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 perpet-

ual 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.

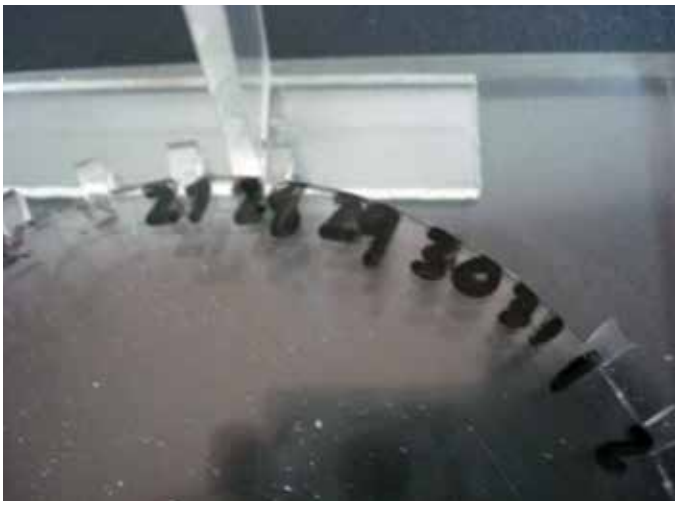


Figure 69. Detail showing days 29-31 missing.

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

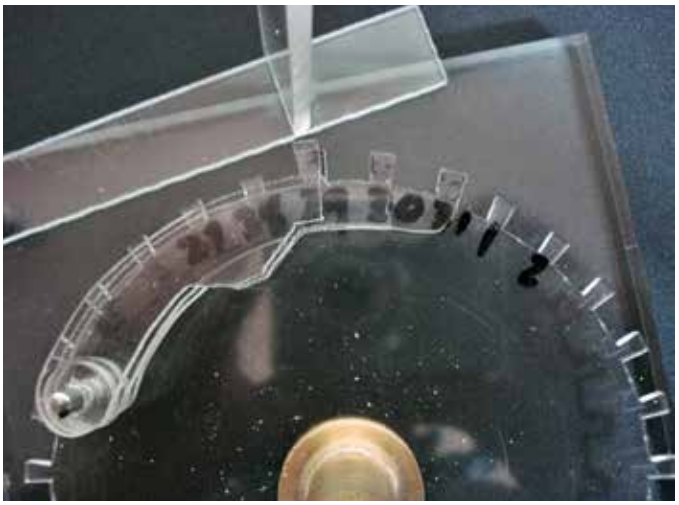


Figure 71. Surprise pieces over index wheel.

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

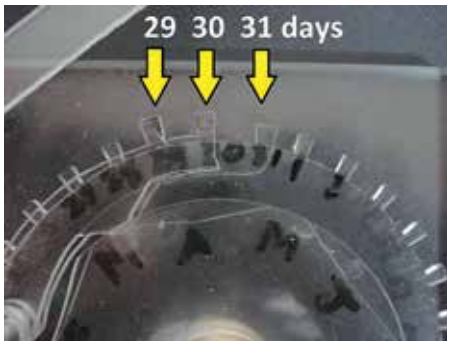


Figure 74. Arrows point to three raised surprise pieces, creating a 31-day month.

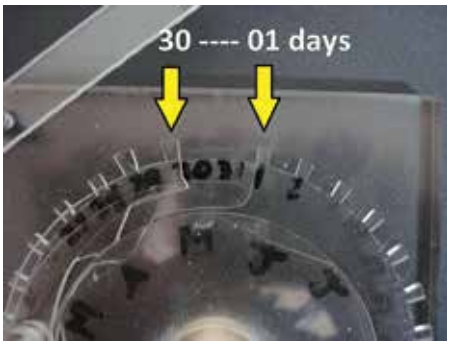


Figure 75. The surprise piece for Day 31 between the two arrows is lowered, giving a 30-day month.

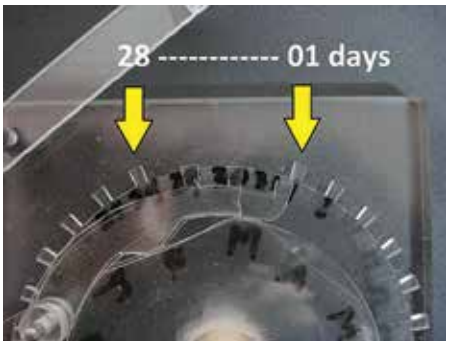


Figure 76. The surprise pieces for Days 29, 30 and 31between the two arrows are lowered, giving February 28 days.

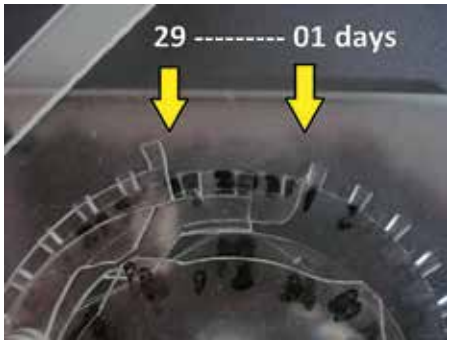


Figure 77. The surprise pieces for Days 30 and 31 between the arrows are lowered, giving February 29 days.

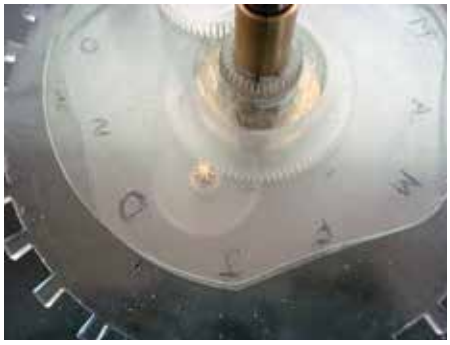


Figure 78. Cam with flat cut for February.

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.

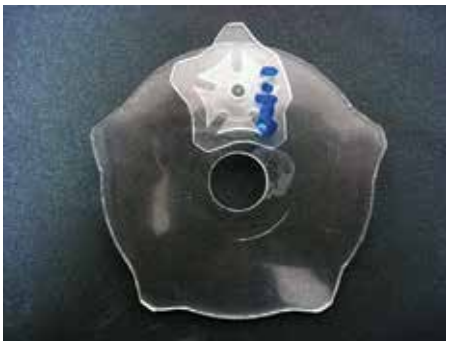


Figure 80. A 100-year correction cam.

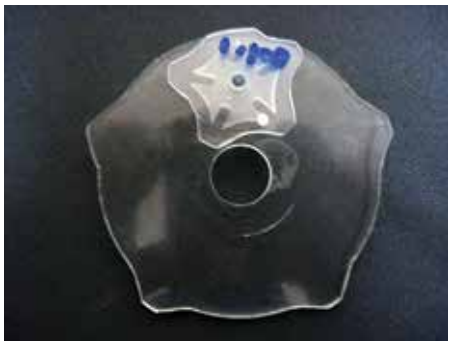


Figure 81. A 100-year cam at correction.

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.

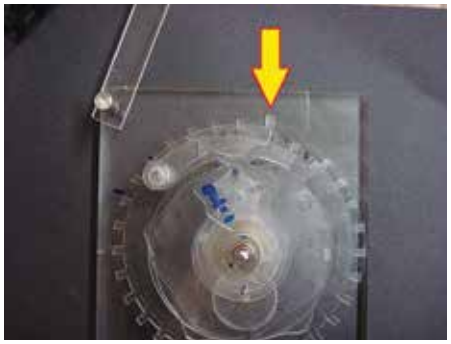


Figure 85. Cam making insertion of 29th day. Arrow points to February's 29th day.

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.

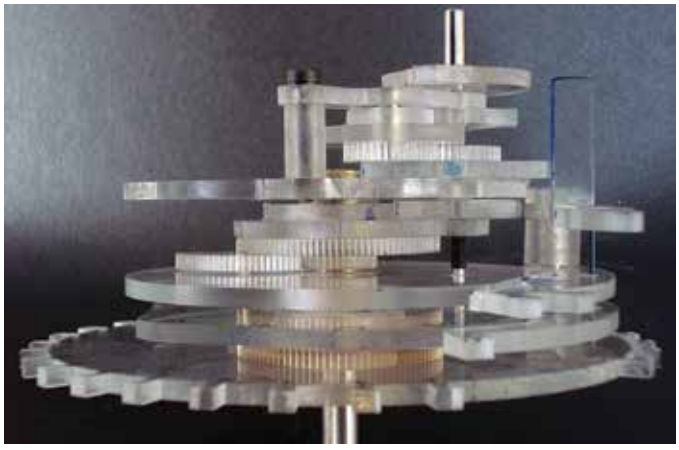


Figure 89. Edge-on view of perpetual calendar model.

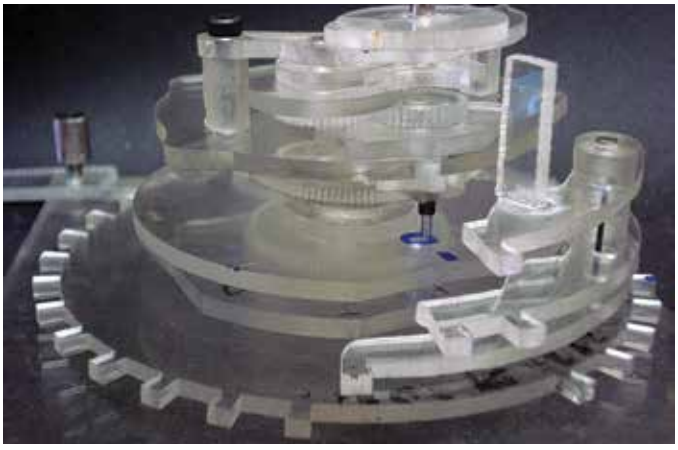


Figure 90. Three-quarter view of perpetual calendar module.

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.

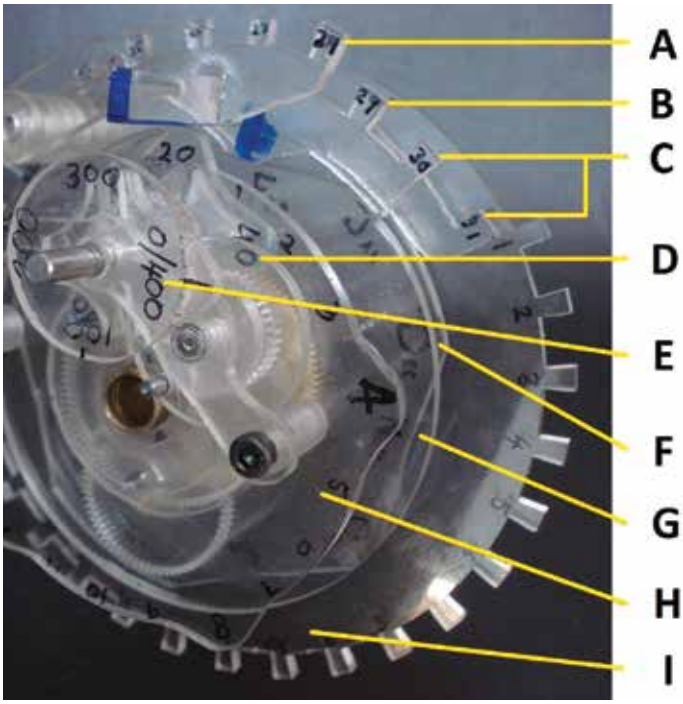
E. A 400-year cam inserts leap year once every 400 years.

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.



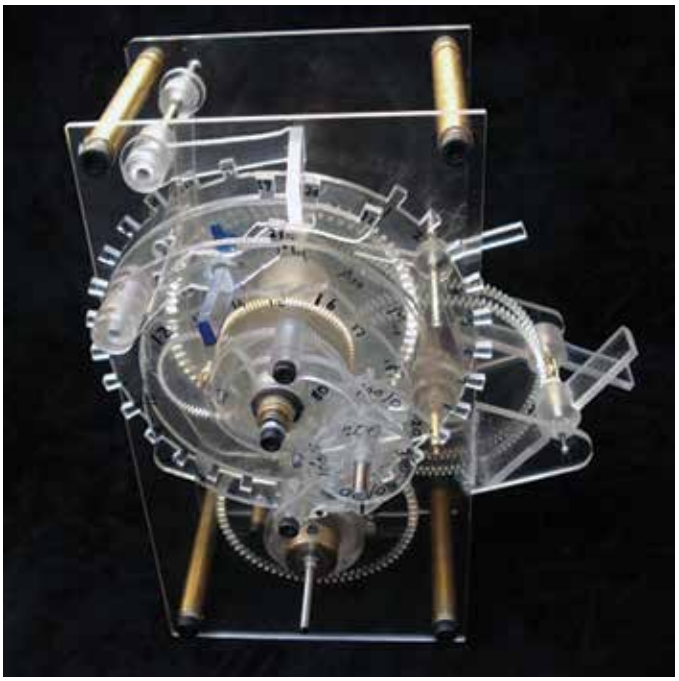


Figure 92. Front view of perpetual module with the calendar drive.

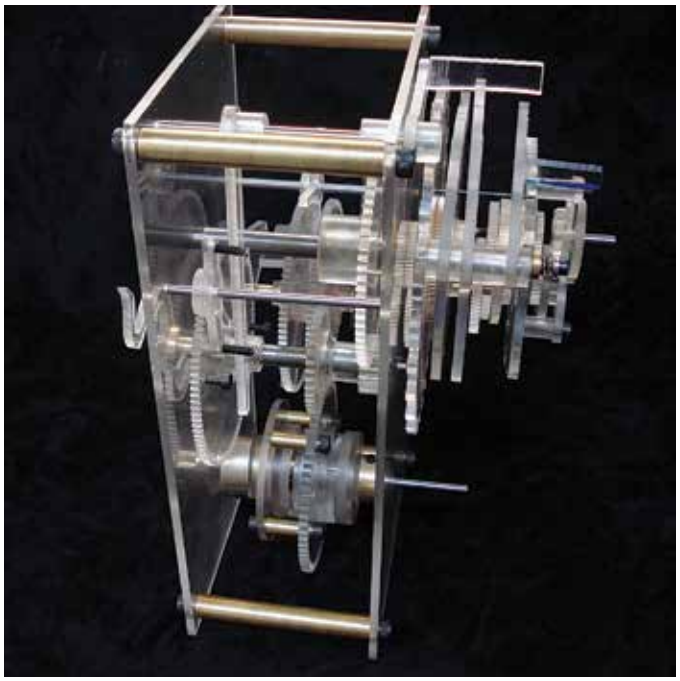


Figure 93. Side view of perpetual module with the calendar drive.

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.

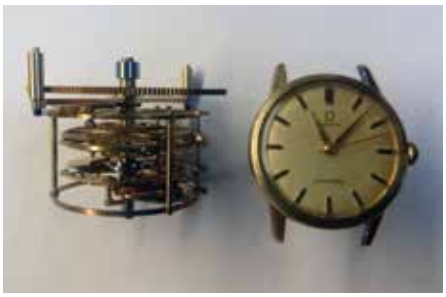


Figure 97. Side view of completed module. It is next to a wristwatch to show proportional size.

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

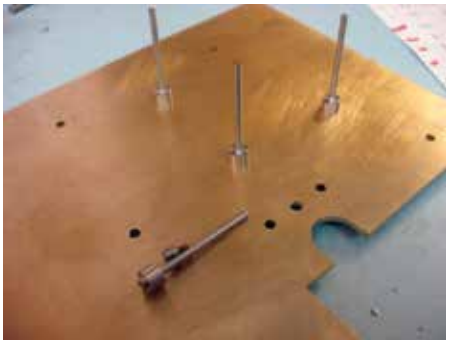


Figure 99. Arbor posts attached at only one end for dial wheels.

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.

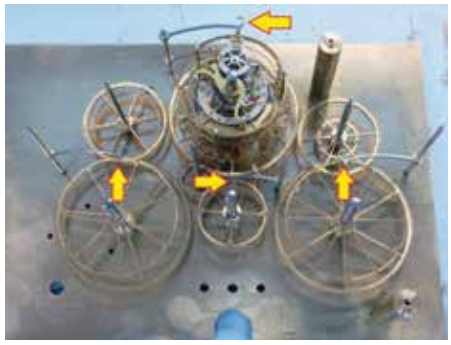


Figure 105. Date detent reader for the perpetual module.

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

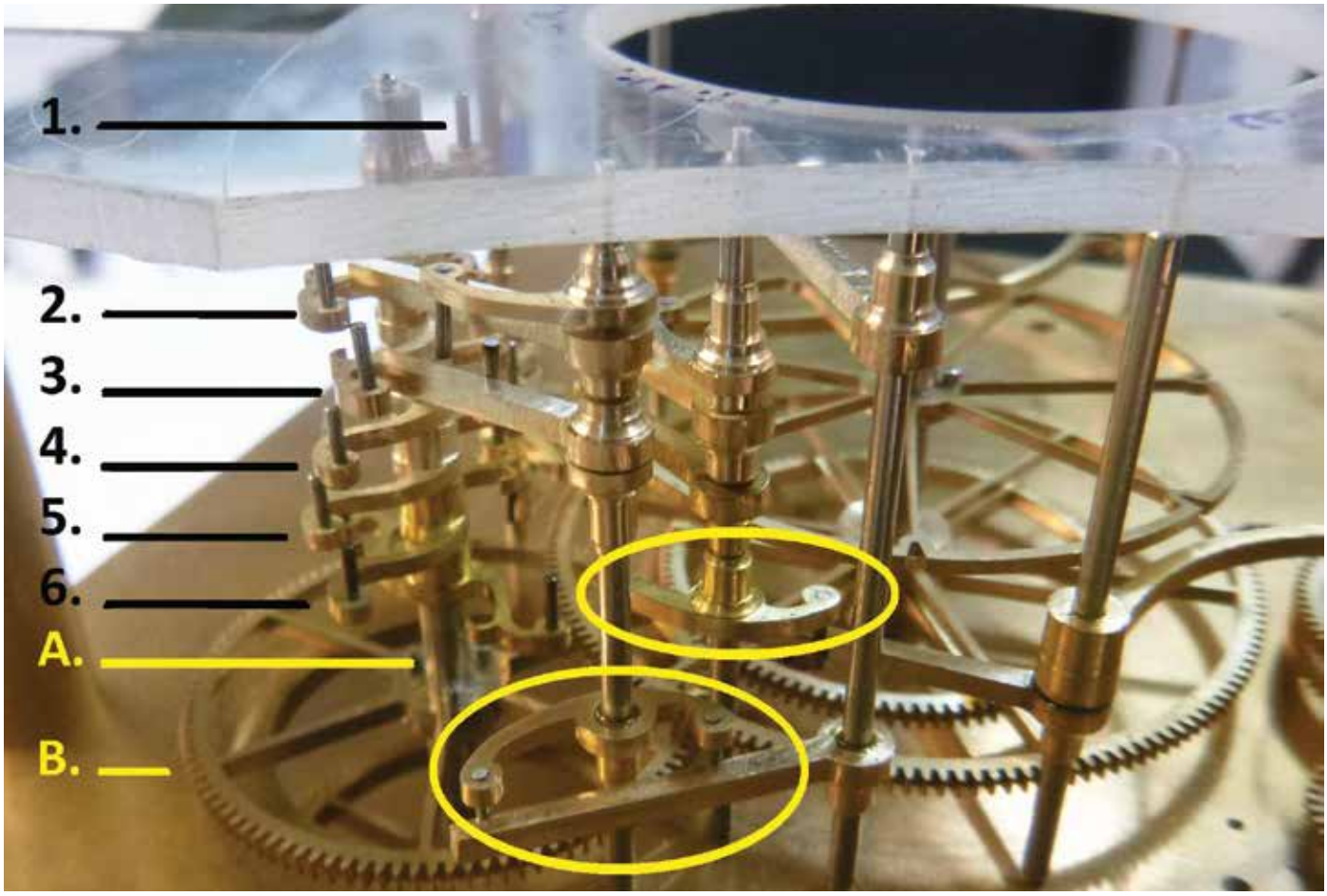


Figure 107. Analog clock controller for logic circuitry. Items numbered 1-6 point to the rotating time cam stack. The letter "A" points to the arbor and letter "B" to the drive wheel. The circled areas are two of three rocker assemblies.

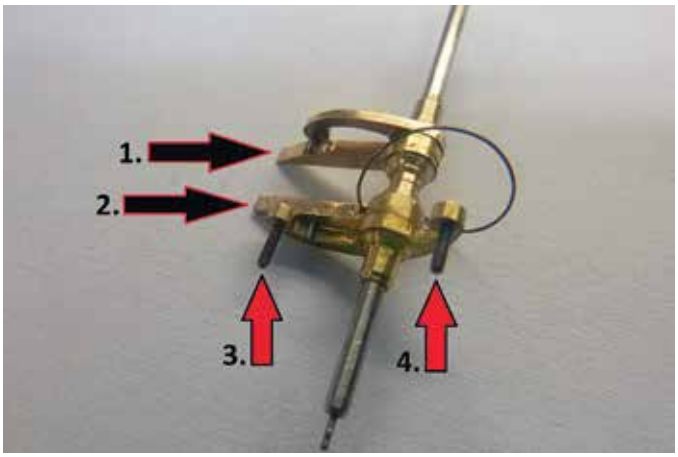


Figure 108. Lever rockers and one-way impulse paddles. Black arrows 1 and 2 point to the impulse paddles and the red arrows 3 and 4 to the pins.

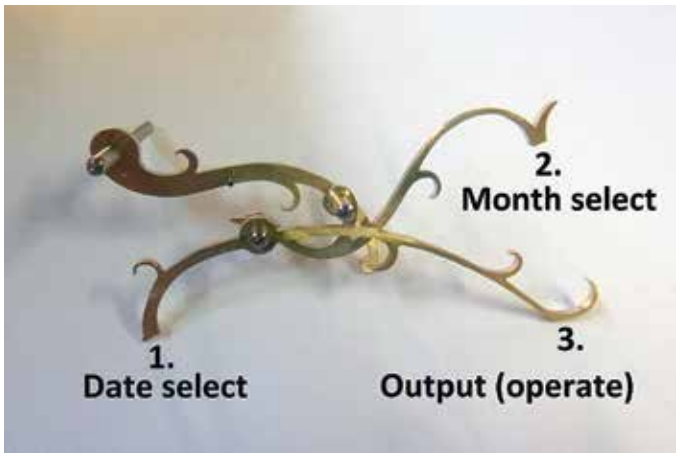


Figure 109. Logic lever functioning as an AND gate.

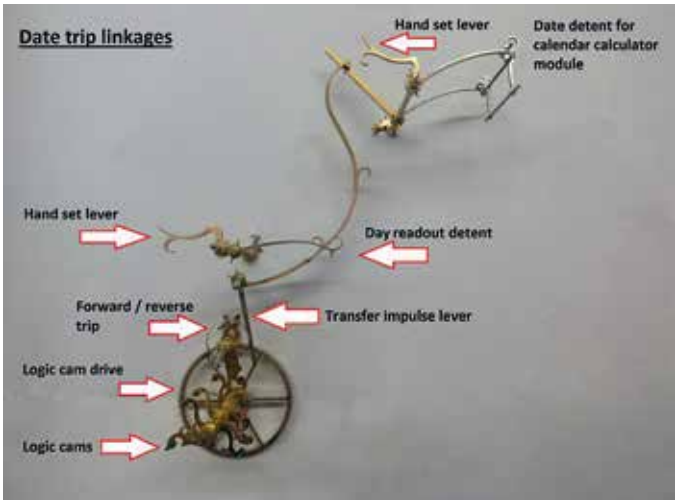


Figure 110. Day and date trip linkages.

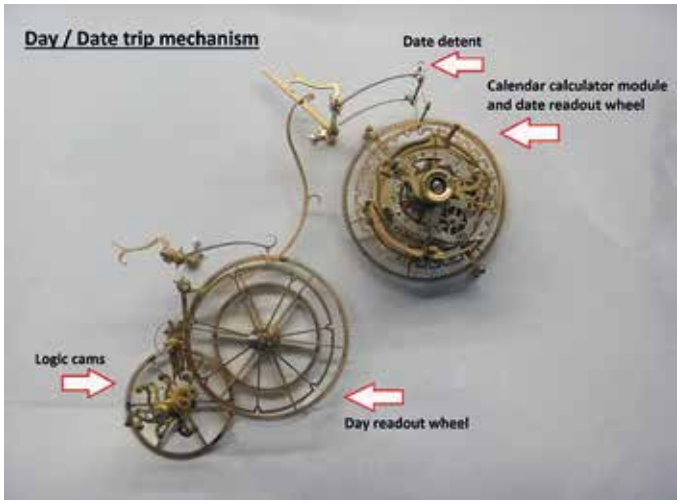


Figure 111. Day and date calculation mechanism.

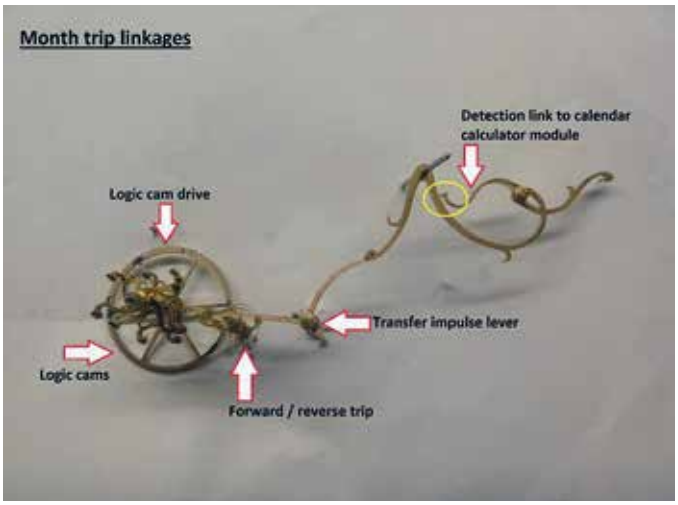


Figure 112. Month trip linkages.

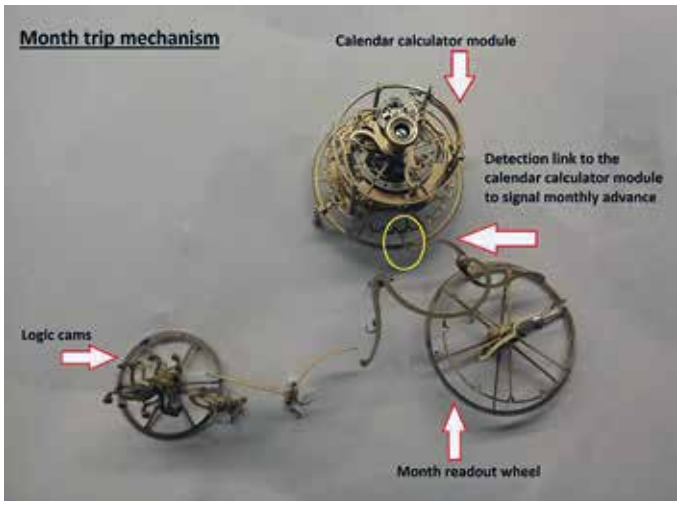


Figure 113. Month calculation mechanism.

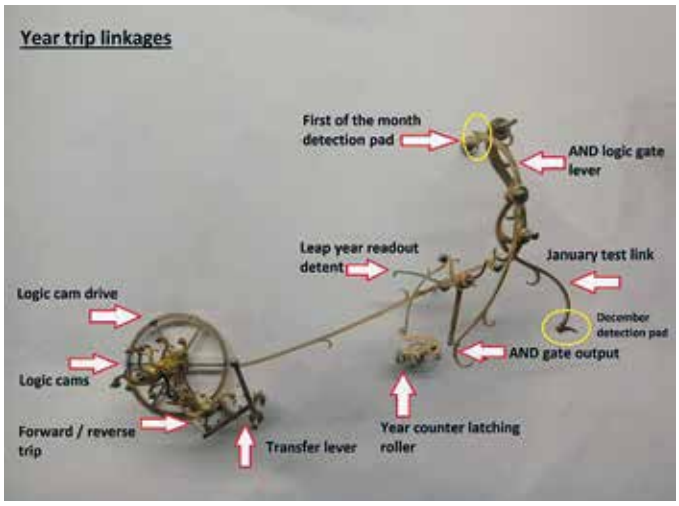


Figure 114. Year trip linkages.

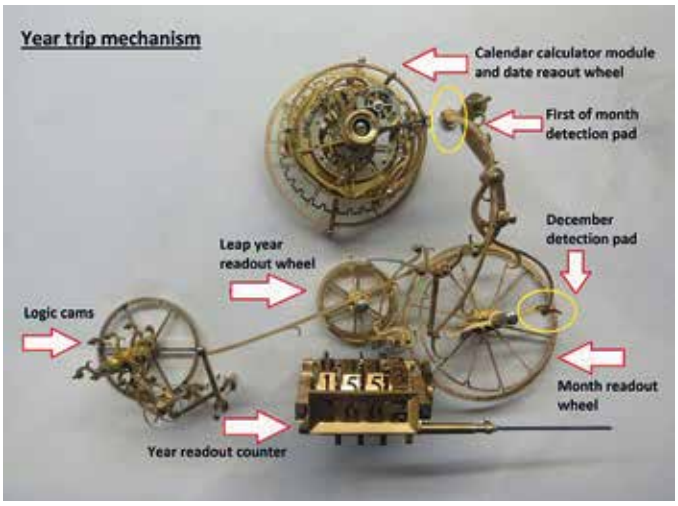


Figure 115. Year calculation mechanism.

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

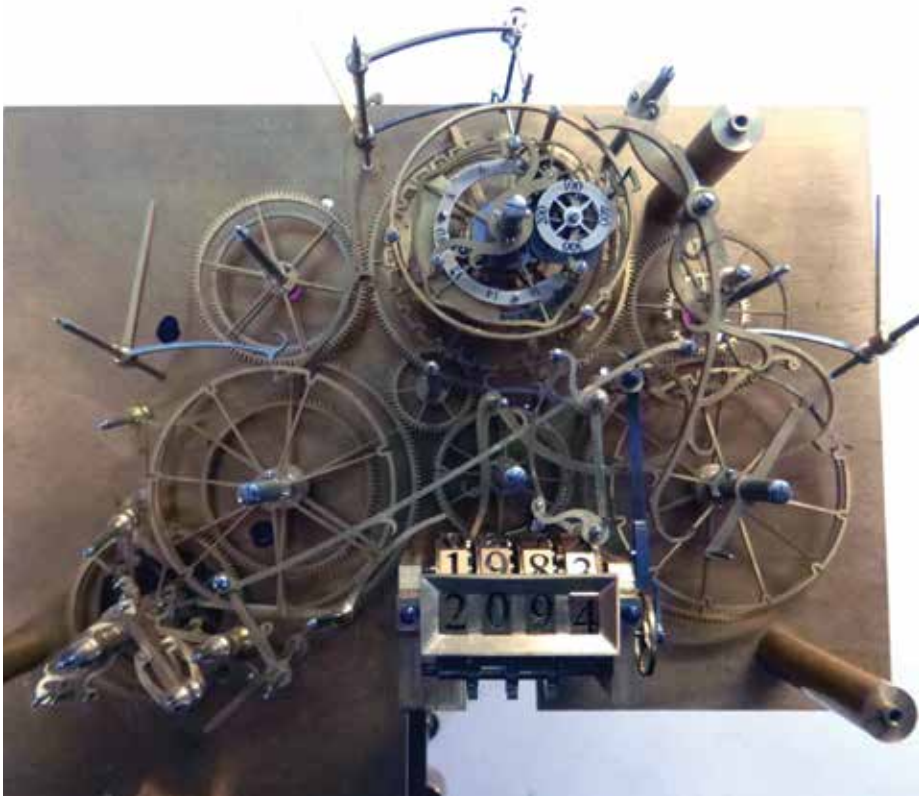


Figure 117. Complete calendar with front dial plate removed.

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

Figure 119. Skeletonized front dial plate.

Figure 120. Materials used for rear plate design ideas.

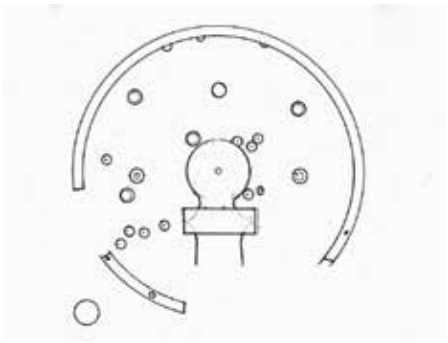


Figure 121. Initial drawing showing extant pivot locations.

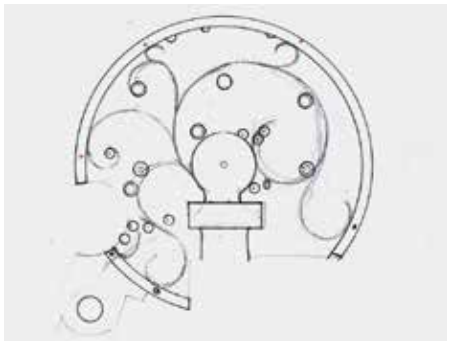


Figure 122. Early concept drawing connecting pivots.

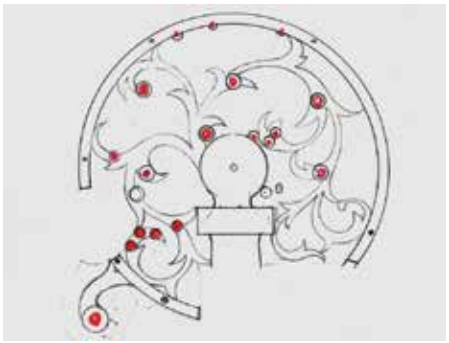


Figure 123. Rear frame design more fully developed.

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.

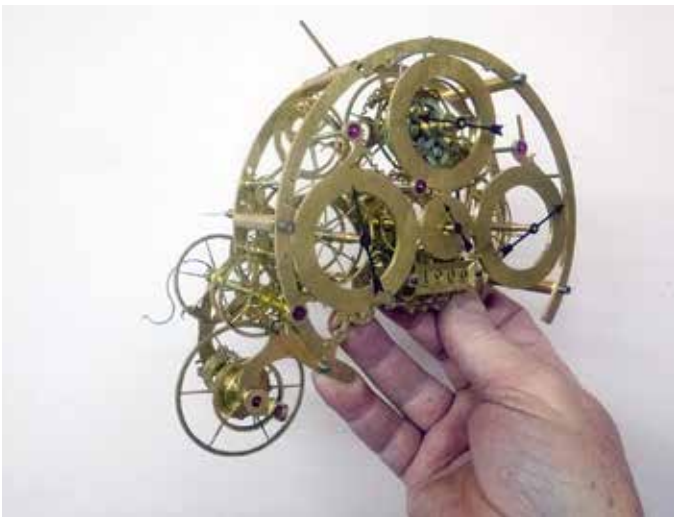


Figure 127. Completed calendar complication.

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.

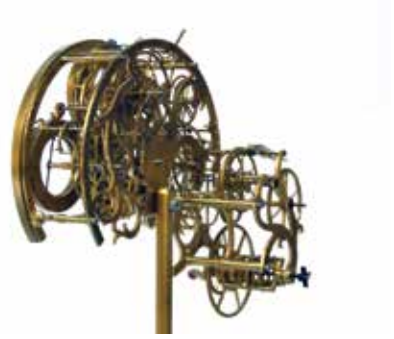


Figure 132. Rear three-quarter view of calendar complication.

- 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.

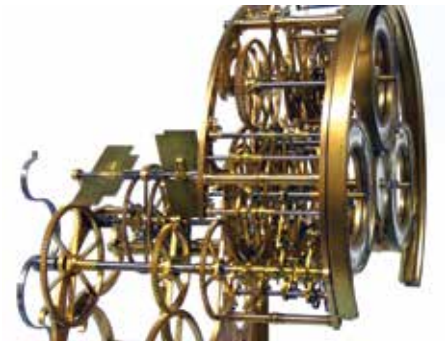


Figure 134. Front three-quarter view of calendar complication.

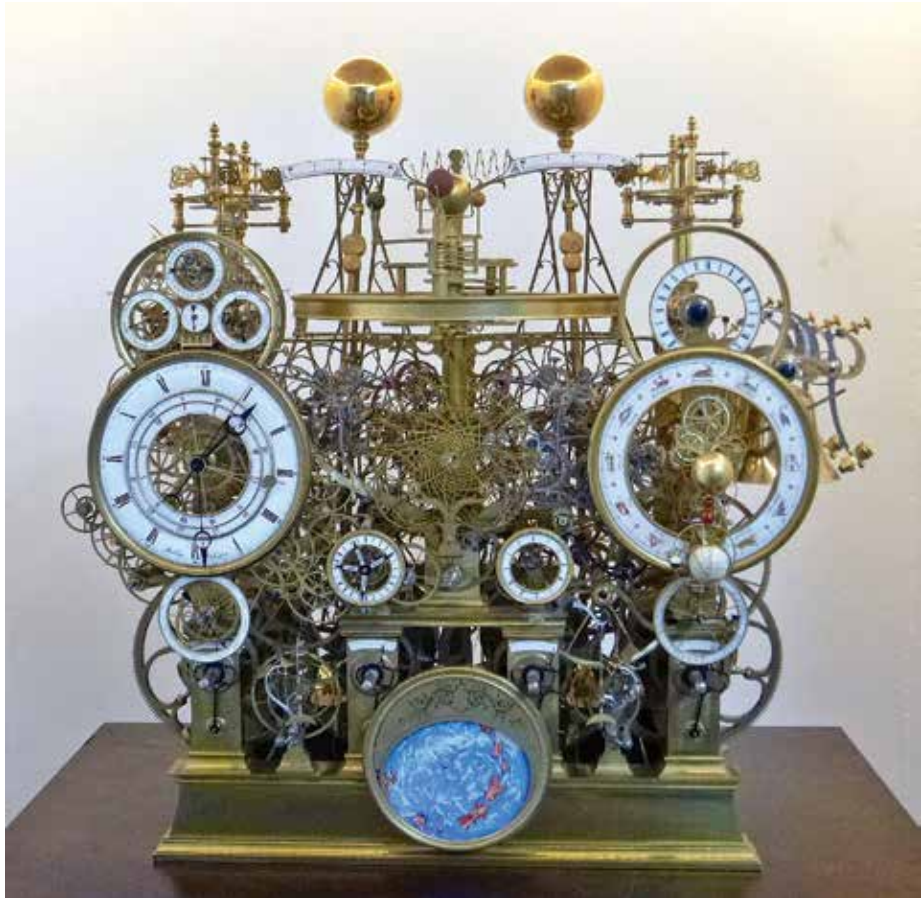


Figure 135. Front view of astronomical clock with mock-ups of remaining components yet to be fabricated.

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.