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Software for Telescope Servo System

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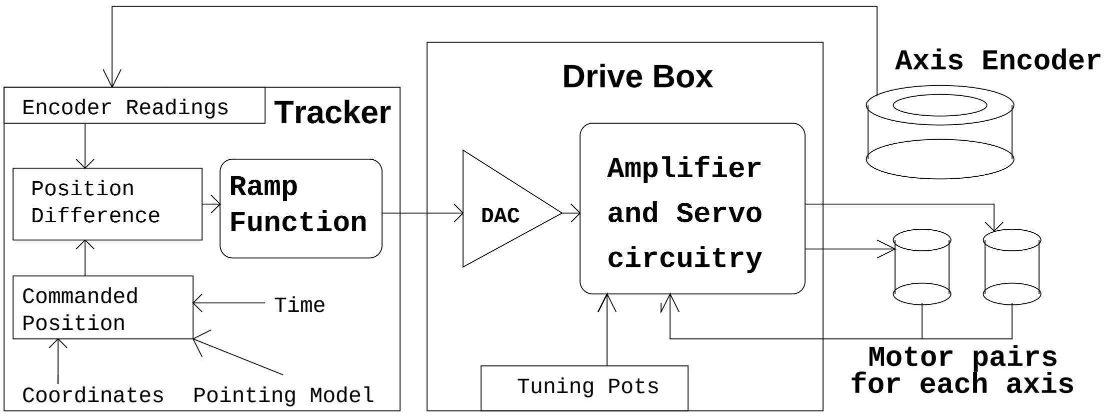
Abstract

This memorandum describes the software servo system used on AST/RO. The tracking program `tracker` controls the movement of the telescope. The form and parameters of the Ramp Function is described and discussed. The user can change these parameters to fine-tune the responsivity and stability of the telescope. The optical telescope and the `rc` command can be used to observe the dynamic properties of the telescope.

1 The drive system for AST/RO

The AST/RO drive system controls the motions of the telescope. Several levels of servo loops keep the telescope pointing and tracking accurately and smoothly. The block diagram below shows the structure of the computer-drivebox-motor-encoder servo loop, and the amplifier-ServoCircuity-motor-tachometer servo loop.



Servos for the AST/RO Drive System

For the computer-drivebox-motor-encoder loop, the program `tracker` that runs on the computer reads the axis encoders to obtain the position of the telescope, and sends angular velocity commands to the Drive Box. The Drive Box translates the command to the amount of current that powers the axial motor pairs for each of the azimuth and elevation axis.

The hardware servo circuitries in the amplifier-ServoCircuitry-motor-tachometer servo loop keeps the motor rotating as close to the computer-issued commanded angular velocity as possible. Although tuning of the hardware servo using the pots mounted on the circuit board can be crucial to the telescope pointing and tracking performance, details of this hardware servo loop falls beyond the scope of the memo. The behavior of this loop is simplified here to be : A) when the telescope is slewing at a steady speed, the speed of the telescope rotation is proportional to the angular velocity command that the computer sends to the Servo Box; B) When the telescope is accelerating or decelerating, there exists a difference between the real angular velocity of the telescope and the computer's angular velocity command. This angular velocity difference (hereafter referred as ω_{diff}), when fed into the hardware servo loop, cause a proportional amount of current that flows through the drive motors. Assuming the torque generated by the motors is proportional to to the current flowing through the motors, point B means that ω_{diff} is proportional to the acceleration of the telescope rotation:

$$\frac{d\omega}{dt} = -A\omega_{diff} \tag{1}$$

where A is a positive constant. This relation will be used in to develope the Ramp Function in `tracker`.

2 The `tracker` program

The telescope motion control software `tracker` (named as `ntracker` for AST/RO) controls the pointing and tracking of the telescope. It calculates the difference between the telescope position and the commanded telescope position, and sends out angular velocity command to the telescope drive system to minimize this difference. `Tracker` runs as a separate process from the program OBS, It communicate with OBS using the shared memory mechanism provided by the LynxOS. Most part of `tracker` is inside a perpetual loop. The loop, driven by a clock driver, runs at a period 10 milliseconds.

In every cycle `tracker` calculates the commanded telescope position using the current time, coordinates of the object, and the pointing model. Then `tracker` reads the telescope axis encoders to obtain the current position of the telescope for each of the azimuth and elevation axes. `Tracker` compares the encoder position with the commanded position and calculates the position difference. In addition, `tracker` also uses the current telescope position and old positions obtained in the last several cycles to calculate a "measured angular velocity" (Ω_m) of the telescope.

`Tracker` uses the position difference and the measured angular velocity of the telescope to calculate a angular velocity command using the Ramp Function, which is described in the next section. The angular velocity command is in the form of the input of a 16-bit Digital-Analog Convertor (DAC) used in the motor Drive Box. The output of this DAC is amplified and sent to the drive motors of the telescope.

3 The Ramp Function

In order to keep the telescope movement smooth, responsive and stable, a procedure is developed to calculate the commanded velocity for the telescope according to the telescope status. This procedure is implemented in the Ramp Function.

Two pieces of information are prepared and provided by `tracker` to the Ramp Function for each axis, one is currently how much difference there is between where the telescope is pointing to (p) and where the telescope the computer wants the telescope to (p_{cmd}); the other is the current Ω_m.

3.1 the formula

The formula to calculate the angular velocity command is

$$\omega_{cmd} = \texttt{sign}(p_{cmd} - p) \cdot M \cdot S \cdot |p_{cmd} - p|^{\gamma} + D \tag{2}$$

where ω_{cmd} is the angular velocity command, M the maximum input that the DAC in the Drive Box accepts (`0x7fff`), S the scaling factor, p_{cmd} the position the computer wants the telescope to point to, p the real position of the telescope read from encoder, and D a damping term. The sign function $\texttt{sign}(p_{cmd} - p)$ takes the sign of $(p_{cmd} - p)$.

The exponent γ allows fine-tuning of how steep the commanded velocity increases when the position difference $(p_{cmd} - p)$ becomes larger. This power-law form of the Ramp Function allows the commanded velocity to be small when the position difference is small, and accelerate the telescope quickly when the destination is far from the current position. It can be shown that if a constant torque is to be maintained through out the acceleration period, γ should be 0.5. However, usually the γ is determined by tracking stability considerations.

The angular velocity command remains at a constant maximum value that is M when the position difference is larger than a maximum ramp-up distance. This maximum ramp-up distance, denoted by R_m, is pre-selected and is used to calculate the value of S:

$$S = \frac{1}{R_m^{\gamma}} \tag{3}$$

For azimuth axis R_m is around 6 degrees. The elevation axis has smaller rotational intertia so maximum ramp-up distance is about 4 degrees. When the destination point is farther than R_m, $\pm M$ is sent out as ω_{cmd} depends on the rotation direction.

3.2 servo stability

For each axis, we have the relation described in equation (1)

$$\frac{d\omega}{dt} = -A\omega_{diff} = -A(\omega - \omega_{cmd}) \tag{4}$$

where ω is the angular velocity the telescope rotates at. If we use a linear relation to approximate the behavior of the Ramp Function when $(p_{cmd} - p)$ changes from 0 to a certain small number p_s, then the software servo can be taken as providing the telescope a torque that is proportional to the negative p_s. This can be expressed as

$$\omega_{cmd} = B(p_{cmd} - p) \tag{5}$$

where B is a positive constant:

$$B = \frac{M \cdot S \cdot p_s^{\gamma}}{p_s} \tag{6}$$

Note that when p_s is small compared with R_m, B decreases when γ increases.

Realizing the following relations

$$\frac{dp}{dt} = \omega \tag{7}$$

and

$$\frac{d^2p}{dt^2} = \frac{d\omega}{dt}, \tag{8}$$

from equations (4) and (5) we have

$$\frac{d^2p}{dt^2} + A\frac{dp}{dt} + ABp = ABp_{cmd} \tag{9}$$

The above equation has oscillatory solutions when $A < 4B$. Since A is related to the amplification of the hardware servo and rotational inertia of the telescope, it is basically not affected by changes in S and γ. This means *if either γ or R_m is too small, the telescope will become unstable.*

A rigid servo loop (large B) means quicker responce of the telescope to tracking errors and changes of commanded position. But depending on the tuning of the hardware servo in the the hardware Drive Box, the responce of the AST/RO telescope and the hardware servo becomes unstable with software servo loop that is too rigid. This instability shows in the form of oscillation. Sometimes the vibration can be very strong as to be felt in the control room, or can be subtle as intermittent oscillation which is hard to notice.

The oscillation can be seen from several places such as 1) the RMS of position differences displayed on the `namon` screen has a value that is larger than several millidegrees. This RMS value is calculated using $(p - p_{cmd})$ in the last two seconds for each axis. They can also be accessed by the two dot variables: `.prmsa` and `.prmse`. 2) On the monitor screen of the CCD camera of the optical guide-scope, the stars have streak-like looks. 3) The encoder display on the red LED panel on the Servo Box rack shows varying numbers when the telescope is supposed to stay still, or the az encoder reading isn't counting down smoothly during tracking.

When the telescope vibrates at a small amplitude, the integration will have extra long finish time, and produce a high *Nbad*. To understand this, it is necessary to understand how `tracker` determines when an object is in position. In every 10 ms cycle, `tracker` considers the pointing is good when $(p - p_{cmd})$ is smaller than a preset error criterion. The error criterion is stored in the shared memory as `sm.sv.errorCriterion`, in the unit of turns (i.e. 0.001 means 0.36 degrees) and can be accessed at OBS command line using vaiable `.trcr`. The criterion is usually set in the start-up macro `strt` in the OBS global macro `.nGMACROS`. The variable `sm.sv.servoError` in the shared memory will be set or reset accordingly by `tracker` every cycle. So during an integration when the telescope is supposed to be pointing to a certain derection, `tracker` will discard the scan if the telescope is not in position, and *Nbad* in the scan header is incremented. If the telescope vibrates, it posible that most of the time the telescope is not in position.

3.3 stabilizing and damping

In order to eliminate spurious oscillation, γ should be kept small and R_m remain large. However when B is too small the telescope will move sluggishly. In order for the telescope to have effcient movent, small tracking errors, and stronger resistent wind gusts, the telescope should be responsive to $(p - p_{cmd})$. The servo system that has the fastest settle time when the telescope slews to a new position usually has a slight over-shooting and quickly diminishing ringing after reaching the new position. This means the system is oscillatory but has damping factors.

Damping factors that exist in the AST/RO drive system include the mechanical friction in the bearings used on the telescope, and the negative differential feedback in the hardware servo loop in the Drive Box. Because of the variation of the mechanical friction and difficulty in tuning the hardware servo, the Ramp Function has a built-in damping term D to explicitly influence damping of the telescope motion.

The damping term D emulates a "viscosity effect", which is a deceleration proportional to and in the opposite direction of the current telescope velocity. From equation (1) we know that, in a first order approximation, in a transient state, the hardware servo system will accelerate the telescope at a rate that is proportional to the difference between the commanded angular velocity issued by the computer and the telescope angular velocity measured with the tachometer. So by modifying the commanded angular velocity, the `tracker` can command extra acceleration as is desired. The term D is construct to be proportional to the measured angular velocity of the telescope but in opposite direction:

$$D = -d \cdot \Omega_m \tag{10}$$

where d is a positive damping factor and Ω_m the measured angular velocity. The effect of the term D on the telescope is a viscous deceleration.

In the 1997 austral winter a spurious oscillation caused by the servo hardware problem occured. The damping term was used to reduce the RMS of the oscillation by a factor of 5 so that it was within half telescope beam.

Note that the damping term has its limitations. The assumptions about the hardware servo isn't always a good one. The 10 ms cycle of `tracker` isn't always fast enough for all conditions. The damping term in the Ramp Function is usually set to 0 to reduce the system complexity. Well tuned hardware damping is preferable than software damping.

3.4 code for the Ramp Function and software tuning parameters

The Ramp Function has three coefficients S, γ, and d that can be used to change the responsive character of the telescope. By default d is set to 0. These coefficient can be accessed in OBS by the user via a set of *dot variables*. They are `.faz1` for S, `.faz2` for γ, `.faz3` for d, and `.fel1`, `.fel2`, and `.fel3` for the elevation axis. These variables will be referred as tuning parameters.

The tuning parameters have counter parts in the shared memory. The initialization of them have been discussed above, and is carried out when `tracker` is started when these lines of code are run:

```
svp->faz3 = 0.;
svp->faz2 = 1.0;
svp->faz1 = 1.0/pow(6.5/360,svp->faz2);
svp->fel3 = 0.0;
svp->fel2 = 1.0;
svp->fel1 = 1.0/pow(6.5/360,svp->fel2);
```

The pointer `svp` points to the `sm.sv` structure in the shared memory.

The Ramp Function

$$\omega_{cmd} = \mathtt{sign}(p_{cmd} - p) \cdot M \cdot S \cdot |p_{cmd} - p|^{\gamma} - d \cdot \Omega_m \qquad (11)$$

is implemented in `tracker` as two simple functions `azSpeed()` and `elSpeed()`. This is `azSpeed()`:

```
int azSpeed(diff, encV)
double diff;
short int encV;
{
    register int v, max;
```

```
    max = (int) (MAXVP * sm->sv.faz1);
    /* objective velocity according to a certain curve at this spot */
    v = max * pow(fabs(diff),sm->sv.faz2);
    /* servo quirk. goes to "-" when sending "+"*/
    if ( diff > 0 ) v = -v;
    /* velocity feed back. */
    /* damping */
    v = v - sm->sv.faz3*encV;
    /* cut at the limit */
    if (abs(v) > MAXVP) v = (v>=0) ? MAXVP : -MAXVP;
    return v;
}
```

`MAXVP` is the M in the Ramp Function that is `0x7fff`.

The next section some useful techniques to tune the telescope servo responsiveness will be discussed.

4 Telescope servo tuning using software parameters

Without going into a full-blown transfer-function analysis, there are methods to observe the dynamic characters of the telescope and tune the telescope by experimenting with the software tuning parameters according to the observing result. Two methods that can be used to to examine the transient movement and behaviors of telescope are described in following sections, one involves using the optical pointing telescope, the other using the `rc` command to record the encoder readings of the telescope.

4.1 using the optical telescope

Using the optical guide telescope that was installed for optical pointing, one can see the telescope movement from the shifting of the star on the display of the CCD. Set the CCD display software at a high refreshing rate, e.g. 200 ms, and select a star that is bright enough to see on the computer monitor screen easily, but not so bright as to result streaks or strong saturation trails. When the telescope is moved into the position of the star, one can see on the CCD screen whether the track of the star shows behaviors such as over-shooting, ringing, oscillation that is not dying down, or whether the telescope is inching toward the final position too slowly. One can use the

The reason to have a responsive telescope has been mentioned in the previous section. A good tuning results short moving time between one telescope position to another. This efficiency of movement benefits the position-switched observations, in which case the telescope keeps moving back and forth from fixed source and reference positions. Experience shows that the minimum moving time between to position is obtained when the telescope over-shoots a little and quickly settles down on the target position. However note that the exact setting of the tuning parameters depends on many other factors such as how far apart these two points are and which elevation the telescope is pointing to. Small R_m and small γ usually results faster acceleration and makes the telescope more prone to over-shooting. When B is too large the telescope tracking becomes instable and prone to oscillation when small perturbations occur. The damping term can be used to stabilize the telescope either when explicit damping control is needed or during experiments.

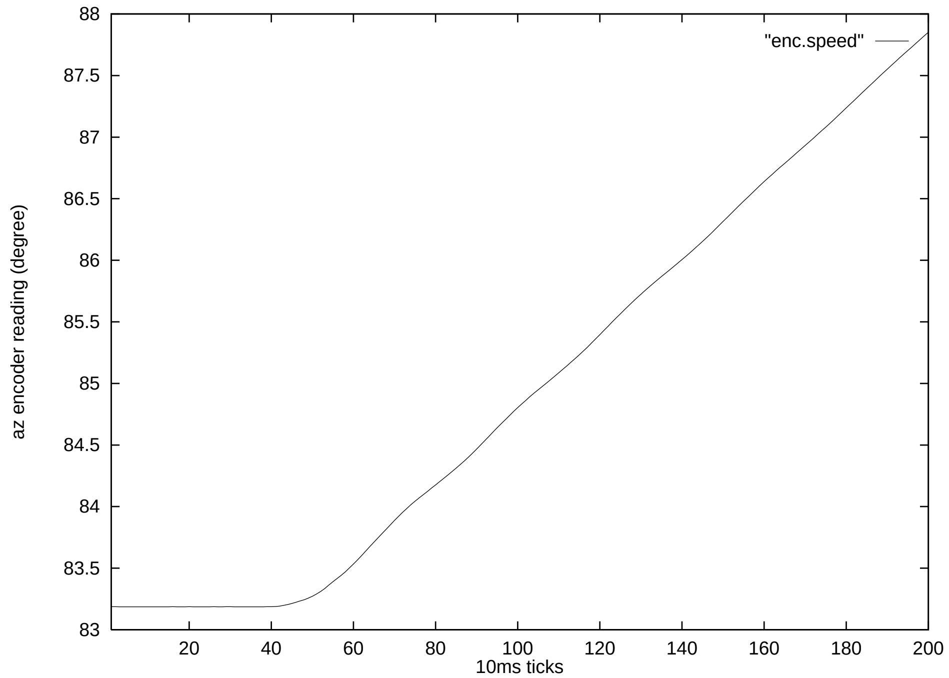
4.2 using the `rc` command

Although the optical telescope can allow quick visual examination of the telescope behaviors, often a quantitative description of the telescope movement during a long period of time is needed.

The `rc` command in OBS is able to log the encoder readings of the telescope in a buffer of the computer memory, and dump the reading into a file when needed. The on-line documentation of the `rc` command describes how to start and stop recording, and how to write the recorded result to a file.

Since the recording can be made when OBS is running normal commands, `rc` can be used to catch intermittent drive problems.

The figure below show an example recording of the azimuth encoder readings using the `rc` command.



The unit of the vertical axis in the figure has been converted from 23-bit binary to degrees. The x axis shows time in the unit of 10 ms ticks.

The OBS commands used to generate the recording are in the form of:

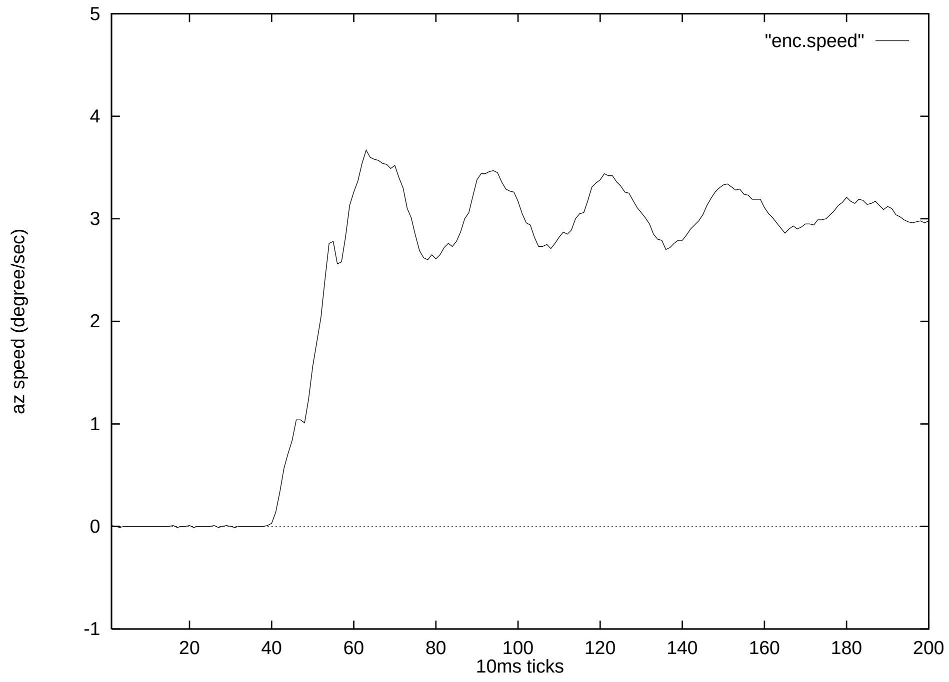
```
-> az 0; pa tr: // wait for the telescope to stop
-> rc enc:30
-> az 100 // telescope will start to slew
...
-> rc en:-1 f:"enc"
```

The above figure only shows the azimuth encoder reading during acceleration period. Since the target azimuth is farther than the maximum ramp-up distance (usually about 6 degrees), the maximum velocity command allowed by the Ramp Function is sent to the Drive Box when the `az 100` command is entered. So the angular velocity command sent to the DAC resembles to a step function with respect to time.

With quantatitive measurement of the telescope movement recorded, more sophisticated analysis can be conducted to calculate the properties of the telescope and the status of the servo syste. Adjustment of the servo system can be made based on result of these analyes.

However experience and simple figure-reading can often be sufficient to find out the problem of the servo. Tuning using the experiment method discussed in the section of using optical telescope can still be used.

The next figure shows the telescope speed calculated from encoder readings shown in the above figure. The unit of the vertical axis is degree per second.



5 Discussions

There are many other factors to consider when tuning the telescope besides the moving efficiency and stability of the servo. For example when the telescope accelerates or decelerates, the telescope will shake the base structure and the optic table. Receivers and optics working at submilimeter wavelengths could be affected by residual vibration, which could cause baseline problem in the spectra that is being taken.

Note that the tuning of the hardware servo, which is not being dicussed in this memo, can grately affect the dynamic properties of the telescope. For example even a simple non-zero offset in the op-amp used with the DAC can cause very puzzling problem. Due to the said offset, a slow drifting of the telescope will occur when the angular velocity command from the computer is 0 and when the brake is released. However the puzzling part of this problem is that when tracker is off, the telescope brake usually is applied so the operator doesn't see the drifting. When the problem does show, it is a mysterious constant pointing error when tracker is on, because `tracker` has to maintain a pointing error to compensate the velocity drift caused by the non-zero op-amp offset. An unsuspecting operator usually is tricked into looking for software reason to solve the problem.

Apparently more refined tuning and Ramp Function can be developed based on more rigorous analyses of the telescope. It can be tempting to add more sophistication to the Ramp Function. However, as memory tells, the "Keep It Simple and Stupid" rule has been vindicated many times.