The Antikythera Mechanism

Michael Wright

Introduction

The Antikythera Mechanism, a small but elaborate Hellenistic instrument that displayed indications of astronomical events as functions of date, embodies by far the earliest known application of toothed gearing[1]. Due to its fragmentary, ruined state it has proved hard to understand, and it remains a difficult artefact to interpret and to appreciate without the use of supporting material. For these reasons it was an apt subject for reconstruction. In developing the reconstruction that forms the subject of this chapter, the author has contributed significantly to the understanding of the instrument, and at the time of writing his models remain the best illustrations of the original in all its detail[2, 3].

The instrument had two dials, front and back, interconnected by toothed gearing driven by hand. The back dial bore two displays. The upper exhibited an astronomically-based calendrical cycle; and the lower showed another temporal cycle offering a means of predicting the possibility of lunar and solar eclipses. The full extent and exact nature of the display of the front dial is less clear. The outer of its two concentric rings showed the days and months of the year, so that a pointer might indicate the date. For the inner ring, representing the Zodiac, there were undoubtedly pointers indicating the positions of Sun and Moon in a geocentric scheme, and the motion of the Moon-pointer was cleverly modified to model Hellenistic single-anomaly lunar theory. Near the centre, the rotation of a small half-white, half-black ball displayed the phase of the Moon. That much is certain, but we see clear evidence of the loss of other mechanical parts that drove further pointers on this dial, indicating, we argue, the places in the Zodiac of the five planets then known. We suggest also that the motion of the Sun-pointer was modified to model the single-anomaly solar theory. Our initial purpose in realising our reconstruction as a full-sized model was to satisfy ourselves and to demonstrate to others that this reconstruction, more elaborate than any other and accounting more fully for the detail found in the original, was fully practicable.

We do not attempt here either to reason the case for our interpretation or to explain the detailed functioning of the instrument[4, 5]. Our present purpose is to discuss particular points that arose in the course of our work which are of a more general interest and relevance.

Discovery, and Earlier Attempts at Reconstruction

We begin with a brief account of the discovery of the Antikythera Mechanism, of the context in which it was found, and of previous attempts to reconstruct it[6].

Antikythera is a small island off the South coast of mainland Greece, in the middle of the strait connecting the Aegean Sea to the Western Mediterranean Sea. There, in 1900, sponge divers found statues in deep water just off shore, the largest items of a cargo of mixed luxury goods in an ancient shipwreck. The wreck itself is now dated to the second quarter of the first century B.C., most securely on the basis of coins found at the site. Much of its cargo appears to be contemporary with the wreck itself or just a little earlier, but a few items of large-scale bronze statuary are thought to be older still. Inconclusive evidence and historical considerations suggest various dates for the Mechanism, ranging from the second century B.C. to nearly the time of the wreck.

The Greek government hired the divers to recover what they could, and a great mass of varied material, the “Antikythera Treasure”, was taken to the National Museum in Athens, where much of it is on display. The fragmentary bronze Mechanism was noticed amongst this material only later, when engraved lettering (in Greek) and traces of a few wheels were seen on its surfaces. It became clear that the instrument had an astronomical purpose, and some mistaken commentators described it as an astrolabe. Over the ensuing decades there were several attempts to offer reconstructions of it, but all – based only on literally superficial examination – were sketchy and speculative. In 1959 Derek de Solla Price was the first to suggest an approach to the correct general layout[7], but only in 1974, after radiography had revealed much hidden detail, could he build on his own earlier description by offering an account of the internal mechanism[8]. Price’s reconstruction is now known to be wrong in many respects, but it was the first to reflect at all closely the actual degree of intricate internal detail. His paper was widely read, causing a ripple of sensation through much of the scholarly world.

Our Research

Many scholars found it difficult to adjust their perception of Hellenistic mechanical achievement, and there was a degree of incredulity that the instrument described by Price could have been made so early, using only simple tools. The present author was struck by the idea that one could, through model-making, demonstrate that this difficulty was illusory. At the same time, however, he was dismayed to find that parts of the argument through which Price arrived at his reconstruction were, at best, unintelligible. The doubts thus cast on its correctness seemed confirmed a few years later, when a model made under Price’s supervision, borrowed for temporary exhibition at the Science Museum, proved both unconvincing and unworkable. Thereupon the author became determined to examine the original for himself.

This examination of the original fragments was carried out in collaboration with the late Allan Bromley of the University of Sydney. We began with a minute direct examination using the naked eye and various types of magnifier. Direct measurements were made of the positions of many surface features, using a simple measuring jig. Straightforward and stereoscopic photography was extensively employed. The fine radiographs which Price had used, prepared by the Greek physicist Charalambos Karakalos, were not available for our study. Therefore we made our own.

The fragments of the Mechanism are essentially flat, its gears and other components lying in a number of closely-spaced layers. Conventional radiographs of good resolution could be made only with the rays passing roughly at right-angles to the layers. They showed most features clearly, but could not show the depth of each feature within the mass. Karakalos had attempted stereoscopic radiography but had found it of limited use. We therefore devised and made apparatus for use with the conventional X-ray apparatus available at the Museum, allowing us to exploit linear tomography. Using this technique, one makes radiographs in which the features in a single chosen plane yield sharp images while features out of the plane are more or less blurred. By taking sets of exposures, with a small adjustment of the apparatus between each so as to shift the chosen plane by a fraction of a millimetre, we prepared sequences of images in which the depth of each of the several features in the specimen might be found. With application, these sequences allowed us to build up a mental picture of the arrangement in depth[9].

Having accumulated a great deal of material, we then faced the problem of its analysis. Bromley took the material to Sydney for this purpose but his attempt proved abortive, due largely to his advancing terminal illness. Some years later the author recovered as much as could still be found, and began again.

Reconstruction as a Research Tool

It was clear that Price had been led astray through having formed too firm an idea as to how the instrument must have functioned. Once that idea had taken root, he had then laid emphasis on evidence that supported it, and – perhaps unknowingly – had distorted or suppressed evidence that led in any other direction. He offered arguments, now seen to be specious, in support of this manipulation; and he presented further ideas which distracted the reader’s attention, and perhaps his own, from its extent.

It was important to avoid the same error of self-deception, and the author’s prior experience offered a different way forward. As a museum curator, he was often obliged to deduce the purpose of an unidentified artefact from a study of its detail. The same approach was applied in this case; everything that had been written about the instrument was ignored, and attention was directed wholly and simply to a study of the fragments themselves.

The detail of each part, once grasped, was then modelled, and the several small assemblies thus created were brought together. The original is incomplete, and so this process could take us only so far. Thereafter, as a second phase, lost features had to be restored in order to make sense of what had been copied. This phase of reconstruction would have been very much harder had it not been for the stimulus of mechanical necessity to fit parts to the model, and the resulting direct confirmation of the appropriateness of each step taken. Indeed, had the work been carried out merely as a “paper exercise” or in any other way, it would still have been necessary to build the instrument before the reconstruction could be published with any confidence.

Nothing but actually making the instrument and trying it out in practice could have shown, so directly and so definitively, that the restored parts fitted and that the whole was workable. Computer modelling, for example, as usually carried out, generates no more than a moving diagram. In such a virtual model the parts have no mass and no inertia. There are no loads and there is no friction. There is no deformation and no breakage. There is no wear. The computer-generated virtual model has great value, but for our purpose it is not an adequate substitute for reality. It might be added, that for us it represents a far more difficult procedure. In any case, it is a fact that in this instance physical reconstruction was a central feature of the heuristic method.

Most of the detailed discussion that follows relates to the author's first model which was, as we have described, built during the process of reconstruction and as a means of developing that reconstruction. As a pragmatic choice, it was built of scrap materials that lay to hand.

A second model has been more tidily made, of new material. Initially, it differed only slightly from the first. A few details of the original had been better understood, and could be modelled more accurately. Better design solutions had been found for some restored parts, which either were more serviceable or conformed more closely to precedents found in the original fragments; or, interestingly, they offered both advantages. The model was exhibited in this state[10, 11]. Meanwhile, further study offered a function for a previously neglected detail, which suggested in turn that, while our restoration of mechanism to drive pointers for the positions of the superior planets was generally correct, the original incorporated an unsuspected subtlety embodying a more advanced form of planetary theory. The second model has consequently been disassembled and, at the time of writing, is being modified to illustrate this further feature. A preliminary announcement has been made[12], but a paper intended to describe this development more fully remains in preparation.

Dimensions

It is desirable to build any reconstruction to the same size as the original where practicable, so as to be free of any effects due to scaling; and in this case, in which the original is of moderate size, it would have been simply perverse to have chosen any other scale. Obviously the ideal is to make the parts of the reconstruction to precisely the same proportions and sizes as those of the original; but for the Antikythera Mechanism that is probably an unattainable ideal.

The precise measurement of what remained was a non-trivial problem. Only some features, and some of the layout, could be measured directly. For the rest, we relied on radiography. Radiographic images, being shadow-pictures, are always larger than the features that they show; but with a little extra information it is possible to scale from them to a reasonable approximation. One can scale from some other feature of known dimension lying nearly enough in the same plane as the one to be dimensioned or, knowing the geometry of the radiographic set-up (distance of the target in the X-ray tube from the feature in question and from the plate), one can invoke the geometry of similar triangles in correcting the size of the image to the size of the original feature. Both techniques were of some use, although it happened that by the time the analysis was made some radiographs, and (more crucially) information on the radiographic geometry, had been lost.

Although it remains in principle possible to derive a full set of dimensions from our data, this course has not been followed; to do so would be both tedious and expensive. A more recent study made by others, using modern CAT apparatus, should make it very much easier to find dimensions, but we have had no access to the results of this work.

Even if we might determine the precise present dimensions of the individual components, it happens that almost none of them remains undamaged. Many are nearly enough complete for the intended geometry to be clear, but whether that intended geometry was accurately carried out remains open to doubt. The original shape and size of other parts is much less certain. Throughout, the thickness of components is a particular problem. There are rather few points at which thickness can be measured directly, and even then the state of the remains is such that it is not easy to estimate whether the measured thickness is the same as the original thickness; it may have been reduced by corrosion and other damage, or increased by the accumulation of marine deposits or corrosion products. In most cases the free edges, at which it was possible to make some direct estimate of thickness, are in fact very obviously wasted.

There is the further important question of fits and clearances which, though often overlooked, are essential points in the construction of mechanism. No doubt the parts were adjusted to one another with as much care as the maker's skill and experience allowed, and it would be most valuable to be able to establish this aspect of his working practice; but unfortunately the state of the original precludes hope of ever being able to do so.

It is possible that some basic dimensions, at least, were related to a length-standard current when and where the instrument was made. Such a discovery would be interesting, perhaps leading to insight into aspects of workshop practice or adding to our knowledge of the place and time of manufacture. This study would however demand the expenditure of much time and effort. Therefore, because it holds no relevance to our primary interest in the function of the instrument, it has not been undertaken.

While we should prefer to replicate the dimensions of the original exactly, it is worth reflecting on the value of investing time in attempting any particular degree of precision. Here, our first priority was to check that ideas for the several parts "made sense"; that the individual parts were compatible; and that the whole was practicable. The great pitfall to avoid was the publication of an unworkable reconstruction. Fortunately, for this purpose alone the precise dimensions of the model were relatively unimportant. It was desirable, though, to maintain a close relationship between model and original, so that later we might hope to use the model as a medium for communicating a true impression of the original to the public without having to rely on their understanding of the insignificance of any observable compromise.

Overall, however, there was little point in going through the very time-consuming process of establishing some dimensions closely, when many others would have to be estimated. The pragmatic solution was to model the instrument on the basis of close approximations to the dimensions and proportions of the original, and it proved possible to do so on the basis of very few absolute measurements. Beyond these we worked from photographs and radiographs, and largely by eye. In fact, no working drawings were prepared; beyond those few check-measurements, the parts were made to “look right”.

Following replication of the parts that remain, we addressed the task of devising restorations of the many that are lost. Here we note only that the dimensions and proportions of the extant parts were taken as guides to the design of all further parts. A separate section is devoted to the more general problems of restoration.

Materials

The problem of replicating the material specifications of the original is yet more difficult than that of copying its dimensions, and seems likely to remain so. Arguably it is at least as important. The choice of materials for an artefact can have a profound effect both on the ease of manufacture and on its satisfactory function. Our reconstruction might be made to the right design and to the right dimensions, using techniques agreed to have been available to, and likely to have been used by, the workman of that time; but if it were built of inappropriate materials, then doubt might remain as to whether it reflected truly either the construction or the function of the original. We consider, however, that the pragmatic compromise that we adopted is acceptable.

It is often stated that the instrument was made of bronze. That is what we would expect for this sort of light metal construction from antiquity. The surfaces of the fragments certainly have the appearance of the corrosion products of bronze, and the radio-opacity of the material is right for bronze. Analyses of some small detached fragments, reported by Price, suggested a bronze with a fairly low proportion of tin (and little else), but unfortunately the tin-content could not be determined with precision[13]. The range within which it was thought to lie is, however, appropriate both for workability and for mechanical strength. So although, strictly speaking, we have no guarantee that these fragments came from the instrument at all, we suppose – provisionally – that they are indicative of the material used for the working parts of the Mechanism.

It appears, however, that some parts were made of a different alloy. Non-destructive tests have recently been carried out on some fragments small enough to be placed in the chamber of an electron microscope[14]. The pieces selected are all ones that bear inscriptions: parts of components called “door plates” or “cover plates” which seem to have formed external covers, lying over the dials. A preliminary announcement indicates that these sheets were made of an alloy with little copper and a very high proportion of tin: a pewter, which is certainly very different in its mechanical properties from the bronze indicated by the previous analyses. So soft a material would have been useless for most of the mechanical parts of the instrument, but a good choice for sheets subjected to little stress which were to be extensively engraved with lettering. The sheets might have been backed by wooden boards to give the covers sufficient mechanical strength; but this remains no more than a guess because no trace of any means of fastening has been noticed on these pieces.

The new analysis, revealing the presence of a material of very different properties from the bronze previously found, raises the possibility that, quite apart from accidental variations such as those due to the reuse of scrap or the preparation of separate batches of alloy, different materials may have been chosen for individual working parts in the attempt to exploit their individual properties. We do not know, for instance, whether it was then recognised that friction and wear are reduced if dissimilar metals are used for parts that rub on one another.

Some observations may be made on the way in which the parts were formed. Just a few parts – spacers and bosses – are of substantial thickness, up to about 10 mm. These may have been prepared as castings, but the odd profiles of some suggest that they were in fact pieces of scrap material, cut down to fit. Arbors may have been cast as rods before being dressed to the required forms and sizes, or they too may have been cut from larger pre-existing pieces.

Most components were, however, of a fairly uniform thickness, about 1.5 mm., and these appear all to have been cut from sheet, bent up where necessary. We do not know whether they were all cut from a single sheet or from several sheets, perhaps made from separate melts. Such sheets would have been cast as slabs which would then have been hammered down to the required thickness, perhaps finished by being scraped or scoured clean.

Aside from their composition, we remain uncertain of the metallurgical state of the components. We would wish to know whether the metal was left as cast, or underwent hammering or other cold-working; and if so whether it was subsequently re-annealed. The stiffness (influencing the strength of components in bending) and the hardness (dictating the resistance to wear) can vary enormously according to such treatment.

For pieces made of sheet, the slab must have required annealing at intervals during the process of beating out; but we cannot lay down any rule as to whether the finished sheet would then have been annealed or left in a work-hardened state. Some non-planar parts were clearly bent up from sheet, which could have been done successfully only after annealing. Typically, however, we find that they have subsequently cracked and broken along the line of the bends. This suggests strongly that they were not annealed after bending, leaving the metal more highly stressed in the region of the bend and liable to the propagation of cracks due to stress-corrosion. In any case, the fact that the material of these parts was beaten out into sheet and then bent up shows that it was not a particularly high-tin bronze, for which this manipulation would have been difficult or, with a very high tin content, impossible. None of this, however, tells us anything about composition of the arbors or of any other parts that may not have been cut from the same sheet.

It may be that further analyses will be carried out in due course, but difficulties will remain. The instrument has spent nearly two thousand years in seawater and considerable chemical changes, such as leaching, may have taken place. On examining radiographs one sees a bright line around the margin of most components, which seems to indicate the migration of tin (of higher atomic number than copper, and so of greater radio-opacity) from the mass to the outside of each part. It follows that any analysis which samples only the surface layer is likely to suggest a deceptively high tin content.

Faced with the possibility that the parts of the original were made from a range of bronze alloys, and with continuing uncertainty as to the exact composition of any one part, we needed a pragmatic solution to the problem of choice of materials for reconstruction. The properties of bronzes vary greatly, depending on the tin-content and the presence of other constituents. As we have indicated above, it was important both to avoid enhancing the operation of the instrument by choosing metals of a higher performance than the original, and to show that we did not evade supposed problems of construction by choosing metals that were significantly easier to work. However, the mechanical behaviour of a low-tin bronze, as indicated by the early analyses, differs rather little from that of modern commercial brass[15]; consequently, for the parts made from sheet-metal, readily-available sheet brass was used. Not only is it far cheaper than bronze, but enough brass of a suitable thickness was already to hand in the workshop; most of the parts were cut from a kicking-plate found on a discarded door, while the main frame plate, a rather thicker piece, was cut from an old office name-plate. Some of the spindles were made of drawn brass, and a few were of soft mild steel. Other thick parts were made of brass scrap.

All the brass used was of rather inferior quality. Compared to the bronze supposed to have been used in the original, it is less stiff and less hard. The same may be said for the few pieces of soft steel used. The parts of the model are therefore less strong, and will wear faster, than they would if made of bronze. Brass sheet is more easily bent to shape, but this difference is not significant; bronze calls for more frequent annealing, but otherwise it is merely a matter of how hard it must be struck. Brass is easier to cut out (using hammer and chisel), but in the accurate formation by filing of gear-teeth and other delicate profiles it is actually easier to work with the firmer bronze, provided one’s files are sharp. The most important point in our choice of brass was that, far from being enhanced, the performance of the instrument was likely to fall short of what it might have been using bronze. If a reconstruction in brass worked, one could be sure that a similar instrument made of bronze would work better, and last longer.

The Design of Lost Parts

Since the Antikythera Mechanism is highly fragmentary, in preparing a reconstruction we were obliged to design replacements for lost parts; and in doing so we introduced some degree of conjecture. We may distinguish three different levels of restoration, carrying with them different degrees of certainty.

The first concerns that part of the internal mechanism which is largely preserved, comprising gearing that drives dial displays for which we have direct evidence: on the front dial, pointers for the places of the Sun and Moon in the Zodiac and the date, and the display of the phases of the Moon; and on the back dial, pointers for the calendrical and eclipse cycles and for the preserved subsidiary dials. While many surviving components are damaged and incomplete, the restoration of most of their forms called for little comment and has provoked no significant controversy. This is not to say that all would-be reconstructors agree; but to date we believe that in all cases of disagreement our observations have proved at least as satisfactory as any others. Thereafter it remained necessary to devise replacements for further components and details, now absent from the original, needed to allow this part of the instrument to function as intended. Here there may be more scope for continuing discussion over the detailed design, even though it is remarkable how far precedents may be cited from among the parts that remain; and in any case the small scope for changes means that they can have only a minor effect on form and function.

Our second level of restoration concerns interconnected questions about the instrument's overall structure and casework. Here the evidence is harder to identify, and there may consequently be less agreement. Small traces of woodwork indicate that the metal mechanism was fitted within a wooden case. Early photographs show more than now remains[16], but there is enough evidence for the reconstruction of a rather complicated, stepped design in place of the simple rectangular design favoured by others.

Nearly all the surviving mechanism, comprising most of the largest fragment of the instrument (fragment A), was mounted on a rectangular frame plate which lay between the two dials. Fragment A also includes a piece of the back dial plate. Down one side, between the frame and dial plates, lies part of a wooden batten separating the two. To the outside, covering the edge of the frame (but not of the dial, which was evidently wider), lies part of a broader piece of wood which formed the side of the case. The early photographs show a third piece of wood, against the end of the frame plate and meeting the second piece at right angles. It is now lost, but it has left a print in the mass of corrosion products surrounding the frame plate, showing that the two pieces came together in a mitred joint. This detail can be understood only as an external corner, showing that the case embraced the frame plate closely all round. We have no indication of its depth, but it certainly did not extend to the rear beyond the inner face of the back dial plate which is seen to be both wider and longer than the frame plate. Details seen in the recently-discovered fragment F – a corner of the back dial plate with traces of wood surrounding it – confirm our conjecture that the woodwork was stepped out to accommodate the large back dial.

Rotating arbors extended from the internal mechanism through the dial plates to carry pointers, but there is no evidence that either dial plate was fastened to the frame plate by metallic components. The simplest assumption – always to be preferred where there is no contraindication – is that each of these three plates was fitted separately to the wooden case. In our reconstruction they rest in rebates in the wooden case; the square front dial drops in to the front of the case, while the taller rectangular frame plate and still larger back dial plate are both inserted from behind.

We know that the front dial was inserted from the front because on the back of the remaining corner of the front dial (preserved in fragment C) is a small bolt which was worked from the front by a thumb-button. We have fitted four such bolts, one to each corner of the dial; but equally there might only have been two at adjacent corners, the opposite edge having a joint or being held in place by a ledge. We adopted the simplest possible shape for the front of the case. Its rectangular section, dictated by the form of the frame plate, continues to the front where it is rebated to accept the square dial and two further pieces that fill the openings above and below the dial. In the first model the filling pieces are metal plates, but in the second they are wooden panels.

The frame plate is held into its rebate from behind by two battens, modelled on the fragmentary one observed in the original, and the back dial lies directly over them, in its larger rebate. Too little of the back dial remains for us to have evidence of the means of holding it in place. Conjecturally, we have fitted it with four bolts modelled on the one from the front dial mentioned above. Possibly this dial was not so readily removable as the front dial, but for our purposes, in demonstrating the construction and function of the internal mechanism, it is convenient to be able to take it out without using tools.

The contrate wheel of the original, through which motion was transmitted to all the internal gearing, is found in fragment A stuck to the frame plate by the cohesion of corrosion products, but there is no fastening to hold it there. We suppose that the “cradle” in which it seems to lie is the remaining part of a circular socket which was fixed to the side of the wooden case; and this is how we have modelled it. The inner part of the socket holds the contrate wheel in place, while the narrower outer part forms a bearing for the stem of a wooden driving knob. The knob is adopted in place of the winch handle suggested by others, since the available evidence suggests that the winch handle was a mediaeval invention.

Our third and final level of restoration refers to further features, beyond those obviously required by the functions listed above. There is evidence for such parts, but it is rather far from obvious and other researchers have tended to suppress it; nevertheless its presence cannot be either denied or ignored. We refer mainly to additional mechanism, driving further pointers on the front dial to indicate the places in the Zodiac of the five planets known in antiquity. Our reasoning for these inclusions has been given in outline elsewhere, and we intend to publish in greater detail on the relation between the design of our restoration and the development of Hellenistic astronomy. Here we confine ourselves to a short discussion of practical considerations.

The restoration of epicyclic mechanism to the largest wheel of the original – the *Mean Sun Wheel*, seen on the front of fragment A – suitably proportioned (with the necessary large epicycle) to drive an indicator for the planet Venus – makes sense of several features that otherwise remain unexplained: not least, the size of the wheel itself. The addition of two further epicycles driven by the same epicyclic gear train, for Mercury and for the solar anomaly, satisfies ideas of consistency and completeness while remaining compatible with the physical evidence. These three epicycles are carried round on the Mean Sun Wheel, as the astronomy requires, at the rate of the Sun (one revolution representing one year); and they are rotated, each at its own speed, by gearing that derives its motion from engagement with a fixed central wheel. We make these points to illustrate the origin of our design for further mechanism for the planets Mars, Jupiter and Saturn.

For these three planets (“superior planets”, as opposed to the “inferior planets” Mercury and Venus) the astronomical model is inverted; the epicycle is carried round at its own speed, but it rotates on its own axis at the speed of the Sun. For each planet this entailed repeating the ensemble restored to the Mean Sun Wheel, with the function of the gearing that drove it inverted, and with the size of the epicycle and the gear ratio chosen to suit the particular planet. Thus three epicylic assemblies were added, but no wholly new mechanical ensemble was introduced because every feature could be related to a precedent already found in the instrument.

The mechanism for Mercury and Venus occupied space which would otherwise have been void, but the inclusion of the extra stages, for Mars, Jupiter and Saturn, called for a small increase in the depth of the case beyond what would otherwise have been necessary. However, that dimension was not defined by what remains of the instrument, so no difficulty arose. Moreover, current work by others, who are reading more of the fragmentary inscriptions on the outside of the instrument, seems increasingly to indicate that the instrument did indeed display planetary motion or events in some way. We maintain that our reconstruction fits the evidence well, and better than any other that has yet been offered.

The simple arrangements described in this section have proved wholly satisfactory in practice, as the model has been taken on extensive tours on which it has repeatedly been demonstrated and disassembled in front of audiences.

Workshop Tools and Technique

Reconstruction proceeded without any need to prepare drawings. After taking thought, and in a few cases making a rough sketch, we found that each new part or assembly simply “designed itself” and fell into place. It is an essentially modern idea that mechanical work must or should be drawn out before it is made, and we ought not to be surprised that it proved possible to dispense with drawing when reconstructing an instrument that was probably not drawn out in the first place. To have achieved this without any drawing seems to us to lend weight to the validity of the outcome.

This validity would however have been called into question if its construction appeared to depend on the use of tools or techniques not available to the maker of the original. Rather than attempting a strict re-enactment of Hellenistic workshop practice, we thought it appropriate to use our own familiar tools but to remain aware of the probable differences between ours and the ancient ones, and to select tools and techniques that would keep these differences small. Most of the work was in fact done using a fairly small selection of hand tools, of which sufficiently similar ancient specimens are known or attested to by the existence of characteristic tool-marks on artefacts. Many historical examples, drawn from the Roman Imperial period, are a little more recent than the Mechanism; but the demonstrable heavy dependence of Roman material culture on Hellenistic technique, the stability of well-established craft practices, and the inertia due to the conservatism of craftsmen, all allow us some historical latitude. To answer a challenge often made, tools of steel were widely available, even though the underlying metallurgy was not understood until modern times. The main difference between the tools of the Hellenistic mechanic and our own is, we suggest, one of efficiency and perhaps of durability, not one of capability. Perhaps the greatest single advantage that the modern mechanic has over his Hellenistic counterpart is in the use of a firm screw-vice to hold his work.

There were many holes to be drilled, including a ring of 365 very small ones in the front dial plate (hidden behind the calendar ring). All these holes could have been made using simple drills, such as the traditional watchmakers' bow drill. We however used a small mechanical drill press for making most of the holes.

There is little doubt that some parts of the original were turned in a lathe, and we certainly found it convenient, if not absolutely necessary, to use one too. The arbors, bushes and similar parts were turned in a foot-lathe built in about 1820, employing hand-held cutting tools and techniques like those habitually used in making clockwork. This machine is far more handy than any Hellenistic lathe, but the two would have been not too distantly related, and we emphasise that in any case none of the parts really had to be turned. In this context the lathe can be regarded simply as a labour-saving device.

Some commentators have seen the making of the gear wheels as a matter of difficulty or at least of wonderment, supposing that such gear teeth could have been made with sufficient precision only by the use of some sort of appliance or machine. The wheels of the original are, though, not particularly precise; we judge that they are just good enough to run adequately. The form of the teeth may have been reasonably consistent, but the angular separation between adjacent teeth, which can have been very little affected by either wear or damage, is quite variable. Appearances are consistent with the teeth having been cut by hand using a file or slip of abrasive stone, after being marked out in a separate operation. Whether this were done by copying from some sort of pattern such as a division plate, or originally (that is, not by copying) for each wheel, is debatable. We have presented an argument for believing that a division plate may have been employed, but even so the teeth would still have been cut by hand[17]. In any case, we have demonstrated on many occasions that wheels of this size may be divided into any chosen number of parts, with sufficient accuracy, using no more than a pair of compasses; and the whole operation can be performed quite fast. When the writer was younger (and so did not need reading-glasses) he found that, taking both operations together, the work could be done at the rate of about 30 seconds for each tooth[18]. The point did not have to be proved again, and so for this reconstruction nearly all the teeth were cut by simple machinery.

Otherwise, we used a machine-tool only for cutting the long S-shaped "spiral" slot in the back dial plate. The geometry is actually a chain of semicircular arcs struck from different centres. Probably the maker of the original scribed the centre-line of the slot and filed it out, perhaps first removing the bulk of the material by "chain-drilling" a series of closely-spaced holes. For expediency, we cut the slot using a slot-drill in a light vertical milling machine, the plate being rotated under the drill about the desired centre for each semicircle.

Joints in the original can be seen to be secured using cotters, rivets formed on the ends of arbors, rivet-pins and nails. Possibly some were also soldered. The details of the original fastenings were replicated where they could be identified, and similar details were adopted elsewhere, with this exception; screws were substituted for some rivets so as to facilitate disassembly. Careful thought was taken in introducing these unauthentic – and anachronistic – fastenings, to ensure that they should not enhance the performance of the altered assemblies in any significant way.

Experience of Wear and Breakdown

The first model was built in stages, as our reconstruction progressed. The front dial, with most of the gearing driving its display, was first assembled in the winter of 2001 – 2002, and it has been widely demonstrated ever since, a period of nine years at the time of writing. Not the least interesting thing about it has been its history of breakdowns, almost always of the same components in the gear-train leading from the one-turn-a-year motion of the Sun and date hands to the one-turn-a-month motion of the Moon hand: an increase in velocity of over twelve times. It is not at all surprising that this happens, in view of the almost unbelievably crude form of the gear teeth, and the far greater difficulty in obtaining a satisfactory action when (as in this train) the driven wheels run faster than the drivers. Some of these wheels have now been replaced five times. Reconstruction has allowed us to experience and appreciate at first hand shortcomings in the design and execution of the original.

Conclusion

In our study of the Antikythera Mechanism, physical modelling was an important feature of the process of reconstruction, and reconstruction was in turn essential to the development of our understanding of the instrument. The experience of making the mechanism led us to significant insights as to why and how parts were fashioned as they were. Without this, and the stimulus of being obliged to restore lost parts to create a coherent and functional whole, our present grasp of the nature of the original, of its good features and its shortcomings, would have been hard to acquire. The experience of working the model and demonstrating it to others has developed a heightened awareness of the way in which the original might have been viewed and used in its own context.

These ends were best achieved by modelling the instrument as faithfully as was practicable. In doing so, we accorded other desiderata a lower priority. For example, in viewing this model, with its gears in closely-spaced layers and enclosed in a wooden case as in the original, the onlooker is denied any immediate appreciation of the internal arrangement and function. That end could better have been served by fitting up the wheel-work in more widely-spaced layers, in a skeletonised frame or one made of transparent material, as others have done; but to do that would have been to compromise seriously the basic validity of the reconstruction.

Computer animation has advantages in communication with the public[19]. The virtual model is portable, clean, easy to store, easy to stop and start whenever one chooses and to watch for as long as one wants. The internal mechanism is seen to move, without the inconvenience of the box getting in the way. However, the virtual model has no friction and suffers no wear. There are no questions of mass, inertia, weight, strength, stiffness or working loads. It is no more than a moving diagram. Without the validity conferred on it by the working of the physical model it would be of very little value, and it lacks much of the appeal of "the real thing" which, we find, the physical model does most definitely possess. It is however an immensely valuable expository device, to supplement the physical reconstruction.

Words in print seem likely to remain paramount as the formal records of our thoughts, and we have much more to write about the Antikythera Mechanism. Before that, though, we believe it has been valuable to show other people that the reconstruction works, and to show how it does so. The fact that it works does not guarantee that the reconstruction is right, but it is a *sine qua non*; more generally, the sight of the reconstructed instrument in motion is the most convincing demonstration possible that it is at least plausible. If a picture is worth a thousand words, an artefact is worth many pictures and a working instrument is worth many more. To put the point differently, there is a case for accepting physical reconstruction as a medium for publication.

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[1] Athens, National Archaeological Museum, inventory number X.15087.

[2] The author's website www.mtwright.co.uk, now under develoment, is intended to provide further information and a full list of his publications.

[3] The author's first model has been demonstrated on a number of documentary programmes broadcast on television. A short amateur video-recording, made by Jo Marchant, has been posted on You Tube. It may be found on Dr Marchant's website www.decodingtheheavens.com under "The Device".

[4] All the author's significant papers to 2006 are listed with full bibliographical details in a review paper: M.T. Wright, "The Antikythera Mechanism reconsidered" Interdisciplinary Science Reviews, 2007, vol. 32, no. 1, pp. 27 – 43. Further papers are in preparation.

[5] Important contributions to the present understanding of the instrument have been made by members of the Antikythera Mechanism Research Group, who have published two papers to date: T. Freeth et al., "Decoding the ancient Greek astronomical calculator known as the Antikythera Mechanism", Nature, 444 (30 November 2006), pp. 587 – 591; T. Freeth et al., "Calendars with Olympiad display and eclipse prediction on the Antikythera Mechanism", Nature, 454 (31 July 2008), pp. 614 – 617. See also the Group's website, www.antikythera-mechanism.gr.

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[6] An accessible account may be found in: J. Marchant, Decoding the Heavens, William Heinemann, London 2008.

[7] D.J. de S. Price: “An Ancient Greek Computer”, Scientific American, Vol. 200 No.6, June 1959, pp. 60 – 67.

[8] D.J. de S. Price: “Gears from the Greeks”, Transactions of the American Philosophical Society, Vol. 64 No.7, 1974; reprinted as an independent monograph, Science History Publications, New York 1975.

[9] M.T. Wright, A.G. Bromley and H. Magou, “Simple X-ray Tomography and the Antikythera Mechanism”, PACT (Révue du groupe européen d'études pour les techniques physiques, chimiques, biologiques et mathématiques appliquées à l'archéologie), vol.45 (1995), pp. 531 – 543.

[10] Exhibition Galileo: Images of the Universe from Antiquity to the Telescope, Palazzo Stozzi, Florence, March – September 2009. Catalogue with the same title, ed. Paolo Galluzzi, Giunti, Firenze 2009. Catalogue entry II.4.3, p. 135.

[11] Exhibition Ex Oriente Lux? Wege zur neuzeitlichen Wissenschaft, Landesmuseum fűr Natur und Mensch, Oldenburg, October 2009 – January 2010. Catalogue with the same title, ed. Mamoun Fansa, Philipp von Zabern, Mainz am Rhein 2009. Catalogue entry VI.6, p. 382.

[12] M.T. Wright, “A practical approach to studying the Antikythera Mechanism”, XXIII International Congress of History of Science and Technology, Budapest, July – August 2009. No proceedings were issued, but an independent paper is in preparation.

[13] Price 1974 (note 8), Appendix I (pp.63 – 66).

[14] Mary Zafeiropoulou & Panhagiotis Mitropoulos, “The Antikythera Shipwreck, the Treasure and he Fragments of the Mechanism”, XXIII International Congress of History of Science and Technology, Budapest, July – August 2009. No proceedings were issued.

[15] A useful overview of the properties of a wide range of brasses and bronzes may be found in C. Holtzapffel, Turning and Mechanical Manipulation vol. I, London 1842, p. 266 ff.

[16] The earliest photographs are those publsihed in I. N. Σβορώνος, Το εν Αθήναις Εθνικόν Μουσείον, Athens, 1903, subsequently published in German as J. N. Svoronos, Das Athener Nationalmuseum, Athens, 1908. Some are reproduced, but poorly, in Price 1974 (note 8).

[17] Wright 2009 (note 12).

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[18] M.T. Wright, “Rational and Irrational Reconstruction: the London Sundial-Calendar and the Early History of Geared Mechanisms”, History of Technology, 12 (1990), pp.65 – 102.

[19] Several computer animations, illustrating different recontructions of the Antikythera Mechanism, can be found on the web. Particular attention is drawn to one prepared by Mogi Massimo Vicentini, based on data provided by M.T. Wright, which may currently be accessed at http://brunelleschi.imss.fi.it/galileopalazzostrozzi/multimedia/TheAntikytheraMechanism.html.