Astronomical Skeleton Clock

Part 1 of a Two-Part Series

by Mark Frank (IL)

Author's note: The NAWCC began documenting the complex astronomical skeleton clock I commissioned that is being built by clock manufacturer and restorer Buchanan Clocks of Chelmsford, AUS,[1] in August 2007.[2] At that time a detailed full-size wood mock-up was completed, and the article covered the proposed clock's mechanical specifications and functions as depicted through the mock-up. An article published in April 2011[3] marked roughly the halfway point in the construction when the four movement trains—time, celestial, basic quarter, and hour strike—with most of the "between the plates" components were completed.

After April 2011, there was a two-year hiatus during which Buchanan moved his shop from England to Australia and took on an intricate restoration project of another complex astronomical clock, the subject of a three-part series.[4] Construction recommenced in mid-2013. I estimate completion in late 2018.

Part 1 focuses on the entire left side of the dial complication work and the small dial below the large tellurian ring on the right, the strike selector. A video of the clock highlighting the components in this article is at https://www.youtube.com/watch?v=IWd-HSOxCMM. Part 2 in the March/April 2017 issue of the Watch & Clock Bulletin will address the dial work that comprises a third-order, reversible perpetual calendar.

Creators Aim for Easy Maintenance and Repairs

As of July 2015 clock manufacturer and restorer Buchanan of Chelmsford, AUS, and I are a decade into the creation of a complex astronomical skeleton clock since the initial design and mock-up and 6-1/2 years into construction (Figure 1). At this point one might ask why this project is taking so long. Very briefly, we are creating a machine with 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 40 complications.[5]

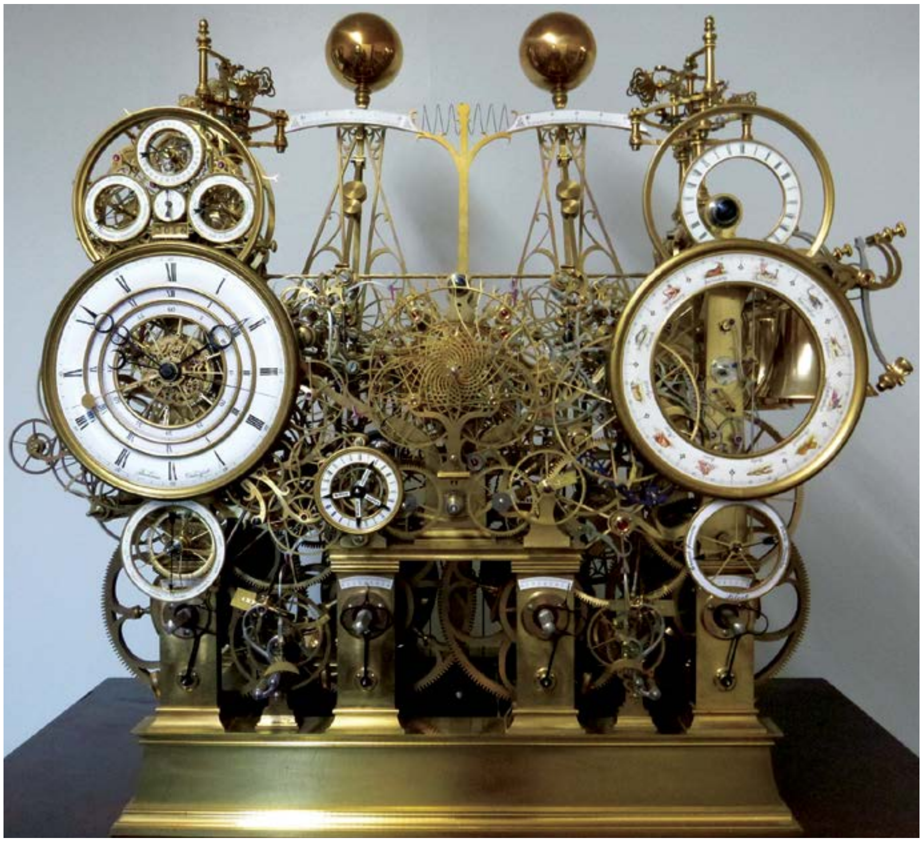

Figure 1. Astronomical skeleton clock 6-1/2 years into its construction.

I knew we could not create the world's most complex skeleton clock, either in the number of complications or components, although excluding institutional public and church clocks, our clock may be among the top 20 or so made that

Figure 2. Left-hand module and time train.

Figure 3. Right-hand module with quarter and hour strike trains. COURTESY OF BUCHANAN.

is small enough to fit comfortably within a domestic setting. My ambition is to create one of the more visually fascinating clocks that will immediately grab the viewer, hold their attention, and not let go.

Many clocks have been made with various visually interesting features, especially those with automata or complex musical apparatus. This creation focuses on the visual display of an overwhelmingly interesting geared mechanism—a gearhead's delight. Our approach to every aspect of this machine's creation was whether we could make a part or mechanical system beautiful and fascinating to the viewer by using multiple, complicated moving components that are actuated in frequent and, in one case, unpredictable ways. The other, no less compelling, feature will be the beautiful design and handcrafted innovative workmanship created by the Buchanan firm. We have also included a bit of whimsy: a forest of wheels in an organic ivy theme in the upper frame structure. And what is a forest without animals? Birds inhabit the trees, and other parts depict animal analogs within the machine's structure. 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 past masters of the horological arts: Thomas Tompion, Abraham-Louis Breguet, Antide Janvier, John Harrison, Jean-Baptiste Schwilgue, Charles Fasoldt, and Jaeger LeCoultre. I can only hope that if a clock heaven exists, these distinguished men are looking down at this creation with a smile.

Many may ask, "How in the world does one maintain, let alone, fix this thing?"

Maintenance

An important goal we had was to make this machine as trouble free and as serviceable as possible despite its enormous complexity. Horological history is littered with exceptional clocks that became unserviceable years after their creation and are ultimately lost. A clock that does not work, unless recognized as a historically significant artifact, eventually will be regarded with neglect, contempt, or ultimately destruction. The first area where we address this problem is in the pivots. The machine's nearly 400 wheels and 900 pivots will run oil free.[6] Oil is the No. 1 reason why clocks fail, because it eventually breaks down, dries out, and attracts contaminates that accelerate pivot wear.

Breguet reputedly 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 bearings do not require oil and are immune to corrosion. They are used wherever we have heavy loading, wherever rotational speeds are in excess of once per hour, or wherever the pivot's configuration would make the use of a jewel impractical. The most common areas of the last example would be bearings in excess of 5 mm, or about 0.2", in diameter or where nested bearings are needed. Full ceramic bearings were fairly rare

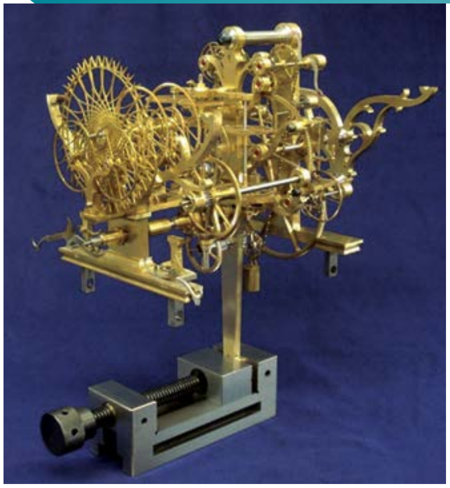

Figure 4. Rearview of center module, celestial train, and escapement with Robin remontoire.

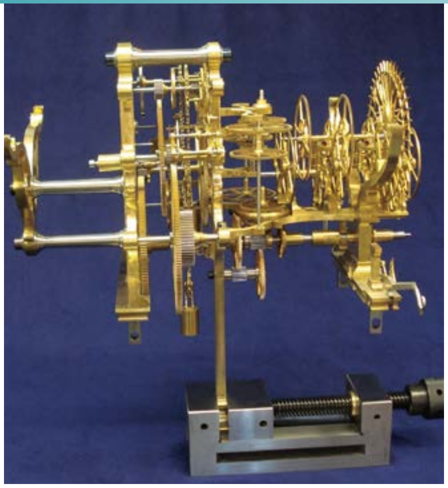

Figure 5. Side view of center module, celestial train, and escapement with Robin remontoire.

Figure 6. Base frame with the 4-train's main wheels.

and expensive when the project was conceived in 2003, but fortunately, they have become widely available. The remaining 550 pivots, which are lightly loaded and have rotational speeds of less than once per hour, run in dry jewel bearings. This idea is not radical; LeCoultre has used this design in its Atmos clocks for decades. Why not use ceramic bearings in all pivots? The reason is that real jewels simply look beautiful. Some jewels are large, up to 5 mm, or about 0.2", and the play of light from a jewel bearing is quite eye-catching. All ceramic bearings will have a simulated jewel endcap held by three screws around the perimeter to keep them virtually dustproof 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 2-second beat, 4-second cycle. This results in all 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 wheel arbors and other steel parts, which will not be blued. In those arbors that run in jeweled bearings, we insert hardened steel pivot points because stainless is not a suitable material in this application.

I estimate that the clock should operate without the need for service for at least 50 years, barring unanticipated problems. And how many problems could there be in a machine of this complexity??? But seriously, we have tried in every possible way 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 will happen at some point? If we were to use conventional clock design, we'd have one or a few large interconnected plates, among which all wheels would be supported, making servicing difficult because of the sheer number of wheels and their disparate sizes. Simply aligning all arbors to fit into the plate being lowered onto them would be difficult. Anyone who has serviced a 3-train conventional chiming or musical clock knows this.

Our solution is to use a base flatbed frame upon which the individual movement trains are mounted, not unlike the common hybrid flatbed 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 2-5). They are mounted on the lower flatbed frame containing the four going barrels and associated power duration indicators (Figure 6).

The time train has a dual Wagner gravity remontoire driving the pendulums.[7] However, this train does not encompass all of the time train functions (Figure 2). The escapement is within the center module, the celestial train, for visual balance (Figures 4 and 5). Because the time train uses a dual remontoire, it requires two fly governors. One is mounted directly above the time train on the left sector of the clock (Figure 2), and the other is mounted above the strike train in the right sector (Figure 3). The quarter and hour trains are contained within the strike train

Figure 7. Time train module mounted to base frame. COURTESY OF BUCHANAN (3).

Figure 8. Strike train module mounted to base frame.

Figure 9. Celestial train mounted to base frame.

module. The strike and repeat control work are not shown here. Those parts and the strike fly governors are spread throughout the front of the clock. Because of the large number of parts, keeping them all within the confines of the strike train module would have been impractical. For aesthetic reasons we located these components where they would have the most visual impact. All control levers, racks, and fly governors are on the outside of the front frames for easy access without having to remove any of the main train modules.

The center train drives the celestial functions. It also uses a Robin remontoire, which controls the release for the timing of all celestial complications controlled by this train.[8] It also has the dual Harrison escapements and is the most complex of the three train modules mounted to the base frame (Figures 4 and 5).[9]

Figures 6 and 7 show 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 in Figure 6. Next, the time train is mounted to the left side of the base as indicated in Figure 7. Then, the strike train module is mounted to the right side of the base. Notice how the upper frame pillar rises smoothly from the 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 visual effect is seamless with no visible fastening points (Figure 8). Then, the center celestial train is added (Figure 9). Most of the dial work has been removed for clarity. Only half the number of final components is seen here: the between-the-plates components, the drive trains. A similar number of parts is needed to complete the strike and repeat work and the entire behind-the-dial work, components as represented by the clock's complications.

Notes and References

1. Buchanan's website is http://buchananclocks.com and the firm can be reached at clocks@buchananesq.com.
2. Mark Frank, "An Astronomical Skeleton Clock," NAWCC Bulletin, No. 369 (August 2007): 393-400.
3. Mark Frank, "Halfway Point for the Astronomical Skeleton Clock," Watch & Clock Bulletin, No. 391 (April 2011): 141-149.
4. Mark Frank, "Paul Pouvillon's Astronomical Clock: A Brief History and Description of the Clock's Restoration, Part 1 of 3," Watch & Clock Bulletin, No. 404 (July/August 2013): 348-360; Mark Frank, "Paul Pouvillon's Astronomical Clock: A Brief History and Description of the Clock's Restoration, Part 2 of 3," Watch & Clock Bulletin, No. 405 (September/October 2013): 463-474; Mark Frank, "Paul Pouvillon's Astronomical Clock: A Brief History and Description of the Clock's Restoration, Part 3 of 3," Watch & Clock Bulletin, No. 406 (November/December 2013): 612-623.
5. Mark Frank, "An Astronomical Skeleton Clock," NAWCC Bulletin, No. 369 (August 2007): 393-400. Mark Frank, "Halfway Point for the Astronomical Skeleton Clock," Watch & Clock Bulletin, No. 391 (April 2011): 141-149. The list of dial and special mechanical complications is published on page 36 of this issue.
6. The remontoire and strike fly governors are the exception. These will run in oiled jewels but are in easily accessible areas.
7. For an explanation and demonstration of the Wagner remontoire, visit Mark Frank's website "Magnificent Time Machines," accessed Septem-

ber 16, 2016, http://www.my-time-machines.net/wagner_remontoir.htm.

8. For an explanation and illustration of the Robert Robin remontoire, visit Mark Frank's website "Magnificent Time Machines," accessed September 16, 2016, http://www.my-time-machines.net/horz_2_train4.htm.

9. There are various grasshopper escapements. An illustration of our type can be found on page 202 of William J. H. Andrewes's *The Quest for Longitude: The Proceedings of the Longitude Symposium*, Harvard University, Cambridge, Massachusetts, November 4-6, 1993 (Cambridge, MA: Collection of Historical Scientific Instruments, 1996). This one uses only one escape wheel, whereas ours uses two.

List of Complications

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

- Day
- Date
- Month
- Year
- Leap year indication
- Reversibility, third-order perpetuity

Center left-hand dial, telling the time

- Mean time
- Equation of time
- Sidereal time

Lower left-hand dial

- Equation of time setting, annual calendar

Upper right-hand dial cluster, the Sun and Moon

- Sunrise and sunset horizon shutters
- Sunrise and sunset time indication
- Sun's declination
- Moonrise and moonset shutters
- Moonrise and moonset time indication
- Moon's declination
- Moon phase globe, "Halifax Moon"
- Age of the Moon
- Period of the Great Anomaly, the Moon's evection
- Period of the Tropical month

Center right-hand dial, Earth's neighborhood

- Tellurian featuring the Earth, Moon, and Sun system
- Additional inner planets of Mercury and Venus
- Zodiacal house
- Month
- Date
- Synodic month dial
- Sidereal month dial
- Adjustable 360° ring allowing user to set any point on earth as zero time, reading the time from any other point
- Approximation of time and location of solar eclipses
- Approximation of time and location of lunar eclipses
- Location of sunrise and set
- Location of moonrise and set

Lower right-hand dial, strike control

- Petite sonnerie
- Grande sonnerie
- Quarter repeat on demand
- Strike and silent

Upper center, grand orrery

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

Middle left center dial

- World time dial and celestial demonstration crank

Middle right center dial

- Thermometer

Lower center dial, the stars above

- Planisphere, showing star field with major stars named, Milky Way, and zodiac figures
- Sun traveling through the zodiac's houses across the star plate

State of wind indicators

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

Special mechanical complications

- Dual Wagner rocking frame remontoire, time train
- Robin remontoire, celestial train
- Spring remontoire, perpetual calendar
- Perpetual, reversible, third-order analog computation calendar
- Calculation of Moon's anomalous motions to the second order
- Antide Janvier-type slant wheel differentials within tumbling cages
- Compound remontoire flies
- Epicyclical strike train flies
- Celestial remontoire fly cam controlled to release at differing time intervals
- Sidereal time read off double, inner concentric counterclockwise rotating dials within mean solar time dial
- All calendar functions feature "instant trip" at precisely midnight

Assembled Functions Reveal Differences in Time

The conception and construction of the complex astronomical skeleton clock have been documented in great detail from its initial sketches to its movement trains being constructed. In this article the control assemblies for strike and repeat work and the sidereal and equation-of-time functions are examined and are overlaid by the mean solar time dial work to allow one to see the differences among the three types of time simultaneously.

At this point Buchanan Clocks of Chelmsford, AUS, 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 to be designed after completion of the basic strike drive trains were the fly control governors. The various fly governors are a major visual component with the greatest attraction when activated, and if designed properly, also at rest. This special attention was demonstrated in the time train remontoire governors. Those ultimately used 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 used in a tower clock remontoire made by Charles Fasoldt in 1874.[1] Fasoldt used an epicyclical gearing and rotating whip to engage a detent at the end of the remontoire recoil cycle. Clearly, he did this for visual appeal and to demonstrate his mechanical artistry, because there were so many easier and more

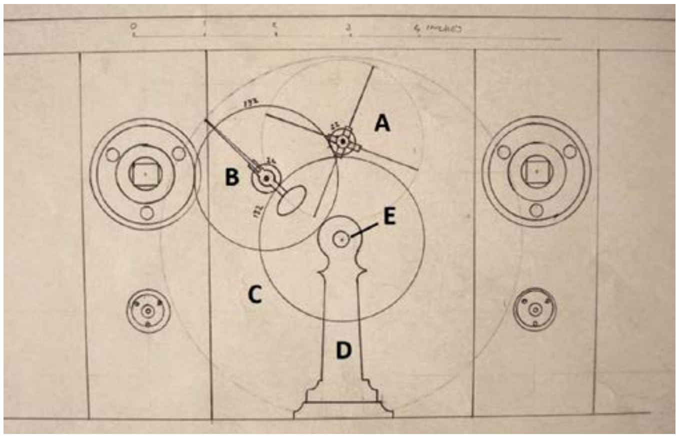

Figure 10. Diagram of Charles Fasoldt's fly governor design with A, the 4-blade fly; B, a wheel with a long train stop piece; C, a center wheel; D, a frame pillar; and E, a fixed wheel.

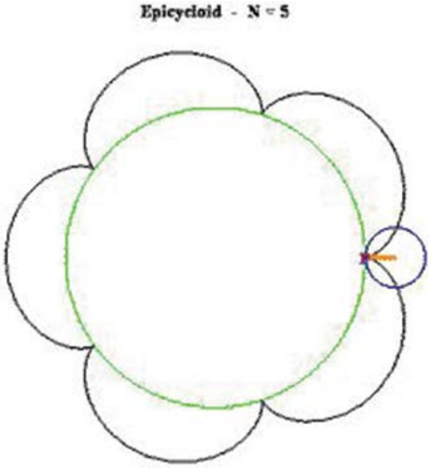

Figure 11. Epicycloid trace of whip tip.

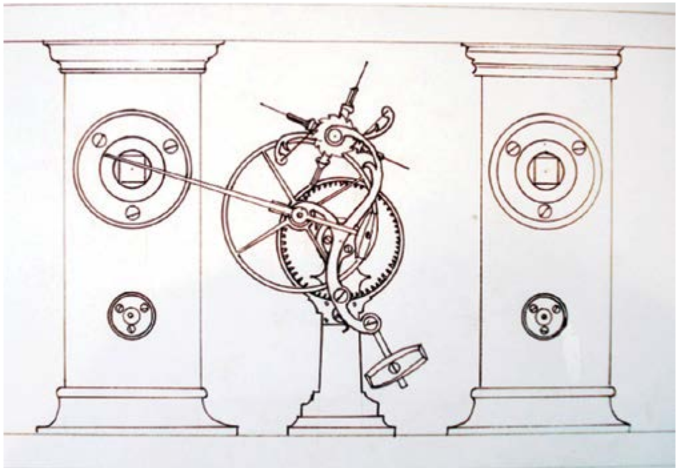

Figure 12. Revised design using internally toothed wheel.

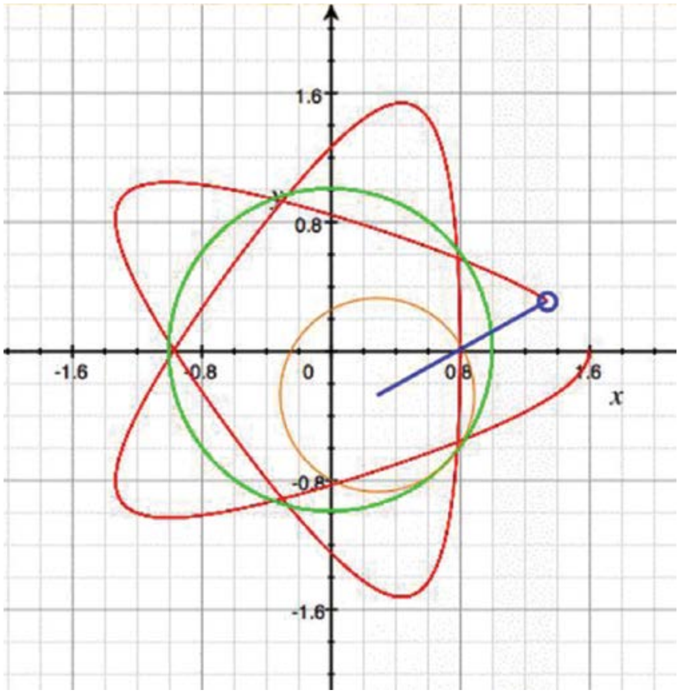

Figure 13. Hypocycloid trace of whip tip.

Figure 14. Two left- and right-hand strike train governors.

Figure 15. Side view of various wheel styles.

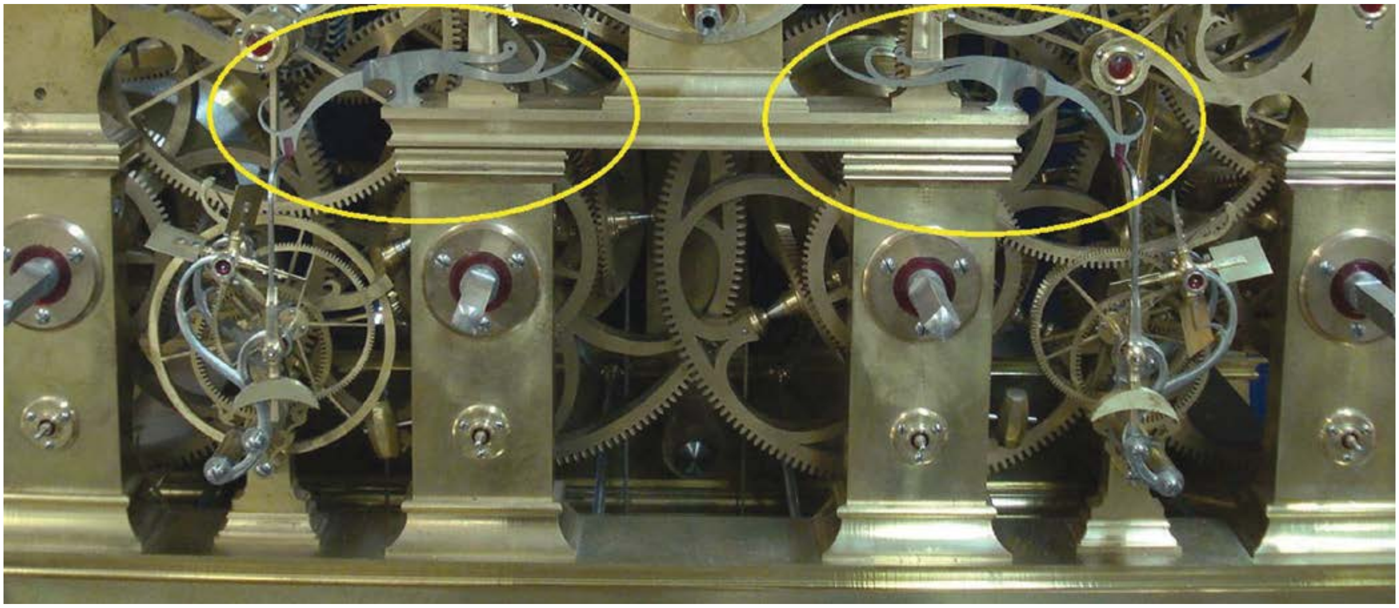

Figure 16. Quarter and hour fly governors with circled pair of bird analog detent stops.

straightforward ways to accomplish this job. I could see that Fasoldt was a man after my own heart.

We used 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 counterclockwise.

The first diagram closely represents Fasoldt's design in Figure 10. A 4-blade fly, marked A, meshes with a wheel that has a long train stop piece that we call "the whip," which is attached to a wheel, marked B, meshing on the outside of a toothed, center wheel, marked 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, marked E. This design allows for only a small length for the whip, because it must clear the winding squares on either side. The tip of the whip traces an epicycloid petal pattern around the perimeter of the fixed wheel as illustrated in Figure 11.

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 (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 with the epicycloid diagram, the whip's length is larger and visually desirable. The second is that using the internal wheel teeth results in the whip traveling in the

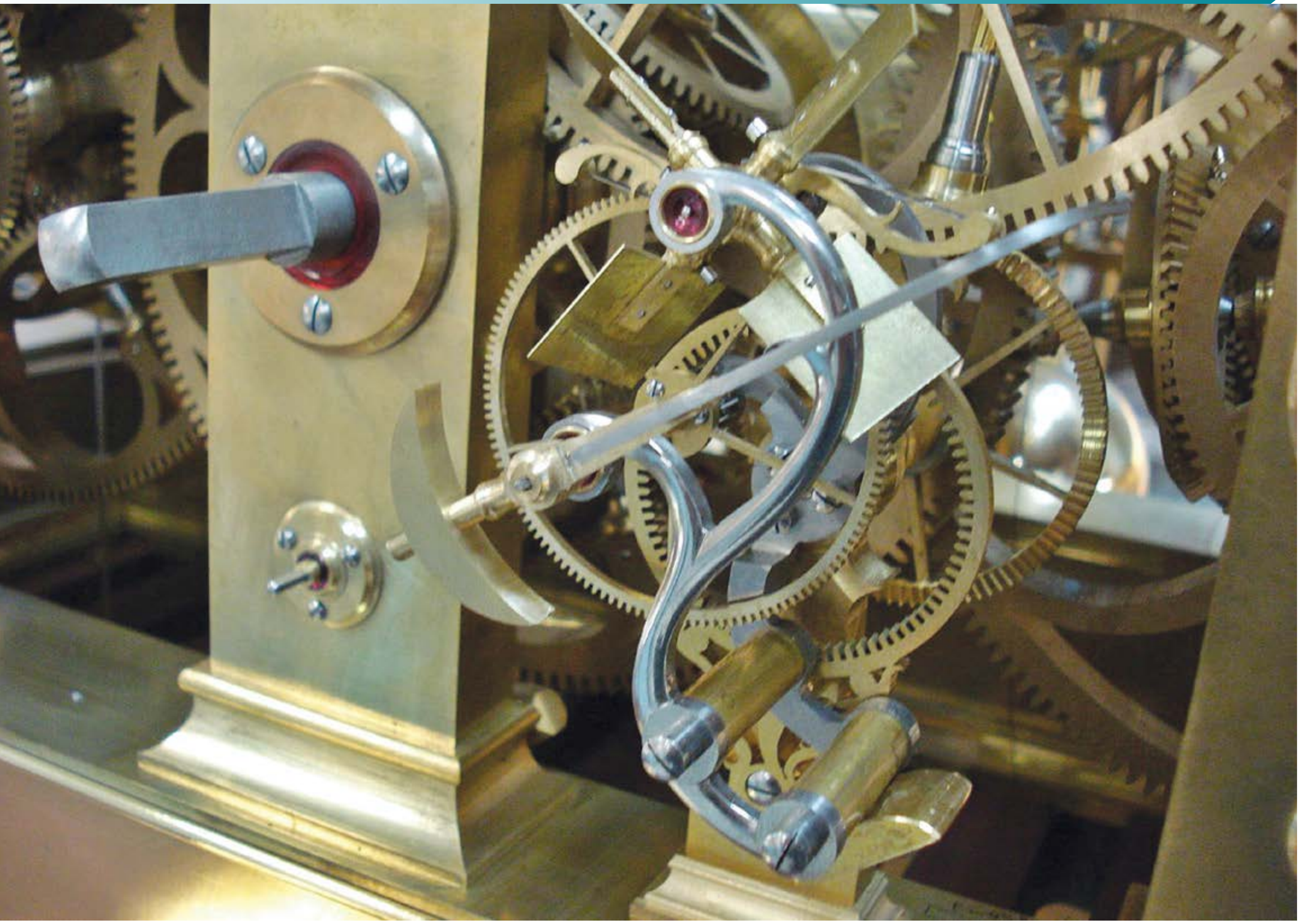

Figure 17. Close-up of strike governor with sculpted stainless steel rotating cage.

opposite rotational direction as the cage, which reduces the locking forces 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. For example, Buchanan drew the whip to actual length, but he positioned it at the wrong side of the fixed internal toothed wheel to show how much more whip tip is allowed past our winding square versus Fasoldt's original design. In practice this conflict could never occur because the hub holding the whip would be located 180° opposite its current position.

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

The two fly governors were mounted within the movement along with a pair of bird analogs serving as strike detents above each one as indicated in the circled areas in Figure 16. 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.

For the rotating cages we used a sculpted, sinuous design, rather than the standard flat material used elsewhere in the project. 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.

Figures 18-23 show the steps in the fabrication of the quarter and hour strike racks. First, a paper mock-up is made to satisfy the criteria 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

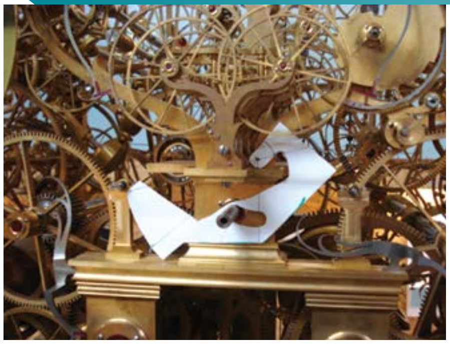

Figure 18. Paper cutout of hour rack.

Figure 19. Hour rack in metal.

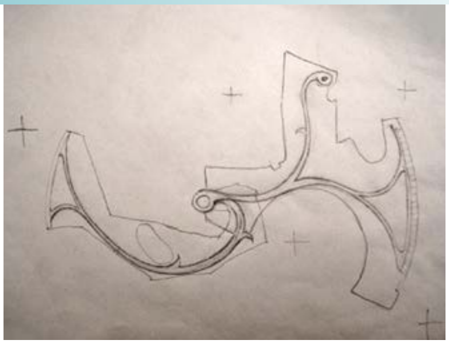

Figure 20. Drawing of hour rack.

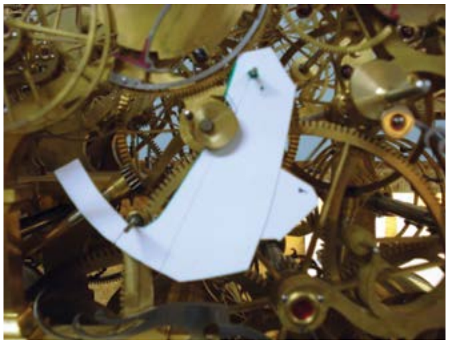

Figure 21. Paper cutout of quarter rack.

Figure 22. Quarter rack in metal.

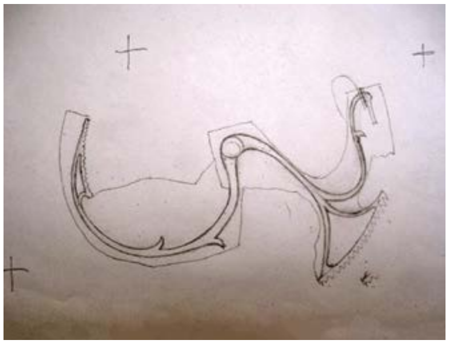

Figure 23. Drawing of quarter rack.

Figure 24. Completed quarter strike rack before finishing.

Figure 25. Hand fretsaw used to cut racks and other parts.

Figure 26. Hour and quarter snails as nautilus shell cross sections.

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

Figure 28. Gear in Figure 27 with external sector.

Figure 29. Some of the parts in the carousels.

point, and any areas that must be avoided to eliminate conflicts with existing components. In addition, a sector gear is attached to the opposite side of the rack that meshes with a fly governor.

These are needed, because the racks are quite large and we wanted the release to be mediated to eliminate any sudden drop. But to be honest, it was another excuse to include a pair of fly fans to enhance the visual entertainment when the strike is being set up a few minutes before the actual striking sequence. After the paper mock-up was verified for accuracy, the part was made in metal (Figures 19 and 22). At this point it was created only for the critical functionalities and clearances. Once testing had confirmed that the component was working reliably, a drawing was made to depict the part's final appearance (Figures 20 and 23). The racks were made from two different materials. The rack is made of steel, which we may later decide to blue or leave polished, depending on how it looks. The other end is made of brass with a sector gear meshing with the fly pinion.

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

Figures 26 and 27 show some of the various components in the strike control mechanism. Figure 26 shows a pair of snails for the quarter and hour strike counts that resemble cross sections of nautilus shells in keeping with our whimsical animal motifs. Figure 27 shows an unusual internally toothed sector gear in the foreground complete with the ivy spur design maintained throughout the project. Figure 28 shows the gear's externally toothed mate in the background mounted within the repeat pumping assembly. This pair of sector gears illustrates how Buchanan's firm makes complex and interesting mechanical displays. Carrying out this function with two identical conventional sector gears would have been easier. The pumper is needed to set up the strike work at will, so it will properly initiate the quarter and the hour on demand and serve 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 silence the strike work.

Figure 30. Quarter strike cam carousel.

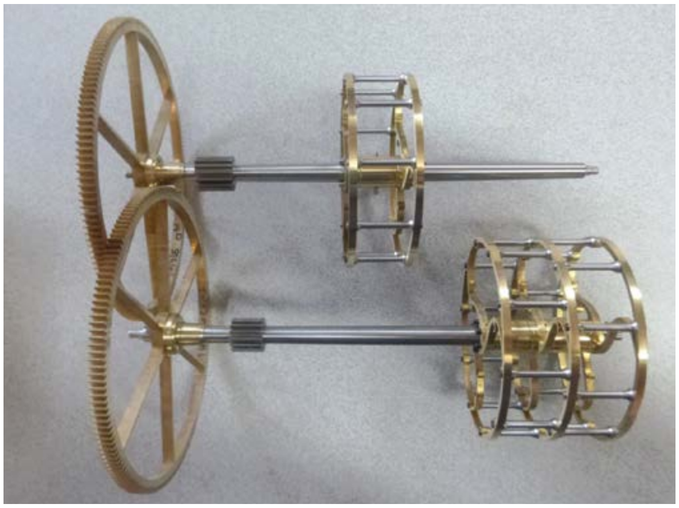

Figure 31. Hour and quarter strike carousels with drive gear.

Any strike mechanism needs a way to raise and release the hammers for bells or gongs. A simple rotating cam or wheel with pins raises and then allows 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 carousels.

The curvilinear spoke designs chosen for the carousels 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 like conventional pins pushing the bell hammer actuators to raise and release the bell hammers.

Next, are two examples of typical bird analogs. 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; they are far more interesting to watch than a simple rotating 1- or 2-toothed pinion (Figure 32). The idea was borrowed from Jean-Baptisté Schwilgue's count rack in his Easter calculator in the cathedral clock at Strasburg, FRA, in 1843.[2]

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 endcap. The two pivots to either side are synthetic ruby jewel bearings. The bird's beak and the center of the metal roller on its tail are also jewel stones. The roller is jeweled because there are no pivots in this mechanism that have a conventional metal-to-metal pivot; conventional pivots require oil, and we use 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 on the rods of the cam carousel to keep proper alignment.

The bird analogs are used throughout the movement. Examples include their repeat and calendar work, the escapement, the hammer actuators, and the strike fly detents. They all inhabit the ivy-laced wheel work forest.

The bell hammer actuator was now installed with the concave curved beak resting on the carrousel cam lifter. As the carousel turns counterclockwise, the lifter rod pushes against the jewel beak of the hammer

Figure 32. Bird analog seesaw quarter rack advancer.

Figure 33. Bird analog bell hammer actuator.

Figure 34. Bell hammer actuator connected to carousel.

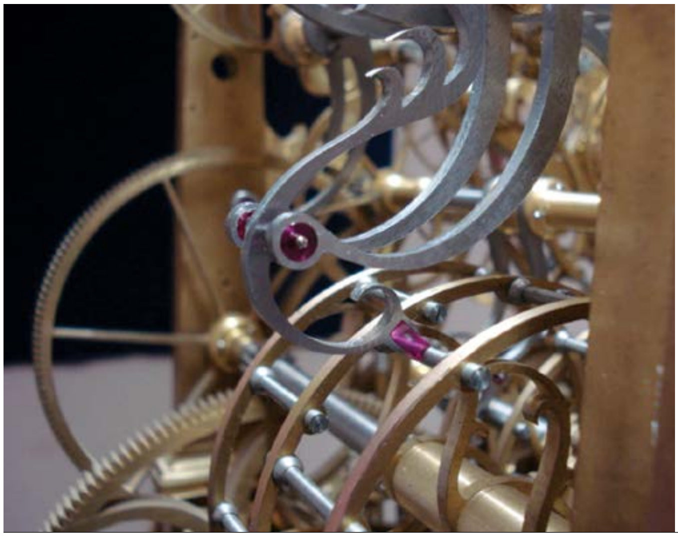

Figure 35. Quarter strike carousels and hammer actuators.

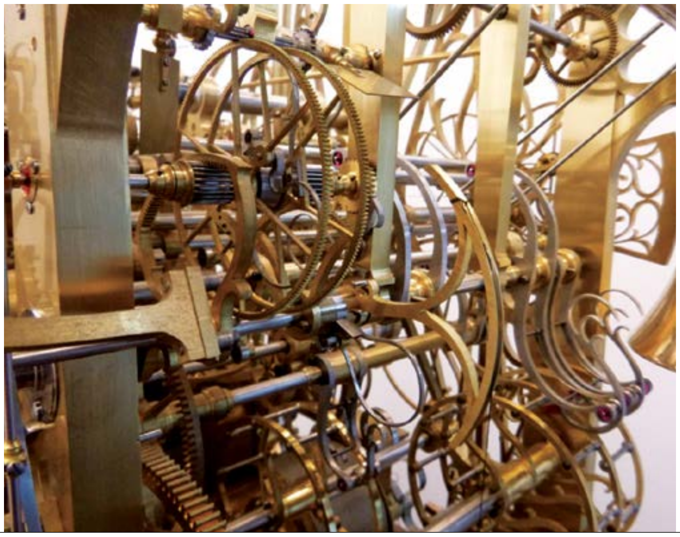

Figure 36. Furnace used to temper all springs.

Figure 37. Springs in copper envelope.

Figure 38. Water used to harden springs in copper envelope.

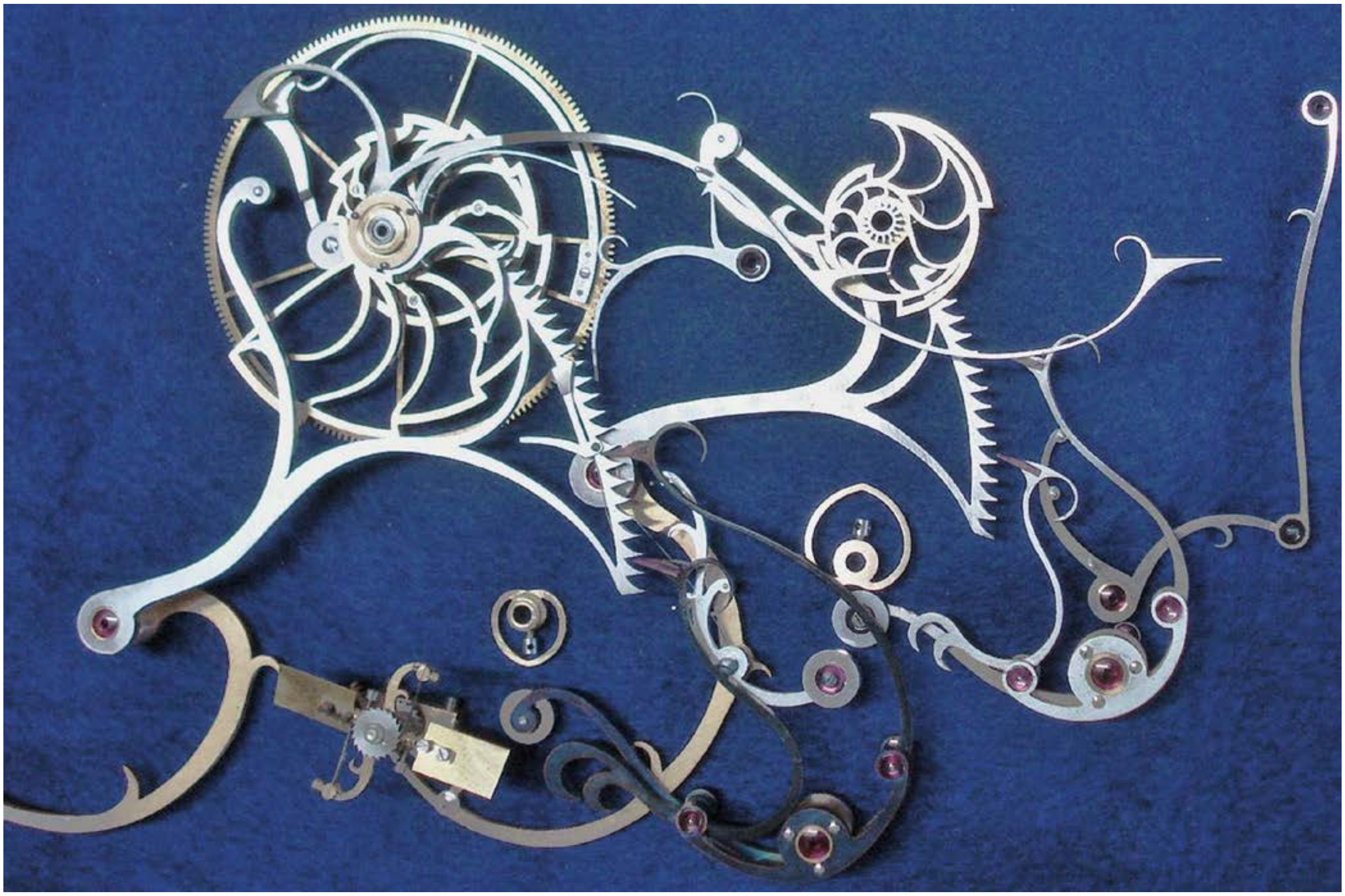

Figure 39. Some of the parts in the strike control mechanism.

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 toward the left, raising the bell hammer (Figure 34). Next, the entire quarter strike dual carousel assembly and a pair of hammer actuators can be seen in front of the single carousel wheel for the hour strike (Figure 35). The pair of wheels in the upper left is the pumper for the repeat mechanism (Figure 28).

Leaf springs within the repeat pumper mechanism supply the power when the springs are loaded by a lever pushed by the operator. All springs in the movement were custom-made and tempered in a furnace (Figure 36). The springs were encapsulated in a copper envelope to protect the steel surface while within the furnace (Figure 37) and then hardened by quenching in water and removed (Figure 38).

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 figure), the

Figure 40. Front view of strike control levers installed.

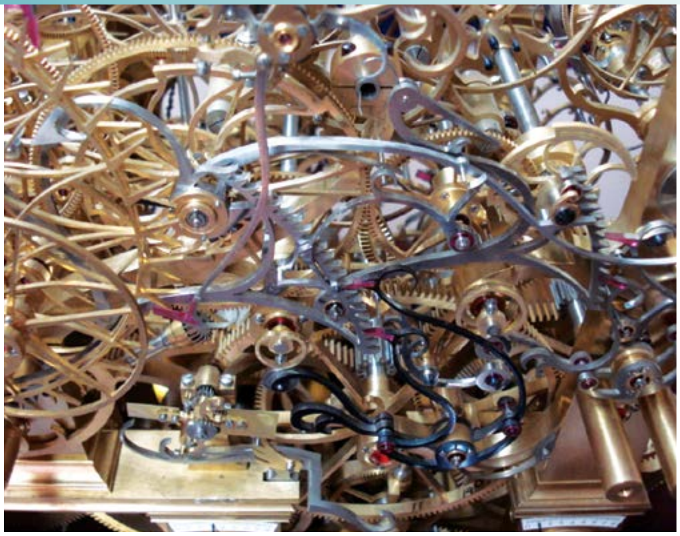

Figure 41. Three-quarter view of strike control levers in Figure 40.

Figure 42. Bell set with decorative hammers.

Figure 43. Hammer adjustment controls with decorative knurls.

seesaw bird analog rack lifters, and the repeat snap positioning cams. The darker colored component at the bottom of the figure is an experimental piece we wanted to examine to evaluate how the strike components might appear 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 figure.

Figures 40 and 41 show the strike and repeat control levers installed on the front of the movement. The components are designed so that when they are combined, 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 setup includes the bird heads being pulled away from the face of the rack prior to it being set upon the snail.

For visual impact—and visual impact is the guiding principle in this endeavor—we chose to have a set of bells custom-made in the shape of miniature church bells 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 analog 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).

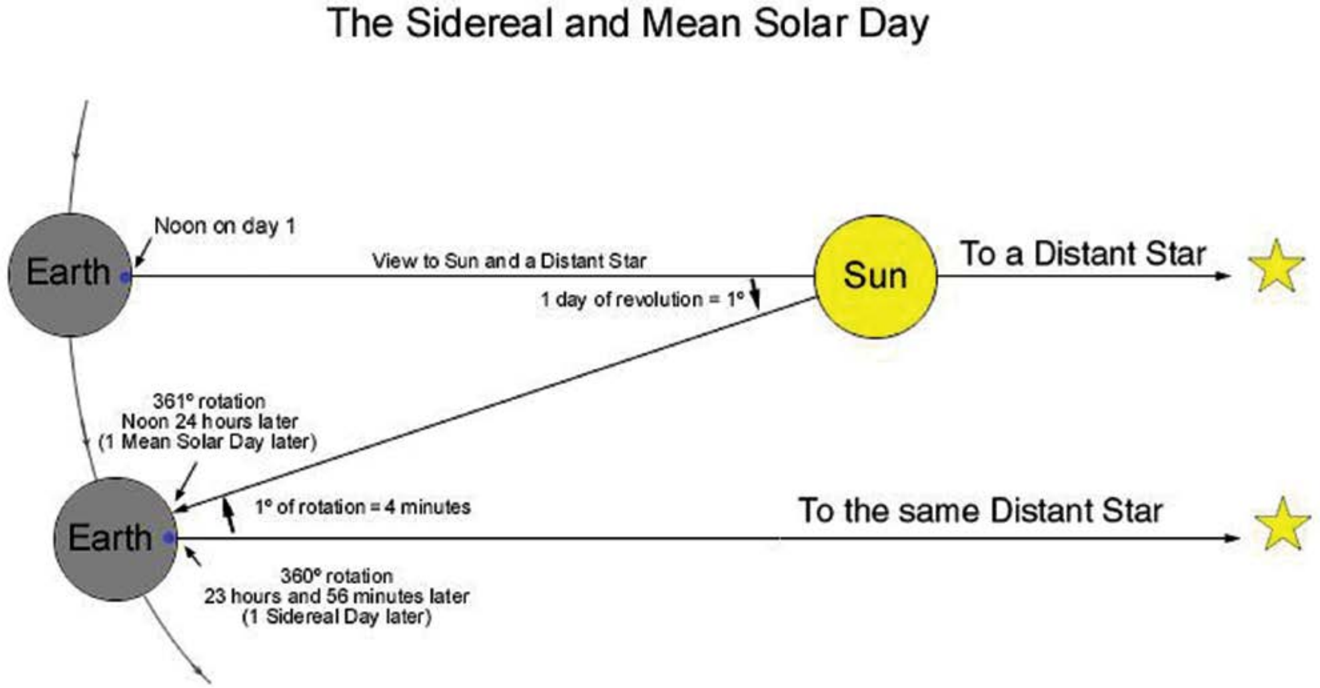

Figure 44. Illustration of the difference between sidereal time and mean solar time.

Figure 45. Mean solar and sidereal dial, Thomas Tompion ca. 1708.

Sidereal Time

During the initial design stages of this project in 2006, we had envisioned a subsidiary dial readout for the sidereal time, which usually uses a 24-hour format. Sidereal time 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, or just under 4 minutes every 24 hours shorter than a solar day (Figure 44). The 24-hour format has helped astronomers avoid confusing time logs when tracking the coordinates for locating their telescopes on a given star in the night sky. After one year, the divergence between the mean solar, which is our conventional "clock time," and sidereal time converge where the difference is exactly 24 hours—another reason for the 24-hour format. My problem with this dial is the difficulty when looking at the 24-hour sidereal time dial to see at a glance its relationship to the familiar mean solar time's 12-hour dial.

In November 2013 when I was a guest speaker at the Ward Francillon Time Symposium at the California Institute of Technology in Pasadena, CA, there was an exhibition of Thomas Tompion clocks and one caught my eye. The circa 1708 clock featured two concentric dial rings (Figure 45). In Tompion's clock the sidereal time is read directly off the fixed inner ring showing 1:14 in this figure. 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 10:00 in Figure 45 to the nearest 5 minutes from that dial for the first 6 months of the year. Because the dial rotates twice yearly, remember to add 12 hours to the mean solar time or subtract the same amount from the sidereal time to get the 24-hour comparison in the second half of the year; 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. This appears to be a manually adjusted hand for the equation of time, but it is not an independently operated complication. I knew instantly that this format was what I wanted for this project.

Tompion was not the only one to address the issue of sidereal and solar time. Londoners Daniel Quare in 1710 (Figure 47) and George Margetts in 1782 (Figure 48) had radically different, yet inspirational ways to accomplish this. Quare's design, the more straightforward, used two separate dials, movements, and pendulums within a single tallcase clock. The two conventional minute and hour chapter rings beautifully overlap below the two separate upper seconds dials with the center dial being a calendar. This approach allows for a direct reading as does our design, but in Quare's and our designs, one must compensate for the 12 hours after June 30, because a 12-hour dial is used. Similarly, Margetts used a tri-

Figure 46. Buchanan and my interpretation of Thomas Tompion's design.

Figure 47. Daniel Quare's use of two separate and cleverly merged dials.

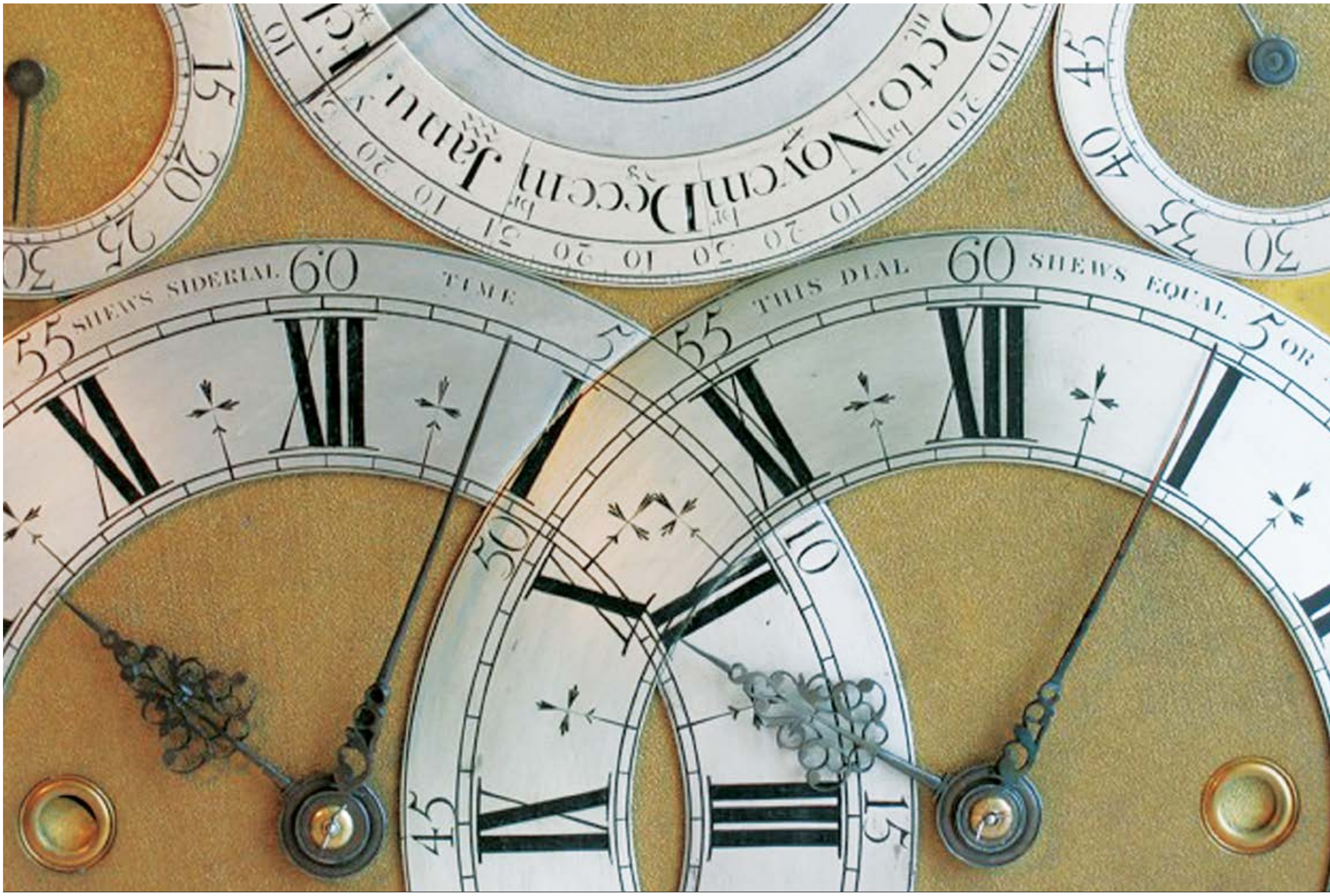

Figure 48. George Margetts's dual dials similar to Buchanan and my dials.

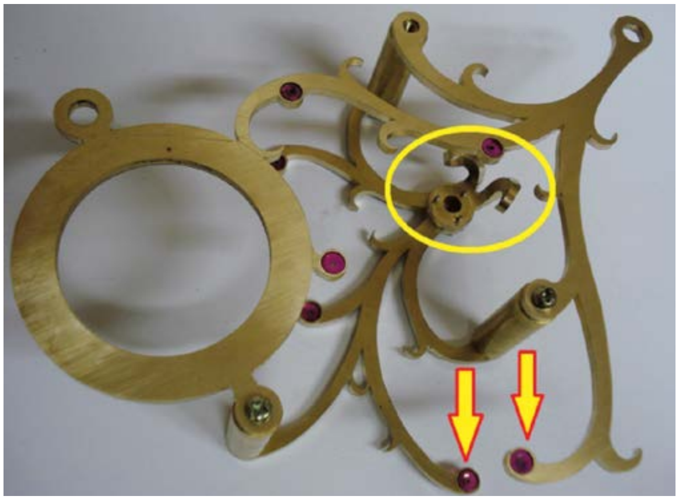

Figure 49. Framework showing unusual opposing pivot points. Arrows point to arbor pivots. Circled area is the dual drive potence in Figure 50.

Figure 50. Complex, twisted profile for drive potence.

ple set of dials for hours, minutes, and seconds, with the inner rotating disks indicating sidereal time and the main, fixed dial measuring mean solar time. As in our clock, the hands are reading mean solar time with the disks rotating to sidereal time, allowing both to be read simultaneously.

Quare's and Margetts's designs read the two times simultaneously. Unquestionably, Margetts's does this in the most efficient and accurate manner using a 24-hour dial for mean solar time and sidereal time. Unfortunately, neither design was applicable to our project. We had to keep the visual symmetry between the left-hand and right-hand sides of the clock; therefore, we chose Tompion's design.

Fortunately, we had not yet created this function, so the changes from a separate 24-hour dial to Tompion's design did not require many changes. Tompion's clock placed greater importance on the sidereal time, which is on the legible inner stationary dial. Our design reversed his priority, making the mean solar time a fixed outer dial with the sidereal time being read off a counterclockwise rotating dial.

However, we did 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 5-minute increments, so the dial can be read to the nearest 2 minutes or so. In our design we have the sidereal hours and the minutes rotating on two independently counterclockwise rotating dials; the inner dial is the hours and the outer dial is minutes (Figure 46) for accuracy to the nearest 10 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 among mean time, solar time, and sidereal time.

This clock also has a functioning equation-of-time hand, the gold hand with disk, which will be examined later in this article. I cannot think of another clock where one can read the mean and sidereal times and equation of time simultaneously off one dial set down to less than 1 minute of accuracy among the three readings comparing sidereal time to the second for the equation of time. The dial readings as seen in Figure 46 are mean time 12:53:37, solar time 12:42:37, and sidereal time 8:37:15. The sidereal reading of 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

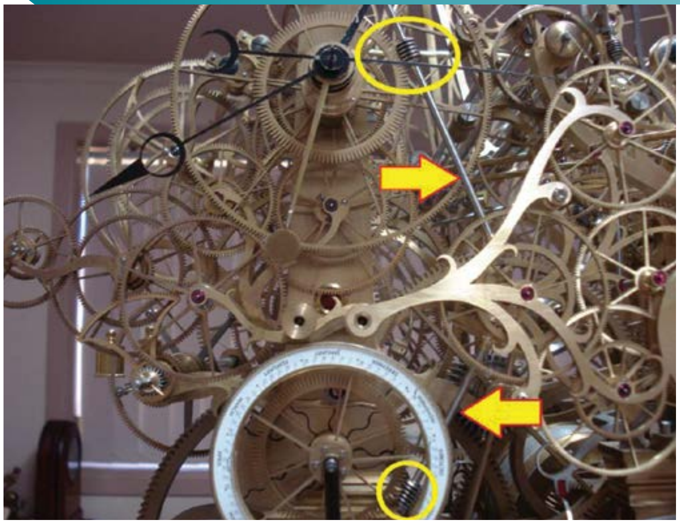

Figure 51. Worm gear, circled, drives arbors to sidereal and equation drives. Arrow points to angled drive arbor.

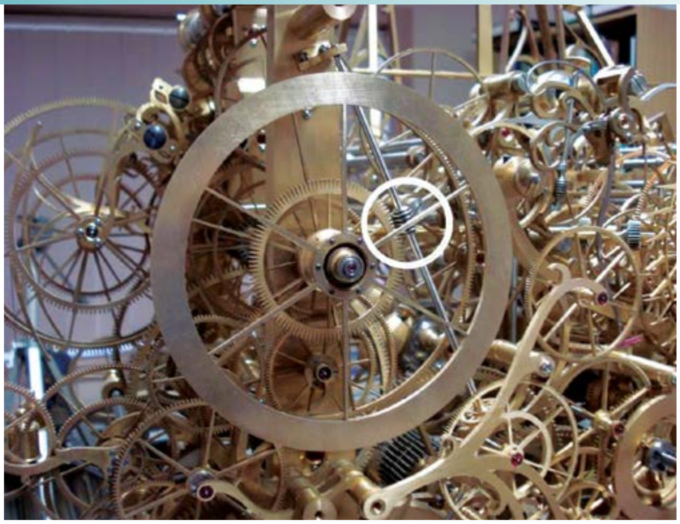

Figure 52. Rotating platter for sidereal hours with circled worm drive.

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

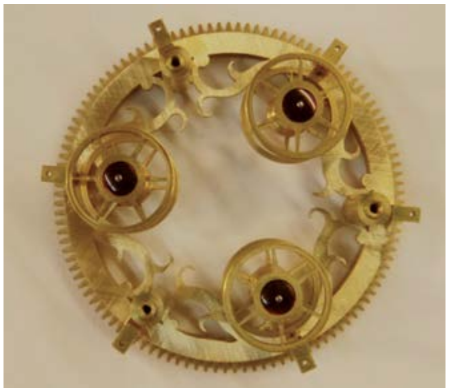

Figure 54. Three roller wheels added to rear frame.

Figure 55. Center hub and rollers set between the frames.

tick marks for 12 seconds each. One cannot use the seconds hand here, because, like the minute and hour hands, it is controlled from the mean time gearing and is not linked to the sidereal gearing. One would need a third counter-rotating ring moving to sidereal seconds to read directly off that hand to obtain accuracy to the second. Figure 49 shows the wheel frame for the sidereal time and equation-of-time drives. The two arrows point out an unusual construction where 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° 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 were required for our midair design. The sidereal rotating dials and equation kidney are driven from a common point. That point is a double potence that 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). Using pliers, Buchanan apparently twisted the potence arms to their current profiles as if the brass had the consistency of soft plastic. But in reality the potence arms were cut with a hand fretsaw out of a solid block of brass. Another view of this part is shown within the circled area in Figure 49. The sidereal and equation wheel frame assembly was mounted to the clock. The sidereal and equation complications were driven via a worm gear, as seen in the circled areas in Figure 51, mounted to an angled drive arbor, marked by arrows in the same figure. The brass ring represents one of the counterclockwise rotating platters that will hold the sidereal dials along with its worm drive, shown in the circled area in Figure 52.

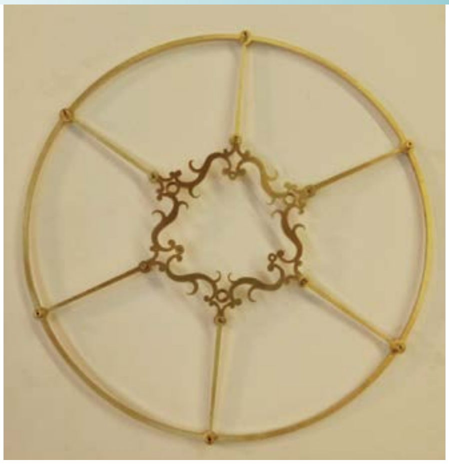

Figure 56. Outer hours ring attached to upper roller frame.

Figure 57. Inner minutes ring mounted to center hub.

Figure 58. Outer hours ring mounted to upper roller frame.

Figure 59. Sixty-eight parts in the sidereal hour and minute concentric ring drives.

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 Buchanan's inventive and artistic abilities. Figure 53 shows the view from the rear of the main worm drive wheel mounted to a decorative frame. The view is from the rear. Next, the assembly was turned over and a set of roller cage wheels were added to the rear frame (Figure 54).

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

Next, the inner ring was secured to the central hub (Figure 57). Upon this assembly 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 depicts the various components—a total of 68 parts in this subsystem—used to drive the two counter-rotating sidereal chapter rings. Additional wheels are needed to derive the sidereal minute from the sidereal hours driven by the main worm input gear. Next, the completed decorative sidereal drive unit was installed within the movement (Figure 60).

Figure 60. Completed sidereal drive unit.

Equation of Time

The equation of time is the difference in the position of the Sun to an observer looking at it 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. Both observations agree only four days a year: April 15 (Tax Day in the United States), June 13, September 1, and December 25 (Christmas). (My guess is the first and fourth dates are coincidental.) The equation of time results from the tilt and elliptical orbit of the Earth, causing 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. These two movements result in the apparent erratic motion of the Sun and are shown on the graph in Figure 61 with their mathematical combination indicated by the black line. That graphical curve of the equation of time represents the contour of the equation kidney cam.

Figure 62 shows 1 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 on the main dial. Once a rough outline was made, the cam was 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 achieve the correct profile. So the total number of tests to reach the correct profile was 1,168, or 16 tests of each of the 73 points on the cam—clearly, a labor-intensive

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

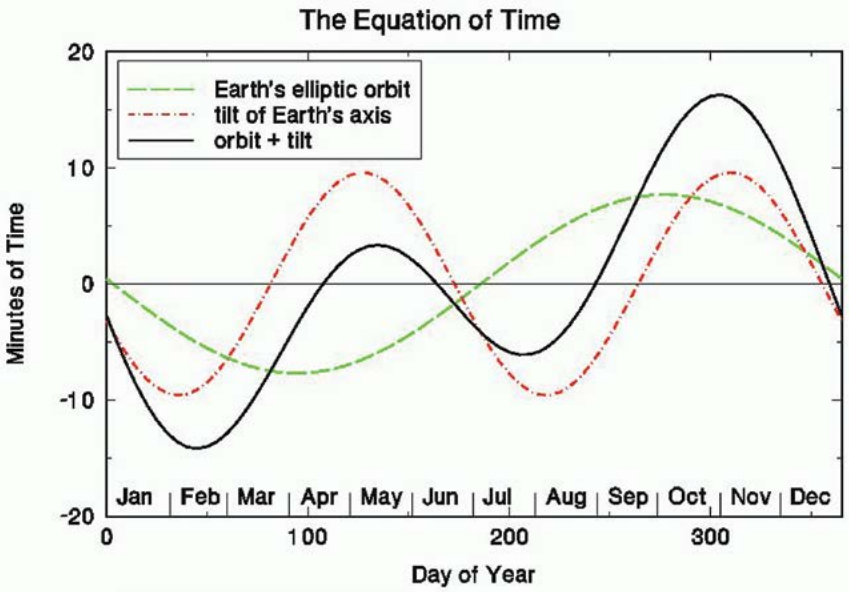

Figure 62. Error correction data for kidney cam.

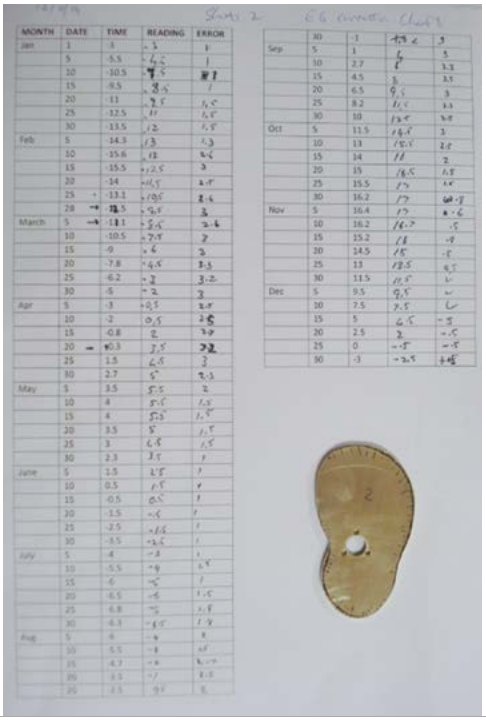

Figure 63. Completed cam with sunray spoke design.

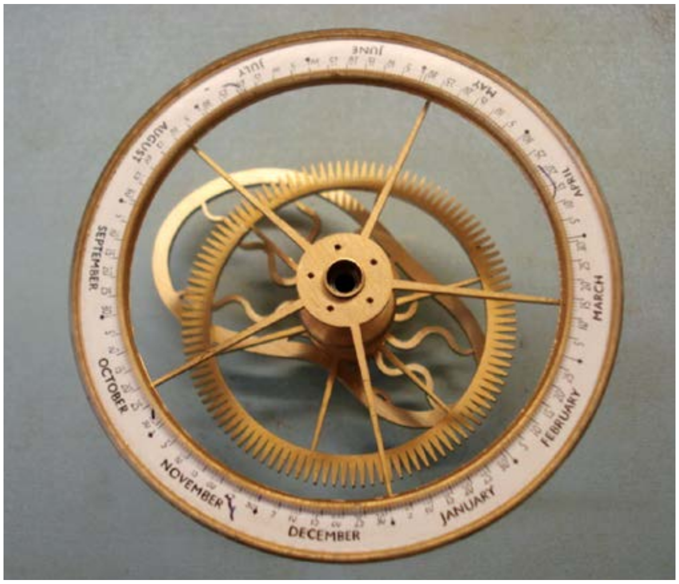

Figure 64. Equation kidney cam with drive and setting dial.

Figure 65. Equation cam works installed on the movement.

process. The difference in the errors from the first iteration to the sixteenth is on an order of 1.5 magnitudes. For example, March 5 has an original error of 4.2 minutes on the first error table and finishes at 0.1 minute or just 6 seconds on the sixteenth table. On March 5 the difference between mean solar time and the actual position of the Sun at its zenith, directly overhead at noon, 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 with 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 its sunray spokes is shown in Figure 63. What better example for a cam that depicts the Sun's time than to have sunrays for the cam's spokes? This is another example along with our animal analogs of adding a bit of whimsy into the movement's design.

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

The readout for the equation hand is 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, circa 1720, was the first to use differentials to display the difference between the solar and mean time simultaneously in clockwork.[3] The differential wheel set was made in May 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 of mean solar time. We took the sun gear in the differential, which normally is sandwiched between two planetary wheels, and flattened it out to where the sun gear rides along the perimeter of the planet wheel. It is visually the most impressive way we could display the movement of the differential in response to the kidney cam.

About the Author

Mark Frank runs a Chicago residential real estate management and development company.

Figure 66. Wheel set for equation-of-time hand and Sun at slowest.

Figure 67. Wheel set with differential and Sun at fastest.

His horological interests are in the research and collecting of timepieces where one can the mechanical works in particular skeleton clocks, tower clocks and bank vault timers. His main interest is in those pieces that exhibit interesting mechanical characteristics as demonstrated through complexity, novelty, or visual appeal. The clock which is the subject of this article is the culmination of many years of research, observations and examples drawn from his collection all combined into a personal fantasy machine. He has been an NAWCC member since 1993.

Notes and References

1. Information and illustrations of Charles Fasoldt's original design within his clock provided by Donald Saff, "American Precision Pendulum Clocks," in Precision Pendulum Clocks, France, Germany, America and Recent Advancement, Derek Roberts, Vol. 3 (Atglen, PA: Schiffer Publishing, 2004), 208-222.
2. Detailed examination of Jean-Baptisté Schwilgue's ecclesiastical computer was written by Joseph Flores, Le comput ecclésiastique de Frédéric Klinghammer (France: Association Française des Amateurs d'Horlogerie Ancienne, 2007), 110. The book contains a DVD.
3. The first use of the differential, at least in connection with the equation of time and probably horology in general, was by Joseph Williamson, circa 1720-1725. H. Alan Lloyd, Some Outstanding Clocks Over 700 years 1250-1950 (London, UK: Leonard Hill Books, 1958), 80-84, illustration on page 83.

Watches with an Environmental Mission

So often the discussion of wristwatches and the watch industry concentrates on history, value, and profits, but what about the environment?

For Sam McAllister, the departure from the traditional watch industry and its profit margins was critical to establishing his new brand, according to *The University Times*, a student newspaper in Ireland published from and financed by Trinity College Dublin.

Student McAllister launched his unisex watch company, Stem Watches, with a social conscience that involves full transparency about pricing and helping the environment.

For every watch sold, a tree is planted—and planting trees creates jobs. He partnered with WeForest, a sustainable reforestation company who has planted more than 13 million trees.

"I wanted to set up my own company, but I also wanted it to have a social impact at the same time. So I figured it would be a good idea to partner with a charity," McAllister told reporter Aislinn McCann.

What about his watches? He offers three watch designs with changeable leather straps, all of which McAllister designed himself. To learn more about his entrepreneurial endeavor, visit http://www.universitytimes.ie/2016/12/the-student-led-watch-company-with-a-conscious/.

—Editor Therese Umerlik (PA)

Astronomical Skeleton Clock

Part 2 of a Two-Part Series
Third-Order, Reversible Perpetual Calendar
Why Do We Need This?

by Mark Frank (IL)

Author's note: The NAWCC has been documenting the complex astronomical skeleton clock I commissioned that is being built by clock manufacturer and restorer Buchanan Clocks of Chelmsford, AUS,[1] *since 2007.*[2] *This article is the second part of a two-part series explaining the developments in the clock's construction. The first part was published in the January/February 2017 issue of the* Watch & Clock Bulletin *and focused on the entire left side of the dial complication work and the small dial below the large tellurian ring on the right, the strike selector. The second part addresses the dial work that comprises a third-order, reversible perpetual calendar.*

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 30 days nor February with 28 days in the three successive non-leap years or 29 days every fourth 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 month: 30 days in April, June, September, and November, and 31 days in January, March, May, July, August, October, and December. Because February is 28 days for three years, the accuracy is good. This is an annual calendar. Once February adds its extra day for leap year—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 to skip the leap year. 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. Another refinement is needed to keep calendars permanently in step with the Earth's orbit, known as the tropical year. Every 400 years, the intercalary day, February 29, is reinserted, which allows the calendar to be permanently perpetual—a third-order perpetual calendar. Technically, there is still a minuscule drift—not more than one day in over 10,000 years—from humanity's arbitrary calendar and the tropical year. 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 Christian celebration based on a number of complex astronomical criteria, and a third-order perpetual calendar is a vital component of the calculator.

Three criteria in the Gregorian calendar 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—a third-order perpetual calendar calculator.

The calendar we have built is a third-order perpetual calendar, but we added one more step. This calendar is also reversible. It will perform all of the calculations needed to keep the calendar perpetual in forward and reverse without the loss of data. The way we achieve reversibility is to do away with the conventional way the dates are advanced with a stepper shaped like a star wheel for the dial indications. Instead, everything is directly geared together and is advanced each day at midnight with a remontoire. The perpetual calculator module has a special provision to allow it to step backward using an index wheel with all other calculating components geared together to facilitate running in reverse. To the best of my knowledge this has never been done—not because it presented a difficult technical challenge, which it did, but because it was never needed. To do this, clock manufacturer and restorer Buchanan Clocks of Chelmsford, AUS,[3] and I created a small mechanical analog computer complete with logic circuitry, a program, a memory, and a small fixed mathematical processor composed of 580 parts—more total parts than many of the most complicated clocks or watches.

Why do we need a reversible perpetual calendar in this astronomical skeleton clock? The reason is the calendar indications of the day, date, month, and year will 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 celestial functions, the calendar will advance or go backward in sync with that demonstration. In this way, one can see exactly how certain celestial events will appear or occur on any given date. This makes the prediction or verification of events, such as solar or lunar eclipses, the time of sunrise and sunset or moonrise and moonset, or the position of the stars in the sky at any given time possible. Looking at the orrery, one will see where the planets and their moons are in relation to each other at any given time. A subsidiary dial will take the accuracy to the hour. It also makes resetting the cosmos back to the correct time frame easier after demonstration. 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. The operator can demonstrate easily and safely the many celestial components and the various functions of the clock.

Figure 68. Daily index wheel for days 1-28.

Figure 69. Detail showing days 29-31 missing.

Figure 70. Surprise pieces for days 29, 30, and 31.

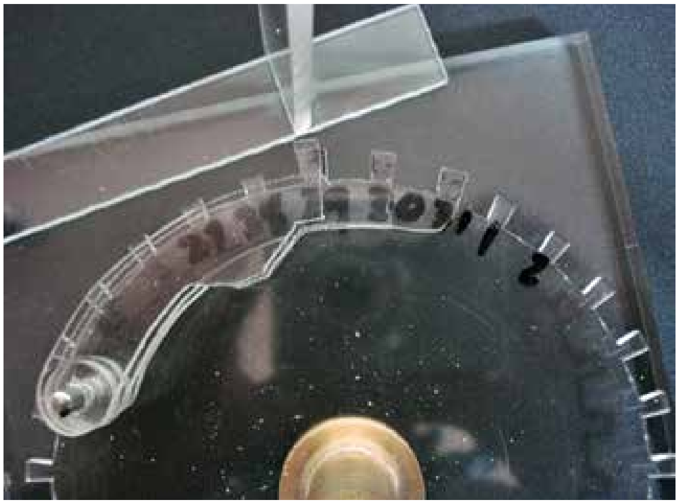

Figure 71. Surprise pieces over index wheel.

Figure 72. Cam pair for 30 and 31 days and February.

Figure 73. A 20-year cam used in 100-year cycle.

Perpetual Module

The first component to be designed was the perpetual module, the heart of the calendar, its program and memory. 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. Because 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 it was fabricated 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, there was a simplified mock-up of the time train using the dual epicyclical remontoire and Harrison's escapement, and third was the planisphere complication. In those mock-ups, the scale was 1:1. Here the model is larger at 1:3, because the finished module will be at the scale of a pocket watch. If we needed to make design changes or to observe the mechanism's functionality, it would be easier to do so 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 figures present the intricacies of the perpetual module.

Figures 68-70 show the basic components of the calendar module if it were a simple perpetual calendar. Figure 68 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 1 through 31 teeth, but with 3 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, there 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).

Next, the three following surprise pieces are installed onto the index wheel (Figure 71):

- The 30- and 31-day regular monthly durations
- Location of February, the one month with 28 days for three consecutive non-leap years
- Addition of February 29 for the leap year.

Figure 72 shows the cams that drive two of the surprise pieces. The monthly deviations between 30

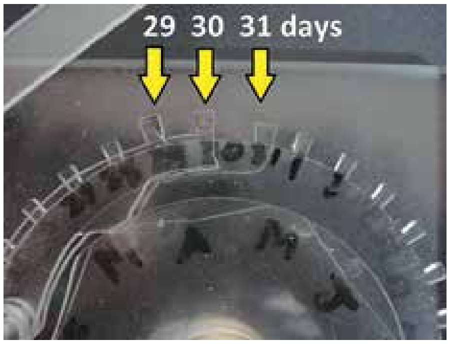

Figure 74. Arrows point to three raised surprise pieces, creating a 31-day month.

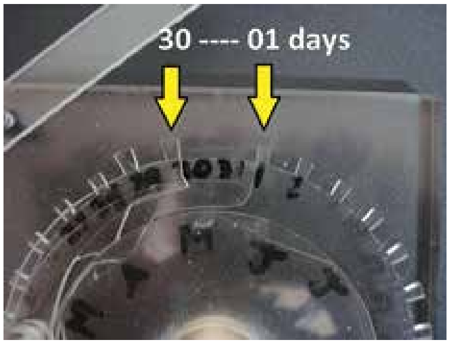

Figure 75. The surprise piece for Day 31 between the two arrows is lowered, giving a 30-day month.

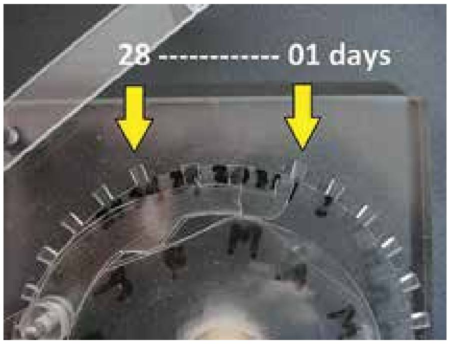

Figure 76. The surprise pieces for Days 29, 30 and 31between the two arrows are lowered, giving February 28 days.

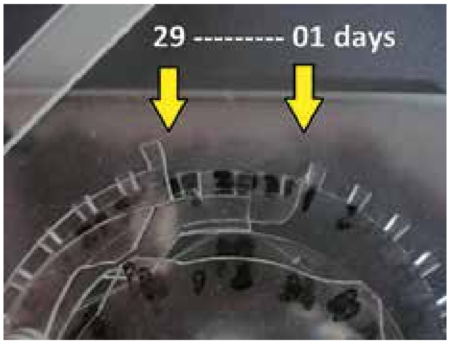

Figure 77. The surprise pieces for Days 30 and 31 between the arrows are lowered, giving February 29 days.

Figure 78. Cam with flat cut for February.

Figure 79. Some drive gear work.

and 31 days are controlled by the irregularly shaped upper cam. The smooth lower cam controls February. Figure 73 is the leap year cam, which runs on a 20-year cycle and is used with another cam to calculate the 100-year exception. This will later have an additional cam and wheel work attached that, combined with this 100-year cycle, will cycle once every 400 years for the next layer of complication discussed later in this article.

The next three figures 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. Figure 75 shows one piece lowered for a 30-day month. All three pieces are lowered for the regular 28-day month of February in Figure 76. Figure 77 is the leap year resulting in February 29 being added with one of the three surprise pieces raised. Figure 78 shows the month duration and February cams. The latter is basically a round disk with a flat cut where February is located. Some of the gear work used to drive the cams are shown in Figure 79.

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

A small 5-lobed Geneva stepper cam is attached to a 5-armed cam attached directly above, with one arm truncated (Figure 80). Because the larger cam to which the smaller cam is attached rotates every 20 years, the smaller cam is stepped once every 20 years or is expected to rotate one revolution in 100 years. 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, causing February not to have 29 days that year. Next is the piece that will advance the Geneva stepper cam (Figure 82). Figures 83 and 84 show the drive piece installed, and the 100-year cam is shown as if February was having 29 days. Next, the cam is shown not giving February 29 days so the leap year is eliminated. Figure 85 shows (arrow) February with 29 days. 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, that makes the calendar permanently perpetual is shown in Figures 86-88.

Figure 80. A 100-year correction cam.

Figure 81. A 100-year cam at correction.

Figure 82. Geneva stepper drive.

Figure 83. A 100-year correction assembly with and without correction.

Figure 84. A 100-year correction assembly with and without correction.

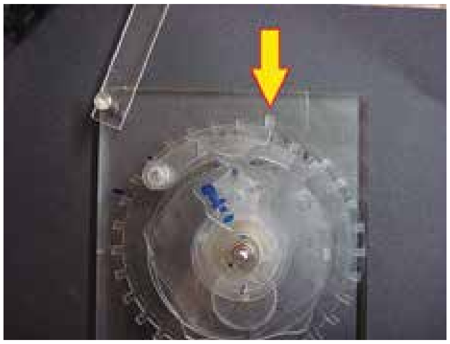

Figure 85. Cam making insertion of 29th day. Arrow points to February's 29th day.

Figure 86 shows a 4-lobed Geneva cam stepped once every 100 years attached to the 400-year cam along with the associated gearing and bridgework needed to install this upon the existing calendar work. That cam is basically a smooth disk with one protruding arm. Figure 87 shows the one protruding arm of the 400-year cam giving February 29 days once every 400 years. The circled area in Figure 88 shows the remaining cam presenting a smooth surface for the remaining 399 years. 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 the 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.

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

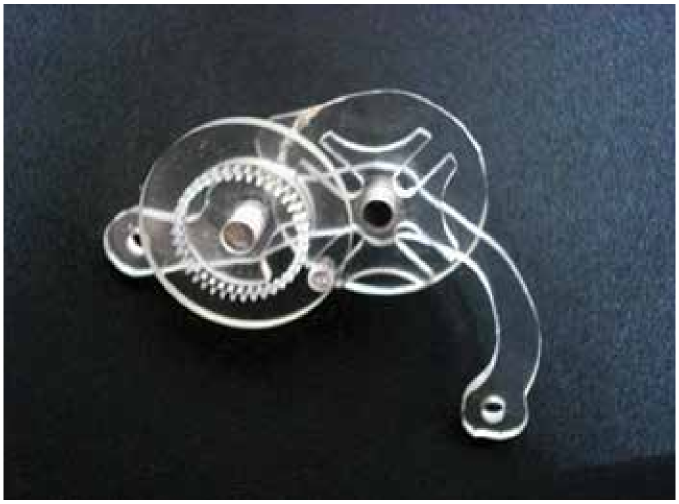

Figure 86. The 400-year correction.

Figure 91 outlines the components of the perpetual module. Figures 92 and 93 show the perpetual module within the context of the remontoire drive mechanism, which will trip the module once per day. An elaborate clutch mechanism is incorporated into this device to prevent unintended damage to the calendar module from a careless operator trying to crank

Figure 87. Cam correcting every 400 years. Arrow points to cam.

Figure 88. Smooth portion for 399 years.

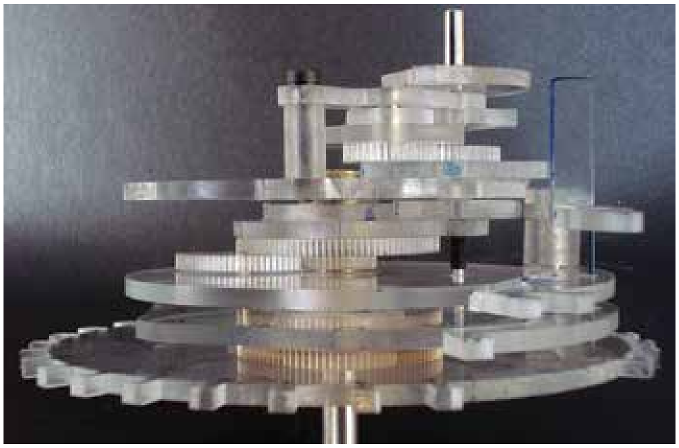

Figure 89. Edge-on view of perpetual calendar model.

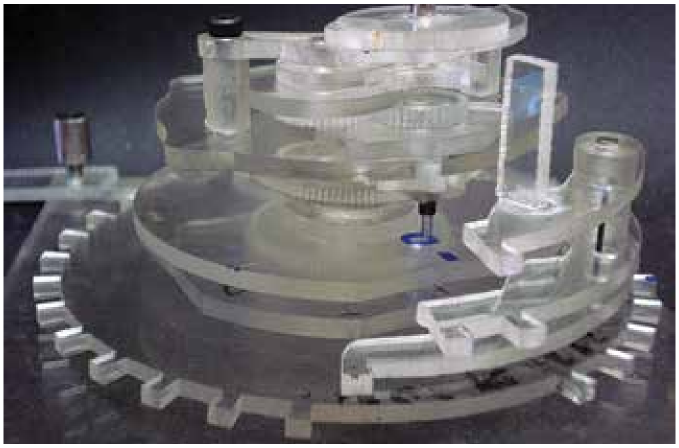

Figure 90. Three-quarter view of perpetual calendar module.

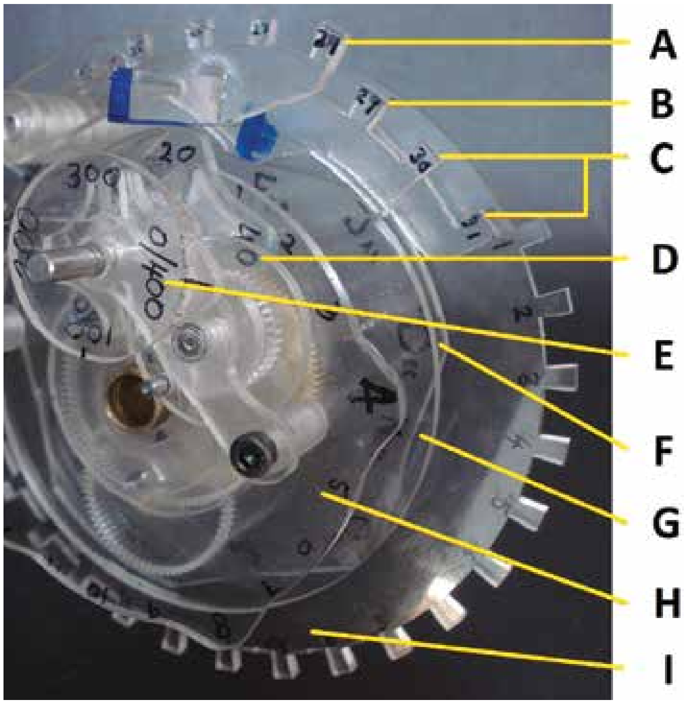

Figure 91. Components of the perpetual calendar module. The letters and their explanations are as follows:

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. A 100-year cam driven one-fifth revolution for each revolution of the 20-year cam eliminates leap year once every 100 years for 300 years.

E. A 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. A 20-year cam gives a leap year at 4-, 8-, and 12-year intervals, but not at the 16th year, because this is controlled by the 100- and 400-year cams.

I. Daily index wheel.

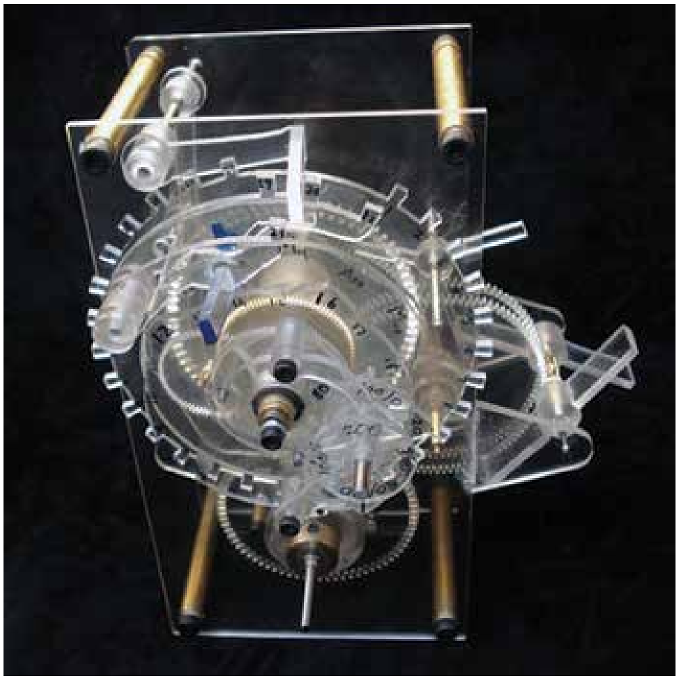

Figure 92. Front view of perpetual module with the calendar drive.

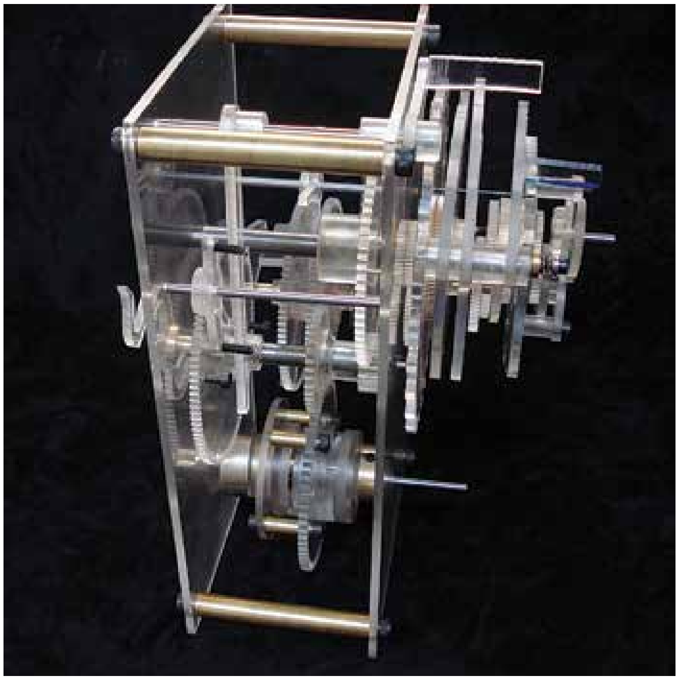

Figure 93. Side view of perpetual module with the calendar drive.

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

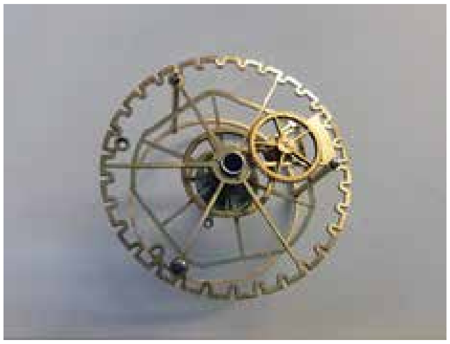

Figure 95. Delicately cut crenulated index wheel and cams.

the demonstration drive too quickly, one of the many safety mechanisms incorporated into the demonstration area of the machine to prevent unintended damage.

Figure 94 shows a few of the completed components of the perpetual module. The scale in the figure has a length of only 1-1/2 inches, or 4 cm. Figure 91 shows the completed plastic mock-up of the perpetual module with the daily index wheel made of a solid plastic 3-inch disk with a crenulated edge. The easiest way to reproduce this module in the final small scale would have been to make it from a solid metal disk with the same tooth profile. The next easier way would have been to make a thick-rimmed wheel with conventional spokes and cut the crenulated design into the edge of the rim similar to a strike train count wheel. But Buchanan took the most difficult and most visually spectacular route by making the entire rim in the sinuous design. The rim was cut by hand with a fretsaw and is about 1inch, or 3 cm, in diameter—a tour de force in the art of decorative fretting. Two more delicate, irregularly shaped cams, the 100-year and February cams, are shown in Figure 95.

Figure 96 shows an exploded view of the main components of the reversible 400-year perpetual calendar calculator module. The total number of parts is more than 102.

The completed module is just slightly larger in diameter than an average wristwatch and quite a bit thick-

Figure 96. Components of the perpetual module. The numbers and the letter as well as their descriptions of the main components are as follow:

1. Daily index wheel that advances the date and is where the drive to the calculator begins.
2. A 1-year cam that controls the duration of February in non-leap years.
3. A 10-year cam.
4. A 20-year cam.
5. A 100-year cam.
6. A 400-year cam.
7. A 20-year chapter ring.
8. Month chapter ring.
9. Calculator frame assembly and partial.

A. A 400-year drive assembly.

The surprise pieces marked S1 through S4 operate in the open area of the rim at the 3 o'clock position on the daily index wheel, marked 1. The explanation of pieces S1-S4 is as follows:

S1and S2. Dual surprise pieces that are controlled by the 100- and 400-year cams.

S3. Surprise piece for introduction of extra day in February in normal 4-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.

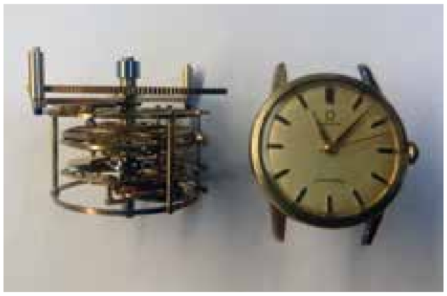

Figure 97. Side view of completed module. It is next to a wristwatch to show proportional size.

Figure 98. Top view of completed module. It is next to a wristwatch to show proportional size.

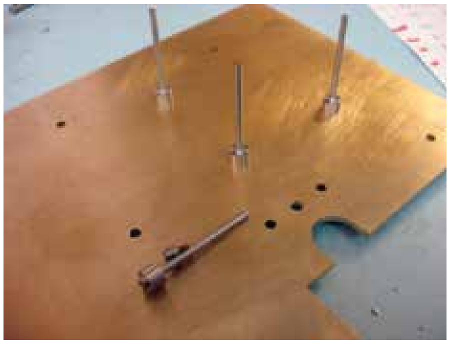

Figure 99. Arbor posts attached at only one end for dial wheels.

Figure 100. Drive wheel mounted to arbor.

er (Figure 97). Note the silvered chapter rings that 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 in the 400-year leap year cycle.

Calendar Readout Components

For each of the four calendar dial outputs, a pair of wheels produces the readout. The first is the drive wheel, 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 wheels allow the dial hands to be stepped instantly at midnight to the correct readings and are a key to the calendar's ability to be reversible.

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

Figure 101 shows a crenulated stepper wheel made in the same elegant style as the daily index wheel within the perpetual module. Each dial has a stepper wheel with the dial's hand attached to it. In this case the days of the week are marked with seven notched areas for a control detent to lock onto. In Figure 102 the stepper wheel's cannon arbor is slid onto the drive wheel's cannon arbor, all of which the dumb arbor post supports. One can see a slight space among the center solid arbor post, the toothed drive wheel cannon arbor, and the stepper wheel's cannon arbor.


Figure 101. Stepper wheel for day of the week.


Figure 102. Stepper wheel mounted above its drive wheel.

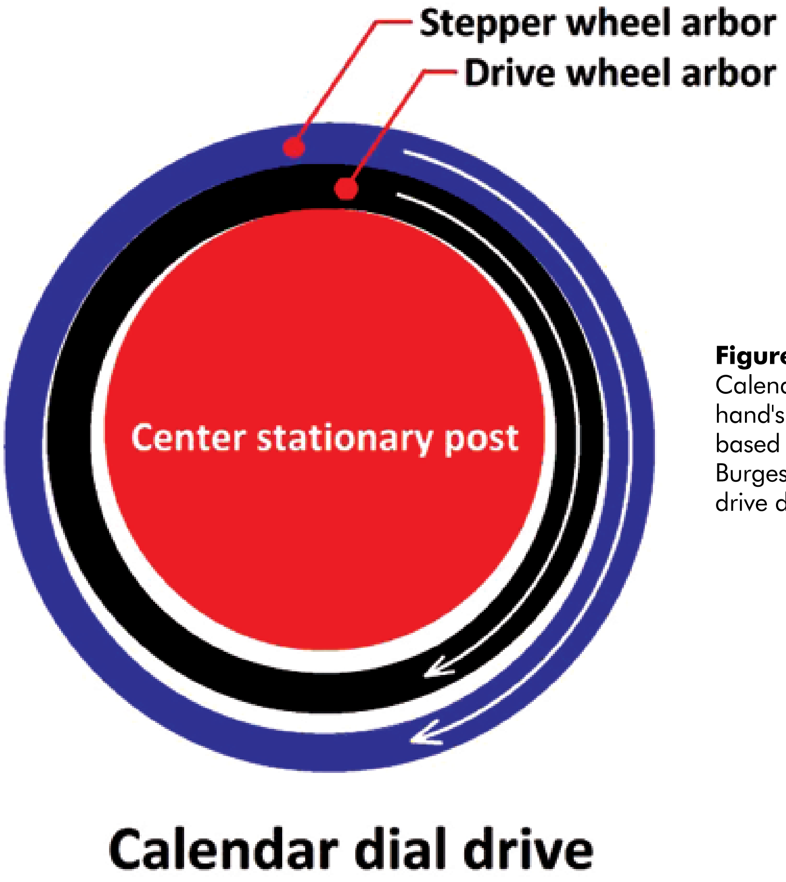

Figure 103. Calendar dial hand's drive is based on the Burgess friction drive design.

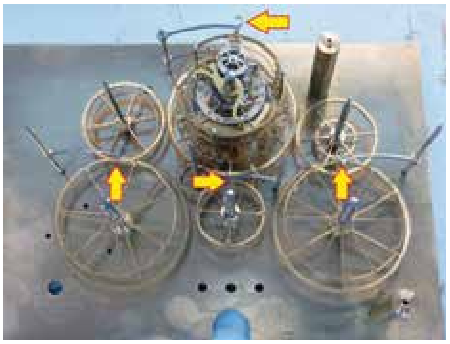
Figure 105. Date detent reader for the perpetual module.

Figure 104. Arrows point to locking detents for each dial's readout.

Figure 106. Digital year readout.

Figure 103 shows how the calendar dial drive works. The drive wheel's cannon arbor fits over the stationary post, like the cannon pinion in a conventional clock. The stepper wheel also is attached to another cannon arbor, which is mounted onto the drive arbor. As the drive wheel turns, the stepper wheel and the dial hand will turn. 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 if the 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, UK, and used the concept here.[4]

All drive and stepper wheels are in place (Figure 104). Each arrow indicates a detent shaped like a bird's head that controls that particular dial readout. The upper arrow in the figure shows the date, and below, from left to right, are the day of the week, the leap year, and the month. All outputs are geared

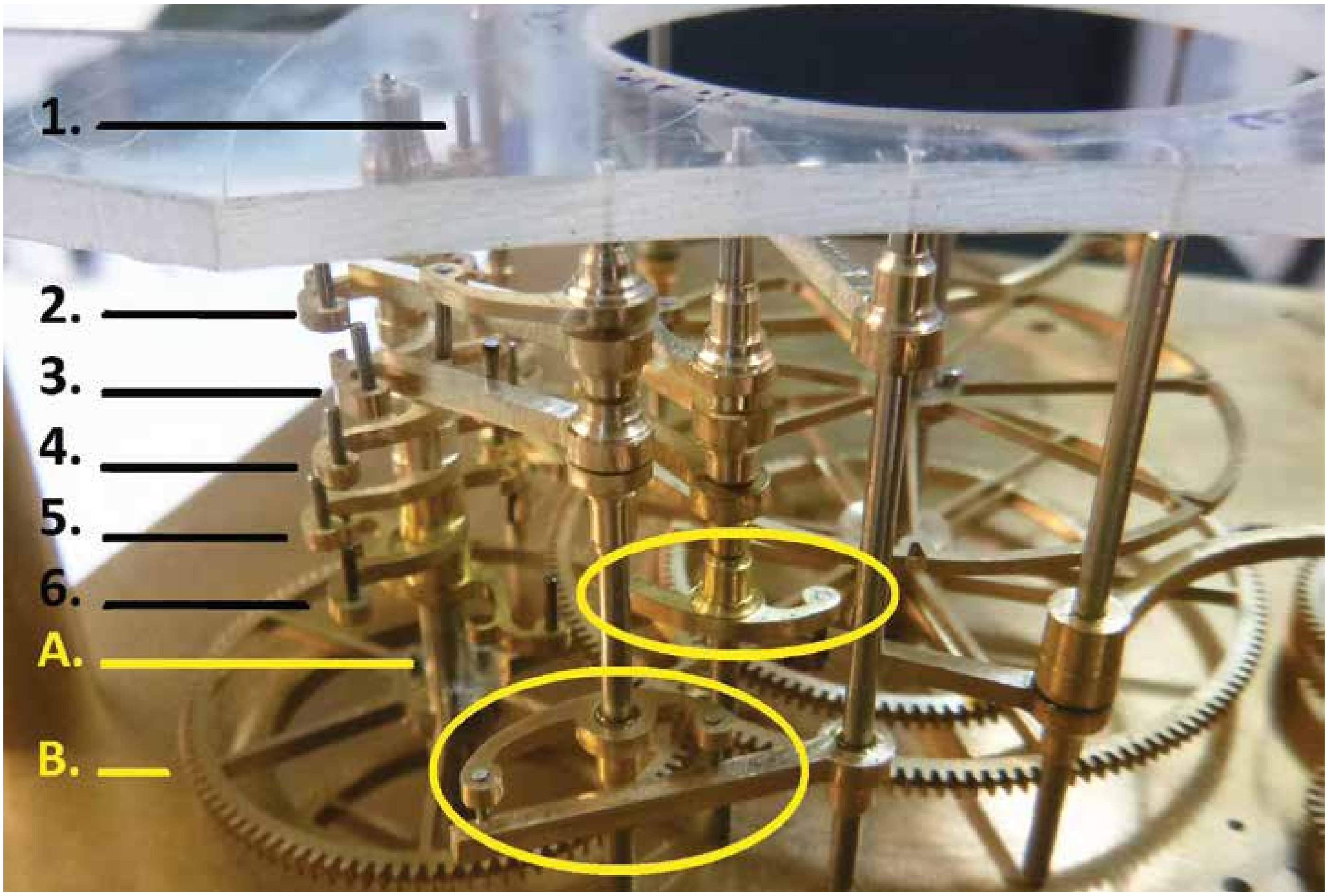

Figure 107. Analog clock controller for logic circuitry. Items numbered 1-6 point to the rotating time cam stack. The letter "A" points to the arbor and letter "B" to the drive wheel. The circled areas are two of three rocker assemblies.

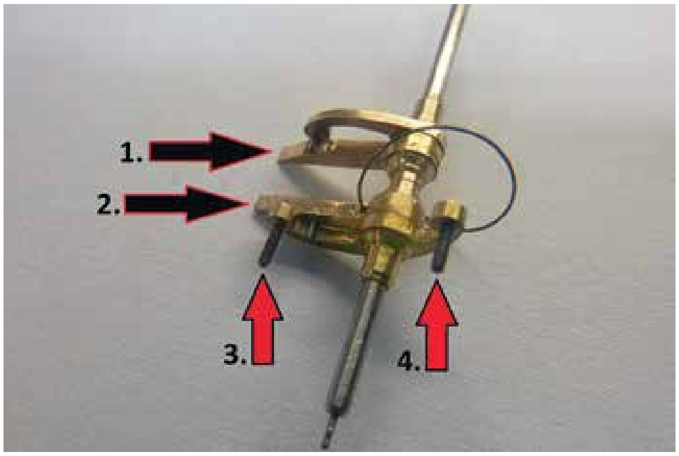

Figure 108. Lever rockers and one-way impulse paddles. Black arrows 1 and 2 point to the impulse paddles and the red arrows 3 and 4 to the pins.

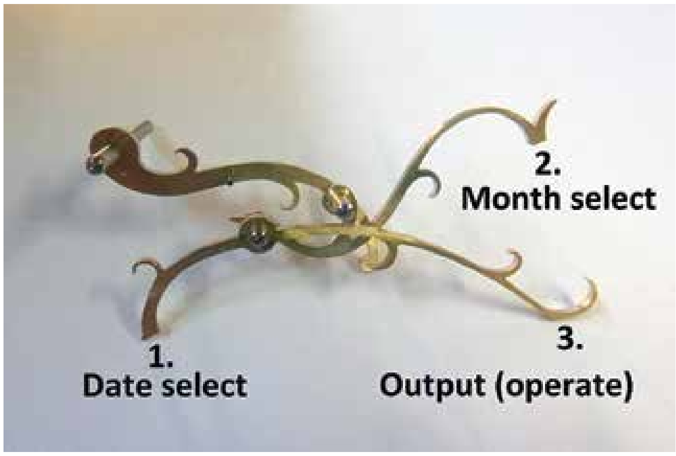

Figure 109. Logic lever functioning as an AND gate.

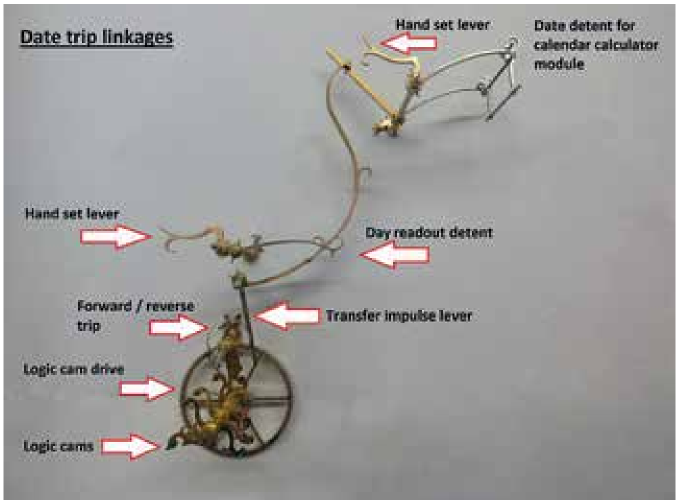

Figure 110. Day and date trip linkages.

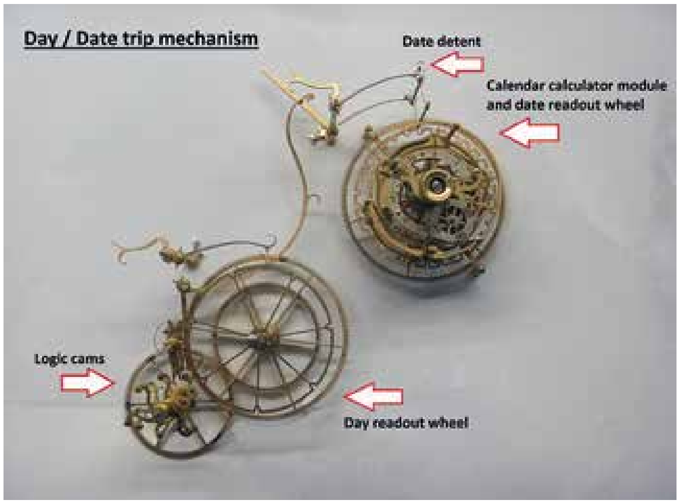

Figure 111. Day and date calculation mechanism.

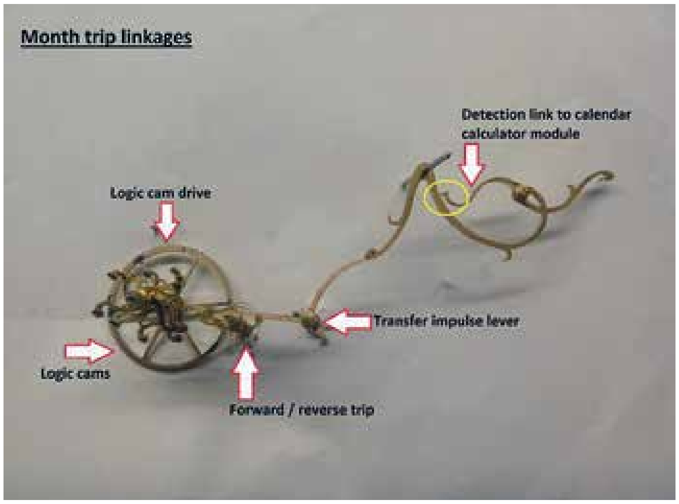

Figure 112. Month trip linkages.

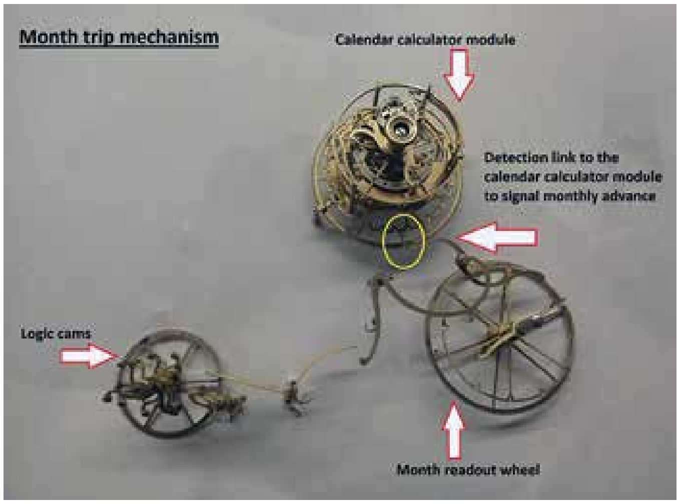

Figure 113. Month calculation mechanism.

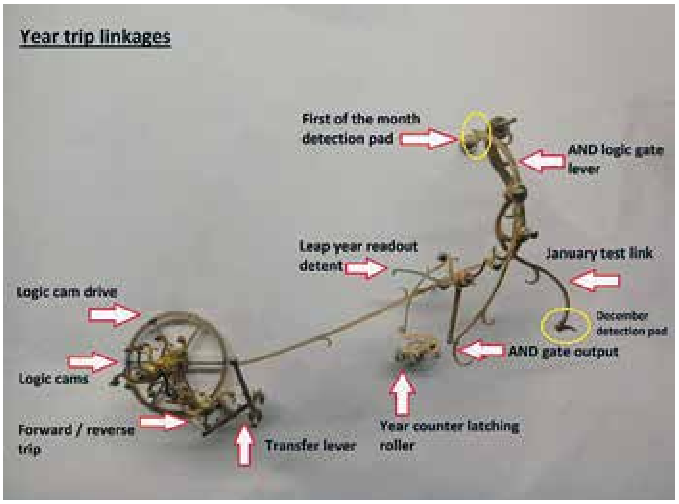

Figure 114. Year trip linkages.

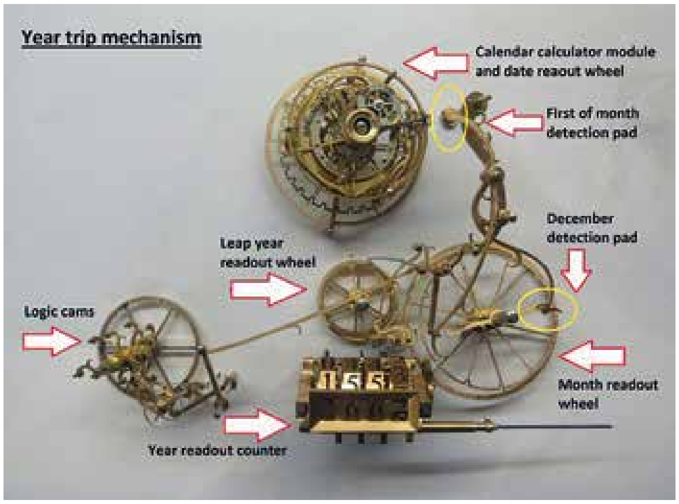

Figure 115. Year calculation mechanism.

Figure 116. Subset of the calendar logic levers and linkages.

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 are 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 not raised will remain unchanged. Because the perpetual module can run backward and all calendar readouts are geared together, the entire calendar can run accurately forward and reverse.

Figure 105 shows a close-up of the perpetual module of the compound date detent, 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. The three arrows to the right of the rod in the figure indicate the three surprise pieces, which 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 surprise 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 digital cylinders

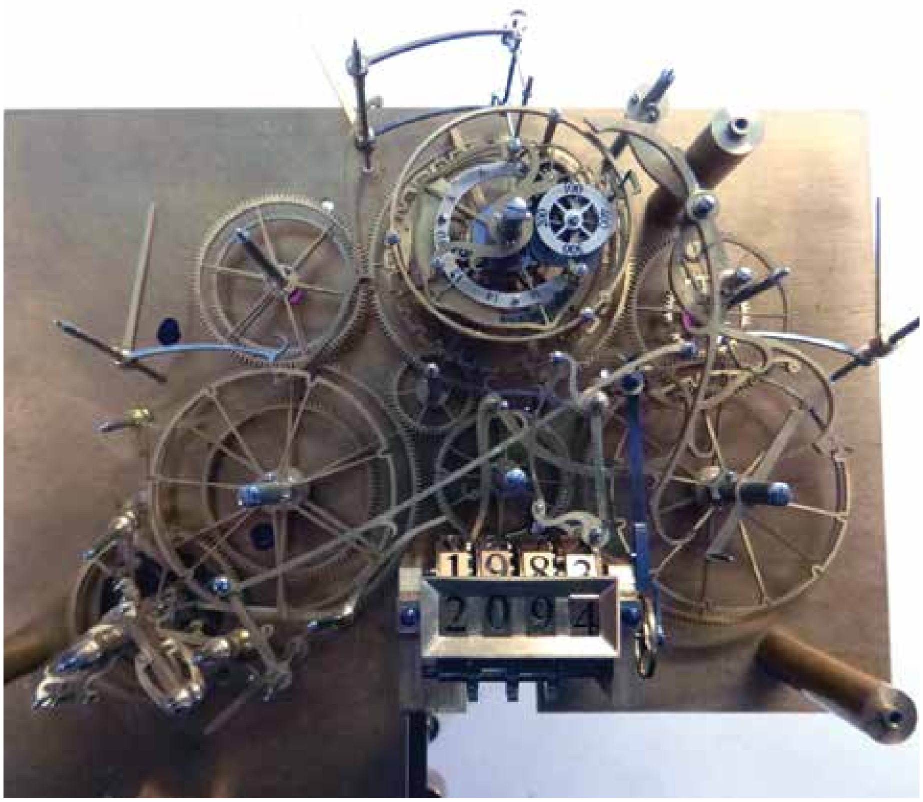

Figure 117. Complete calendar with front dial plate removed.

Figure 118. Plastic mock-up of front dial plate.

Figure 119. Skeletonized front dial plate.

Figure 120. Materials used for rear plate design ideas.

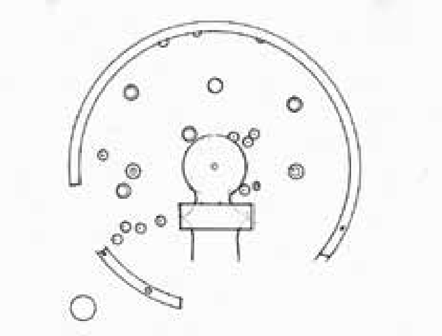

Figure 121. Initial drawing showing extant pivot locations.

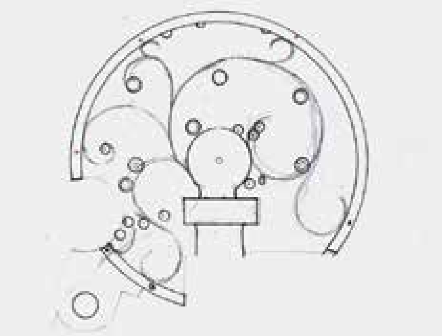

Figure 122. Early concept drawing connecting pivots.

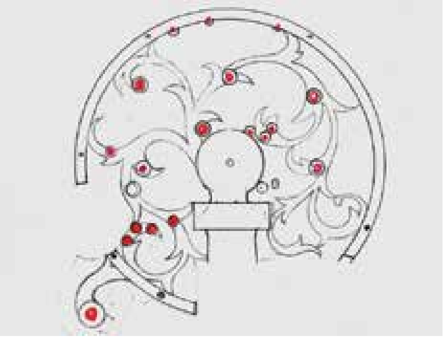

Figure 123. Rear frame design more fully developed.

Figure 124. Intricate design fretted out by hand.

Figure 125. Rear frame fretted, displaying organic ivy design.

Figure 126. Nearly 600 components of the calendar unit.

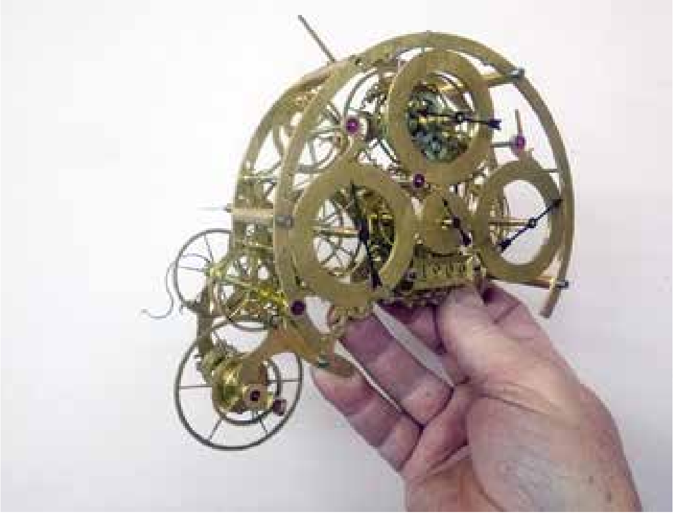

Figure 127. Completed calendar complication.

with 10 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 movie buffs who have seen the 1960 movie *The Time Machine*, based on H. G. Wells's book of the same name, 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, to solve a problem, rather than by expressing the data as digital bits. One of the most famous analog computers was designed by Charles Babbage in 1823, but aside from a small demonstration module, it was never built. The machinery of the time was not accurate enough to produce the full-scale machine requiring thousands of parts and might have cost more than the British government was willing to finance.[5] Even though we are not trying anything so ambitious, we do use mechanical levers to produce logic gates as well as a rotating set of cams to act as the computer "clock" to coordinate the functions of the lever logic gates within the rest of the calendar machine. This assembly is the processor unit of the computer. The perpetual module acts as the machine's hardwired program and memory.

This three-quarter view shows some of the complexity of the calendar components in Figure 107. The logic clock drive is represented by the drive wheel marked **B** and the arbor marked **A**. The wheel just barely visible below the circular opening in the brass plate belongs to the remontoire, which drives the calendar once every 24 hours. On the 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 in Figure 107 show two of the three rocker assemblies; the third is obscured by components in the foreground. Each rocker assembly converts the rotating motion of the cams in the clock drive into lineal motion to move the logic levers and allows 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 shows an example of one of three arbors that carry a lever rocker arm and a pair of one-way impulse paddles. Black arrows **1** and **2** point to the impulse paddles, a compound paddle made of two parts. The paddle itself, referred to by 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 calendar's mechanical logic circuitry. The area of contact is near the tip, marked by arrow **1**. The input cam can rotate in forward or reverse. If the paddle is pushed in one direction, toward the figure's viewer, 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, marked by arrow **2**. The part below it 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 motion.

The two pins red arrows **3** and **4** are pointing to 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's 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[6] where if there is a positive input at 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.

Figures 110-115 will show the various linkages and logic circuits throughout the calendar mechanism. The basic operation is as follows:

- At midnight each day the calendar's analog clock controller's 6-cam stack is actuated through the calendar's onboard spring remontoire and the controller turns a half revolution.
- The controller is geared to each output dial drive gear, the day, date, month, and leap year cycle.
- The controller cam stack actuates the various logic and dial detent levers.
- The day dial is always advanced one position for each half revolution of the analog clock, regardless of anything else going on within the calendar mechanism.

Figure 128. Completed calendar assembly installed.

Figure 129. Completed left-hand sector of the clock.

Figure 130. Front view of calendar complication.

Figure 131. Right-side view of calendar complication.

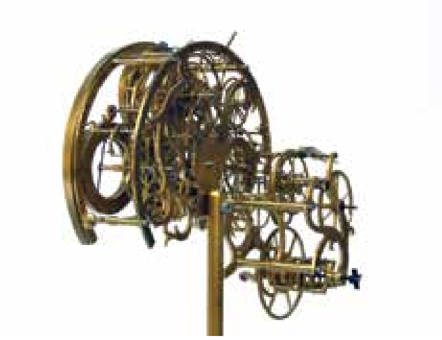

Figure 132. Rear three-quarter view of calendar complication.

- 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 on the position of the surprise pieces and other actuating pins within the perpetual module, various detent levers that connect to the day, month, and leap year cycle will either engage or be disengaged from those dial's output wheels, which are friction-mounted to their respective drive gears. If engaged, the dial hand remains stationary; if disengaged, the hand moves forward one position. The day detent is always disengaged at the beginning of the cycle. After the cycle is complete, all detent levers drop into the engaged position to hold steady the dial output hands throughout the day. This all takes place during the one second it takes for the controller to make a half revolution.
- 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 that indicates the month of December and the 31st day, the output for the lever is positive and the year counter is moved one step forward.
- All data pertaining to the leap year cycle, the number of days for each month, and all of the output seen in the calendar dials are fully reversible without any data loss.

Figures 110 and 111 encompass the calendar assembly's two dials for the day of the week and date readouts. The day readout is the simpler of the two. Monday through Sunday is a 7-day cycle that remains constant throughout the year, regardless of leap year cycles (Figure 110). The date readout is connected to the calendar calculator module, which

Figure 133. Rear view of calendar complication.

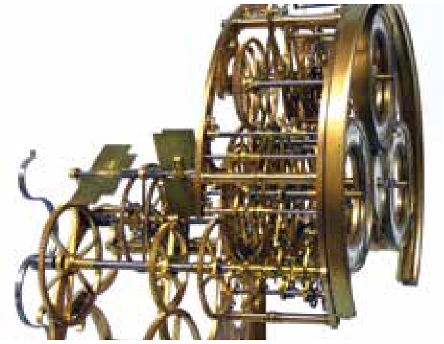

Figure 134. Front three-quarter view of calendar complication.

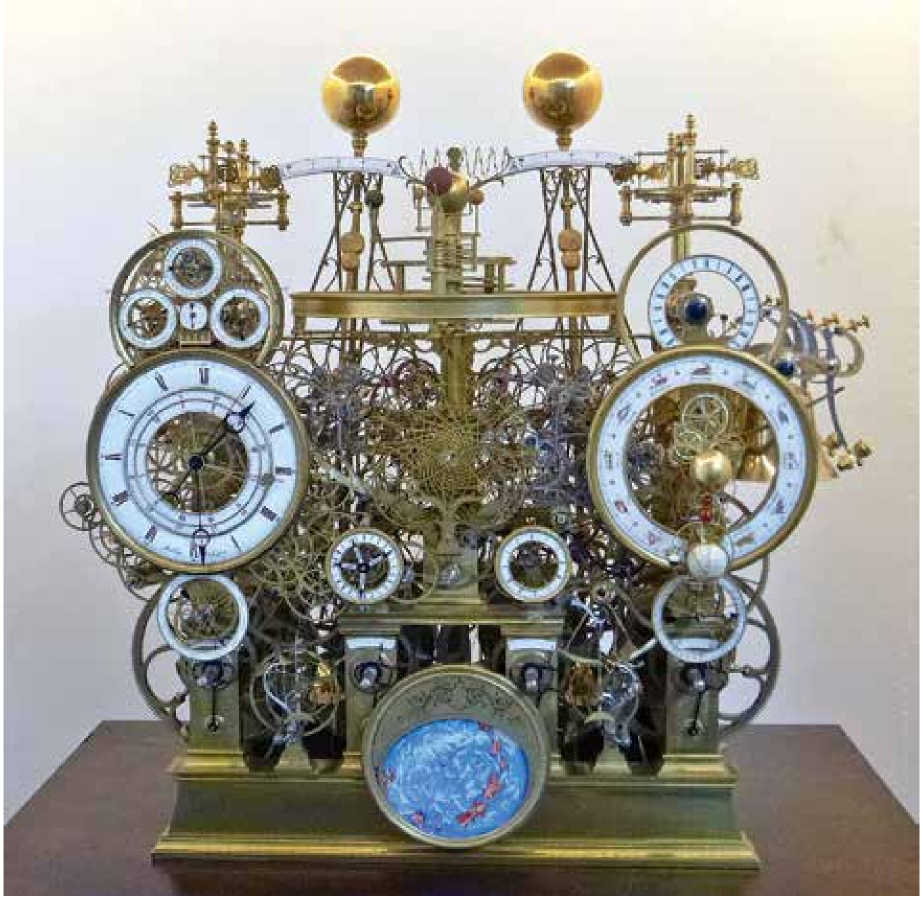

Figure 135. Front view of astronomical clock with mock-ups of remaining components yet to be fabricated.

Figure 136. Top left three-quarter view of astronomical clock with mock-ups of remaining components yet to be fabricated.

determines the number of days for each month (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 fully reversible without data loss.

Figures 112 and 113 show the month calculation. The calculator module controls the month trip, so February is tripped at the correct time according to the perpetual rules. The circled areas in the figures are the detection detent for the month.

Figures 114 and 115 concern the leap year dial and the year counter. The year calculation is the most complex, because it depends on the date and month calculations determined by the calendar calculator and the position of the month readout wheel. The circled areas in the upper right side of the figures are the first of month detection levers and the lower circled areas are the December month detection lever. When both upper and lower levers are actuated, input is allowed to the year readout. Why do we have this occur on the December stop and not the January stop on the month stepper wheel? The reason is we want all calendar functions to flip at midnight on December 31. 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 1.

These examples show the hierarchy in the complexity for determining the calendar readouts. The simplest is the day, unvarying throughout the year, not requiring adjustments. Next is the date, inextricably connected to the February cycle, requiring the use of the calendar calculator module. Next is the leap year, determined by the calculator module to give it perpetuity. And finally is the year counter, which will turn over only after all prior conditions for the year's signal are given on the basis of all prior data sets being met. Depicted in Figure 116 are a few calendar linkages. The compliment of logic linkages is shown with the front plate removed in Figure 117.

Skeletonizing the Calendar Plates

The design for the front plate dial cluster had been determined since the beginning of this project in 2006 and the enamel dial work completed since 2013. A few additional areas needed to be branched from the dial support plate rings to connect pivots. The plastic plate mock-up is shown in Figure 118. The final dial plate design in metal is shown in Figure 119.

The rear plate, however, was a blank slate. Figures 120 and 121 show the process used to design the decorative features for the plates. The open book in the center of the table with the sketch pad containing hand-drawn and handwritten work has a detailed photograph of the back interior of an antique pocket watch showing a fancy, skeletonized balance cock (Figure 120). The initial design begins to germinate in the drawing on the sketch pad in the lower left side. The front and rear blank brass calendar plates are on the lower right side. The first step was to determine the location of the each pivot and pillar hole (Figure 121). The object in the center is an outline of the front pillar of the time train to which the calendar assembly is affixed.

Figure 122 is the same drawing as shown on the sketch pad on the table in Figure 120. The initial design took 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 evolved into the organic ivy and spur design used throughout this project; the red dots are jewels (Figure 123).

Once more Buchanan used the trusty jeweler's saw equipped with binoculars to delicately cut the intricate pattern into the brass sheet and create his ornate design. This same tool cut all flat stock, from the frames to the thousands of wheel spokes, used in this project (Figure 124). Within this piece one can see the inspiration of a pocket watch balance cock as shown in Figure 112. The decoration for the rear mainframe is finished. All ivy appears to be growing just like a real plant from a single location at the 10 o'clock position from the center hub. Before the final polish, the entire piece will be further refined and hand-filed (Figure 125).

Will all this fit back together again? Yes it does (Figures 126 and 127)! The perpetual third-order reversible calendar is expected to be the most challenging and intricate of all the dozens of complications we will build into this machine, but it is central to the demonstration of all other celestial functions (Figures 128-134).

Figures 135 and 136 show the movement outfitted with mock-ups of the remaining components yet to be completed, 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, which represents the strike controller, which along with all 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. The enormous amount of wheelwork and framing incorporated into making the four drive trains and the strike control and repeat assemblies account for more than half the work.

Notes

1. Buchanan's website is http://buchananclocks.com and the firm can be reached at clocks@buchananesq.com.
2. Mark Frank, "An Astronomical Skeleton Clock," *NAWCC Bulletin*, No. 369 *(August 2007): 393-400.*
3. Buchanan's website is http://buchananclocks.com and the firm can be reached at clocks@buchananesq.com.
4. "The World Time Clock, Canary Wharf, London, Part 1," *Horological Journal* (July 2015): 297-300, and "The World Time Clock, Canary Wharf, London, Part 1," *Horological Journal* (August 2015): 348-350.
5. Doron Swade, *The Difference Engine: Charles Babbage and the Quest to Build the First Computer* (New York, NY: Viking, 2001), 118-121. The first complete Babbage Engine was completed in London in 2002, 153 years after it was designed.
6. The AND gate is a basic type of logic gate, which is the building block of a digital circuit. "Logic gate [AND, OR, XOR, NOT, NAND, NOR and XNOR]," Margaret Rouse, Whatis.com, accessed October 13, 2016, http://whatis.techtarget.com/definition/logic-gate-AND-OR-XOR-NOT-NAND-NOR-and-XNOR.

About the Author

Mark Frank runs a Chicago residential real estate management and development company.

His horological interests are in the research and collecting of timepieces where one can the mechanical works in particular skeleton clocks, tower clocks and bank vault timers. His main interest is in those pieces that exhibit interesting mechanical characteristics as demonstrated through complexity, novelty, or visual appeal. The clock which is the subject of this article is the culmination of many years of research, observations and examples drawn from his collection all combined into a personal fantasy machine. He has been an NAWCC member since 1993.

Updates on the project have been posted monthly at www.my-time-machines.net since its initial conception in 2003. Those interested in receiving email notifications when updates are posted should email Frank at mfrank1@rcn.com.