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# IMPROVING TELESCOPE DRIVE PERFORMANCE WITH MICROPROCESSORS

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1. The settling time required for damping oscillations in the right ascension axis has been reduced to 4 seconds.

2. Recent tests indicate that this system is sufficiently responsive to allow the low precision slew worm to be used for tracking. Thus, should the track worm fail, the slew worm could be used for backup.

3. The system now includes an RS-232 serial interface which connects directly into the R65/11EB chip. This allows:

   a) modification of feedback parameters without having to change the EPROM chip

   b) simplified transmission of digital waveforms to other computers for analysis and plotting.

   When used with an ordinary 1200 baud modem and dial-up line, feedback parameters can be altered and the results monitored remotely. This has been done successfully between Santa Cruz and Mount Hamilton.

4. A similar system, using identical hardware, has been installed on the declination axis. This system is able to reduce the settling time of this axis from 15 seconds to 4 seconds, as well as reduce pointing and tracking errors resulting from significant backlash in the tangent arm drive.

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## ABSTRACT

A microprocessor-based control system combined with modern incremental encoders has allowed Lick Observatory to make a valuable but inexpensive improvement in both the tracking performance and the dynamic response of the C. Donald Shane 3-meter Telescope. A modular addition was used to convert an existing open-loop telescope control system into a closed-loop system. A number of techniques for using standard astronomical instruments to calibrate encoders and measure telescope performance were developed as part of this effort. Both these techniques and the control system design may be of value in retrofitting other telescopes that were built without electronic tracking rate control.

## HISTORY

The Lick Observatory Shane 3-meter Telescope (see figure 1) was designed in the 1940s and built in the 1950s. At the time, it was the second largest telescope in the world. In those days, precision tracking was accomplished by very fine mechanical equipment, without recourse to electronic feedback. The right ascension drive of the telescope used two worm gears, a high precision one for tracking and a less precise one for slewing (see figure 2). Track, guide, and set motions were done using 13 separate AC motors coupled to the tracking worm by means of gears and clutches. Selsyn driven encoders with dial indicators were used to display telescope position. The telescope was controlled by electrical push buttons and relays. Observations were made mainly at the prime and coude' focii, and the observer provided fine guiding by watching the position of a star on a cross hair or on the slit of a spectrograph.

Lick has had a long tradition of improving instruments such as the Shane telescope whenever it is feasible. In 1969, Wampler led the installation of automatic cassegrain focus instrumentation, including one of the first uses of a sensistive TV camera for acquisition and guiding of objects to be observed. In the mid 1970s, Robinson and Melsheimer improved the precision of the telescope position readout by installing incremental encoders with 1 arc-second resolution on both the right ascension and declination axes. Soon afterward, Osborne and Ricketts installed stepping motors on both axes so that precise manual guiding and computer controlled offsets could be done. The installation of the incremental encoders allowed McKenna to collect data on telescope pointing errors which Rank used to develop a model of telescope flexure. Using this model, Kibrick developed pointing correction software that reduced pointing errors to less than 10 arc-seconds, a significant achievement for a telescope with several arc-minute flexure.

In 1982, the right ascension drive was further simplified by the installation of a microprocessor-based open loop telescope control system which produced guide, set, and track motions using a single stepping motor. This control system, called TELCO for short, employed the same design as that used at the Observatory's 1-meter Anna L. Nickel Telescope, which was built in 1979. This common control system was developed by Kibrick and Ricketts using partial funding from NSF grant AST 78-10172 to Robinson.

## THE PROBLEM: PERIODIC TRACKING ERRORS

For the past ten years, there have been intermittent reports of tracking errors of 1 to 5 arc-seconds that repeat at two minute intervals in the right ascension drive of the Shane Telescope. The two minute period was easy to correlate with the two minute rotation period of the worm gear, and was attributed to mechanical wear and misalignment accumulated over 25 years of use. Mechanical adjustments of the worm gave no lasting improvement, leading to the suspicion that the worm was damaged. Replacement of the worm was not desirable since it would be extremely expensive, and would require that the telescope be taken out of service for an extended period.

In an effort to get a direct quantitative readout of the tracking error, an inexpensive low-resolution incremental encoder was coupled directly to the polar axle. An up-down counter feeding a digital to analog converter (DAC) was used to compare the encoder pulse rate with an oscillator generated pulse rate. The oscillator rate was adjusted to match the pulse rate that the encoder would generate were there no periodic error. The low-pass filtered analog signal from the DAC was recorded with a pen plotter, and the result is shown in figure 3. Unfortunately, this signal is a composite of the two minute periodic worm gear error plus an error which is introduced by irregularities in the friction roller which couples the low-resolution encoder to the polar axle. This roller error has a 4.62 minute period and a 0.4 arc-second magnitude. Despite this complication, it was obvious that there was indeed a two-minute periodic error.

A higher precision incremental encoder was then mounted on the polar axle (see figure 4), and a small amount of hardware and software was added downstream from TELCO. These were used to remove the tracking errors by continuous adjustment of the rate of pulses fed to the stepping motor that drives the worm. The software and hardware techniques used for this major improvement are quite inexpensive, and may be of interest to others with similar problems.

## DESIGN OBJECTIVES

The Shane Telescope is scheduled for astronomical observations every night of the year and is taken out of service only for re-aluminizing the mirror. This required that the initial testing of the closed-loop system occur during the day, and that it not interfere with normal nighttime operation of the telescope. Because of this constraint, a major design objective was to minimize the modifications to the existing TELCO hardware and software.

Making the system fault tolerant was a related objective. The possibility that a malfunction in the closed-loop portion of the system could interfere with normal tracking and result in lost observing time was a major concern. The design used can detect a failure in any of the vital components and will automatically revert to the open-loop mode should such a failure occur. The open-loop mode, which still satisfies the needs of some observers, can also be selected by means of a manual switch.

A final objective was to make the system as general purpose and modular as possible so that it could be applied to other telescopes which use stepping motors for tracking. Although the components for this system were mounted inside the TELCO chassis, this was done more for economy and convenience than necessity. This system has only minimal electrical connections to TELCO, primarily for power and clock signals, and no software connection; the main TELCO software doesn't even know the closed-loop system is in place.

## IDEALIZED DESIGN DESCRIPTION

This design can be thought of as a post-processor which intercepts the pulse train that the open-loop TELCO system sends to the stepping motors, and substitutes its own modified version of this pulse train. The closed-loop system modifies the spacing between pulses (and hence the stepping motor speed) in response to feedback from the high precision incremental encoder mounted directly on the polar axle (see figure 5).

The closed-loop system can be visualized (see figure 6) as consisting of the following four components:

1. A device which measures the frequency of the incoming pulse train.
2. An up/down counter which uses the encoder pulses and the open-loop pulses as opposing inputs. Its contents represents the instantaneous position error.
3. A device which transforms the position error into a change in the frequency of the outgoing closed-loop pulses.
4. A device which generates the outgoing closed-loop pulses at the desired frequency.

There are a number of practical problems in implementing such an idealized system directly in hardware. First, the circuitry required for such a system is quite complicated. Second, in order for a simple up/down counter to reflect the position error accurately, the increment in position represented by each open-loop pulse and by each encoder pulse must be very nearly the same; otherwise, small incremental errors will rapidly accumulate and induce an error in the tracking rate. Since the size of these two increments is determined by two different mechanical couplings to the telescope, this condition would require more precise machining than was available. Finally, it is difficult to compensate in hardware for periodic errors introduced by imperfections in the position encoder and its coupling to the telescope. These errors proved to be significant.

## DESIGN IMPLEMENTATION

In an effort to avoid most of these problems, a microprocessor-based implementation was used. A Rockwell 6500/11 series (R65/11EB) single-chip microcomputer was selected (see figure 7). This chip contains a 1 MHz. 6502 CPU, 192 bytes of RAM, four 8-bit bidirectional I/O ports, four edge-detect lines, and two multi-mode 16-bit counter-timers. A 4-kilobyte UV erasable EPROM chip (2732 or equivalent), which plugs directly into the top of the R65/11EB chip, contains the program and data tables. The R65/11EB costs about $25 in small quantities, and is available in a 2 MHz. version as well.

The idealized closed-loop system illustrated in figure 6 is implemented within the microcomputer as follows:

1. Pulse Frequency Measurement

   The incoming open-loop pulses are counted for a fixed sampling interval (approximately 25 milliseconds) to obtain a rapidly updating but coarse measurement of the frequency. Each of these samples is then stored in a circulating queue. To obtain more precise measurements of the frequency, a longer sampling interval is achieved by computing a running sum over a window which contains the "n" most recent samples. The width of this window can be adjusted dynamically based on the magnitude of the changes observed between successive samples. The sampling interval is measured using one of the R65/11EB's internal 16-bit counters.

2. Up/Down Counter

   The up/down counter is implemented as a 5-byte quantity in RAM. Its content is a signed two's complement binary integer in units of 2**{-28} arc-second. Five bytes were used to provide sufficient dynamic range and precision to reduce incremental errors to neglible amounts. The scale factor of 2**28 was selected to align the binary point in the middle of the second most significant byte, making its least significant bit equal to 1/16th arc-second. Only the upper two bytes of this counter are used in calculation, while the lower three serve as precision guard bytes. Thus, the precision to which the system controls is 1/16th arc-second.

When a "West" pulse from the ENCODER is detected, the up/down counter is incremented by 2**28 times the ENCODER step-size in arc-seconds. When an incoming OPEN-LOOP "West" pulse is detected, the counter is decremented by 2**28 times the STEPPING MOTOR step-size in arc-seconds. For "East" pulses, the scenario is simply reversed, with encoder pulses decrementing and open-loop pulses incrementing.

Note that the ENCODER step-size and the STEPPING MOTOR step-size need not be the same, and this is usually the case. While it is difficult to precisely measure these step-sizes individually, it is simple to obtain a precise measure of their ratio, and that is what is important anyway. The measurement of this ratio is made at installation time by counting the number of encoder pulses obtained as a result of sending a very large number of pulses to the stepping motor.

The four types of pulses to be counted ("West" and "East" encoder pulses and "West" and "East" open-loop pulses) can be detected by means of the edge detect circuits provided by the 65/11EB chip. The various increments and decrements are performed in the interrupt service routines associated with each of these edge detect lines. Note that while the encoder puts out separate East and West pulses, the incoming open-loop pulses consist of a directionless pulse and a separate level indicating the direction of that pulse. Thus, while there is a separate interrupt service for the two types of encoder pulses, the open-loop pulses are handled by one routine, and it either decrements or increments the up/down counter based on the state of the direction level.

### 3. Transformation of Position Error into Change in Frequency

Since this transformation is done in software, a variety of control strategies, such as simple proportional control or error-rate control, are possible. The optimal strategy depends on the mechanical characteristics of the telescope to be controlled and on the stepping motor used to drive it. Table look-up provides a convenient means of implementing the selected strategy.

### 4. Output Pulse Generator

This was the easiest part to implement. A large look-up table in EPROM is used to convert a desired frequency into a pulse period, and this pulse period is loaded into the 65/11EB's second 16-bit counter timer (counter B), which is configured to operate in the asymmetric pulse generation mode. The output frequency (and hence the period) are updated at each 25 millisecond input frequency sampling interval. The use of a look-up table also allows the avoidance of frequencies which could induce stepping motor resonances.

## OTHER COMPLICATIONS

This design is relatively sensitive to small machining errors in the friction roller and ball-bearing assembly which couples the encoder to the polar axle. These errors cause the friction roller rotation to be eccentric, and thus distort the encoder's perception of the polar axle position. This introduces a new periodic tracking error which, depending on the degree of eccentricity, can be very significant. Following final machining, the friction roller was measured in its bearing assembly using a sensitive extensometer and was found to have a total indicated runout of about 0.0003 inches. This runout produces a periodic tracking error with a magnitude of 0.9 arcseconds peak to peak, which is not much less than the magnitude of the worm gear error. However, this roller error is fairly smooth and repeatable, and can be corrected by the software.

The eccentric roller motion alters the value of each encoder pulse so that the encoder step-size varies as a function of roller position angle. To eliminate the periodic error this introduces, the design is modified so that whenever an encoder pulse is detected, the up/down counter is updated not by a constant step-size, but by the step-size corresponding to the roller position angle. Since the roller is already attached to an encoder, and since this encoder has an index mark, the position angle is readily available. The only difficult part is making the initial measurement of encoder step-size versus roller position angle.

Once the encoder assembly was installed and the friction roller loaded against the polar axle, a number of strategies were tried to make this measurement. First, direct measurement of the roller surface was attempted using an extensometer. However, since the extensometer contacted the roller at only a single sharp point, these measurements were extremely noisy. Next, the telescope itself was used to measure the tracking error caused by the roller runout. A prototype version of the system, in which the encoder step-size was treated as constant, was installed. With this system in operation, photographic plates were taken of a star field on the equator trailed in declination at a rate of 0.5 arc-seconds/second. The resulting star trails were analyzed using a Grant Machine (which gives a digital measure of the center position of a line), and indicated a smoothly varying and repeatable error of the predicted magnitude.

A third strategy for measuring the roller error made use of the original low-resolution encoder that was mounted on the polar axle. With the same prototype system in operation as was used to take the plates, the position angle of the high-precision encoder roller was recorded simultaneously with the output from the low-resolution encoder. The signal obtained from that encoder is a composite of the error due to the run out of the high-resolution encoder roller plus the error due to the run out of the low-resolution encoder roller. Since these two rollers have different radii, the errors associated with each have different periods (8.13 minutes and 4.62 minutes). Fortunately, these periods are not multiples of each other, reducing the hazard of aliasing. The error signals from each roller were approximated by sinusoids, and using a non-linear least squares fit routine in which the phase shifts and amplitudes were free parameters, the two signals were separated. The advantage of this technique is that it doesn't require nighttime observing, and that unlike photographic plates, the measuring time is not limited.

The third strategy produced results that were consistent with the plate data. Based on these results, a look-up table that maps roller position angle into encoder step-size was produced and stored along with the other data tables in the piggyback EPROM chip. Note that this approach provides for future maintenance of the system. Since these measurements are easy to perform, they can be repeated periodically to check the roller for wear. If these new measurements indicate significant changes, a new look-up table is easily produced and reprogrammed in the EPROM.

Having mapped and corrected for the error introduced by the encoder roller, the up/down counter now reflected the actual error in position of the polar axle. By monitoring its contents while the correction mechanism was disabled, an undistorted picture of the worm gear error was obtained (see figure 8). It clearly shows that the period is two minutes, but that while periodic, the error is far from sinusoidal.

A version of the system containing the map of the encoder step-size is now in routine operation at the Shane Telescope. It effectively eliminates the periodic error without introducing any significant new sources of error. Short term tracking errors are now reduced to under 0.15 arc-second.

## SIDE BENEFITS - IMPROVED DYNAMIC RESPONSE

While elimination of the worm gear tracking error was the primary goal of this system, it has proved to be a useful tool both for studying and improving the dynamic response of the telescope. To aid such studies, one of the four 8-bit I/O ports on the R65/11EB chip was reserved for diagnostic output. It can be used to monitor in real-time the value of any of the variables in the program. By connecting this port to an 8-bit DAC which feeds a chart recorder, plots of telescope position and velocity errors can be obtained easily and inexpensively. This provides the ability to empirically adjust parameters of the feedback loop and to have immediate quantitative measures of the effect of the adjustment. For more detailed analysis of these signals, the digital output can be directly recorded by one of the data acquisition computers.

Accurate measurements of a number of important telescope parameters have been made using this system. One such parameter, the resonant frequency of the right ascension axis as a function of telescope declination, had an important effect on the selection of gains and delays in the feedback loop. This frequency was found to vary by a factor of 2.5 between the equator and the pole. This change results from the moment of inertia about the polar axis being much higher when the telescope tube is perpendicular to the fork (equator) than when it is parallel (pole).

The closed-loop system has also improved the dynamic response of the telescope. Previously, the telescope would oscillate in right ascension for a period of up to 20 seconds if it were hit by a gust of wind, or if its position were rapidly changed, such as in offsetting to a guide star. Although this closed-loop system was not originally designed to damp out such oscillations, it is currently able to reduce the settling time by at least a factor of two. Work is currently in progress to optimize the feedback loop to provide faster damping of these oscillations, with the hope that the settling time can be reduced to 2 to 3 seconds.

However, before investing further effort in improving the dynamic response of the system, it seemed advisable to determine the torsional stiffness of the polar axle. It was conceivable that the base of the polar axle could twist a significant amount relative to the telescope optics. Since the encoder is mounted at the polar axle base, the oscillations that were measured with this system were those occuring at the base, and not necessarily those occuring at the telescope optics. Thus, improving the dynamic response of the feedback loop might not significantly reduce the settling time of a star image.

The correlation between oscillations at the base of the polar axle with oscillation of the optical image was measured using a 500 row by 500 column CCD, each pixel of which covered a 0.71 arc-second square of sky. A bright star on the equator was trailed in declination across the CCD at an effective rate of 10 CCD rows per second. As the image entered the CCD's field of view, the telescope was moved in right ascension in order to induce an oscillation. At the same time, the output from the closed-loop system's up/down counter was recorded to obtain a record of the oscillation occuring at the base of the polar axle. Comparison of the two records indicates that the polar axle is reasonably stiff relative to the stiffness of the drive, and that damping of the oscillations at the polar axle will also damp out the corresponding oscillations at the image plane.

## LIMITATIONS

Since the open-loop pulses and encoder pulses are counted by interrupt service routines, the maximum pulse rate that this design can handle is limited by how fast the microprocessor can service interrupts. Typical interrupt service time is on the order of 100 microseconds or less using the 1 MHz. version of the R65/11EB chip, so that pulse rates of a few kilohertz are manageable; switching to the 2 MHz. version would double this range. In the open-loop TELCO system, the maximum stepping motor pulse rate is 1800 Hz. at top set speed (this corresponds to a set rate of 45 arc-seconds/second), so this constraint was not a problem. However, new stepper motors and drivers are available which operate at step rates in the 20 to 30 KHz. range; the design as implemented could not function with such motors.

When the telescope is slewed, the pulse rate from the polar axle encoder reaches almost 60 KHz., which would saturate the microprocessor with interrupts. However, this isn't a problem. Because a separate motor and worm gear are used for slewing, the stepping motor used for tracking is de-clutched from the telescope, and as a result, the control system has nothing to control while the telescope is slewing. During the slew, the pulses from the polar axle encoder could be ignored were it not for the need to keep track of the position angle of the encoder roller. To allow the microprocessor to maintain the roller position, the encoder pulses are routed through a divide-by-1000 counter during slew, and each of these pulses updates the roller position by 1000 ticks. This reduces the interrupt rate from the encoder pulses to a manageable 60 Hz.

# ACKNOWLEDGEMENTS

This system represents the work of many individuals. Jack Osborne designed the mechanical hardware, which was built by the Lick Instrument Shop. Terry Ricketts designed the electronics, which were assembled by the Lick Electronics Shop. Special thanks go to Lloyd Robinson, who initiated the project and guided its design, to Burt Jones, who shot the photographic plates, and to Richard Stover, who assisted in separating the roller errors and performing the CCD observations. This work was partially supported by NSF grant AST 78-10172.

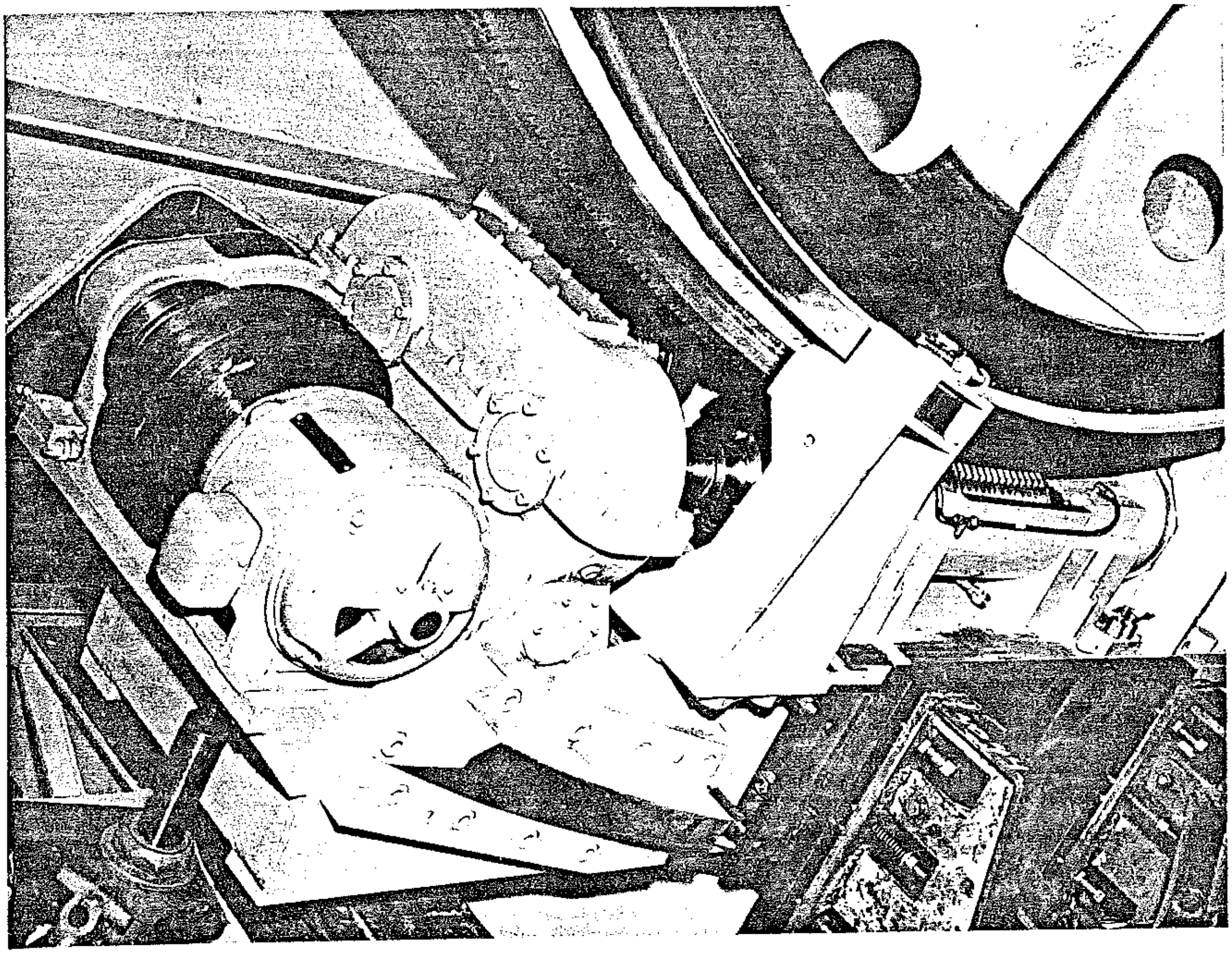


Figure 2. Worm gear and wheel assembly at base of polar axle.

Note the two separate sets of gears, one for slewing and one for tracking, setting, and guiding. The slew motor and flywheel are the left side of the picture. This 1955 photograph was taken from the area now occupied by the Coude' slit room.

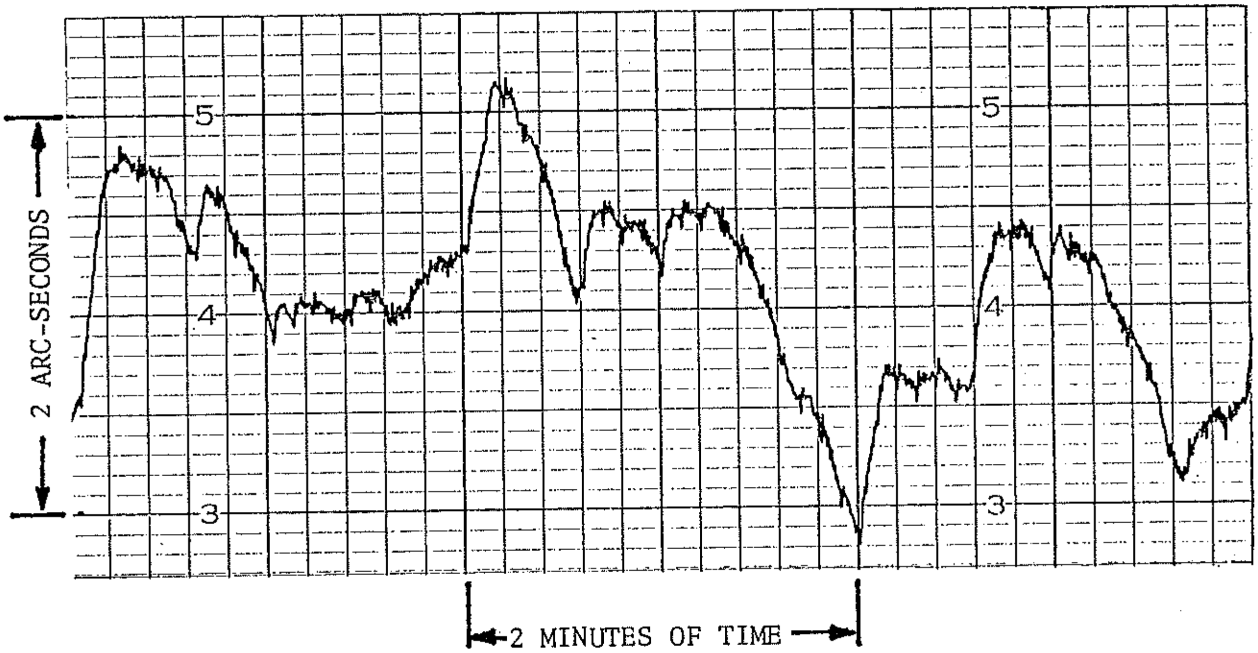
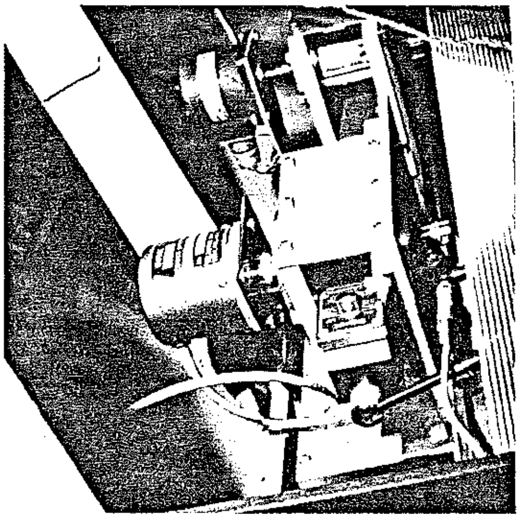


Figure 3. Plot of telescope tracking error versus time.

Signal measured using low-resolution encoder and includes errors introduced by irregularities in the encoder roller.

Figure 4. Incremental encoders mounted at base of polar axle.

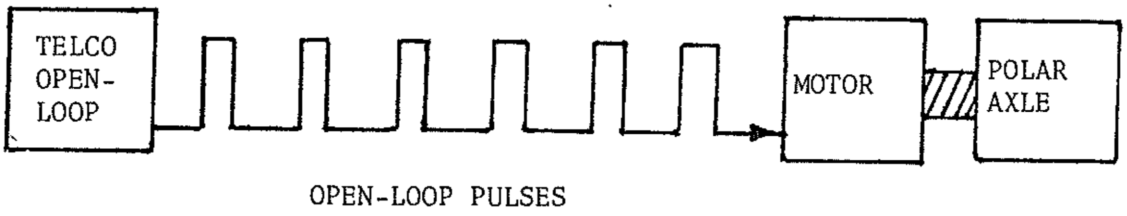


High-resolution encoder in foreground is Teledyne-Gurley model 8626 with 144,000 counts per revolution. It is coupled by a 0.7749 inch diameter friction roller to a machine surface on the 137.25 inch diameter polar axle. This provides a ratio of 177.12:1. An extensometer probe is shown attached to this roller for runout measurement.

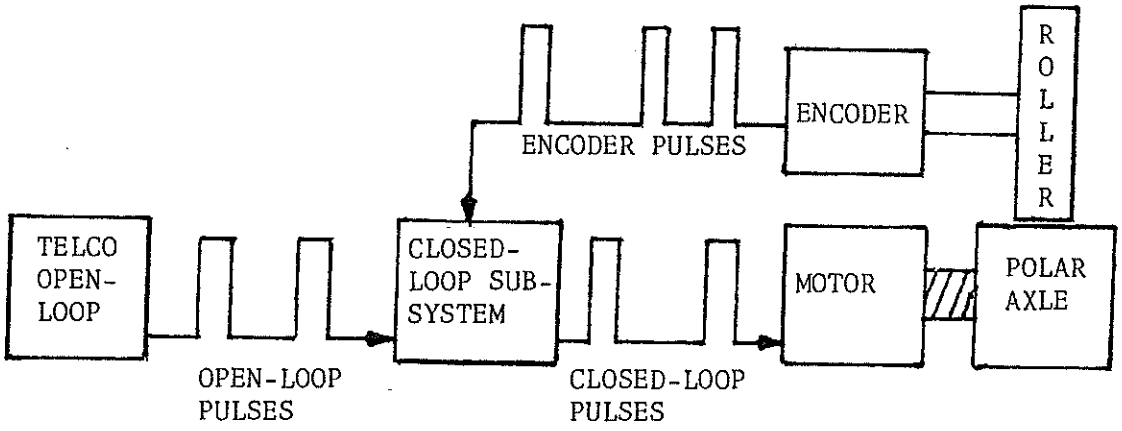
Low-resolution encoder in background has 10,160 counts per revolution and is coupled by a 0.4402 inch diameter roller.

The worm wheels are underneath the shroud at the right edge of picture.

Figure 5. Comparison of open-loop and closed-loop design.



OPEN-LOOP SYSTEM



CLOSED-LOOP SYSTEM

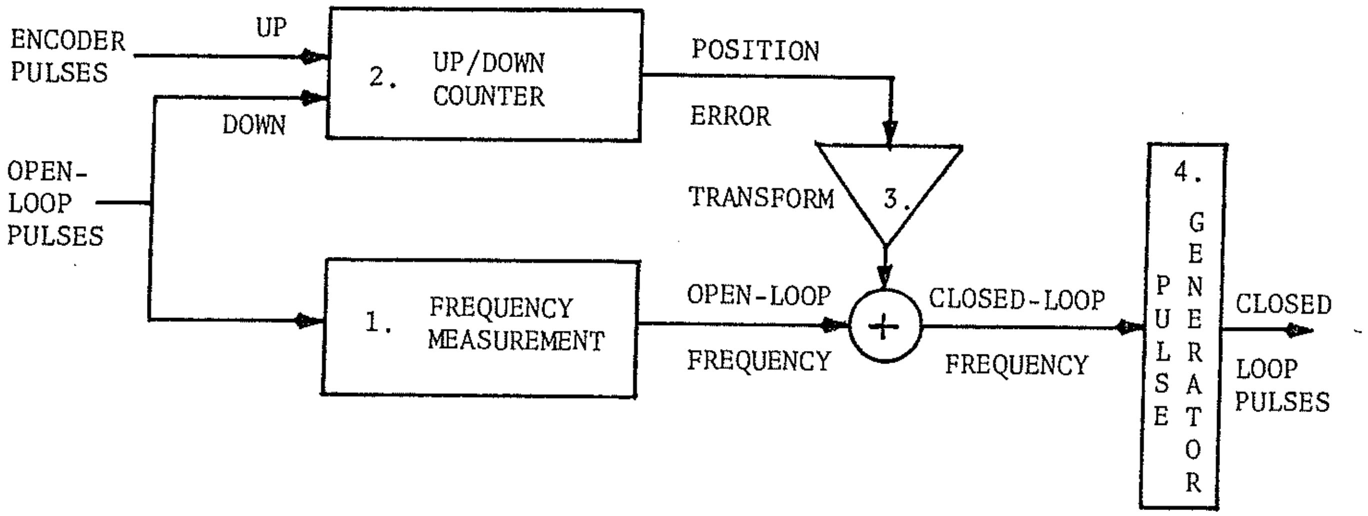
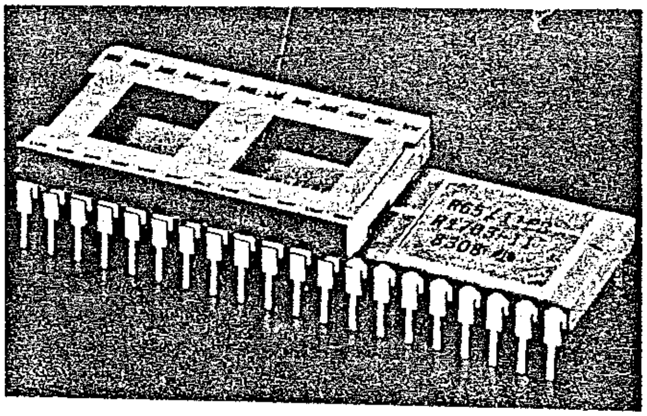
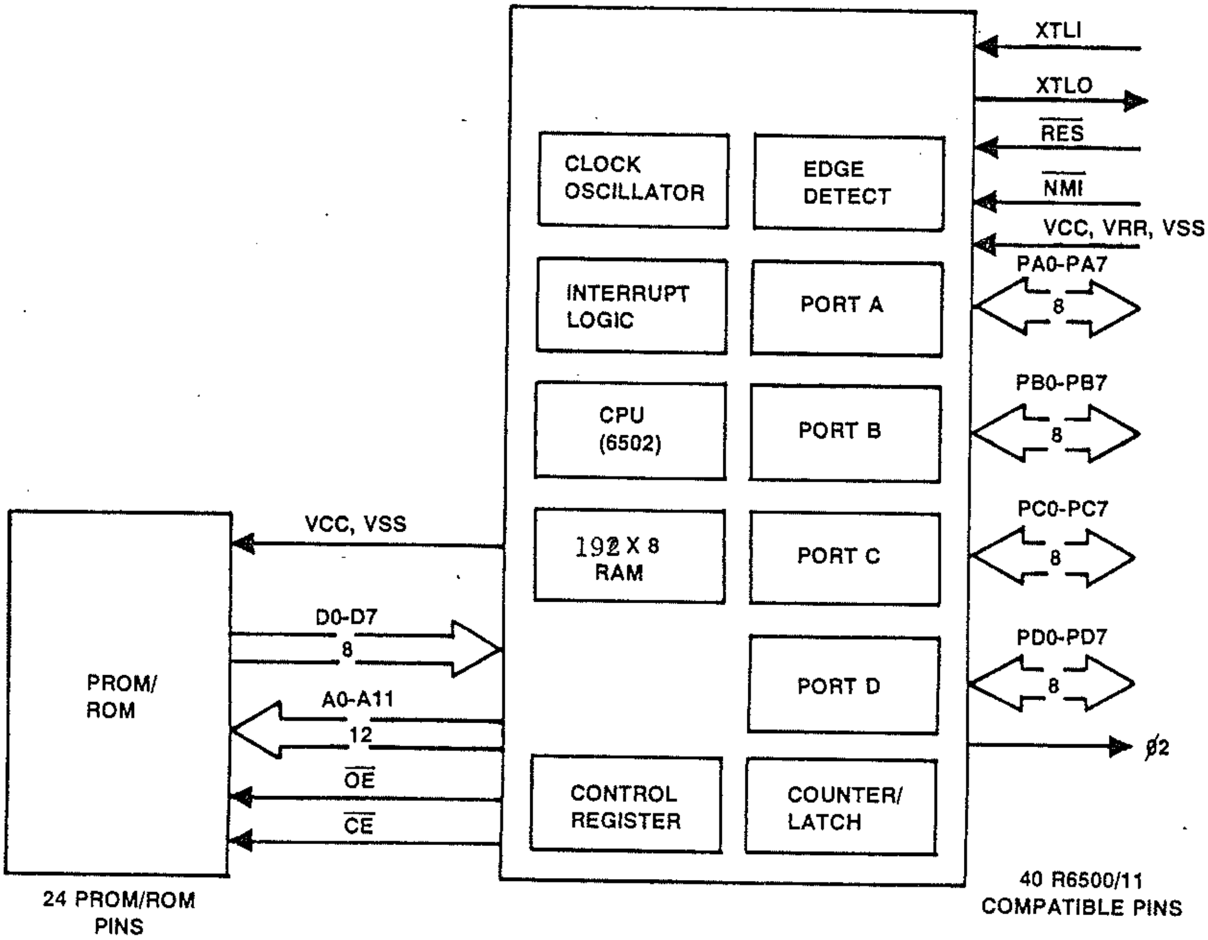


Figure 6. Idealized design of closed-loop system

Figure 7. The R65/11EB microcomputer





R65/11EB Interface Diagram

Figure 8. Repeated plots of telescope tracking error versus time

Signal measured using high-resolution encoder after removal of roller runout error.

Repeated pattern shows signature of worm gear error.