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Digital Control of the Kuiper Airborne Observatory Telescope

Ann C. McCormack and Philip K. Snyder, Ames Research Center, Moffett Field, California

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Moffett Field, California 94035

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Ann C. McCormack and Philip K. Snyder
NASA Ames Research Center
Moffett Field, CA 94035

ABSTRACT

This paper investigates the feasibility of using a digital controller to stabilize a telescope mounted in an airplane. The telescope is a 30-in. infrared telescope mounted aboard a NASA C141 aircraft known as the Kuiper Airborne Observatory. Current efforts to refurbish the 14-year-old compensation system have led to considering a digital controller. A typical digital controller is modeled and added into the telescope system model. This model is simulated on a computer to generate the Bode plots and time responses which determine system stability and performance parameters. Important aspects of digital control system hardware are discussed. A summary of the findings shows that a digital control system would result in satisfactory telescope performance.

Key Words: Digital Controllers
Controller Modeling

INTRODUCTION

An analog compensation system has satisfactorily stabilized the Kuiper Airborne Observatory (KAO) telescope since 1974. Recent glitches in the system stability have spurred interest in rebuilding the compensation system. Since the present compensation system was built, one of the most noticeable advances in control technology has been the use of commercially available microprocessor controllers. This paper is the result of an effort to investigate the potential improvements that a digital controller would provide in system performance and noise-free operation.

In the following section the model of a digital compensation system is developed. Formulae are derived to aid in selecting parameters for the digital controller. The compensation-system model is then combined with a telescope-system model for the purpose of simulating the complete system. A control-system simulations package (MATRIX$_X$, Integrated Systems Inc.) is used to compare the performance of the system stabilized by the digital controller to that stabilized by the present analog design. A major concern is how the added computational delay of the controller and quantization of the analog-to-digital signal conversion affect the telescope stability. The last section reviews the digital controller hardware and some pertinent aspects of it.

MODEL DEVELOPMENT AND TESTING

Modeling the Compensated Telescope System

The purpose of the compensation system is to serve as a regulator. That is, after the telescope has been aligned with a point in space, the controller must maintain the telescope's alignment with this point. To do this, it must reject random disturbances such as aircraft vibrations and air pressure fluctuations as well as constant inputs such as the telescope imbalance.

System compensation consists of dynamic manipulation in the system loop to achieve a better response. Traditionally, this has been implemented in analog form using operational amplifiers. In digital compensation a microprocessor controller performs these tasks, and analog-to-digital (ADC) and digital-to-analog (DAC) converters are used to transform the loop signal into and out of digital format.

In this section both compensation systems, the present analog system and the proposed digital system, are modeled on the computer. These models are used to simulate the system's response to a variety of inputs, and to generate Bode plots. The model of the present analog system provides a comparison for the proposed digital system model. These models are created using a software package for control systems engineering called MATRIX$_X$.

The entire telescope system is divided into subsystems and is represented by the block diagram in Figure 1. Models for the amplifier, torquer, telescope and gyro were available from an internal NASA report (1). These models will be used to evaluate performance, but their development will not be discussed here.

The present analog system includes a commonly used control law called proportional, integral, and differential (PID) compensation. PID compensation consists of proportional, integral, and differential feedback of the plant output (or sensor signal). Mathematically these are represented in the Laplace domain as K_p, K_i/s, and $K_d s$, respectively. The sum of these three components results in the generic PID compensator. Each component provides a service but can cause instability if not properly tuned. A short summary of the benefits and trade-offs of the PID components follows.

The proportional term adds to the system's restoring force, which speeds up the response and works toward a zero steady-state error. The tradeoff is a loss of stability at high gains. The integral component is very important because it allows the system to tolerate disturbances, constant loads, and parameter variations with zero error at steady state. Again, this comes at the price of a lower damping ratio and reduced stability. Derivative feedback increases system damping and stability (2). A drawback to derivative control is the noise that results from taking the derivative of the signal to be controlled. This high-frequency noise can be attenuated by placing an additional pole out at a high frequency (called the cutoff frequency) where it will not influence the frequencies useful to the system; the effect is to lower the gain at high frequencies. The block diagram of the compensator which results when this pole is added to the differential portion of a PID compensator is shown in Figure 2. The equation describing this control law (the transfer function) is

$$G'(s) = K_p + \frac{K_i}{s} + K_d s\left(\frac{1}{1 + s/p}\right) \qquad (1)$$

A description equivalent to Equation 1 is the lead-lag plus integral form

$$G(s) = g\,\frac{s + a}{s + b} + \frac{f}{s} \qquad (2)$$

where a, b, f, and g can be found from K_p, K_i, K_d, and p:

$$a \equiv \frac{p}{p\frac{K_d}{K_p} + 1}$$

$$b \equiv p$$

$$f \equiv K_i$$

$$g \equiv pK_d + K_p$$

Some manufacturers of digital controllers choose to describe their compensation in this form. In order to compare typical parameters with a particular manufacturer's allowable parameter ranges, the discrete equivalent of Equation 2 will be developed.

Present Analog Compensation System. The present analog compensator contains PID components, the additional pole, and several other filters. Figure 3 shows the block diagram of the present analog compensator for the elevation angle control. Since the more complex of the commercially available digital controllers offer only PID-type compensation, we did not seek to digitally perform the analog compensator's control law exactly.

For later comparison to a digital controller using a transfer function similar to Equation 2, we can simplify this more complex network (by ignoring all filters except the high-frequency cutoff pole on the differentiator component). The parameters which correspond to the transfer function given by Equation 1 are

$$K_p = 43$$
$$K_i = 271$$
$$K_d = 1.25$$
$$p = 227$$

It would be useful to determine whether a commercially available digital controller could be configured to reproduce this transfer function.

Proposed Digital Compensation System. The digital compensator consists of an ADC, the digital controller processor, and a DAC. The block diagram for the digital-compensation-system model is shown in Figure 4 (2). The effects of the ADC and DAC converters are to change the gain of the controller as well as to quantize ("round") the input and output. The rounding effect comes from the fact that a converter increases or decreases only in units of one count. The selection of this quantization step for the ADC is important because it determines the ultimate pointing resolution of the telescope resulting from a one-count limit cycle which is inherent in all digital systems. For a 12-bit ADC over a 20-V range, one count is equal to $20V/2^{12}$, or 0.005 V. (Note that a resolution of 0.005 V limits the pointing accuracy to 0.2 arcsec, which is acceptable.) An eight-bit DAC would result in rounding fractions of $20V/2^8$, or 0.08 V. (Note, however, that the pointing accuracy is not dependent on the DAC.) Gains result from the unit analysis in counts-per-volt and volts-per-count figures. Therefore, the converters are modeled as gain and quantization blocks. In Figure 4 the controller's gain is increased by a net factor of 17.

The controller we have selected to study is of the PID variety, having the continuous transfer function given by Equation 2. Derivation of digital-controller parameters equivalent to present-analog-system parameters is necessary so that we (1) have approximate figures with which we can begin testing, and (2) ensure that the digital parameters will fall within the range allowed by the controller.

To relate the continuous parameters used in the simplified analog transfer function to the input parameters of the digital controller, we must first relate the continuous analog transfer function parameters (Equation 2) and the discrete transfer function parameters. The discrete parameters can then be converted to those which are input to the controller via relationships given by the manufacturer in the controller documentation.

The transfer function in the z-domain (used in discrete systems) can be found by applying the Trapezoidal (or Tuskin's) Rule to the continuous transfer function (3). After adjusting for the effects of the converters' net gain, the discrete transfer function is

$$G(z) = K\frac{z - A}{z - B} + \frac{C}{z - 1} \qquad (3)$$

where a particular manufacturer's discrete parameters A, B, C, and K are related to the continuous parameters a, b, f, and g by

$$a = \frac{4000(1 - A)}{1 + A}$$

$$b = \frac{4000(1 - B)}{1 + B}$$

$$f = 17\,\frac{C}{T}$$

$$g = 17K\,\frac{1 + A}{1 + B}$$

and, where T is the controller sampling time, which is 0.0005 s.

Using these relations and the parameters of the simplified model of the present analog system, the analogous discrete parameters are

Discrete Parameter		Manufacturer's Allowable Range
A= 0.9851	A	0 through 0.99609
B= 0.8926	B	0 through 0.99609
C= 0.00797	C	0 through 0.99609
K= 18.32	K	0 through 127.5 (but not 0.5)

Compensator Comparison

From Bode plots of the simplified analog (Figure 2) and digital compensator (Figure 4) we find that the magnitudes of the output-to-input signal ratio are identical (which would indicate that the parameter conversion formulas are good approximations). The effect of the computational time delay is a phase lag seen in the digital controller, as shown in Figure 5. This phase lag is due to the computational time step and can be shown to be 0.09 times the frequency in hertz. At the gain crossover frequency of approximately 10 Hz this amounts to a tolerable 0.9° of additional phase lag (or less phase margin). If three axes of the telescope are controlled via multiplexing the controller, the time step will increase by a factor of three. This results in a phase lag three times larger (also shown in Figure 5). This would lower the phase margin at the 10-Hz crossover frequency by 2.7°.

The other comparison that is important here is that of the digital controller to the actual nonsimplified analog controller with its additional networks. The Bode plots of these two systems, shown in Figure 6, are not identical because of the simplification of the analog controller model. The digital system is close enough, however, to serve as a starting point for fine-tuning the system performance.

Entire-System Open-Loop Response

Criteria for system stability are adequate phase margin and gain margins, which are determined from a Bode plot of the open-loop system. These margins can be improved by fine-tuning the controller parameters. (The authors used a simple iterative process). The open-loop Bode plot for the digitally compensated system using a tuned-up set of controller parameters is shown in Figure 7. This Bode plot indicates that the phase margin is 46° and the gain margin is 22 db, occurring at 9 Hz and 90 Hz, respectively. If we consider 30° of phase margin and 10 db of gain margin as the minimum acceptable margins, then the margins resulting from the digitally compensated open-loop system are indicative of a very stable system.

Entire-System Simulation

A requirement of system performance is adequate rise and settling time in response to a step input. The computer model was set up to accept an input into the closed-loop system at the PID input as shown in Figure 1. In response to a 0.5-V step input, the telescope reacts as indicated by the gyro response shown in Figure 8. The rise time in this figure is 0.05 s with the overshoot settling in 0.47 s. This response is an improvement over recent experimental tests on the telescope where 0.1-s rise times have been typical followed by several damped oscillations which produce longer settling times. After 0.5 s the transients have settled, and the gyro output shown in Figure 8 demonstrates the limit cycle between plus and minus 0.0024 V.

Noise Rejection

Noise rejection is the final performance criterion investigated. Noise disturbances in the telescope system originate from pressure variations in the telescope cavity, plane vibration, electrical noise, and other sources. Flight-test data indicate that disturbances equivalent to 1 amp RMS of torquer current and a bandwidth of 20 Hz are typical. Feeding random noise with these characteristics into the closed-loop system at the torquer input (shown in Figure 1) produced the gyro output shown in Figure 9. Ideal telescope performance would result in excursions of less than 0.5 arcsec (0.011 V) RMS. From this plot we see that the telescope rarely makes excursions further than 0.006 V of gyro output or 0.27 arcsec.

HARDWARE CONSIDERATIONS

Many hardware configurations are possible considering the increasing number of motion-control components available on the market. The block diagram in Figure 10 includes the most desirable hardware options for use in the telescope system. The selection of components for the telescope control system is driven by factors such as (1) stand-alone vs. host-controlled operation, (2) noise-free signal transmission, (3) package size and distribution, and (4) cost.

Stand-Alone vs. Host-Controlled Operation

Since the digital motion controller's primary function is to regulate the position of the telescope, a stand-alone configuration would be sufficient to perform this relatively simple task while minimizing the hardware involved. A PC-compatible or other type of computer would be required as a temporary programming device--a smaller hand-held model would suffice. Controller parameters would be downloaded over a communication line such as RS-232, after which the PC would be disconnected. Many manufacturers do not offer a stand-alone unit, but require the use of a host computer over a bus system such as STD, VME, PC, MULTIBUS II, or many of the other standards available.

Additional advantages can be gained by incorporating a host computer permanently into the system. For example, graphical displays of the telescope position and tracking performance become possible because of the higher bus speeds, and can be made available to the user on demand. Also, auto-tuning programs which excite the telescope and optimize the control parameters are possible. Although these features might be desirable, it is important to consider whether the additional time to develop and debug the software is worthwhile.

Noise Immunity

Since this system would be required to perform in an aircraft with many other instruments, it is particularly important to take every precaution to minimize the noise it picks up, or adds to the aircraft systems (4). This is especially a problem because the gyros and torquers are not located near the control system--it is therefore important to pay careful attention to grounding and shielding.

Referring to Figure 10, a useful system might incorporate a 12-bit ADC which is located near the gyros. Line drivers would transmit the parallel or serial digital information over to the digital controller, where it would be intercepted with optical isolators. If the information is transmitted serially, one might consider the use of a fiber optic system.

Many commercially available digital motion controllers typically provide inputs for optical encoders. Some offer optional analog inputs by supplying an additional ADC card which may multiplex several analog channels. Also, converters which make the analog signals emulate A/B-quadrature-encoder counts are also available. Either way, it is advantageous to transmit digital rather than analog information over the longer distances because of the relative ease of dealing with interference. Of course this involves locating the digital converters near the gyro package.

A two-wire digital transmission system which includes line drivers and receivers can help minimize noise interference . This is effective because noise common to both lines is rejected by the differential receivers.

Ground isolation is important because it eliminates noise arising from varying ground potentials; this occurs especially when the various sensors and actuators are located at long distances from the controller. Optical isolators can be used to isolate digital signals inexpensively, and some manufacturers include these on their controller boards. If not, they should be included on a separate card.

Commercially available motion controllers typically offer either ±10 V analog outputs or pulse-width-modulated-(PWM-) type outputs. To minimize noise introduced at the actuators, it is more advisable to use the PWM signals--especially if transmission occurs over a long distance. If the system requires the use of linear amplifiers, it is still possible to use the PWM output signal by converting it to ±10 V at the remote location of the linear amplifiers. The additional hardware to demodulate the PWM signals may be worthwhile if superior noise immunity is gained.

Packaging

The actual packaging arrangement can vary substantially, depending on how much integration has already been done by the manufacturer. Some manufacturers offer cards which are "industrially toughened" and thus eliminate the need for adding line receivers and optical isolators.

It is conceivable to mount all the controller hardware in a single 19-in. rack arrangement. A stand-alone version would include one three-axis control card or three single-axis cards. If isolation is required, an additional card would contain line receivers and optical isolators. If a host computer is used, an additional host processor card would be involved. This might be included in the same 19-in. rack with an external keyboard and monitor, or be located in a separate rack with a built-in minimonitor. Cost can vary considerably depending on the manufacturer, but $1,500 per axis is reasonable for industrial-quality controller cards. A single-board STD PC with a powered rack starts at $1,000 without the monitor; this same rack can hold the controller hardware.

At least one manufacturer offers an analog monitor card which allows one to look at the feedback signals on an oscilloscope or strip-chart recorder. If a host computer with graphical display is not incorporated, this card would be useful in facilitating tune-up operations.

The ADC or digital encoder interface should be located in a separate package near the gyros themselves. It is also possible that some prefiltering of the gyro signals might be required. A card containing notch filters and/or anti-aliasing filters should be included at this point. Two to four cards would be involved for all these items.

Since most manufacturers offer a built-in ±10 V DAC output in their motion controllers, no additional hardware will be necessary unless a PWM system is considered. In this case, three PWM cards and their associated power supply will be required. If isolation is not supplied, this will have to be added separately. As previously discussed, the linear amplifiers may be completely replaced by a PWM system, in which case a large 100-V power supply with sufficient amperage would supply the PWM cards. Because of the higher power involved, each PWM axis would require a separate card; however, the resulting combination may prove to be more compact than the linear amplifiers. If PWM is used solely as a means of digital transmission, a smaller three-axis PWM card would be required to demodulate the pulse information.

SUMMARY

The transfer function for a typical commercial digital controller was shown to be equivalent to a PID with an additional filter pole for protecting against high-frequency noise. The transfer function of the present analog control system was simplified so that the basic PID parameters could be extracted from it and serve as a starting point for tuning the digital controller. A frequency response comparison of the analog and digital controllers indicated that the analog simplification was reasonable. The effect of a fixed sampling time of 0.0005 s amounted to only a 0.9° loss in phase at 9 Hz, which is easily acceptable.

The controller model was combined with an available model of the amplifier, telescope, and gyro to investigate the open-loop characteristics as well as to perform time-domain simulations.

After some fine-tuning of the controller parameters, 44° of phase margin (at 10 Hz) and 22 db of gain margin were obtained. These exceed the present performance specifications of the analog system. The rise time of the simulated step response is 0.05 s, which compares well to recently measured rise times of 0.1 s. Additionally, the response is well damped as compared to the present system. A simulation of typical telescope disturbance noise shows that the digitally compensated telescope responds with tracking errors peaking around 0.27 arcsec (a tracking error of less than 1 arcsec RMS is acceptable). No problems caused by quantization were apparent.

The healthy stability margins, fast rise time and satisfactory noise-rejection characteristics imply that a digital controller can provide robust stabilization for the KAO telescope.

Several hardware arrangements are possible. The most important considerations involve designing for noise immunity and the choice of using a host computer vs. a stand-alone arrangement. Since a digital system can become very complex, a specific hardware arrangement should be studied to determine whether the advantages outweigh the simplicity of the analog design.

REFERENCES

(1) Snyder, Philip K., "Modeling and Analysis of the KAO Gyro Stabilization System," NASA Ames Research Center, Moffett Field, California, July, 1988.

(2) Franklin, Gene F. and Powell, David J., "Essential Principles of Feedback," Feedback Control of Dynamic Systems, Addison-Wesley Publishing Company, Menlo Park, California, 1987, pp. 95-100.

(3) Franklin, Gene F. and Powell, David J., Digital Control of Dynamic Systems, Addison-Wesley Publishing Company, Menlo Park, California, 1980.

(4) Robinson, David T., "Comparing Dedicated and General-purpose Industrial Controllers," Machine Design, May 26, 1988.

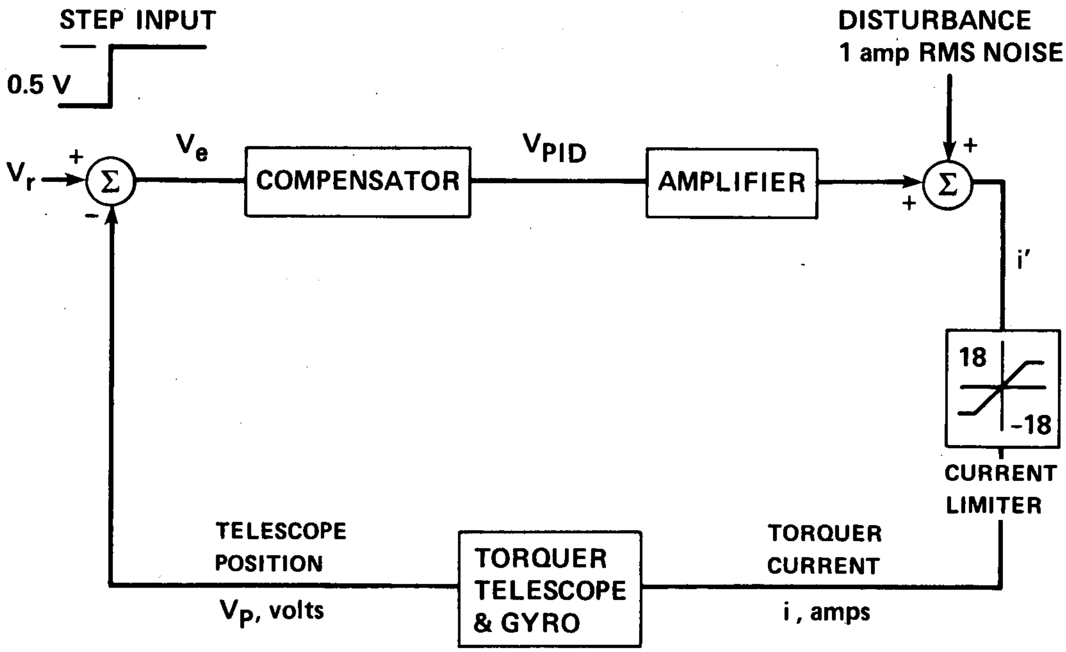

Figure 1.– System block diagram.

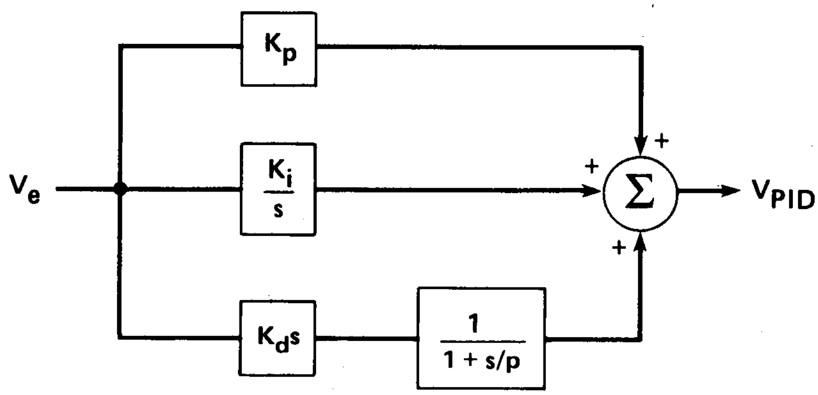

Figure 2.– PID compensator.

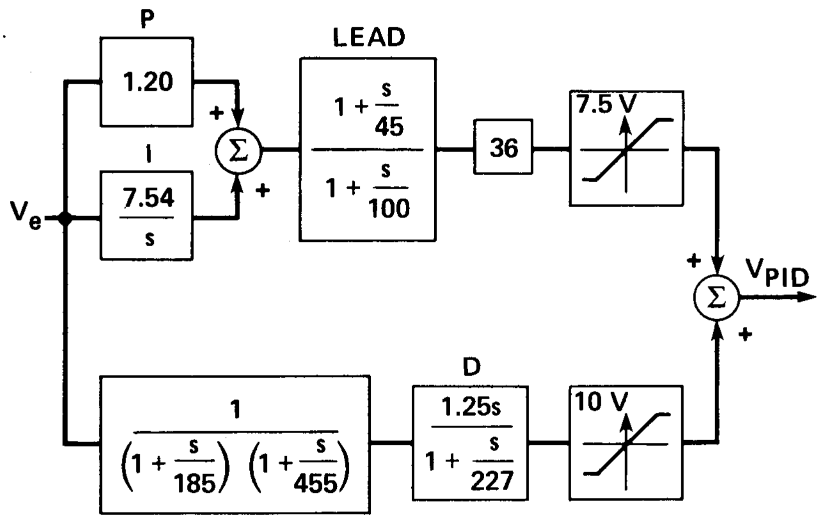

Figure 3.– Present analog compensator.

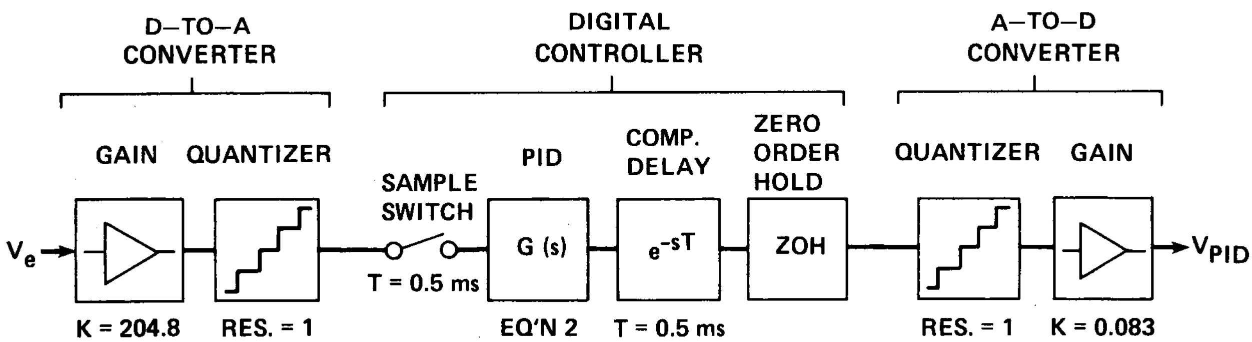

Figure 4.– Digital compensator.

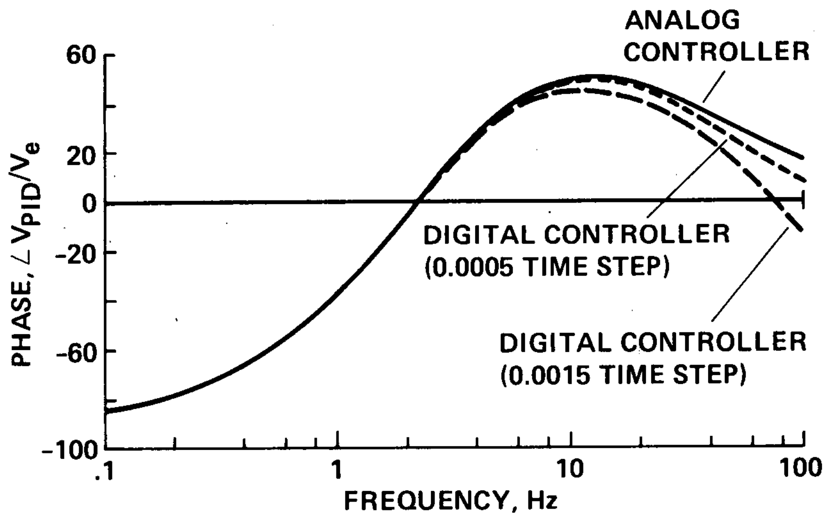

Figure 5.– Effect of time step on controller phase.

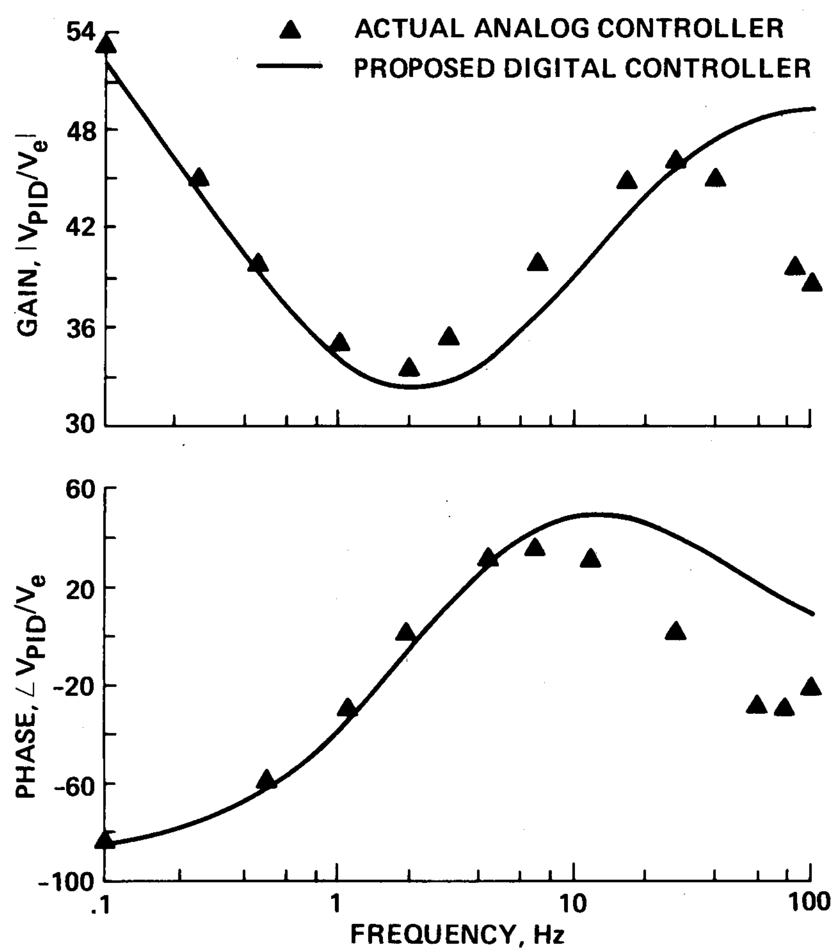

Figure 6.– Bode plots of present analog and proposed digital controllers.

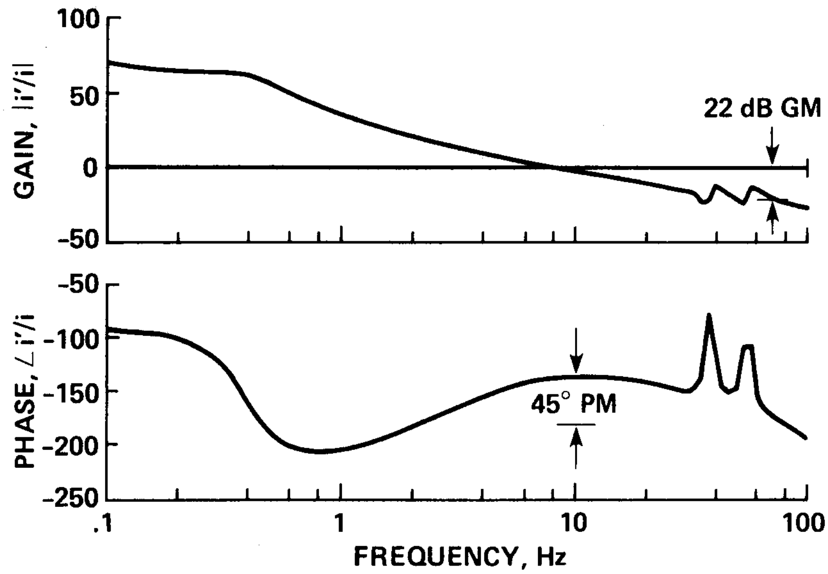

Figure 7.– Entire-system open-loop Bode plot.

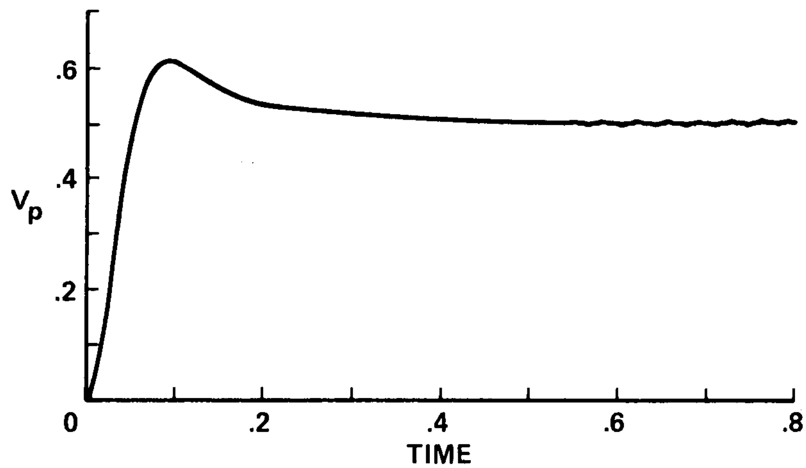

Figure 8.– Step response (0.5 V).

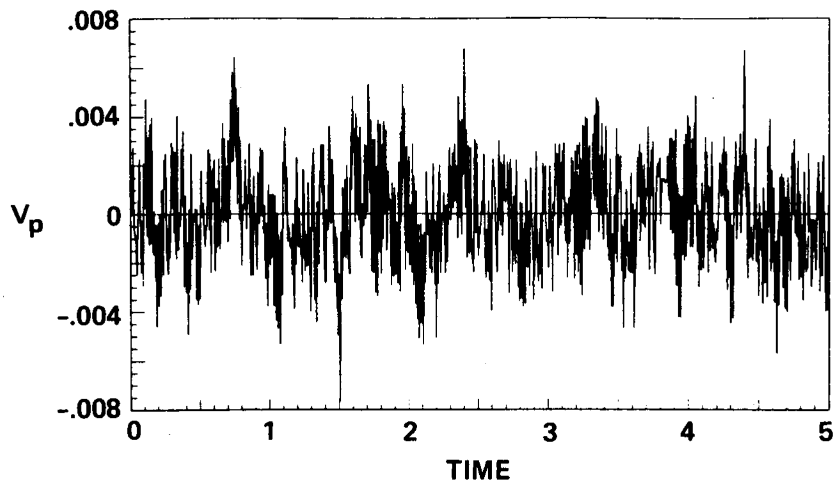

Figure 9.– Gyro response to disturbance input.

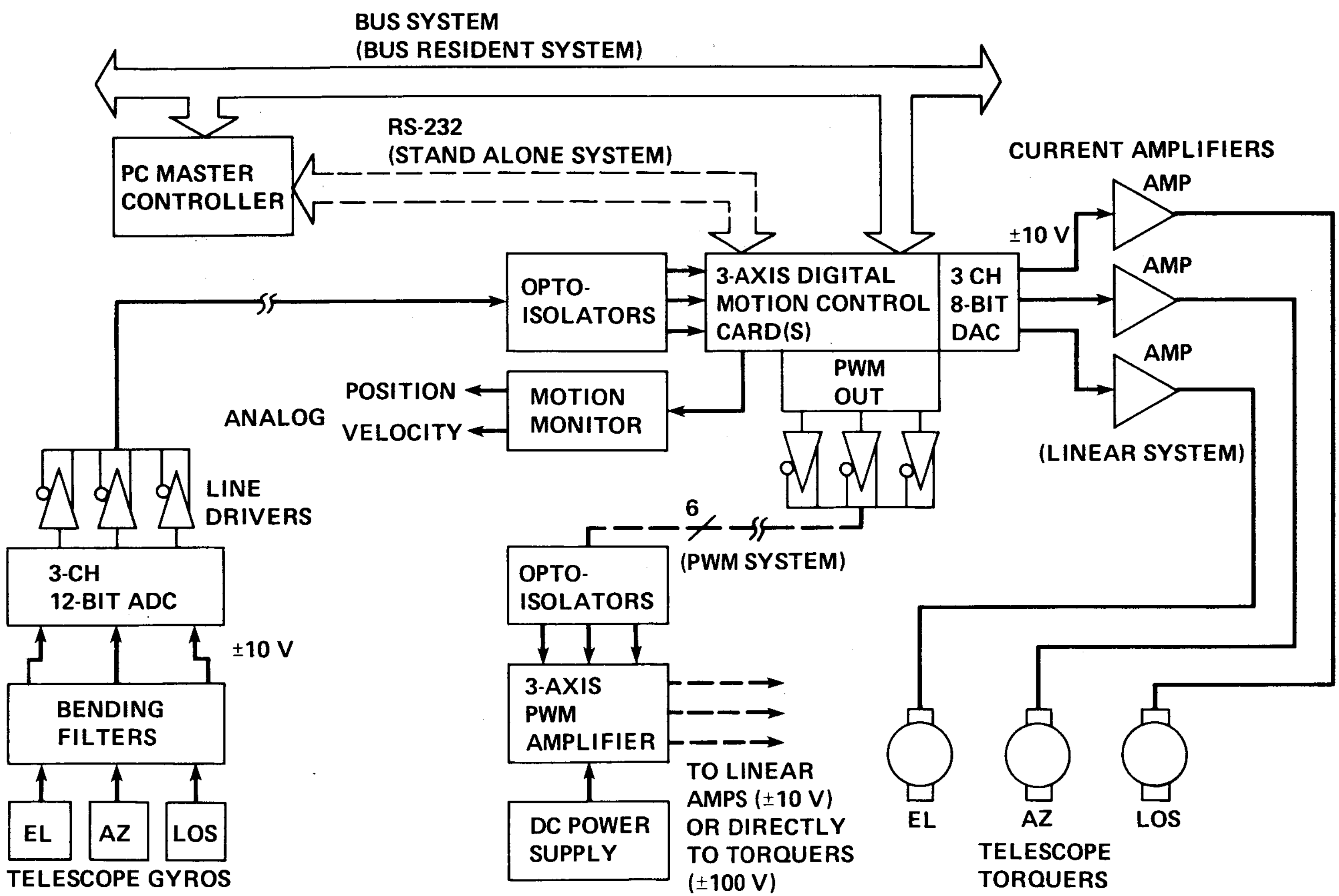

Figure 10.– Digital control hardware.

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Point of contact: Ann C. McCormack, Ames Research Center, MS 213-4, Moffett Field, CA 94035
(415) 694-4088 or FTS 464-4088

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16. Abstract

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