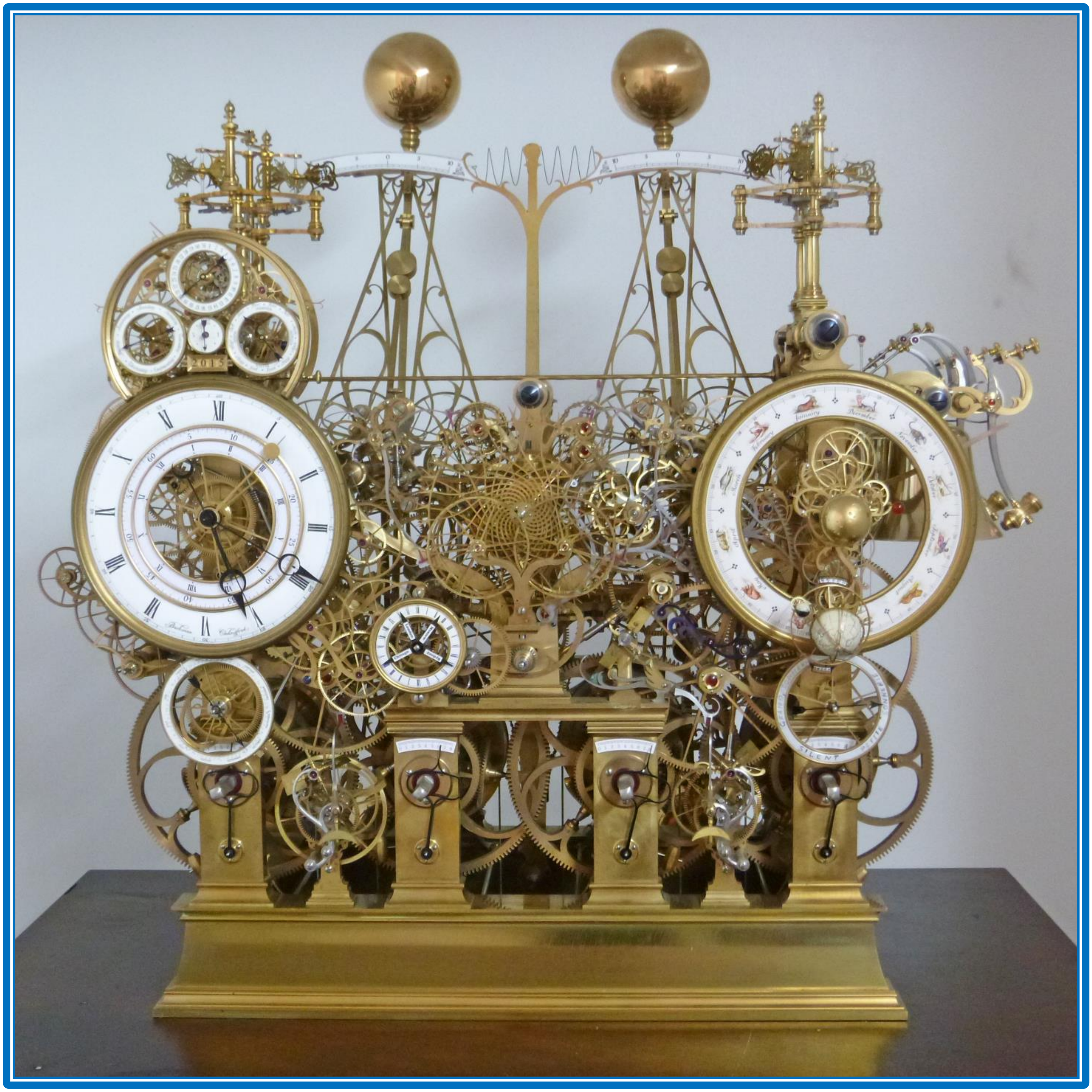
# An Astronomical Skeleton Clock

## Where we stand after six and one-half years of construction



## Overview

In August of 2007 the NAWCC *Bulletin* published the first article on a complex astronomical skeleton clock commissioned by the author and being built by Buchanan of Chelmsford, Australia.[1] At that time a detailed full size wood mockup was completed and that article covered the proposed clock's mechanical specifications and functions as depicted through the mockup. A follow up article was published in April 2011 marking roughly the halfway point in the construction. At that time the four movement trains with much of the 'between the plates' components were completed. These are the time, celestial, basic quarter and hour strike trains.

As of July 2015 we are a decade on since the initial design and mockup and six and one-half years into construction. Right after the April 2011 *Bulletin* article there was a hiatus of two years during which time Buchanan had moved his shop to new quarters and taken on an intricate restoration project of another complex astronomical clock which was also the subject of a three part series in the *Bulletin*.[2] Construction recommenced in the middle of 2013. I estimate completion sometime in 2018. In this third segment I will cover what has been accomplished since the 2011 *Bulletin* article. The entire left hand side of the dial complication work is complete as well as what is represented by the small dial below the large tellurian ring on the right, the strike selector, (Figure 1, prior page). The dial work is comprised of a third-order, reversible perpetual calendar. An equation of time and sidereal time functions that are overlaid by the mean solar time dial work allowing one to see the difference between all three types of time simultaneously. A small world time dial as well as the strike selector representing completion of the quarter repeat on demand in Grande Sonnerie as well as silencing.

At this point one might ask, "Why is this taking so long?" I would direct the reader to the earlier two articles for a full explanation of the complexities and mechanical innovations of this clock. Very briefly we are creating a machine that will have nearly 10,000 parts; including about 400 wheels, four remontoire, dual Harrison grasshopper escapements, compound and epicyclical governor fly fans and depending on how one counts, about forty complications.[3]

I knew we could not create the world's most complex skeleton clock, either in the number of complications or components. That was beyond the scope of this endeavor, although excluding institutional public and church clocks, we will probably be within the top twenty or so made that is small enough to fit comfortably within a domestic setting. My ambition is to create one of the more visually fascinating clocks. I will create a machine that will immediately grab the viewer, hold him and not let go. There have been many clocks made with a variety of visually interesting features, especially those employing automata or complex musical apparatus. This creation focuses on the visual display of an overwhelmingly interesting geared mechanism – a "gear head's" delight. Our approach to every aspect of this machine's creation was, 'How can we make this part or mechanical system both beautiful and fascinating to the viewer?' This is done through the use of multiple, complicated moving components that are actuated in frequent and in one case unpredictable ways. The other and no less compelling feature will be the beautiful design and hand crafted innovative workmanship created by the Buchanan firm which I think the reader will see, is second to none. We have also included a bit of whimsy. There is a forest of wheels within an organic ivy themed upper frame structure. And what is a forest without animals? So we have birds to inhabit the trees as well as other parts depicting animal analogs within the structure of the machine. And finally the enormity of uniquely designed components will draw the viewer in through a journey of its many layers of mechanical discovery. I have borrowed liberally from the designs of the past masters of the horological arts, Tompion, Breguet, Janvier, Harrison, Schwilgue, Fasoldt, LeCoultre, and others. I can only hope that if there is a 'clock heaven' they are looking down at this creation with a smile. Video link: https://www.youtube.com/watch?v=lWd-HSOxCMM

Before I begin to describe what has transpired since the last time the clock was featured in the April 2011*Bulletin*, I want to address what often comes to the mind of people who see this machine, especially those who work in the field of clock fabrication, maintenance and repair. More to the point, "How in the world does one maintain let alone fix this thing?"

## Maintenance

An important goal we had in this project was to make this machine as trouble free and serviceable as one could accomplish given its enormous complexity. Horological history is littered with exceptional clocks that became unserviceable years after their creation and ultimately lost. A clock that does not work, unless recognized in time as a historically significant artifact, eventually will be regarded with neglect, contempt and ultimately destruction. The first area where we address this problem is in the pivots. This complex machine of nearly 400 wheels and 900 pivots will run oil free.[4] Oil is the number one reason why clocks fail. Oil eventually breaks down, dries out and is an attractant for contamination that will accelerate pivot wear. As Breguet is reputed to have said, "Give me the perfect oil and I will give you the perfect watch." We have chosen full ball and ball race ceramic bearings wherever ball bearing pivots are called for. Unlike metal bearings these require no oil whatsoever and are also immune to corrosion. They are used wherever we have heavy loading or there are rotational speeds in excess of once per hour or where the configuration of the pivot would make the use of a jewel impractical. The most common areas of the last example would be bearings in excess of 5 mm in diameter or where there is the need for nested bearings. Full ceramic bearings were fairly rare and expensive when the project was first conceived in 2003, but fortunately have become widely available in time to fulfill this important criterion. The remaining 550 pivots that are lightly loaded and have rotational speeds of less than once per hour will run in dry jewel bearings. This idea is not so radical; Jaeger LeCoultre has used this design in their Atmos clocks for decades. Why not use ceramic bearings in all pivots? The reason is that real jewels simply look beautiful. Some of the jewels are large, up to 5mm, and the play of light from a jewel bearing is quite eye-catching. All of the ceramic bearings will have a simulated jewel end cap held by three screws around the perimeter so as to keep them virtually dust proof and give each one the look of a jeweled chaton. Our use of Harrison's grasshopper escapement obviates the need for oil where it would be required in many other conventional escapements. This design has no sliding surfaces. Furthermore, the compound pendulums run at half the rate of Harrison's original one second beat in other words a two second beat, four second cycle. This results in all of the time train components running at half speed, again a nod to the Atmos way of achieving longevity between servicing.

We also avoid corrosion by using stainless steel for all of the wheel arbors and other steel parts which will not be later blued. In those arbors that run in jeweled bearings we insert hardened steel pivot points since stainless is not a suitable material in this application.

I estimate that the clock should be able to run successfully without the need for service for at least 50 years. That is, of course, barring unanticipated problems, and how many of those could there possibly be in a machine of this complexity??? But seriously we have tried in every way imaginable to over-engineer for this very problem of complexity, the oil-free nature of the clock being an important example.

**Repair**

But what happens when the movement has to be disassembled which at some point it must be? If we were to use conventional clock design, we'd have one or a few large interconnected plates between which all the wheels would be supported. This would make servicing very difficult because of the sheer number of wheels and their disparate sizes. Simply aligning all of the arbors to get them to fit into the plate being lowered onto them would be very difficult. Anyone who has serviced a three train conventional chiming or musical clock knows this. Our solution is to use a base flat bed frame upon which the individual movement trains are mounted, not unlike the common hybrid flat bed frame designs made popular in tower clocks at the beginning of the twentieth century. Basically the clock consists of four interconnected components. The first three are the upper frame components consisting of the time, quarter and hour, and the celestial trains, (Figures 2 through 5). They are all mounted on the lower flat bed frame containing the four going barrels and associated power duration indicators, (Figure 6).

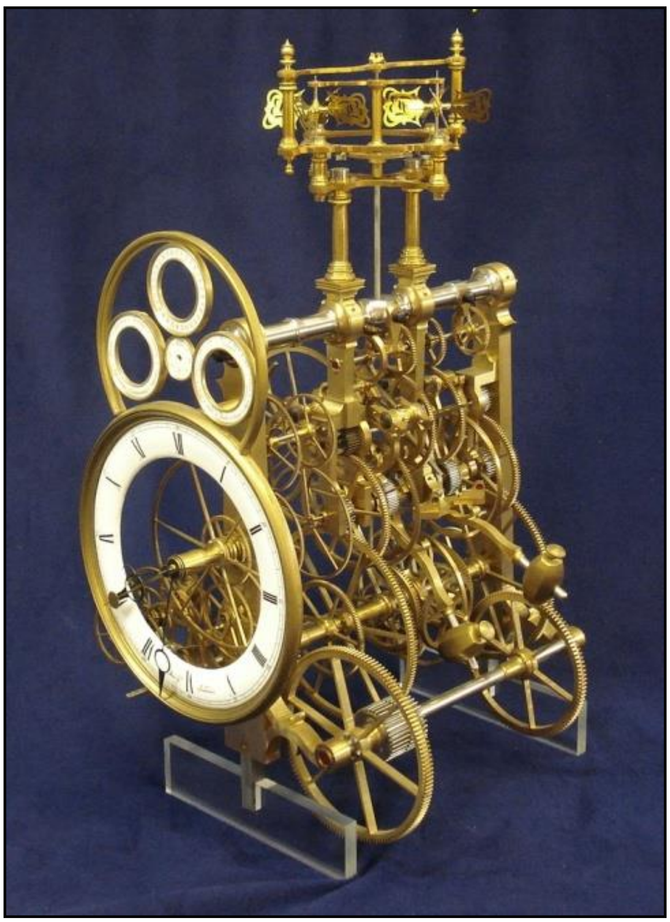
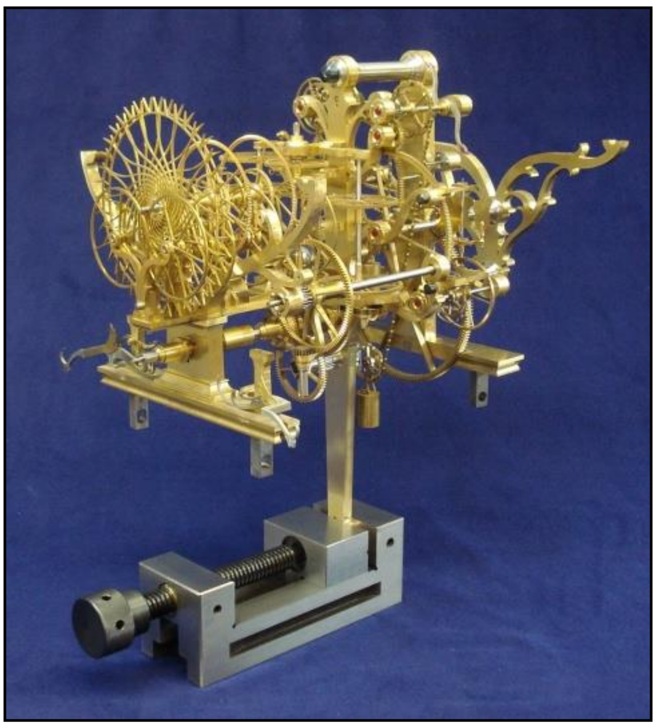
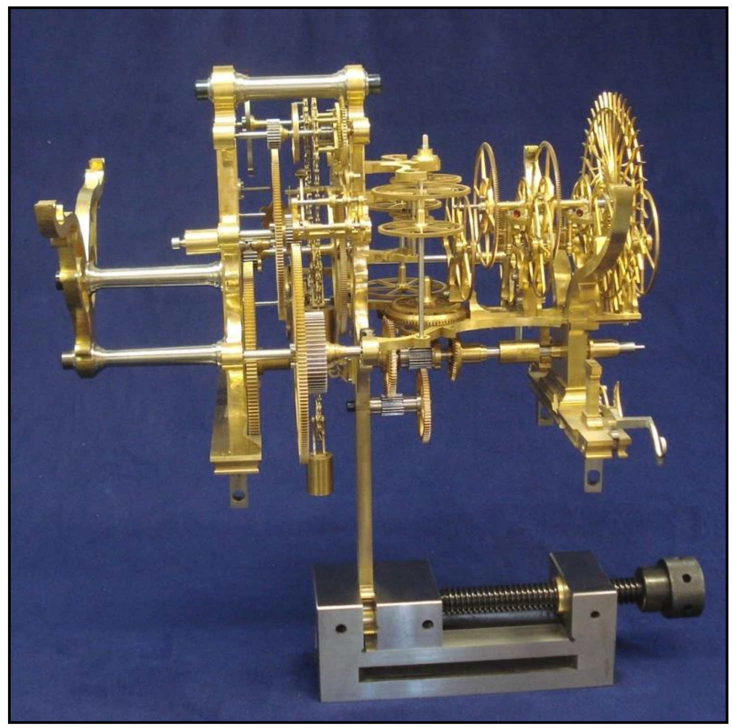


**Figure 2.** Left hand module, the time train

**Figure 3.** Right hand module, the quarter and hour strike trains

The time train has a dual Wagner gravity remontoire driving the pendulums.[5] However this train does not encompass all of the time train functions, (Figure 2). The escapement is located within the center module, the celestial train, for visual balance (Figures 4 and 5). Since the time train employs a dual remontoire it requires two fly governors. One is mounted directly above the time train which is located on the left sector of the clock, (Figure 2) and the other is mounted above the strike train which is located in the right sector, (Figure 3). Both the quarter and hours trains are contained within the one module. None of strike or repeat control work is shown here. Those parts as well as the strike fly governors are spread throughout the front of the clock. Due to the large number of parts it would have been impractical to keep them all within the confines of the strike train module. For esthetic reasons we located these components where they would have the most visual impact. All of the control levers, racks and fly governors are located on the outside of the front frames making their access as easy as possible without the necessity of removing any of the main train modules.



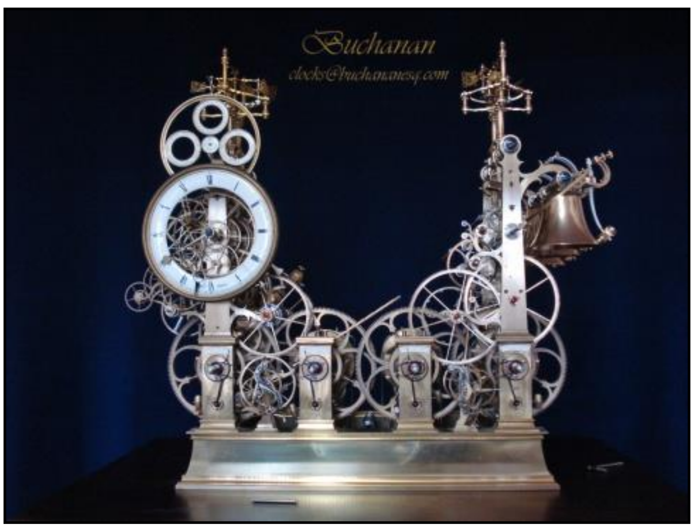


**Figures 4 and 5.** Center module, the celestial train and escapement with Robin remontoire

The center train drives the celestial functions. It also employs a Robin remontoire which controls the release for the timing of all of the celestial complications controlled by this train.[6] It also has the dual Harrison escapements and is the most complex of the three train modules mounted to the base frame, (Figures 4, 5).[7]


**Figure 6.** Base frame with the four train's main wheels **Figure 7.** The time train module is mounted to the base frame

The next two photos demonstrate the modularity of the clock design. First the base frame containing the main drive weight barrels along with the four state-of-wind indicators is shown, (Figure 6). Next the time train is mounted to the left side of the base, (Figure 7).



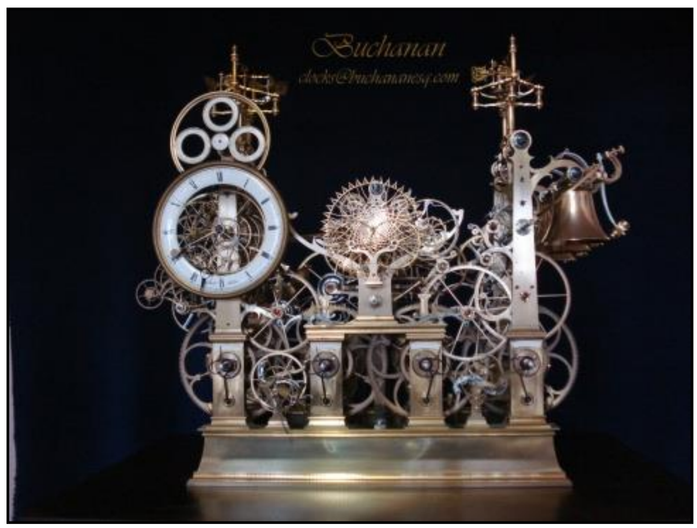




**Figure 8.** The strike train module is mounted to the base frame **Figure 9.** The celestial train is mounted to the base frame

Next the strike train module is mounted to the right side of the base. Notice how the upper frame pillar rises smoothly from the existing pillar attached to the base frame. We use a locking-cam feature contained within the frame structure to conceal the way these frames are secured to each other. The effect is a seamless look with no visible fastening points, (Figure 8). And then the center celestial train is added, (Figure 9). Most of the dial work has been removed for clarity. What is seen here is only half the number of final components. These are the 'between-the-plates' components, the drive trains. A similar number is needed to complete the strike and repeat work and the entire 'behind-the dial-work', components as represented by the clock's complications. In this article we will examine the control assemblies for strike and repeat work, the sidereal and equation of time functions, and perpetual calendar. At this point Buchanan had commented, "We have created the Christmas tree, now we must hang the ornaments." Bring on the ornaments!

## Strike and repeat work

The first components after completion of the basic strike drive trains, to be designed were the fly control governors. The various fly governors are a major visual component in this project. They are the parts that have the greatest visual attraction when activated and if designed properly also at rest. This special attention was demonstrated in the time train remontoire governors. Those ultimately utilized a double fly assembly for each of the two governors of our own design. For the strike governors I borrowed a design I had seen employed in a tower clock remontoire made by Charles Fasoldt, 1874.[8] Fasoldt employed epicyclical gearing and rotating whip which was used to engage a detent at the end of the remontoire recoil cycle. Clearly he did this for visual appeal and to demonstrate mechanical artistry; there were so many easier and straightforward ways to accomplish this job. I could see that Mr. Fasoldt was a man after my own heart.

We will use a pair of these and like the governors used for the time train remontoire they will be handed, in that one will spin clockwise and the other anticlockwise.

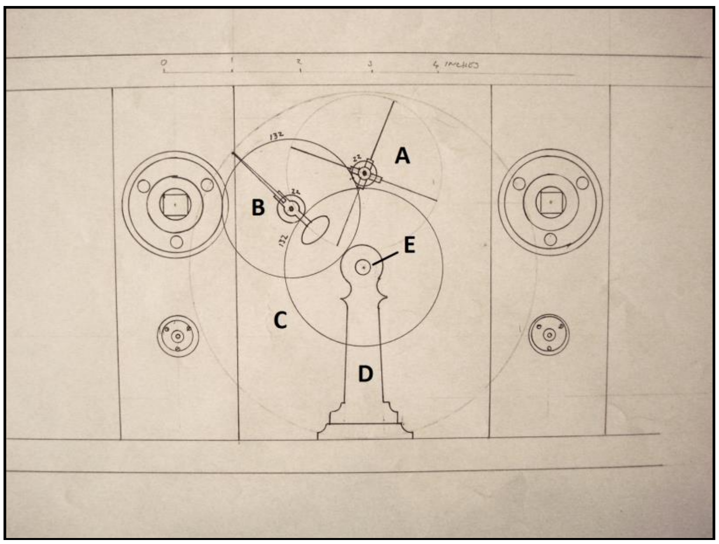


**Figure 10.** Diagram of Fasoldt's fly governor design

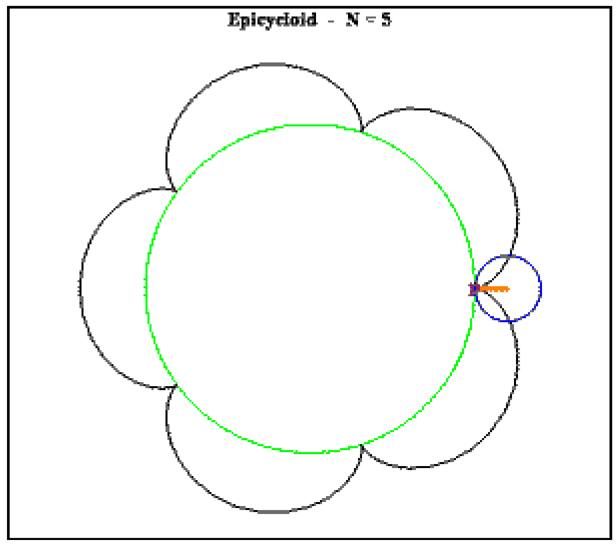


**Figure 11.** Epicycloid trace of whip tip

The first diagram closely represents Fasoldt's design, (Figure 10). A four-blade fly, **A**, meshes with a wheel that has a long train stop piece, what we call 'the whip' and is attached to a wheel, **B**, meshing on the outside of a toothed, center wheel, **C**, fixed to the frame pillar, **D**. The whip and fly wheels are contained within a rotating cage (not shown) centered on the axis of the fixed wheel, **E**. This design only allows for a small length for the whip since it must be able to clear the winding squares on either side. The tip of the whip traces an epicycloids petal pattern around the perimeter of the fixed wheel as illustrated in Figure 11.

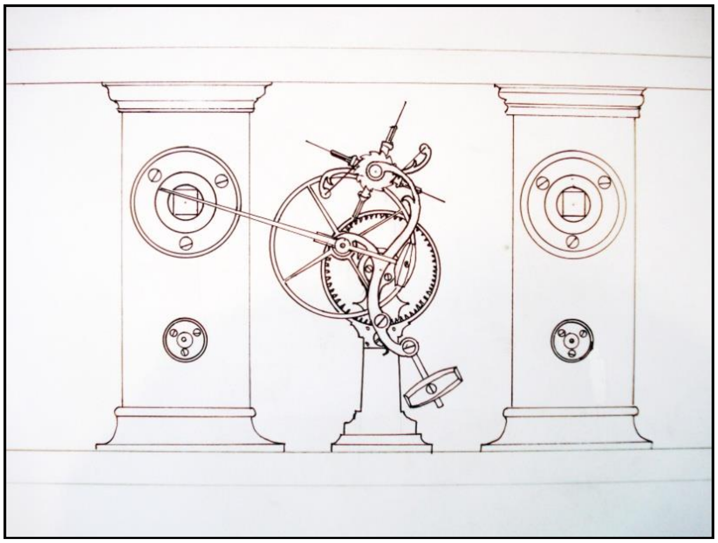


**Figure 12.** Revised design using internally toothed wheel

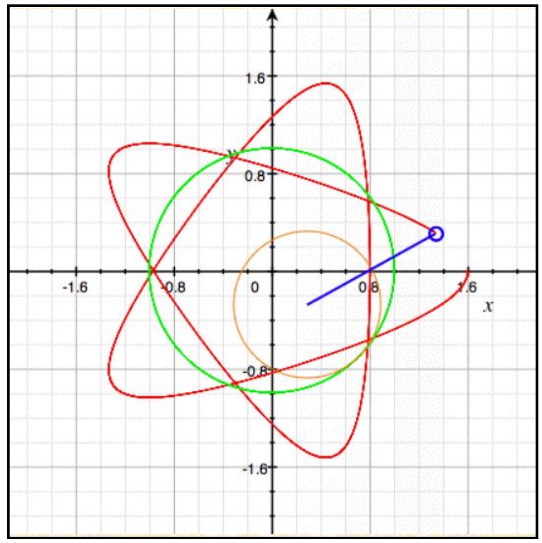




**Figure 13.** Hypocycloid trace of whip tip

Our revised design substitutes an internally toothed wheel for the conventional wheel fixed to the frame pillar. The wheel with the whip meshes with the internal teeth and drives the fly. The cage still rotates on an axis centered on the fixed wheel's axis, now shown, (Figure 12). This change results in two advantages over Fasoldt's original design. The first is that the tip of the whip traces a hypocycloid pattern, (Figure 13). Compared to the epicycloids diagram the length of the whip is greatly increased and visually this is desirable. The second is that employing the internal wheel teeth results in the whip traveling in the opposite rotational direction as the cage. This reduces the locking forces that come to bear when the longer whip stops the fly governor assembly as opposed to the cage, whip and fly fan assembly all rotating in the same direction. As an illustration, Buchanan drew the whip to actual length, but positioned it at the 'wrong side' of the fixed internal toothed wheel to show how much more whip tip is allowed past the winding square vs. the Fasoldt's original design. In practice this conflict could never occur since the hub holding the whip would be located $180^0$ opposite of its current position.

**Figure 14.** The two left and right hand strike train governors

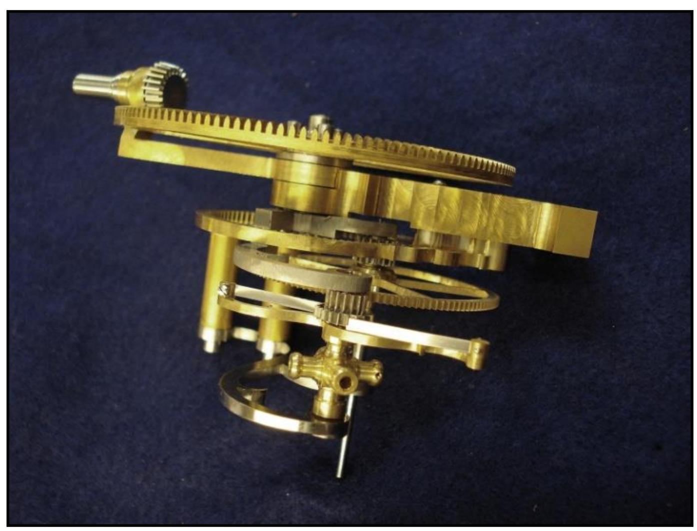


**Figure 15.** Side view showing variety of wheel styles

The completed pair of strike governors is just a bit more complex than a conventional fly design! (Figure 14). Notice the variety of gear cutting techniques employed. There are bevel, internal, conventional external, pinion and ratchet wheel teeth all displayed in just this one component, (Figure 15).

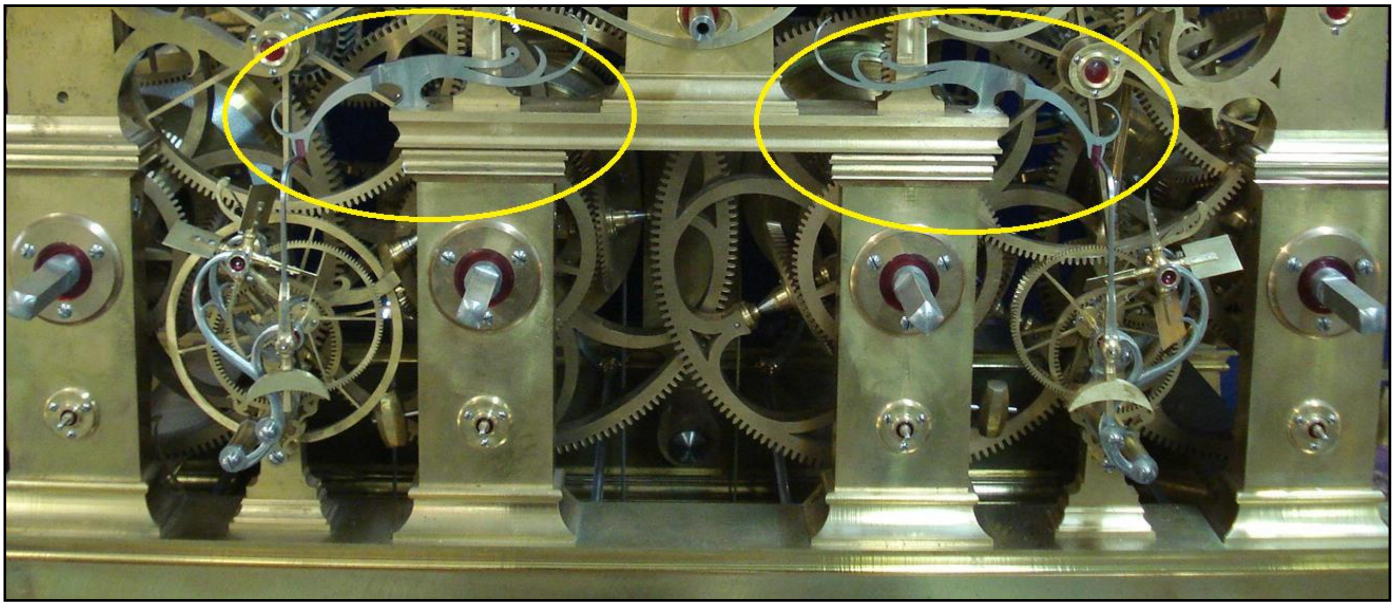


**Figure 16.** Quarter and hour fly governors with pair of bird analogue detent stops

The two fly governors are now mounted within the movement along with a pair of bird analogs serving as strike detents above each one, circled areas. The bird’s head is raised and striking begins, then its jewel beak lowers a bit with each strike cycle until it intersects the path of the whip, stopping the train, (Figure 16).

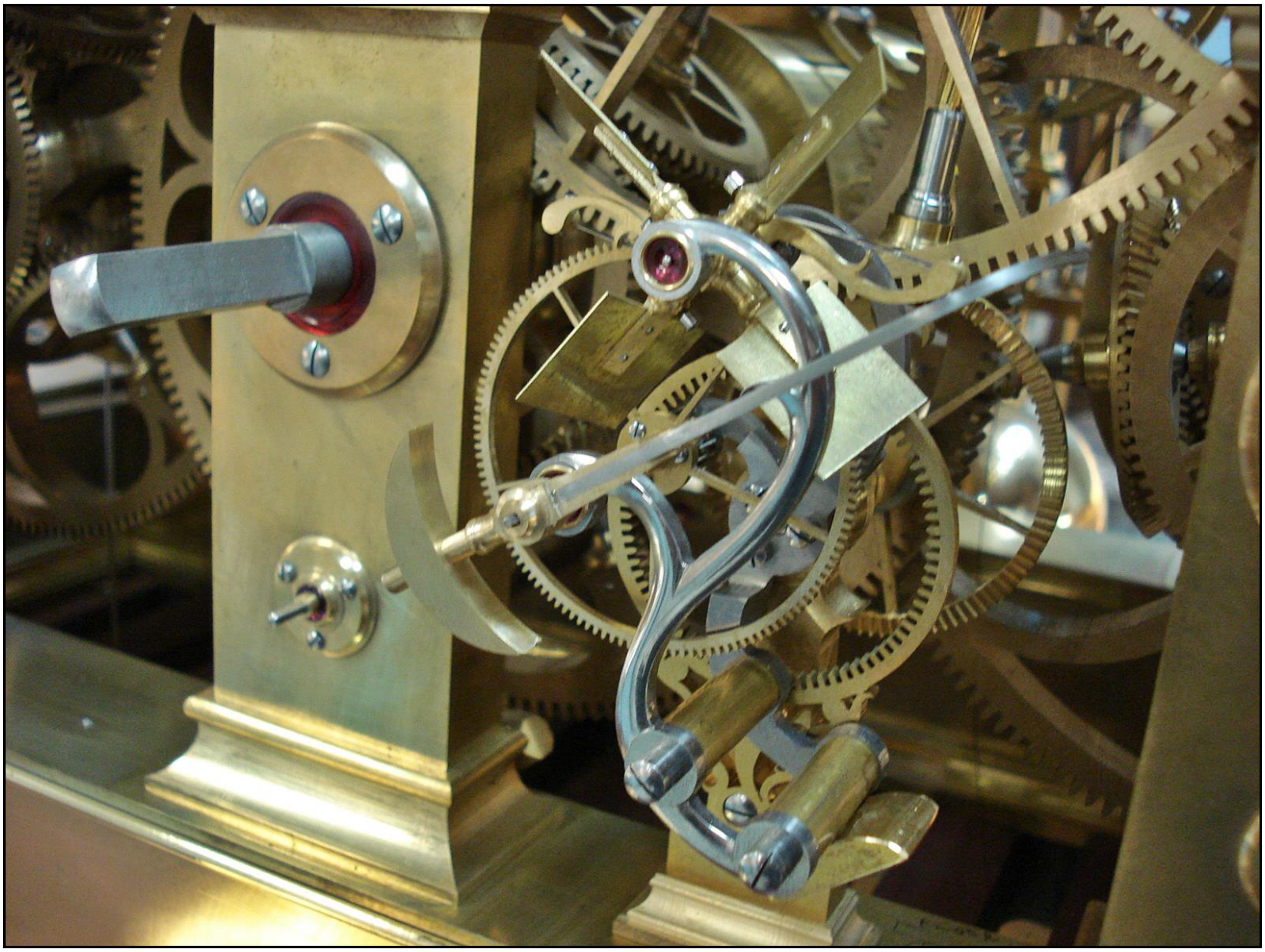
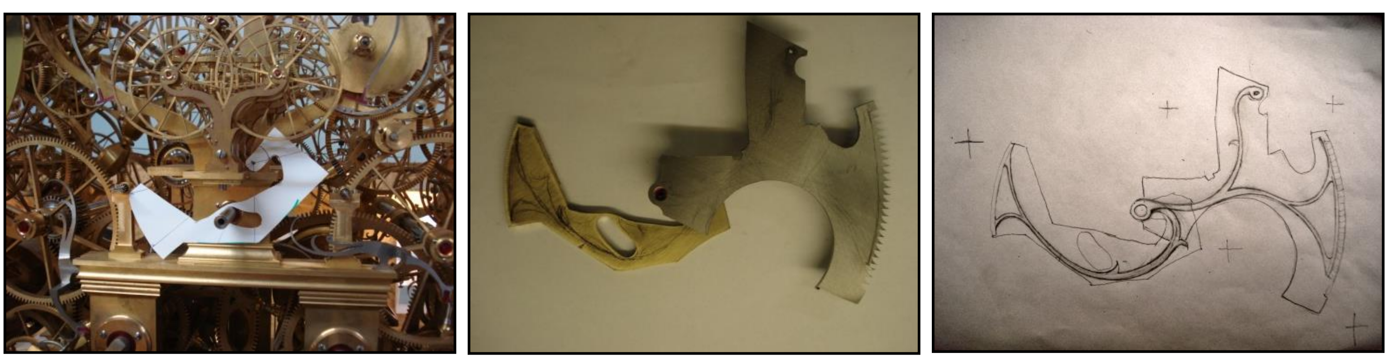
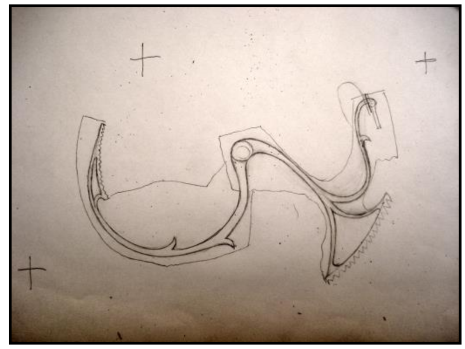


**Figure 17.** A close up of a strike governor with the sculpted stainless steel rotating cage

For the rotating cages we chose to make these a sculpted, sinuous design, rather than from flat stock. I wanted to convey a feeling of speed and grace to what looks very much like a tourbillon movement. The cage pillars have yet to be decoratively turned, (Figure 17). Next the strike and repeat work control assemblies were addressed. Video link:



**Figures 18 – 20.** The steps in making the hour rack



**Figures 21 – 23**. The steps in making the quarter rack

Figures 18 through 23 show the steps in the fabrication of the quarter and hour strike racks. First a paper mockup is made to satisfy the criterion that must be met for a functioning component, (Figures 18 and 21). These include the areas where the gathering pallets must contact the rack to count the strike and raise the rack, the rack pivot point and any areas that must be avoided to eliminate conflicts with existing components. In addition there is a sector gear attached to the opposite side of the rack that meshes with a fly governor. These are needed as the racks are quite large and we wanted the release to be mediated so as to eliminate any sudden drop. But to be honest it was another excuse to include a pair of fly fans that will enhance the visual entertainment when the strike is being 'set up' a few minutes before the actual striking sequence. After the paper mockup is verified for accuracy the part is made in metal, (Figures 19 and 22). At this point it is created only with regard to the critical functionalities and clearances. Once testing has confirmed that the component is working reliably, a drawing is made to depict the parts final appearance, (Figures 20 and 23). The racks are made from two different materials. The rack itself is made of steel, which we may later decide to blue or leave a polished steel depending upon how it looks. The other end is made of brass and this has a sector gear meshing with the fly pinion.

**Figure 24.** The completed quarter strike rack before finishing

**Figure 25.** Hand fret saw used to cut the racks and other parts

The curvaceous quarter strike rack before final form finishing, (Figure 24). Note how the sector gear, on the left, is steeply raked to compliment the general curvature of that part of the component. It almost disappears within the curve. Compare this to the drawing in Figure 23. The steel components are cut with an old fashioned fretting saw, all by hand with lots of elbow grease, (Figure 25).

**Figure 26.** Hour, quarter snails as nautilus shell cross sections

**Figure 27.** Interior toothed sector gear with ivy spur design

The next two photos show some of the various components used in the strike control mechanism. The first photo shows a pair of snails for the quarter and hour strike counts. They resemble cross sections of Nautilus shells, (Figure 26). This is no accident; it is in keeping with our whimsical animal motifs, in particular birds. Figure 27 shows an unusual internally toothed sector gear complete with the ivy spur design maintained throughout the project.

**Figure 28.** Gear in figure 27 with external sector, background

**Figure 29.** A few of the parts needed to make the carrousels

The internally toothed sector gear in the foreground depicted in Figure 27 with its externally toothed mate in the background mounted within the repeat pumping assembly, (Figure 28). I wanted to point out this pair of sector gears to illustrate how Buchanan uses every opportunity to demonstrate the firm's talent for the making of complex and interesting mechanical displays. It would have been so much easier to simply carry out this function with two identical conventional sector gears. The pumper is needed to set up the strike work at will so it will properly initiate the quarter as well as the hour on demand and serves as an auxiliary source of power for this purpose. Other control systems allow the operator to select the strike train to perform Petite or Grande Sonnerie strike as well as silencing the strike work.

Any strike mechanism needs a way to raise and release the hammers for bells or gongs; this is usually done through the use of a simple rotating cam or wheel with pins to raise and then allow the levers connected to the strike hammer to drop away after passing the cam or pin. We chose to make a set of caged 'carousels' with a fancy spoke design to accomplish this. Figure 29 shows the numerous parts needed to make these.

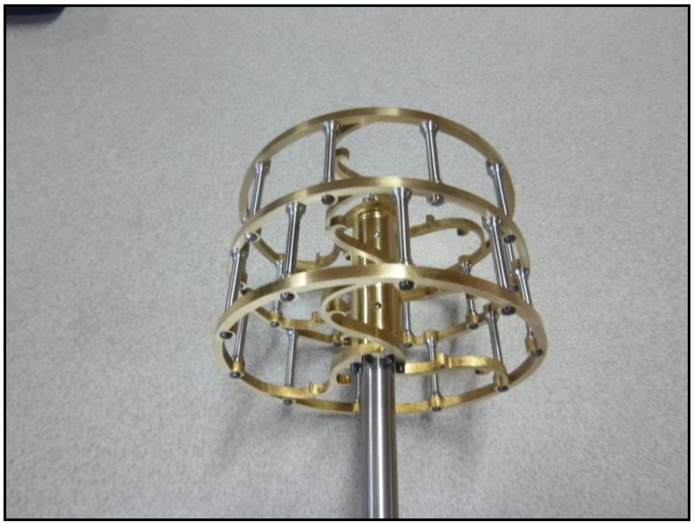


**Figure 30.** Quarter strike cam carousel

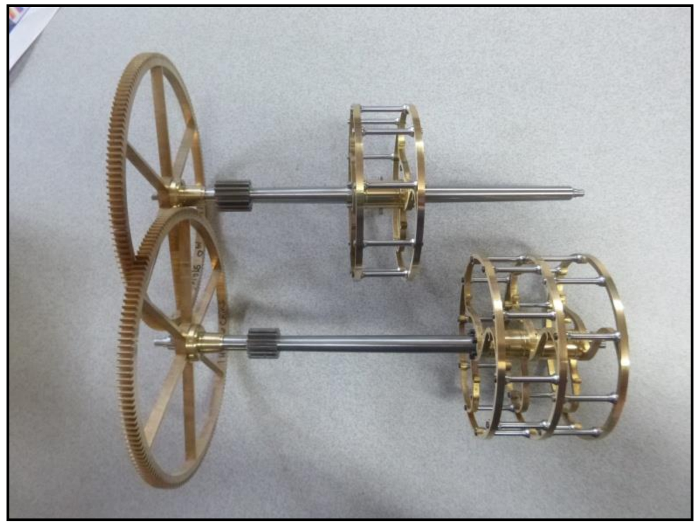


**Figure 31.** Hour and quarter strike carrousels with drive gear

The curvilinear spoke designs chosen for the carrousels are unique to these parts only, (Figure 30) and the quarter and hour strike train carousels are shown with their drive wheels from the hour and quarter strike trains, (Figure 31). As these rotate, the rods between the wheels act as would conventional pins to push the bell hammer actuators to raise and release the bell hammers.

**Figure 32.** Bird analog see-saw quarter rack advancer

**Figure 33.** Bird analog bell hammer actuator

Next are two examples of the typical bird analog. The first pair of birds serves as the quarter rack counter, lifting the rack one notch for each stroke of the bell. These operate in a teeter-totter fashion with each beak alternately pecking at the rack teeth and are far more interesting to watch than a simple rotating one or two toothed pinion, (Figure 32). The idea was borrowed from Jean-Baptisté Schwilgue's count rack within his Easter calculator in the cathedral clock at Strasburg, France, 1843.[9] This component illustrates the two types of pivots used throughout the project. The center, larger pivot is actually a ceramic, oil-free roller bearing covered by a traditional looking jeweled chaton, complete with screws securing the removable dust cover end cap. The two pivots to either side are synthetic ruby jewel bearings. The bird's beaks as well as the center of the metal roller on its tail are also jewel stones. The roller is jeweled since there are no pivots in this mechanism that have a conventional metal-to-metal pivot; conventional pivots require oil and we employ only oil-free roller bearings and jewels. The second bird is one of the bell hammer actuators, (Figure 33). Look closely at the bird's jeweled beak, it has a concave profile that fits precisely upon the rods of the cam carousel to keep proper alignment. The bird analogues are used throughout the movement; examples being the repeat and calendar work, the escapement, hammer actuators and as we have seen the strike fly detents. They all inhabit the ivy-laced wheel work forest.

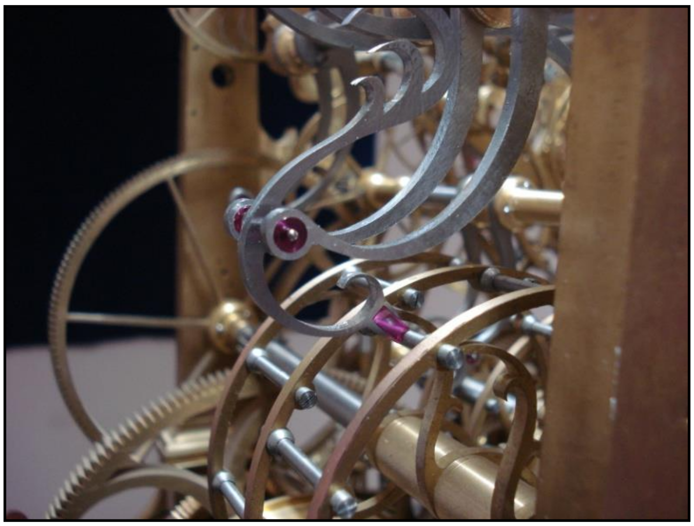


**Figure 34.** Bell hammer actuator connected to carrousel

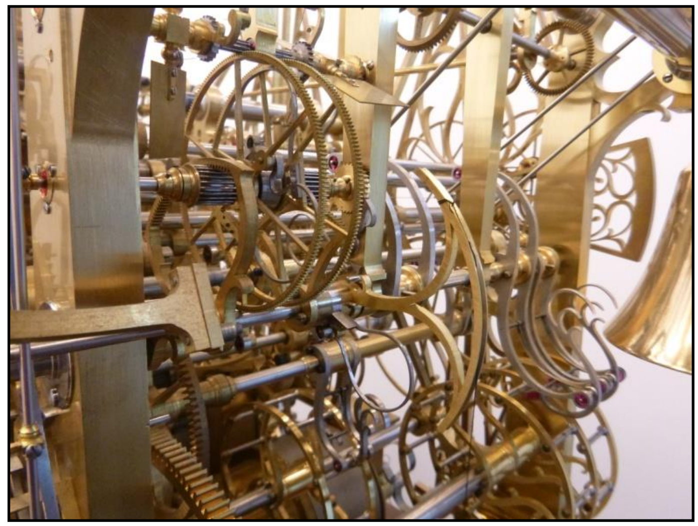


**Figure 35.** Quarter strike carrousels and hammer actuators

The bell hammer actuator is now installed with the concave curved beak resting upon the carrousel cam lifter. As the carousel turns anticlockwise the lifter rod pushes against the jewel beak of the hammer actuator. The bird analog is pivoted in its middle allowing the beak to follow the rotation of the carousel as the middle pivot causes the connecting linkage to move leftward, raising the bell hammer, (Figure 34). Next the entire quarter strike dual carrousel assembly along with a pair of hammer actuators can be seen just in front of the single carrousel wheel for the hour strike, (Figure 35). The pair of wheels in the upper left is the pumper for the repeat mechanism illustrated in Figure 28. Video link: [https://youtu.be/9MVgBz-ZltY](https://youtu.be/9MVgBz-ZltY)

**Figures 36-38.** Each spring is custom made and tempered. A copper envelope protects the springs. Next removal after quenching

Leaf springs within the repeat pumper mechanism supply the power when loaded by a lever pushed by the operator. All of the springs in the movement are custom-made and tempered in a furnace, (Figure 36). The springs are encapsulated in a copper envelope to protect the steel surface while within the furnace, (Figure 37) prior page, and next are shown immediately after hardening by water quenching and subsequent removal, (Figure 38).

**Figure 39.** Some of the various parts involved with the strike control mechanism

Figure 39 shows the layout of the quarter and hour strike control mechanisms in their approximate positions. Depicted are the snails, racks and a drop fly fan (only the quarter fly is shown here, the hour fly would be located to the left outside the photo), the see-saw bird analog rack lifters, as well as the repeat snap positioning cams. The darker colored component at the bottom of the photo is an experimental piece that we wanted to examine to evaluate how the strike components might look like in a blued metal as opposed to a natural polished steel color. The pumper for the repeat is not shown and would be located just above the right corner of the photo.

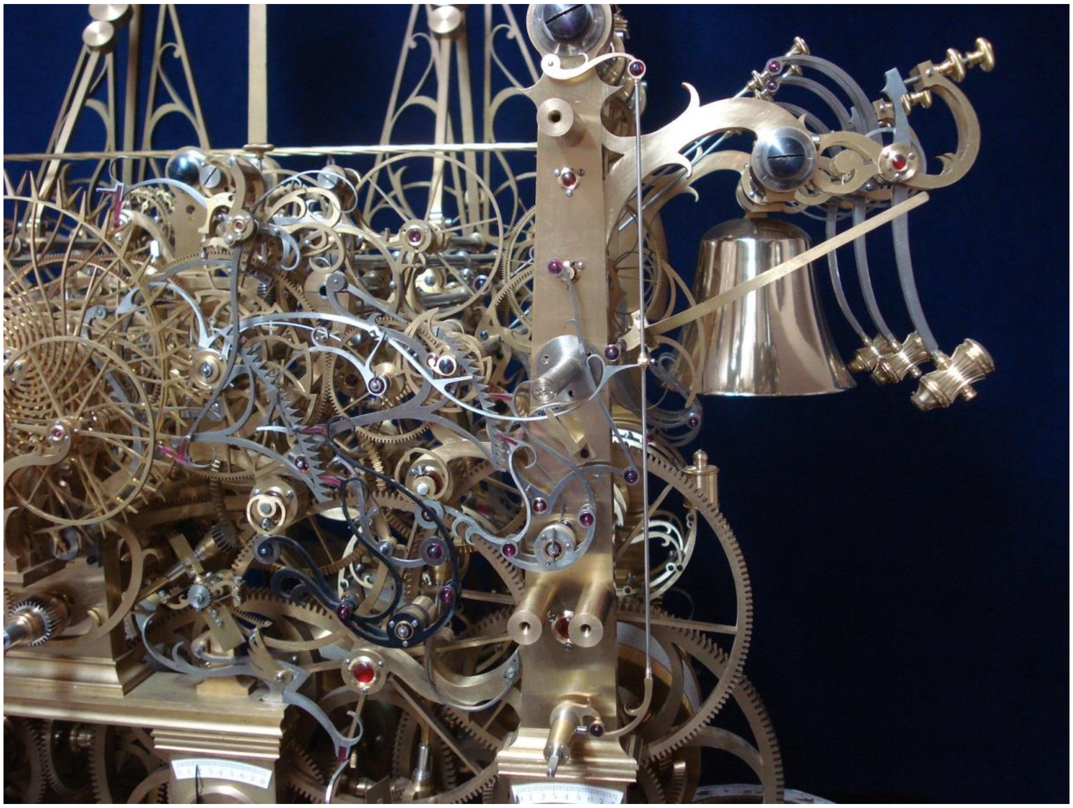


**Figure 40.** Front view showing the strike control levers installed

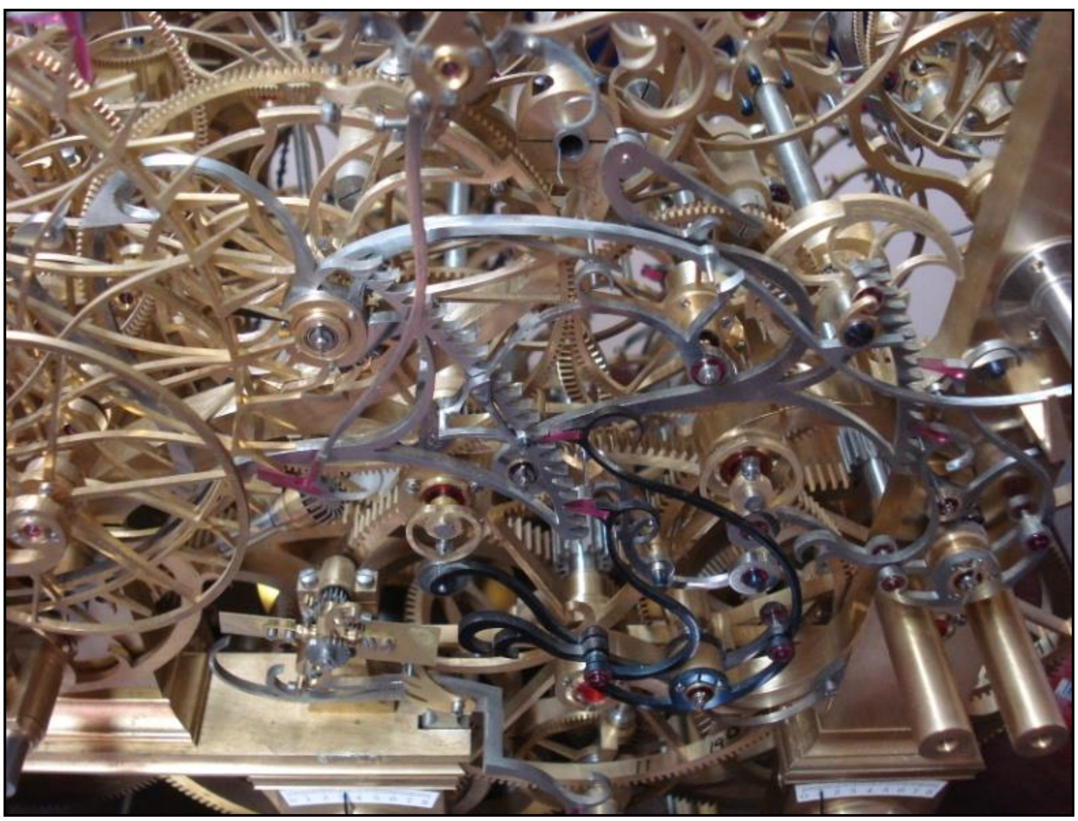


**Figure 41.** A three quarter view of the same parts

Figures 40 and 41 show the strike and repeat control levers installed on the front of the movement. The components are designed so when combined together one sees a complex, lacy effect. If one looks carefully the bird analogs can be seen engaging with the rack teeth. The beaks remain engaged with the racks during dormancy. Part of the strike set up includes the bird heads being pulled away from the face of the rack prior to it being set upon the snail. Video link:
https://www.youtube.com/watch?feature=player_embedded&v=5r41XzNG01c

**Figure 42.** Bell set with decorative hammers

**Figure 43.** Hammer adjustment controls with decorative knurls

For visual impact, and visual impact is *the* guiding principal in this endeavor, we chose to have a set of bells in the shape of miniature church bells custom made by the Whitechapel bell foundry of London. Founded in 1570, it is one of the oldest business establishments in England, (Figure 42). Each bell actuator and hammer can be minutely positioned through a complex set of levers complete with multiple adjustments via an array of knurled knobs to precisely adjust and then lock down each of the bird analogue hammer actuator's positions in relation to the carousel as well as the hammer's stroke from soft to loud. The hammer heads are fitted with traditional leather inserts (Figure 43).

## Sidereal time

During the initial design stages of this project in 2006 we had envisioned a subsidiary dial readout for the sidereal time. This usually takes the form of a twenty four hour format. Briefly, sidereal time is a time scale that is based on the Earth's rate of rotation measured relative to the fixed stars rather than the Sun. A mean sidereal day is 23 hours, 56 minutes, 4.0916 seconds (23.9344) hours or just under four minutes every twenty four hours shorter than a solar day, (Figure 44). The twenty four hour format is useful for astronomers to avoid confusion in time logs to keep track of the coordinates to locate their telescopes on a given star in the night sky. After one year the divergence between the solar and sidereal time converge where the difference is exactly 24 hours; another reason for the 24 hour format. The problem I have had with this type of dial is the difficulty for someone who is looking at the twenty four hour sidereal time dial to see at a glance how it relates to the mean solar time's 12 hour dial.

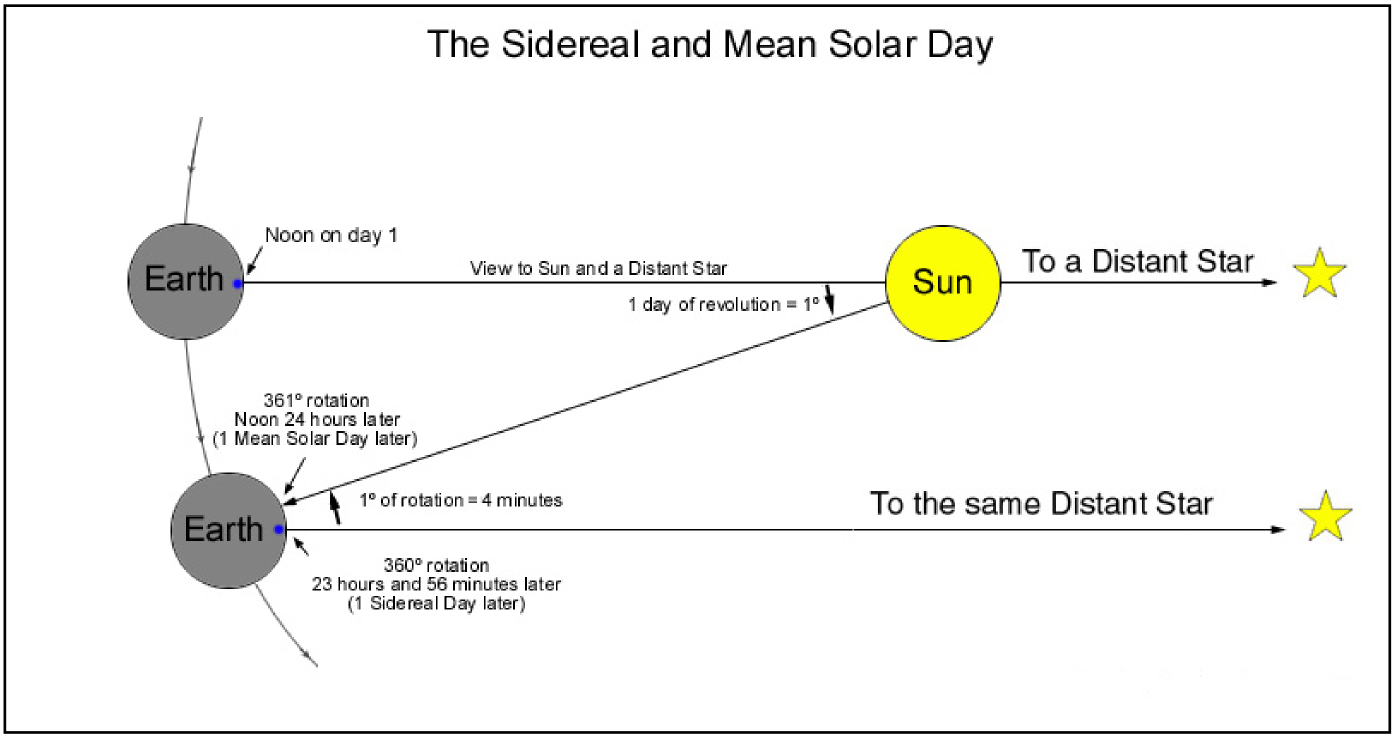



**Figure 44.** Illustration of the difference between sidereal and mean solar time

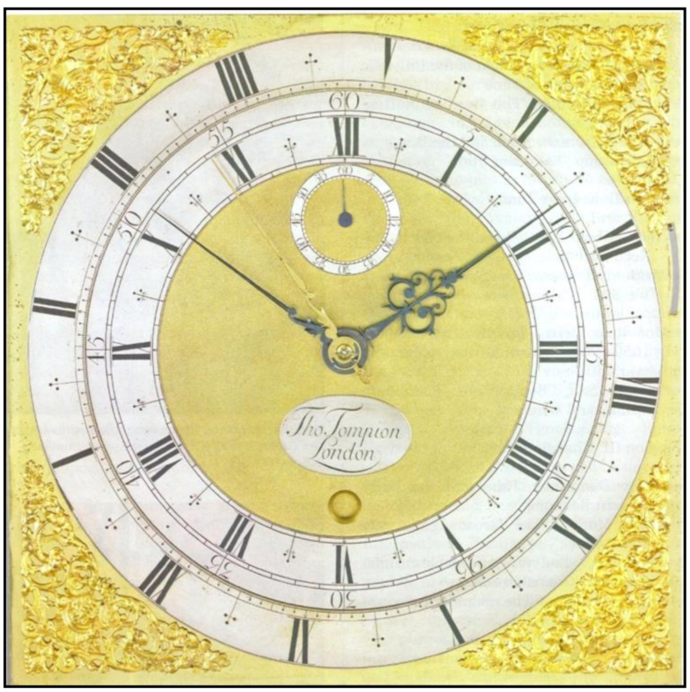




**Figure 45.** Mean solar and sidereal dial, Thos. Tompion c.1708 **Figure 46.** Our interpretation of Tompion's design

In November 2013 I was a guest speaker at the Ward Francillon Time Symposium sponsored by the NAWCC and held at the California Institute of Technology, Pasadena, California. At that symposium there was an exhibition of Tompion clocks and one in particular caught my eye from c.1708. It featured two concentric dial rings, (Figure 45). In his clock the sidereal time is read directly off the fixed inner ring here showing 1:51. The outer ring indicates mean solar time and rotates clockwise twice yearly and the tip of the hour hand reads the mean solar time, about 6:35, to the nearest five minutes from that dial for the first six months of the year. Since the dial rotates twice yearly, for the second half of the year one must remember to add twelve hours to the mean solar time or subtract the same from the sidereal time to get the twenty-four hour comparison in the second half of the year. But otherwise one can easily and exactly contrast and compare the difference between the two times. The gold hand on Tompion's dial is a dummy and is always fixed to the minute hand. It appears this is a manually adjusted hand for the equation of time but is not an independently operated complication. I knew instantly that this format was what I wanted for this project.

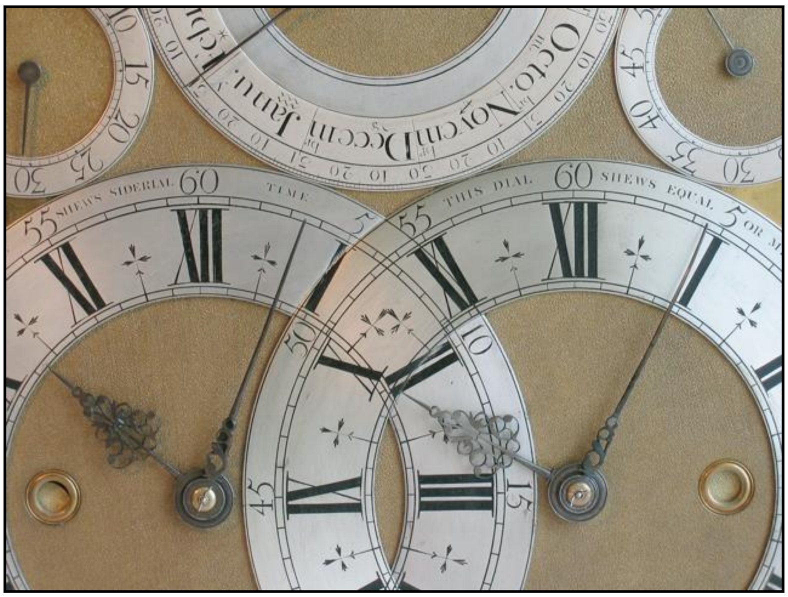



**Figure 47.** Daniel Quare using two separate and cleverly merged dials


**Figure 48.** George Margetts dual dials, similar to ours

Tompion was not the only one to try to address this issue. Daniel Quare, London, 1710, (Figure 47) and George Margetts, London 1782, (Figure 48) both had radically different, yet each inspirational ways to accomplish this. Quare's design, the more straightforward, used two separate dials, movements and pendulums within a single longcase clock. The two conventional minute and hour chapter rings beautifully overlap and are located below the two separate upper seconds dials, with the center dial being a calendar. This allows a direct reading as does our design, but in both cases one must remember to compensate the twelve hours after June 30 since a twelve hour dial is employed. Margetts was thinking very much along the same lines as we are. He uses a triple set of dials for hours minutes and seconds with the inner rotating discs indicating sidereal time and the main, fixed dial having mean solar time. The hands are, as in our clock, reading mean solar time with the discs rotating to sidereal time allowing both to be read simultaneously. Each design accomplishes the end of reading the two times simultaneously. Unquestionably Margetts does this in the most efficient and accurate manner using a twenty four hour dial for both mean and sidereal time. Unfortunately neither design was applicable to our project. We had to keep the visual symmetry between the left and right hand sides of the clock, therefore Tompion's design was chosen. Video link: https://youtu.be/86XsLf20h3U

Fortunately we had not yet created this function, so the changes from a separate twenty four hour dial to Tompion's design did not require too many changes. Clearly Tompion's clock placed greater importance on the sidereal time, as this is the readily legible inner stationary dial. Our design reverses his priority making the mean solar time a fixed outer dial with the sidereal time read off a counterclockwise rotating dial. However we do his design one better. In Tompion's clock the mean solar time was read off the tip of the sidereal hour hand and the mean solar dial was denoted to five minute increments so it is possible to read that dial to the nearest 2 minutes or so. In our design we have both the sidereal hours *and* the minutes rotating on two independently counterclockwise rotating dials; the inner dial being the hours with the outer dial minutes, (Figure 46). This allows accuracy to the nearest ten seconds or so. The minute chapter ring also rotates fast enough in real time to provide an interesting display. This quality is made even more interesting during the demonstration function where one can see the interplay between mean, solar and sidereal times. Significantly, this clock also has a functioning equation of time hand, the gold hand with disc to be examined later. I cannot think of another clock where one can read the mean time, equation and sidereal times directly at a glance and simultaneously off one dial set down to less than minute of accuracy between the three readings when comparing sidereal time and to the second for the equation of time. The dial readings are: mean time 12:53:37, solar time 12:42:37, and sidereal time 8:37:15. The sidereal reading's seconds is interpolated from the sidereal minute dial ring where the minute hand is just one tick mark after the 37 marker. Each minute has 5 tick marks for 12 seconds each. One cannot use the seconds hand here since it is controlled as is the minute and hour hands from the mean time gearing and is not linked to the sidereal gearing. One would have needed a third counter rotating ring moving to sidereal seconds to read directly off that hand to obtain accuracy to the second.

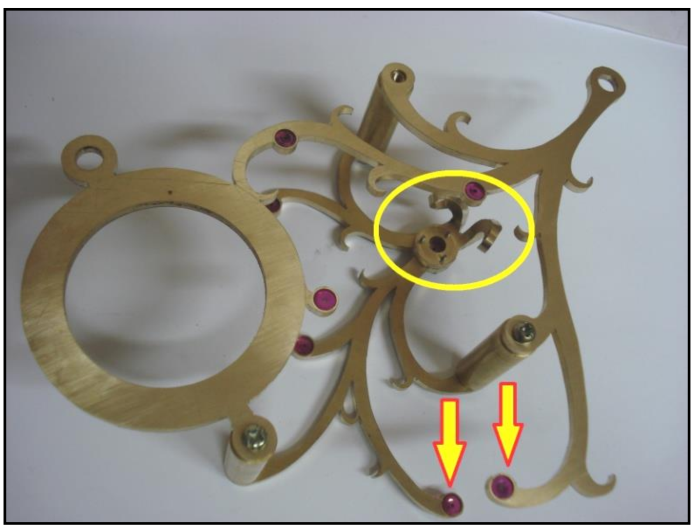


**Figure 49.** Framework showing unusual opposing pivot points

**Figure 50.** Complex, twisted profile for drive potence

Figure 49 shows the wheel frame for both the sidereal and equation drives. The two arrows point out an unusual construction where we have a wheel's arbor pivots at the endpoints between two unique frames that approach each other from opposite ends on opposite frames. Each frame's 'ivy stalk' reaches out midair from coordinates $180^0$ opposite each other to delicately hold a wheel arbor. This is another departure from the way most skeleton clock frames are made as mirror or near mirror images of each other between which the wheels are mounted. Greater planning and careful execution are required for our mid-air design. Both the sidereal rotating dials and equation kidney are driven from a common point. That point is a double potence which takes on a complex and twisted shape to exactly match the angles needed for the worm drive end of each arbor to mesh with its mating wheel, (Figure 50). It looks like Buchanan simply took a pair of pliers and twisted the potence arms to their current profiles as if the brass was the consistency of soft plastic. But in reality, this was cut with a hand fret saw out of a solid block of brass. Another view of this part is shown within the circled area, (Figure 49).

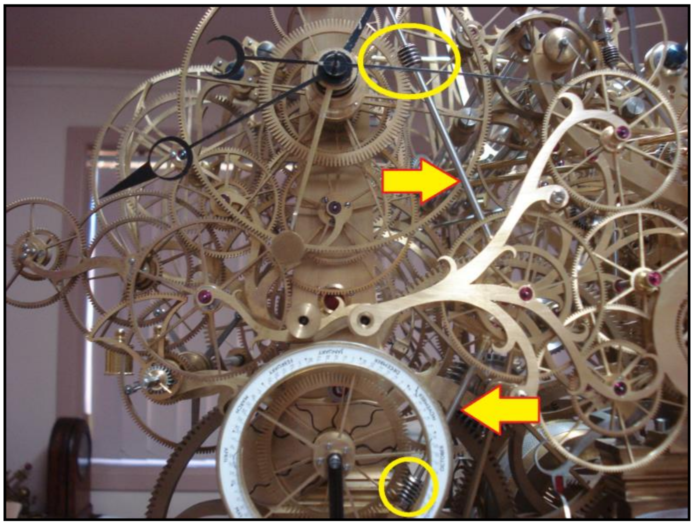


**Figure 51.** Worm gear arbors to sidereal and equation drives

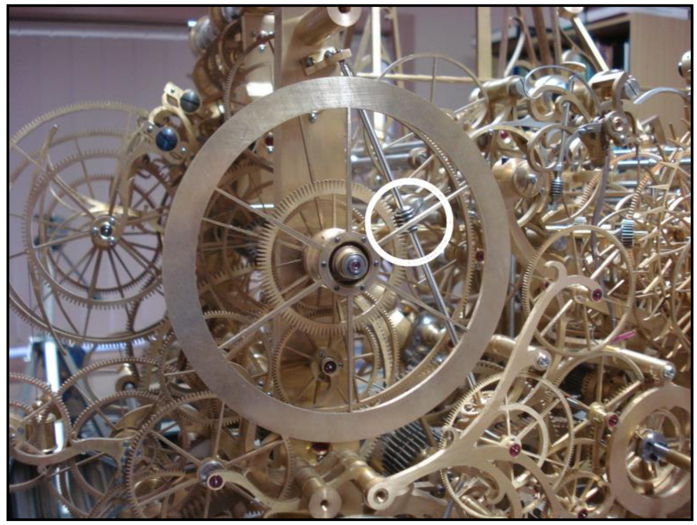


**Figure 52.** Rotating platter for sidereal hours with its worm drive

The sidereal and equation wheel frame assembly is now mounted to the clock. The sidereal and equation complications are driven via a worm gear, circled areas, mounted to an angled drive arbor, arrows, (figure 51). The brass ring represents one of the counterclockwise rotating platters that will hold the sidereal dials along with its worm drive, circled area, (Figure 52).

The central worm connecting the sidereal drive rotates once per sidereal hour. We must also derive sidereal minutes. How we do this is another tribute to the inventive and artistic abilities of Buchanan.

**Figure 53.** Main worm-driven gear attached to rear roller frame

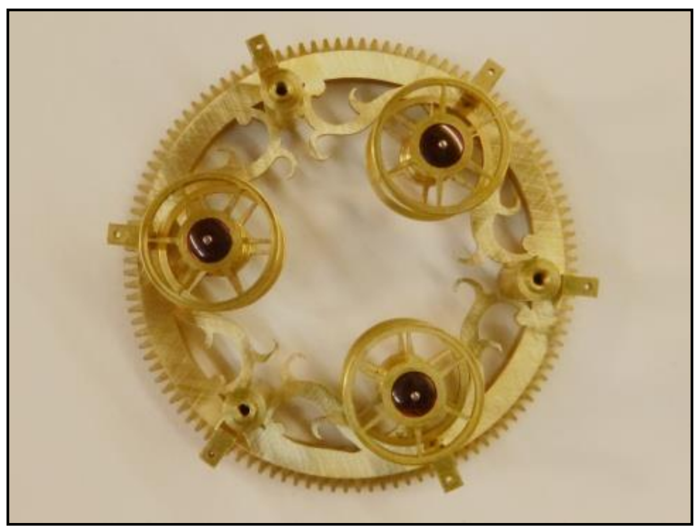


**Figure 54.** Three roller wheels are next added to the rear frame

Figure 53 shows the main worm drive wheel mounted to a decorative frame. The view is from the rear. Next the assembly is turned over and a set of roller cage wheels are added to the rear frame, (Figure 54).

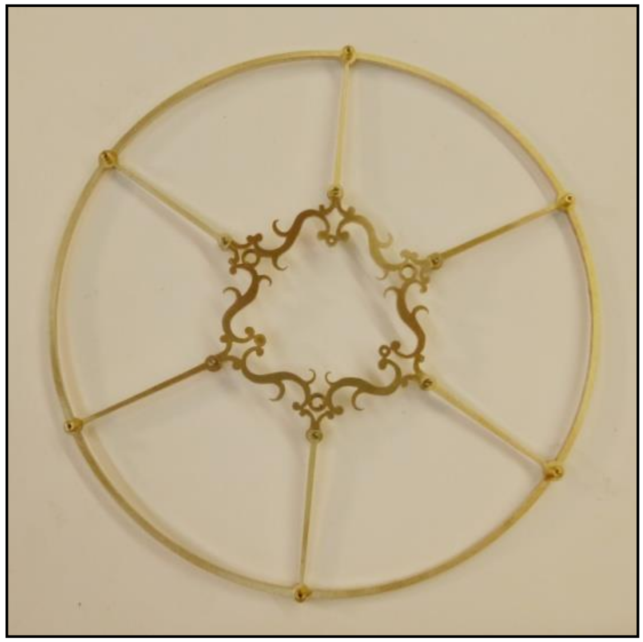


**Figure 55.** Center hub, and rollers set between the frames **Figure 56.** Outer hours ring attached to upper roller frame

Another decorative frame holds the rollers creating a roller cage between the two frames. These three rollers support a central hub seen with the six mounting holes that will secure the inner sidereal minutes ring, (Figure 55). Next a smooth rimmed wheel is mounted to the front decorative roller frame and will serve as the mounting for the larger, sidereal hours chapter ring driven by the worm gear in the rear, (Figure 56).

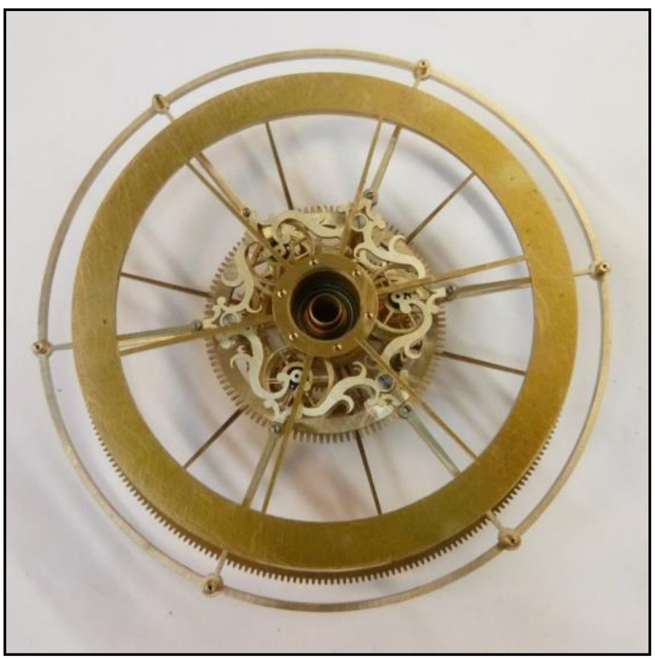


**Figure 57.** Inner minutes ring mounted to center hub **Figure 58.** Outer hours ring mounted to upper roller frame

Next the inner ring is secured to the central hub, (Figure 57). Upon this is secured the sidereal minutes enamel chapter ring. Figure 58 shows the outer concentric ring mounted to the wheel shown in Figure 56.

**Figure 59.** The 68 parts needed to make the sidereal hours and minutes concentric ring drives

Figure 59 depicts the various components used to drive the two counter rotating sidereal chapter rings. There are 68 parts in this subsystem. Additional wheels are needed to derive the sidereal minute from the sidereal hours driven by the main worm input gear. Video link: https://youtu.be/niSJLnJZt3s

**Figure 60.** Completed sidereal drive unit

Next the completed decorative sidereal drive unit installed within the movement, (Figure 60).

## Equation of time

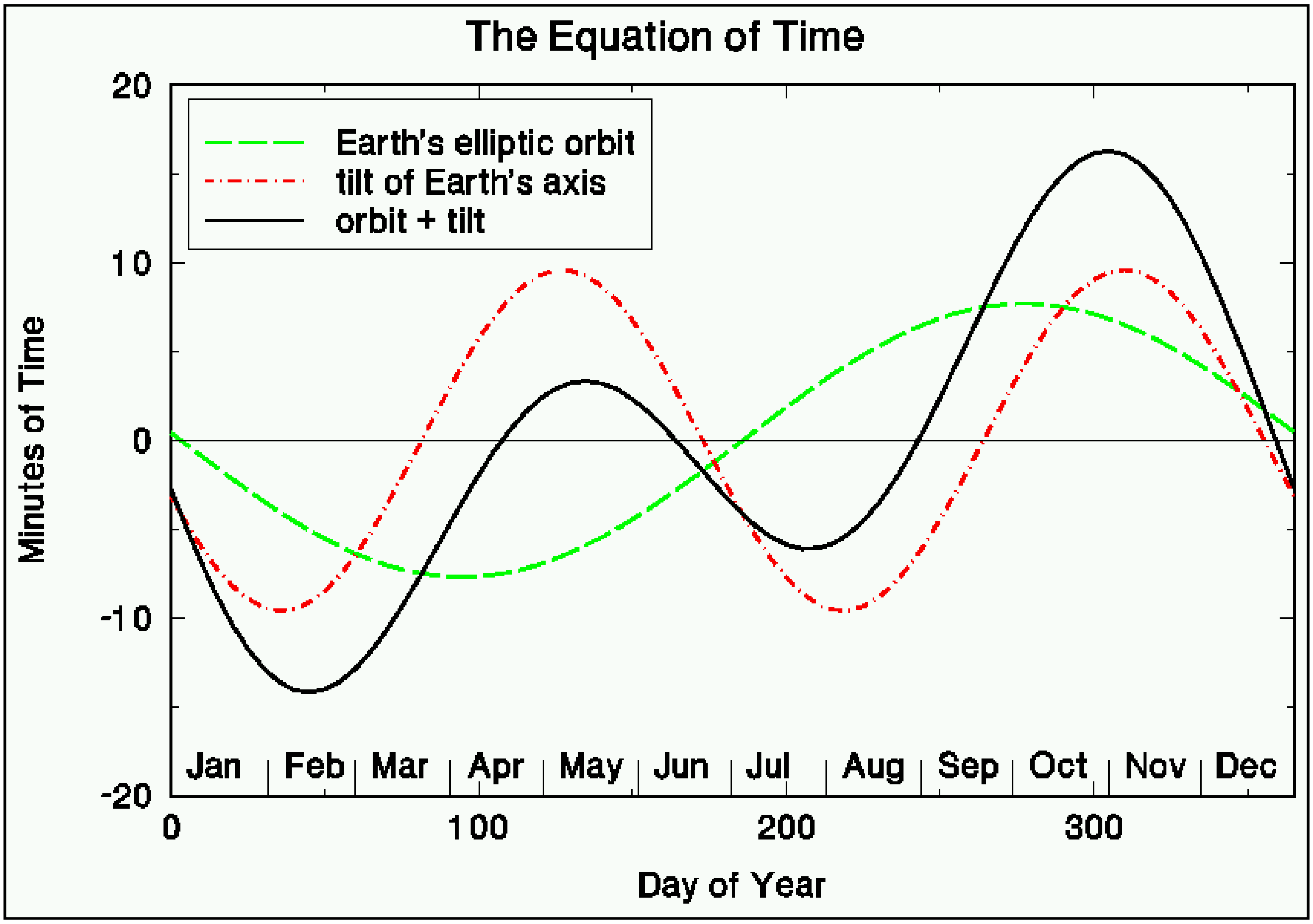
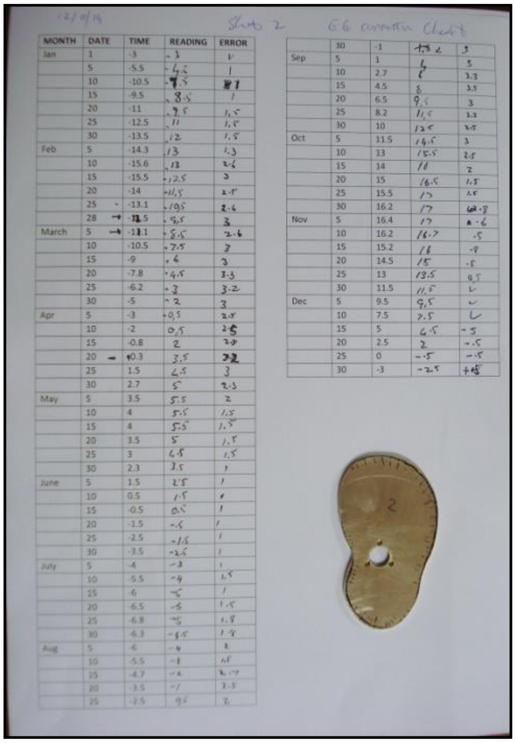



**Figure 61.** Diagram showing how the equation of time is derived

The equation of time is the difference in the position of the sun to an observer looking at the sun at midday, or Noon, on any given day of the year and the mean solar time, or 'clock time' that is read on your watch or living room clock. Only four days a year will both observations agree. Those are April 15, (tax day!), June 13, September 1, December 25, (Christmas). My guess is the first and fourth dates are coincidental. The equation of time is the result of both the tilt and elliptical orbit of the Earth. These factors combine to cause the apparent position of the sun in the sky directly overhead at noon to appear ahead of clock time by a maximum of 16 minutes 33 seconds on November 3, to being late by 14 minutes 6 seconds on February 12. The combinations of these two movements result in the apparent erratic motion of the sun. Both of these factors are shown on the graph and their mathematical combination is the black line, (Figure 61). That graphical curve of the equation of time is what is physically represented by the contour of the equation kidney cam.



| MONTH | DATE | TIME | READING | ERROR |
|---|---|---|---|---|
| Jan | 1 | -3 | -3 | 1 |
| | 5 | -5.5 | -4.5 | 1 |
| | 10 | -10.5 | -7.5 | [illegible] |
| | 15 | -9.5 | -8.5 | 1 |
| | 20 | -11 | -9.5 | 1.5 |
| | 25 | -12.5 | -11 | 1.5 |
| | 30 | -13.5 | -12 | 1.5 |
| Feb | 5 | -14.3 | -13 | 1.3 |
| | 10 | -15.6 | -13 | 2.6 |
| | 15 | -15.5 | -12.5 | 3 |
| | 20 | -14 | -11.5 | 2.5 |
| | 25 | -13.1 | -10.5 | 2.6 |
| | 28 | [illegible] | [illegible] | 3 |
| March | 5 | [illegible] | -8.5 | 2.6 |
| | 10 | -10.5 | -7.5 | 3 |
| | 15 | -9 | -6 | 3 |
| | 20 | -7.8 | -4.5 | 3.3 |
| | 25 | -6.2 | -3 | 3.2 |
| | 30 | -5 | -2 | 3 |
| Apr | 5 | -3 | -0.5 | 2.5 |
| | 10 | -2 | 0.5 | 2.5 |
| | 15 | -0.8 | 2 | [illegible] |
| | 20 | +0.3 | 3.5 | [illegible] |
| | 25 | 1.5 | 4.5 | 3 |
| | 30 | 2.7 | 5 | 2.3 |
| May | 5 | 3.5 | 5.5 | 2 |
| | 10 | 4 | 5.5 | 1.5 |
| | 15 | 4 | 5.5 | 1.5 |
| | 20 | 3.5 | 5 | 1.5 |
| | 25 | 3 | 4.5 | 1.5 |
| | 30 | 2.3 | 3.5 | 1 |
| June | 5 | 1.5 | 2.5 | 1 |
| | 10 | 0.5 | 1.5 | 1 |
| | 15 | -0.5 | 0.5 | 1 |
| | 20 | -1.5 | -.5 | 1 |
| | 25 | -2.5 | -1.5 | 1 |
| | 30 | -3.5 | -2.5 | 1 |
| July | 5 | -4 | -3 | 1 |
| | 10 | -5.5 | -4 | 1.5 |
| | 15 | -6 | -5 | 1 |
| | 20 | -6.5 | -5 | 1.5 |
| | 25 | -6.8 | -5 | 1.8 |
| | 30 | -6.3 | -4.5 | [illegible] |
| Aug | 5 | -6 | -4 | 2 |
| | 10 | -5.5 | [illegible] | [illegible] |
| | 15 | -4.7 | [illegible] | [illegible] |
| | 20 | -3.5 | [illegible] | [illegible] |
| | 25 | -2.5 | [illegible] | 2 |
| | 30 | -1 | [illegible] | 3 |
| Sep | 5 | 1 | 4 | 3 |
| | 10 | 2.7 | 6 | 3.3 |
| | 15 | 4.5 | 8 | 3.5 |
| | 20 | 6.5 | 9.5 | 3 |
| | 25 | 8.2 | 11.5 | 3.3 |
| | 30 | 10 | 12.5 | 2.5 |
| Oct | 5 | 11.5 | 14.5 | 3 |
| | 10 | 13 | 15.5 | 2.5 |
| | 15 | 14 | 16 | 2 |
| | 20 | 15 | 16.5 | 1.5 |
| | 25 | 15.5 | 17 | 1.5 |
| | 30 | 16.2 | 17 | [illegible] |
| Nov | 5 | 16.4 | 17 | [illegible] |
| | 10 | 16.2 | 16.7 | .5 |
| | 15 | 15.2 | 16 | [illegible] |
| | 20 | 14.5 | 15 | .5 |
| | 25 | 13 | 13.5 | 0.5 |
| | 30 | 11.5 | 11.5 | [illegible] |
| Dec | 5 | 9.5 | 9.5 | [illegible] |
| | 10 | 7.5 | 7.5 | [illegible] |
| | 15 | 5 | 4.5 | -.5 |
| | 20 | 2.5 | 2 | -.5 |
| | 25 | 0 | -.5 | -.5 |
| | 30 | -3 | -2.5 | +.5 |

**Figure 62.** Error correction data for kidney cam

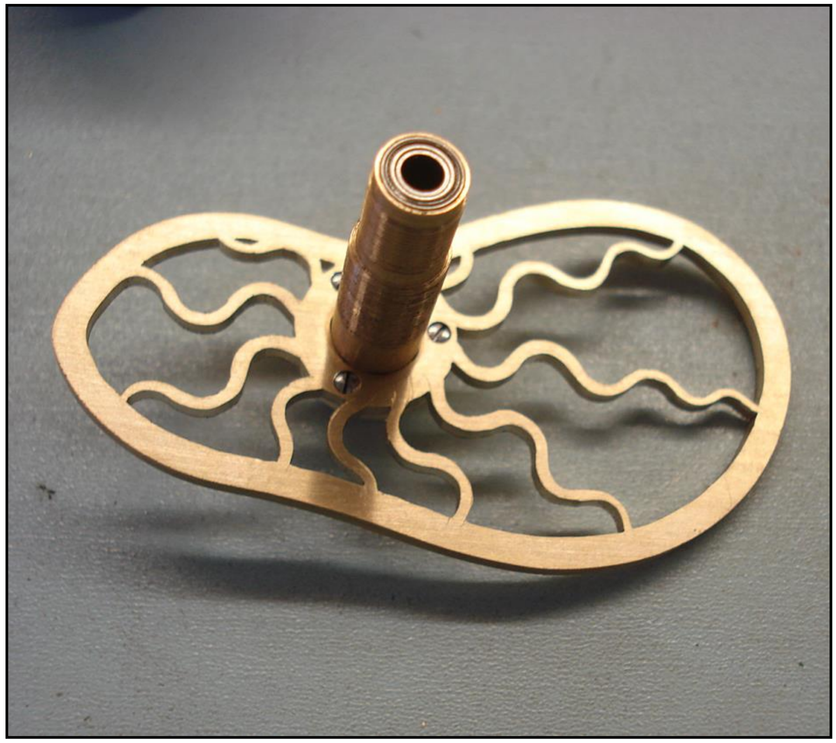


**Figure 63.** Completed cam with 'sun ray' spoke design

Figure 62 shows one of 16 error correction tables used to create the profile of the equation kidney cam. The cam must be contoured perfectly to give the correct readout to the equation minute hand located on the main dial. Once a rough outline is made, the cam is fitted and then tested against the dial. There are 73 test points on the perimeter corresponding to 5 day increments totaling 365 days and these are shown on the error table. It took 16 iterations to get to the correct profile. So the total number of tests to achieve the final profile was 16 x 73 or 1168 trials; clearly a labor intensive process. The difference in the errors from the first iteration and the sixteenth are on an order of 1.5 magnitudes. For example March 5th has an original error of 4.2 minutes on the first error table and finishes at 0.1 minute or just six seconds on the sixteenth table. On March 5th the difference between mean solar time and the actual position of the sun when it is at its zenith, directly overhead, noon for the sun's position is 13.5 minutes. In other words when the sun is directly overhead the clock will read 12:13:30. At this time of the year the sun is *slow* compared to standard clock time. One must keep in mind that this cam is rather small at just under 3" or 7 cm at its widest point. The smaller the cam, all other factors being equal, the harder it is to achieve accuracy. The completed cam with it sunray spokes is shown in Figure 63. What better example for a cam that depicts 'sun time' than to have sun rays for the cam's spokes? This is another example along with our animal analogues of adding a bit of whimsy into the movement's design.

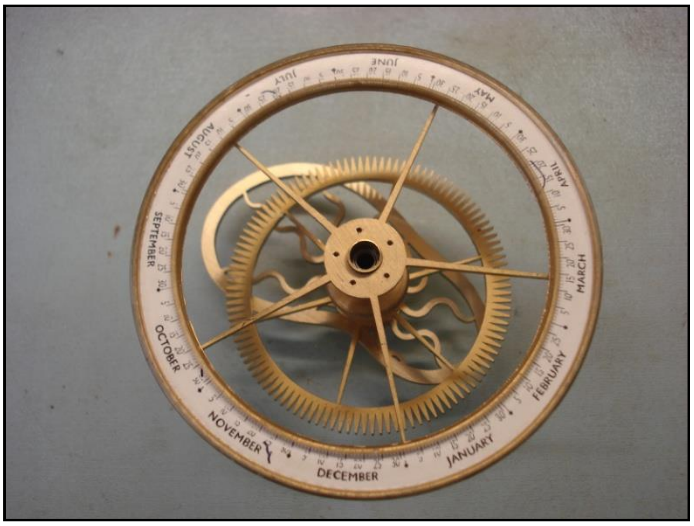



**Figure 64.** Equation kidney cam with drive and setting dial


**Figure 65.** The equation cam works installed on the movement

The completed equation kidney and its adjustment dial, (Figure 64). Figure 65 shows the cam assembly installed within the movement. The hub winding square allows one to adjust the kidney cam using a key.

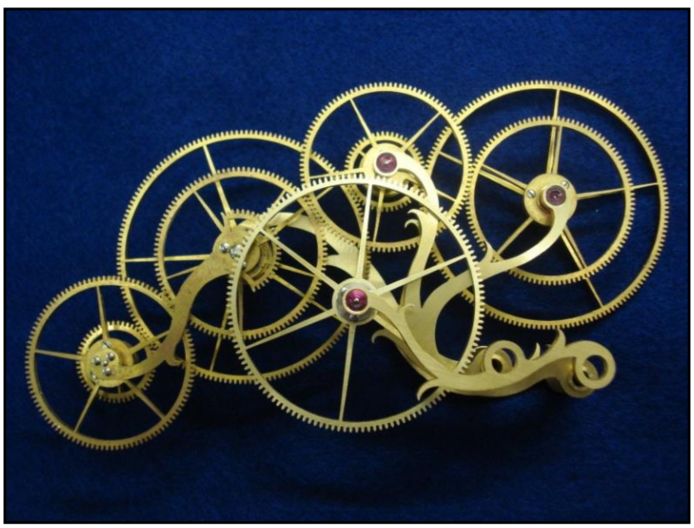


**Figure 66.** Wheel set for equation of time hand, sun at slowest

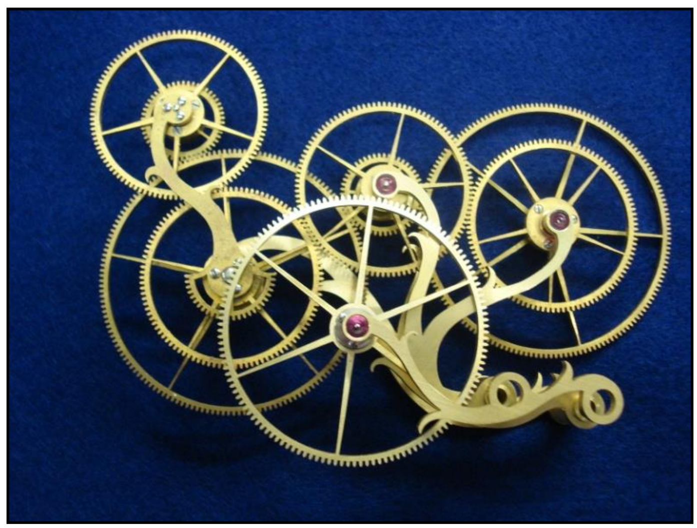


**Figure 67.** Wheel set with differential, sun at fastest

The readout for the equation hand is located on the main dial and is controlled through a differential wheel set attached to a wheeled idler arm riding on the surface of the kidney cam. This allows the equation hand to continuously show the correct number of minutes the sun is either ahead or behind the mean solar time minute hand throughout the year, (Figure 46). Joseph Williamson, c.1720 was the first to use differentials to display the difference between the solar and mean time simultaneously in clockwork.[10] The differential wheel set was made in May of 2009, (Figures 66 and 67). The leftmost wheel seen in the lower left hand corner of Figure 66 can be seen raised to the upper left hand corner in Figure 67 and represents the two extremes of the sun being behind or ahead mean solar time. We take the sun gear in the differential which normally is sandwiched between two planetary wheels and flatten it out to where the sun gear rides along the perimeter of the planet wheel. It is visually the most impressive way we could find to display the movement of the differential in response to the kidney cam.

## The third-order, reversible perpetual calendar, why do we need this?

Most calendar work seen in clocks is not perpetual. The dial indicating the date may have 31 divisions but it does not distinguish which of the four months of the year have only 30 days not to mention February with 28 days in the three successive non leap years or 29 each fourth leap year. The owner was expected to adjust the date back to the first at the beginning of each month. These are known as *simple calendars*.

The next step toward accuracy allows for the correct number of days for each of the months containing 30 days (April, June, September, November), or 31 days (January, March, May, July, August, October, December). However February never changes and remains at 28 days, so the accuracy is good for the three years that February remains with 28 days; this is an *annual calendar.* Once February is automatically adjusted to add an extra day every four years, also known as the intercalary day, the calendar becomes a *first order* perpetual calendar. This is what nearly all clocks have when they are said to contain a perpetual calendar.

However, the hierarchy does not end there. A first order perpetual calendar will remain accurate for only 100 years. The seasons do not follow lockstep with our mechanical tracking devices and so, like the leap year, an additional refinement is needed every 100 years where the leap year is skipped, that is February will not have an extra day. This type of perpetual calendar will be accurate for an additional 399 years and is known as a *second order* perpetual calendar.

But it does not end there. A further refinement is needed to keep our calendars permanently in step with the Earth’s orbit also known as the tropical year. Every 400 years the intercalary day is reinserted giving February 29 days. This allows the calendar to be permanently perpetual and becomes a *third order* perpetual calendar. Technically there is still a miniscule drift from man’s arbitrary calendar and the tropical year, but this does not amount to more than one day in over 10,000 years. I know of no fourth order calendars! Third order calendars are rare and have historically been used in astronomical clocks that contain an Easter calculator. Easter is a movable feast based on a number of complex astronomical criteria, and a third order perpetual calendar is a vital component of the calculator.

So in the Gregorian calendar three criteria must be taken into account to identify leap years: A year will be a leap year if it is divisible by 4 but not by 100. If a year is divisible by 4 and by 100, it is not a leap year unless it is also divisible by 400. This means that 2000 and 2400 are leap years, while 1800, 1900, 2100, 2200, 2300 and 2500 are not leap years. When these criteria are accounted for the calculator is permanently perpetual; it is a third order perpetual calendar calculator.

The calendar we have built is a third order perpetual calendar, but we go one additional step. This calendar is also reversible. It will perform all the calculations needed to keep the calendar perpetual in both forward and reverse without the loss of data. The way we achieve reversibility is to do away with the conventional manner in which the dates are advanced using a stepper in the form of a star wheel for the dial indications. Instead everything is directly geared together and is advanced each day at midnight using a remontoire. The perpetual calculator module has a special provision to allow it to step backward using an index wheel with all of the other calculating components being geared together facilitating the ability to run in reverse. To the best of my knowledge this has never been done before. Not because it presented a difficult technical challenge, which it did, but because it was never needed. In the end we had to create a small mechanical analog computer complete with logic circuitry, program, memory and small fixed mathematical processor. It is comprised of 580 parts, more than many of the most complicated clocks or watches in their totality.

Why do we need a reversible perpetual calendar in this project? The reason is that we will use the calendar indications of the day, date, month and year to give an exact temporal reference to the demonstration of the celestial functions of the clock. In other words, when the machine is in demonstration mode for all of the rest of the celestial functions, the calendar will advance or go backwards in synch with that demonstration. In this way one can see exactly how certain celestial events will look like or occur on any given date. This makes the prediction or verification of events such as solar or lunar eclipses, the time of sun or moon rise and set, or what the position of the stars in the sky are at any given time possible. Looking at the orrery one will be able to see the where the various planets and their moons are in relation to each other at any given time. A subsidiary dial will take the accuracy further down to the hour. It also makes resetting the cosmos back to the right time frame after demonstration very easy. As one may be starting to guess, this complication was a challenge. Nearly all complex astronomical clocks made in the past were designed to be set up and run in real time to show celestial events as they occur. My machine does this too but it also encourages the observer to come and play. It is made for the operator to demonstrate easily and safely the many celestial components in ways that compare and contrast between the various functions of the clock.

## The perpetual module

The first component to be designed was the perpetual module. This is the heart of the calendar and contains the program and memory of the calendar. Its components are on the scale of a pocket watch and contain the wheel and cam work that execute the first, second and third order calculations. Since this was a novel concept and we had no prior examples, we designed a ‘proof of concept’ fully functional model in plastic to test our design before fabrication in metal. The modeling approach has been used in other areas of this project. The first was the epicyclical maintaining power system for the four winding barrels. Next was a simplified mockup of the time train employing the dual epicyclical remontoire and Harrison’s escapement and third was the planisphere complication. In those mockups the scale was one-to-one, 1:1. Here the model is larger at one-to-three, 1:3 because the finished module will be at the scale of a pocket watch. We needed to be able to make changes in the design and observe the functionality of the mechanism which is easier to do at a larger scale. It also would have been difficult to make this a functional model from over-the-counter plastic at that scale. The following set of photos takes one through the intricacies of the perpetual module.

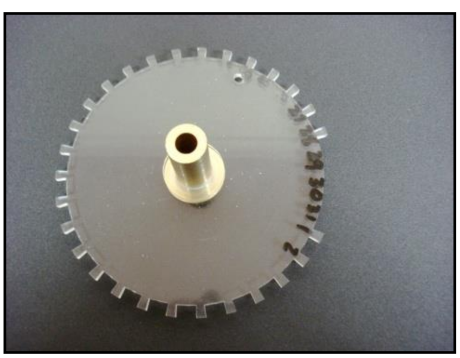


**Fig. 68.** Daily index wheel, days 1-28

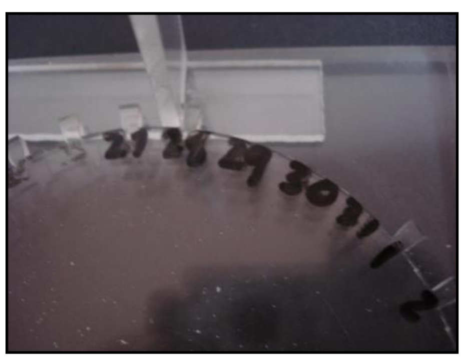


**Fig. 69.** Detail showing day 29-31 missing

**Fig. 70.** Surprise pieces for days 29, 30 31

Figures 68-70 show the basic components of the calendar module if it were to be a simple perpetual calendar. Figure 60 is the daily index wheel which acts much like a count wheel in a French strike train. It has the days of the month represented by one through thirty one teeth, but with three teeth for 29 through 31 removed. Next this section is shown in detail along with the daily index reader detent just above which is used to read the index wheel, (Figure 69). Next are three movable teeth that substitute for the three vacant spaces representing 29-31 on the index wheel. These can be moved into position as needed and in the parlance of watch repeater mechanisms these would be called ‘surprise pieces’, (Figure 70).

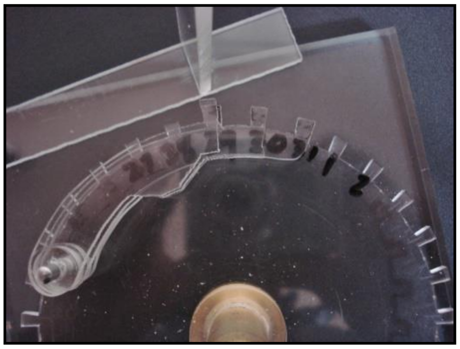


**Fig. 71.** Surprise pieces over index wheel

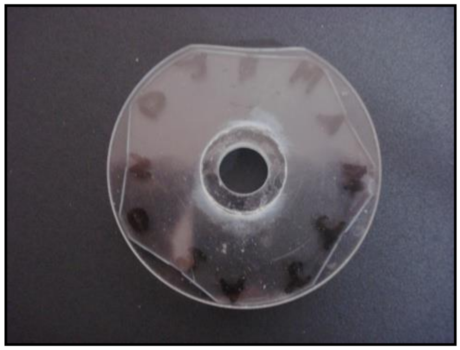


**Fig. 72.** Cam pair for 30,31 days; and Feb.

**Fig. 73.** 20 year cam used in 100 year cycle

Next the three surprise pieces are shown installed onto the index wheel, (Figure 71). The three pieces do the following: First account for the 30 and 31 day regular monthly durations, second account for where February is the one month that has a shorter period than any other month, 28 days and third the addition of a day in February, giving 29 days, for the leap year. Figure 72 shows the cams that drive two of the surprise pieces. The monthly deviations between 30 and 31 days are controlled by the upper, irregular shaped cam. The lower smooth shaped cam controls for February. Figure 73 is the leap year cam which runs on a twenty year cycle and is used in conjunction with another cam in calculating the 100 year exception. This will later have an additional cam and wheel work attached that in combination with this 100 year cycle will cycle once every 400 years for the next layer of complication to be discussed later.

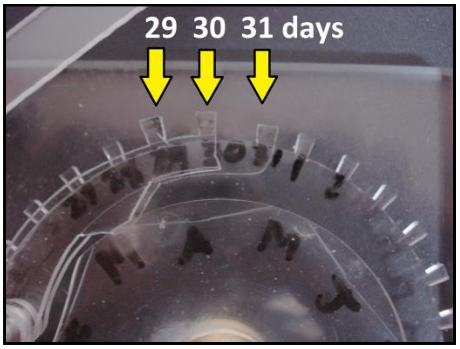



**Fig. 74.** All detent pieces raised, 31 days

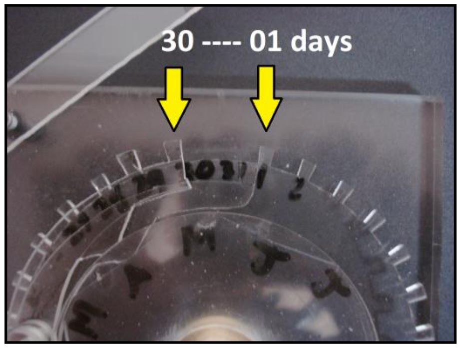



**Fig. 75.**One detent piece lowered, 30 days

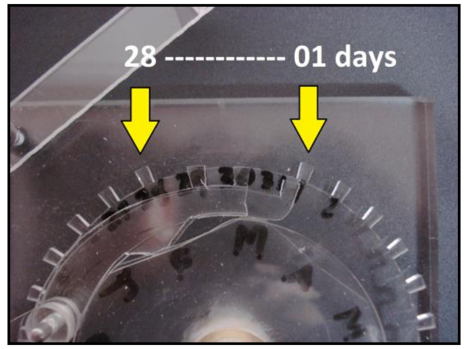



**Fig. 76.** Two detent pieces lowered, 28 days

The next three photos show the normal month durations for non leap years. Figure 74 shows all three surprise pieces in their raised positions to give a 31 day period, next one piece lowered for a 30 day month, (Figure 75) and next all three pieces are lowered for the regular 28 day month of February, (Figures 76).
Video link, demo of length of each month: https://youtu.be/3z0LpLOhjyQ
Video link, demo of 29 day month: https://youtu.be/iq0hjAJtzxQ
Video link, demo of 30 day month: https://youtu.be/HJf2JvouPHM
Video link, demo of 31 day month: https://youtu.be/PCH4N24CuZM
Video link, demo of February in leap year: https://youtu.be/eq7wlq1jMFI

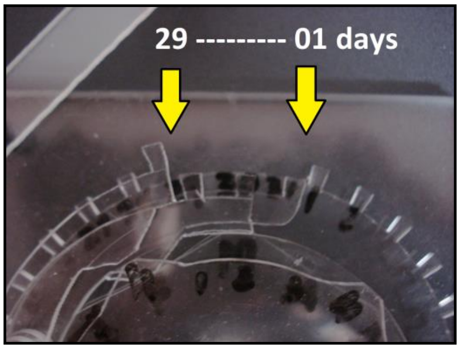



**Fig. 77.** Two detent pieces raised, 29 days

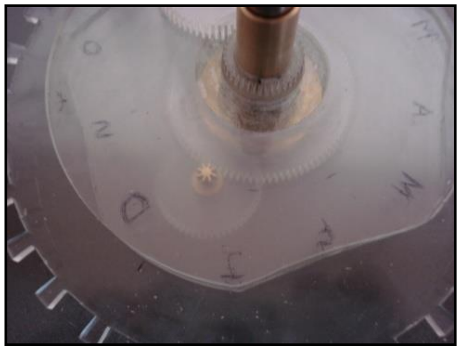


**Fig. 78.** Cam w/ flat cut for February

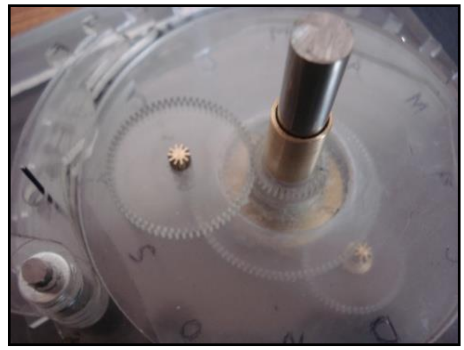


**Fig. 79.** Some of the drive gear work

Figure 77 is the leap year where February has an extra day for 29 days with one of the three surprise pieces raised. Figure 78 shows the month duration and February cams. The latter is basically a round disc with a flat cut where February is located. Next is some of the gear work used to drive the cams, (Figure 79).

Now another layer of complexity is added to make the calendar perpetual for 100 years.

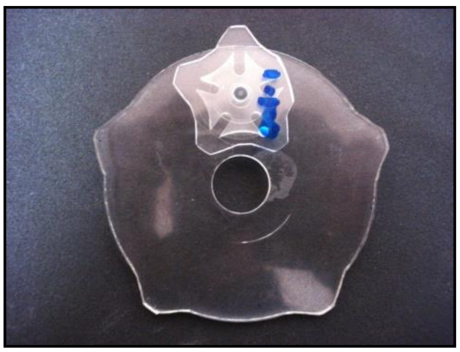


**Fig. 80.** 100 year correction cam

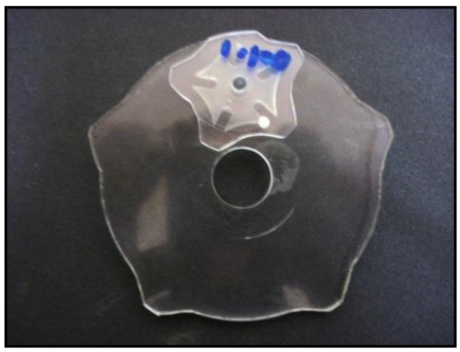
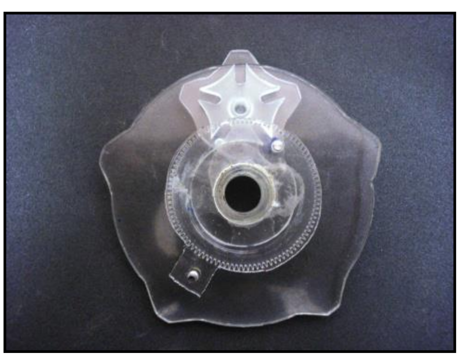


**Fig. 81.** 100 year cam at correction

**Fig. 82.** Geneva stepper drive

Here we see a small five lobed Geneva stepper cam attached to a five armed cam attached directly above, with one arm truncated, (Figure 80). Since the larger cam to which the smaller cam is attached rotates every 20 years that smaller cam is stepped once every 20 years or will rotate one revolution in 100 years. In this photo the cam presents an intact arm allowing for February to have 29 days for a leap year. Figure 81 shows the cam with the truncated arm positioned to provide the correction needed every 100 years where the surprise piece for the leap year is not raised and therefore is skipped and the leap year February will not have 29 days. Next is the piece that will advance the Geneva stepper cam, (Figure 82).



**Figures 83-84.** 100 year correction assembly with and without correction

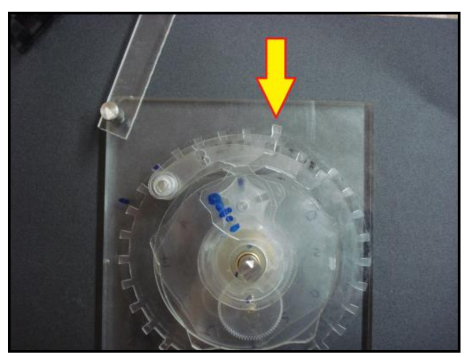


**Fig. 85.** Cam making insertion of 29$^{th}$ day

Figures 83 and 84 shows the drive piece installed and the 100 year cam is shown as if February was having 29 days, which is a leap year. Next the cam is shown not giving February 29 days so the leap year is eliminated. Figure 85 shows February having 29 days (arrow). So now we have a system that will skip a leap year once every 100 years.

The final layer of complexity, the 400 year correction, to make the calendar permanently perpetual is described below.

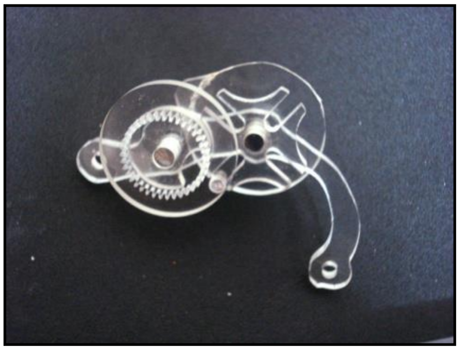


**Fig. 86.** The 400 year correction

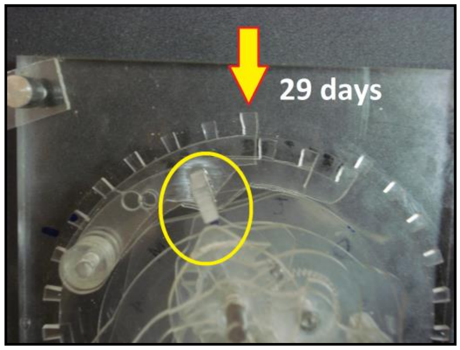



**Fig. 87.** Cam correcting every 400 years

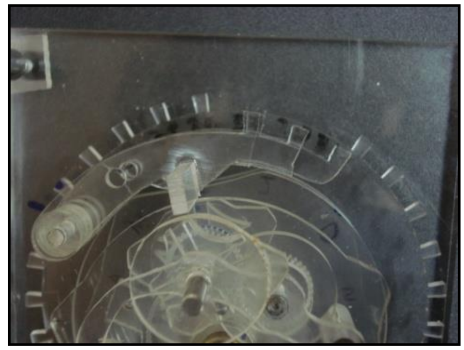


**Fig. 88.** Smooth portion for 399 years.

Figure 86 shows a four lobed Geneva cam stepped once every 100 years and is attached to the 400 year cam along with the associated gearing and bridge work needed to install this upon the existing calendar work. That cam is basically a smooth disc with one protruding arm. Figure 87 shows that one protruding arm of the four hundred year cam giving February 29, days once every 400 years, circled area with the next photo showing the remaining cam presenting a smooth surface for the remaining 399 years, (Figure 88). One might ask how it can be that with this cam rotating only once every 400 years, the detent does not ride slowly up the one raised lobe thus confusing the insertion of the 29 day correction in the preceding and following years of the one correction year. Here is where the Geneva cam comes in. It ‘flips’ the cam every 100 years, so that cam is never actually continuously rotating but only jumps to the exact position each 100 years. The jump is made and the surprise piece rides instantly on the curved surface to present itself to the index detent reader.

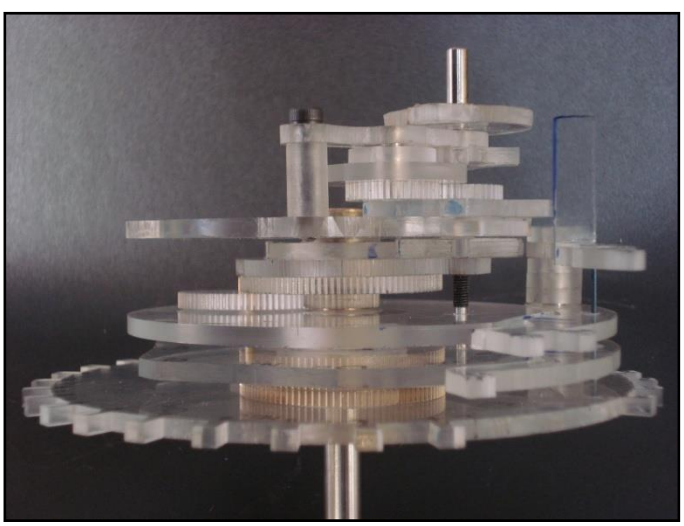


**Figure 89.** Edge-on view of the perpetual calendar model

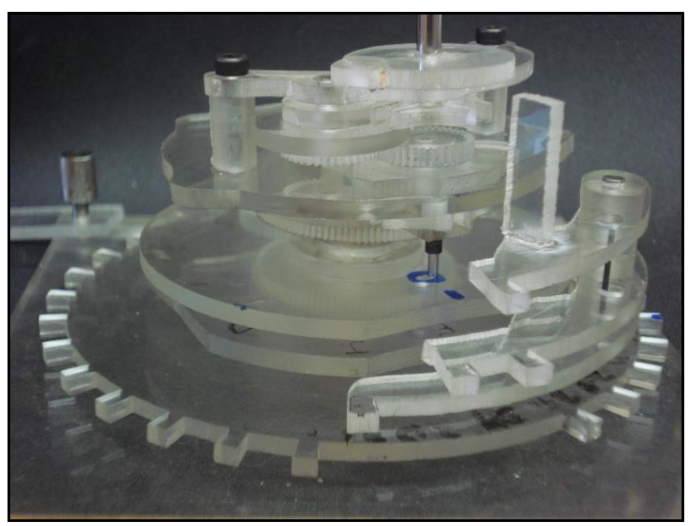


**Figure 90.** Three quarter view of perpetual calendar module

Figures 89 and 90 show an edge on and upper three-quarter view of the completed perpetual module.

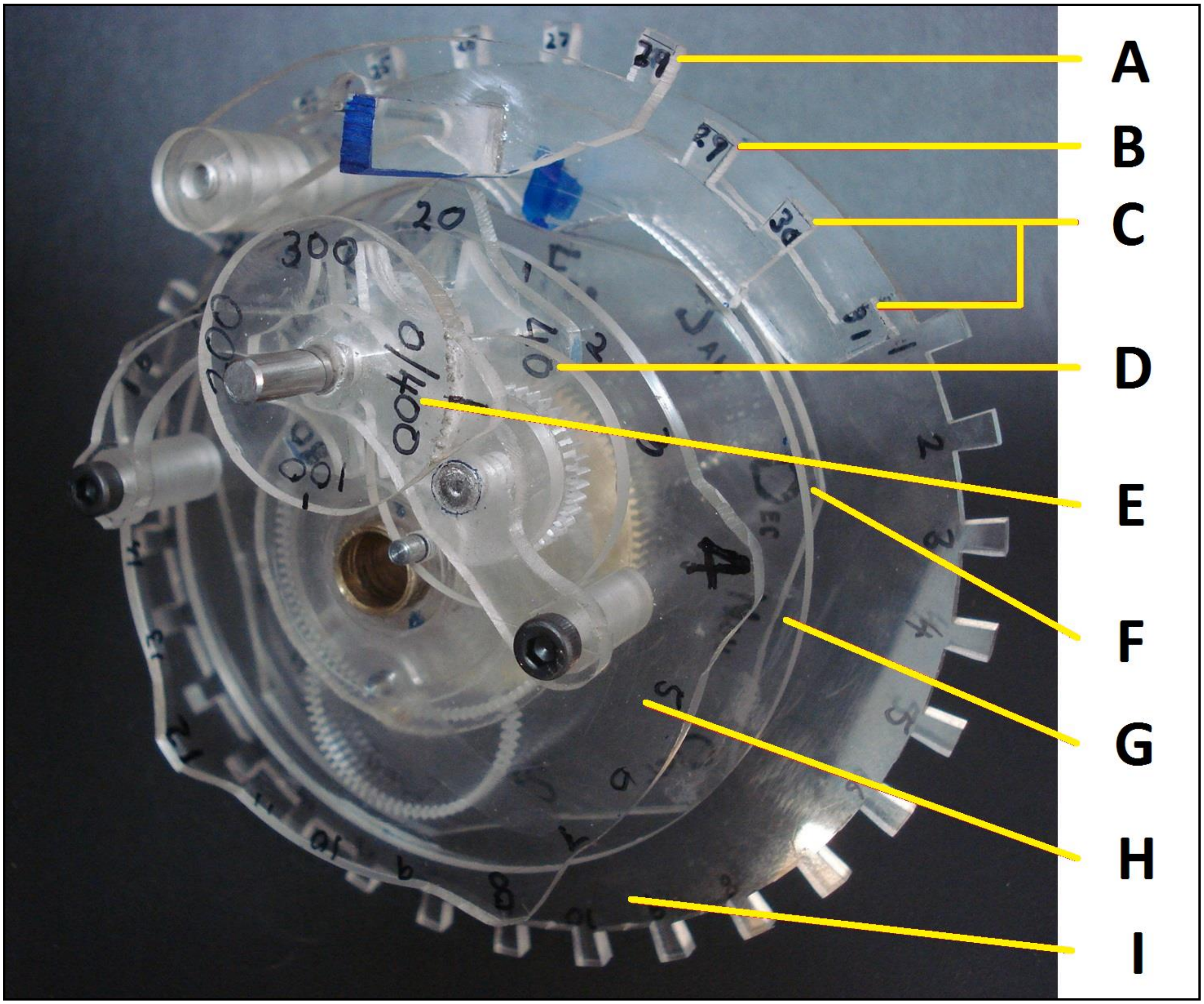



**Figure 91.** Components of the perpetual calendar module

Components of the perpetual calendar module, (Figure 91)
A. February surprise piece controlled by the 100 and 400 year cams
B. February surprise piece controlled by the month cam
C. Surprise pieces for months ending in 30 or 31 days controlled by month cam
D. 100 year cam driven 1/5 revolution for each revolution of the 20 year cam, eliminates leap year once every 100 years for three hundred years
E. 400 year cam, inserts leap year once every 400 years
F. Month cam, rotates once per year and controls the 30 and 31 day surprise pieces
G. February cam fixed to the month cam and lowers the surprise piece annually to allow for a non leap year February of 28 days
H. 20 year cam, gives a leap year at 4/8/12 year intervals, but not at the 16th year as this is controlled by the 100 and 400 year cams
I. The daily index wheel

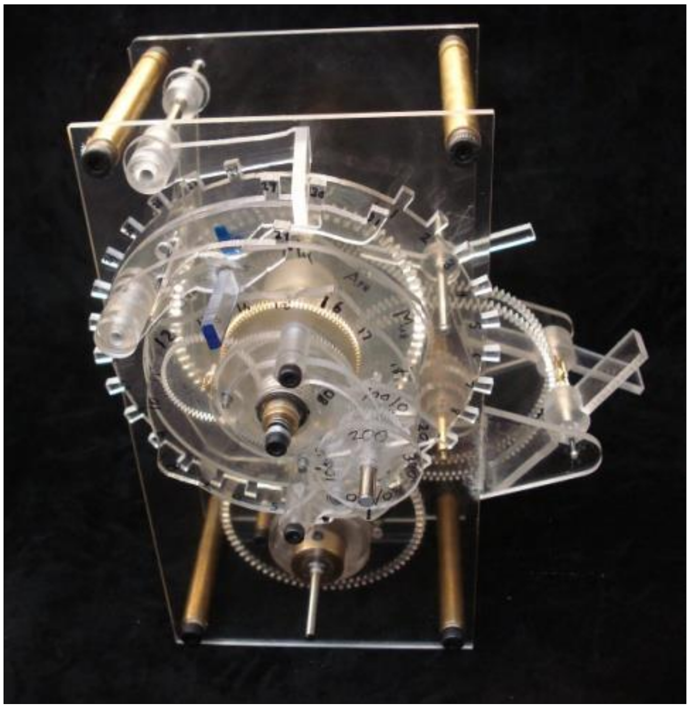


**Figure 92.** Perpetual module with the calendar drive, front

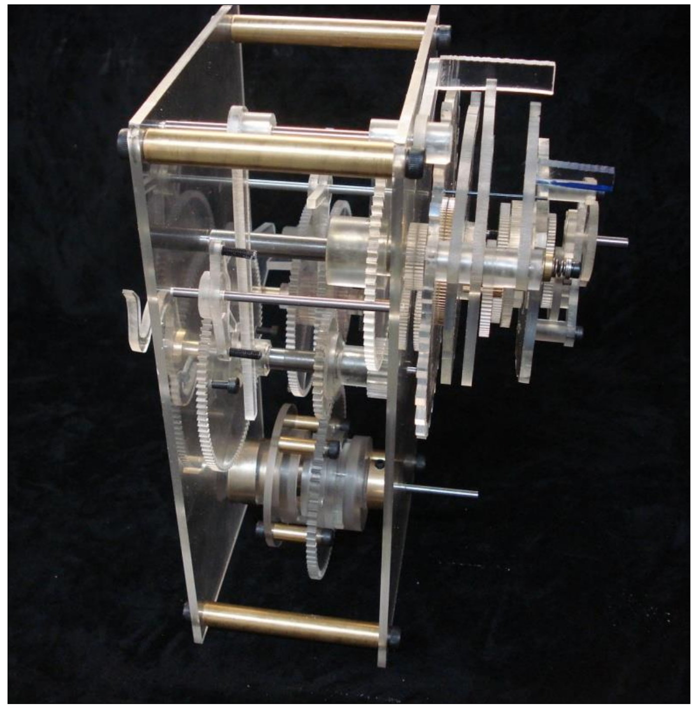


**Figure 93.** Perpetual module with the calendar drive, side

Figures 92 and 93 show the perpetual module within the context of the remontoire drive mechanism which will trip the module once per day. There is an elaborate clutch mechanism incorporated into this device to prevent unintended damage to the calendar module from a careless operator trying to crank the demonstration drive too quickly, one of the many safety mechanism incorporated into the demonstration area of the machine to prevent unintended damage. Video link: [https://youtu.be/lE8yxEXjRgw](https://youtu.be/lE8yxEXjRgw)


**Figure 94.** Diminutive 100 and 400 year cam components

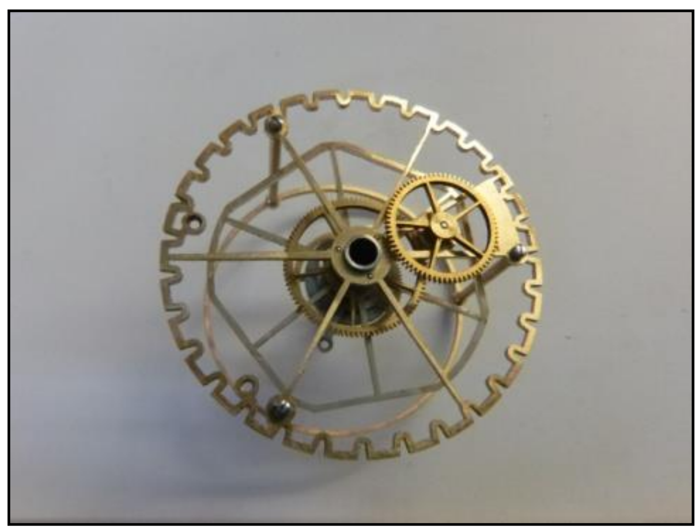


**Figure 95.** Delicately cut crenulated index wheel and cams

Figure 94 shows a few of the completed components of the perpetual module. The scale in the photo has a length of only one and one-half inch or four centimeters. Refer back to Figure 91 showing the completed plastic mockup of the perpetual module with the daily index wheel made of a solid plastic 3” disk with a crenulated edge. The easiest route to reproducing this in the final small scale would have been to make it from a solid metal disk with the same tooth profile. Or, the next easier way would be to make a thick-rimmed conventional spoked wheel and cut the crenulated design into the edge of the rim in the manner of a strike train count wheel. But Buchanan takes the most difficult and yet most visually spectacular route and makes the entire rim nothing but the sinuous design. This is all cut by hand with a fret saw and is about one inch or 3 cm in diameter – *a tour de force* in the art of decorative fretting. There are two more delicate, irregular-shaped cams below, the 100 year and February cams, (Figure 95).

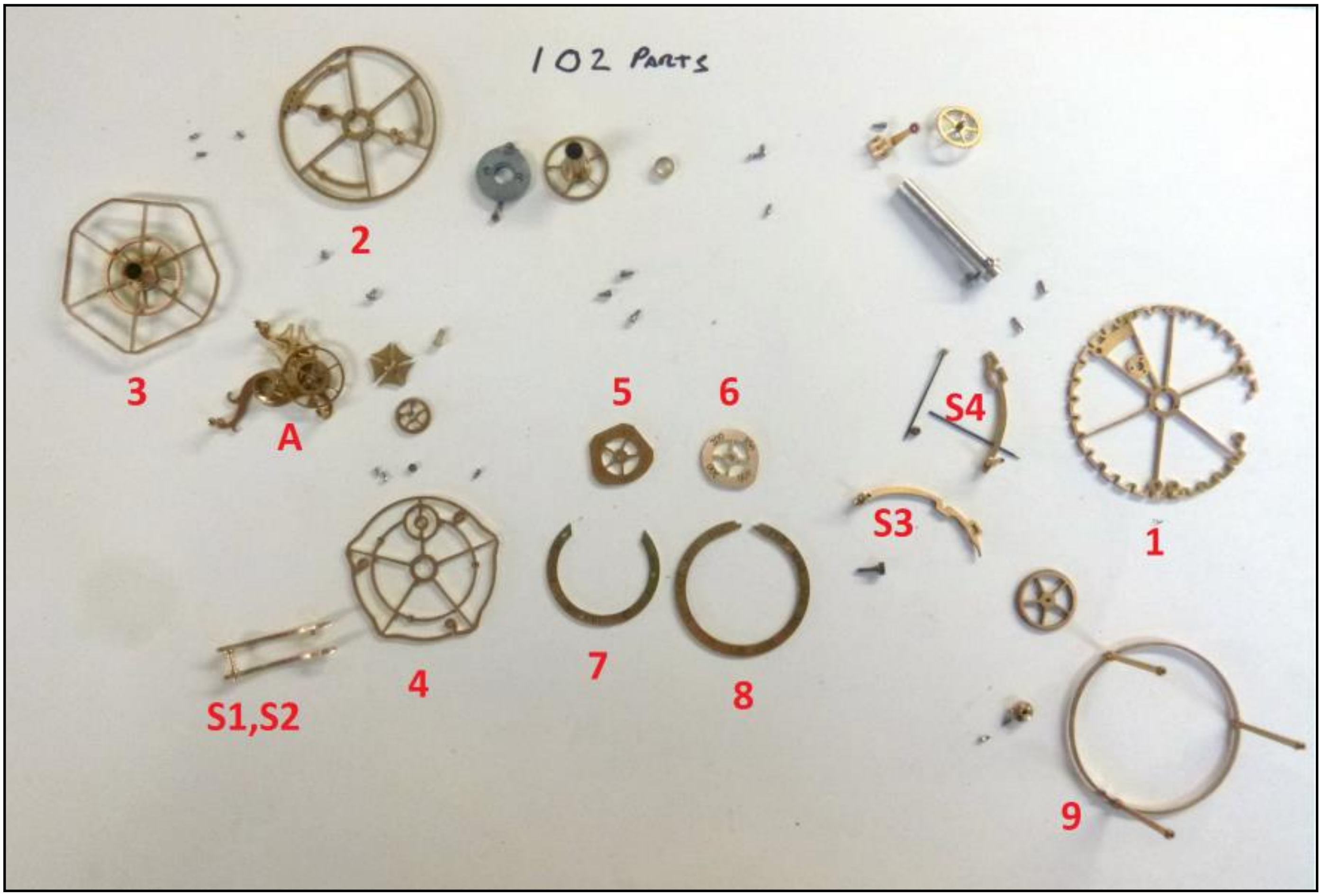



**Figure 96.** Components of the perpetual module

Figure 96 shows an exploded view of the main components of the reversible 400 year perpetual calendar calculator module. The total comes in at a bit over 102 parts. The main components are as follows:

1. Daily index wheel, this advances the date and is where the drive to the calculator begins
2. One year cam, controls the duration of February in non leap years
3. Ten year cam
4. Twenty year cam
5. One hundred year cam
6. Four hundred year cam
7. Twenty year chapter ring
8. Month chapter ring

9. Calculator frame assembly, partial
A. Four hundred year drive assembly

The S1 through S4 surprise pieces described below operate in the open area of the rim at the 3 o'clock position on part #1, the daily index wheel:

S1, S2. Dual surprise pieces that are controlled by both the 100 and 400 year cams
S3. Surprise piece for introduction of extra day in February in normal four year leap cycle
S4. Surprise piece for the introduction of the 31st day in the appropriate months, excluding February
The remaining parts are ancillary drive wheels, Geneva drives, fasteners and support parts.

**Figure 97.** Completed module next to a wristwatch, side view


**Figure 98.** Completed module next to wristwatch, top view

The completed module is just slightly larger in diameter than wrist watch, but of course quite a bit thicker, (Figure 97). Note the silvered chapter rings which allow the user to easily program the module, (Figure 98). Each dial allows the operator to independently adjust the cam work to bring the calendar into the correct readings for where one would currently be in the 400 year leap year cycle.

**Calendar readout components**

For each of the four calendar dial outputs there is a pair of wheels to produce the readout. The first is the drive wheel, which is a conventional geared wheel. The second is a crenulated wheel with the number of indentations on the rim corresponding to the positions on each dial. These allow for the dial hands to be stepped instantly at midnight to the correct readings, and are a key to the ability of the calendar to be reversible.

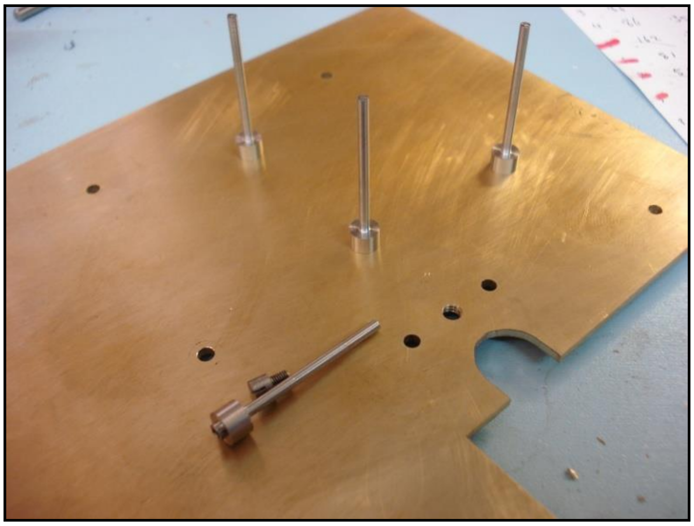


**Figure 99.** Arbor posts attached at only one end for dial wheels

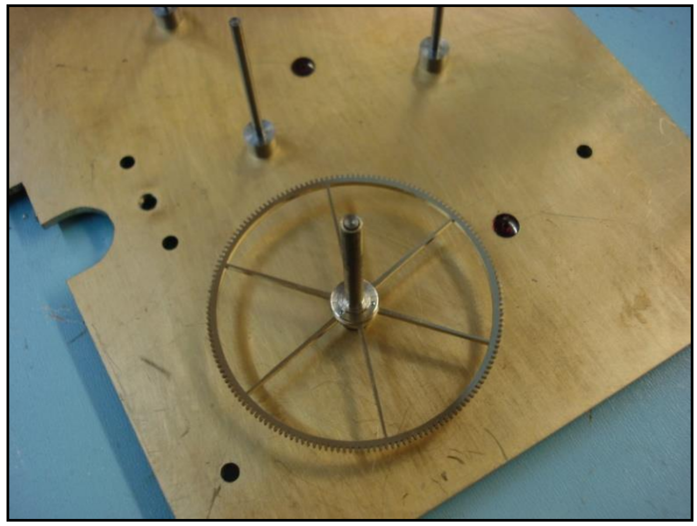


**Figure 100.** Drive wheel mounted to arbor

At the location of the center point of where each dial will be located is a post secured at one end to the rear calendar plate. This type of open ended arbor is called a dumb arbor, (Figure 99). Next a toothed drive wheel mounted to a cannon arbor is seen slid onto to the dumb arbor post, (Figure 100).

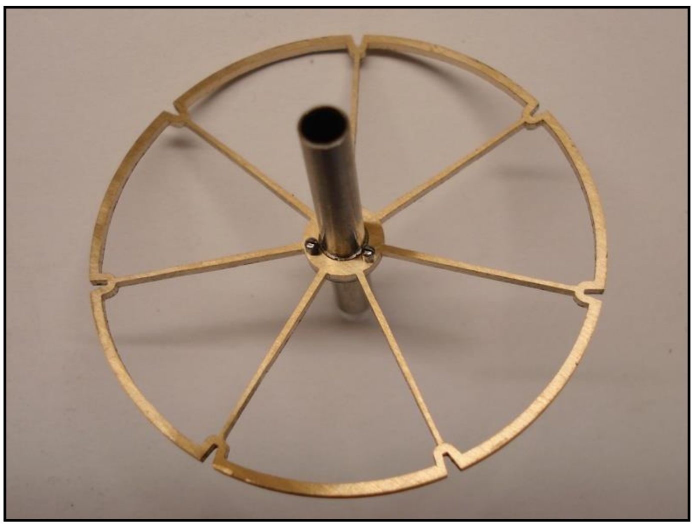


**Figure 101.** Stepper wheel for the day of the week

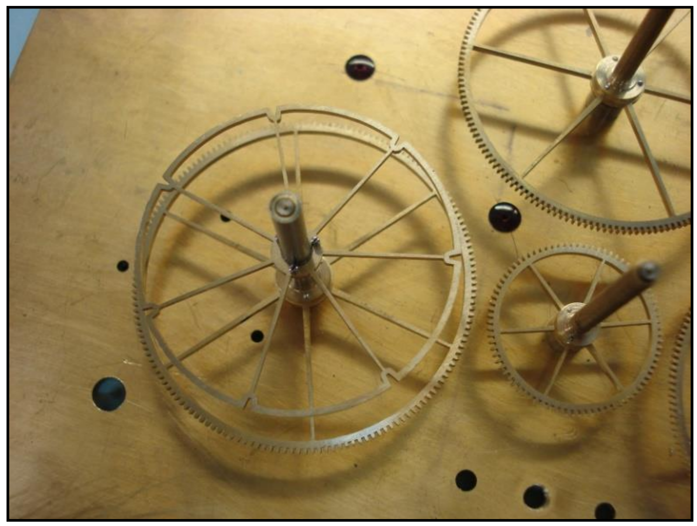


**Figure 102.** The stepper wheel mounted above its drive wheel

Figure 101 shows a crenulated stepper wheel made in the same elegant style as the daily index wheel within the perpetual module. There is one for each dial and the dial hand is attached to this. In this case it is for the day of the week and so there are seven notched areas for a control detent to lock onto. Next the stepper wheel's cannon arbor is slid onto the drive wheel's cannon arbor and these are in turn supported by the dumb arbor post. One can see that there is a slight space all between the center solid arbor post, the toothed drive wheel cannon arbor and the cannon arbor of the stepper wheel, (Figure 102).

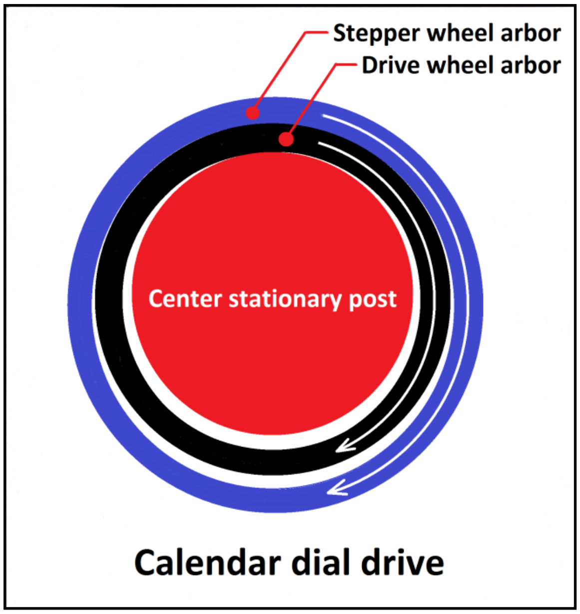



**Figure 103.** Burgess friction drive

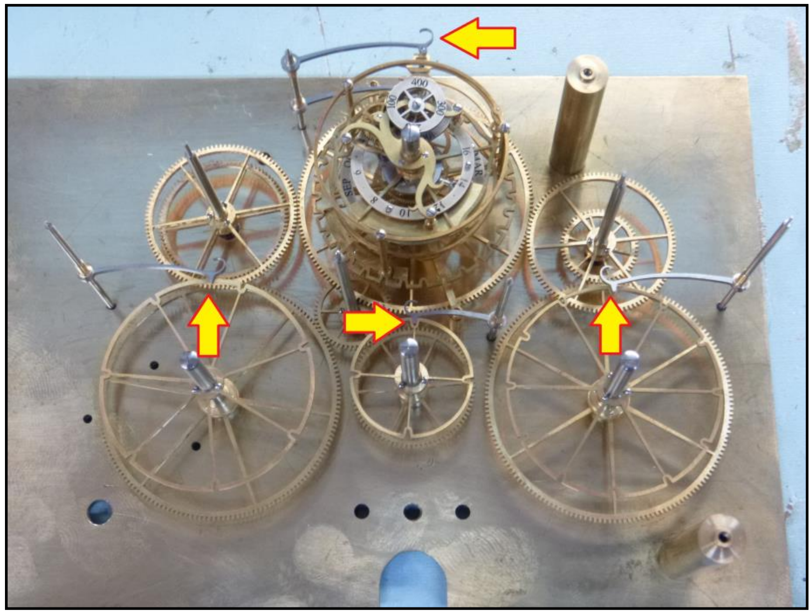


**Figure 104.** Red arrows show the locking detents for each dial's readout

Figure 103 shows how the calendar dial drive works. The drive wheel's cannon arbor fits over the stationary post, just as the cannon pinion in a conventional clock motion work. In addition the stepper wheel is attached to another cannon arbor which is mounted onto the drive arbor. As the drive wheel turns, the stepper wheel will turn with it along with the dial hand. But if a detent is engaged in any of the stepper wheel's notches that wheel will remain stationary and the dial reading will not change even as its drive wheel continues to turn. Buchanan had seen this example used on one of the monumental sculptural clocks made by Martin Burgess, the World Time Clock at Citigroup Centre, in Canary Wharf, England and employed the concept here.[11]

All of the drive and stepper wheels are now in place, (Figure 104). Each arrow indicates a detent in the form of a bird's head that controls that particular dial readout. The upper arrow shows the date, and below from left to right are the day of the week, the leap year and the month. All of the outputs are geared together so how do we achieve a 'jumper' display for dial readouts with differing numbers of indications? The drive wheels are advanced once per day via a remontoire within the calendar assembly. A series of levers and cams which comprise a set of mechanical analog logic circuits and controlled by the perpetual module determine which detents will be engaged or disengaged from each stepper wheel of the calendar at each cycling of the remontoire. Those wheels that have their detents momentarily raised during the remontoire cycle will have their stepper wheels advanced by one notch with the detents returning to their locking positions at the end of the cycle. Those that are not raised will remain unchanged. Since the perpetual module can run backward, and all of the calendar readouts are geared together, the entire calendar can run accurately in both forward and reverse.

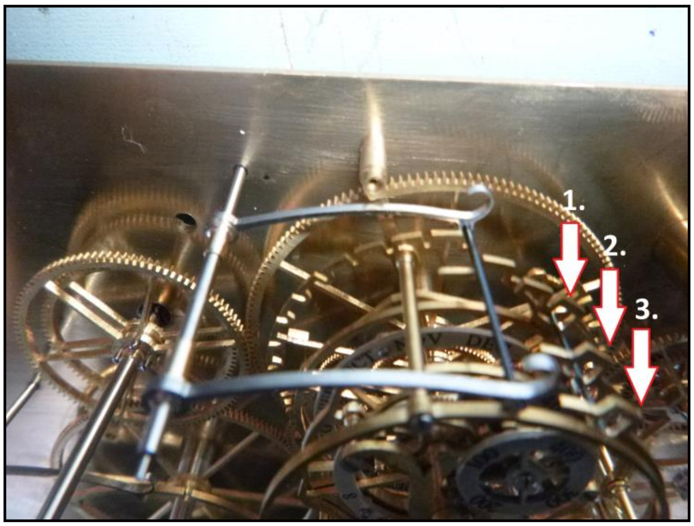



**Figure 105.** The date detent reader for the perpetual module.

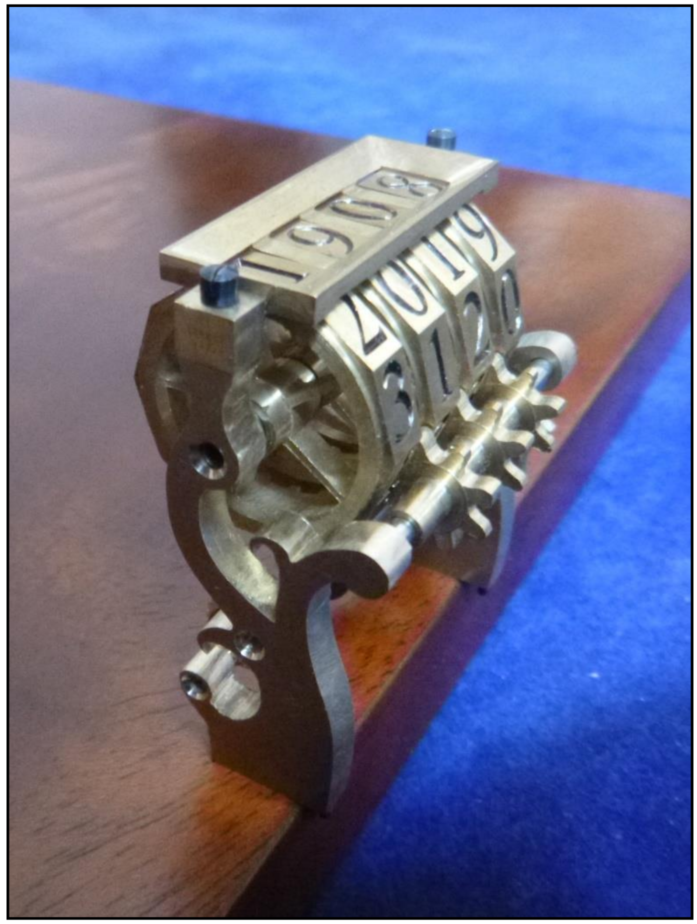


**Figure 106.** Digital year readout

Figure 105 shows a close up of the compound date detent above the perpetual module. This is constructed from a pair of detents joined together with a transverse metal rod. The background detent reads the daily index wheel as the perpetual module advances each day. Just to the right of the rod are the three surprise pieces as indicated by the three arrows. These control whether there will be a reading of 29, 30 or 31 days for each month on the index wheel. The transverse rod reaches across the width of the calculator and can be engaged by any combination of the surprises pieces. Those pieces in turn are actuated by the cams programmed within the perpetual module. The last readout on the calendar is not an analog dial but a digital counter to indicate the year, (Figure 106). We chose digit cylinders with ten flat sides to make the display more legible and because these are seldom seen. This display also flips over instantly at midnight on the New Year. For those movie buffs that have seen the movie The Time Machine, made in1960 and based on H.G. Wells book, the counter is reminiscent of the front control panel of the protagonist’s time travel machine.

## Analog logic components of the calendar

An analog computer represents data by measurable quantities, such as voltages or, formerly, the rotation of gears, in order to solve a problem, rather than by expressing the data as digital bits. One of the most famous analog computers was one designed by Charles Babbage in 1823, but aside from a small demonstration module was never built. The machine tooling of the time was not accurate enough to produce the full scale machine requiring thousands of parts and if possible would have been at a cost the British government was unwilling to finance.[12]

Fortunately we are not trying anything so ambitious. But we do employ mechanical levers to produce logic gates as well as a rotating set of cams that act as the computer 'clock' to coordinate the functions of the lever logic gates within the rest of the calendar machine; it is the processor unit of the computer. The perpetual module acts as the machine's hard-wired program and memory.

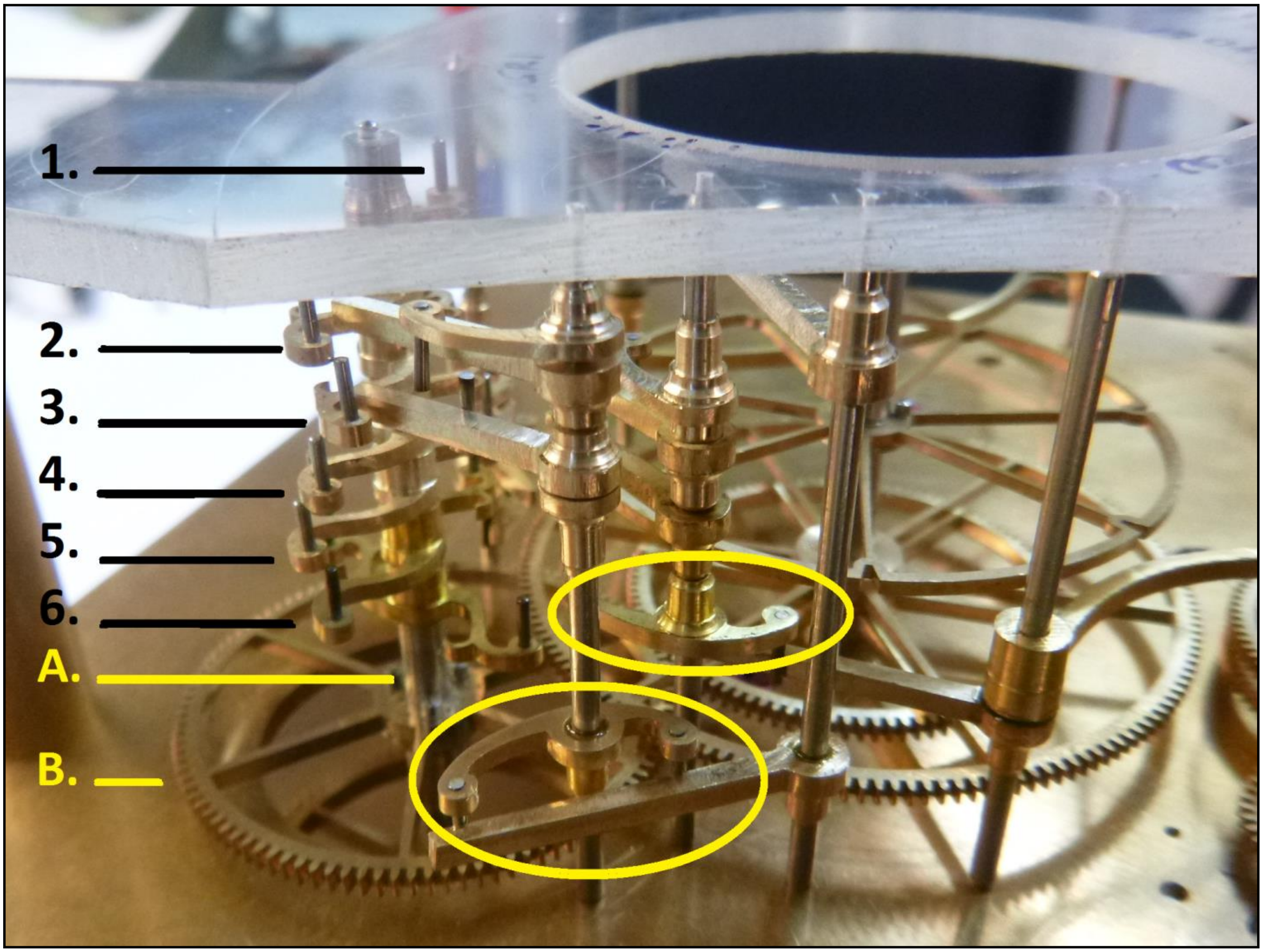



**Figure 107.** Analog clock controller for logic circuitry containing actuator cam stack, no's. 1-6

This three-quarter view shows some of the complexity of the calendar components, (Figure 107). The logic clock drive is represented by the drive wheel, **B** and arbor **A**. The wheel just barely visible below the circular opening in the brass plate belongs to the remontoire which drives the calendar once every twenty four hours. Upon arbor **A** are mounted the six rotating timing cams which begin the logic functions of the calendar numbered **1** through **6**. The first cam is largely obscured by the upper temporary plastic plate. The two circled areas show two of the three rocker assemblies, the third being obscured by components in the foreground. Each rocker assembly is responsible for converting the rotating motion of the cams in the clock drive into lineal motion to move the logic levers and allowing the clock to run in forward or reverse. Each rocker requires a pair of cams in the clock drive. This system coordinates the detents for the three dials of the day, date and month. The leap year and year counter are derived from the output of the date and month components.

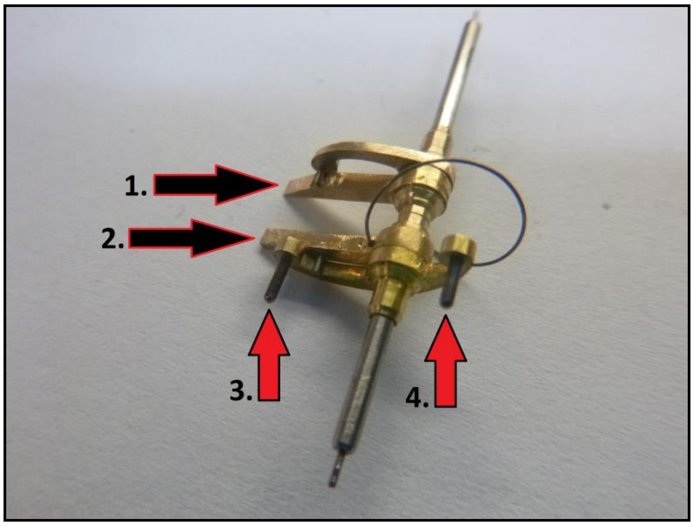


**Figure 108.** Lever rockers and one-way impulse paddles

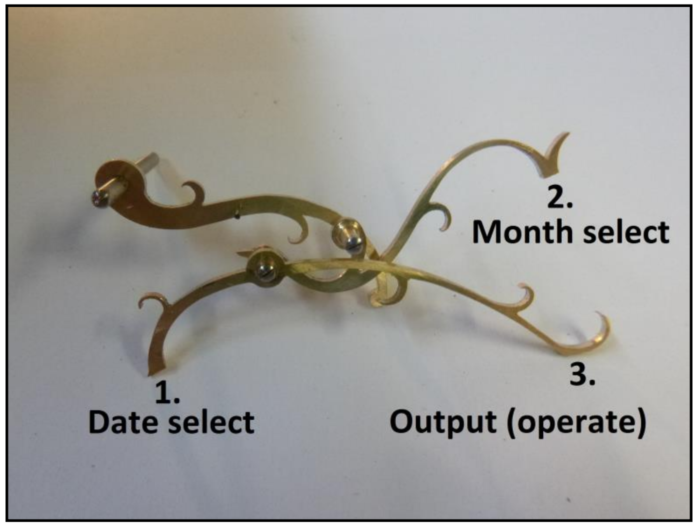


**Figure 109.** Logic lever, functioning as an AND gate

Figure 108 shows an example of one of three arbors that carry a lever rocker arm and a pair of one-way impulse paddles. The impulse paddles are shown by the black arrows **1** and **2**. This is a compound paddle made of two parts. The paddle itself, arrow **1**, is mounted loosely on the arbor and can move back and forth leaving the arbor to which it is mounted unaffected. The paddle is actuated by one of the rotating input cams mounted to what was described previously as the 'clock controller' in the mechanical logic circuitry of the calendar. The area of contact is near the tip of arrow **1**. The input cam can rotate in either forward or reverse. If the paddle is pushed in one direction, toward the viewer in this photo, the paddle will push the pin connected to the curved part next to it. That piece is fixed to the arbor and will cause the entire assembly to rotate in a small arc. If the cam encounters the paddle in the opposite direction, the paddle swings away from the curved piece and nothing happens. The opposite occurs for the second paddle, arrow **2**. The part below is a lever rocker and is fixed to the arbor. This basically converts the rotary motion of the input cams into a back and forth motions. The two pins located by red arrows **3** and **4** will push against the various logic levers that will ultimately control the action of the dial's detents and thus the position of each dial hand in the calendar. The spring acts as a return bias for the rocker as soon as the rotating cam has passed the point of contact on the paddle.

Figure 109 shows one of the logic levers. This one works like an AND gate where if there is a positive input at both the date select AND the month select lever points there will be a positive output operation on the third lever actuating the leap year dial and the year digital counter. If either or both of the date or month levers are not receiving an input there will be no output. The operation of the calendar is as follows:

- At midnight each day the calendar's analog clock controller's six cam stack is actuated through the calendar's on-board spring remontoire and the controller turns one – half revolution
- The controller is geared to each output dial drive gear, the day, date, month, and leap year cycle
- The day dial is always advanced one iteration for each one-half revolution of the analog clock regardless of anything else going on within the calendar mechanism
- The perpetual calendar module is mounted to the date gear. As the module turns throughout the year various cams within that module raise and lower three "surprise pieces" that control the length of the month from 29 through 31 days. This module also provides the tracking of the additional leap day for February every four years, as well as the exceptions to that rule every 100 and 400 years

- Depending upon the position of the surprise pieces as well as other actuating pins within the perpetual module, various detent levers that connect to the day, month and leap and year cycle will either engage or be disengaged from those dials output wheels which are friction-mounted to their drive gears, (the day detent is always disengaged). If engaged, the dial hand remains stationary, if disengaged the hand moves forward one iteration. After the cycle is complete all detent levers drop into the engaged position to hold steady the dial output hands throughout the day.
- The digital year output indicator is controlled by a compound lever that acts as an AND logic gate. When the lever comes into contact with a pin indicating both the month being December and the day being the 31st the output for the lever is positive and the year counter is moved one step forward

The following photos will show the various linkages and logic circuits throughout the calendar mechanism.

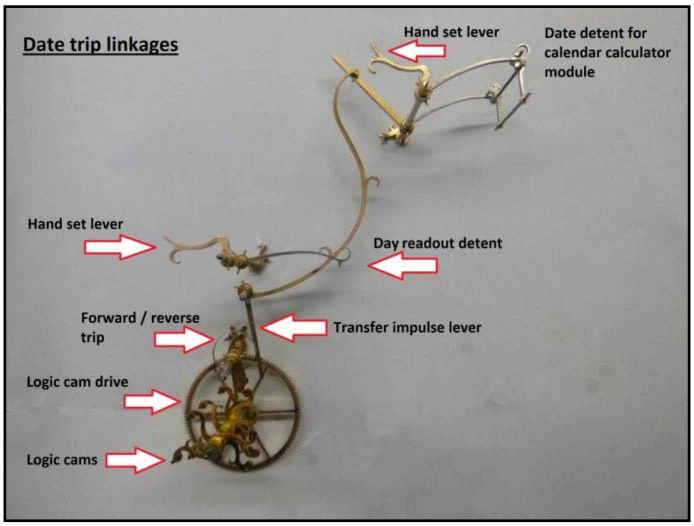


**Figure 110.** Day and date trip linkages

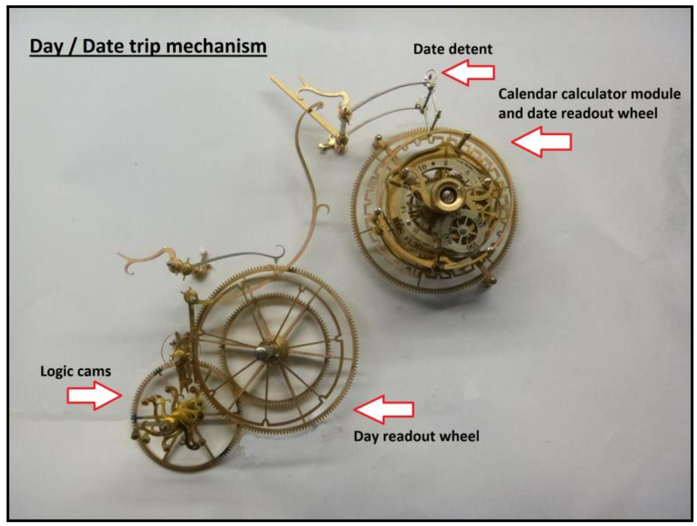


**Figure 111.** Day and date calculation mechanism

The first pair of photos encompasses two dials of the calendar assembly. These are the day of the week and date readouts. The day readout is the simplest of the calendar. Monday through Sunday is a seven day cycle that remains constant throughout the year regardless of the other complications to account for the variances in February or the leap year cycles, (Figure 110). The date is an entirely different matter and the date readout is connected to the calendar calculator module which determines the number of days for each month that has 30 or 31 days as well as what February should have in any given year, (Figure 111). This module accounts for not only the quadrennial leap year, but the 100 and 400 year exceptions to the February rule and is also fully reversible without the loss of data.

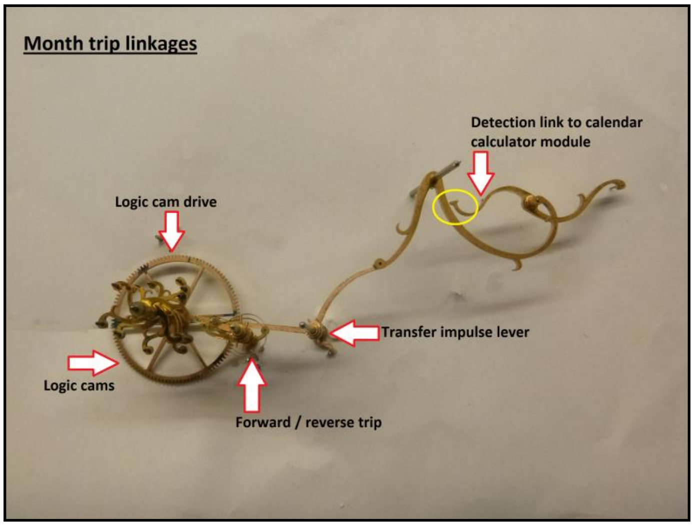



Figure 112. Month trip linkages

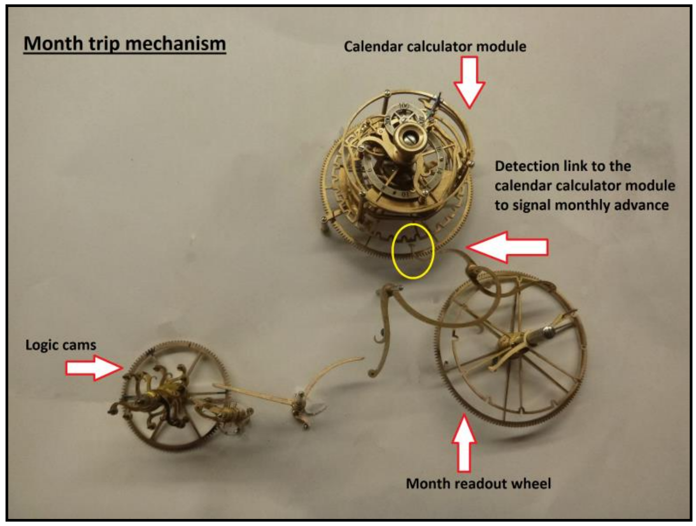



Figure 113. Month calculation mechanism

The next pair of photos shows the month calculation, (Figures 112and 113). The month trip is controlled by the calculator module so February is tripped at the right time according to the perpetual rules. The circled area in both photos is the detection detent for the month.

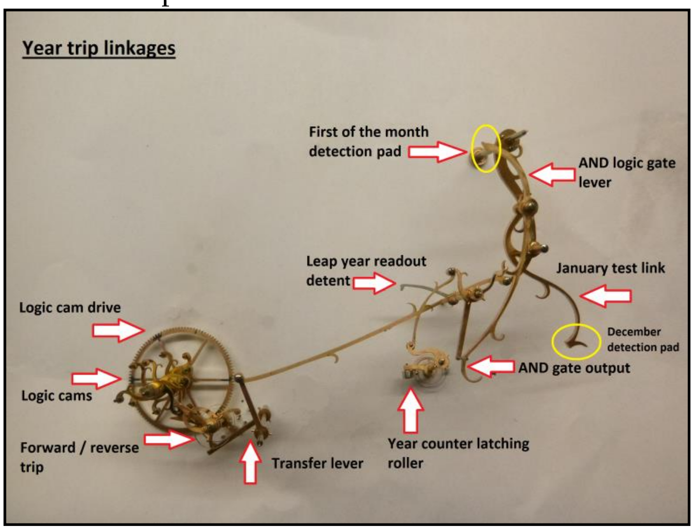



Figure 114. Year trip linkages

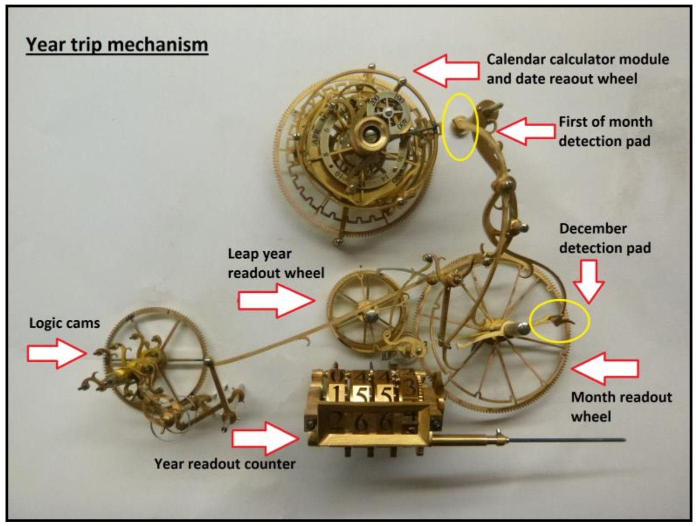



Figure 115. Year calculation mechanism

The third set of photos concerns the leap year dial and the year counter. The year calculation is the most complex since it is dependent on the date and month calculations as determined by the calendar calculator and the position of the month readout wheel, (Figures 114 and 115). The two circled areas in the upper area of the photos is the first of month detection lever and the lower circled areas are the December month detection lever. When both of these are actuated, input is allowed to the year readout. Why do we have this occur on the December and not January stop on the month stepper wheel? The reason is that we want all of the calendar functions to flip at exactly 12:00 midnight on December 31st. So while technically the upper lever is sensing the first of the month, we are still on the final moments of the December stepper wheel. Otherwise, the changeover would occur at midnight on January 1st.

From these examples one can see the hierarchy in the complexity for determining the calendar readouts. The simplest is the day, unvarying throughout the year, there are no adjustments here. Next is the date which is inextricably connected to the February cycle and requires the use of the calendar calculator module. Next is the leap year which is determined by the calculator module to give it perpetuity. And finally the year counter which only will turn over after all of the prior conditions for the signal of the year is given based on all of the prior data sets being met.

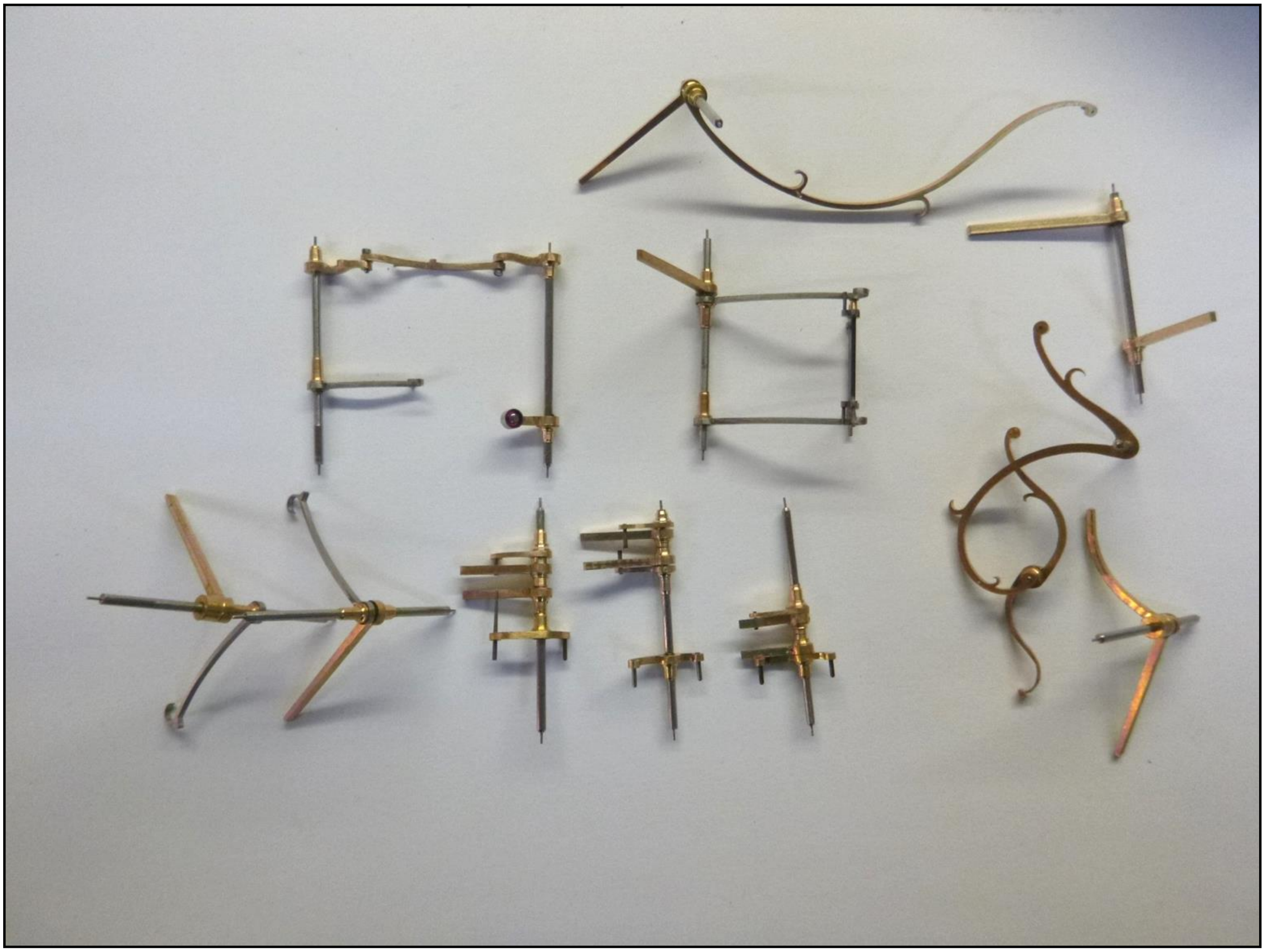


**Figure 116.** A subset of the calendar logic levers and linkages

Depicted here are a few of the calendar linkages, (Figure 116).

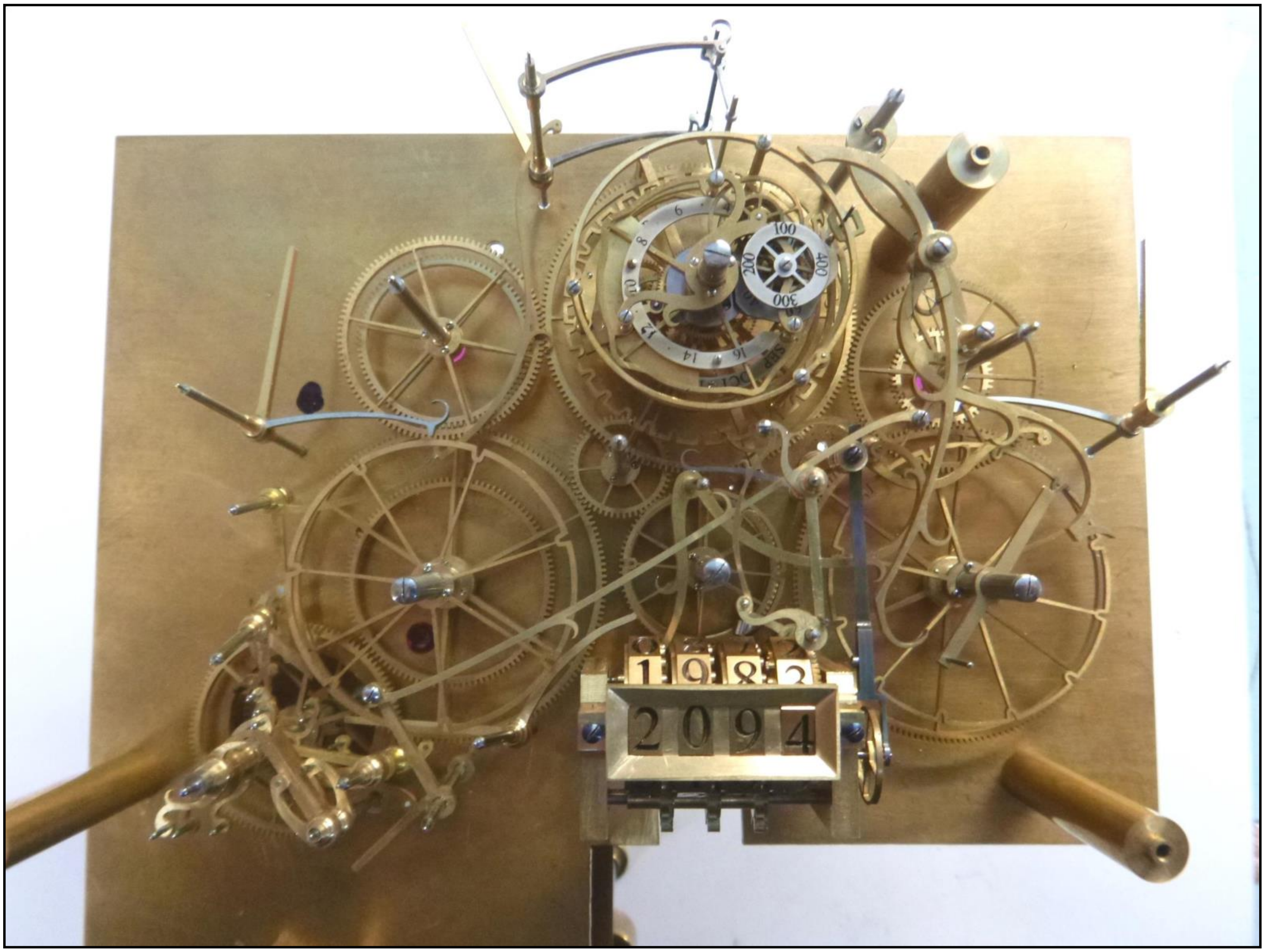


**Figure 117.** The complete calendar with front dial plate removed

The compliment of logic linkages shown with the front plate removed, (Figure 117).
Video link: https://youtu.be/RFbKiZfZEEs

Skeltonizing of the calendar plates

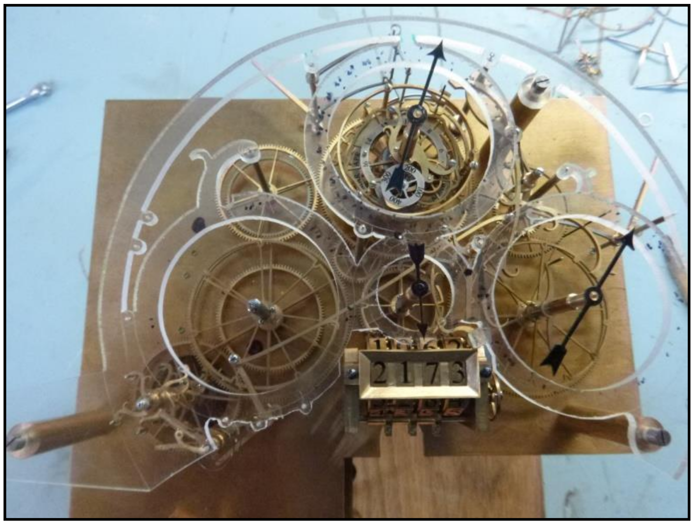



**Figure 118.** Plastic mockup of front dial plate

**Figure 119.** The skeletonized front dial plate

The design for the front plate dial cluster had been set since the very beginning of this project in 2006 and the enamel dial work has been completed since 2013. There just needed to be a few additional areas branching from the dial support plate rings to connect pivots. The plastic mockup plate is shown here, (Figure 118); with the final dial plate design in metal, (Figure 119).

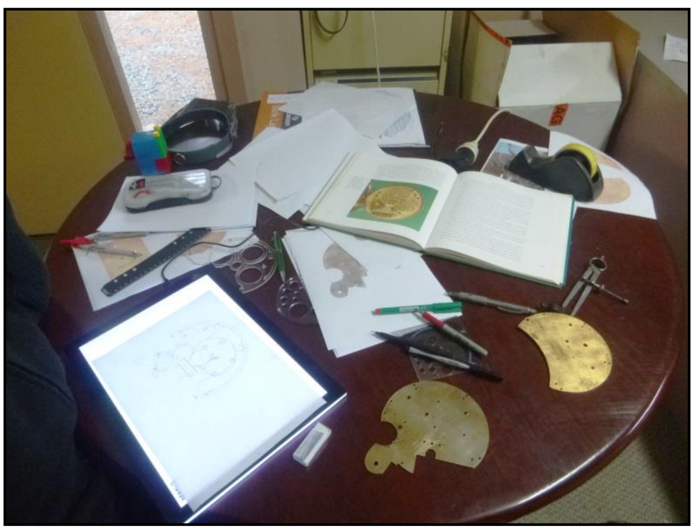


**Figure 120.** Materials used for rear plate design ideas

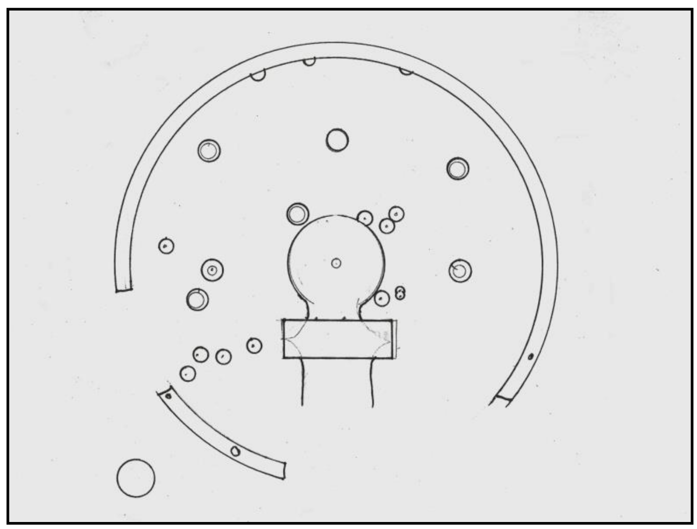


**Figure 121.** Initial drawing showing extant pivot locations

The rear plate however, was a blank slate. We see here the process used to design the decorative features for the plates. The open book in the center of the table has a detailed photo of the back interior of an antique pocket watch showing a fancy, skeletonized balance cock. The initial design begins to germinate in the drawing on the sketch pad in the lower left. To the right are both the front and rear blank brass calendar plates, (Figure 120). The first thing that had to be done was to accurately depict where each pivot and pillar hole was located. Figure 121 shows where all of these are positioned. The object in the center is an outline of the front pillar of the time train to which the calendar assembly is affixed. ***Here is where ideas are imagined*.**

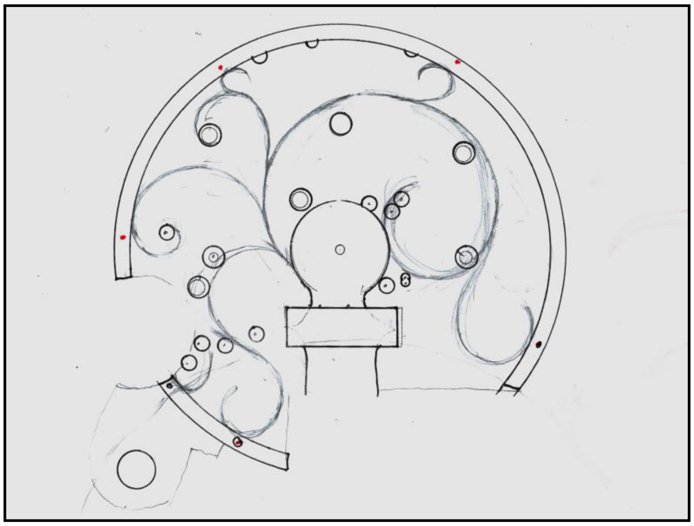


**Figure 122.** Early concept drawing connecting the pivots

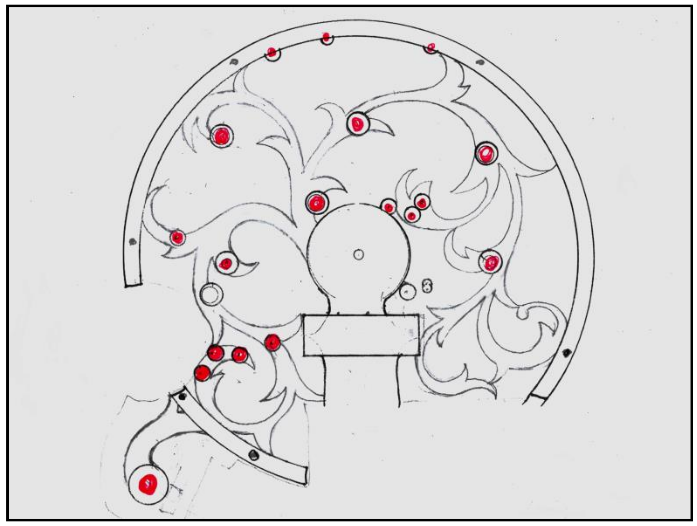


**Figure 123.** The rear frame design more fully developed.

Figure 122 is the same drawing as that shown on the sketch pad on the table in Figure 120. The initial design begins to take shape with simple curves that attempt to engage with as many of the hole locations as possible without contorting the curvilinear design. Next those lines have evolved into the organic ivy and spur design used throughout this project; the red dots are jewels. (Figure 123). ***<u>Here is where imagination meets artistry</u>*****.**

**Figure 124.** The intricate design is fretted out by hand

**Figure 125.** Rear frame fretted; displaying organic ivy design

Now the fun begins! Once more Buchanan employs the trusty jeweler's saw equipped with binoculars to delicately cut the intricate pattern into the brass sheet and create his ornate design. This is the same tool that has cut all of the flat stock, from the frames to the thousands of wheel spokes on this project, (Figure 124). One can see the inspiration of a pocket watch balance cock that was seen in Figure 112 within this piece. The decoration for the rear main frame is now finished. All of the ivy appears to be growing just like a real plant from a single location at the 10 o'clock position from the center hub. There will be further hand filing and refining of the entire piece before the final polish, (Figure 125). ***<u>Here artistry is made real through hand-crafted machining skills</u>*****.**

**Figure 126.** The nearly 600 components of the calendar unit

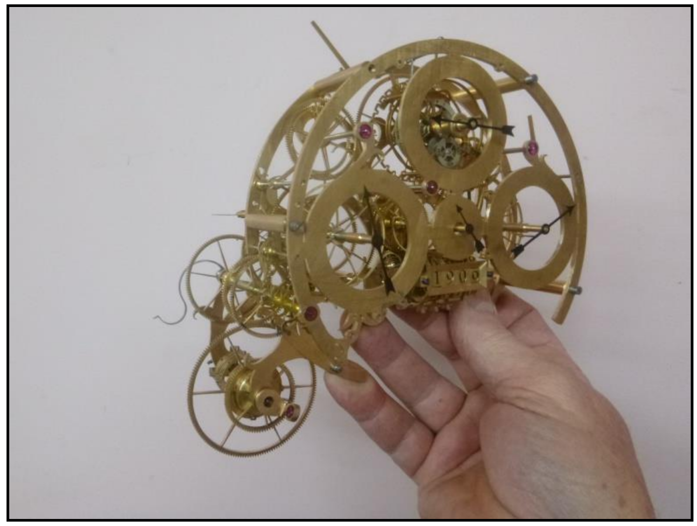


**Figure 127.** The completed calendar complication

Will all this fit back together again? Well, yes it does! (Figures 126 and 127). The perpetual third-order reversible calendar is expected to be the most challenging and intricate of all of the dozens of complications we will be building into this machine. But it is central to the demonstration of all of the other celestial functions. Parts count 580 including 36 jewels.


**Figure 128.** The completed calendar assembly installed.

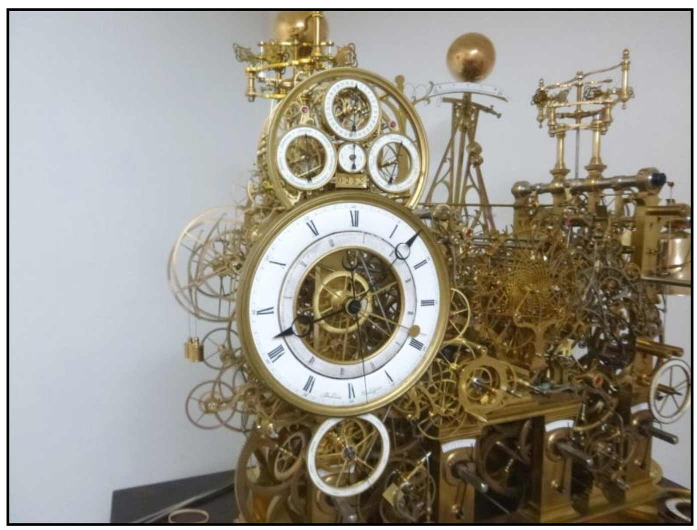


**Figure 129.** The left hand sector of the clock is now complete.

***<u>Here kinetic art is made manifest in this complex, fantasy machine</u>.***

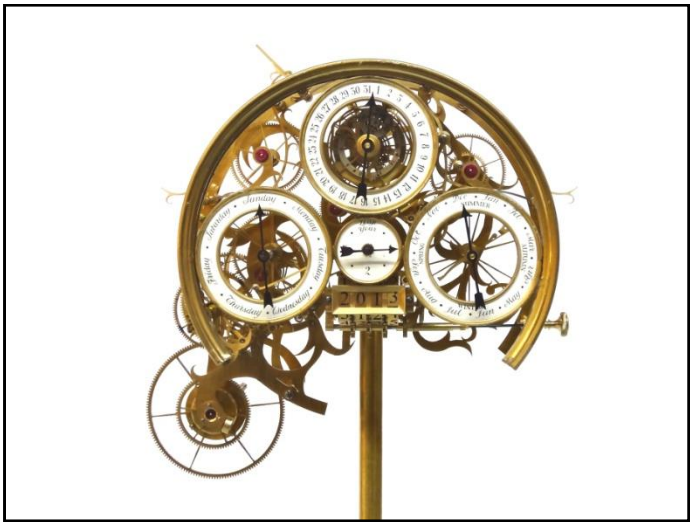


**Figure 130.** Calendar complication, front elevation

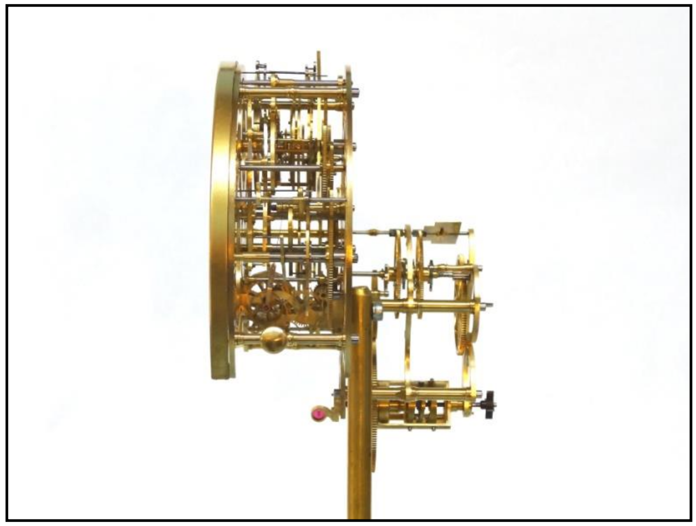


**Figure 131.** Calendar complication, right elevation

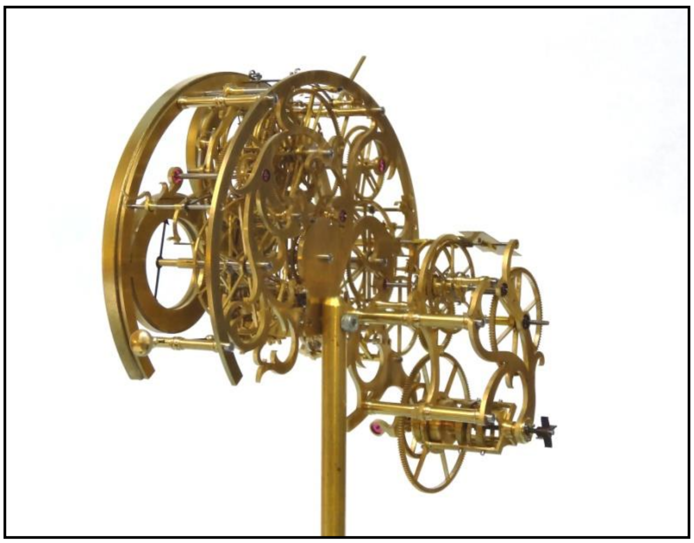


**Figure 132.** Calendar complication, rear three-quarter elevation

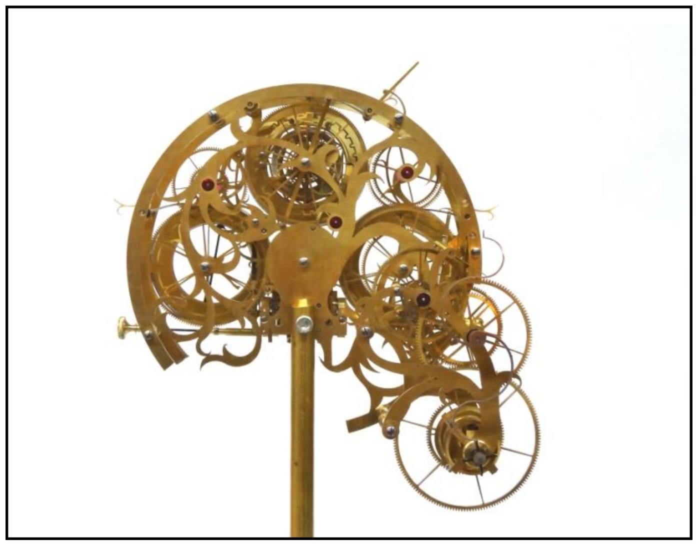


**Figure 133.** Calendar complication, rear elevation

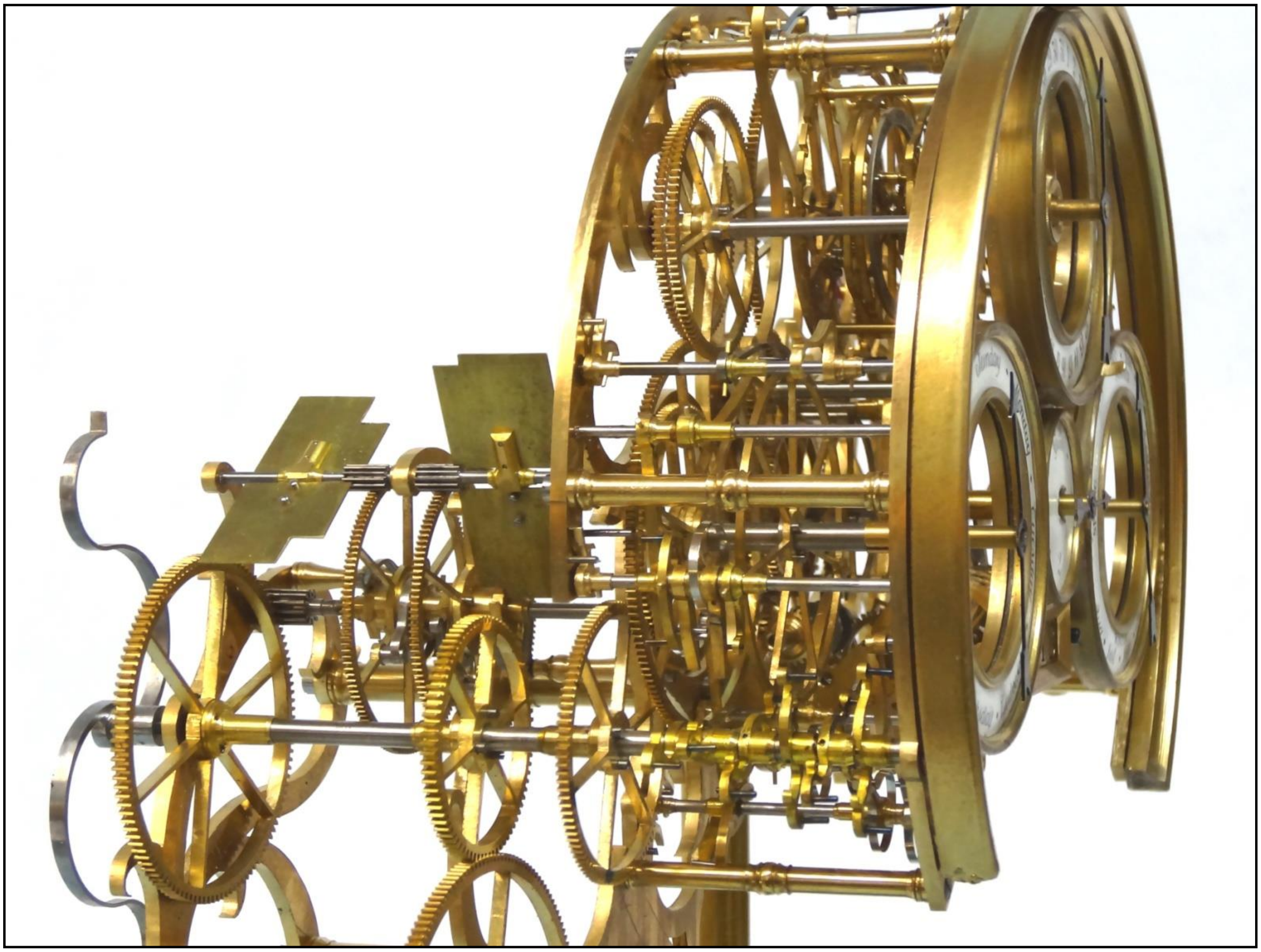


**Figure 134.** Calendar complication front, three quarter view

Video link: https://youtu.be/IAP3SpGf77U

## The Tellurion

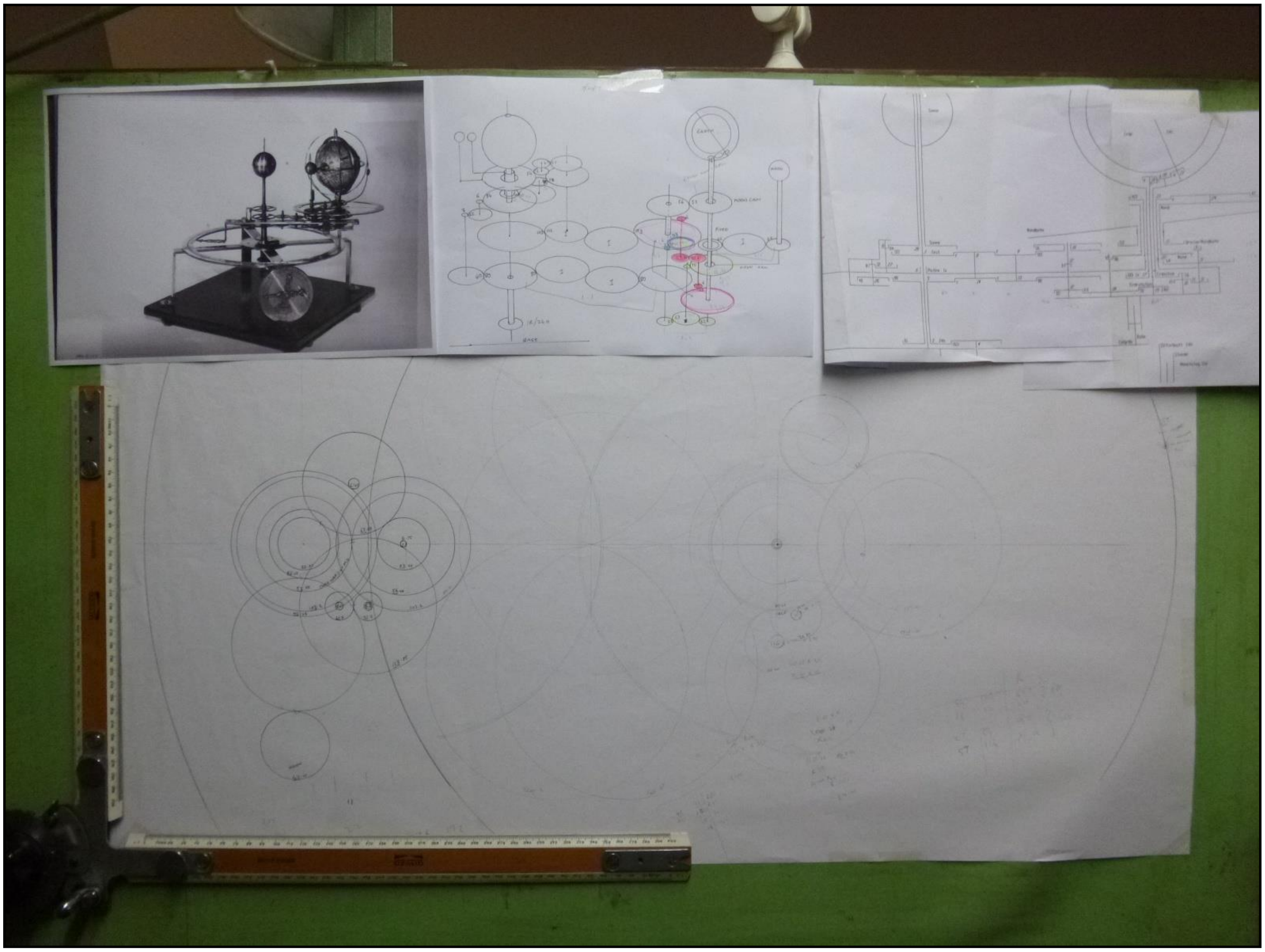


**Figure 135.** The starting point for the tellurion

Figure 135 shows the kick-off for the tellurion complication. We begin with a photograph of an example of a stand-alone tellurion by Mathias Hahn, 1780 in the upper left hand corner. The upper right corner has a schematic of that mechanism. The upper center is a drawing of our version which has the addition of the inner planets Mercury and Venus as well as the Earth-Moon system found in Hahn's piece. The lower, oversized paper is a scale drawing, oversized to 1:5. When a formal drawing is needed, Buchanan usually draws a large scale size to more clearly see how the various components are arranged.

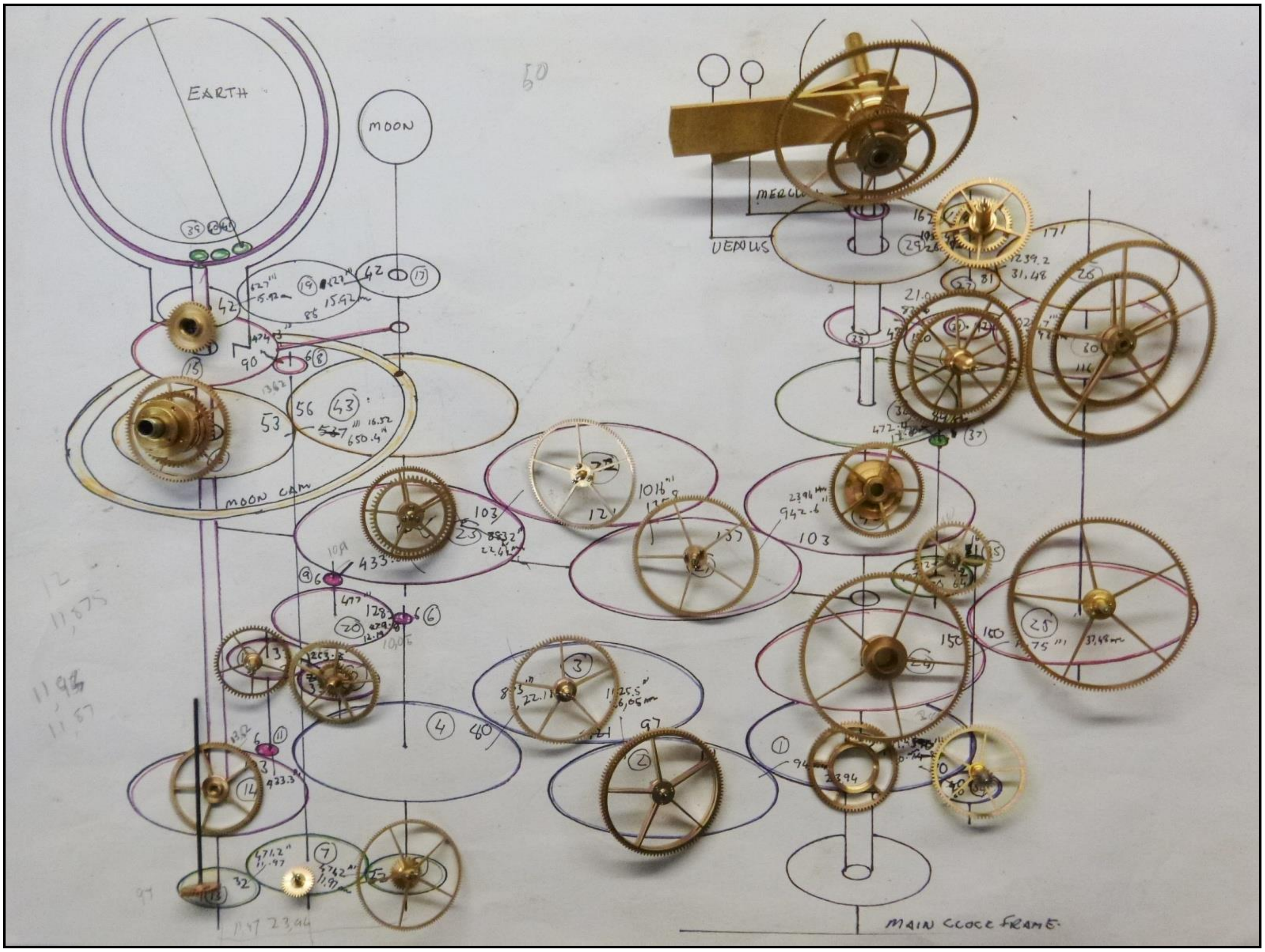



**Figure 136.** Buchanan's tooth-count drawing with many of the completed wheels

Figure 136 shows the majority of the 39 wheels that will be needed for this complication.

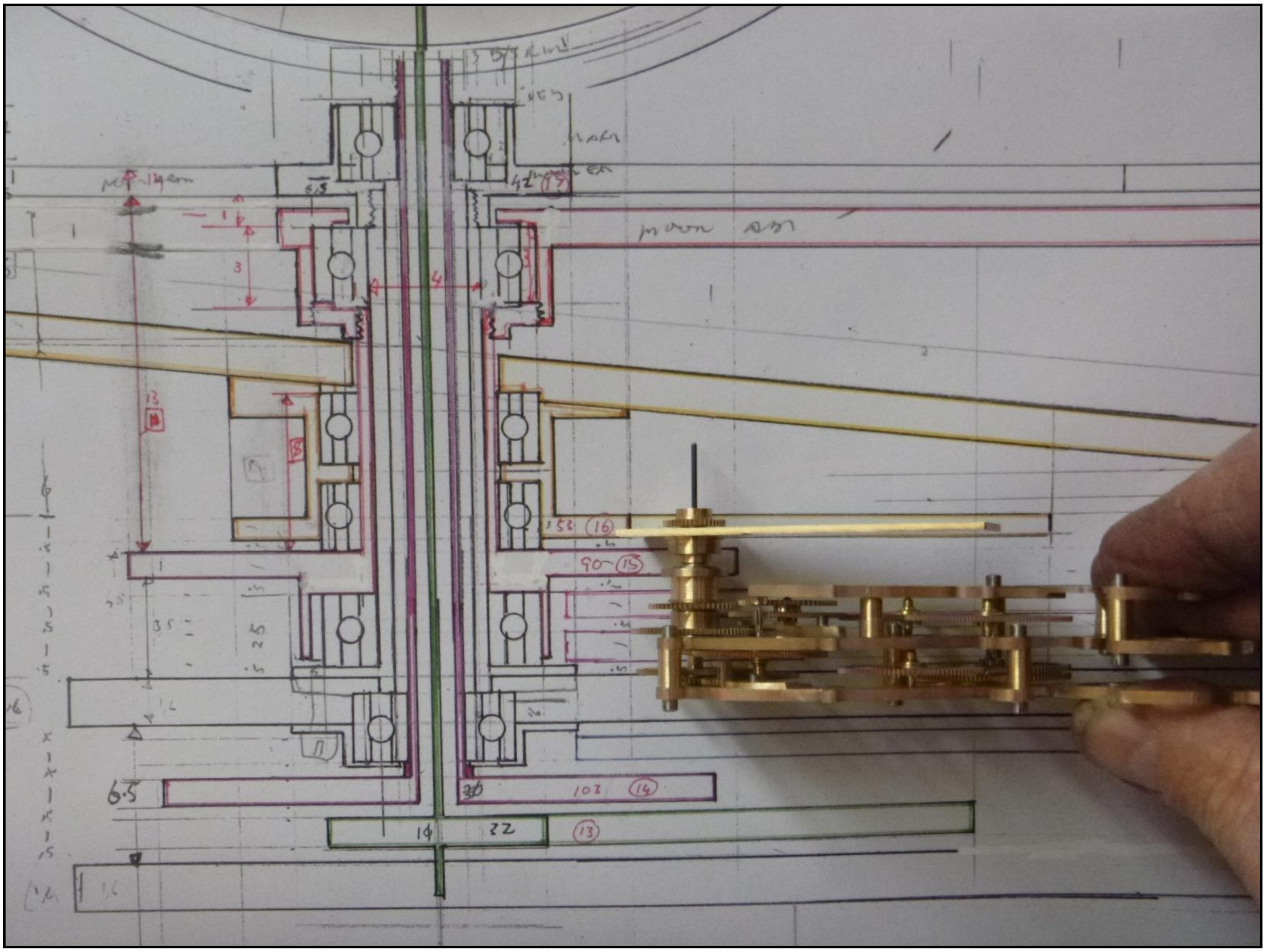


**Figure 137.** Cut away drawing of the central drive for the Earth-Moon system

Figure 137 shows a closer view of the side elevation depicting a cut away view of the complex set of concentric drives for the Earth-Moon system as well as the Moon's slanted node ring depicting the $5.15^0$ incline in its orbit compared to the Earth's ecliptic. One can see the advantages of having the large scale drawing to more clearly show the many components as compared to the actual part. In most cases tellurians and orrerys are mounted horizontally, that is the horizontal display is mounted to a vertical central drive. In our clock the tellurian is turned ninety-degrees for a vertical display. The drawing as well as the part is oriented the 'wrong' way in this figure to make it easier to understand. Normally a set of concentric tubes are used to drive the planetary display much like the cannon pinions used in conventional clocks to drive the minute and hour hands. But more are needed for this application. Here we have four tubes along with a center arbor. Notice the set of five ball bearing rings. These are essential when the concentric tubes are mounted horizontally. A set of tubes oriented horizontally and all rotating upon each other would produce too much friction.

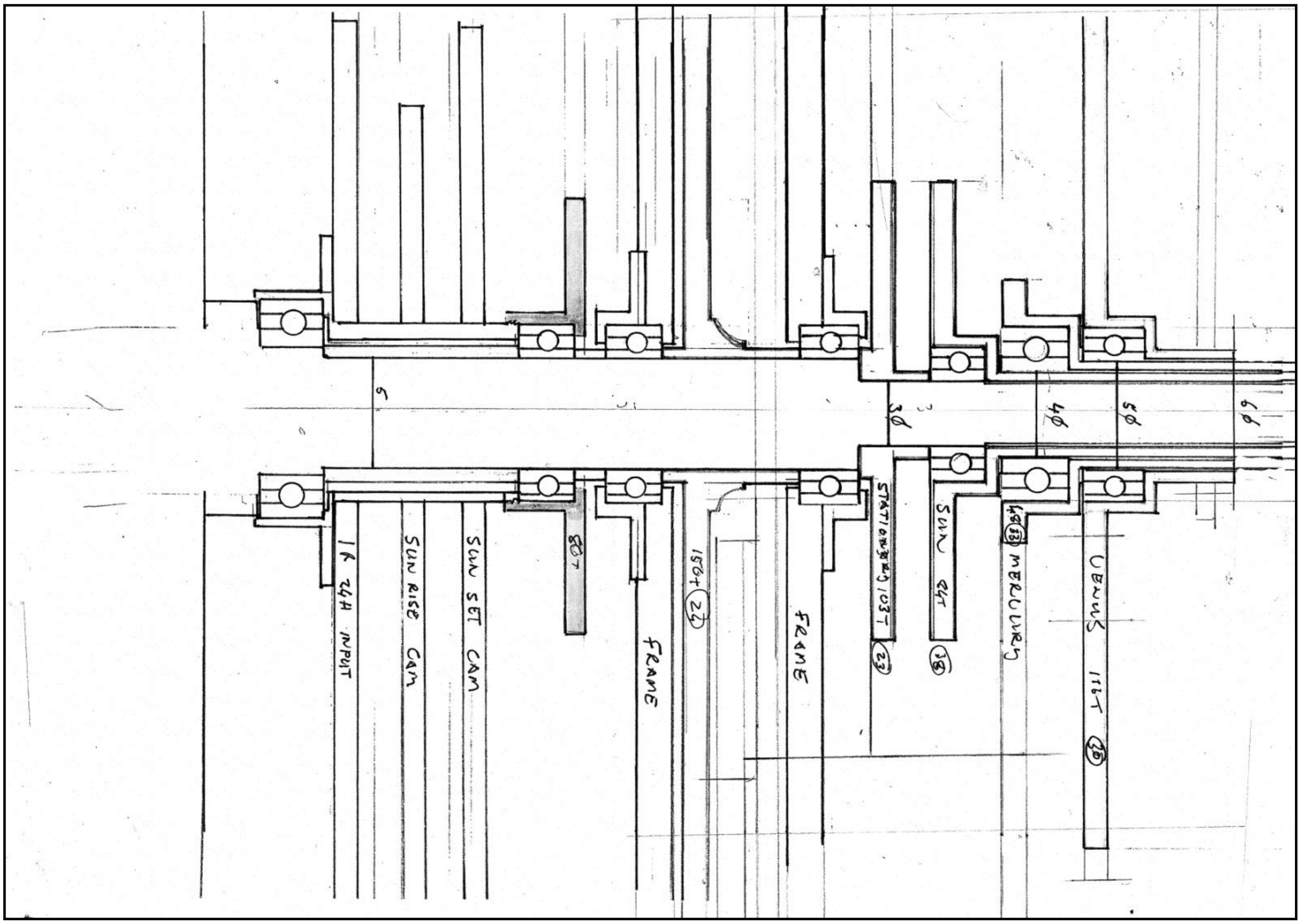



**Figure 138.** Cut away drawing of the central drive for Sun, Mercury, Venus and rotating tellurian frame

Figure 138 shows the central drive upon which the entire tellurion is mounted and rotates. It contains seven ball bearings. Two pair of bearings is for the rotating frame and support for the tellurian on the main stationary mounting post attached to the clock and three for the drives to the Sun, Mercury, Venus. Many tellurions and orrerys simply employ a Sun that does not rotate, but the Sun does have an approximate rotation of 24.47 days. This is approximate because the sun is a ball of slippery plasma and the poles actually rotate more slowly at 38 days than the areas near the equator. The view of this drawing is in the correct orientation and it becomes immediately apparent why ball bearings are necessary in this application.

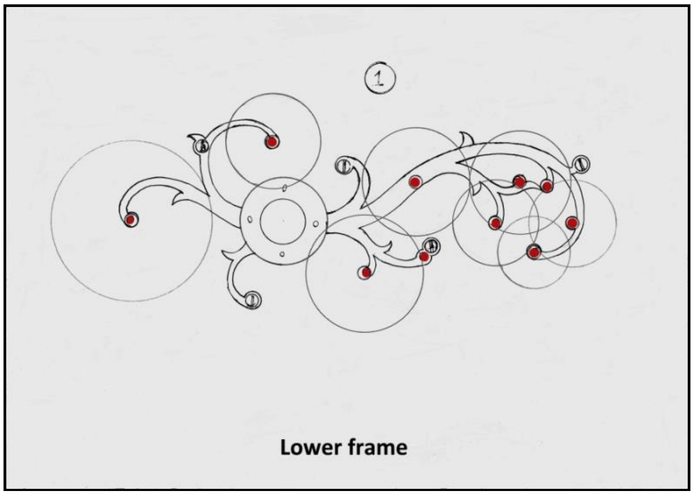


**Figure 139.** Design drawing for lower tellurion frame

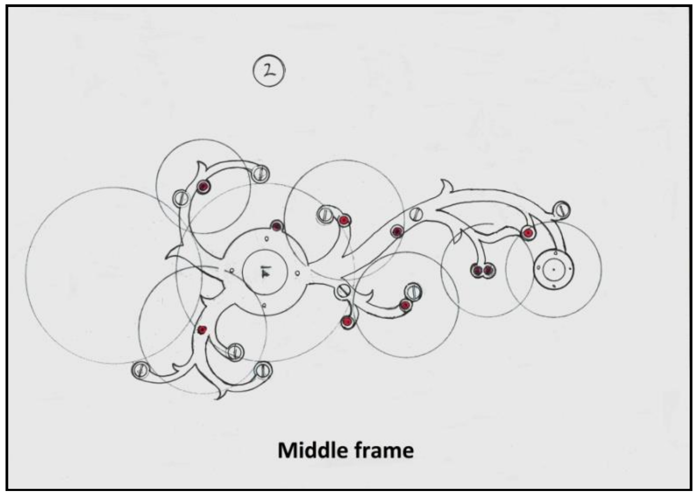


**Figure 140.** Design drawing for middle tellurion frame

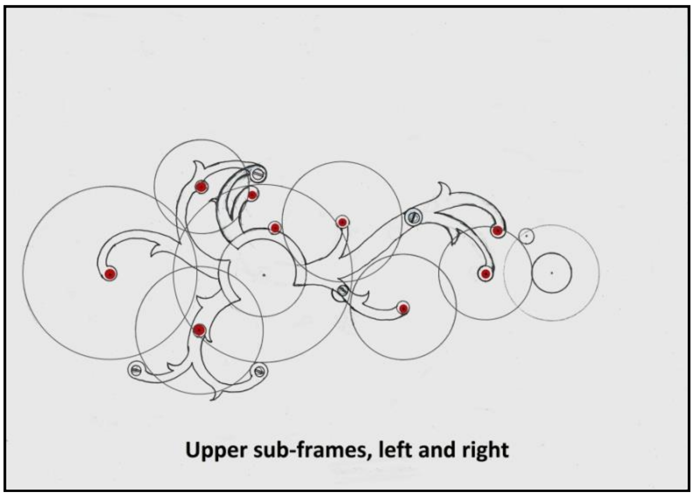


**Figure 141.** Design drawing for two upper tellurion sub-frames


**Figure 142.** Initial test plate for fitting of tellurion to clock

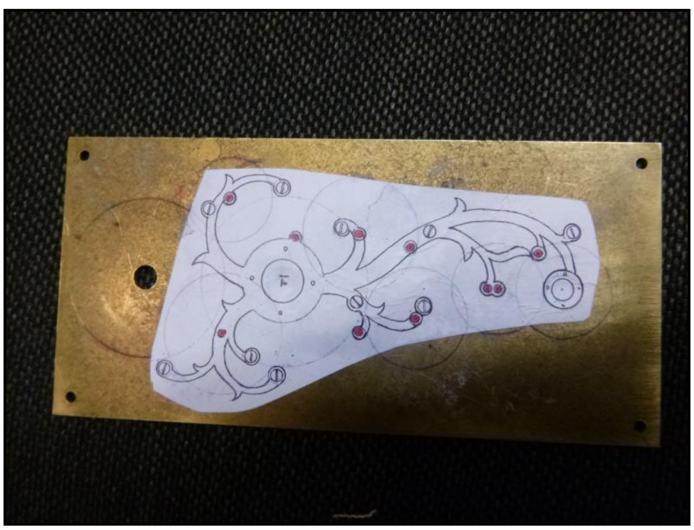


**Figure 143.** Design drawing is positioned for transfer to plate


**Figure 144.** The completed full frames and sub-frame pairs

Figures 139 through 141 show the design of the tellurion frames. All of these are cut out from the solid brass blank on a jeweler's fret saw by hand, a laborious process; all of the red dots represent pivot jewels. Figure 142 shows the initial sizing of the brass blank representing the tellurion to the clock and Figure 143 the frame design transferred to that blank and ready for tracing. Figure 144 shows the completed frames.

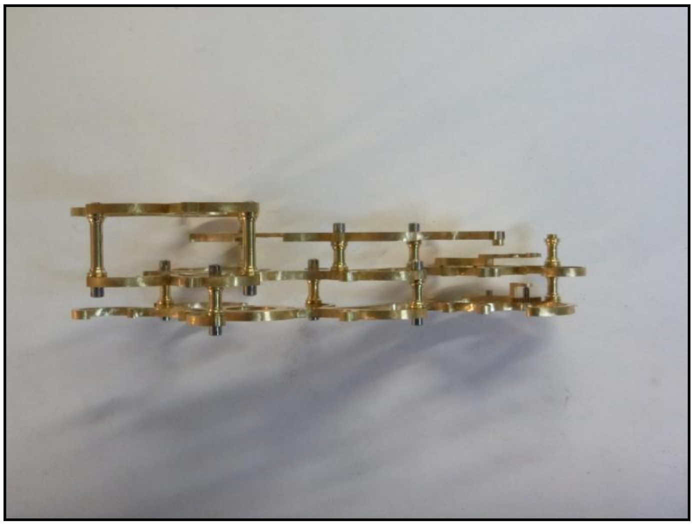


**Figure 145.** Side elevation shows the double frame design

**Figure 146.** The completed filigree frames with jewelling

The completed frame is shown in Figures 145 and 146. One can see the double frame construction in the first photo. A conventional frame has two plates; a double frame has three. Next the completed assembly ready for the wheels and other components.

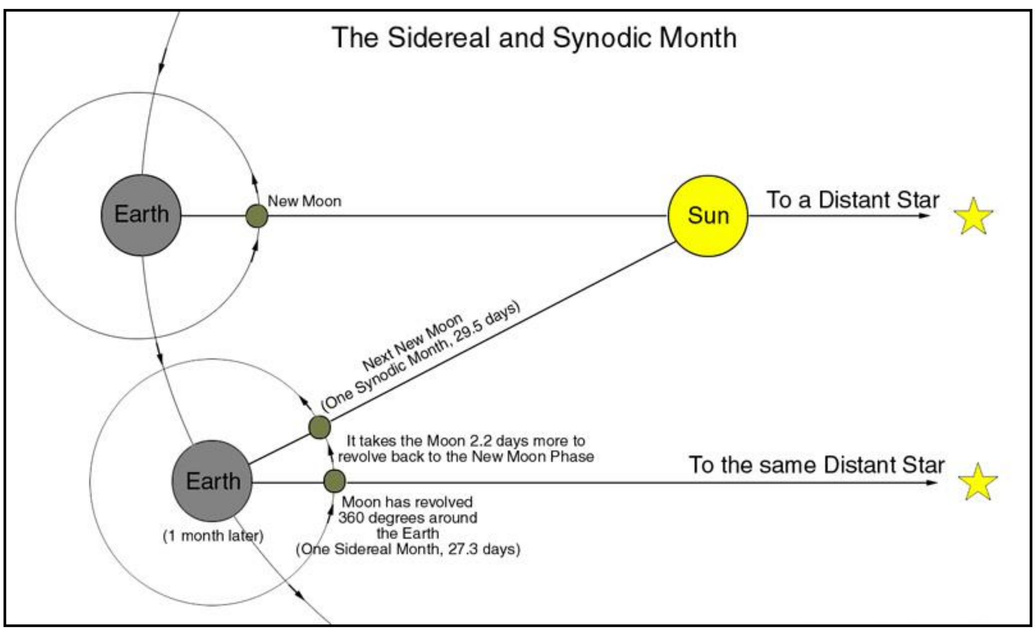



**Figure 147.** Sidereal and synodic months

We now begin the next complication within the tellurion. There will be two dials that will denote the sidereal and synodic months. Figure 147 explains the differences between the two. The sidereal month closely resembles sidereal time displayed on the clock's main time dial, but substitutes the Moon for the Earth in relation to the observation of a distant star. The sidereal month is 27.322 days, while the synodic month is 29.531 days the period we are familiar with for the moons motion.

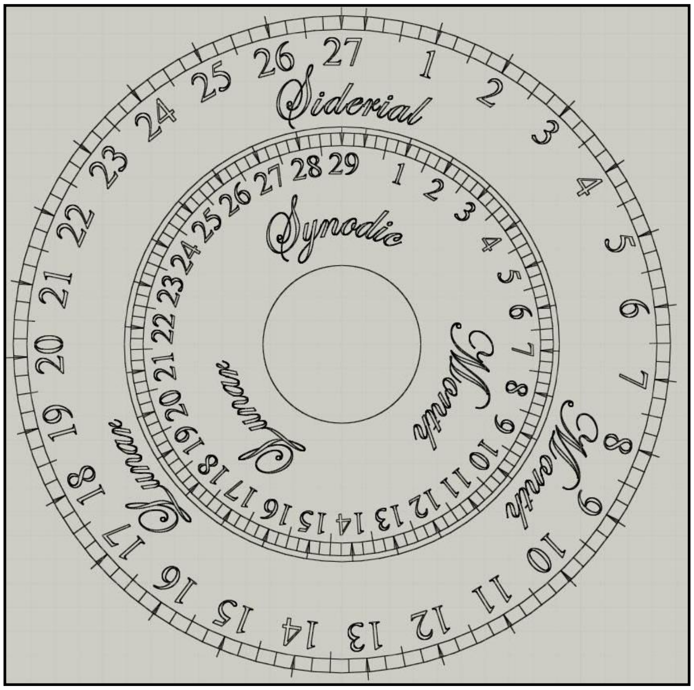



**Figure 148.** The artwork for the sidereal and synodic dials


**Figure 149.** The completed dials

**Figure 150.** Diminutive size of dial and miniature engraving

**Figure 151.** The dials installed below where the Earth resides

Figure 149 and 150 shows the small scale at which we are now working. The size of engraving here is that which one finds on a watch dial. Here Buchanan does employ computer aided design and machinery. The diagram in figure 148 is compiled into a CNC mill equipped with a precision cutter to engrave the dial on this tiny scale. Both dials are shown mounted within the area that will be below where the Earth globe will be positioned, Figure 151. The circled areas show the tiny pointers that read the information from the dials. The two tiny gears will drive the Earth which will pivot in the adjacent jewel bearing.

**Figure 152.** A pair of sunrise and set horizon markers

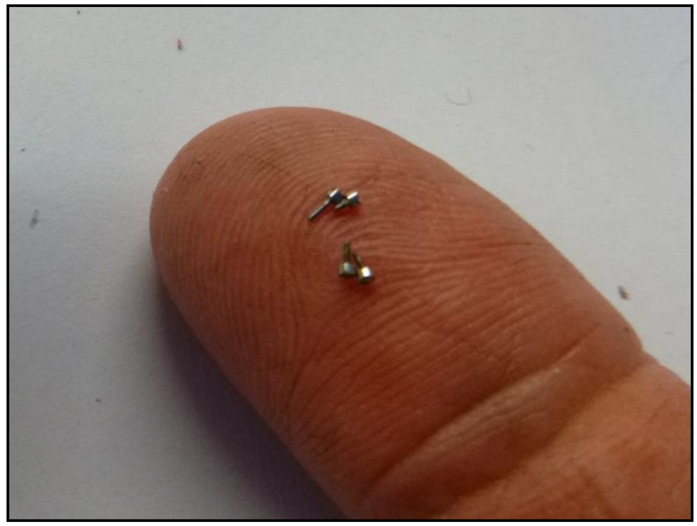


**Figure 153.** Tiny custom made screws secure the markers

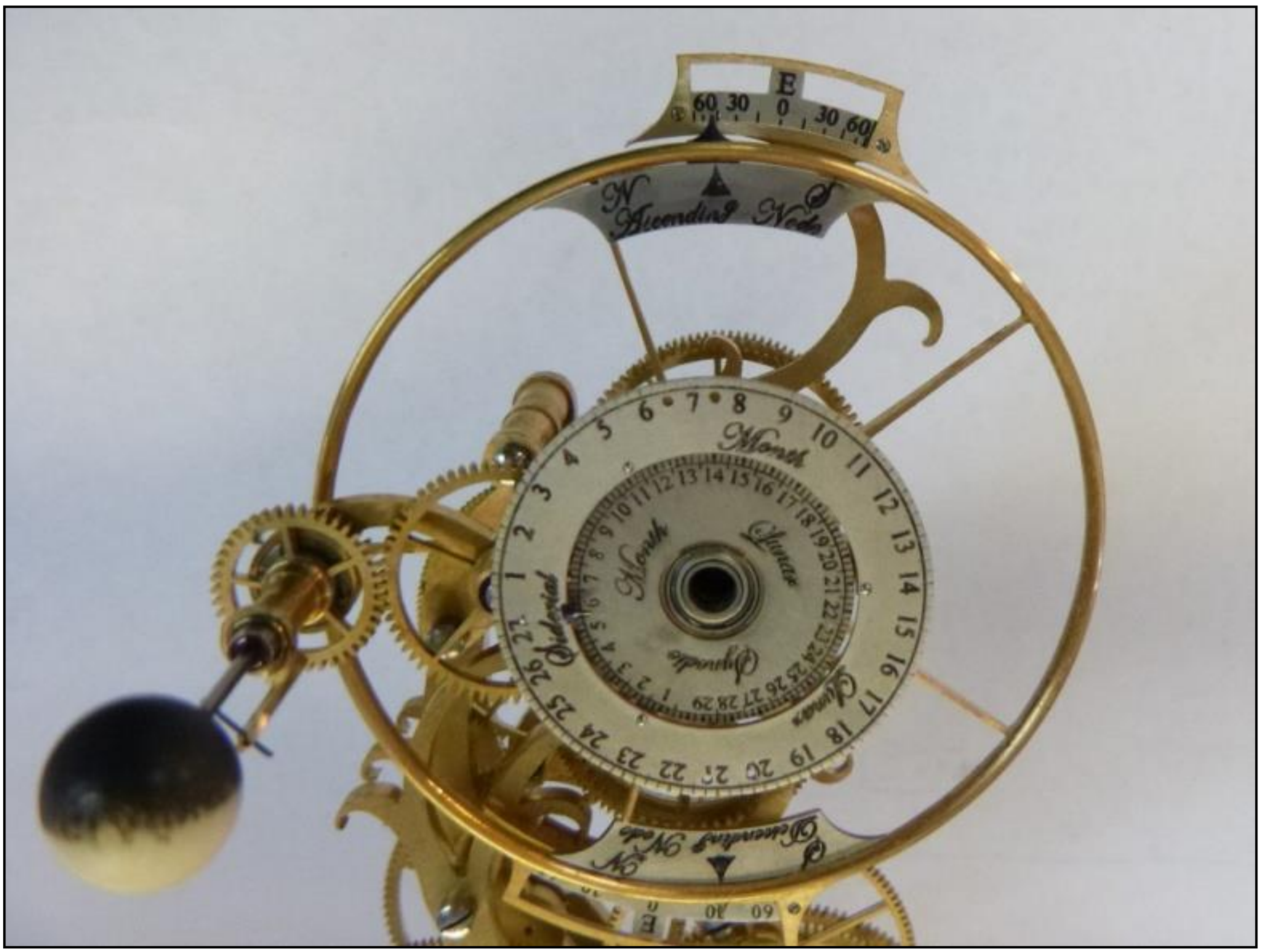



**Figure 154.** The node ring with eclipse season windows

Figure 152 show one of a pair of Earth horizon markers. As the earth rotates this pair indicates where on Earth the Sun will rise and set. A second pair indicates the same information for the Moon’s rise and set. Figure 153 shows the extremely small screws used to secure the horizon markers as well as other small sector dials located in this area. Figure 154 shows the Moon’s node ring. This ring represents the Moon’s $5.15^0$ tilt in relation to the Earth’s ecliptic. The upper and lowest points of the Moon’s tilted orbit are its *nodes.* The node points are indicated by the triangular indicator on the sector dial mounted to the inside of the node ring. The ascending node, uppermost point, is located at the 12 o’clock and the descending node, lowest point, at 6 o’clock position. The Moon’s nodes are in precession around the Earth orbiting once every 18.6 years as does the ring. A smaller sector dial is seen near the 12 o’clock position outside the node ring. This is the *eclipse season window* dial. When a node is within the season window and the Moon is directly between the Earth and Sun an eclipse will occur somewhere on the Earth’s surface. One can use the degree scale on the season window dial along with a movable latitude ring around the earth to locate where an eclipse will begin. The ‘E’ on the season dial is the *eclipse window*, the approximately eight hour window through which the Moon moves and that an eclipse will be visible upon the Earth covering about one-third of Earth’s revolution. The same principals apply for a lunar eclipse. When the celestial train is in demonstration mode one can use the 400 year perpetual calendar and the twenty four hour world time dial in conjunction with these components to predict where and when a solar or lunar eclipse will occur to with an accuracy of a few hours. Since the demonstration also works is reverse one can see when an eclipse has last occurred. And because the calendar is perpetual for four hundred years, theoretically if one wanted to crank the demonstration dial the many hundreds of times necessary, an eight hundred year period could be observed. This is the only tellurion this author knows of that has these capabilities. To see a video demonstration of how this works: https://youtu.be/HvTJ3G5qbZ8

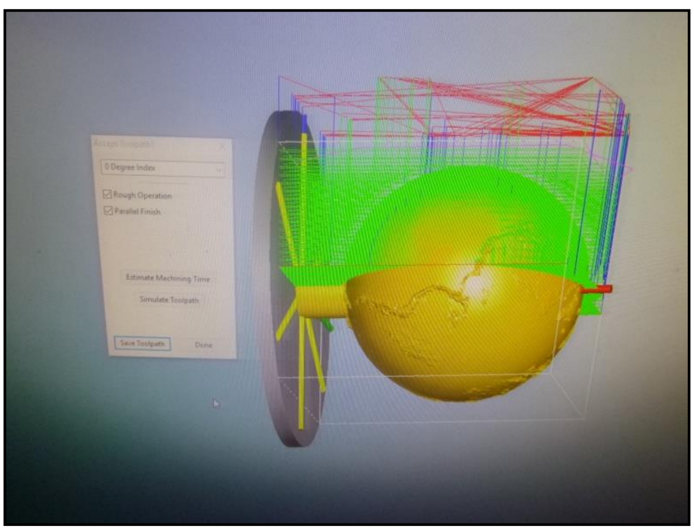


**Figure 155.** Globe continents in relief modeled on computer

**Figure 156.** Earth globe cut from Mammoth ivory section

We explored a number of designs for the Earth globe. This besides the Sun is the largest planetary body represented in any the celestial displays, (we still have an orrery to complete). So it will command special attention. I wanted it to be immediately recognizable as the Earth so a natural stone analogy would not work. There are globes made from stone mosaic but these need to be much larger than our 1.3” (3 cm) diameter to get the detail necessary. We will, however, be using semiprecious stone spheres for the remaining planetary bodies as well as the Sun in both the tellurion and future orrery. The current Sun and other planets as seen here are still mockups.

I wanted the Earth globe to have a special look. I have always admired the quality of walrus and ivory scrimshaw artwork. Scrimshaw allows the artist to create a very detailed design on the bone surface and when dyed with black tea or ink creates a beautiful effect. Since ivory importation has been banned in many countries as well as this machine's ultimate destination, we had to use an alternate material. Walrus was the first choice, but it was too difficult to find a piece of walrus tusk large enough to obtain the piece we needed. One must remember that these are natural materials and often have cracks and other imperfections around the perimeter reaching inward. One needs a large cross section of material to get a perfect area at the heart of the tusk to obtain a flawless piece. Any imperfections would be picked up in the dying process after the scrimshaw has been completed. Figure 156 shows the Mammoth ivory piece we used. One can see how large it needed to be to get the perfect rough blank. Mammoth also has a nice patina with natural growth markings, just the look I wanted. There is enough material left over for us to use elsewhere for winding handles. Another feature that Mammoth afforded was the ability to create land features on the globe. From the beginning we decided against political boundaries. First these are simply too complicated for a globe of this size and second these will change throughout the life of the machine. But we could outline the land masses as well as adding longitude and latitude lines. This material also allows one to carve the piece in relief to illustrate the various continental mountain ranges; another departure from the standard smooth Earth globe found on other tellurions, especially at this scale. Mammoth also yields easily to the cutting tool and is not brittle, so an accurate model could be produced. Figure 155 shows the Earth globe modeled on the computer, a mountain range is clearly visible.

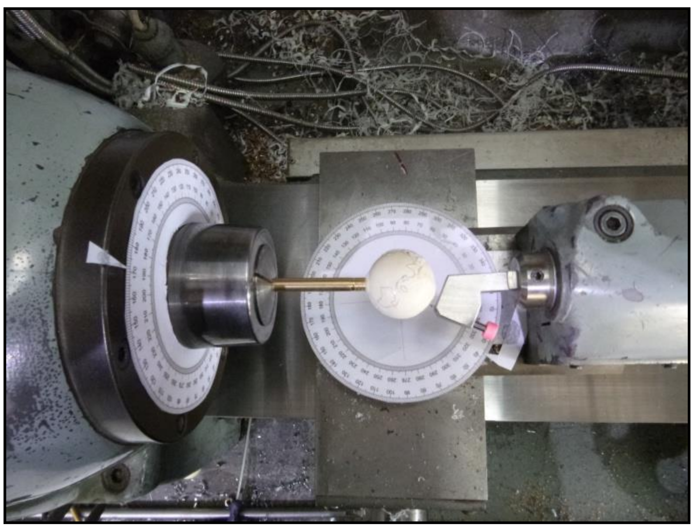


**Figure 157.** Setup with X-Y scales for latitude, longitude lines

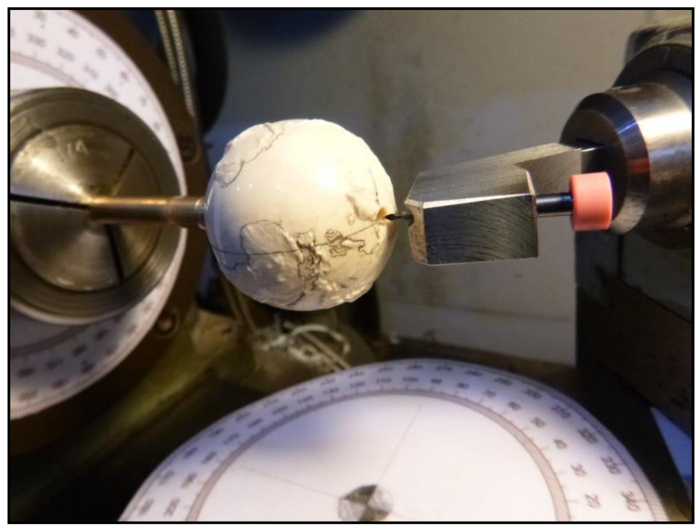


**Figure 158.** Close up of the latitude, longitude scrimshaw lines

Figures 157 and 158 shows the scrimshaw process for cutting the latitude and longitude lines. Notice the two protractor scales attached to the tooling used to rotate the globe and move the cutter. This gives an accurate positioning of both the globe and cutter in the X-Y axis for perfectly accurate latitude and longitude lines. The scrimshaw work outlining the land masses was done by hand.

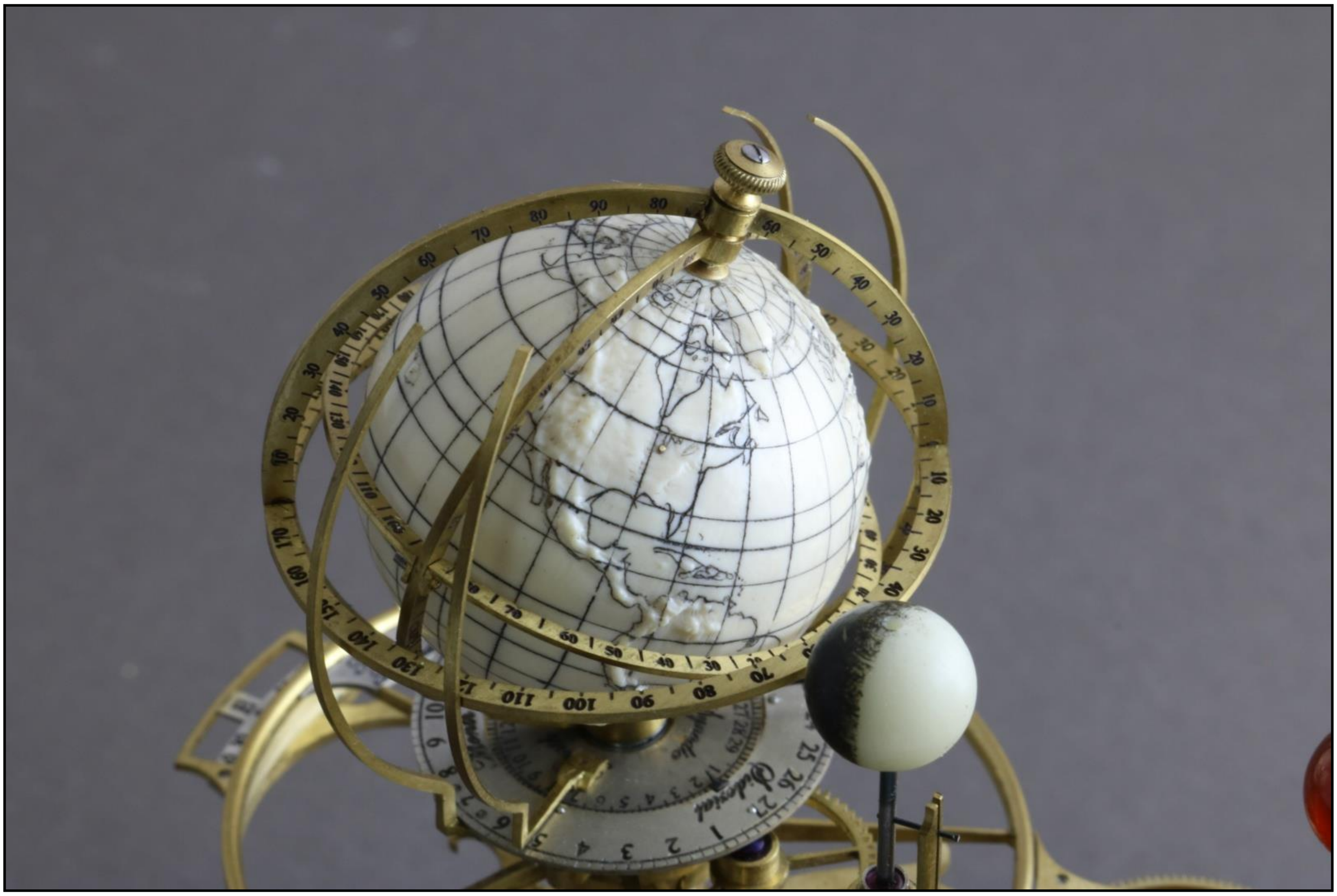


**Figure 159.** The completed globe and engraved rings

The completed Earth globe, Figure 158 with all of the scrimshaw work and continental topography. We did not inscribe all of the latitude lines because it would have become 'too busy' detracting from the continental outlines. Notice the engraved detail of the metal longitude and latitude rings as well as the additional moveable latitude ring controlled by the small knurled nut at the top used to interpolate the position of an eclipse in conjunction with the eclipse season dial, lower left. The two curved horizon markers for the sun and moon are seen in the foreground and the sidereal and synodic month dials below.

A video of the tellurion as shown in Figures 160 and 161, next page, can be seen here:
https://youtu.be/9BPT1vyB8Mc

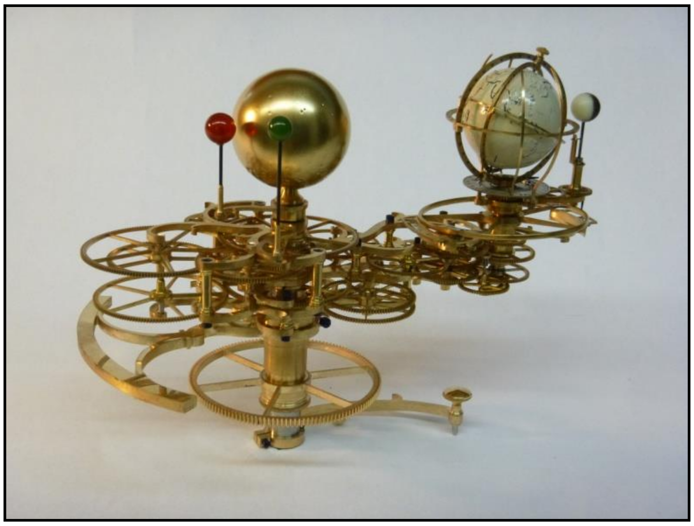


**Figure 160.** Completed tellurion, side elevation

**Figure 161.** Completed tellurion top elevation


**Figure 162.** The tellurion mounted within the clock.

**Figure 163.** The tellurion mounted within the clock.

The completed tellurion as shown in, Figures 162 and 163. It is easily removable from the mounting post as a module. This complication has 395 parts including 30 jeweled pivots. Anyone who has seen tellurions made by the famous makers of Raingo, Balthazar, Berthoud or even Janvier will immediately recognize the superior visual appeal of this design. It is what the maker calls the “Buchananization” of what otherwise is a conventional design. This philosophy is not just restricted to making fancy designs for frames and parts, but extends to the entire engineering design of the wheel works and other assemblies. Wheel diameters are stretched to fill in spaces or multiple wheels are used when visually appealing. Unusual and unique ways to accomplish an otherwise mundane functional task are designed and created. Examples abound throughout the machine from the animal analogues to interior toothed sector gears, to the panoply of remontoire and their associated complex fly governors. We often do this for no other reason than that we want to create a visual mechanical paradise.

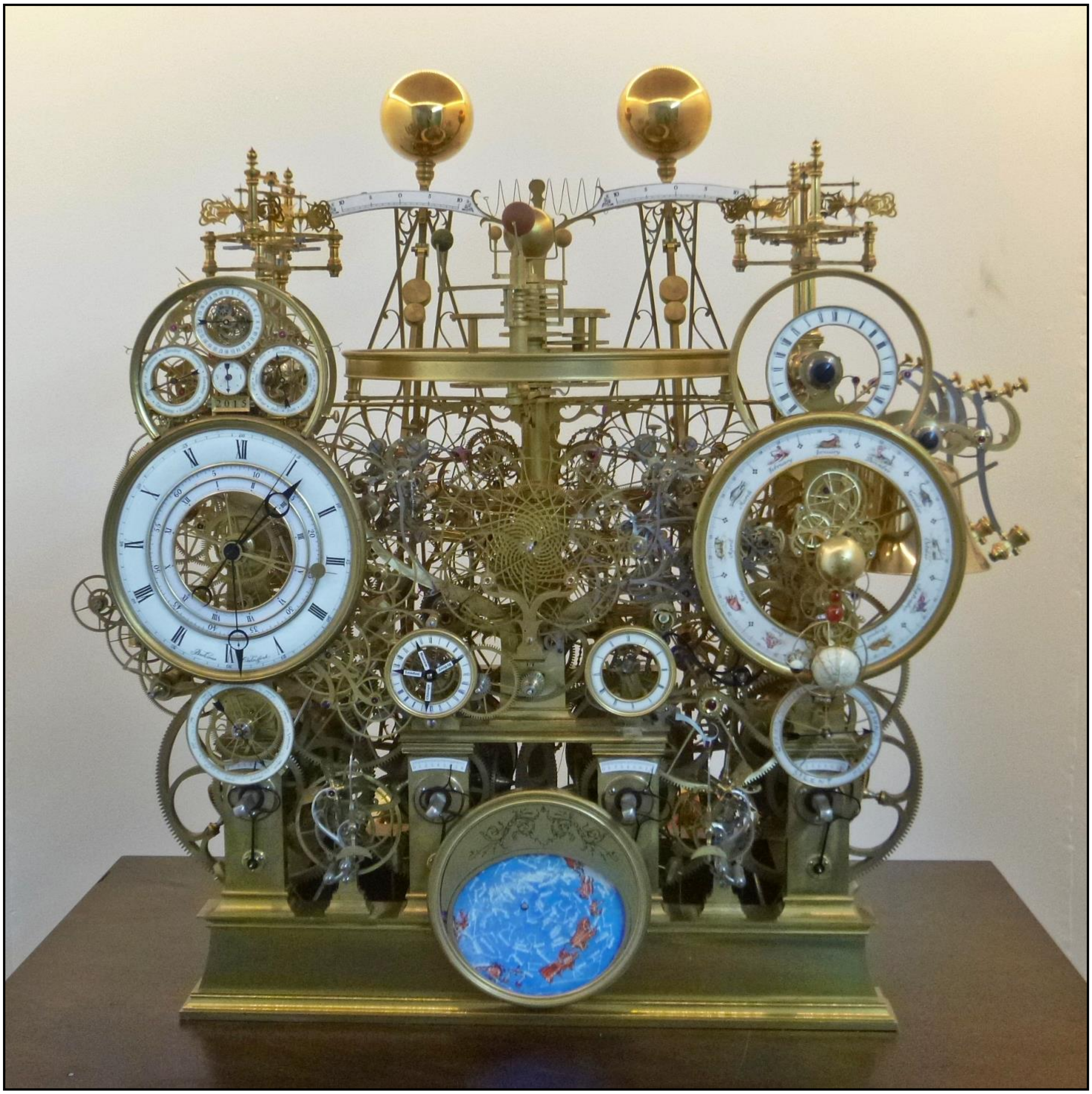


**Figure 164.** Front elevation of astronomical clock with mockups of remaining components yet to be fabricated.

Figures 164 and 165 show the movement outfitted with mockups of the remaining components yet to be completed. These are all located on the right as well as the top and bottom quadrants. Beginning from the top they are the orrery, the sun and moon rise and set, a small thermometer, the tellurian and the planisphere. The one exception is the small dial ring below the large tellurian dial on the right. This represents the strike controller, which along with all the strike and repeat functions is finished.

It may appear that we are a long way from completion, but we estimate that the project is now about two-thirds finished. Although the majority of the complications have yet to be completed, the most complex one is done. Also the enormous amount of wheel work and framing incorporated into the making of the four drive trains in addition to the strike control and repeat assemblies account for over half of the work.

**Figure 165.** Upper, left three quarter elevation of astronomical clock with mockups of remaining components yet to be fabricated

Part of the fun of making one's fantasy a reality is sharing it with others who may be interested in seeing the creation as it happens. The project has been posted monthly on my website since its initial conceptual stages back in 2003.[13] I put out an emailing notifying members that a new posting on the project's progress. If you would like to be added to notifications posting, email me.

Footnotes:

1. Buchanan can be reached at: clocks@buchananesq.com
2. The Pouvillon astronomical clock restoration was described in a three part series featured in the July, September and November 2013 issues of the NAWCC *Bulletin*.
3. Those articles are in the August 2007 and April 2011 issues of the NAWCC *Bulletin*. The list of dial and special mechanical complications appears below the footnotes section.
4. The remontoire and strike fly governors are the exception, where these will run in oiled jewels, but are in easily accessible areas.
5. For an explanation and demonstration of the Wagner remontoire: http://www.my-time-machines.net/wagner_remontoir.htm
6. For an explanation and illustration of the Robert robin remontoire: http://www.my-time-machines.net/horz_2_train4.htm
7. There are a variety of grasshopper escapements. An illustration of our type is in The Quest for Longitude, William Andrews, pg. 202. This one uses only one escape wheel where ours uses two.
8. For information and illustrations of Charles Fasoldt's original design within his clock, *American Precision pendulum Clocks*, Donald Saff, pp. 208-222, within Precision Pendulum Clocks, France, Germany and America, Derek Roberts.
9. An extraordinary detailed examination of the Schwilgue ecclesiastical computer, Le Comput Ecclésiastique, Frédéric Klinghammer, pg 110 and attached DVD disc.
10. The first use of the differential, at least in connection with the equation of time and probably horology in general was by Joseph Williamson, c.1720-1725. Ref. Some Outstanding clocks Over 700 years. Pg.80-84, with illustration pg, 83.
11. *Horological Journal*, July 2015, The World Time Clock, Canary Wharf, London, pp. 297-300.
12. The Difference Engine: Charles Babbage and the Quest to Build the First Computer, Doran Swade, pp.118-121
13. mfrank1@rcn.com , www.my-time-machines.net

**List of Complications**

**Upper left-hand dial cluster, 400-year perpetual calendar**

1. Day
2. Date
3. Month
4. Year
5. Leap year indication
6. Reversibility, third-order perpetuity

**Center left-hand dial, telling the time**

- Mean time

**7.** Equation of time

8. Sidereal time

**Lower left-hand dial**

9. Equation of time setting, annual calendar

**Upper right-hand dial cluster, the Sun and Moon**

10. Sunrise and sunset horizon shutters
11. Sunrise and sunset time indication
12. Sun's declination
13. Moonrise and moonset shutters
14. Moonrise and moonset time indication
15. Moon's declination
15. Moon phase globe, "Halifax Moon"
16. Age of the Moon

17. Period of the Great Anomaly, the Moon’s evection
18. Period of the Tropical month

**Center right-hand dial, Earth’s neighborhood**

19. Tellurion featuring the Earth, Moon, and Sun system
20. Additional inner planets of Mercury and Venus
21. Zodiacal house
22. Month
23. Date
24. Synodic month dial
25. Sidereal month dial
26. Adjustable 360˚ ring allowing user to set any point on earth as zero time, reading the time from any other point
27. Approximation of time and location of solar eclipses
28. Approximation of time and location of lunar eclipses
29. Location of sunrise and set
30. Location of moonrise and set

**Lower right-hand dial, strike control**

31. Petite sonnerie
32. Grande sonnerie
33. Quarter repeat on demand
34. Strike and silent

**Upper center, grand orrery**

35. Grand orrery, Mercury through Saturn, with Jupiter and Saturn each having five orbiting moons
36. Correct depiction of eccentricity of orbits of Jupiter and Saturn
37. Planetary orbital distance from Sun in astronomical units
38. Planetary orbital time in years
39. Position of all orrery components in degrees, 0-360˚
40. Two speed transmission for slow and fast demonstration

**Middle left center dial**

41. World time dial and celestial demonstration crank

**Middle right center dial**

42. Thermometer

**Lower center dial, the stars above**

43. Planisphere, showing star field with major stars named, Milky Way, and zodiac figures
44. Sun traveling through the zodiac’s houses across the star plate

**State of wind indicators**

45 Time train
- Celestial train
- Quarter strike train
- Hour strike train

**Special mechanical complications**

46. Dual Wagner rocking frame remontoire, time train
47. Robin remontoire, celestial train
48. Spring remontoire, perpetual calendar
49. Perpetual, reversible, third-order analog computation calendar
50. Calculation of Moon’s anomalous motions to the second order
51. Antide Janvier-type slant wheel differentials within tumbling cages
52. Compound remontoire flies
53. Epicyclical strike train flies
54. Celestial remontoire fly cam controlled to release at differing time intervals
55. Sidereal time read off double, inner concentric anti-clockwise rotating dials within mean solar time dial
56. All calendar functions feature “instant trip” at precisely midnight