exeligmos pointer: $H = 8$.

Fig. 27. Displays on the front site of the Mechanism for June 15, 2011.

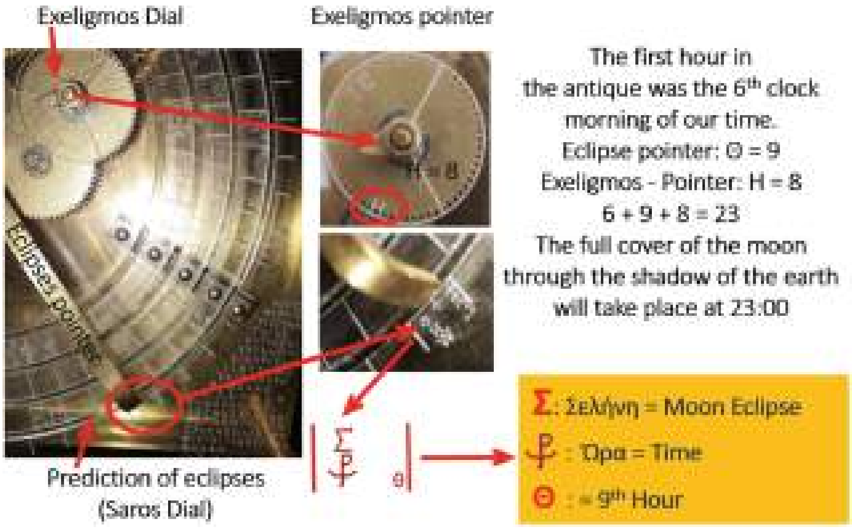

Fig. 28. Predictions on the lower part of the back side for June 15, 2011.

Taking into consideration, that the first hour in antiquity was the 6th hour the day, the full coverage of the moon from the shadow of the Earth will occur at 23:00 (9 + 8 + 6), exactly at the same time of the prediction of the device.

3.2.1.4 Place and Date of the Construction of the Antikythera Mechanism

The Mechanism was possibly built in Rhodes, between 150 and 200 BC. Early evidence of similar machines, are references reported to Archimedes (287–212 BC) as a constructor of devices which depicted the celestial bodies [2, 3]. The Mechanism cannot have been built later than the shipwreck dated by the Pergamon coins within a few years of 60 BC. The inscriptions letter style suggested that it was constructed in the period of 50–200 BC. An important date could be set if we knew when the parameters required for the pin- and-slot lunar anomaly Mechanism were first deduced. It is known through Ptolemy that Hipparchos did characterize and quantify the anomaly by epicyclic and eccentric models of the lunar orbit. Therefore, it would be necessary for Hipparchos's values to be involved the manufacture so it must have taken place after 170 BC [2].

The optimum latitude for fitting the astronomical phenomena listed in the parapegma of the Mechanism is consistent with the mid-Mediterranean around 35° [16]. Rhodes (36°) remains as the most likely candidate. The Antikythera ship may have called there before it wrecked. Rhodes was known as a highly technological naval port with a thriving bronze industry. It was home to Hipparcho and is the place for which we have a record of the Mechanism being sighted. It may also explain the presence of the Halieia Games on the Games' dial as they were held in Rhodes [2].

Another connection to Rhodes is the construction of similar Mechanisms, which are referenced by Cicero, from when he visited the laboratory of Poseidonios (135–51 BC) in Rhodes, where he admired a celestial sphere made by Poseidonios [2].

The Metonic cycle, found in the upper back dial, contained a full calendar, which is repeated 19 times. Comparing this calendar with the calendars of the ancient Greek cities, it was found that it coincided with the cities of Kerkyra, Vouthrotos and Dodona (in NW Greece) and Tavromenion (in Sicily) [16]. This could indicate that the Antikythera Mechanism was used, but not, necessarily, constructed in NW Greece.

3.2.2 Documentation of the Necessary Knowledge for the Mechanism Design, Construction and Manufacturing at the Time and Place of Its Construction

3.2.2.1 Scientific and Technological Knowledge Necessary for the Design of the Mechanism

A question, which arises, is whether the Greek astronomers 2200 years ago, had the necessary knowledge to calculate astronomical phenomena, using the Mechanism. Various sources, discussed below, show that they did.

The only accurate clock that the Ancients had was the moon months. Meton in the fifth century BC, connected the moon calendar to the annual. He calculated that 19 years include 235 lunar months [2]. Callipos (370–300 BC) calculated that Meton was making a mistake one day every 76 years [2]. These calculations are performed by the Mechanism and appear on two scales on the back side of the Mechanism. The Callippic pointer of the subsidiary dial within the Meton scale (upper back spiral of the Mechanism) indicated when the correction must take place.

Aristarchus (310–230 BC) was the first astronomer in history, who discussed the heliocentric system [20], he calculated the size of Earth, Sun and Moon. Hipparchus [20] (190–120 BC) is considered as one of the greatest astronomers of all time. He lived contemporaneously to the time of the construction of the Mechanism in Rhodes. He calculated, the transient motion of the Earth which lasts 25,800 years. Another calculation developed was the determination of the distance between the Earth and the Sun & the Earth and the Moon.

3.2.2.2 Technological Knowledge Necessary for the Manufacturing of the Mechanism

Another question, which arises, is whether the ancient Greek mechanicians had the necessary technological knowledge for the manufacturing of the Mechanism. Various sources show that they had them.

Until the discovery of the Antikythera Mechanism the construction of the first real gears was dated centuries later. Aristotle describes the rotation of cylindrical objects by friction, due to the roughness of their cylindrical surfaces. The creation of surfaces with higher roughness slowly led to the development of teeth and gears. The gears of the Antikythera Mechanism (second century BC) are the first known example. Two references related to calculations and constructions of gears are from Heron and Pappus. Heron of Alexandria was an engineer and geometry, who lived in Alexandria, Egypt. In his description of the construction of an odometer he mentions and describes gears. Pappus of Alexandria describes several machines that were described by earlier mathematicians and engineers, such as Archimedes, Heron, etc. and included gears [26]. For two gears to work together, they must have the same ratios of diameter to the number of teeth. This relationship is called today "module". From Papus's writings, it is clear, without any doubt that the Greeks knew the module in antiquity.

Very likely, the gears of the Mechanism were made of cold forged thin bronze plates by sawing, removing redundant material and leveling with a hammer [25].

In order to manufacture the mechanism particular tools were necessary. The text of the inscription from the fourth century BC shown in Fig. 29 concerns the construction of bronze axes "Πόλος" for the Filonian gallery in Eleusis, using lathe. On this marble inscription is written among others *"… a copper alloy from Marion (Cyprus) must be used, consisting of 11 parts copper and one part tin …"* This alloy is called bronze today. The parts of Antikythera Mechanism are made of bronze (see Sect. 3.2.1.1). Subsequently is written *"… Turn the axes according to the example …"* This inscription shows that many years before the creation of the Mechanism, the Greeks had and used lathes. This is also apparent from other sources [25].

For the machining of bronze pieces, steel cutting tools are necessary. It follows from several sources that the Greeks at that time had such machine tools and cutting tools [25].

Fig. 29. Marble inscription fourth century BC. Archaeological Museum of Eleusis.

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