Single-Loop Antenna Control

W. Gawronski[1]

This article presents a study of a single-loop antenna control system. A typical antenna control system consists of two feedback loops. The first one—an inner loop—is called a rate loop. It uses tachometers to control the drive rate. The second loop—called a position loop—uses encoders to control antenna position. The questions arise: Does one need two loops to control antenna motions? Can one achieve similar performance for a system with the position loop only? In order to answer these questions, we studied three types of antennas with a single-loop control: a rigid (or idealized) antenna in order to obtain initial insight into properties of the closed-loop antenna systems; a small antenna, 5 meters in diameter; and a large antenna, 34 meters in diameter. The study compares command following and rejection of wind disturbances of antennas with and without rate loops, and we show that both configurations are equivalent.

I. Introduction

An antenna array proposed recently will consist of thousands of small antennas with dish diameters between 6 and 12 meters. Because of their large numbers, the antennas should be individually inexpensive and also reliable in order to lower construction and maintenance costs. One possible means of achieving this goal is to simplify the control system.

Control systems of the DSN antennas (and many other antennas and radio telescopes) consist of two feedback loops: the rate loop and the position loop. The rate feedback is an inner loop that controls motor rate. The position feedback is an outer loop that controls the antenna position. The questions arise: Is the rate loop necessary, and for what reason? Do we degrade the antenna pointing performance when the rate feedback is removed? This article tries to answer these questions. Simplicity is the reason for the proposed removal of the rate feedback, since removing the rate feedback simplifies the hardware, lowers the cost of the antennas, and lowers the cost of their maintenance. A similar trend of eliminating the velocity feedback loop can be observed in spacecraft and robot control. Recent articles (see [1,2]) show that spacecraft can be stabilized and controlled without velocity feedback and that robots can be controlled without velocity measurements (see [3–6]).

We started our analysis with an ideal (or rigid) antenna to obtain initial assessment of performance in a closed form; then we proceed to a 5-meter antenna with flexible drives; and finally we analyzed a 34-meter antenna that displays drive as well as structural flexibility. We compare the performances of these

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[1] Communications Ground Systems Section.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

antennas with and without a rate feedback loop—specifically, we compare their responses to commands and disturbances. We show that the performances of both configurations are comparable.

II. Rigid Antenna

We begin our analysis with a rigid-body antenna model. Such a model represents an antenna without flexible deformations in the disturbance frequency band. This is a model of an idealized antenna, with rigid gearboxes and a rigid structure. Such a model might be applicable to small antennas, but in our case it serves as a tool for deriving antenna properties in a closed form (while for larger, flexible antennas the analysis is based on Matlab and Simulink simulations).

A rigid antenna in the open-loop configuration has torque input and rate output. The relationship between the torque, τ, and angular rate, ω, follows from the Newton inertia law:

$$J\dot{\omega} = \tau \tag{1}$$

where J is the antenna inertia. The Laplace transform of the above equation gives $Js\omega(s) = \tau(s)$; hence, the antenna transfer function is represented by an integrator:

$$G(s) = \frac{\omega(s)}{\tau(s)} = \frac{1}{Js} \tag{2}$$

A. Rigid Antenna with Rate and Position Loops

A classical control system for a rigid-body antenna consists of the rate and position loops, as shown in Fig. 1(a). A proportional controller is used to control the rate loop. The transfer function of the closed-rate-loop system, from rate command u to antenna rate $\dot{\varphi}$ is as follows:

$$G_{rl}(s) = \frac{\dot{\varphi}(s)}{u(s)} = \frac{k_o G(s)}{1 + k_o G(s)} = \frac{1}{1 + Ts} \tag{3}$$

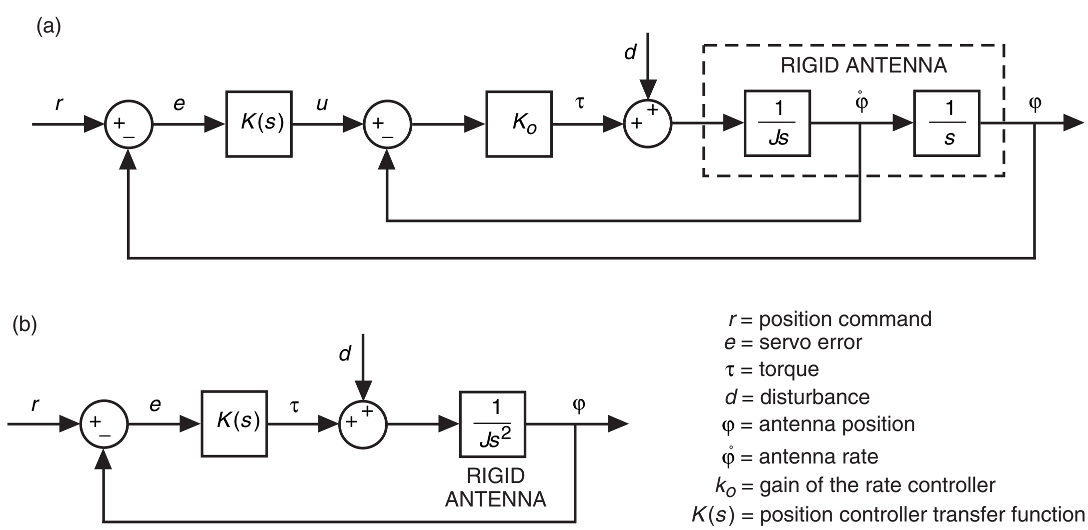

Fig. 1. Rigid-antenna control system: (a) with the rate and position feedback and (b) with the position feedback only.

where $T = J/k_o$. The bandwidth of the rate-loop system is equal to $B = 1/T = k_o/J$ rad/s. The gain, k_o, is tuned to obtain the required bandwidth of the system. The required bandwidth is $B = 20$ rad/s; the inertia is assumed to be $J = 1$ Nms^2/rad; thus, $k_o = 20$ Nms.

The position loop is closed using a proportional-integral-derivative (PID) controller. The PID controller transfer function is $K(s) = k_d s + k_p + k_i/s$, where k_d, k_p, and k_i are derivative, proportional, and integral parts, respectively. The transfer function of the closed position loop (from the command, r, to the encoder position, φ) is as follows:

$$G_{cl}(s) = \frac{\varphi(s)}{r(s)} = \frac{K(s)G_{rl}(s)/s}{1 + K(s)G_{rl}(s)/s} = \frac{k_o(k_d s^2 + k_p s + k_i)}{Js^3 + k_o(1 + k_d)s^2 + k_o k_p s + k_o k_i} \tag{4}$$

This system is stable for $k_p > Tk_i$. The above equation shows that for low frequencies ($s \to 0$) the magnitude of the transfer function is unity; thus, for these frequencies, $\varphi = r$, i.e., the antenna follows exactly the command. For high frequencies ($s \to \infty$), the magnitude of the transfer function tends to zero, i.e., the antenna does not respond to the command or to the high-frequency noise.

The transfer function from the disturbance, d, to the encoder position, φ, for the PID controller is as follows [derived from Fig. 1(a)]:

$$G_d(s) = \frac{\varphi(s)}{d(s)} = \frac{s}{Js^3 + k_o s^2(1 + k_d) + k_o k_p s + k_o k_i} \tag{5}$$

It shows that for low frequencies ($s \to 0$) and for high frequencies ($s \to \infty$) the magnitude of the disturbance transfer function tends to zero, i.e., for these frequencies, the disturbances are completely rejected.

B. Rigid Antenna with Position Loop Only

When we remove the rate-loop feedback, the antenna transfer function from the torque input to the position output is

$$G(s) = \frac{\varphi(s)}{\tau(s)} = \frac{1}{Js^2} \tag{6}$$

The closed-loop control without the rate feedback is shown in Fig. 1(b). By closing the position feedback with a PI controller, the system becomes unstable. Indeed, the closed-loop transfer function is

$$G_{cl}(s) = \frac{\varphi(s)}{r(s)} = \frac{K(s)G(s)}{1 + K(s)G(s)} = \frac{k_p s + k_i}{Js^3 + k_p s + k_i} \tag{7}$$

From the Routh–Hurwitz criterion, the above system is unstable for arbitrary positive gains, i.e., for $k_p > 0$ and $k_i > 0$.

However, we add a derivative gain to the PI controller, obtaining the PID controller. For this controller, the position-only loop is stable. The transfer function of the PID controller is $K(s) = k_i/s + k_p + k_d s$; thus, the closed-loop transfer function is

$$G_{cl}(s) = \frac{\varphi(s)}{r(s)} = \frac{K(s)G(s)}{1 + K(s)G(s)} = \frac{k_d s^2 + k_p s + k_i}{Js^3 + k_d s^2 + k_p s + k_i} \tag{8}$$

From the Routh–Hurwitz criterion, this system is stable for $k_d > 0$. The above transfer function shows that for low frequencies ($s \to 0$) the magnitude of the transfer function is unity; thus, for these frequencies, we have $\varphi = r$, i.e., the antenna exactly follows the command. For high frequencies ($s \to \infty$), the magnitude of the transfer function tends to zero, i.e., the antenna does not respond to high-frequency noise.

The disturbance transfer function is derived as shown in Fig. 1(b), obtaining

$$G_d(s) = \frac{\varphi(s)}{d(s)} = \frac{s}{Js^3 + k_d s^2 + k_p s + k_i} \tag{9}$$

It shows that for low frequencies ($s \to 0$) and for high frequencies ($s \to \infty$) the magnitude of the disturbance transfer function tends to zero, $|G_d| \approx 0$, i.e., for these frequencies, the disturbances are rejected.

C. Simulation Results

We simulated the rigid-body antenna with and without rate-loop feedback. The gains of the PID controller for the rigid antenna with and without a rate loop are given in Table 1. For these controllers, we simulated the closed-loop system responses to a 1-deg command step and to a 1-deg/s disturbance step; they are shown in Figs. 2(a) and 2(b), respectively. The figures show that the antenna without a rate loop has a shorter settling time (0.06 s) than does the antenna with a rate loop (0.28 s). However, the disturbance rejection properties of the antenna without a rate loop are much worse than those for the antenna with a rate loop (the amplitude and the duration of the response of the antenna without a rate loop are much larger than those of the antenna with a rate loop). Magnitudes of the transfer functions of the closed-loop systems from the command to the encoder are shown in Fig. 3(a) and from the disturbance to the encoder in Fig. 3(b). The figures show that the bandwidth of the antenna without the rate loop is 28 Hz, while that of the antenna with the rate loop is 7 Hz, showing superiority of the former. However, the magnitude of the disturbance transfer function of the antenna with the rate loop is smaller for all frequencies, showing again that it has better disturbance rejection properties. Finally, note that the controller gains of the antenna without a rate loop are higher than those of the antenna with a rate loop, indicating that the control effort (torques) might be higher in the case of the antenna without a rate loop.

In summary, an antenna without a rate loop has better tracking properties, but poorer disturbance rejection properties, and possibly it requires a higher control effort.

Table 1. Controller gains of the rigid antenna.

Antenna	k_o	k_d	k_p	k_i
With rate feedback	200	0	30	250
Without rate feedback	0	100	5200	4000

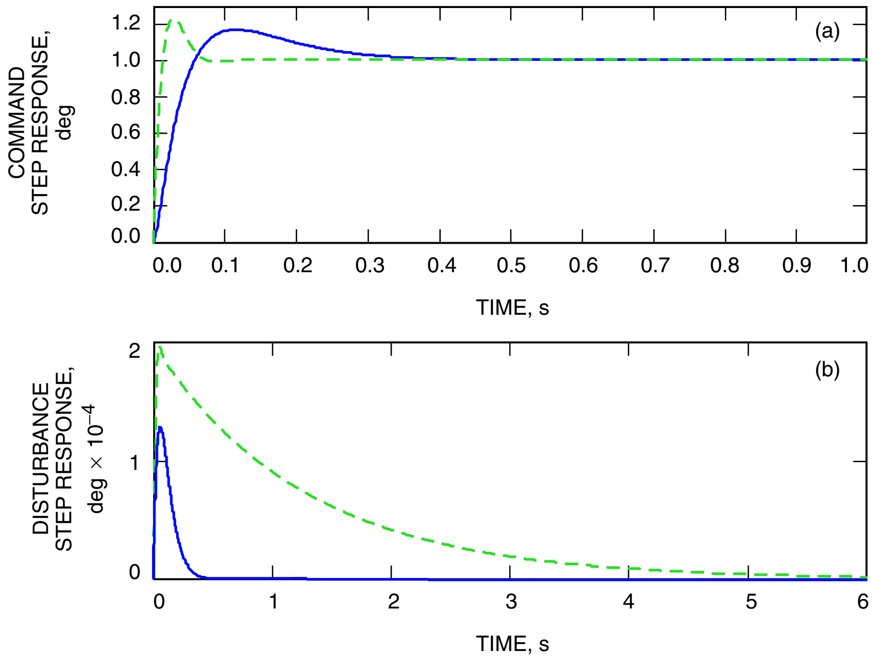

Fig. 2. Step responses of the rigid antenna with a rate loop (solid line) and without a rate loop (dashed line) to the: (a) unit command step and (b) unit disturbance step.

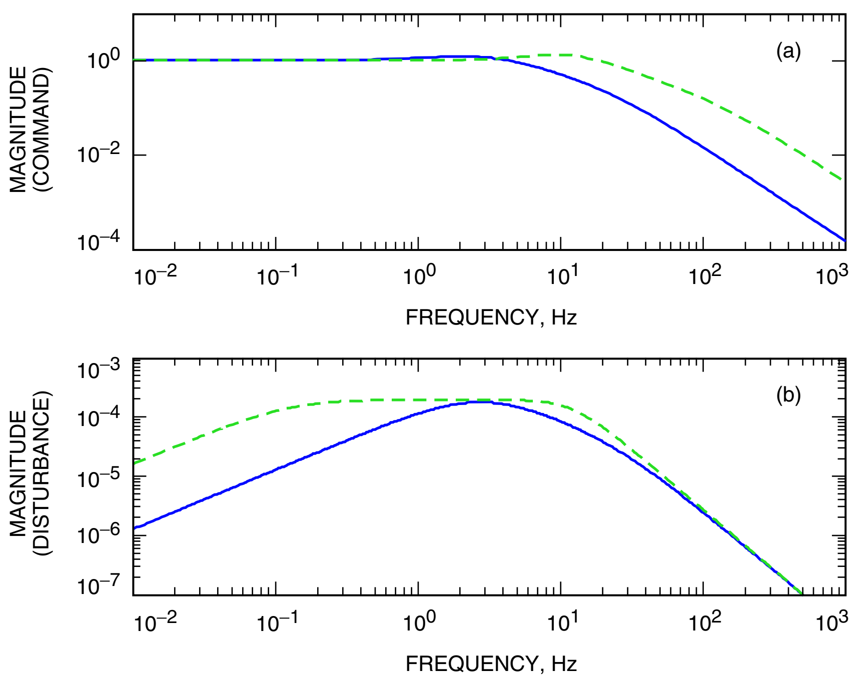

Fig. 3. Magnitudes of the transfer functions of the rigid antenna with a rate loop (solid line) and without a rate loop (dashed line) from the (a) command input and (b) disturbance input.

III. 5-Meter Antenna

In the next step, we analyze a 5-meter antenna with a rigid dish and flexible drives. It was analyzed in a memorandum,[2] in which the control system consisted of the rate and the position loops. The question remains: Can we remove the antenna's rate loop and replace its PI controller with the PID controller to obtain performance similar to that of the control system with the rate loop (as described in the memorandum)?

The control system of a 5-meter antenna is shown in Fig. 4(a). It consists of the position loop controller [Fig. 4(b)], which is a PID type, and the antenna open-loop system [Fig. 4(c)]. The open-loop system consists of a rigid antenna structure, flexible drive, and the rate feedback. The rate feedback coefficient is $k_{\text{rate}} = 1$; in order to eliminate the rate feedback, we set the rate-feedback coefficient to zero, $k_{\text{rate}} = 0$. The controller gains for the system with and without rate feedback are given in Table 2.

The performances of the 5-meter antenna control system with and without rate feedback are illustrated in Figs. 5 and 6. Figure 5(a) shows antenna responses to a 1-deg step command, where the antenna without rate feedback has a shorter settling time but displays higher overshoot. This indicates that the rate loop increases the system damping. The plots of magnitudes of the transfer functions (from the command input to encoder output) are shown in Fig. 6(a), where the antenna without rate feedback has a higher bandwidth. The disturbance rejection properties are compared in Figs. 5(b) and 6(b). The response to the disturbance step [Fig. 5(b)] is slightly better for the antenna without rate feedback (the area under the response curve is smaller for the antenna without rate feedback). The disturbance transfer functions displayed in Fig. 6(b) also show a slight advantage of the antenna without rate feedback—it is smaller than the transfer function of the antenna with rate feedback—for most frequencies.

We also simulated the antenna response to wind-gust disturbances. The simulation showed that the antenna without rate feedback has a smaller servo error due to wind gusts; it is 76 percent of the servo error of the antenna with the rate feedback:

$$\frac{\sigma_{\text{without rate feedback}}}{\sigma_{\text{with rate feedback}}} = 0.76 \tag{10}$$

In summary, the performances of both configurations are similar, with slightly better performance of the antenna without rate feedback.

IV. 34-Meter Antenna

The DSS-13 antenna model, as described in [7], is used for this analysis. Our task is to design and compare linear quadratic Gaussian (LQG) controllers for the antenna with a rate feedback and without a rate feedback. The description of the LQG controller for the DSS-13 antenna with rate feedback was given in [8]. The LQG control loop is shown in Fig. 7, which includes the antenna drive.

We will consider two kinds of drives: one with a rate feedback and another without a rate feedback. The antenna drive with rate-loop feedback is shown in Fig. 8. In this figure, the k_{tach} gain represents the rate (tachometer) feedback gain. The same drive without rate feedback is shown in Fig. 9. It was obtained from the original drive by breaking the rate feedback (by setting the feedback gain to zero, $k_{\text{tach}} = 0$) and by replacing amplifier 1 of Fig. 8 with the gain k_r. The value of the latter gain is determined such that the open-loop gain (from rate input to the antenna rate output) is equal to 1.

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[2] W. Gawronski, "Pointing Error Estimate of the 5-Meter Antenna," JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, November 16, 2000.

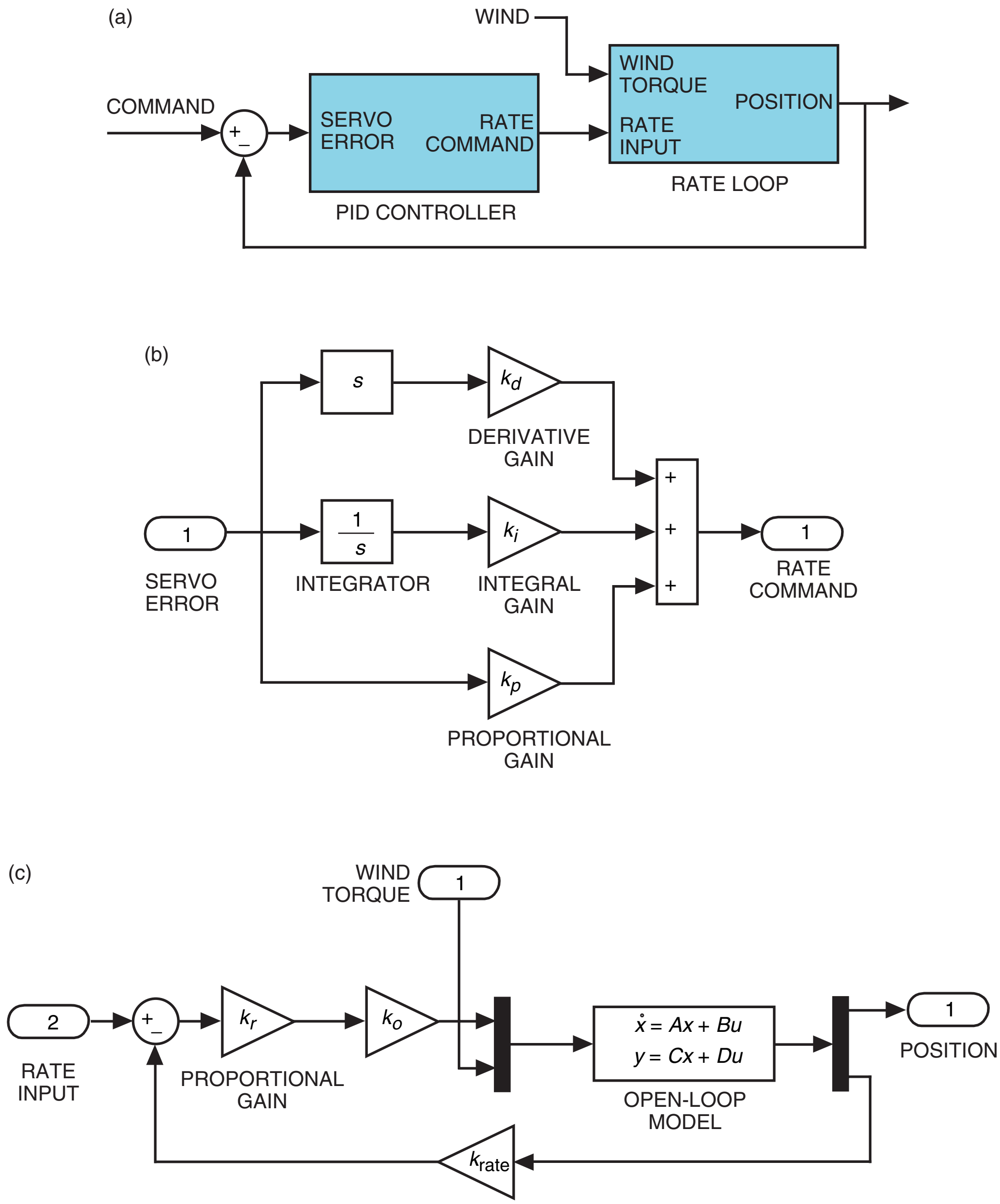

Fig. 4. Control system of the 5-meter antenna: (a) position loop closed, (b) PID controller, and (c) rate loop.

Table 2. Controller gains of the 5-meter antenna.

Antenna	k_{rate}	k_r	k_d	k_p	k_i
With rate feedback	1	40	0	20	30
Without rate feedback	0	9	5	50	300

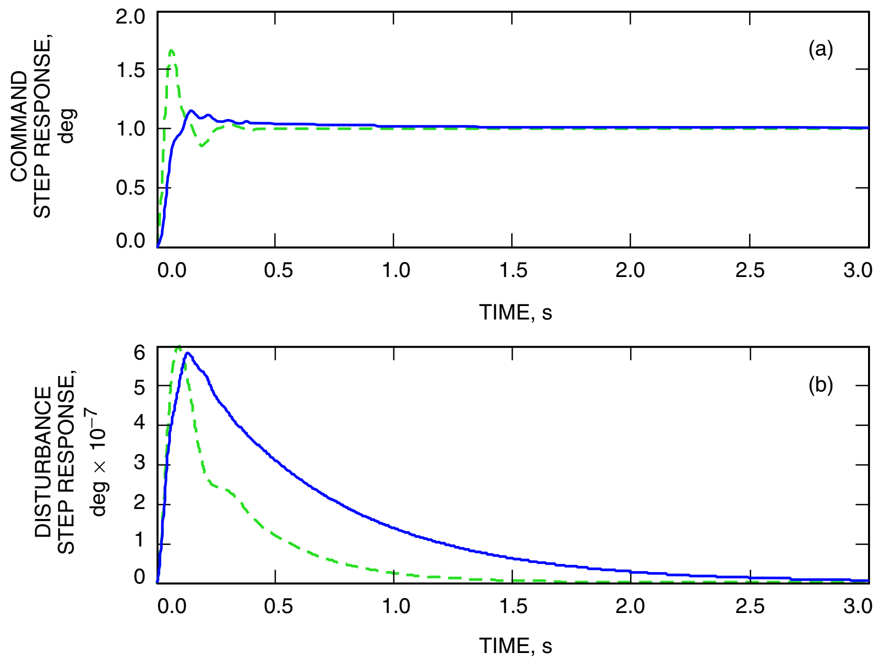

Fig. 5. Step responses of the 5-meter antenna with a rate loop (solid line) and without a rate loop (dashed line) to the: (a) unit command step and (b) unit disturbance step.

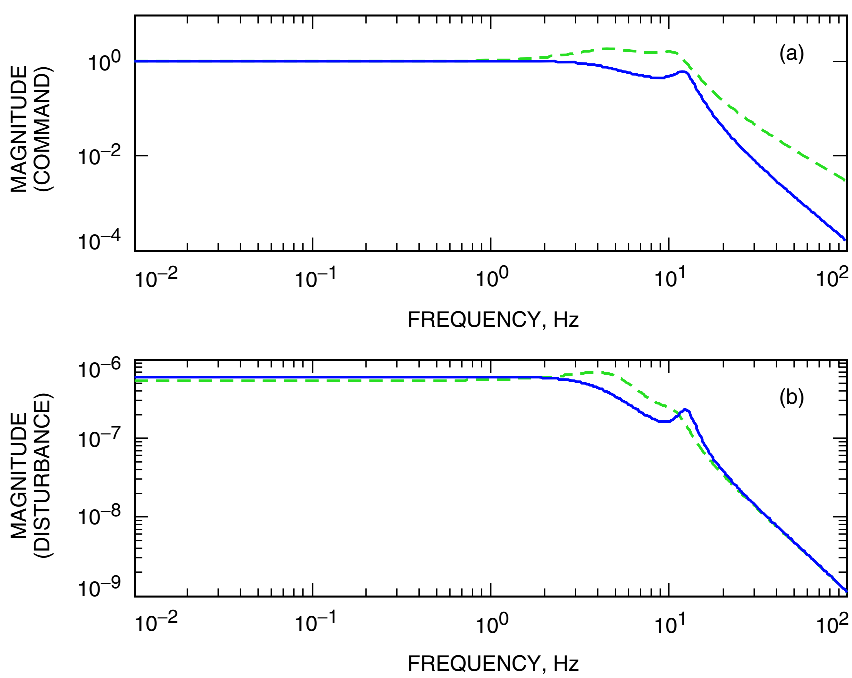

Fig. 6. Magnitudes of the transfer functions of the 5-meter antenna with a rate loop (solid line) and without a rate loop (dashed line) from the (a) command input and (b) disturbance input.

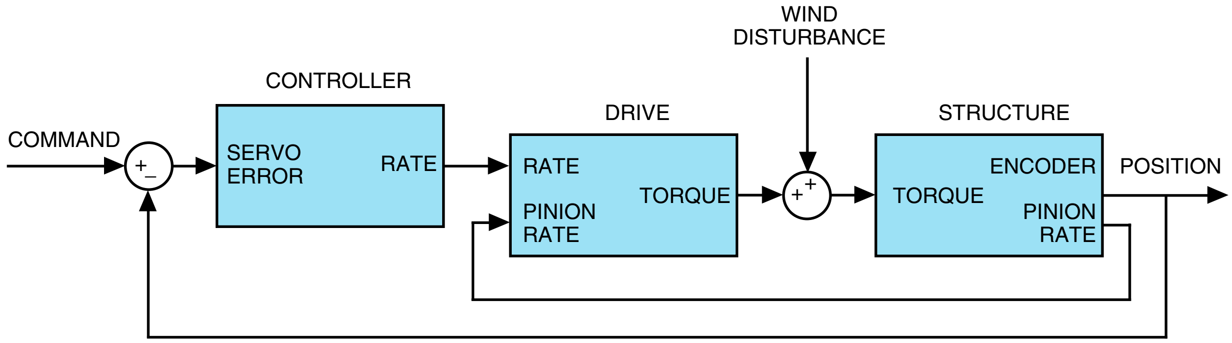

Fig. 7. Control system of the 34-meter antenna.

The LQG controller gains for the antenna with rate feedback were determined in [7]. We designed a similar controller for the antenna without a rate loop and compared the performances of the two systems. We compared the command step responses, disturbance step responses, command transfer functions, and disturbance transfer functions. The command step responses are shown in Fig. 10(a). The figure shows very similar responses of the antenna with and without a rate loop (i.e., similar overshoots and settling times). The disturbance step responses (representing a rapid increase of wind torque) are shown in Fig. 10(b). The plot shows an improved response of the antenna without rate feedback. Figure 11(a) shows the antenna transfer function from the position command to the antenna encoder position. The transfer functions (of the antenna with and without rate feedback) are similar, with a bandwidth of 1.5 Hz. Figure 11(b) shows the antenna transfer function from the wind disturbance to the antenna encoder position, where the antenna without rate feedback has slightly better performance (the magnitude of the transfer function is smaller than the one for the antenna with rate feedback). In summary, the 34-meter antenna performances with and without rate feedback are similar, with slightly better wind-disturbance rejection of the antenna without rate feedback.

V. Conclusions

We investigated antenna control systems with dual loops (consisting of the rate and position loop) and with a single (position) loop. The analyses and performance evaluations were completed for a rigid antenna, for a small (5-meter) antenna with flexible drives, and for a large (34-meter) antenna. Except for the rigid-body antenna, the performances of both configurations (with and without rate loops) are similar, indicating that the rate loop can be removed without loss of performance, thus simplifying the control system. However, the single-loop equivalent results were obtained through a significant increase of the controller gains. It is not clear at the moment if this translates into a significant increase of the control effort (such as motor torque and current). The analysis also showed that the rate loop adds damping to the system, suppressing the structural oscillations.

Safety is one of the reasons that the rate feedback is implemented at the DSN antennas. In case of failure of the position loop, the rate feedback controls antenna rate, maintaining it at a zero value. Note, however, that the rate loop is unnecessary for safety reasons, since even in the case of failure of the rate and position feedback, the antenna remains motionless because the gearboxes oppose antenna motion (a gearbox can be moved only from the motor side and cannot be moved from the antenna side). Also, brakes can be applied automatically in case of position-loop failure. Another reason for implementing rate feedback is its ability to increase damping in the system. This is justified in a case when a simple (PI-type) controller is in the position loop. However, if an LQG controller is implemented in the position loop, it significantly increases the damping of the closed-loop system, and the rate loop is not necessary. Finally, the rate signal from the tachometer is sensitive to electrical noise and may lead to the loss of performance of the closed-loop system.

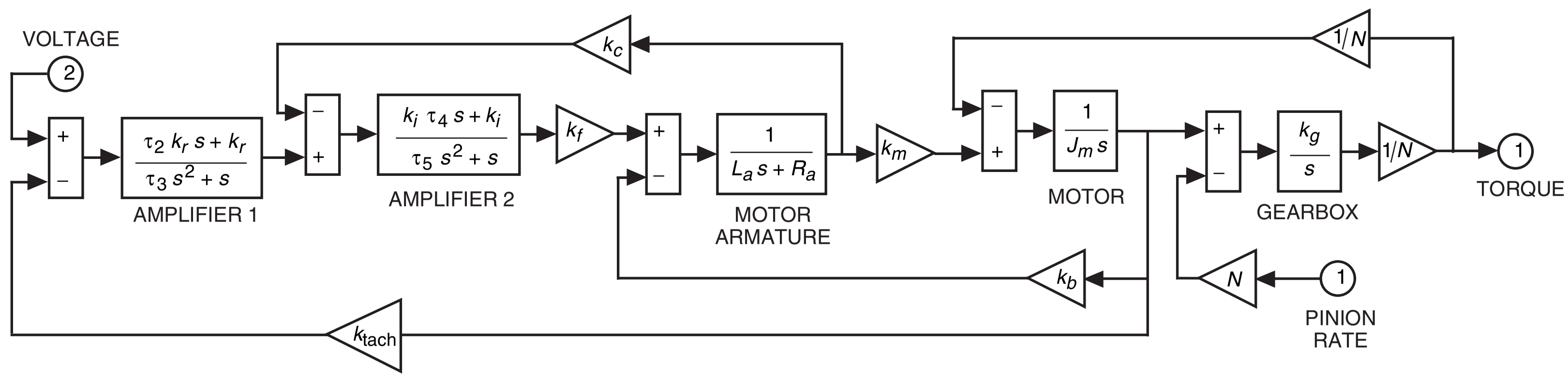

Fig. 8. The 34-meter antenna drive with rate loop feedback.

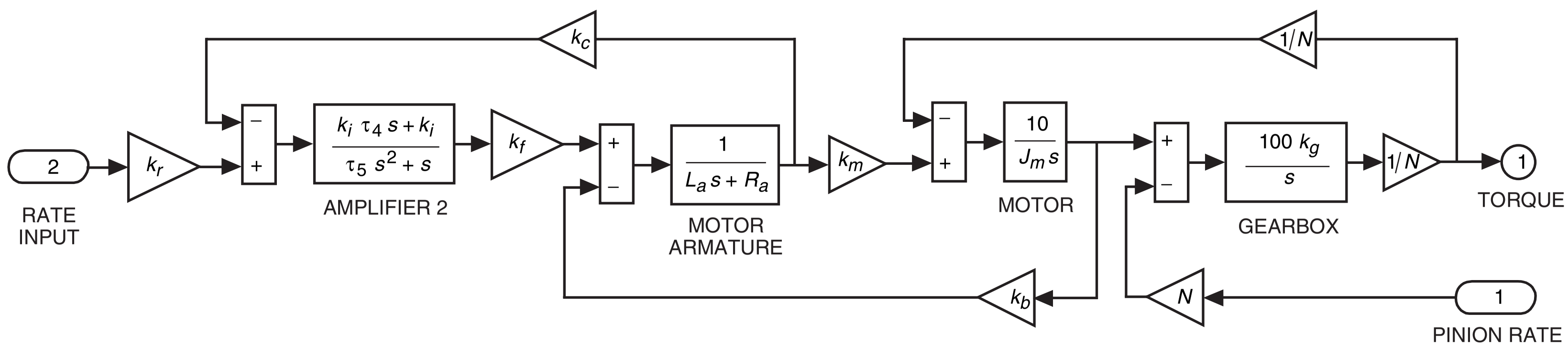

Fig. 9. The 34-meter antenna drive without rate loop feedback.

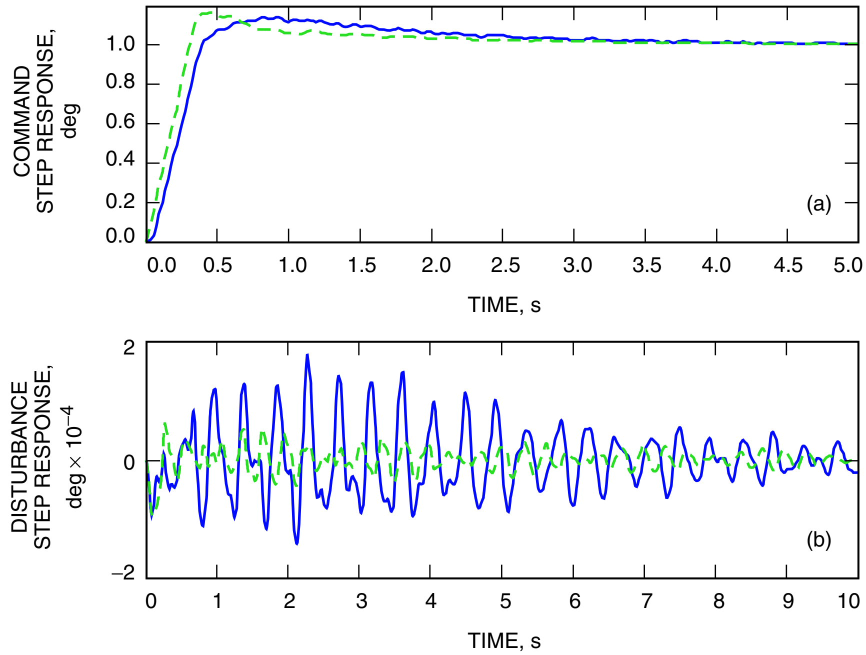

Fig. 10. Step responses of the 34-meter antenna with a rate loop (solid line) and without a rate loop (dashed line) to the: (a) unit command step and (b) unit disturbance step.

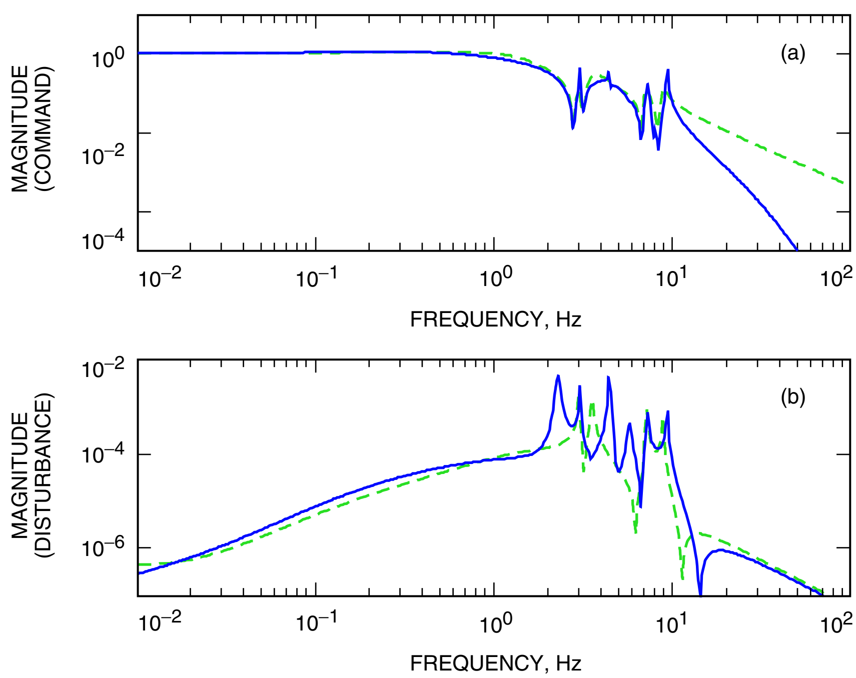

Fig. 11. Magnitudes of the transfer functions of the 34-meter antenna with a rate loop (solid line) and without a rate loop (dashed line) from the (a) command input and (b) disturbance input.

Acknowledgment

I would like to thank Dr. Bill Hurd for technical discussions and encouragement.

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