

Design of a Motion Controller for VLA Antenna Azimuth and Elevation

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NATIONAL RADIO ASTRONOMY OBSERVATORY
CHARLOTTESVILLE, VA

A Senior Design Project with the New Mexico Institute of Mining and Technology
Electrical Engineering Department in the service of the National Radio Astronomy
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Design Group Members: Nathaniel Dale and Jack Landes, NMIMT.
Advisor: Kevin Wedeward, Electrical Engineering Dept., NMIMT
Customers: Clint Janes and Bob Broilo, National Radio Astronomy Observatory
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Introduction

The main objective of our project is to design a motion controller whereby point-to-point repositioning and tracking motion of a radio telescope antenna at the Very Large Array (VLA) site can be achieved in the least amount of time and to prevent damage to its structure and mechanical systems. The motion controller, which serves to simultaneously change the azimuth and elevation orientations of the primary reflectors (the dish) of an individual antenna's parabolic reflector, actuates two motors per axis using position data sent via a data line from a computer in the Control Building at the VLA site. In actuating the motors, the controller smoothly varies the acceleration rate between zero and maximum values such that the antenna can be moved without noticeably overshooting an intended target position. By preventing overshoot the settling time and the angle by which overshoot occurs can be reduced, resulting in a lower overall time for antenna motion and a decrease in stresses applied to the antenna. The actual controller designed for this purpose has a user interface, a software control panel, where loop gains and maximum absolute accelerations and velocities can be set, allowing for the system response to be optimized.

1.1 Final Results

A primary result of this project is the provision of a well-documented report, given here, to VLA engineering personnel that has the necessary details for implementing a desirable motion controller that meets their demands. Firstly, the design of the motion controller takes the form of a computer simulation that uses flow diagrams from control theory, and, secondly, as a C-based program for running software-based motion control hardware. Additionally, there will be a CD provided with this report that contains this report (in MS Word format), and all simulations and programs; however, none of the software needed for running those files will be included.

1.2 Types of Motion

There are two basic types of motion that the antennas at the VLA will undergo: point-to-point and tracking. In point-to-point operation, where an antenna is changed from one fixed position to a new fixed position, it is made to increase from zero to maximum rotational speed and then back to zero velocity to stop at the target location. For tracking motion an antenna is made to follow a point or region as it moves across the sky with the earth's rotation.

The Currently Used Motion Controllers

Presently, the control cards, whose design dates from the 1970s, which drive the motors to position the antenna, are composed almost entirely of discrete analog electronic components that were currently available. The two identical controllers, otherwise known as the A4 and A5 cards, control the azimuth and elevation motion, respectively. As well, the two control cards are used to indicate and respond to

different fault signals that may result from equipment failure. Also, they allow what's called Manual Mode operation where direct user control is applied through the control panel of the Antenna Control Unit (ACU) in which they are installed via on/off switches and potentiometer dials and a plug-in point for applying signals. As input under their normal mode of operation, referred to as Auto Mode, the control cards are sent a differential voltage proportional to the error or difference between the current and desired azimuth/elevation angles. The error signal is used by the controllers to drive the antenna toward the desired position. For feedback, they use analog input from tachometers, which indicate motor speed, that are connected to the armature of the motors; and as output, they provide an analog voltage that drives the motors with a proportional armature current. A more detailed look at how the A4 and A5 cards operate is available in the May 1999 report by the Senior Design group comprised of Tamara Barber and Shawn Sharp (1).

2.1 Problems With the Present Controllers

The currently used motion controller have the disadvantage of having fixed operation in that they cannot be adjusted to give different output responses, and as such are system-specific. Besides having very old components and their not having any means by which to make adjustments, the A4 and A5 cards' performance as motion controllers is rather low by current standards. To start and stop a point-to-point type of motion the controllers simply jump the motor current to full value to accelerate the motors until maximum velocity is reached, hold the velocity at maximum, then pulse the motors with a rapid deceleration-producing current as the antenna nears its endpoint. Large spikes in acceleration or deceleration occur at the hard starts and stops of this 'bang-bang' acceleration (2).

2.2 Mechanical Stress and Vibration Problems

The "hard starts" and "hard stops" of the currently used bang-bang acceleration type controller cause a large amount of position overshoot and oscillation of the antenna. This overshoot and oscillation combined with the large mass moment of the antenna generate extreme physical stresses that have occasionally resulted in damage to the driving gear system and structure, such as the motor and motor mount tearing loose from the antenna along its welds. Not only is the overshoot and oscillation damaging the antennas it is also reducing effective observation time with the large amount of time required for the antenna to settle to a point that usable data can be obtained, as is discussed in Section 3.1.

2.3 Tachometer Failure

At the time of this report, the tachometers connected to the motors that provide a DC voltage signal proportional to motor speed are being replaced. The tachometers, though accurate, are noisy, prone to failure, and expensive to repair, costing some \$750 to rebuilt each time, as they are no longer commercially available. The result is upon failure, with feedback to the controller no longer being available, the inability of

the motor to be controlled as needed. Their replacement will be 5-bit optical position encoders, which are comparatively cheap and much less prone to failure since they have fewer internal moving parts and have no electrical contacts or motor brushes, plus they will provide feedback containing information about motor position rather than simply motor speed.

Design Criteria

When complete, the newly designed controller will be able to provide smoother point-to-point and tracking motion, as well as to take over the other tasks required of the A4 and A5 control cards. Additionally, the ability to adjust or reprogram the motor controller is required, most preferably through the use of software controls. The controller should be capable enough to work properly during the different modes and types of motion.

3.1 A Comparison of Motion Types

As indicated previously, sudden jumps in acceleration or too large of absolute accelerations lead to overshoot as the antenna nears its designated position and is forced to stop. For point-to-point type motion, this requires, of course, that the maximum absolute accelerations actuated by the motors be decreased and, in order to compensate for the longer times resulting from the smoothing of the acceleration phases, the motors would be driven to a higher maximum speed between stopping and starting. Although it seems paradoxical that lower maximum accelerations would decrease the overall time duration for moving from point-to-point, the lower accelerations and a smoothing of the acceleration profile would allow for better dampening of the motion of the antenna mass. If, as a result of the antenna being accelerated too fast or too jerkily such that it overshoots its desired position then it would result in mechanical vibrations and, thus, large settling times of the springy antenna mass, increasing the overall time for repositioning. In situations where a large number of, say, 1 second duration motions are needed it might be required that the user or computer in the Control Building wait an additional 2 seconds between each movement, resulting in a smaller duration of time that an antenna can be pointed at a stellar object and be able to take data. In the case of tracking-type motion, where the velocities and accelerations used are both smaller, a smoothing of acceleration is still greatly needed. On the other hand, if the antenna is made to follow a smoothed trajectory then the transient effects of overshoot can more easily settle out. Figure 1 below shows qualitatively how trajectory profiles of the old controller and an optimal controller would compare:

Per Axis Motion Profiles

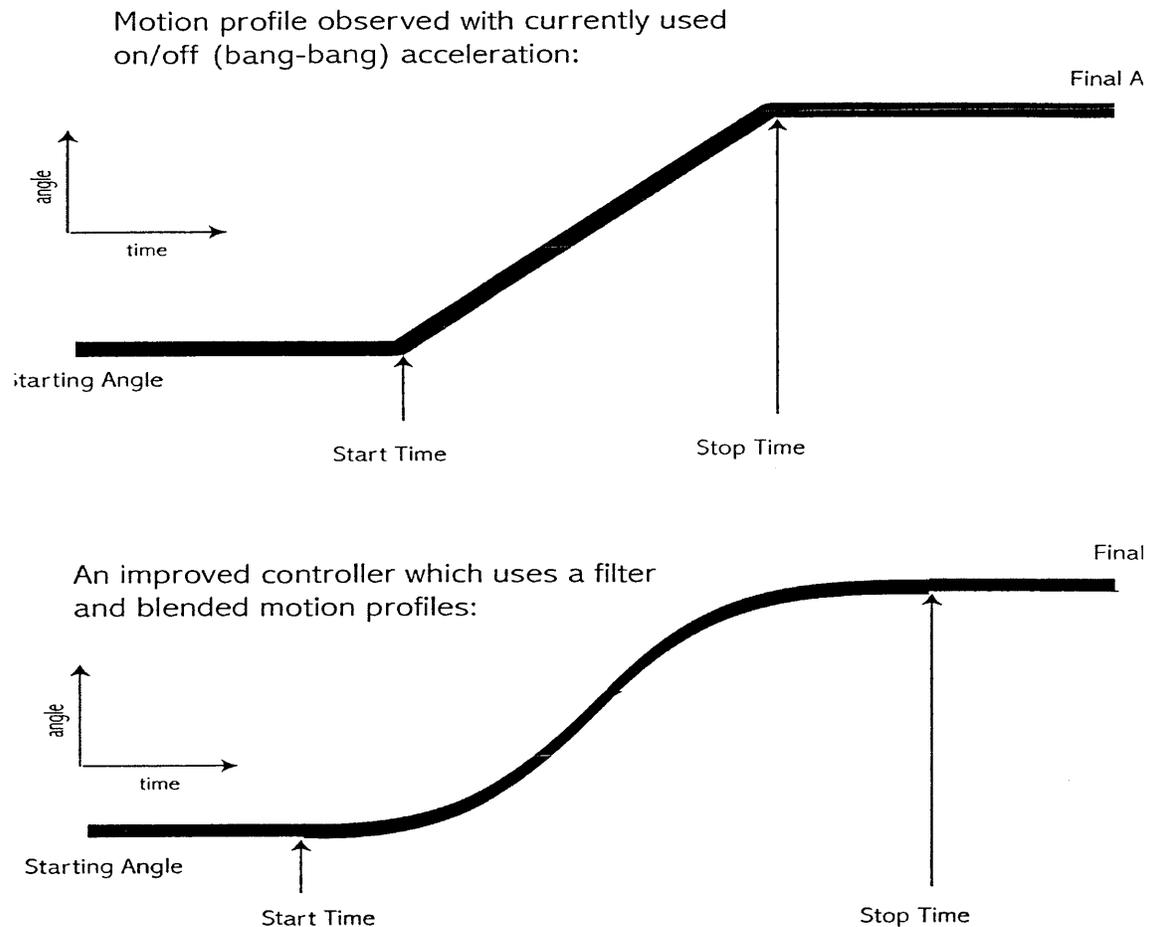


Figure 1: Motion Profile Comparison

3.2 Blended Motion Profiles

The most important motion criteria are “soft starts” and “soft stops”. These can be accomplished by using smooth acceleration profiles, which can then be twice integrated to give an angular position profile along which the motors can be made to track during an interval of time. In the case of point-to-point motion, the first step in creating a trajectory profile for the motors to track consists of creating smooth parabolic segments for acceleration phases of the motion, as shown in Figure 2a. This results in a profile where the acceleration increases from zero up to a maximum value before then being decreased back to zero in order to bring the speed of the motors and antenna to maximum speed; to stop, the reverse procedure is done where the acceleration is brought smoothly from zero to the minimum (negative)

acceleration rate and then back to zero. Shown in figure 2b is the first time integral of the acceleration to which the criteria of maximum attainable velocity is applied. Finally, the acceleration profile is integrated a second time and fit to the initial and final angle conditions shown in Figure 2c. The Barber and Sharp report gives a more complete discussion of how this is performed (3).

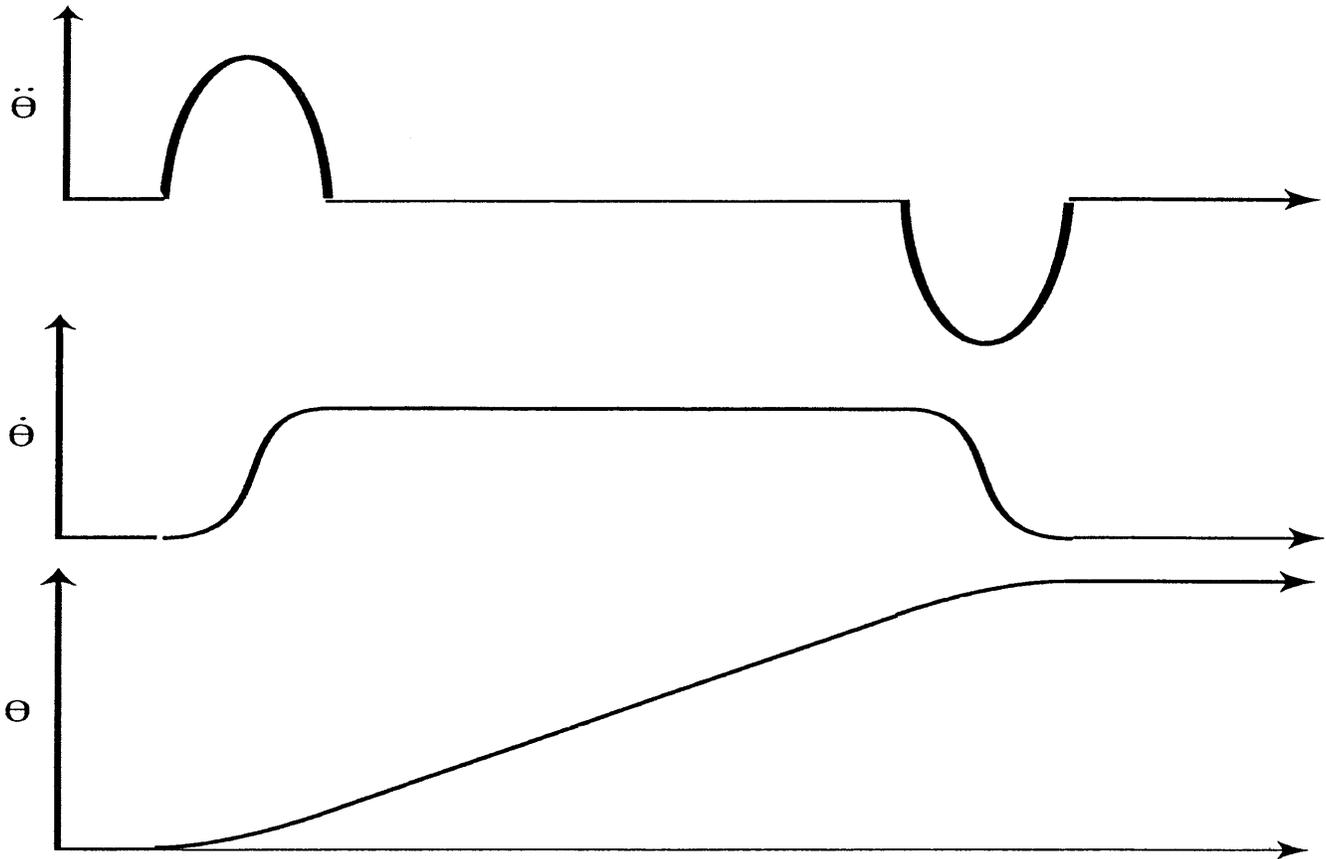


Figure 2: Blended Motion Profiles

3.3 A Tunable or Reprogrammable Controller

To ensure the ease of testing and reprogramming, the LabWindows/CVI program will be written to provide virtual instrumentation (VI), or user interfaces, that will appear as windows on the screen of the host PC. The VI's will not only provide an easy means of monitoring the functioning of the antennas, they will also enable users access to the controller gain settings and many other functions of the motion control card and its programming.

4. An Analysis of the Electromechanical System

Here we describe the general functionality of the azimuth/elevation motion control system, which include input and feedback signals, the controller, the motors and their drive circuitry, the gearing, and the antenna structure itself. A diagram representing the overall system is shown below in Figure 3:

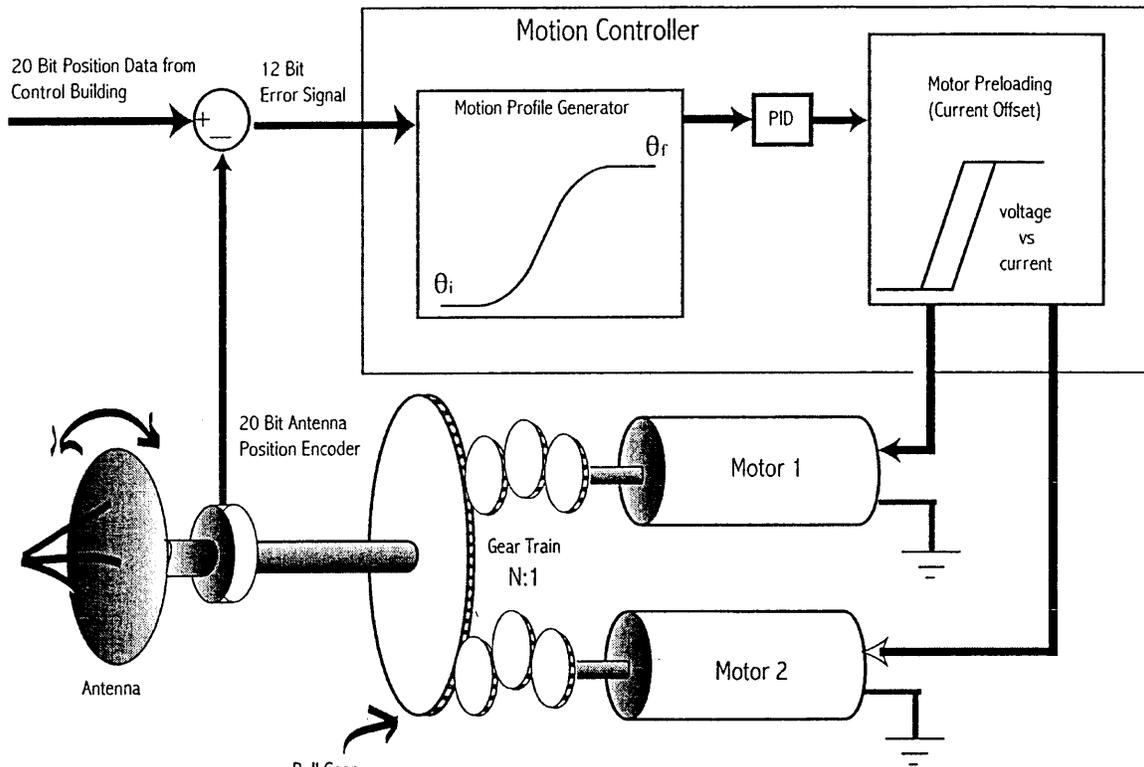


Figure 3: Antenna Motion System

4.1 Proportional Integral Derivative (PID) Control

As shown in the Figure 3 the trajectory profile computed for the given error signals are used by the proportional integral derivative (PID) filter to track the path as the profile is updated. The filter directly uses a feedback error generated by subtracting scaled motor position data, which is scaled to the antenna angle by the gear ratio 1:N.

4.2 Signal Input and Feedback

The primary signals going in and out of the controller include those of the antenna error position, the current command signal going into the motor drive circuitry, and scaled position feedback from the motors. Amongst the antenna error position and motor position feedback signals only the latter can be considered feedback since it is

updated frequently at a constant rate; the former, though useful, is not currently updated frequently enough for use as feed back but only for use as a command signal. If in the future, the antenna error position is made so that can be updated at a rate similar to the motor position feedback it would then be possible to combine the feedbacks, producing a state-feedback controller. It should be noted that a proper PID controller must have position data, in this case, from the motors, rather than velocity feedback from tachometers since velocity feedback does not actually carry positional information (simply integrating the signal before feeding it back won't work!); however, feeding velocity feedback into the PID would also be useful.

4.3 Motor Current Preloading

The effect of preloading is to make the two motors driving the antenna along each of its axes to act against each other when the antenna is stopped. At low speeds the motors still act against each other somewhat, maintaining gear tension to prevent gear slap; and at higher speeds where gear tension can be maintained without preloading, the motors are driven with the same current. Shown in Figure 4 below are the individual motor currents as seen by the motors. The voltage axis shown in the diagram is not an actually voltage appearing on the output of the controller but is merely a conceptual entity. As shown, the two separate current commands are scaled by the current amplifier constant of the motor drive circuitry, in this case, a Voltage Controlled Current Source (VCCS), giving each of the motors' currents in the diagram. Observe that the preloading around zero applied voltage is plus and minus 15% of the 30 A motor current maximum.

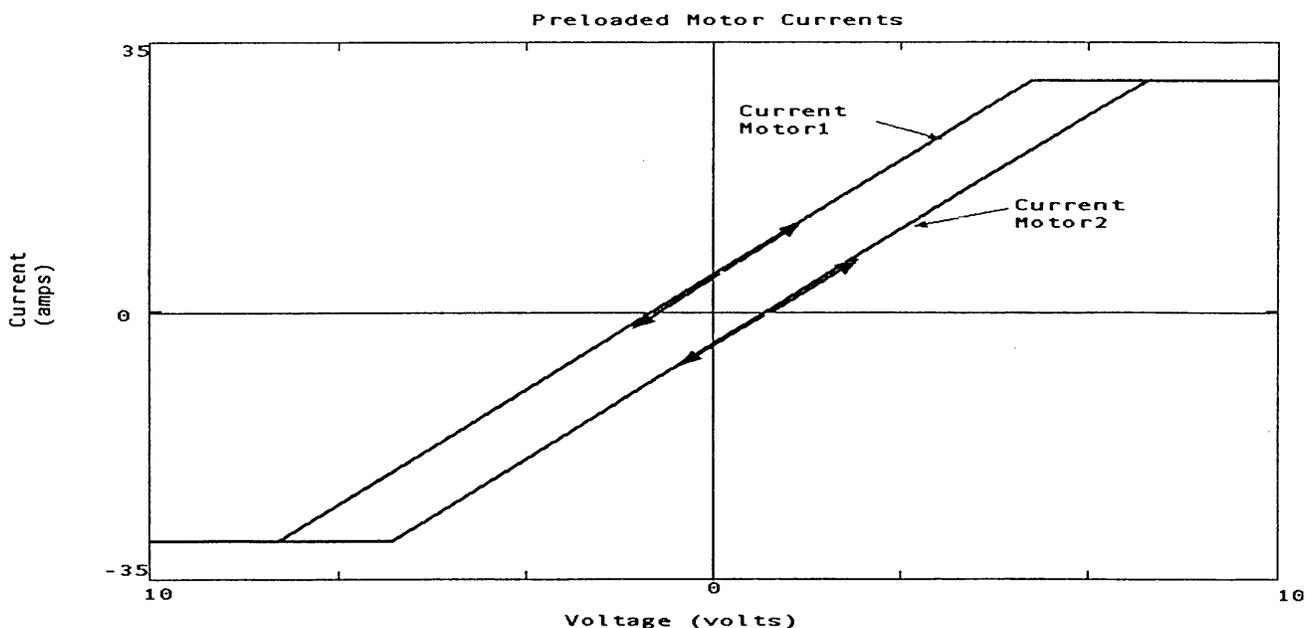


Figure 4: Motor Current Preloading

4.4 Transfer Functions for the Antenna Structure

The primary goal here is finding representative transfer functions of the antenna structure which relate the antenna angle to a linear combination of the motor positions. The basis for this analysis is the assumption that at the bull gear of the antenna the sum of the torques from motor 1 and motor 2 is equivalent to the response torque of the antenna in the manner of Newton's second law. Essentially

$$\tau_{m1} + \tau_{m2} = \tau_A$$

The second assumption that we make is that the antenna itself can be represented as a series of torsional oscillators made by breaking up the total moment of inertia into two parts, such that

$$J = J_A + J_{A'}$$

(where J_A is the measured antenna angle from the encoder and $J_{A'}$ is the actual orientation at the end of the antenna) and connecting each with their own torsional springs and dampers as shown below in Figure 5:

Figure 5: Torsional Oscillator Model of the Antenna

From Figure 5 we can write the equations equating the torques applied to each of the J_A and $J_{A'}$ moments of inertia as follows:

$$\tau_{m1} + \tau_{m2} = K_G(\theta_{m1}/N - \theta_{m2}) + K_G(\theta_{m1}/N - \theta_{m2}) + \beta_G \left(\frac{d\theta_{m1}/N - \theta_{m2}}{dt} \right) + \beta_G \left(\frac{d\theta_{m1}/N - \theta_{m2}}{dt} \right);$$

The Simulink Model

The Simulink model was initially a very simplified model of an antenna and its motors. The model was soon expanded into a much more complex model, which included preloading and complex torsional and damping factors. In the end, the model became a very close approximation of the actual antenna and motor system at the VLA. Figure 6 is a diagram of the final Simulink model.

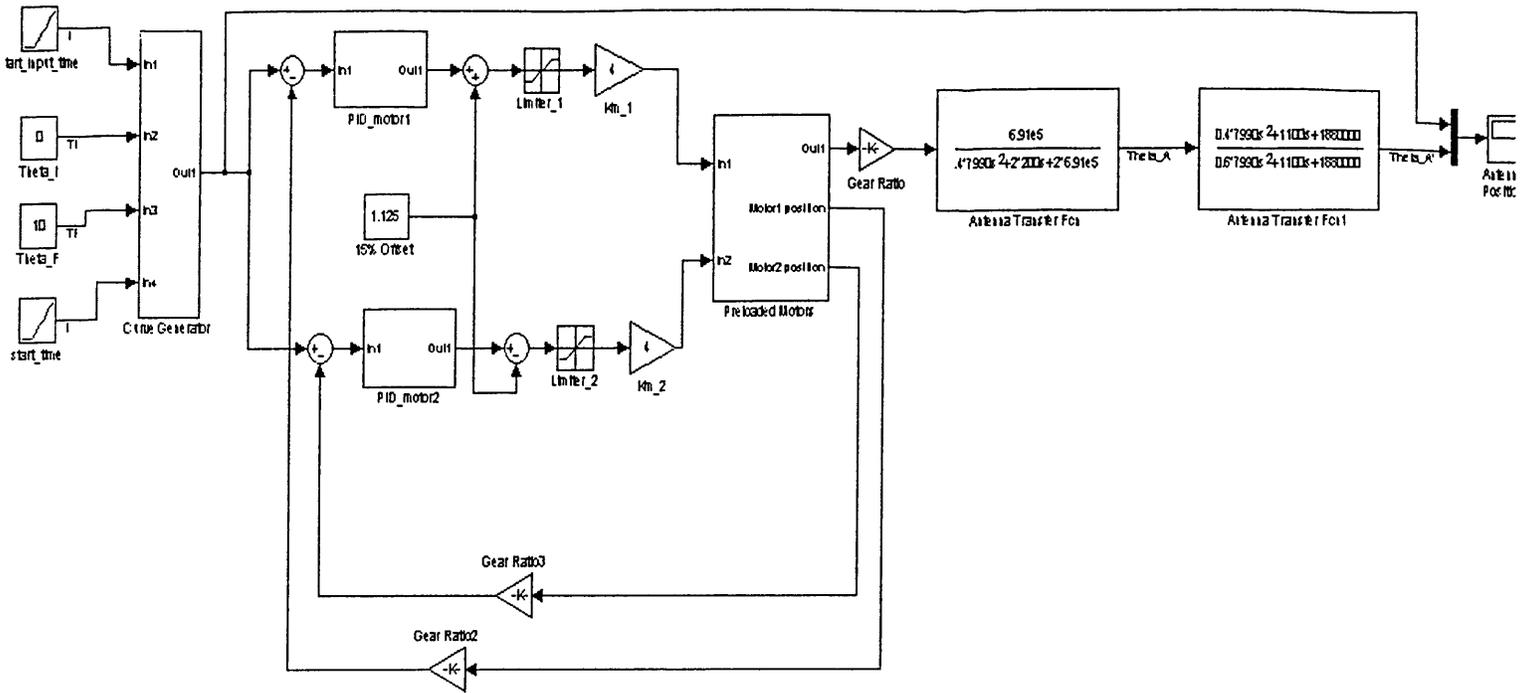


Figure 6: The Simulink Model

6. Design Implementation

6.1 Hardware

The hardware used was the National Instruments Flexmotion 6C motion controller card. This card has an onboard microprocessor, which allows stand-alone operation of the controller, and is capable of controlling up to 6 axes and has a PID controller built onto the card itself. This card takes digital quadrature encoder signals and was purported to be able to use analog feedback as well. In reality, the controller did very well with encoder feedback but was unable to utilize analog feedback. This led to problems interfacing with the existing ACU's at the VLA.

There were also some other National Instruments parts used for interfacing, these were an optically isolated 100 conductor cable and a terminal block which performed some minor signal conditioning. These two components worked as advertised and greatly simplified the task of interfacing with the ACU.

6.2 Software

The software used was National Instruments LabWindows/CVI. This is a programming engine that is based on prewritten libraries of functions written in C, where programming can be done using C/C++. This particular software package has a very steep learning curve and much of the final semester was given over to learning the use of LabWindows and creating a program for use with the chosen controller.

7. Test Procedures and Data Analysis

7.1 Tests to Obtain Motor Parameters

To correctly model the system the electromechanical constants that describe the action of the motors used at the VLA were required; however, the data sheets were unavailable, or, rather, non-existent. Since there were no data sheets, finding the motor constants became an important and vital part of the project. To find the motor constants, a number of tests were devised and implemented on a pair of extra motors, known as a test jig, located in an electronics maintenance facility at the VLA site.

First, the resistance and inductance of the motors were measured using an LCR meter. Then the two motors were coupled together by a drive belt and one motor was used to drive the other to a known rotational velocity. The voltage generated from driving the passive motor's armature was then measured and used to calculate the back electromotive force of the motors. Next the two motors were uncoupled and the driven motor was run at a known velocity. The power to the driven motor was removed by means of an integrated emergency stop mechanism which acted to break the power circuit connected to the motor terminals and the time required for the motor to stop was measured with an oscilloscope attached to the tachometer. Then a mass with a known moment of inertia was attached to the shaft of the driven motor and the above process was repeated. These two processes yielded values that allowed the calculation of the moment of inertia for the motor. Finally, the driven motor was once again run at a known velocity that was measured with a tachometer. The gain of the mechanical tachometer was then calculated and the armature voltage of the driven motor at this speed was measured.

7.1.1 List of Motor Parameters

Motor Type:

90 volt, 30 amp, field generating, brushed DC powered by rectified three-phase

Motor capabilities:

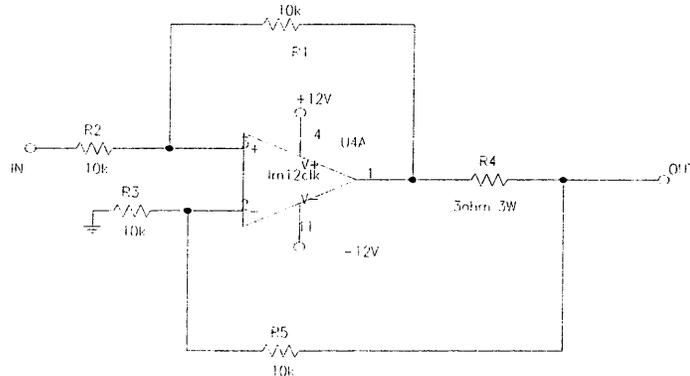
5 horsepower, 1250 rpm maximum

Table of Motor Constants

Name	Symbol	Value	Units
Back EMF Constant	K_b	.193	V/RPM
Resistance	R	.8	Ohms
Inductance	L	55	MH
Tach Gain	K_{tach}	.09964	V/RPM
Moment of Inertia	J_m	.052	$Kg\ m^2$
Damping	β_m	.024	$Kg\ m^2$
Torque Constant	K_m	.193	V/RPM

7.2 Testing of the Prototype on the Test Jig and Antenna

The prototype controller was tested on a simplified motor setup that consisted of a Pittman Series GM9000 Brush-Commutated Gearmotor with an Integrated Hewlett Packard® Optical Encoder. This motor setup required a power circuit, which eventually took the shape of an LM12CLK 80 Watt power amplifier connected in a current source configuration as shown in the following figure:



The reason for using this circuit was that it closely mimicked the SCR's in the drive cabinets at the VLA.

After completing the driver circuit for the test motor it was discovered that the optical encoders did not source enough current to correctly drive the encoder feedback of the motion controller. It was therefore necessary to use pull-up resistors to supply the correct amount of current to the motion controller. These resistors were experimentally found to be 5.6 k Ω .

The testing of this simplified drive circuit gave a good indication of what the response of the larger and more complicated test jig would have to our controller. The smaller model was a success in that it had soft starts and stops, and smooth acceleration throughout moves of many different magnitudes. The tests on the actual test jig at the VLA were hampered by hardware interfacing problems that prevented full testing of the controller, namely the issue of analog, rather than digital feedback.

7.3 Maintenance Information

The information given here is not intended to actually serve as maintenance procedures but to indicate which maintenance test methods should be adapted.

7.3.1 Background

As the motion controller described here will become a subsystem of a larger overall system referred to as the Antenna Control Unit (ACU), the currently used test procedures for the ACU, which involve the to-be-replaced motion controller comprising the A4 and A5 cards, will need to be adapted. The present maintenance

tests are included in the document named “Servo Test of VLA Antenna Control Systems” (4). This document provides technicians with a check list with which to test the operation of components of the ACU, ranging from heating/cooling blowers to manual axis control, as well as a means of recording data on, for instance, the azimuth and elevation resonant frequencies for each antenna. Such tests are performed periodically and the gathered data is filed for reference. Our goal here in this report is not to provide a complete set of new maintenance-related test procedures but to instead give a full account of the system and how it can be operated, the details of which can then be incorporated into new procedures by the user.

Currently, as described in the test procedures, the tests involve recording tachometer feedback to the ACU A4 and A5 cards to directly obtain the motor and antenna speed, and to indirectly obtain the position and acceleration by integrating and differentiating the speed of the motors on an antenna. Maximum acceleration can be found by finding the largest slope of tachometer voltage over time from a plot. The ACU can be set to manual mode so that the DC motors can be forced to track signal inputs from a function generator; with a square wave input the settling time can be observed and measured from a waveform taken using a data acquisition card on a PC. Similarly, the motors can be made to track a sinusoidal voltage input over a range of 1.0 to 12.0 Hz to observe the resonant frequency of the antenna structure, typically observed to be 2 - 3 Hz. When not in manual mode, the normal mode of operation, an error signal proportional to the current and desired positions can be input to the A4 and A5 cards to make the controller move to a new desired position, thus checking how accurately the antenna can be repositioned. The maximum accelerations, settling times, resonant frequencies, and accuracy of repositioning the antenna are then recorded and checked whether they are within tolerance.

7.3.2 Necessary Revisions

With the new controller that we have designed the maintenance test procedures should be quite similar. However, the National Instruments motion controller has the ability to send out data to a PC where LabWindows software can be used to show data and plots on display panels. Inside these user interfaces (UI's), acquired data can be plotted and system variables adjusted, if required, eliminating the need for having a data acquisition card. In addition, some of these procedures can be automated to the extent that maintenance tests could be made remotely from a PC using a LabWindows/CVI user interface. With a user interface set up for this purpose the user running the tests could apply preprogrammed signals in order to simulate a signal generator, and be able to check error bits, simulate fault conditions, and so forth.

7.4 User Instructions

The items required for using the motion controller include:

- National Instruments Flexmotion 6C Motion Control card

- 100-pin (50x2) opto-22 cable (male connectors), about two meters in length
- A PC running Windows 9x/NT/2000 with a PCI slot with room to accommodate the motion control card
- National Instruments LabWindows software (v.4.0 or later)
- A copy of the LabWindows file `motorcontrol.prj`
- Modified extender boards
- Universal Motion Interface (UMI)

7.4.1 Hardware Installation

With the program written to flash memory on the motion control card, the only required preparations for installing the hardware into the Antenna Control Unit will be as follows:

1. Power down main power to the ACU and motors.
2. Open rack (rackname/number) containing the A4 and A5 cards.
3. Replace the A4 and A5 cards with the modified extender boards.
4. Place the A4 and A5 cards into the end slot of their corresponding extender boards.
5. Connect the labeled leads of the extender boards to the screw terminals of the motion interface according to the I/O information in Section 6.3.
6. Set the motion interface on the bottom of the open rack.
7. Connect the opto-22 cable from the interface to the motion controller in the PCI slot of the PC.
8. Turn power on for the ACU and motors. The motion controller should already be installed as detailed in the included pamphlet.

7.4.2 Running the Software and User Interfaces

Information about the LabWindows code programmed onto the National Instruments Flexmotion 6C card is included in Section 8.1, as well as procedures for writing the program to flash memory on each card.

7.4.3 Using the Simulink Model

Included in the following three figures (pages) are the Mathworks Simulink models used to model the antenna motion control system.

Appendix

8.1 The National Instruments LabWindows/CVI Programs

The two C programs `InitializeAlt.c` and `AzAndElevControl.c` created under LabWindows are shown and explained in this section, as are the user interface files `azimuthcontrol.uir` and `elevationcontrol.uir`.

8.1.1 The `initialize.c` File

The `initialize.c` file found under `Flexmotion\cvi\Examples\Initialize\` in its present state acts first to provide power-up reset of the board, assigns a Board Identification number given by the user when prompted (which is 1 in this case since there is only one device being run with the `AzAndElevControl.c` program) and assigns or maps digital and analog I/O lines appropriate for controlling all six axes for servo motor control. However, since only two of the six axes were used for the single-axis test described earlier in the report, the `initialize.c` program was altered to allow for the unused input and output lines dedicated to axes 3 and 4 to be remapped, and used for different purposes other than servo motor control. For example, the two analog outputs to what would have been motors 3 and 4 are now used as analog feedback from the tachometers on the test jig. The resulting program we used, `InitializeAlt.c`, is not included here in the printed copy of this report but is included as part of the report and LabWindows/CVI files written to the accompanying CD.

8.1.2 The `AzAndElevControl.c` File

Starting with the LabWindows/CVI example `Sequence of Two-Axis VectorMoves.c` found under `Flexmotion\cvi\Examples\Multi-Axis_Motion\` a much-revised and expanded version was made, resulting in the `AzAndElevControl.c` program used for the test purposes described earlier in this report. This latter program bears little resemblance to its predecessor, but it still should be noted where a little bit of its content came from. Again, the code for this program is not shown here in the printed version of the report but is instead included with the CD files.

8.1.3 The LabWindows/CVI User Interface Windows

8.2 Specifications for the National Instruments Motion Controller

These are described in part on the

8.3 Cable I/O

To interface the new controller prototype with the existing antenna control unit (ACU) an interface was created by modifying an existing extension card from the VLA which would be connected with a screw terminal block and cable specifically designed by National Instruments for the selected series of motion controller. The modification of the extension card was accomplished through the replacement of a number of jumpers designed to interrupt the signals along the input and output lines with wires soldered into their place. These new wires allow for both signal continuity and for leads that allow the signals to be fed into the new motion controller via the terminal block. This allows the existing controller card to handle the complex task of fault detection, while allowing for the insertion of current command signals from the new controller. This greatly simplified the design of the new controller and eliminated the possibility of erroneous fault detection.

8.4 Miscellaneous VLA Data Sheets

What's intended here is to include many of the various data sheets from which values were taken. These include . Values or specifications are circled in ink.