The Automatic Control of Large Optical Telescopes

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INTRODUCTION

The aims of the automatic control system are to position the mechanical axis of the telescope to specified right ascension and declination coordinates, and to track the right ascension axis smoothly at sidereal rate, atmospheric refraction variations being taken care of by an auto-guider. The design problems involved fall naturally into two groups, the mechanical ones of measuring the rotations of the axes and of applying drives to these, and the electronic ones of providing supervisory control and calculation facilities.

Solutions to these problems depend to a large extent on whether automatic control is being added to an existing telescope with existing drive systems, or a new telescope design is being carried out with automatic control in mind, and on whether an on-line process control computer is to be incorporated or not.

THE MEASUREMENT SYSTEMS

Since the angular position of the mechanical axes will be required to an accuracy in the range 1 to 10 arcsec, or 1 in 10^6 to 1 in 10^5, a digital method of measurement is essential, and should be applied as near to the axis as possible, normally at the final shaft of the drive system, to avoid errors due to backlash and compliance. Three possibilities present themselves—a 19 or 20 bit shaft encoder, a radial grating moiré digitizer, and, if a large diameter ring is available on the telescope axis, a wrap-around technique using an etched stainless steel tape linear grating in a moiré reflection mode. The shaft encoder has the advantage of providing an absolute indication of angle, as against the moiré systems which, being differential in operation, require some form of datum system to synchronize the following counter. However, shaft encoders with sufficient bits are not readily available, whereas a design for a radial digitizer using a 254 mm diameter grating, giving 360 degree measurement to an accuracy of 3.6 arcsec with built-in datum facility, is in existence and has been successfully employed in control systems on radio telescopes in France and Germany. This digitizer is a self-contained unit having its own bearings and is driven through a specially designed coupling having a high torsional rigidity. The radial grating and associated reading unit may however be built directly into the telescope, as has been done on the twin 16-inch telescope at the Royal Observatory, Edinburgh. The wrap-around system is also a proved technique. In this case resolution is limited only by the radius of the ring on which the grating is mounted and by the quality of the bearings. Accuracy problems can however arise, due to imperfect concentricity of the mounting surface and uneven tension in the tape, but these can be calibrated out, particularly if an on-line computer is employed, since it is a high order of repeatability rather than absolute accuracy that matters.

The main problem that arises with an existing telescope is in finding suitable places to mount the measuring units. With a new telescope this can be taken care of at the design stage.

THE DRIVE SYSTEMS

In applying servo drive to an automatically controlled system the main requirements are a high drive stiffness and a high efficiency. The former leads to the possibility of applying a high servo loop gain with stability, to give good tracking accuracy, and the latter leads to economy in expensive servo power and a low level of undesirable heat production.

Drive stiffness is improved by avoiding application of the torque at a point remote from the centre of mass, as this could induce torsional oscillations under acceleration conditions. The weight load in the case of the polar axis is also best supported near the centre of mass. Plain bearings are a simple solution to the support problem, but the resulting high friction would reduce efficiency, and so a hydrostatic bearing is a better answer. It also has an adequate stiffness.

The requirements of tracking at sidereal rate with as constant a velocity as possible, and slewing at about 45 degrees per min with acceleration limits, lead to a velocity ratio of about 180 : 1. This raises the problem of whether to use one motor for both operations or to have separate motors for tracking and slewing. The use of two motors would probably be less costly in terms of driving amplifiers and servo motors, since the slewing control would only have to be rather crude to limit accelerations. This scheme would however involve a more complicated and more costly gearbox design, with clutches or gear change systems which are liable to introduce backlash. The use of a single servo motor is therefore favoured.

The requirements for the motor are that at tracking rate it should develop the required torque at a relatively low speed, and that under slewing conditions it should supply a much larger torque during acceleration and, if the drive is efficient, during deceleration. During steady state slewing speed the torque is likely to be little more than the tracking torque, but the motor is now required to run under control at a speed about 180 times faster than tracking rate. The peak power output is demanded while still accelerating just before maximum slewing rate is reached. The motor size is therefore dictated by the need to run at slewing speed and to deliver accelerating torque, friction and out of balance load torques.

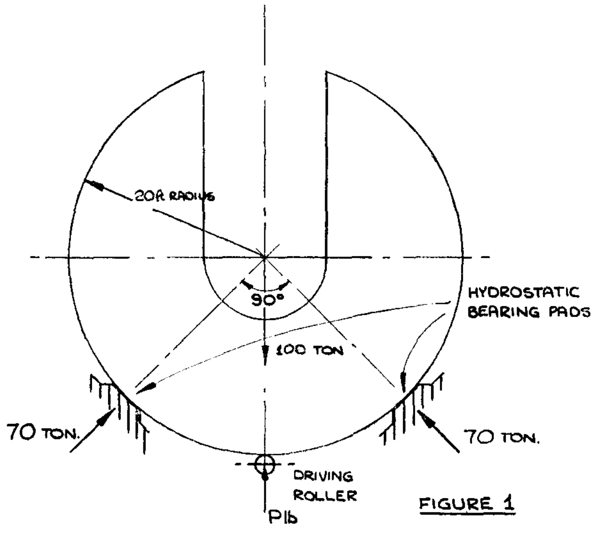


FIGURE 1

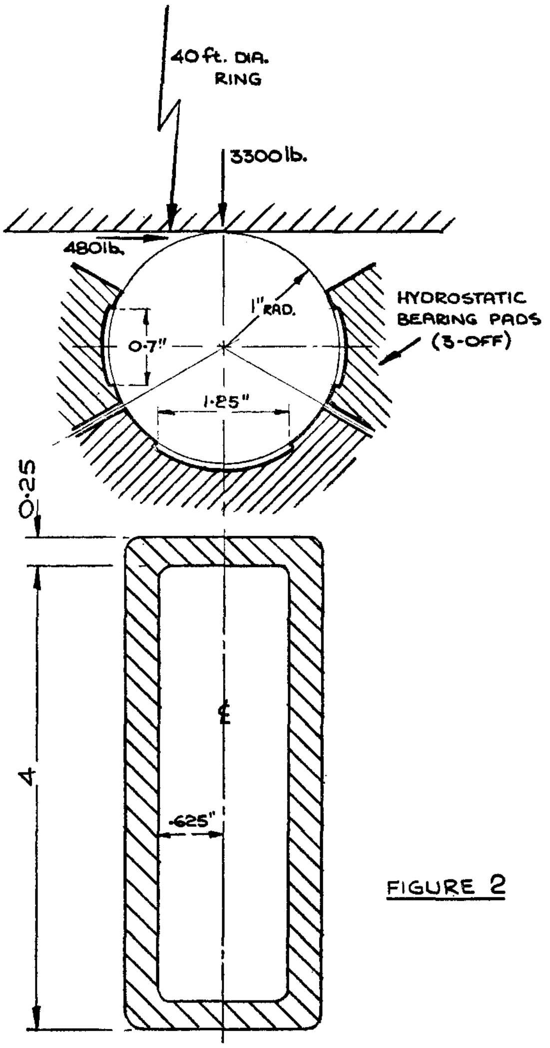
— REACTIONS SHOWN FOR HORSESHOE IN VERT. PLANE —

PROPOSED HYDROSTATIC BEARING SYSTEM FOR TELESCOPE POLAR AXIS

Fig. 1

Considering now the question of how to apply the motor output to the telescope axis, it immediately becomes obvious that a very large gear ratio is necessary since even at slewing speed the axis is rotating at only 1/8 r.p.m. Since the power output of an electric motor is proportional to its volume and speed, it is possible to keep the motor size reasonable only by increasing running speed and hence gear ratio. The problem therefore is to find a suitable method of obtaining as large a gear ratio as possible with a minimum number of gear trains. The classical answer is to use a worm and wormwheel, which is relatively simple in concept and not too expensive to produce provided one does not ask for high accuracy in the form of precise velocity ratio. It is possible to drive a 720 : 1 worm reduction directly with a servo motor having a top speed of 90 r.p.m. at slewing rate and a tracking speed of 0.5 r.p.m. However the efficiency would only be about 15 per cent under starting conditions and might rise to about 25 per cent at high speed if well lubricated. This leads to an increase in the power requirement, and a further increase is necessitated by the addition of extra inertia to the motor shaft to avoid deceleration damage to the telescope as a result of the non reversible gearing. The resulting design could well have a ratio of referred servo inertia to telescope inertia of 5 : 1, causing the telescope to follow the steady servo velocity modified by the worm to wormwheel gear errors, since the inertia of the telescope would have little effect in smoothing out the error.

It would seem desirable to use a drive system that has considerably less inertia than the telescope itself, so that the telescope inertia will be the dominant factor in maintaining constant angular velocity.



PROPOSED HYDROSTATICALLY SUPPORTED DRIVE ROLLER FOR TELESCOPE POLAR AXIS.

Fig. 2

To benefit from this it is necessary to reduce friction as much as possible. The drive system about to be described is an attempt to put these principles into practice.

The polar axis is supported at a point slightly forward of its centre of gravity in a radial slot in a 40 feet (12.2 m) diameter disc, such that the main tube can swing into the slot as it rotates on its own declination axis. The slotted disc of "horseshoe" is supported radially on two hydrostatic bearing pads at right angles to each other (see Fig. 1). Axial loads are also supported by hydrostatic bearings, which at a latitude of 45° would have bearing areas and pressures similar to those in the radial supports. Assuming a total weight load of 100 tonnes, the thrust on each pad is about 50 tonnes. Oil can be collected from the pads by ducts, filtered and recirculated by the hydraulic pump. The drive is applied to the horseshoe by pushing a solid metal roller into contact with it and locating the roller accurately in a hydrostatic bearing system, thus minimizing the friction which occurs as a result of the reaction load (Fig. 2). The load maintaining the roller in contact with the horseshoe is about 1.5 tonnes, and is sufficient with a suitable margin to allow maximum slewing acceleration and out-of-balance load.

The peak torque to be transmitted to the roller is about 480 lb-inches (550 kg-cm), and this is achieved by a D.C. servo motor via a step down ratio of about 50 : 1 using two spur gear trains, the final one possibly requiring to be backlash loaded to give a peak to peak backlash at the telescope axis of about 0.04 arcsec. At peak slewing accelerating power the motor would demand about 500 watts, falling off to about 25 watts on steady-state slewing. Under tracking conditions it would consume about 5 watts. The ratio of reflected servo inertia to telescope inertia is about 0.05 as against 5 for the worm drive. Also the efficiency is about 70 per cent so that regenerative braking is possible for a simple controlled emergency stop. In the event of a violent stop, due for example to a lock up in the gearbox, the telescope would suffer a deceleration limited by the adhesion between roller and horseshoe, which, though it may cause slight damage to the roller, would be unlikely to damage the telescope.

The cost of the proposed drive system, servo motor amplifier, gearbox, and roller with hydrostatic bearing is likely to be less than that of the worm and wheel alone. Although the design has concentrated on the polar axis, it is equally applicable to the less stringent requirements of the declination axis, provided a large enough ring equivalent to the horseshoe can be accommodated. In both cases digitization is by the moiré reflection method using a wrap around etched stainless steel grating tape.

THE ELECTRONIC CONTROL SYSTEM

The control system has to perform two distinct tasks, to set the telescope to specified coordinates and to track the guide star to a high degree of accuracy for a period of up to an hour. This means that the servos must be a combination of positioning and following types. During tracking, what is required is a smooth accurate velocity, a small constant error in position being tolerable, and so a velocity error method of control is used.

A computer will normally be associated with the telescope, and the design of the control equipment will be largely influenced by whether the computer is used on-line or off-line with a paper or magnetic tape link. The present trend is towards integration of the computer with the control. This offers greater flexibility with the possibility of adaptive methods of operation. Also a reduction in special purpose hardware is possible, as storage of demanded and present position coordinates, etc. can be in the computer store, although a demand for decimal displays and back-up facilities to allow limited operation during computer down-time can reverse this trend. However the reliability of modern small process computers is high, and monitoring is easily achieved by visual binary read-out or by peripheral print-out in any required form.

Digitization of the angles of the telescope axes should, as was described earlier, be on the final shafts of the drivers, and the measuring increment should preferably be an order smaller than the required maximum error. If incremental type digitizers are used, either the computer must have a direct store access add facility or preferably a limited capacity buffer store should be provided for each axis, as a relatively high pulse rate occurs during slewing. Absolute type digitizers could be interrogated by the computer from its internal timing system. Including the complete drive system in the control loop may produce stability problems, and so it will generally be necessary to add velocity feedback from a point in the drive nearer to the motor to stabilize the servo. This may take the form of a direct current tachometer, although, even if fitted to the motor shaft, low sensitivity and poor signal to noise ratio can result from the low motor speed. One solution to this problem is to employ an additional optical digitizer along with some form of pulse integrator giving an output proportional to rotational velocity.

Tracking rate components are readily produced by one of two methods, namely the overflowing accumulator and the binary rate multiplier. Both involve the use of a crystal-controlled oscillator whose frequency is a binary multiple of the sidereal rate, but the binary rate multiplier is the simpler method as it does not involve a full adder. Basically it is a device that produces a number of pulses, specified by a binary number, approximately equally spaced in time over its repetition period. It is ideally suited to the production of tracking rates, as the precision is a function only of the number of binary bits used and of the stability of the crystal oscillator. By modifying the rate selection numbers, corrections may be applied for such factors as change in refractive index with declination and temperature, and distortions in the structure with changing coordinates, provided the computer is supplied with the relevant calibration and ambient information.

Figure 3 shows the right ascension axis control system of a proposed design. The declination axis system is similar except that the rate generator produces only corrections instead of sidereal rate + corrections. The computer provides storage for demanded position and present position coordinates, and from these computes the position error at a repetition rate high enough to avoid producing ripple components within the servo bandwidth. This is fed to a digital/analogue converter to control the servo during setting. For tracking the servo is controlled by the analogue of the velocity error obtained by comparing the rate pulse train with the digitizer pulse train using a time sampling technique. The rate pulse train is produced by supplying to the demand rate store binary numbers representing the sidereal rate and the computer assessment of the rate correction. The corrected value is then used in the binary rate multiplier to produce the required pulse train. This operation is carried out in special purpose hardware external to the computer since it is a reasonably high frequency real-time process, and so if performed by the computer itself would carry a severe time penalty.

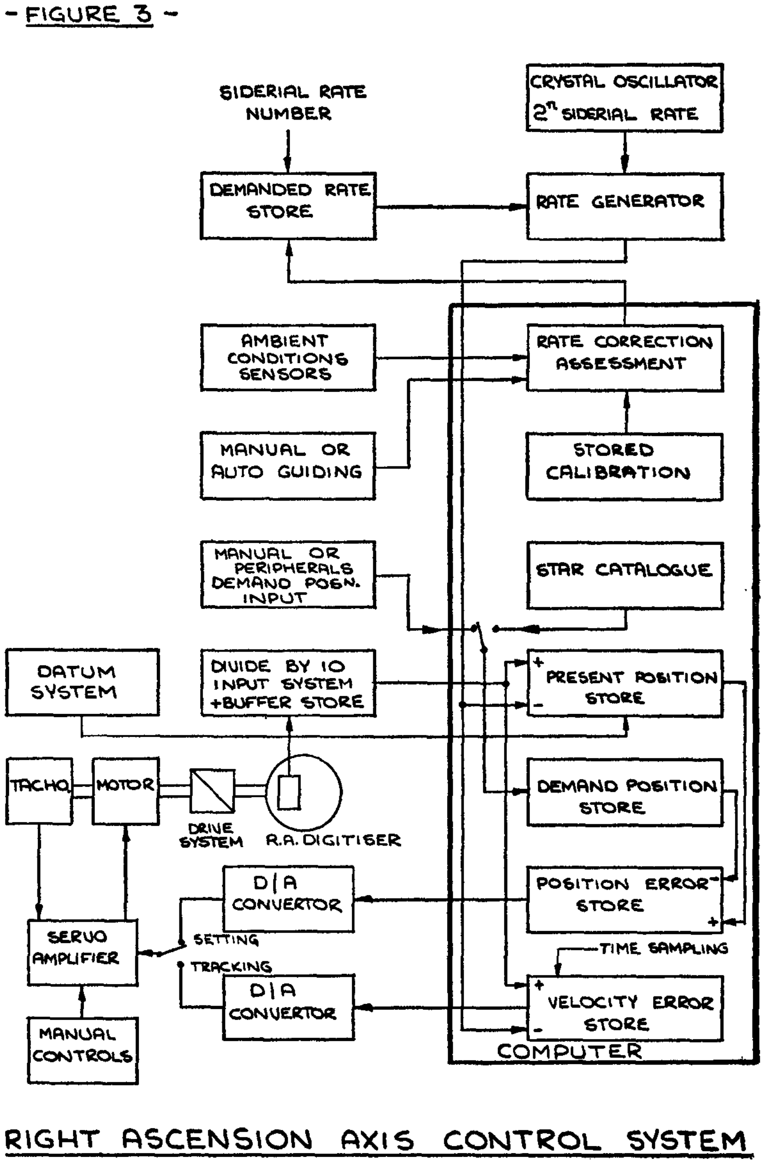


Fig. 3

The motor is supplied by the servo amplifier, to which velocity feedback is applied from the tachometer, and rotates the digitizer through the drive system. This produces pulses in the divide-by-ten input system which are stored in a limited-capacity buffer store until interrogated by the computer in its own timing system, causing the present position store to follow the axis movement. This store is also fed in the opposite sense by the rate pulse train, causing it to indicate the R.A. If it is desired to operate in terms of hour angle this train would instead be supplied to the demand position store in the same sense as the digitizer pulses, when the differencing would be carried out in the position error store.

Demand positions for setting are fed in from manual switches or from computer peripherals, or if computer storage allows may be supplied from a stored star catalogue. These are inserted into the demand position store, causing a non-zero value in the position error store and hence servo follow-up. The changeover from setting to tracking takes place automatically when the error reaches a value less than a preset threshold.

The rate correction assessment is made by the computer on the basis of stored calibration information and the inputs of ambient conditions sensors, plus a knowledge of the present declination. This will not give sufficiently precise results for some applications, *e.g.* the recording of star fields using a Schmidt telescope, since it does not take account of transient atmospheric effects. In these cases some form of manual or auto guiding is required. This can either be applied as an additional rate correction as shown, if the information is readily obtainable in digital form, or may be fed to the servo amplifier input network as an analogue. The use of an auto-guider is preferred, since along with additional instrumentation such as a cloud cover meter, the system could form the basis of an entirely automatic programmed telescope control.

For automatic control of dome and shield, and also for the telescope control if an altazimuth mount is employed, a polar to altazimuth coordinate transformation is necessary, and the computer is ideally suited to this operation. The demanded position coordinates are stored as altitude and azimuth, and the control system operates in these terms. A relatively crude form of digitization and servo suffice for dome and shield, and so the drive can be of the start-stop rather than continuously controlled type, with consequent saving in cost. Anomalous behaviour of the system at the zenith can be obviated by specifying a small guard cone around the zenith through which tracking is not permissible.

DISCUSSION

J RÖSCH: At the Pic-du-Midi Observatory we have had several years' experience with a 43-inch friction-drive mounting, to which the mounting planned for the ESO 3.6-metre reflector is very similar. The diameter of the circle is 280 cm, and it is supported and driven by two wheels, each 28 cm in diameter. The motion is satisfactory, except that occasionally a small jump of the order of a few arcseconds occurs, which we have been unable to explain or prevent. This should be a warning for potential users of friction drives. For the 80-inch high-resolution instrument that we are building now, we do not plan to use a friction drive.

R. B. DUNN: Since 1951 we have used friction drives on solar telescopes in servo-loops. The servo bandwidth is limited by resonance or windup in the drive. Most of this windup comes from lateral displacement of the bearings that support the drive roller. Have you calculated the resonance of this drive? From experience on the solar tower, we strongly recommend mechanical viscous damping at the load, in addition to tachometer feedback at the motor or at the load.

G. S. WALKER: We have done some calculations, and the first resonance is quite suitable. A certain amount of damping is supplied by the velocity feedback. It is possible, however, to put in additional feedback by adding digitizers at various places, so that you can get velocity feedback from any point in the drive. In this design the horseshoe is a very rigid structure, and is purposely made very heavy and thick, so that its resonant frequency is very high.

C. N. W. REECE; There's a perfect analogy to this in linear motion, which Dr. Parks will talk about later. It is true that, if you are controlling a system with virtually no friction, it is absolutely essential, as well as having electrical feedback in the servo control system, that you have if possible some pure viscous damping. The combination of the two usually gives the answer that you want in this type of control system.

R. F. NIELSEN: Being very concerned with the heat dissipation of power amplifiers, I should like to know what type of amplifier you use. Is it pulse-modulated or any other switched power?

G. S. WALKER: It would normally be of the type used to drive the torque motors, produced by Inland. It would be a switched type. We are concerned with economy in servo power, firstly because it is expensive, and secondly because of heat production in the vicinity of the telescope. We're talking here of somewhere around 500 watts for the system I've outlined. If you were driving through a worm system, this would go up many times, and you'd be into tens of kilowatts in no time to get similar performance.

J. TINBERGEN: Isn't one of the essential points to separate the measurement of position from the application of driving power, whether the drive is frictional or not? Such a separation might yield a telescope mechanical system that would be more accurate and reliable, indeed astronomer-proof.

G. S. WALKER: If you have two drives, you have problems in switching from one to the other. You have to declutch somewhere, clutching systems introduce the possibility of backlash, and you have servo problems again. To avoid this problem we prefer to use one single motor which is permanently coupled in a tight drive system. The measurement is done at the axis itself; this is always the principle in using digitizer techniques, to measure at the final place, whether it is an axis or a table slide. You always make the measurement on the actual object that you're setting. This eliminates backlash from the measuring point of view; you cannot eliminate it from the servo point of view, but you can reduce it tremendously by backlash-loading, thus increasing servo bandwidth considerably. There's another point about this friction drive system, there is one variable available, in changing the amount of frictional load on the system, you can change the pressure on the lower pad and the roller. I think that probably concerns the point made by Professor Rösch, that the system could be subject to small uncontrolled movements, this implies that the frictional force is insufficient for the requirements. In a hydraulically loaded system like this it is a simple matter to change the friction by changing the hydraulic pressure to the pad and roller. I should mention that this is not yet a working system, but a proposal, though we do have the digitizer system working.

D. L. CRAWFORD: There is an excellent 5-metre telescope at Palomar that has operated for many years with a very smooth and accurate drive system. We "automatic" types must offer something better than just gadgetry. Would Dr. Dennison comment on what they would do now, for the CARSO 200-inch?

E. W. DENNISON: It is certainly true that on the 200-inch telescope with the twin worm drive—the initial concept was that it had one worm for slewing and the other for tracking, and these two worms are locked together in the gear train so that they track with each other—as you know, this system works extremely well. I think the modern thinking, now, of Bruce Rule, on the mechanical design of our telescopes, is that in fact one can use a single worm for better slewing and tracking. This has been done on two of our 60-inch telescopes now, and I think it will also be done in the future on the 100-inch telescope when it is modernized. The problems of switching between the slewing motor and tracking motor, the encoder connections and all these things are done on shafts that go at high enough speeds so that the angular resolution is not a serious problem. All of these problems seem to be soluble in a very simple and direct and satisfactory way, so I think I would also add my voice to the comment that the worm drive is not all that bad, and in fact seems to have some advantages over the other forms of drive.

G. M. SISSON: Can I add my voice, sir?