Chapter Eleven
Drives

Without doubt, the most demanding mechanical design task is a mount and drive system suitable for astrophotography with long focal lengths (high magnifications). If you want a long focal length system that can be set on target, switched on, and have it deliver a crisp photograph with no intervention on your part (other than opening and closing the shutter), you have quite a task ahead of you. Until relatively recently, with the advent of auto-guiders, even professional observatories didn't do this. If you don't mind intervening, or just want the convenience of viewing without constantly moving the scope by hand, the constraints are not so great and you can do it. The problem is simple: the telescope magnifies any errors in the drive train or pointing as well as, or better than, it magnifies the image. By that I mean that long after you've run out of useful optical magnification, the errors in tracking still get magnified.

Motor drives bring up several complex and interacting trades. You can use a conventional AC or DC motor, or a stepper motor. A stepper must be controlled by a digital controller, but a conventional motor may be powered (depending on the type) from a DC source, the AC mains, or a crystal derived source for tighter frequency and rate control. Conventional and stepper motors can use a variety of gearing methods to reduce the motor speed to sidereal rate (to put this into perspective, the movement of the telescope is approximately half the speed of the hour hand on a clock). The drive must include a method for slewing across the sky to different objects. This can be as complex as a micro-stepper motor with varying step sizes, or as simple as a friction clutch that releases the drive when you press on it.

My intent in this chapter is to cover the problem areas, along with some solutions, and design approaches in enough detail to get you started toward a successful drive design. The emphasis will be on equatorial systems, not Alt-Az, although many of the things I'll bring up apply to them as well. Let's start where you should start in any design, by examining the requirements for the system.

How Good Does it Have to Be?

The accuracy that you need depends on what you want to do with your drive. If you are only going to view through the eyepiece, the requirements are quite lax. You only need to keep the object "more or less" centered in the eyepiece. If you intend to do high magnification photography, such as planetary work, the requirements tighten enormously.

For 35 mm film, the resulting prints appear sharp if the resolution is 40 line pairs per millimeter or better. The tolerance required of the mount and your

guiding efforts depend on the effective focal length of your system (EFL is defined in most astrophotography books). A useful equation for determining the required accuracy is:

$$Tolerance = 2 \times \arctan(\frac{0.0125}{F}) \quad (1)$$

where F is the focal length of the system, not necessarily the telescope's own focal length. This would include the effects of a Barlow, for instance. For example, the 10 inch (250 mm) f6 system we have used as our standard in this book has a focal length of approximate 1520 mm, which yields a guiding tolerance of 3.4 seconds of arc. Of course, this is for this telescope used at prime focus. With eyepiece projection or another means of drastically increasing the effective focal length, this tolerance goes down. Most sources imply that a tracking accuracy of ½ arcsecond (0.5") is all that is needed because that is the limit the atmosphere imposes on seeing for good sites.

This limit is also considered acceptable for CCD imaging. In fact, for CCD work, you can determine how many arcseconds per pixel in the camera and keep your guiding tolerance to less than one pixel – even better; under ½ pixel. For wide field photography, the focal lengths are shorter and that makes the tolerance looser. That's why it's easier to start out with wide field photography.

With that in mind, let's look at some of the sources of errors and see where the problems lie.

1. **Polar Alignment Errors:** These cause the image to wander around or rotate in the field during tracking. For example, say you are tracking an overhead star and find it drifts to the south in the eyepiece. This indicates the polar axis is displaced to the east. If it drifts north, the displacement is to the west. Likewise, if you track a star near the eastern horizon and it moves south, the polar angle is too shallow (the axis is too low), and if the star moves north, the angle is too steep (axis too high). This slow wander is annoying but can be tracked out as you guide your exposure. The bigger problem is that it can cause image rotation that you can't track out. To make sure rotation is negligible for long exposures, the polar axis needs to be aligned with great accuracy.

2. **Periodic Errors in the Gear Train of the Drive**: Motor drives gear down a faster motor to the required rate. The resulting gear train can run alternately fast and slow due to minute differences in the spacing of the gears' teeth and errors in their shapes. This error is the most pernicious. You must constantly correct the drive rate for these to keep the object centered and keep the image from smearing. This is called Periodic Error Correction and most commercial equatorials above the cheapest class allow this. Not all gear error can be corrected out; it needs to be a simple error waveform.

3. **Fluctuations in the Drive Rate:** This is a problem when using AC power. In most of the world the long term frequency accuracy of the AC mains is astonishingly good. From minute to minute, though, it can vary enough to be devastating to a photograph. It alternates fast and slow so that the long-term average is better than a quartz crystal. For a drive motor, though, a quartz crystal drive is an excellent way to achieve high accuracy. To be honest, most modern systems do not have this problem. In the days of AC motors, you stood at the guiding eyepiece constantly adjusting the motor rate to keep a guide star centered.

4. **Flexure of the Telescope Tube:** We discussed this in extensive detail back in chapter three and concluded that flexure of several seconds will not cause aberrations, but will change the image position. This depends on the optical system, but is the case for the system we've been looking at. Larger flexures cause image degradation, and we design to avoid this. Small amount of flexure will cause the image to move during longer exposures, and can be corrected gradually while guiding, since the worst case motion will happen as the telescope goes from pointing horizontally to vertically. From horizon to zenith takes hours. We also saw that, if we want to, we can make it stiff enough so that image movement isn't a problem.

5. **Non-Perpendicular Axes:** The polar and declination axes need to be precisely perpendicular to each other. Any errors here turn into pointing errors that shift an object's position. This is generally calibrated out during alignment of the polar axis, because once the polar axis is set, the error turns into a declination error, and this won't damage tracking. It will, however, interfere with the performance of digital setting circles or other automatic pointing devices unless it can be calibrated out.

6. **Atmospheric Refraction:** In addition to these considerations, atmospheric refraction will change the apparent position of an object as the viewing position gets closer to the horizon (and I'll ignore the argument that you shouldn't be observing or photographing that close to the horizon). This effect takes place slowly; for example, if you start imaging an object when it's overhead, as it approaches the horizon its apparent position stays higher and its apparent rate of motion slows down. Since a potential guide star will be close to the object, refraction is relatively easy to correct. As with the previous error class, if you use digital setting circles or another automated method to find objects, be aware that objects may not appear where you expect them to be as you approach the horizon.

Gears: How Good is Good?

When we started out by looking at optical tubes, the most important design question was how stiff the tube could be made. In mounts, we found that the strength was not so much the problem but stiffness was still needed to resist vibration. In drive trains the question is often not design; rather it is how accurately the gears can be machined. The requirements for accuracy in gears are not insurmountable, but can be intimidating.

The gears that actually touch the polar shaft have the highest accuracy requirements. Eccentricity, or out-of-roundness, can cause the shaft of the driven axis to rise and fall as the gears turn, moving the image. This is one source of the Periodic Error referred to above. Depending on the mount geometry, a lever arm may magnify this effect.

If gears are used to reduce the motor speed, they can have the same errors in tooth spacing. This makes the drive run faster and slower as well but instead of happening once per night, it can happen over shorter time scales. The exact time scale depends on the motor speeds, and where in the chain the gear error is found. The gears closest to the motor turn at the highest speed, and they may cause the most speed error. As you get closer to the last gear, the error happens more slowly and can take all night in the case of the last gear.

Backlash is often cited as a concern, but is it? What is backlash, anyway? In gear talk, backlash is the difference between the size of the space for a gear tooth and the size of the tooth that fits in it. Stated another way, a gear may be designed to have a gap between teeth of 50 mils (0.050 inch). If the engaging tooth is 49 mils wide, there is a backlash of 1 mil. The word backlash comes from the feeling you get when adjusting something that has this problem. You may have seen this with older radios or UHF TV tuners, where you tune it to a station and find that the radio de-tunes itself when you let go of the knob; the control has slipped backwards. The key here is that backlash is a problem when the tension on the shaft is removed. It's also important to realize that any set of gears will have backlash because the gaps can not be machined to be exactly the same size. Consistency can be achieved by a higher gear quality, but backlash can not be eliminated.

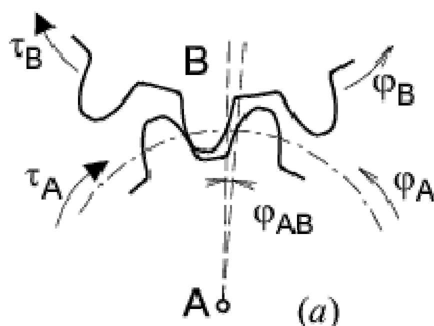


Figure 1 - Gear Backlash is the difference between tooth size and its engagement

In radio tuning systems, one approach to minimizing backlash was to split the gear into two parallel disks, and couple them with a spring. This closed the space and reduced backlash, but the spring still allowed the two gears to move.

Backlash is then a problem in intermittently driven systems. When an autoguided mount slows down and speeds up, the mount may go through periods when it is not under tension. This is when backlash shows up. If you have a multiple gear drive train and change direction, the backlash must be taken out of every pair of gears successively before the motion reversal can start. Say you have a hand controller and can move the telescope in either direction. Observe a star in the field of view, preferably with cross hairs or a reticle. Reverse the direction of star and see how long it takes to start moving. This is the backlash getting taken up. Even if you're not doing this, a stepper motor system is really starting and stopping continuously. If the motor speed is too slow, you may see backlash effects. This is the reason for the often-heard advice to not balance your mount extremely precisely – to leave it heavy on one side of the meridian. The lack of balance puts pressure on the drive train and helps take out the backlash.

I'm sure you can see from this discussion that if the gear and tooth are precisely machined and matched to each other that the problem is minimized. In the US, the AGMA, American Gear Manufacturers Association, has developed a set of gear classes from the coarsest #3 to ultra-precision #16. Aerospace applications are often class 14 and above. The best way to ensure the precision of the gears you buy is to choose gears in the highest classes, 14 to 16. Bring large amounts of money. There's no doubt that the system will work better with the finer machining used in these classes. But people make serviceable drives from gears of unknown pedigree, or even threaded rod and this last stuff is hardly the most accurate thread made!

This discussion of gear accuracy and threaded rod leads into the areas of precision positioning, motion control and screw threads. The simple screw is one of the most important inventions in history for many different reasons. One of these is that when precisely made, a screw will advance anything mounted to it in very precise amounts. For example, a US standard ¼-20 threaded bolt will advance 1/20 of an inch (0.050 inch) in one rotation. With a pointer and dial, it is easy to set a quarter turn by eye, and that will move anything attached to the screw 0.0125 inch. You may not be able to move something 12.5 thousandths of an inch by pushing it with your finger, but putting a screw positioner on it makes it easy. Finer pitch screws, such as the 40, 56 or 80 turns per inch screws commonly available allow even finer control. The accuracy of this motion depends on the accuracy with which the screw is made. SAE Micrometers use 50 turn per inch screws made to very tight tolerances and are used to measure to 0.001 inch routinely. The US system of screw classes goes from Coarse (UNC) through fine to extra fine, with additional tolerance classes that range from 1 to 3 (the higher the number the more accurate the screw threads).

A Simple Drive, the Tangent Arm.

Using threads for positioning is the basis of the tangent arm drive. In this approach, a solid arm with a nut or other threaded portion is driven by a screw. **Figure** 2 shows the concept.

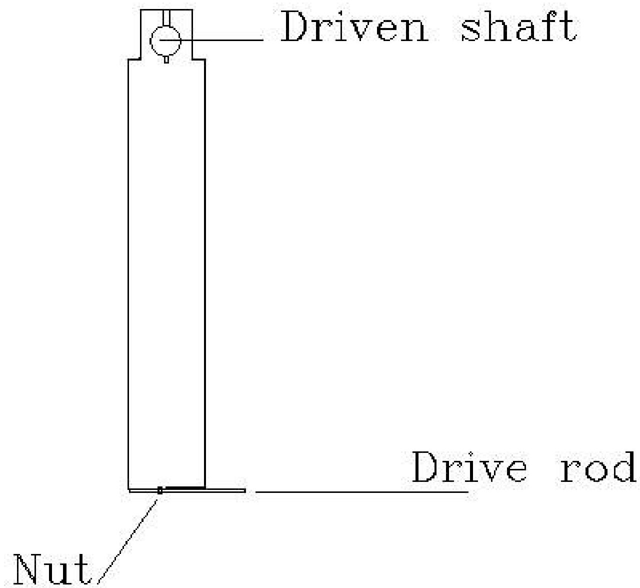


Figure 2 - Tangent Arm Drive

The name tangent arm comes from the relationship of motion of the nut on the drive rod to the angular rotation of the shaft. The definition of the tangent in a right triangle is:

$$\tan\theta = \frac{y}{x} \qquad 2$$

We can call the linear movement of the screw y and the length of the tangent arm x. We find that the angular motion of the shaft is the arctangent of *y* over *x*. The small angle approximation says that the angle itself is *y* / *x*, where the angle found is in radians (multiply by 180 over π to get degrees).

Example: If we have a 15 inch long tangent arm, measured from the center of the shaft to the nut, and move the end ¼ of a turn of a ¼ - 20 screw, 0.0125 inch, we find:

$\theta = 0.0125/15 = 8.332 \times l0^{-6}$ radian = 0.0477°.

This is equivalent to 171.9 seconds of arc. You probably wouldn't use a tangent arm for the polar drive because of this drive's big problem. You'll use this on the declination axis for mild adjustments of the scope north-south during tracking.

The big problem with this drive is that the arm is rigid and "wants" to trace out a circular arc while it rotates, but it can't. The threaded driving rod won't let it. This tends to limit the use of tangent arms to the declination axis, since this axis doesn't move as much over the course of the night. An obvious improvement is to allow the arm to move for longer periods, and to do that we make it into a section of a circle.

The Sector Drive

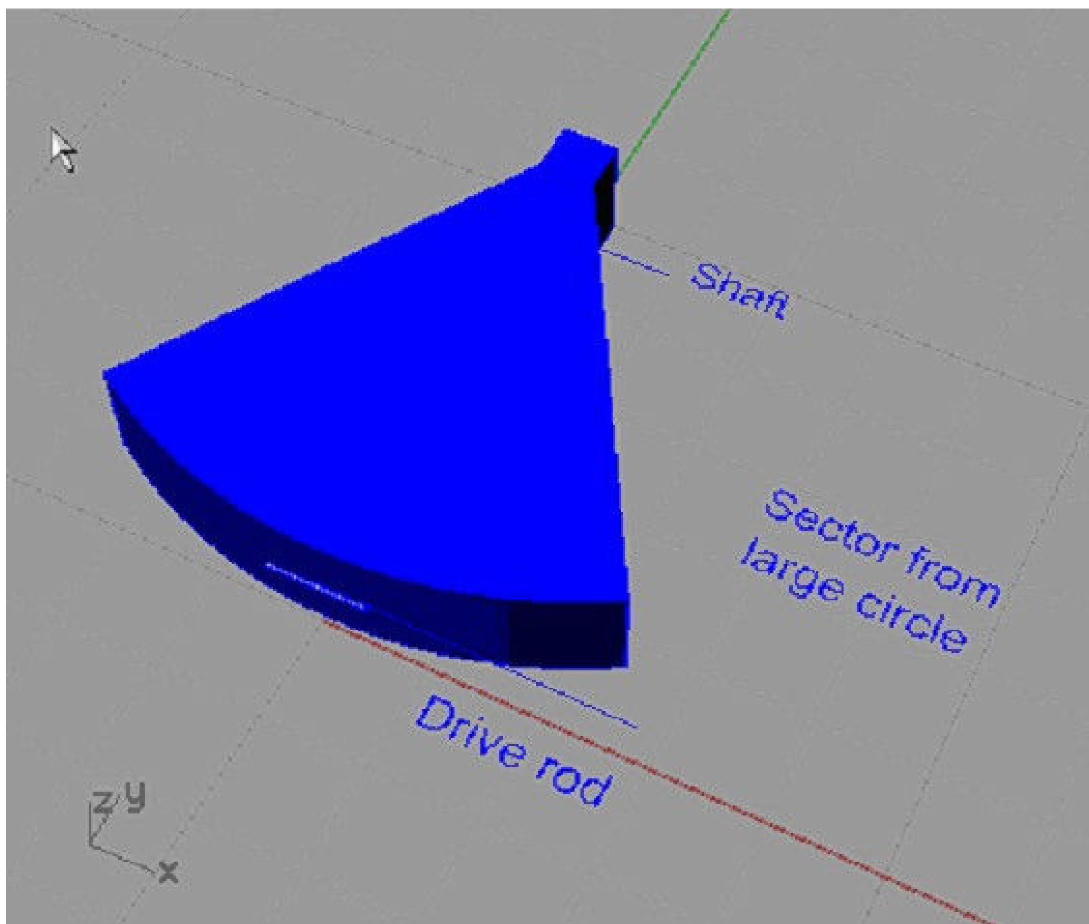


Figure 3 - A Sector Drive

The sector drive, shown in Figure 3, uses the same basic principle as the tangent arm. Since the sector has a circular profile, it can rotate without breaking its drive source – or requiring it to "float". The disadvantage of this drive is that the sector needs to be reset during the course of the night. If the sector is 60

degrees wide, it will track for about 4 hours – which could be all you need for summer nights in Oregon or farther north. In practice, re-setting before exposures or every couple of hours is probably a good idea. The drive mechanism can be implemented in a couple of different ways. The nicest way is as a sector of a worm gear combination, with the drive being supplied by a threaded rod, screw, or worm. Alternately, a friction drive using a wheel attached directly to a motor can be effective.

Texereau uses this type drive with a steel band attached to the sector. A motor turns a threaded rod, and a nut slides along its length. The nut, in turn, is attached to the steel band which then pulls the sector toward it (pushing on the band is not wise; it's like pushing on a rope). The band is fastened to the sector at the far end, and the end of the band farthest from the motor is attached to a weight suspended over a pulley. This keeps the band in tension, eliminating backlash in the screw/nut combination, and aiding in keeping the drive moving smoothly. Having not seen one of these in operation, though, it sure seems like the weight on the band would be a pretty bad vibrator. This approach seems to have declined in popularity in the recent past.

Figure 4 Using a Sector with friction instead of gearing. The driving metal section rides on a driven threaded rod – courtesy Dave Harbor, Great Plains Instruments

A sector drive of this type is very similar to a worm gear, now the most popular way to drive a telescope. Very big worm gears, or sectors, don't need to be custom made for you. You can obtain the same results from a large rack gear bent into a circle or around the sector, and then bonded to it. This is the same

approach that car engine makers have used for making the billions of flywheels that get installed in new car engines, so it is a technique proven to be reliable. You can get gear racks from a variety of gear manufacturers. You could use a flywheel from an old car engine, if weight is not a big concern. The speed required for driving a worm gear combination can be found from the following relationship:

$$RPM = \pi * DP/1440 \quad (4)$$

where D is the diameter of the gear, P is the pitch in turns per inch, and 1440 the number of minutes in a day. For sidereal rate, 1346.5 yields a better approximation, but it is just as feasible (and possibly easier) to vary the motor speed to set this. The equation can be re-arranged to find the required gear diameter given the motor speed.

Perhaps the most innovative drive that I've ever seen for a sector- type driven system was reported by A.L. Woods in Telescope Making #30 magazine. He made a mold of a threaded rod in epoxy paste and used this on a plywood sector. Woods said that he had tried several approaches and had best results with pressing the rod into a flat strip of epoxy paste. He used an epoxy paste that took a long time to harden, allowing him to work the epoxy into a long strip, place the greased threaded rod into it and then work the epoxy up against the rod with his fingers to eliminate any voids or air bubbles. The rod is then removed from the paste carefully and slowly, once the paste has started to get very firm, by lifting gently on either end of the rod. The epoxy is then allowed to harden further, over night. The next step requires the epoxy to be hard, but pliable. You then roll the epoxy onto the edge of your plywood sector, bending it gently, a little at a time. Much like bending wood, where you use as many clamps as you can get your hands on, you use plenty of duct tape to hold it in place or another day or two until it is fully set.

The exact ratio of resin to hardener that you use, as well as the chemistry of the epoxy brand you choose, will have a large impact on your success. Woods used E-POX-E brand. A similar material sold in Marine boating stores is called "Marine-Tex". This is a putty that hardens after the addition of a catalyst. I have no other information on these, so I must warn you to expect to experiment to make this work.

The molded epoxy is then driven by the same threaded rod that was used to make it. The rod is held against the epoxy with pressure from springs, but any other method would probably work well. Your biggest fear is breaking the epoxy gear teeth, so be sure that the rod is engaged properly before applying force.

The Worm Gear Drive

The sector becomes a worm gear drive when the sector is extended to become a complete circle. This can be embodied as the polar disk of a split-ring equatorial, a round plate holding the arms of a fork mount, a gear added to the shaft of a German equatorial, yoke or any other mount you can think of. The distinguishing feature that makes it a worm gear drive is that it is a full circle in profile and is driven by a worm. The proper nomenclature, by the way, is that the driving gear is called the worm, and the driven gear is just called a gear. A worm is a screw-like device with a thread spiraling down its length.

Worm gears are currently very commonly used to drive a telescope, and are provided commercially by many companies. The big two telescope companies sell these, as do the high quality small machine shops such as Optic Craft Machining. Optic Craft makes their gears to AGMA class 15. The required drive motor speed can be calculated from equation 4 above. As with the sector drive, the gear can be constructed from a rack gear bonded to a softer steel wheel.

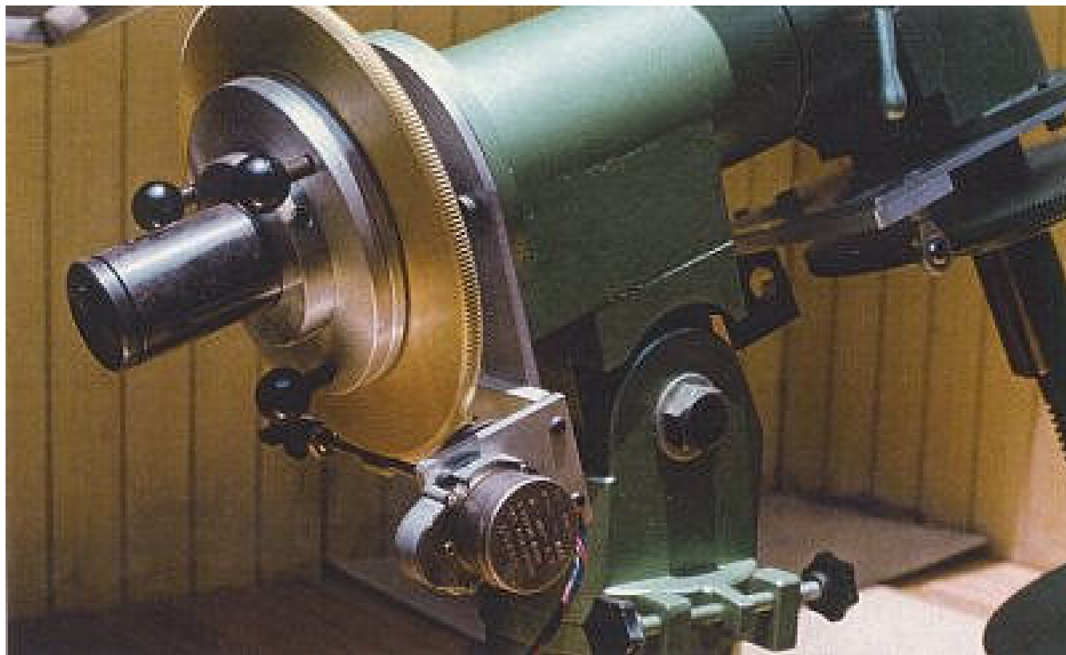


Figure 5 - Optic Craft "Polaris" Drive - capable of 95 pound load. This is a class 15 worm/gear combination. Courtesy Optic Craft.

If steel gears aren't your favorite approach, consider a hose clamp. Hose clamps come in very large sizes, easily several feet in circumference, and are cut for a screw that engages them to adjust the size. The clamp bands are available with cuts arranged perpendicular to the length of the band or with cuts that are angled (also called elliptical cuts). The tighter the clamp screw worm engages this band, the less problem backlash can present, and it has been reported that mixing the worm from an angle-cut clamp with the band from a parallel-cut clamp gives the best results. A hose clamp is an easy way to adapt to an available

motor that may be an unusual speed. You have the freedom of making the rest of the “gear” the required diameter, and it can be made from plywood, or any other material you want.

Speed Reducers

If you are going to adapt a motor for a drive, you will almost certainly have to concern yourself with speed reduction. Surplus AC motors tend to run at high RPM's (3600, or 1800 are common speeds), and need to be reduced by large factors to get the output shaft speeds needed. Gear speed reducers are not conceptually complicated, but finding the gears to make them can be. If you are a machinist, of course, you can cut whatever gears you need.

The basis for a gear speed reduction is an equation we’ve seen several times already. It says that if two rotating bodies are in contact and not slipping, then the linear speed where they contact has to be the same. Denoting the gear radius and rotational speed as 1 and 2, we see:

$$\omega_1 \cdot r_1 = \omega_2 \cdot r_2 \qquad (5)$$

or

$$\frac{\omega 1}{\omega 2} = \frac{r2}{r1} \qquad (6)$$

which says that the ratio of the shaft speeds ($\omega 1$ and $\omega 2$) is inversely proportional to the radius. This equation means that we can reduce the speed by driving a big gear with a smaller gear, as in Figure 6. A bigger radius makes a slower speed in RPM. If we want the output speed ω_2 to be 1/10 of the input, or $0.1^* \omega_1$, that comes out as

$\omega_1 {}^* r_1 = 0.1^* \omega_1 {}^* r_2$ the ω_1 terms cancel (divide out)

or $r_1 = 0.1^* r_2$

and $10^* r_1 = r_2$

To slow down the speed by a factor of 10, the output gear is 10 times the size of the input gear.

Since we are dealing with ratios, you can replace the radius with the gear diameter and the built-in factor of two cancels out when we divide.

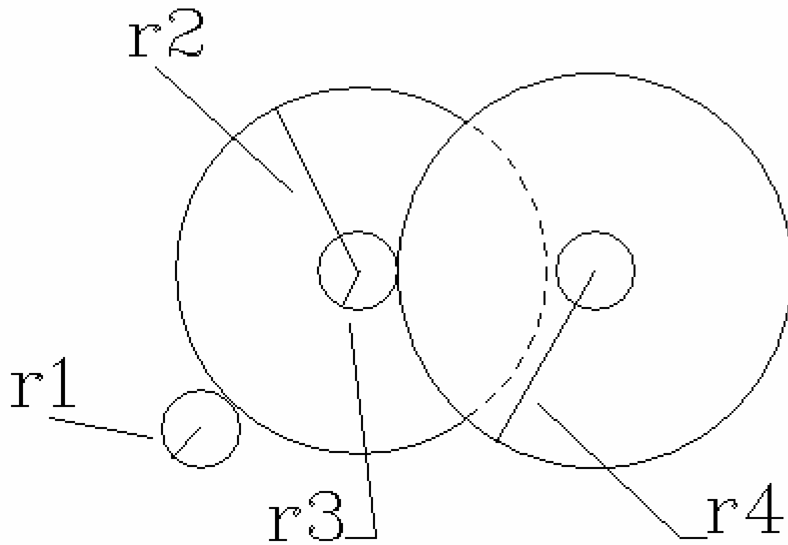


Figure 6 - Speed Reducer

Figure 6 shows a gear speed reducer. The gear radii are sized such that r1 and r3 are the same, r2 is 3 times r1, and r4 is 4 times r1. If the driven input gear is the small one on the left, the second gear has a shaft speed reduced by the ratio of their radii, here 3:1. The second gear has a smaller gear of radius r3 on its shaft rotating at 1/3 of the input speed, and the speed of the third big gear's shaft, radius r4, is ¼ the input speed of r3, due to ratio of radius r4 to the driving radius r3. This combination of gear radii reduces the output speed to 1/3 times ¼ or 1/12 of the input speed at the shaft in gear 4. This isn't a large reduction, but the method can be extended further by continuing the process of putting small gears on the shafts of the large gears; in effect, continuing our illustration to the right. Large speed reductions are possible with this technique.

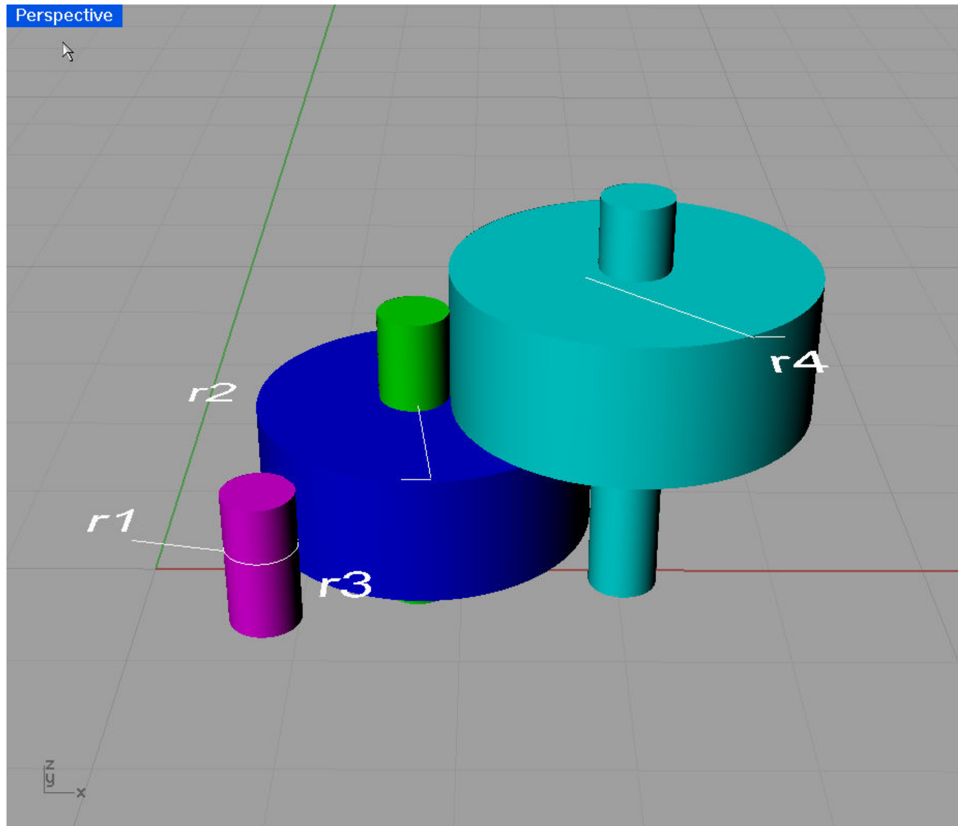


Figure 7 Speed Reducer – perspective drawing in "psychedelic color"

The thing that limits your freedom is that the gears (obviously) must mesh. In order to mesh, the teeth must be the same size, and that has an interesting implication: the speed reduction can be expressed as the ratio of the number of teeth on the gear! The explanation for this is that the gear radius determines the circumference, and the circumference of the gear must be sized to contain an integer number of teeth. The exact number of the teeth – e.g., 24 or 20 – depends on the torque that the gears will supply because that determines how wide they must be in order to handle the shearing stresses that they exert on each other. The torque required to drive the mount is the amount required to overcome the friction in the mount, but it is modified by the gear ratio. For example, the 12:1 speed reduction that we obtained came from multiplying the effective radius of the gear by 12. Since torque is in units of force times distance, we multiplied the torque the motor exerts by 12! This means that relatively light duty motors can exert the necessary torque to turn big telescopes. You may have read that the torque required to drive the 200 inch Hale telescope is provided by a 1/2 HP motor.

Motors

The torque to drive your scope across the sky is provided by a motor of some sort, and choosing your motor is a major part of designing your drive system. Many drives are designed based on the availability of a motor scrounged

up or given to the telescope maker. Stepper motors, DC motors that change shaft position in precise steps in response to a drive pulse, are currently quite popular and the speed control flexibility they offer is one good reason for this popularity. In their haste to jump to stepper motors, though, ATMs seem to have forgotten or never learned about the other technologies available. There are at least three main classes of motor available, AC, DC and stepper (purists may have a hard time with that classification). Let's examine them and see how to use them

1. AC Motors

Not very long ago, an AC motor was considered the only answer to how to drive a telescope. AC motors are often called synchronous motors because their shaft speed is synchronous to the frequency of the AC that drives them. For 60 Hz AC mains, as found in the US, the most common speed is 3600 RPM, but they can be made to run at slower speeds by increasing the number of poles in the motor (poles are a component of the motor). This type of motor is commonly found at 3600, 1800, and 1200 rpm. If the motor is powered from an AC source that is not precisely 60 Hz, the motor speed will run proportional to the new frequency. This gives us a way of changing the motor speed; electronic circuits are available that can vary the AC supplied to the motor. Crystals are sometimes used for this, but this produces a rate that is hard to vary. Variable rate oscillators are sometimes seen that allow the drive to run fast or slow.

How can we use a motor that runs at 3600 or 1800 rpm to drive a telescope? A sidereal day is approximately 23 hours, 56 minutes and 4.09 1 seconds, or (equivalently) 23.93447 hours long. An 1800 rpm motor will rotate through 2,584,923 revolutions in that time period, and we want to reduce it to one! Our task is to find a set of factors for this number, we'd ideally like as few factors as possible, and we'd like them similar in size.

A few seconds of trial with a calculator convinces me to round the number off, and I round it down to 2,584,800. This is equivalent to making the day 23 hours and 56 minutes long — 4.091 seconds shorter than reality. The mount will track fast, completing one rotation 4 seconds ahead of the earth. This new number, 2,584,800, is immediately divisible by 100 leaving 25,848. This later number has a prime factor of 359, leaving a factor of 72. The large prime number, 359, makes an excellent choice for our final worm wheel. In fact, this is a well known set of gears; once you've solved this problem once for an 1800 rpm motor, it is solved forever. This gear set is described in several places. It reduces the 1800 rpm motor to 1 revolution in a sidereal day, using 100:1, 359:1 and 72:1 gear tooth ratios. The extra 4.1 seconds can be adjusted out with a variable speed drive.

This is really a bigger problem, though. The moon moves at a different rate than the stars, completing a revolution roughly an hour ahead of the sidereal

day. The sun, of course, takes 24 hours to return to its position. Comets move at different rates, and their rates vary with the position of the comet in its orbit. Satellites move at widely varying speeds. Tracking the motion of everything in the sky that you might want to observe or photograph requires different speeds for the drive system. The differing speeds can be achieved with gear ratios and swapping gears, but amateurs have increasingly turned to the motor for the speed control.

2. DC Motors

As any slot car jockey or RC modeler can tell you, you can vary the speed of a DC motor by varying the applied voltage. This versatility puts DC motors in applications where a range of motor speeds is called for, and careful management of the applied voltage can yield a motor with excellent properties.

Careful management means just that: careful attention to the voltage applied to the motor, perhaps with an electronic circuit to control the voltage in precise increments. How precise? Consider the 1800 rpm motor we just examined. Now assume that it runs at 1800 rpm if the applied voltage is 12.000 Volts. What happens if the voltage drops 10/1000 of a volt (10 millivolts)?

This change represents 0.0833%, so that reduces the 1800 rpm to 1798.5 rpm. That doesn't sound like much, but over the course of a day it means that the motor turns 2,582,768.7 revolutions instead of the 2,584,800 we designed for. To make up the difference requires 2031 revolutions or almost 1 minute and 8 seconds more time. At 15 arcseconds of sky per second of time, 68 seconds means we're off by 1020 arcseconds, an intolerable error considering our goal of 0.5 arc second.

Now 10 millivolts is not an unusual error; you often find errors of this magnitude in a short wiring harness. Furthermore, the voltage source itself is subject to error. Batteries give a different voltage depending on their state of charge. Some types, notably NiCd (nickel-cadmium or NiCad) yield a rather constant voltage throughout their discharge (nowhere near 10 mV out of 12 volts, however). Others, such as lead acid ("gel-cells") have more voltage change over their discharge curve. If you run the motor from a power supply and a voltage regulator you will find that these parts have an error as well. The common voltage regulator ICs have a tolerance of 5%.

Does this mean the DC motor is dead for astronomical use? Not really, although it may mean you need to track more closely. A precisely adjustable regulated supply with a multi-turn pot to adjust the output voltage will allow close enough control over short periods to allow use of a DC motor. Electronics hobbyists will be able to build DC supplies that are very precisely adjustable using adjustable voltage regulators like the venerable LM317 and 20 turn potentiometers.

Another approach for the electronics experimenter is the phase locked loop or PLL. A PLL is a widely-used system that compares the phase, or timing, of two signals. One of these would come from (in this case) the motor, and the other would come from a precise reference such as the 60 Hz AC main power or, better yet, a crystal oscillator. If the motor phase is ahead of the reference, the circuit generates a correction voltage to slow down the motor. Conversely, if the motor phase lags behind the reference, the correction voltage speeds it up. This type of circuit is capable of very accurate speed control, and is often used in computer printers, hard disk drives, and other places where the motor speed must be tightly controlled.

The first problem that must be solved is how to turn the motor speed into something that can be compared to the reference. The most common way of accomplishing this is to use an optical shaft speed encoder. This is a disk of clear plastic with dark sectors photographically reproduced on it. A light source is aimed through the disk at a detector, and as the disk rotates, the light is blocked by the dark sectors turning the detector on and off at a rate proportional to the disk speed. Another approach uses a non-conductive disk with metallic sectors etched on it. As the sectors rotate under thin metal contacts, a circuit is momentarily made then broken. Generally speaking, the number of sectors goes up as the disk diameter goes up, but sector sizes of 5° down to 2° seem to be common. A disk with 2° sectors will pulse 180 times per rotation, and an 1800 rpm motor will produce a pulse train at 324 kHz.

Shaft speed encoders are produced by electronics manufacturers like Hewlett-Packard Corp., or by motor control specialists like Spectrol Electronics. They are sometimes found at surplus dealers. Of course, they can be obtained new from the manufacturer or their representatives.

Continuing this discussion, we have a pulse train at 324 kHz that can be applied as input to a phase comparison circuit (phase detector). The reference frequency into the phase detector must be exactly the same, and for best accuracy, divided down from a higher frequency crystal. The phase detection does not have to take place at this frequency (324 kHz), we can just as easily divide this down to a lower frequency, and doing so gives you a surprising advantage. Let’s say we have divided the frequency from both the motor and the reference by 100; the output frequency for the comparison is 3.24 kHz. If we then program the divider to divide by 101 (by changing the state of one switch), the output of the motor pulse train is now lower in frequency than the reference. The action of the phase detector and the rest of the loop is to speed up the motor until the new frequency divided by 101 is 3.24 kHz, the reference. The motor is now running at 327.24 kHz, or 1% faster. The motor will slow down by 1% if we divide by 99 instead of 100. If we did our comparison at 32.4 kHz, we could change the motor speed by 10% with each unit change in division, but it’s probably better to have the finer control of speed that the lower reference frequency gives us. If we

want finer control of speed, we just need to divide the frequency farther down than 3.24 kHz. This makes the PLL a very powerful way of controlling motor speed during tracking, speeding up or slowing down the motor as required.

The output of the phase detector is filtered to smooth out the voltage applied to the motor and ensure that the system's dynamic response is proper. This is essential to the operation of the PLL, but doesn't need to be elaborate. A simple resistor-capacitor filter is adequate. Op amp filters generally have a more nearly ideal response and are preferred. The output of this filter can be used to drive the motor directly, if it's a low power motor. If high current is required, a driver stage needs to be added.

You shouldn't let the reference frequency go too low for two reasons. First, the correction can't be applied as quickly as the frequency gets lower, and second, the filter components get rather large and therefore hard to get. Still, you could certainly divide 3.24 kHz by another 2 to 4 without trouble. The only requirement for the reference crystal is that you can divide it down to the same frequency that you will apply to the phase detector.

There are other approaches to designing a PLL that don't involve frequency dividers. It is possible to use a voltage derived from the motor and compare it to the reference oscillator without dividing it down. The motor speed sensor is then not a shaft encoder that generates pulses proportional to the motor speed, but a Hall effect device which generates a voltage proportional to the motor speed. Doing this negates the simple programming that changes speed, and removes some of the PLL's flexibility. However, it can lock the motor speed to a desired value to very high accuracy. This method has been used in hard disk drives and high speed printers for years.

Finally, note that I did not say that a PLL must be a circuit; the PLL can be implemented in software. This approach, using software in a powerful Digital Signal Processing chip, is in some of the new hard disk drives.

Phase locked loops are available as single integrated circuits. The Signetics NE567 has been available for years, and when combined with external frequency dividers can make a functional PLL. Other PLL ICs specifically intended for motor speed control without external programmable dividers for the motor speed include the Unitrode UC3633. This is not to understate the task; PLL design can be rather tricky, but is within the realm of circuits that the hobbyist can design and build, especially with parts like these.

Motor control systems are available off the shelf from Superior Electric, Kolmorgen, Parker and others. These often find their way into surplus houses and can be obtained for small fraction of their list price.

3. Stepper Motors

Stepper motors are currently very widely used by the telescope drive designer. These are specialized DC motors with a rotor that turns discrete fractions of a rotation when a DC pulse is applied. The standard stepper motor steps in 1.8° increments (200 per revolution), but half-step motors (0.9°, as the name implies) are widely available as well. Most motors can be made to step in very small increments; microstepping in up to 200,000 steps per revolution by carefully varying the timing of pulses applied to the motor's windings. This is not without performance penalty, and the accuracy of microsteps is often not as good as the accuracy of larger steps. The main contribution of microstepping is to smooth the motion of the motor.

Another thing to note is that 200,000 steps per revolution still leaves the step size bigger than the desired ½ arcsecond accuracy we set for ourselves earlier (it's 6.48 arcseconds per step) so we still need to drive some sort of gearing. When you look at real applications for stepper motors in modern telescopes, they almost invariably are being used simply as a variable speed motor.

Let's consider a motor with the more common 0.9° step size, commonly called a half-step motor. There are 400 of these steps in one rotation. We want each step to be 0.5 arcsecond at the driven shaft, so let's find the gear reduction we need:

$$\text{Gear Reduction} = \frac{0.9°}{(138.89 \times 10^{-6})} = 6480$$

where 138.89×10^{-6} degree is the equivalent of 0.5 arcsecond. Now 6480 is not a very large gear reduction, especially compared to the one we examined in the AC motor section. What's the shaft speed of this motor? We need for the motor to cover 15 arcseconds of sky per second of clock time. Since we make two steps to cover one arcsecond, we need 30 steps per second. We thus rotate 30 steps X 0.9° per step, or 27 degrees per second at the motor. 27 degrees per second for 60 seconds yields 1620 degrees in one minute. Finally, dividing by 360 degrees per revolution yields 4.5 RPM at the motor. Carrying out higher precision calculations, based on the length of the sidereal day being 23 hrs, 56 minutes, 4.09 seconds long, we find a motor speed of 4.5123 RPM.

How many steps are required to turn 4.5123 RPM? There are 400 steps per rotation so 400 times 4.5123 or 1804.9 steps. This will typically take a multiple of this number of steps on the wires of the motor.

One of the advantages of this scheme is that if we want to slew the telescope, we can step at a higher rate. Most motors will allow us to toggle at a much higher rate than this, and with the full step sizes, instead of the half step size just shown, fairly large slew rates are possible.

How do we find a 6480:1 gear ratio? 6400 is 80^2 so we see 6480 is 80 x 81. That's not a very good pair, but it's also 36 x 180, which I like. If I make a 36 inch polar wheel driven by a friction drive with a one inch diameter bearing, this one inch wheel needs to be driven by a 180:1 gear ratio. A 12 tooth and 15 tooth gear combine to give that reduction, as do 10 X 18, 9 X 20, and 6 X 30. Another way of doing it is a common 180 tooth worm slowed down by a 36:1 speed reducer.

In a more practical system, you might want to step in less than ½ arcsecond, perhaps ¼ or less. You can cut the step size in half by doubling the gear ratio, but you need to make up for the decrease in speed at the driven axis by doubling the motor speed. You could also decide you are going to run the motor at some higher speed, perhaps 200—400 RPM, and then compute the drive gears in any of the ways we've seen already. This ensures that your smallest step will be much smaller than the 0.5 arcsecond we have been shooting for. If you are going to replace a motor in an existing drive train, you need to match the motor speed to the motor that's being replaced.

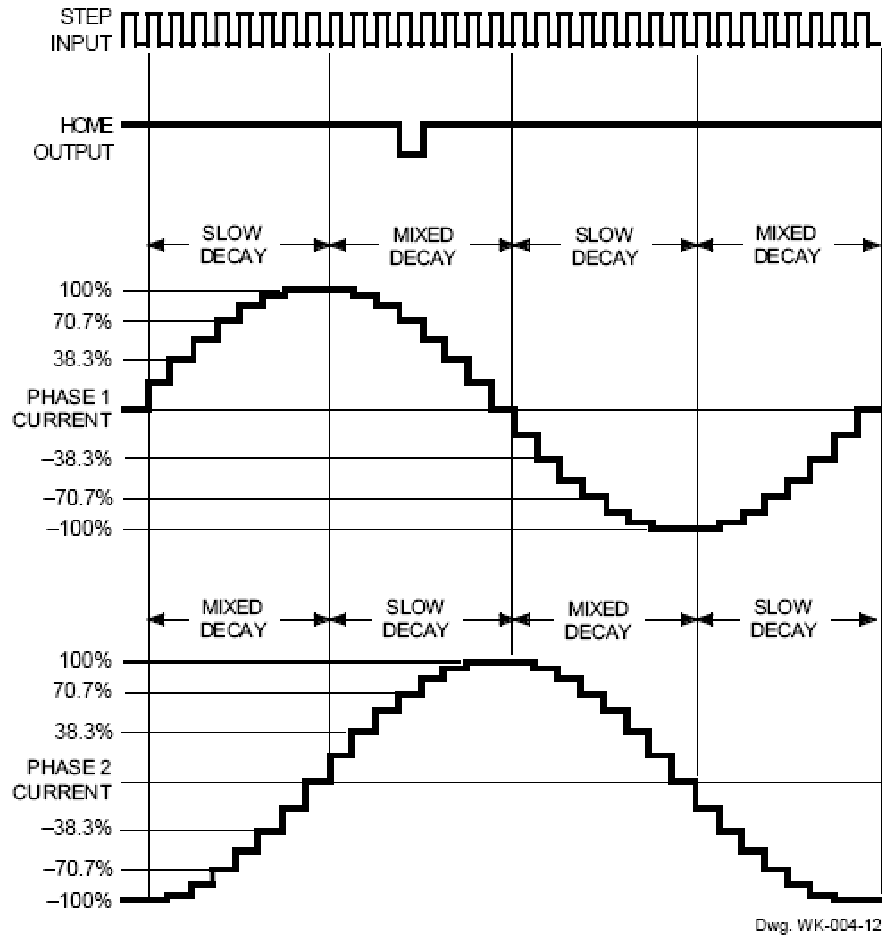
A modern Xylotex Nema 23 size motor. This little brute will deliver 260 in-oz of torque. Early NEMA 23 motors hardly delivered 75 in-oz.

Some Stepper Practicalities

Stepper motors have torque ratings that are expressed as “Holding torque” or simply torque. This is at the point where the motor is about to stall, and is the most torque the motor can deliver. When the motor is moving faster, it is capable of less torque. Like most electrical components, steppers get better every year, and you might think twice about using motors from an old floppy disk drive in that dream scope of yours. That said, since you’re usually driving a heavily geared down motor, the torque of the motor is multiplied up by that ratio and small motors will move large scopes if everything is balanced properly.

Stepper motors have more intricate drive requirements than AC or conventional DC motors. They need to be provided with sources of pulse trains, not simple voltages. All of the manufacturers of stepper motors supply controllers that will run their motors without the need for computer control. There are also suppliers of stepper motor controllers for various hobby activities and circuits that the hobbyist can build to drive them directly.

The basic principle is to generate square wave current pulses for the two windings. The frequency of these steps sets the motor speed, and stopping the pulses stops the motor. Because it is difficult to change the current through a motor quickly (the motor coil resists this change), high current driver circuits are needed. There are single IC drivers available from Motorola, Sprague and others to provide the current needed. The Allegro semiconductor A3977 controller allows you to microstep in 1/8 steps and will drive many small motors easily, with a properly handled external power supply. It is very popular with the home CNC machining crowd, and in industry.



Microstepping Operation for a motor stepping in 1/8 steps. – A3977 datasheet.

Discrete power transistors are a good option if you don't want to use an integrated solution like the A3977, and they don't have to be fancy or high speed. One way to force more current into the motor is simply to run higher voltages. Some circuits will tailor the shape of the current pulse, making the start of the pulse higher voltage than the rest of the pulse. This helps overcome the start up problem. Other circuits will "chop" the drive voltage (switch it on and off quickly) to reduce the average power consumption.

There is another problem that can be even more difficult to find, and that is resonance. Thankfully, it is relatively rare. If a motor is lightly loaded or used with a gear train that has excessive backlash, a speed can be found where zero torque is available. This can be at the speed you want to run.

Motors are electrically noisy. All motors suffer from this to some extent, but steppers are particularly bad. If you are controlling the motor with your

computer, be sure to run big ground wires to the motors and the power circuit. Run a separate ground wire from your battery to the motors, rather than using the ground wire to your electronics/computer. Shielding may be necessary, especially if you listen to an AM radio or time occultations with WWV on a shortwave receiver!

In a similar way, stepper motors and their controllers can be susceptible to noise pickup from the environment. If your motor has periods of erratic operation, perhaps skipping steps or moving when you're not trying to move it, suspect interference from other noisy things in the area. It could be a transmitter, like an FRS radio, or some other type. While I haven't seen strange motion caused by Bluetooth, or WiFi setups, that would not be terribly surprising.

The most commonly found motors in the surplus arena are those from old disk drives. The old 8 inch drives used a big stepper for positioning the read/write head. These motors are often still good even when the drive has been junked, and 8 inch drives are usually free for the asking, if you can find them. (I've seen them under the table at amateur radio swapfests, usually a sign that the seller will take just about anything for them or be glad to give them to you if they're getting ready to leave!). The surplus dealers frequently carry small motors for modest prices and these motors have all the torque that small telescopes will need.

Steppers are sized by the NEMA class, which refers to their mounting hole pattern. Nema 23 motors, with typically 100 to 200 in-oz of torque and simple drive requirements will handle any well-balanced telescope in up to meter-class diameters.

An Autoguider Standard

Santa Barbara Instruments Group – SBIG, makers of some of the most highly regarded CCD cameras – initiated a standard interface for autoguiders to feed back commands to a motor drive. You would be wise to use this standard instead of inventing your own. The standard connector is the RJ11 6 pin connector used on telephone cables. These are less common than the 4 pin cables used on single line phones, but are widely available.

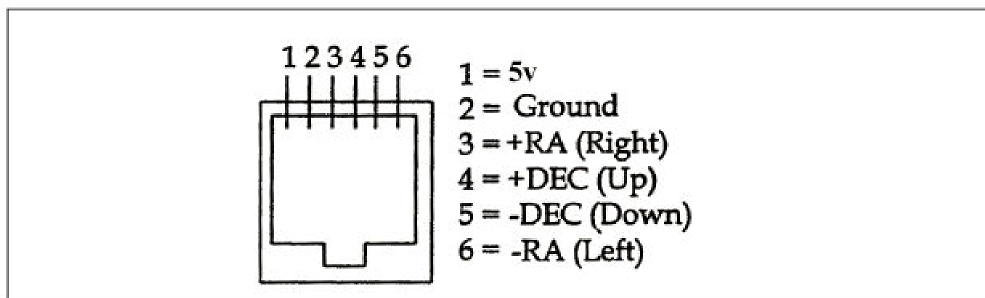


Figure 10 Standard Autoguider Port

The hardware protocol is that the camera feeds back contact closures between the pin RA right (positive) or RA left (negative) for instance, and the ground. The pins are active low (ground) and pulled up to 5V on the camera. The camera's output pins will sink 25 mA. The contact closure tells the system to go in that direction.

Clutch Answers

Any motor will need a mechanism for removing it from the drive chain, so that if you push the telescope the motor doesn't get damaged. This is the job of a clutch. The principle is not difficult; you simply need to allow the drive shaft to slip if torque is applied. Clutches are among the basic mechanical devices: all power transmission systems have one. Cars, trucks, motorcycles, even lawnmowers and chainsaws have a method of removing the moving load from the running motor. The manual transmission car has a separate clutch pedal, while the automatic transmission uses fluids to achieve the same motions (arguably, smoother and better than the typical car driver can). The execution can be harder than the concept.

A common approach is to have the drive system apply drive at all time, but slip when you want to move the scope by hand. An adaptation of the drag system used on fishing reels, especially those used by light tackle sport fishermen would fit nicely here. An exploded diagram of a sample friction drag system is shown in Figure 11.

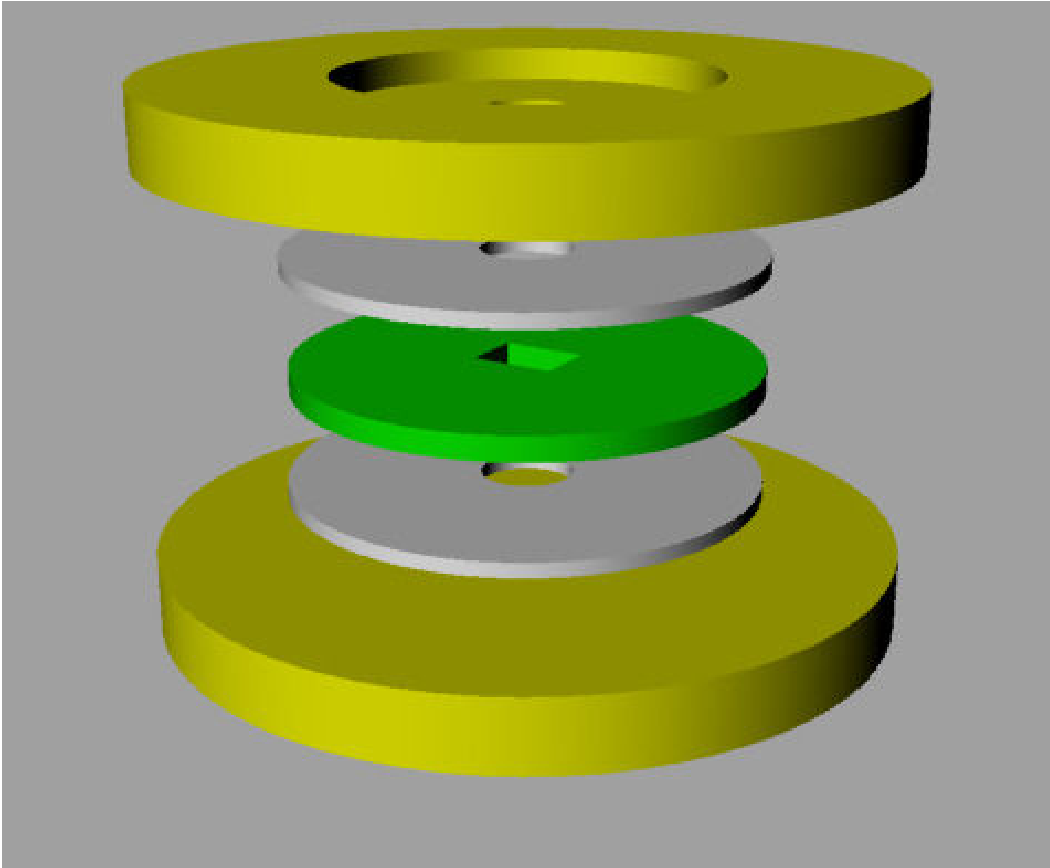


Figure 11 A Friction Clutch System

In operation, the motor drive shaft drives only the inner metal washer – shown here in green – by having a flat spot ground or machined into the round shaft. The shaft passes all the way through the stack and the mount contacts the top yellow disk, which is held in place with a nut on the drive shaft. The base yellow wheel serves simply as the other side of the mechanical stack up. When the nut is tightened, the stack is compressed clamping the friction washers, shown in gray, and increasing the friction force the washers offer. When the friction is high, it rotates the yellow wheels and thereby the driven part of the mount. When the nut is loose and the friction low, the green disk will rotate freely with respect to the rest of the stack up and nothing gets driven. Getting the tension right is accomplished by tightening the nut on the top until the motor can turn the load without slipping, but manually moving the scope causes it to slip.

A cheap and dirty approach to the problem is to pick up a fishing reel at a garage sale or department store, and use the shaft and spool. Saltwater spinning reels typically use a one piece spool driven by a long shaft, and the combination will work well for lighter instruments. The stack of hardware similar to this illustration is inside the spool, and can be revealed by removing the drag adjustment knob. The so-called “deep sea” reels, typified by the Penn brand Senator models, use strong spools and shafts. The Teflon in the smaller reels is replaced by much tougher materials, not subject to the cold flow that Teflon

shows. The spools are quite big, but may be appropriate for a larger telescope. Due to the design of these reels, the shaft is very short and probably unusable.

You may not really need a clutch, though. The popular GoTo mounts sold by the big companies have abandoned clutches for a simple reason: for the controller to keep track of where the scope is pointing, it needs constant drive. If you were to allow the motors and encoders to slip at any rate, that would make the controller loose track of where it's pointed. These telescopes have a gear engagement lock instead of a clutch. When the lock is not engaged, the telescope moves freely. When it is engaged it can not slip (under reasonable loads).

References and Further Reading

1. Covington, Michael, Astrophotography for the Amateur, 1985, Cambridge University Press, Cambridge, United Kingdom.

2. Texereau, Jean, How to Make a Telescope, 2nd English Edition, 1984, Willmann-Bell, Richmond, VA.

3. Trueblood, Mark and Genet, Russell, Microcomputer Control of Tele scopes, 1985, Willmann-Bell, Richmond, VA.

4. Wright, John, "A Method of Making Worm Gears of Any Diameter," Telescope Making #33, Summer, 1988, Kalmbach Publishing, Milwaukee, WI.

5. Woods, A.L., "An Equatorial Plate Fork Mounting," Telescope Making #30, Summer, 1987, Kalmbach Publishing, Milwaukee, WI.

6. Avallone, Eugene A., and Baumeister, Theodore, editors, Mark's Standard Handbook for Mechanical Engineers, 9th ed., 1987, McGraw-Hill, New York, NY.

7. Xylotex: http://www.xylotex.com/ produces stepper controller products and sells motor and the other necessary parts for hooking up stepper motors.

8. "Dr. Gears" http://www.drgears.com/GearTerms/GearTermIndex.htm an online glossary of gear terms with illustrations and animations.