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Rotating-Unbalanced-Mass Devices for Scanning Balloon-Borne Experiments, Free-Flying Spacecraft, and Space Shuttle/Space Station Experiments

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TECHNICAL PAPER

ROTATING-UNBALANCED-MASS DEVICES FOR SCANNING BALLOON-BORNE EXPERIMENTS, FREE-FLYING SPACECRAFT, AND SPACE SHUTTLE/ SPACE STATION EXPERIMENTS

I. INTRODUCTION

It is not uncommon for balloon-borne experiments, free-flying spacecraft, and gimballed experiments mounted to the space shuttle or the space station to require some type of scanning to meet their scientific objectives (for example, see Refs. 1 to 3). In some cases, the only possible way to achieve the required scan motion is to physically scan the entire experiment or spacecraft, as the case may be. This is typical of x-ray and gamma-ray experiments [1]. Three types of scan patterns are commonly desired. One is the circular scan, characterized by the experiment or spacecraft line-of-sight repeatedly tracing out a circle centered on a target. A second is the line scan, characterized by the line-of-sight repeatedly moving back-and-forth in a line centered on a target. A third is the raster scan, which is like the line scan except with some slow complementary motion in the direction perpendicular to the line scan that could be stepping, constant velocity, or sawtoothed. Prior methods for achieving these scan motions can be plagued by problems with power, weight, cost, performance, stability, or a combination of these. This paper presents a new method for generating these scan motions without any of these problems, in many cases. It uses a new device that is called a rotating-unbalanced-mass (RUM).* This device and the scheme for using it to scan are described in section III. Setting the stage for this, prior methods for scanning and their disadvantages are described briefly in section II. Section IV presents an example of how the RUM devices are used for scanning a balloon-borne solar experiment. Final comments are made in section V.

II. PRIOR METHODS FOR SCANNING

Prior methods available for scanning a balloon-borne experiment use control moment gyroscopes (CMG's), reaction wheels, torque motors, or a combination of these. CMG's are usually very expensive devices. Reaction wheels can also be expensive and are known to be very inefficient powerwise. Depending on the size of the experiment and the characteriistics of the scan (e.g., amplitude and period), they can require a great deal of power. The simplest approach is to use torque motors and scan the experiment by torquing against the gondola, the structure between the experiment and the flight train which attaches to the balloon. However, unless the inertia of the gondola is much larger than that of the experiment, the gondola may move as much or more than the experiment, much like the proverbial tail-wagging-the-dog. Furthermore, this effect can set up gondola rocking motion or pendulous oscillations by virtue of the dynamics of the gondola and the flight train. In turn, these oscillations can feed disturbances back into the experiment being scanned, causing performance and/or stability problems.

*Patent is pending.

Prior methods for scanning free-flying spacecraft use CMG's, reactions wheels, or a reaction control system (RCS). The problems with CMG's and reaction wheels are the same as those described before. The problem with a RCS is that it is usually very expensive and may require a large amount of propellant, and hence a large amount of weight, to scan for long periods of time. Furthermore, the on-off characteristic of a RCS can make it impractical for precise scanning.

Prior methods available for scanning gimballed experiments mounted to the space shuttle or the space station are the same as those described for balloon-borne experiments. Hence, the problems are the same, although the torque motor approach in this case has the advantage of the large mass of the space shuttle or space station to torque against, plus there is no flight train to further complicate the dynamics of the system. On the other hand, these advantages may be offset by the performance or stability problems caused by local structural flexibility of the space shuttle or the space station and the large-amplitude/high-frequency reaction torques of the torque motors.

III. A NEW METHOD FOR SCANNING USING RUM DEVICES

The new method for scanning uses RUM devices, either one or two depending on the application and the type of scan required. A RUM device consists of a mass on a lever arm rotating at a constant angular velocity. The centrifugal force on the experiment or spacecraft caused by the rotating mass creates a time-varying torque about the experiment gimbals, or the spacecraft center-of-mass, which produces the desired scan motion. When two RUM devices are needed, their relative positions are synchronized to achieve the desired net torque and, hence, the desired scan motion.

For a balloon-borne experiment, two RUM devices are required. For a circular scan, they would be configured as shown in Figure 1. For a line or raster scan, they are as shown in Figure 2. For a free-flying spacecraft, one RUM device is needed as shown in Figures 3 and 4 for a circular and line/raster scan, respectively. For a gimballed experiment mounted to the space shuttle or the space station, one or two are required as shown in Figures 5 and 6 for a circular and line/raster scan, respectively.

In all of these applications, an auxiliary control system is needed to supplement the RUM devices. It is used for target acquisition, keeping the center-of-scan on the target, and producing the complementary motion for raster scanning. To perform these functions, the auxiliary control system need only produce low-amplitude and low-frequency torques while the RUM devices generate the large-amplitude/high-frequency torques for scanning. Hence, one of the approaches described in section II should work quite well for auxiliary control.

The RUM devices can be implemented using standard servo components. A typical design uses a torque motor, tachometer, resolver or encoder, and feedback control electronics. Variations of this are possible.

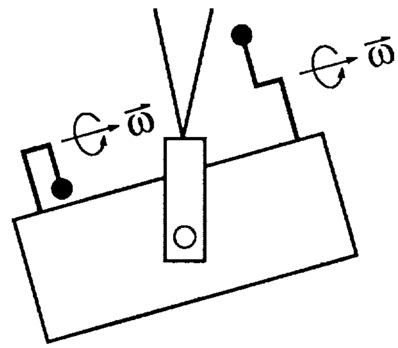


Figure 1. Balloon-borne experiment in a circular scan.

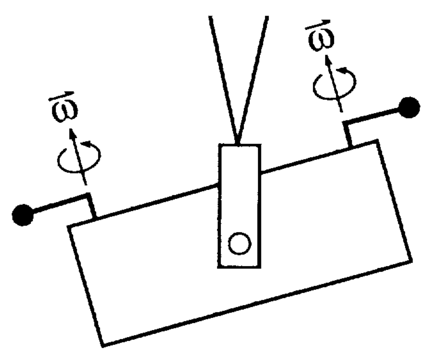


Figure 2. Balloon-borne experiment in a line/raster scan.

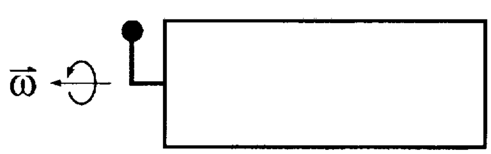


Figure 3. Free-flying spacecraft in a circular scan.

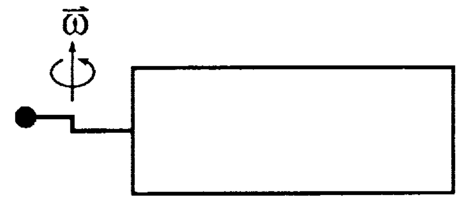


Figure 4. Free-flying spacecraft in a line/raster scan.

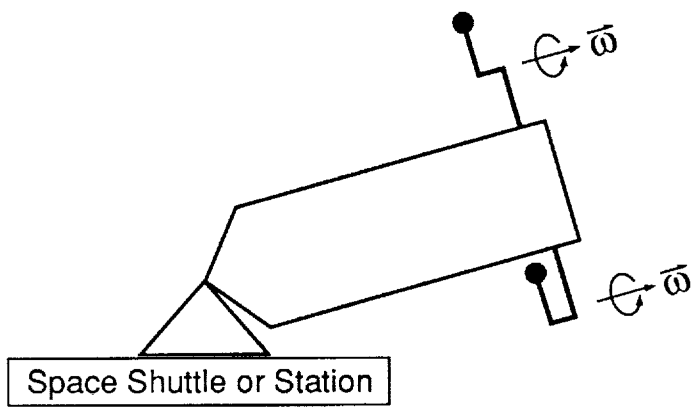


Figure 5. Space shuttle/station, gimballed experiment in a circular scan.

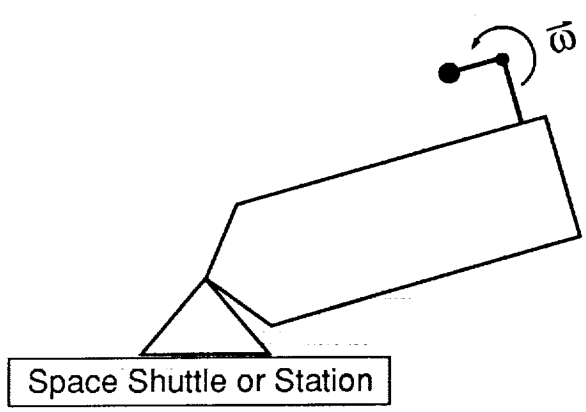


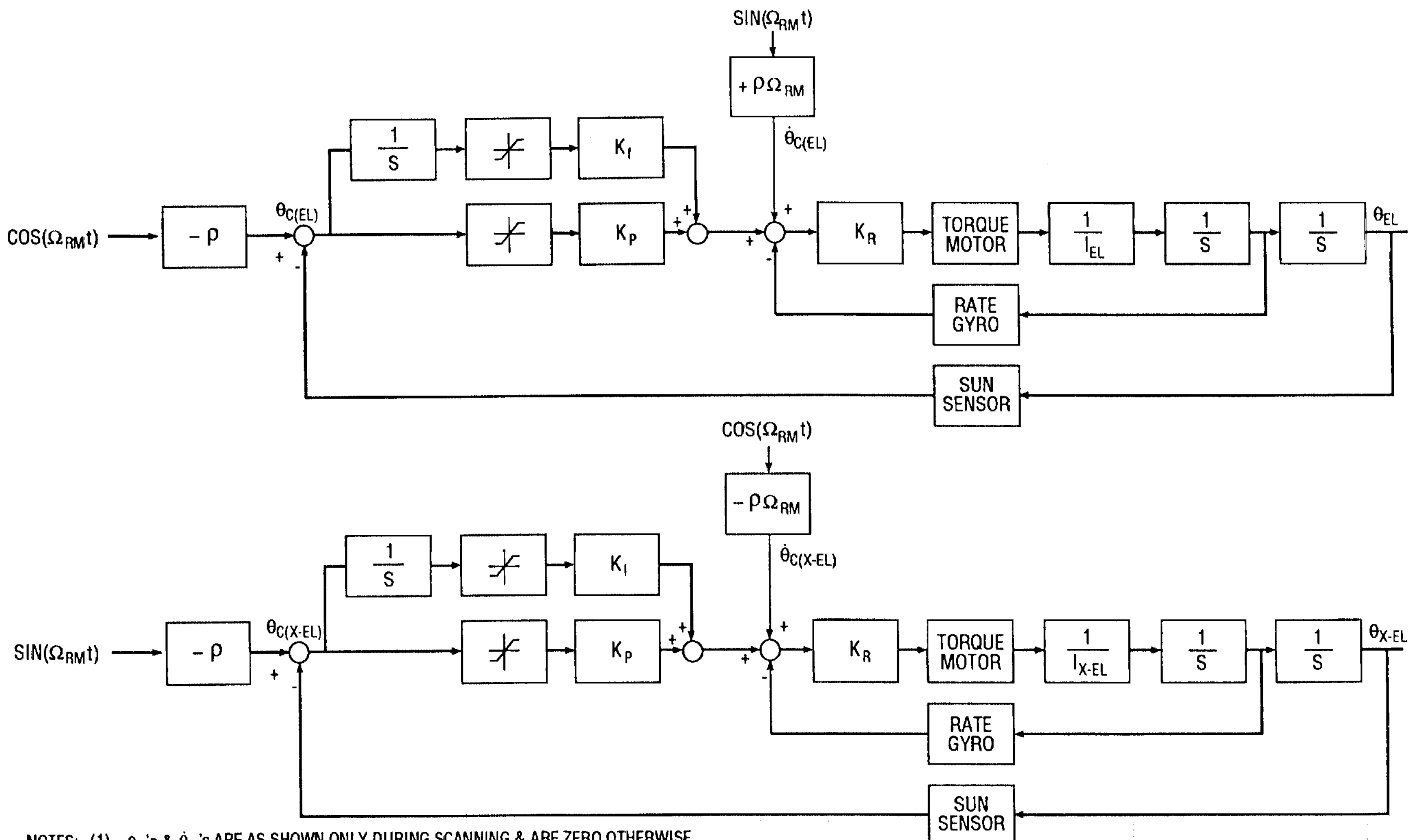
Figure 6. Space shuttle/station, gimballed experiment in a line/raster scan.

IV. SCANNING A BALLOON-BORNE SOLAR EXPERIMENT USING RUM DEVICES

The gamma-ray imaging device (GRID) is a balloon-borne experiment that requires continual circular scanning around the center of the Sun [1]. A scan radius of 0.0009 radians and a scan period of 4 s is required. However, it is highly desirable to be able to select scan periods of 8, 4, 2, or 1 s inflight, if possible. In addition, the scan center must stay within 0.0017 radians rms of Sun center. By the nature of this experiment, the only way to accomplish this scan is by scanning the entire experiment, which is shaped like a cylinder that is about 20 ft long, 4 ft in diameter, and weighs 1,000 lb. Also, weight is critical so the gondola needs to be as light as possible.

A pointing system with RUM devices was defined to meet these scan requirements. It has the following characteristics. There are two RUM devices, mounted as shown in Figure 1. Each device has a 5.3-lb mass on an 8-in lever arm, located 6.2 ft from the center-of-mass of the GRID, in the direction of its line-of-sight. The masses are 180 degrees out of phase with each other and rotate in the same direction with a period of rotation equal to the scan period. The GRID is attached to the gondola by an elevation/cross-elevation gimbal system. The auxiliary control system has torque motors, tachometers, and resolvers on the gimbals and a two-axis Sun sensor and rate gyro on the GRID. During scanning, the control laws for the elevation and cross-elevation control loops are shown in Figure 7. Attitude and rate commands corresponding to the desired scan pattern are input into the control law. In Figure 7, ρ is the desired scan radius and Ω_{RM} is the desired angular velocity of the RUM devices. Should the center of the scan deviate from the center of the Sun, a non-zero torque motor command is generated for recentering it. There is also a gondola azimuth control system consisting of a torque motor, reaction wheel, and a single-axis Sun sensor and rate gyro. The control law is like those in Figure 7, except that the attitude and rate commands are zero. The gondola azimuth control loop keeps the gondola pointed at the Sun in azimuth, preventing azimuth balloon rotations from perturbing the GRID.

A computer simulation of this system was developed by modifying the one in Reference 4. In this simulation, the GRID and gondola are modeled as rigid bodies. The suspension train is modeled as a massless and extensionless cable with some torsional stiffness. The balloon can rotate in azimuth and its motion is assumed to be unaffected by the dynamics of the gondola and the GRID. Other conditions for the simulation are listed in Table 1. Building RUM devices as good as those in the simulation should be possible without a great deal of expense. Simulation results for these conditions are shown in Figures 8 to 10 for a 1-s scan period, the most difficult case. After about 20 s, the system reaches steady state, the scan requirements are met, and the RUM devices are doing most of the work. Simulation results were obtained for scan periods of 2, 4, and 8 s also, with similar favorable results. A tabulation of the simulation results is given in Table 2, along with estimates for the peak power of the RUM devices. For comparison, Table 2 also shows the peak power required by a pair of reaction wheels on the GRID used in place of the RUM devices. This assumes each reaction wheel is 1 ft in diameter and has a mass of 20 lb located around the rim of the wheel. One can see the RUM devices offer not only a weight advantage (4X) over the reaction wheels, but also a power advantage (2X to 132X), that is enormous at the smaller scan periods.



NOTES: (1). θ_c's & $\dot{\theta}_c$'s ARE AS SHOWN ONLY DURING SCANNING & ARE ZERO OTHERWISE.

(2). TACH'S & ENCODERS REPLACE RATE GYRO & SUN SENSOR IN GIMBAL COMMAND MODE.

(3). GONDOLA AZIMUTH SUN POINTING LOOP HAS THE SAME FORM AS EL OR X-EL LOOP EXCEPT WITH ATTITUDE & RATE COMMANDS EQUAL ZERO.

Figure 7. Control laws for the elevation and cross-elevation control loops.

TABLE 1. SIMULATION CONDITIONS

A. ±0.25° pendulous oscillations with a period ≈ 20 s (0.05 hz)

B. Sinusoidal balloon rotations in azimuth with peak rates = ±0.42°/s and a period = 100 s (0.01 hz)

C. Control loop bandwidths:
   1. 0.5 hz for gondola azimuth control loop
   2. 0.1 hz for GRID elevation and cross-elevation control loops

D. Sun elevation angle = 33°

E. Errors in RUM devices:
   1. Weight error = 1.0 oz
   2. Radius error = 0.25 in
   3. Bias phase error = 2.0°
   4. Maximum rate error = 1 percent of average rate at nominal scan frequency
   5. Distance to GRID center-of-mass error = 1.0 in

F. Elevation/cross-elevation torque motor characteristics:
   1. Maximum torque = 20 ft-lb
   2. Coulomb friction = ±0.125 ft-lb
   3. Cogging torque = 0.125 ft-lb maximum at 89 cyc/rev

G. GRID axis of minimum principal moment-of-inertia offset 0.25° from GRID line-of-sight

TABLE 2. TABULATION OF THE SIMULATION RESULTS

Scan period in seconds	1	2	4	8
Max torque on GRID from auxiliary actuators, in ft-lb	2.6	1.7	1.2	1.0
Max torque on GRID from RUM devices, in ft-lb	55	14	4	1.4
Peak power from RUM devices, in watts	86	43	21	11
Peak power from reaction wheels, if used in place of RUM devices, in watts	11,335	1,417	177	22

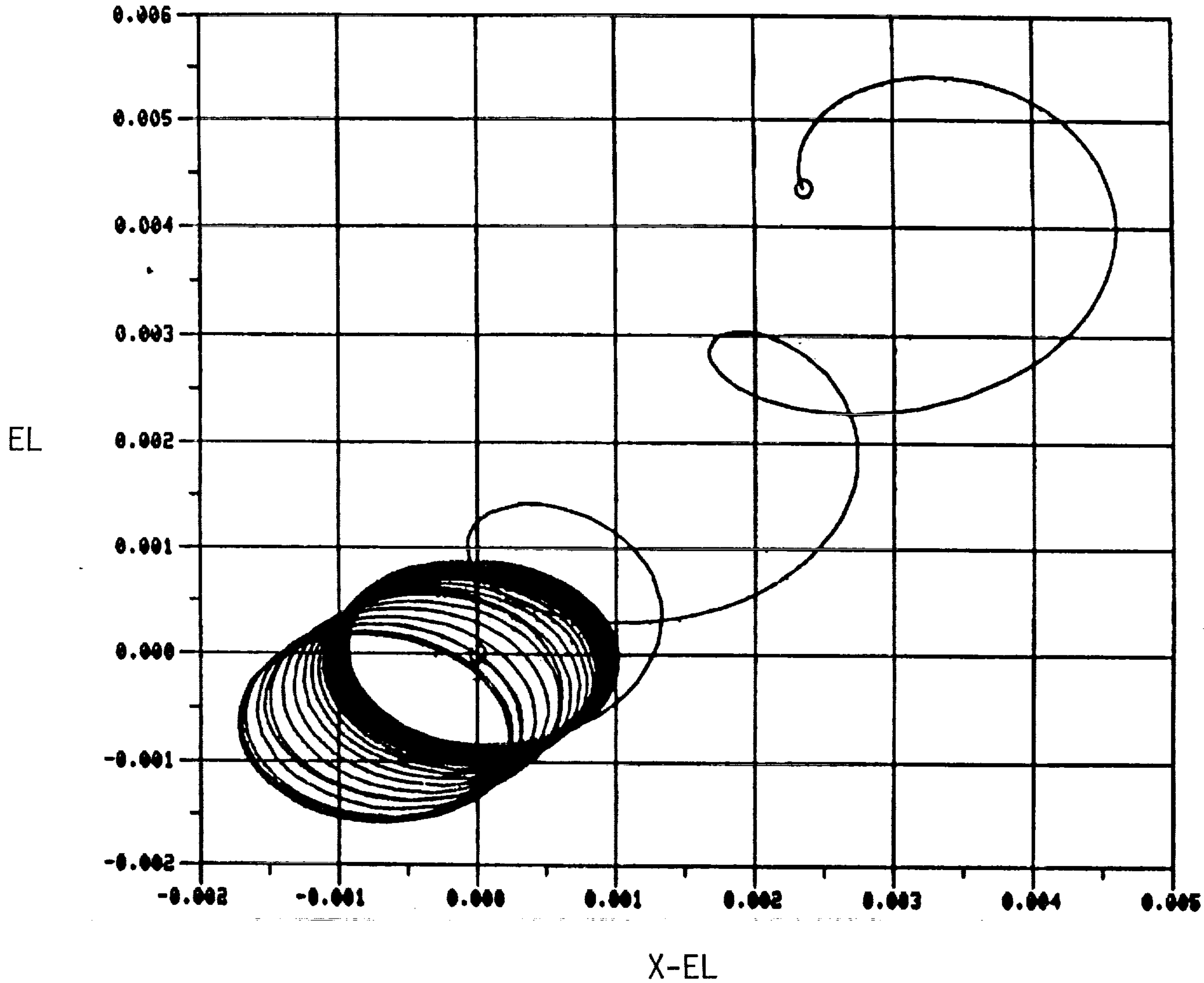


Figure 8. GRID line-of-sight with respect to Sun center in radians for a 1-s scan period.

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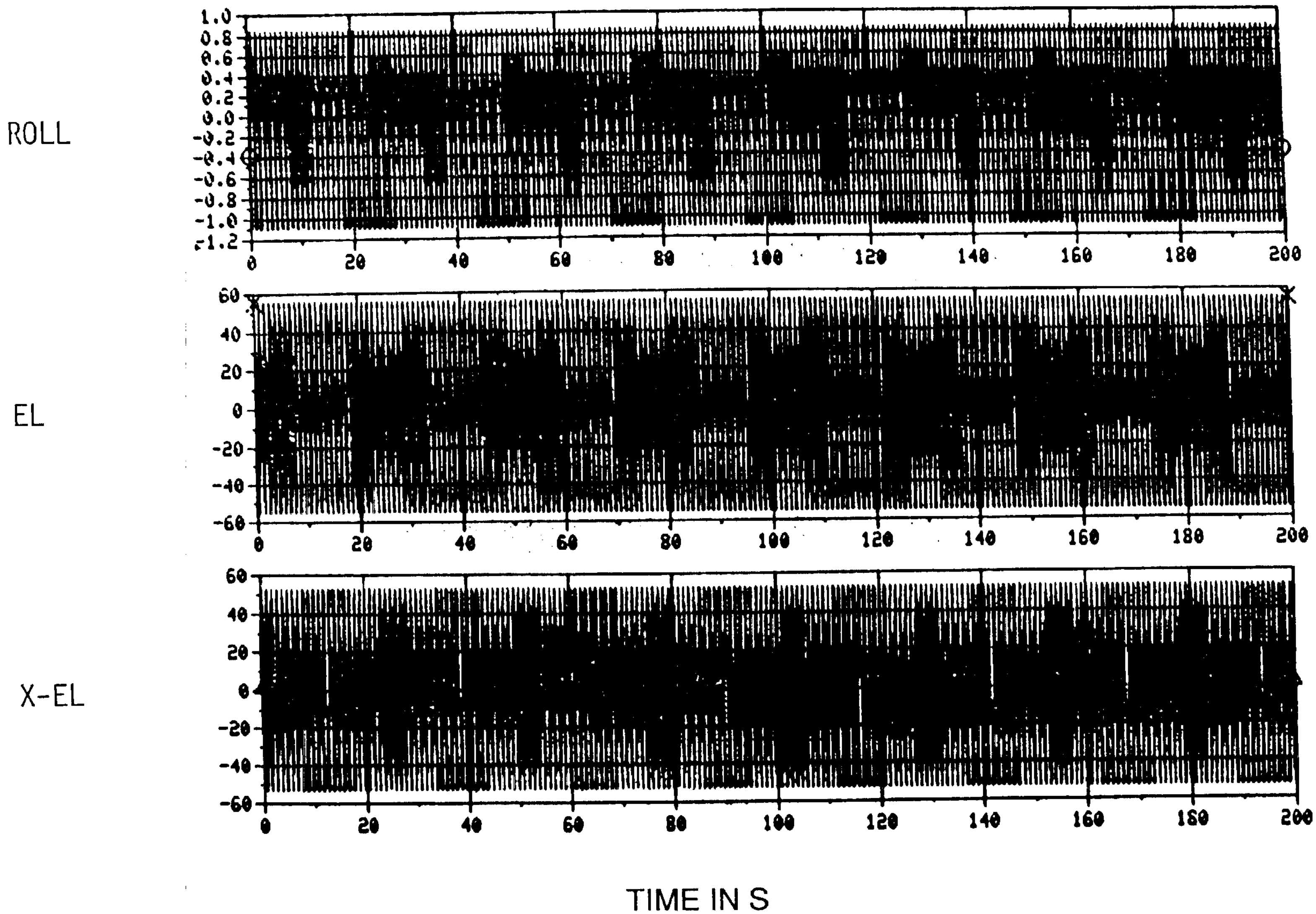

Figure 9. Torque on GRID from RUM devices in ft-lb for a 1-s scan period.

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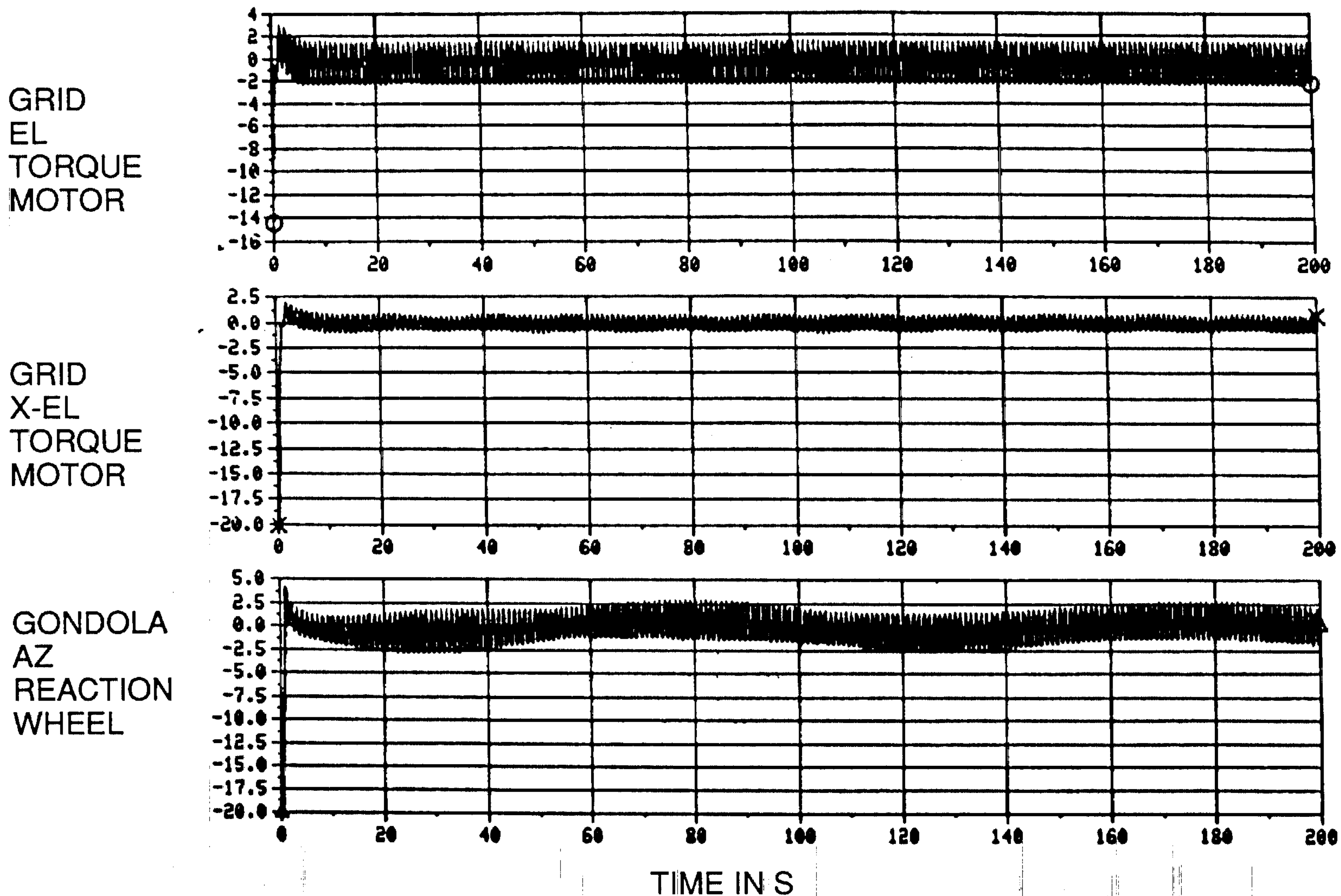

Figure 10. Auxiliary control torques in ft-lb for a 1-s scan period.

V. CONCLUSION

In summary, this paper has presented a new method for scanning balloon-borne experiments, free-flying spacecraft, and gimballed experiments mounted to the space shuttle or the space station. It uses RUM devices for generating circular, line, or raster scan patterns and an auxiliary control system for target acquisition, keeping the scan centered on the target, and producing complementary motion for raster scanning. This method can have significant advantages over prior methods of scanning in terms of either power, weight, cost, performance, stability, or a combination of these. The arguments in section II and the example in section IV support this contention.

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16. Abstract

This paper presents a new method for scanning balloon-borne experiments, free-flying spacecraft, and gimballed experiments mounted to the space shuttle or the space station. It uses rotating-unbalanced-mass (RUM) devices for generating circular, line, or raster scan patterns and an auxiliary control system for target acquisition, keeping the scan centered on the target, and producing complementary motion for raster scanning. It is ideal for applications where the only possible way to accomplish the required scan is to physically scan the entire experiment or spacecraft as in x-ray and gamma-ray experiments. In such cases, this new method should have advantages over prior methods in terms of either power, weight, cost, performance, stability, or a combination of these.

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