The latest techniques reveal the earliest technology – A new inspection of the Antikythera Mechanism

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Abstract
In the National Archaeological Museum in Athens sit the remains of a remarkable machine, 1600 years ahead of its time. The Antikythera Mechanism, found on an ancient Greek shipwreck in 1901 is thought to date from the early second century BC. Early examination of the mechanism gave rise to theories that it was an astronomical computer. Later X-ray images revealed meticulous ancient workmanship not seen for another 1600 years – bronze interlocking gears and inscriptions. Last year X-Tek was asked to use its new 450kV microtomography system, originally developed to inspect aircraft turbine blades, to do a complete 3D CT inspection of the mechanism, which revealed details that had lain hidden for over 2000 years. The inspection showed hidden text and symbols that confirmed that the Antikythera Mechanism was a complex astronomical calculator, capable of predicting the position of the Sun, the Moon and possibly the planets to a remarkable accuracy, and could not only predict the date, but also the time that solar and lunar eclipses were to occur.
Keywords: High-energy microfocus X-ray computed tomography (CT), ancient Greek artefact, Antikythera Mechanism

1. Introduction

I want you to cast your minds back, 2000 years, to Ancient Greece - a land of masters and slaves, of primitive farming methods, though where art and sculpture, and architecture were crafts that had been developed to a high degree of skill. Great strides had also been made in mathematics, especially geometry. It was a land where astronomers tried to make sense of the heavens, especially the movement of the Sun, Moon and planets, and where computers were used to predict the occurrence of solar and lunar eclipses.

What was that? Not heard of ancient Greek computing, you say? Well prepare to change your views on the ancient world, because the latest evidence suggests they were a lot cleverer than we often give them credit for – evidence which was gathered using X-ray computed tomography on a small box recovered from an ancient Greek shipwreck in 1901.

Just over two thousand years ago, a Roman ship was carrying treasure, possibly taken from a Greek city just sacked in battle, back to Rome. On the ship were several large marble and bronze statues, many coins and jewellery. Perhaps there was too much on the ship, because in a storm which brewed as they were passing the small island of Antikythera the ship sank.

It lay thirty metres down, partially buried in silt, at the bottom of the Mediterranean Sea for almost two thousand years until Greek sponge divers, sheltering from another storm in the area in 1900, decided to dive. They were amazed at what they found and the following year a major expedition was launched to recover the treasure. Amongst all the artefacts was a small wooden box which, when it dried out, split to reveal the corroded remains of a bronze mechanism containing gear wheels.

2. Earlier studies

Figure1. The largest fragment of the Antikythera Mechanism

After some initial interest shortly after discovery, the Mechanism was not studied much until the 1950s, when an Englishman, Derek de Solla Price formed the theory that it was an astronomical calculator [1]. In fact, the Roman statesman Cicero had written about just such a calculating machine in 79BC [2] referring to a machine which Posidonius, a student of the great astronomer Hipparchus had built which predicted the motion of the Sun, Moon and the five planets known at that time. In 1980, Price got permission to X-ray the fragments on film and again pushed the theory. However, at the time alien artefact theories abounded and the idea was largely dismissed. From his images Price built a model of the Mechanism that remained the standard for many years. However, from projection images alone it was difficult to separate the individual gears.

In 1990 Michael Wright, a museum curator at the Science Museum, London and Allan Bromley used a method of laminography to try to do just this. Wright continued to analyse the data for many years and found several mistakes in Price’s conclusions. Wright, a mechanic by training, built another model, by hand, following the simple methods that the original maker may have used.

In 2000 Tony Freeth, a freelance film-maker from London, brought together teams from Cardiff University, Wales and Athens and Thessaloniki Universities in Greece, and enlisted the help of X-Tek Systems and Hewlett Packard. After five years of discussion with the National Archaeological Museum in Athens, permission was finally given for another inspection, this time a complete 3D tomographic inspection, which took place in October 2005.

3. The Equipment

The Mechanism is now in 82 fragments, the largest of which is 130mm across, though many are much smaller. To inspect such a large bronze artefact and yet see details only a few microns in size is quite a challenge. Until a few months before the inspection finally got its funding and go-ahead X-Tek’s highest energy X-ray sources were only 225kV, except for a couple of sources still in the R&D department. A huge effort was needed to finish developing the higher energy sources to produce a prototype 400kV source (since increased to 450kV). The method used to produce a higher energy microfocus X-ray source is to take two sources and put them back-to-back. Make one module positive instead of negative and the electrons which produce the X-rays will be accelerated from –225kV all the way up to +225kV – giving a maximum theoretical energy of X-rays of 450kV. This also gives the flexibility of taking off the positive module and replacing it with a standard microfocus target to give an even smaller 225kV X-ray source – useful for looking in more detail at the smaller fragments. It sounds simple, but solving the technological problems with such a source took many months of hard work by X-Tek R&D staff.

Figure 2. X-Tek's Bladerunner 450kV microfocus X-ray CT system

Although the inspection of the Antikythera Mechanism was the driving force behind this development, X-Tek had other reasons to develop such a source. The computed tomography of small dense castings requires high X-ray energies. To obtain high resolution images requires that the source size is kept small and the images are magnified on to detectors.

One market for such a technique is the inspection of aircraft turbine blades and X-Tek has worked with Rolls Royce and other companies to develop a complete turbine blade metrology system – hence the name of our X-ray system, the "BladeRunner". Such turbine blades operate in gases with a temperature greater than their melting point and the presence and efficiency of their cooling channels is vital. One common problem in blade manufacture is that the ceramic core can slip during casting. By using a linear detector array and taking a few 2D CT slices of each blade (a process which only takes a minute or two) such slippage and the consequent effect on wall thickness can be seen. The wall thicknesses can be measured to an accuracy of 25μm.

The Bladerunner can also be equipped with a large area (400x400mm) flat panel detector to perform 3D CT, in which a whole CT volume is reconstructed from a single set of projection images. Both methods were used on the Antikythera mechanism.

4. The Inspection

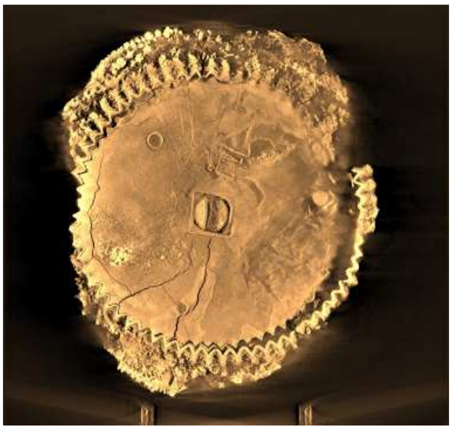

Figure 3. CT slice of Fragment D

Continuous rotation CT was used to inspect the Mechanism. Between 1500 and 3000 images were taken for each 3D CT scan (giving an angular increment of between 0.12° and 0.24°). Such CT scans, using an exposure of about 0.7 second per projection image, took between 20 and 40 minutes. Image correction and reconstruction took a further hour or two. Today image correction is performed in real-time and reconstruction times are of the order of 10 to 15 minutes.

Larger fragments were inspected using the high-voltage double-ended X-ray source, giving scan resolutions down to 50µm, whereas the smaller fragments were scanned using a single-ended 225kV source approximately 3µm in size. This allowed magnification on to the detector – a 2000x2000-pixel PerkinElmer amorphous silicon 16-bit flat panel giving 3½ frames per second.

5. The Findings

The largest fragment of the Mechanism, Fragment A, was found to contain 30 gears ranging in tooth numbers from 12 to 224 teeth. The teeth appeared to be hand-cut (probably filed). Scales on the Mechanism were found to represent both the solar and lunar calendars. A spiral scale was found on the back of the device marked out in lunar months. A pointer-follower device in which a slider on a dial ran in a groove around the spiral dial, told the user which turn of the spiral was being indicated. After 18 years, 11 days (the Saros or eclipse-repeat cycle period) the slider came out of a hole at the end of the groove and was slid along the dial and pushed into an identical hole at the start of the groove, to start its journey again.

Figure 4. Writing on the spiral Saros scale indicates the lunar months in which solar and lunar eclipses will occur, and the time of day.

Symbols in some of the months on the spiral scale appear to indicate the occurrence of solar or lunar eclipses. These were marked by an "H" for "Ηλιος" ("Helios" = "Sun") or a "Σ" for "Σελενι" = "Seleni" = "Moon"). Not only is the month marked, however, but an "hour" symbol seems to give the time of day of the eclipse. A subsidiary dial with three divisions revolves every three Saros cycles, since the exact length of the Saros cycle is an integer number of days plus 8 hours, so eclipses only repeat at the same longitude every three Saros cycles (every 54 years).

An ingenious pin and slot mechanism on eccentrically mounted gears modelled the elliptical nature of the Moon's orbit about the Earth. By calculating the way the tilt of this elliptical orbit slowly revolves around the Earth, they could have been able to predict when the Sun and Moon appeared coincident in the sky thus causing a solar eclipse, or opposite each other to cause a lunar eclipse. Another possibility is that they used ancient Babylonian records for this – there are many hundreds of tablets in the British Museum with such records on them. However they did it, the eclipse dates and times are recorded on the spiral dial to predict future eclipses.

The most remarkable findings of the inspection were the inscriptions. Far more letters than could ever be read before could be seen in the CT data. In places where corrosion covered the surface of the metal, writing could now clearly be seen. In all, the new inspection doubled the amount of text that could be deciphered. Much of the text was astronomical in content and referred either to the use of the Mechanism (e.g. "a spiral divided into 235 sections") or to astronomical events, such as the point when Venus appears (from the Earth) to stop moving away from the Sun and starts to move back towards it. No astrological references were found, suggesting that this was a purely scientific instrument – astronomy and astrology at that time were often studied together.

The style of writing suggested a date in the latter half of the second century BC or the first half of the first century BC, which is compatible with the dates of coins found in the wreck. Carbon dating of the ship's timbers had suggested an earlier date (around 300BC), and therefore perhaps another reason why the ship sank!

6. Conclusion

X-Tek has developed a high-energy microfocus X-ray source which can be used for high-resolution computed tomography of small to medium-sized dense objects. The new X-ray source was proved during the inspection of probably the most fascinating artefact from the ancient Greek world, the Antikythera Mechanism. Features down to 25µm in size were imaged. The Mechanism was shown to be a complex solar and lunar calendar, as well as a calculator to predict the days and times of both solar and lunar eclipses. It shows mechanical workmanship far in advance of its time, as well as ingenious mathematics in its efficient design.

7. Acknowledgements

I would like to thank the Antikythera Mechanism Research Project for their invitation to take part in this inspection, particularly Tony Freeth of Images First, London, Professor Mike Edmunds of Cardiff University, Wales, Professor Xenophon Moussas, Yanis Bitsakis and Agamemnon Tselikas of Athens National and Kapodistrian University and John Seiradakis of Thessaloniki University. I would also like to thank the staff of the National Archaeological Museum of Greece in Athens for their hospitality during our visit. I would like to thank the Leverhulme Trust for their funding to make the inspection possible and for paying for the shipment of the Bladerunner to Greece. Lastly I would like to thank all my colleagues at X-Tek who made this inspection possible, especially Martin Allen, David Bate, Alan Crawley, Roger Hadland, Ian Haig, Peter Hockley and Matt Williams.

8. References

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