An Advanced Controls Technology Flight Experiment

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ABSTRACT

TRW has designed, fabricated, ground tested, and integrated with a host spacecraft an advanced controls technology flight experiment. The purpose of the experiment is to demonstrate advanced controls hardware and controllers for use on operational NASA and DoD spacecraft. Planned experiments include on-orbit vibration suppression, health monitoring, adaptability, and acquisition of lifetime/reliability data. The experiment structure consists of an active tripod where each leg of the tripod has piezoceramic actuators and sensors embedded within a composite material. Driving the active tripod legs is an electronics module which consists of digitally programmable analog compensators. The compensators can be reprogrammed from the ground so that the active structure can serve as an on-orbit test platform for new and robust control laws. A full set of accelerometers and thermistors provide additional data concerning the performance of the active tripod in various orbital environments. Details on the design, dynamic characteristics, ground-based environmental testing (for flight qualification), and ground-based performance testing are presented in this paper along with the level of performance that is expected from the flight experiment.

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INTRODUCTION

Many future space missions will have extremely stringent pointing and alignment performance goals. Designing structures to meet these performance goals through mass and stiffness tailoring is doomed to failure. A certain amount of designed-in structural control will be required in order to to achieve their mission objectives. Utilization of advanced controls-structures interactions (CSI) technologies should be exploited whenever possible to achieve a suitable design.

Recent multidisciplinary advances in CSI technologies have yielded great promise in meeting stringent mission requirements. Some of these advances are new structural damping algorithms, such as impedance matching compensators [1] and robust controllers [2], new sensor and actuator materials [3], and new flexible electronics [4]. As these technologies become ground tested, lifetime and reliability data become available and expand our knowledge base as to their advantages and limitations. However, there is a lack of space flight experience to give spacecraft designers confidence in advanced CSI technologies.

This paper describes the development of an advanced controls technology experiment facility that is expected to be launched into orbit in late 1993. The work was performed on the Advanced Controls Technology Experiment (ACTEX) contract managed by the Air Force Phillips Laboratory. The ACTEX experiment will be a pioneering mission in the area of structural control in that it provides a number of "firsts" for space-based technology verification. It will be the first space flight of embedded piezoceramic sensors and actuators, the first on-orbit adaptive structure experiment, the first flight of digitally programmable analog electronics, the first flight of field programmable gate arrays, and the first flight of a Nitinol latch.

Achieving the objectives of the ACTEX flight experiment will demonstrate the flight-readiness of CSI hardware and algorithms. Chief among the objectives of the flight experiment is to demonstrate integrated active/passive damping using piezoceramic sensors and actuators embedded in graphite composite members. Successful launch and checkout of the ACTEX sysem will provide experimenters with an on-orbit test facility to conduct independent system identification and vibration suppression experiments. Another objective of the experiment is to demonstrate the concept of adaptive structures throught the use of electronics that are programmable from the ground. Finally, objectives in the area of system identification are to validate preflight design and analysis tools, to monitor the long term effects of the space environment on the active structural control components, and to monitor the health of the system over long periods of time.

EXPERIMENT DESCRIPTION

A number of conflicting requirements were placed on the design of the flight experiment; specifically, two distinct sets of requirements, one set associated with the technology demonstration objectives, and the other set associated with the host spacecraft accomodation constraints. These host spacecraft requirements, as well as all other design requirements, are listed in Table 1. Because the flight experiment was a secondary payload, it had to fit into the existing space envelope (10" by 12" by 22"), had to have minimal effect on primary spacecraft orbital operations (by proper orbit average power scheduling), and had to fit into the paging telemetry format of the spacecraft bus. In addition, it was desirable to mount the flight experiment external to the spacecraft for maximum exposure to the space environment while mounting the electronics internal to the spacecraft for maximum reliability. Finally, power and electronics designs had to fit into the exisitng 30 Volt maximum spacecraft power system.

Table 1: Experiment Requirements

Host Interface Requirements	
-Head room	10" maximum
-Low power	16 W OAP
-Telemetry format	Paging format
-Thermal	Thermally isolated
-Drive voltage	$\leq$30 Volts
Host Compatibility Requirements	
-Small size	10" by 12" by 22"
-Low weight	18# structure,35#electronics
-Low ops impact	OAP scheduling
-Location	External structure, Internal electronics
-Schedule	Deliver $\leq$ 12 months
Performance	
-Demonstrate damping	5-10% modal damping
-Provide space testbed	Other users possible
-Validate preflight analysis	On-orbit ID
-Demo adaptive structures	Uplink changes
-Traceability	Scaleable dynamics
-Long life effects	Detailed ID and health monitoring
Risk Reduction	
-Strength	Margins $\geq$ 1.0
-Outgassing	TML$\leq$1.0%,CVCM$\leq$0.1%
-Radiation	Good to 10 kRads
-Workmanship	Extensive test program
-Environment	Extensive test program

The resulting flight experiment is shown schematically in Figure 1. The active tripod

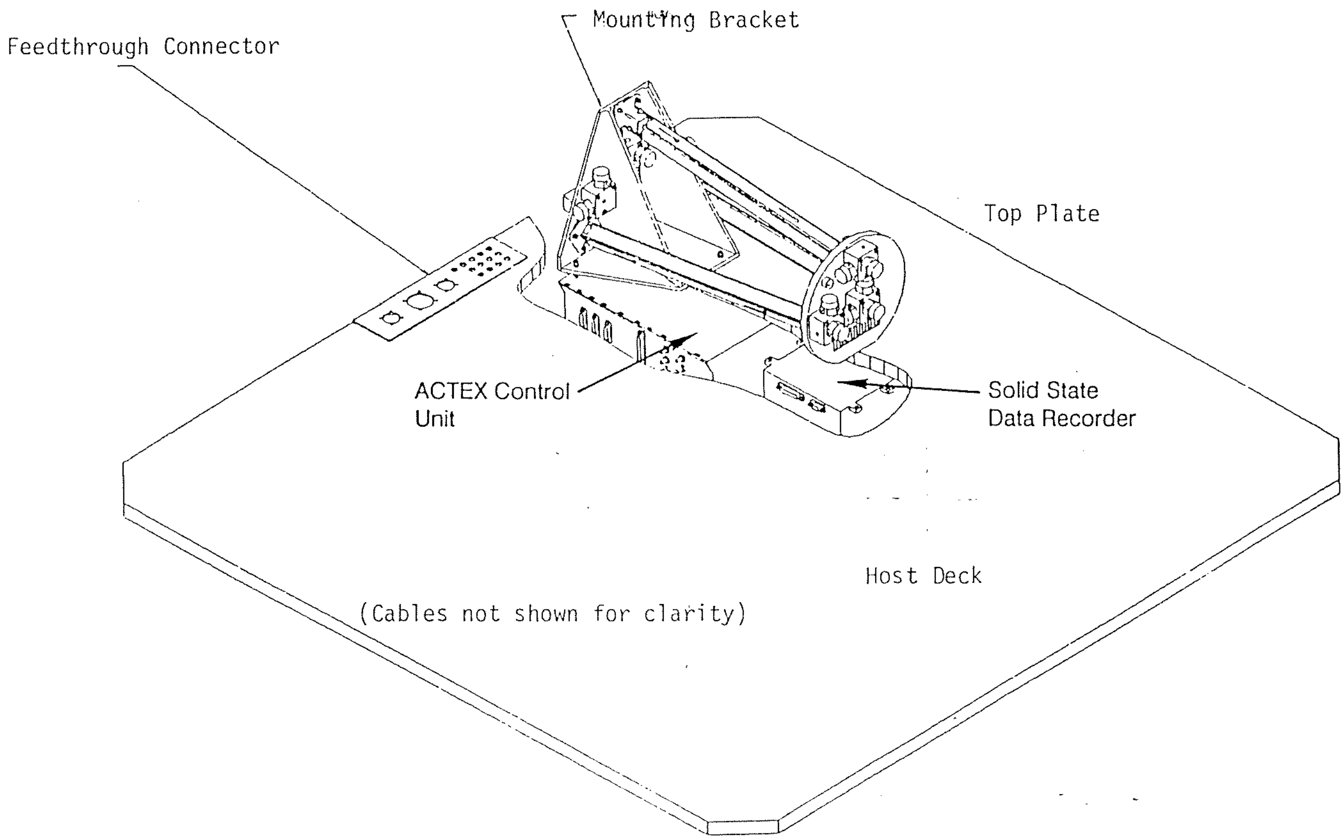


Figure 1: ACTEX Flight Experiment Schematic

is mounted external to the host spacecraft, on a large secondary payload deck. Internal to the spacecraft are the electronics which configure the experiment, drive the active tripod legs, and control the solid state data recorder. The tripod is connected to the electronics with a number of cables (not shown in Figure 1 for clarity) which feedthrough the secondary payload deck. A photograph of the complete ACTEX flight experiment is shown in Figure 2 (minus cables and thermal blankets for clarity).

Figure 3 contains a closeup photograph of the active tripod itself. The tripod consists of three square cross section T300 graphite composite legs with piezoceramic sensors and actuators embedded in all four faces of each leg. Members A and C are covered with multi-layer insulation (MLI) for thermal control, whereas member B (i.e., the silver leg in Figure 3) is covered with leafing aluminum paint. Twelve thermistors monitor the temperatures at various points along the active members, on the top plate, and on the bottom bracket. Six accelerometers are used to monitor the motions of the bottom bracket (i.e., monitor the input motions to the base of the tripod). Figure 4 shows a photograph of the top plate of the flight experiment. Seven accelerometers are used to monitor the motions of the top plate.

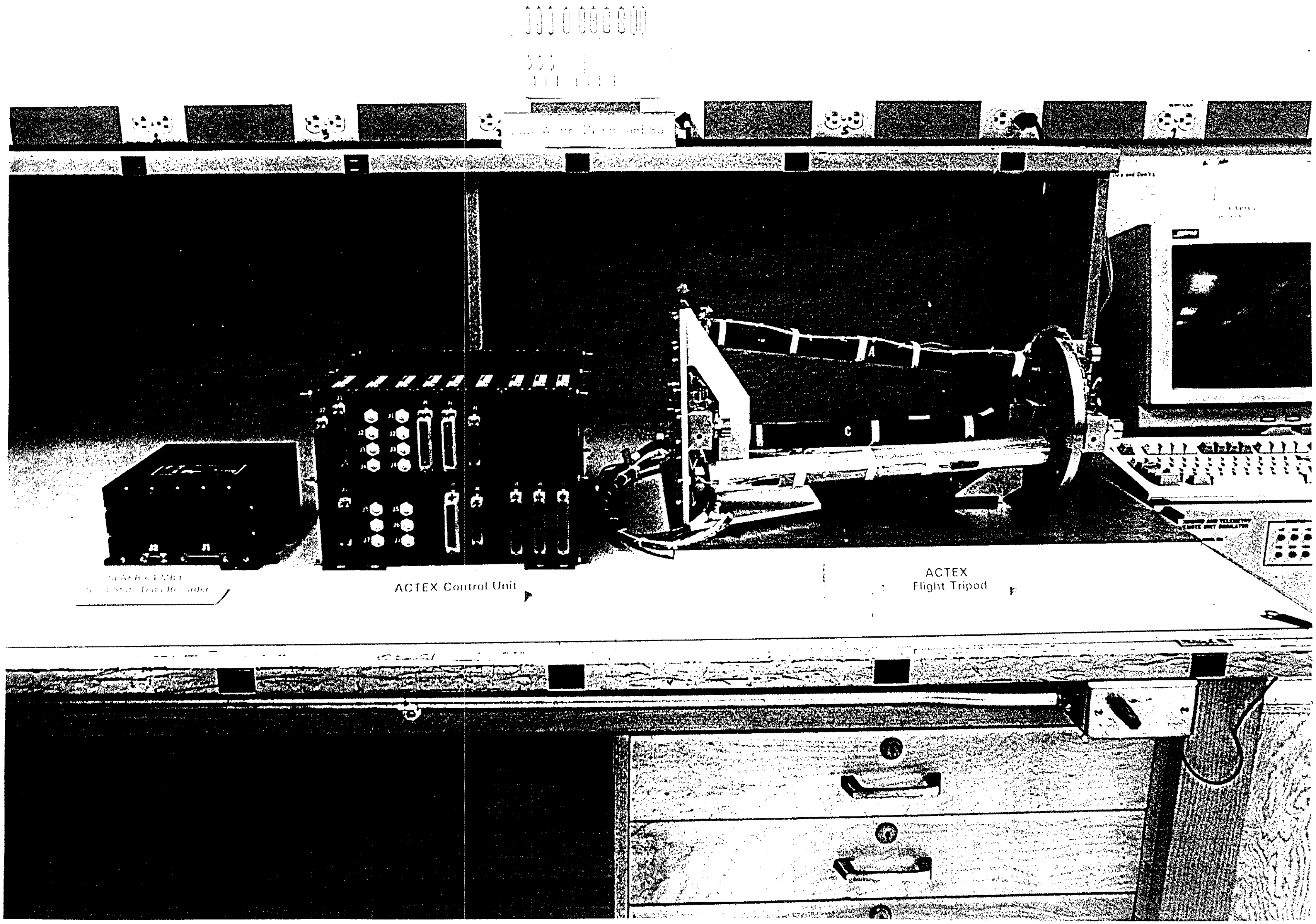


Figure 2: Flight Experiment Hardware

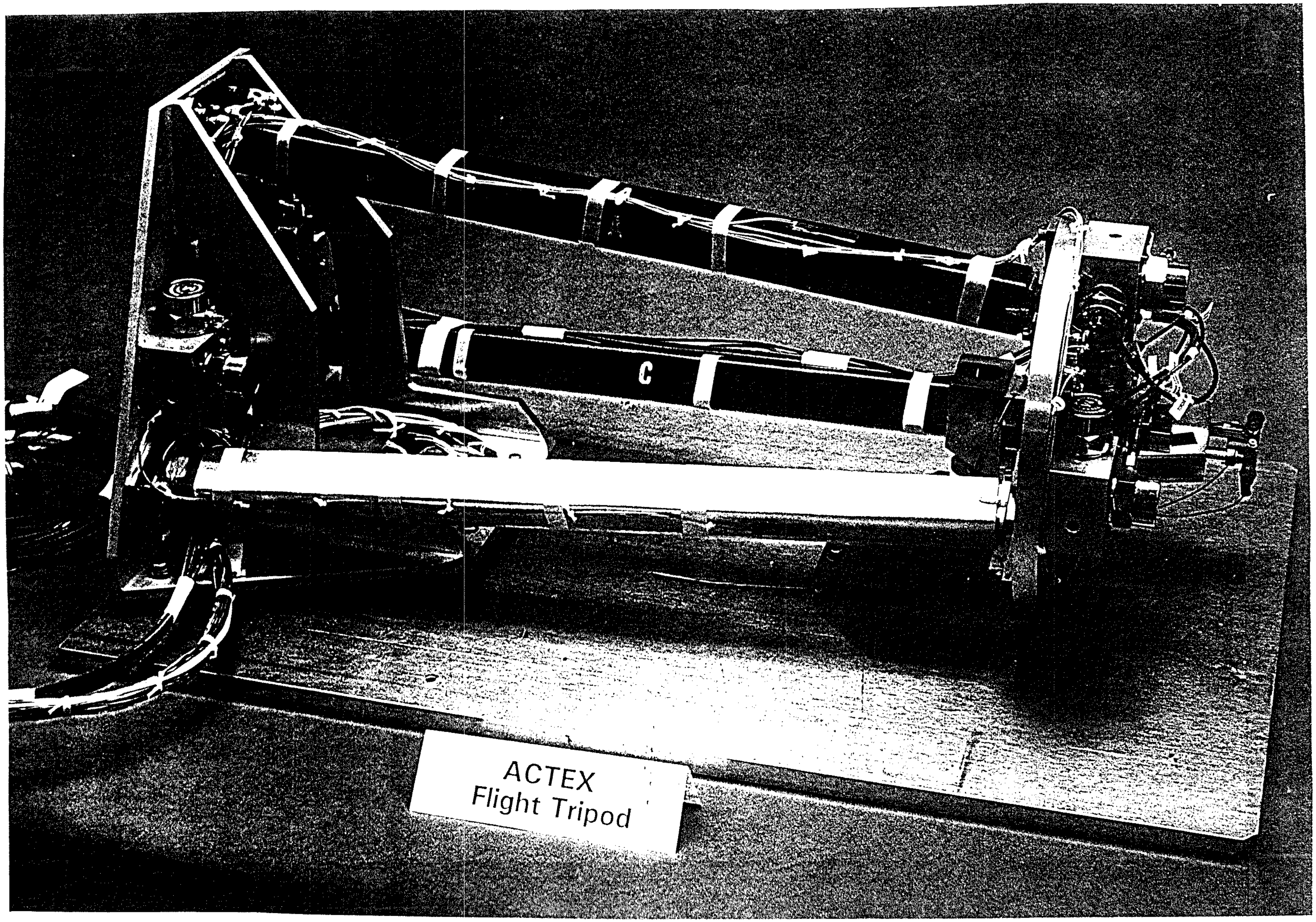


Figure 3: Active Tripod Flight Experiment

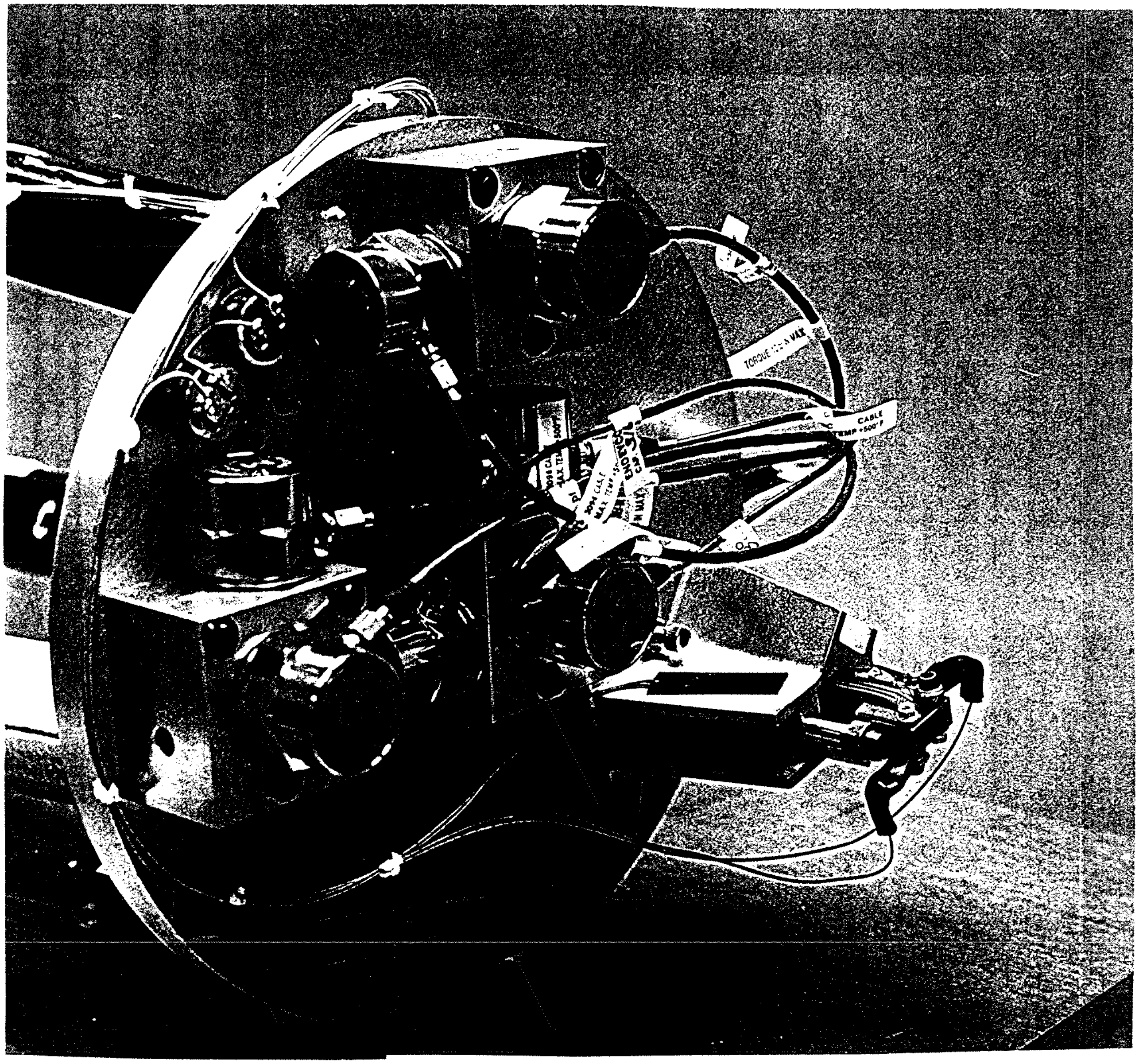


Figure 4: Top Plate Details

By mixing the signals of the seven accelerometers, all three translations and rotations of the top plate can be recovered for use in monitoring the open and closed loop performance of the tripod. Also contained on the top plate is a heater and redundant thermostats for active thermal control of the top plate. The active thermal control system was required in order to prevent the accelerometers from falling below their failure temperature of -55 °C. An additional heater/redundant thermostat set are contained on the bottom bracket near the other six accelerometers.

Figure 5 contains a photograph of the bottom surface of the top plate. The active members are connected to the top plate through flexures. The flexures were designed to provide the appropriate flexibility such that the active members are closer to clamped-free boundary conditions rather than clamped-clamped. These boundary conditions enhance the controllability of the system by preventing the actuators from being located in regions of reverse curvature for the first two bending modes. Also seen in Figure 5 are the grounding beads drawn between the exterior surface of the active members and the end fittings to prevent charge differences from building up between different regions of the structure.

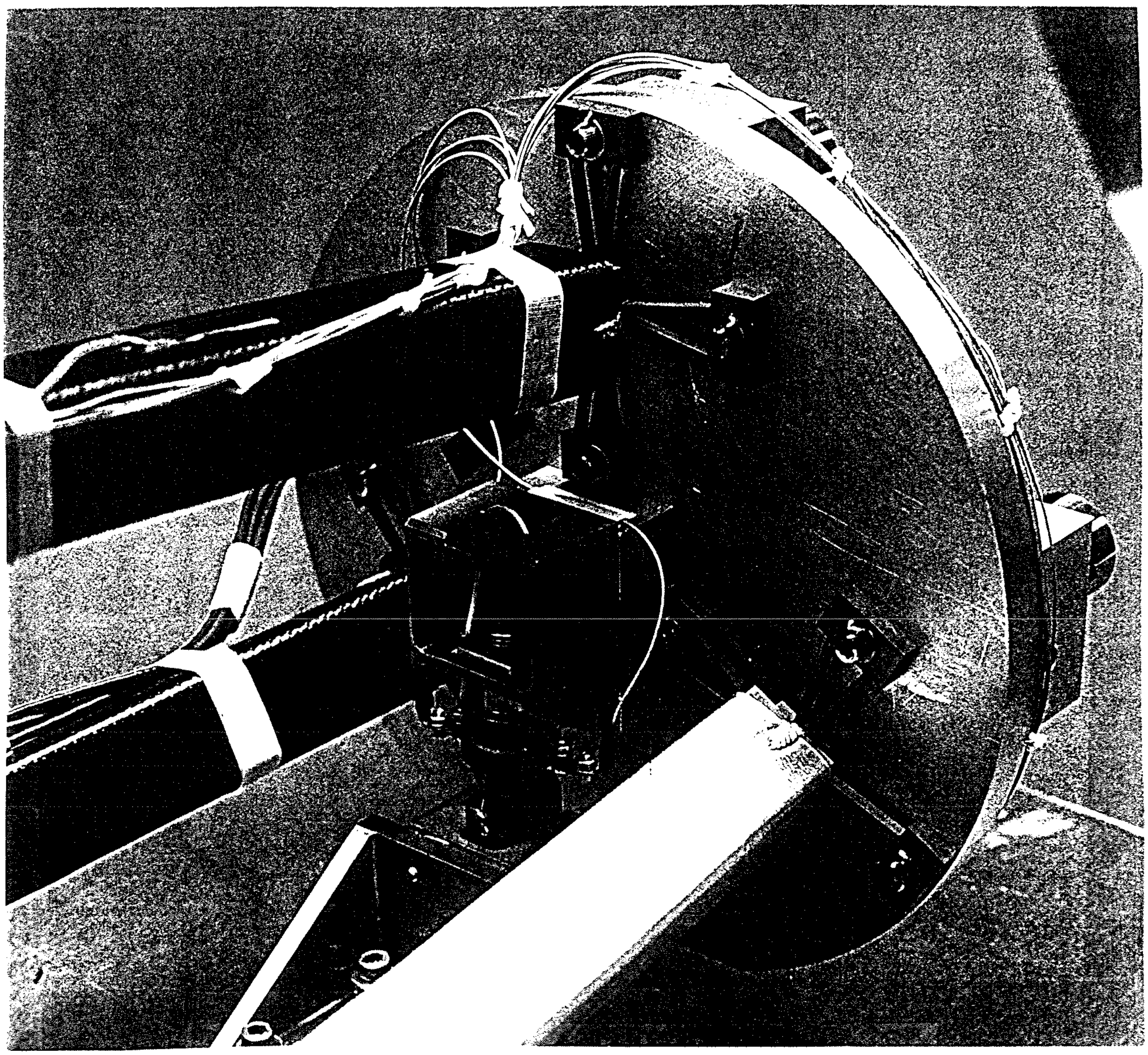


Figure 5: Bottom Surface of the Top Plate

Figures 4 and 5 also contain photographs of the Nitinol mechanisms of the ACTEX flight experiment. A Nitinol-actuated latch, attached to the center of the bottom surface of the top plate (see Figure 5), is used to take the loads during the severe environment of a Titan IV launch. Taking the launch loads with the latch relieves some of the strength requirements on the active members and enhances the experiment quality by allowing a lower frequency on-orbit system. Additional Nitinol strands are contained in the Dynamic Change Mechanism (DCM) which can be seen in Figure 4. By actuating the DCM, the Nitinol shrinks and draws the flexures up against the bottom surface of the top plate. In effect, actuating the DCM locks out one of the flexures and raises the natural frequency of the system. Ground tests showed that a 20% change in primary bending modes could be achieved by actuating the Nitinol in the DCM. Use of the DCM to change the dynamics characteristics can demonstrate the adaptivity of the tripod and electronics and can be used to demonstrate the robustness of the controllers.

FLIGHT ELECTRONICS

The flight electronics were designed to satisfy the host interface requirements and to perform the identification, damping, and adaptivity experiments necessary to space validate adaptive structures. The functions of the electronics can be roughly broken down into control electronics, data collection/telemetry electronics, command processing electronics, and miscellaneous functional electronics. Each of these functions are described in the following paragraphs.

Figure 6 shows a block diagram of the complete electronics subsystem. At the heart of the vibration suppression capability of the active tripod are the control electronics. These circuits implement the tripod leg controllers in an analog fashion. However, the controller topology and gains are programmable via digital commands from the ground, hence the name digitally programmable analog electronics [4]. By varying the charge amplifier gains, K_1 and K_2 in Figure 6, the piezoceramic sensor signals can be amplified and averaged together to give a transfer function which is advantageous from a control design standpoint. By varying the digital switches, low pass and band pass filters can be enabled or disabled, thus changing the controller topology between third or fifth order rate feedback, third order positive integration, and second order Positive Position Feedback [5] controllers. Filter cutoffs are varied by changing the clock rate into the filter, in effect varying the bandwidth of the controller. Finally, the overall gain of the controllers can be changed by varying the K_3 and K_4 parameters (see Figure 6). The great flexibility in the digitally programmable analog electronics allows a large number of controllers to be available for space test and allows a degree of adaptiveness in the experiment.

The data collection/telemetry electronics collect data from the active members, the accelerometers, and the thermistors, and loads it into the solid state data recorder for playback at a later time. Each of the six active member signals and thirteen accelerometer signals are sampled at a 4 kHz rate. The twelve thermistors are subcommed together onto one channel and are thus effectively sampled at a somewhat slower rate. A formatter and timing generator converts the multichannel data into serial data for loading into the data recorder. The data recorder itself has a 64 Mbit storage capacity and is semi-fault tolerant. The data

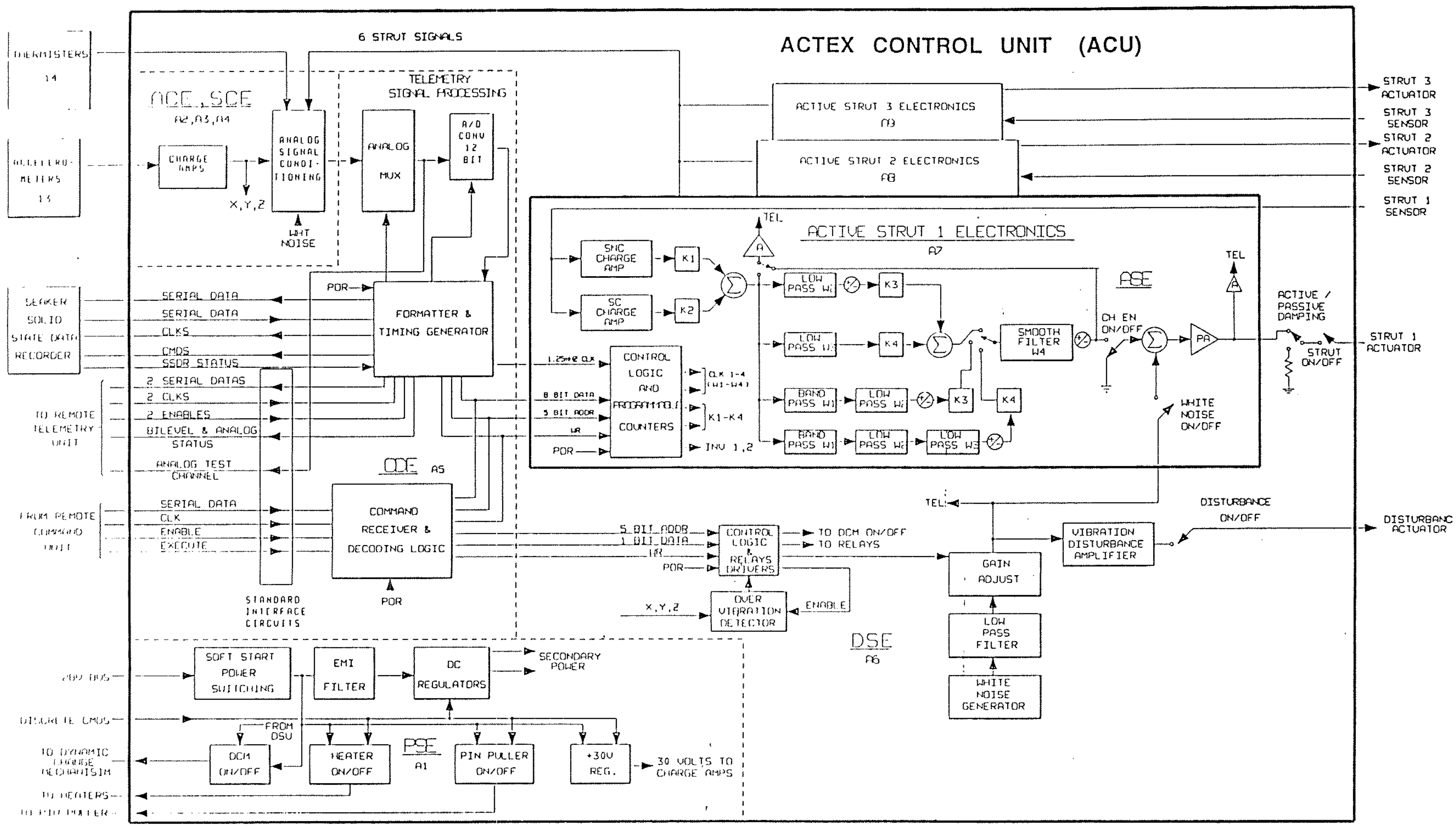


Figure 6: Electronics Functional Block Diagram

recorder monitors it's own health and avoids certain blocks within the recorder when it detects a fault. Thus, end of life storage is somewhat reduced from the 64 Mbits depending on the number of faults the data recorder develops. The data collection/telemetry electronics also reads serial data out of the recorder and downlinks the data to the ground via the host spacecraft telemetry system. Digital commands uplinked from the ground control the functions which the data collection/telemetry electronics perform.

The command processing electronics is the dispatcher for setting up and communicating with the flight experiment. Ground commands for control of the overall experiment are received. This subsystem reconfigures the experiment, selects among the 80 preprogrammed experiments stored in PROM, and controls the data acquisition and readout operations. In addition, the command processing electronics can modify the experiments stored in PROM, in effect yielding a virtually unlimited number of possible experiments.

The miscellaneous electronics takes 28 Volts of fused spacecraft power and produces the ± 15 and ± 5 Volt secondary levels needed to operate the experiment. In addition, the Nitinol drivers for the latch and for the Dynamic Change Mechanism are contained within this subsystem. Finally, a white noise generator, for running system identifications and forced frequency responses, are contained within the flight electronics.

Figure 7 shows a closeup photograph of the electronics packaging. Separate "slices" were used for portions of the electronics to maintain a degree of modularity for ease of assembly and repair. The slices communicate amongst each other via an experiment bus which contains the necessary electrical connections for proper operation. The slices provide a rugged packaging method for survival of harsh environments and for protection of electronic circuits.

GROUND TESTING AND VALIDATION

A comprehensive ground test program was conducted to verify the workmanship and integrity of the flight experiment, to demonstrate the survivability to thermal and launch environments, and to provide a catalog of system identification and damping data for comparison with on-orbit data.

Static proof tests on individual active members were run to verify design loads and proof of workmanship. Member forces were extracted from the NASTRAN finite element model and test loads were derived to attain these member forces. Strains up to 1200μstrain were observed in the regions of the piezoceramic sensors and actuators. Before and after transfer functions indicated no degradation in sensing or actuation capability following the static proof tests.

The active tripod was subjected to six thermal cycles to verify the survivability of the structure to expected thermal loads. Survival limits of testing of -157/+148 °C for the structure were derived from thermal models of the experiment, the host spacecraft, and the orbital parameters. Temperatures of -89/+113 °C for the structure and 0/+40 °C for the electronics

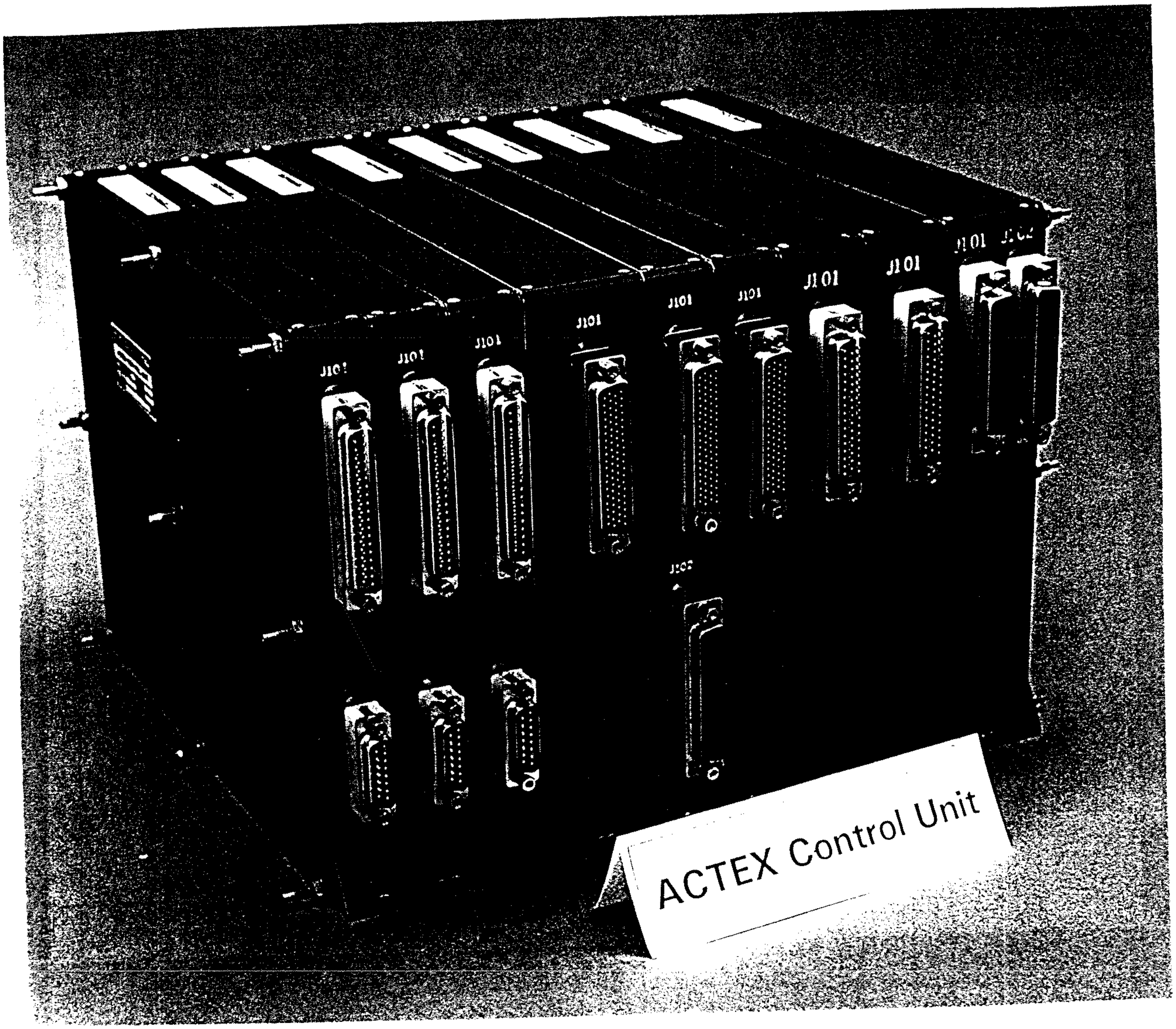
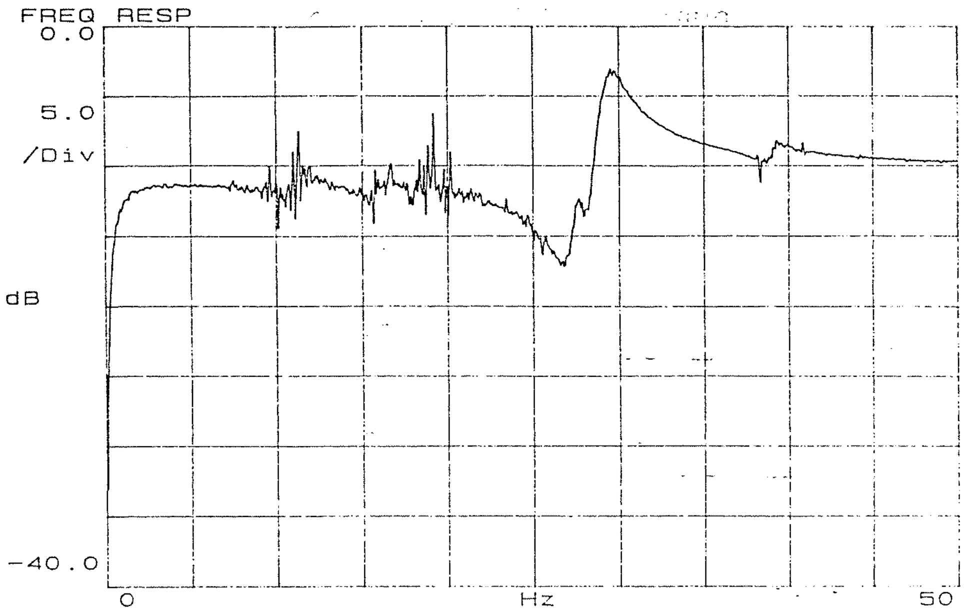


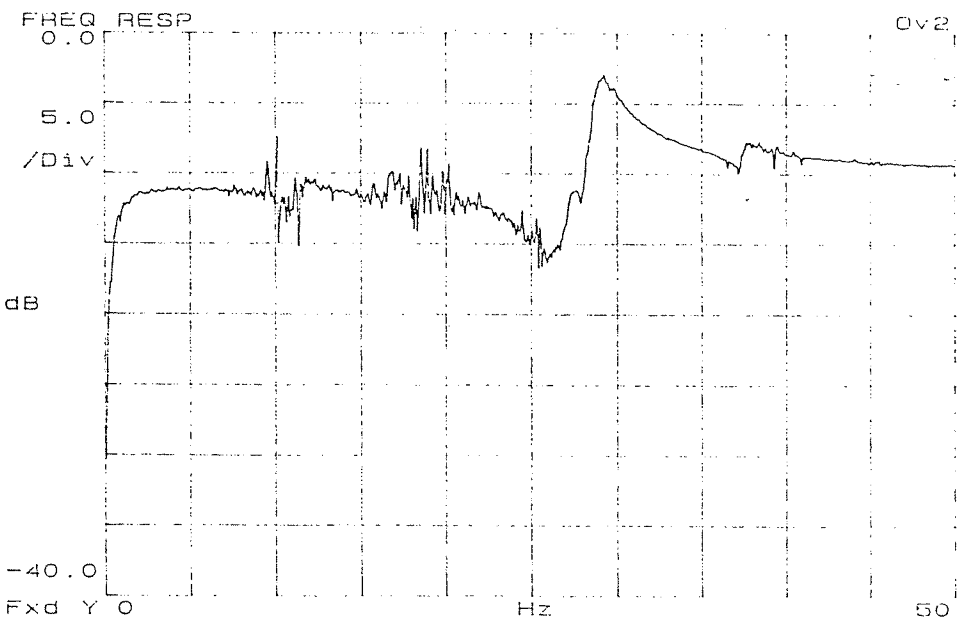
Figure 7: Electronics Packaging

were determined for flight experiment operation. Thermal cycling of the electronics at the operational limit and the active tripod at the survivable limit were conducted, with testing done before and after to verify the functionality of the system. Figure 8 contains before and after transfer functions for one channel of the active tripod. No significant deviations were observed in the data following the thermal cycling tests.

The electronics and tripod were subjected to a random vibration test with independent base inputs of 11.1 g_{rms} applied axially and 10.5 g_{rms} applied laterally. These input vibration levels are compatible with a secondary payload requirement on a Titan IV launch vehicle. Before and after vibration testing indicated all subsystems in working order and ready for launch.



Pre-Thermal Cycling Transfer Function, Ch. 2



Post-Thermal Cycling Transfer Function, Ch. 2

Figure 8: Before and After Thermal Cycling Transfer Functions

Transfer function and forced frequency response data were taken to characterize the dynamic behavior of the active tripod and to get a catalog of ground-based data. This data will be compared with the on-orbit data and will be used to debug the flight experiment in the event of flight anomalies. A typical averaged transfer function for the active members is shown in Figure 9. A good degree of controllability and observability are demonstrated for a lateral bending mode and the torsional mode of the structure. Open and closed loop forced frequency reponses are shown in Figure 10, where only the control loop associated with the previously shown transfer function is closed. Both the torsional mode and a lateral bending mode are highly damped. The second lateral bending mode near 21 Hz is unaffected in this case because the actuator/sensor pair used for control is orthogonal to this bending mode. Either of the other two control loops can observe and control this mode however. Table 2 contains a summary of the ground-based open and closed loop damping performance that

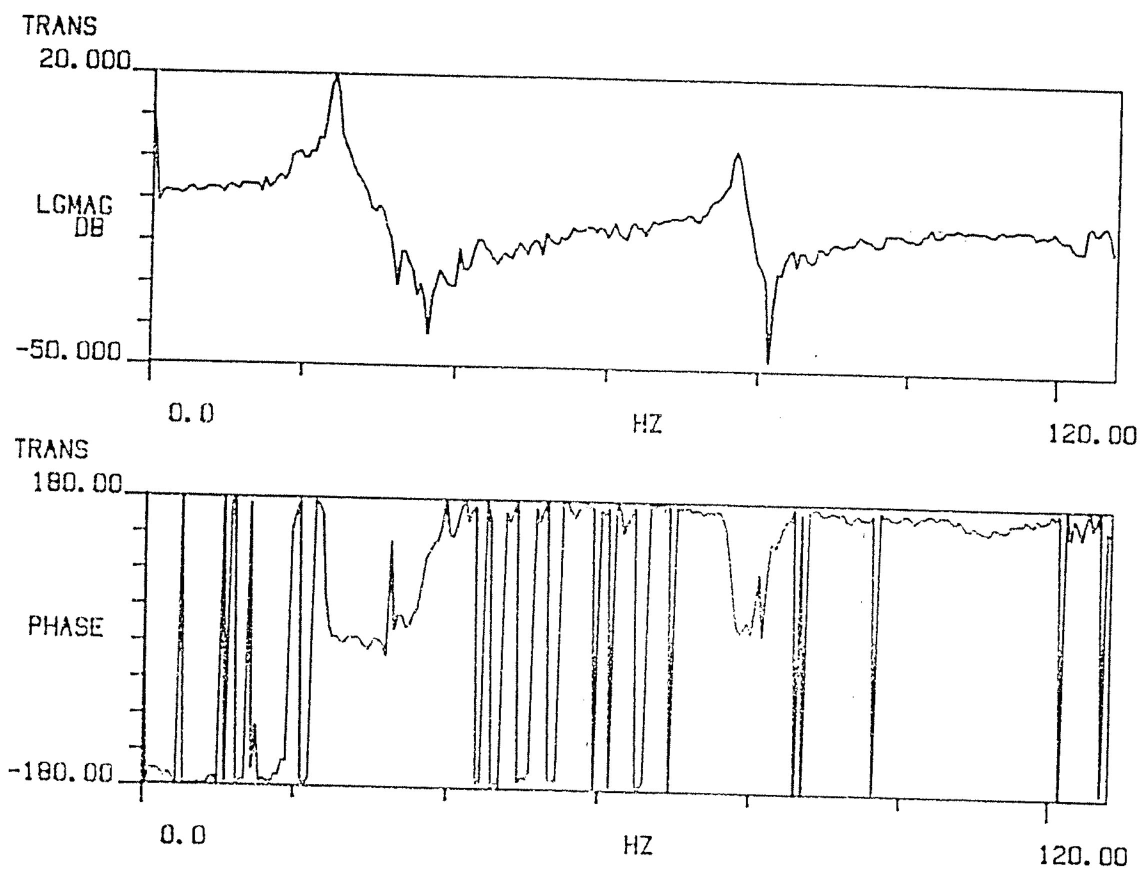


Figure 9: Typical Averaged Transfer Function

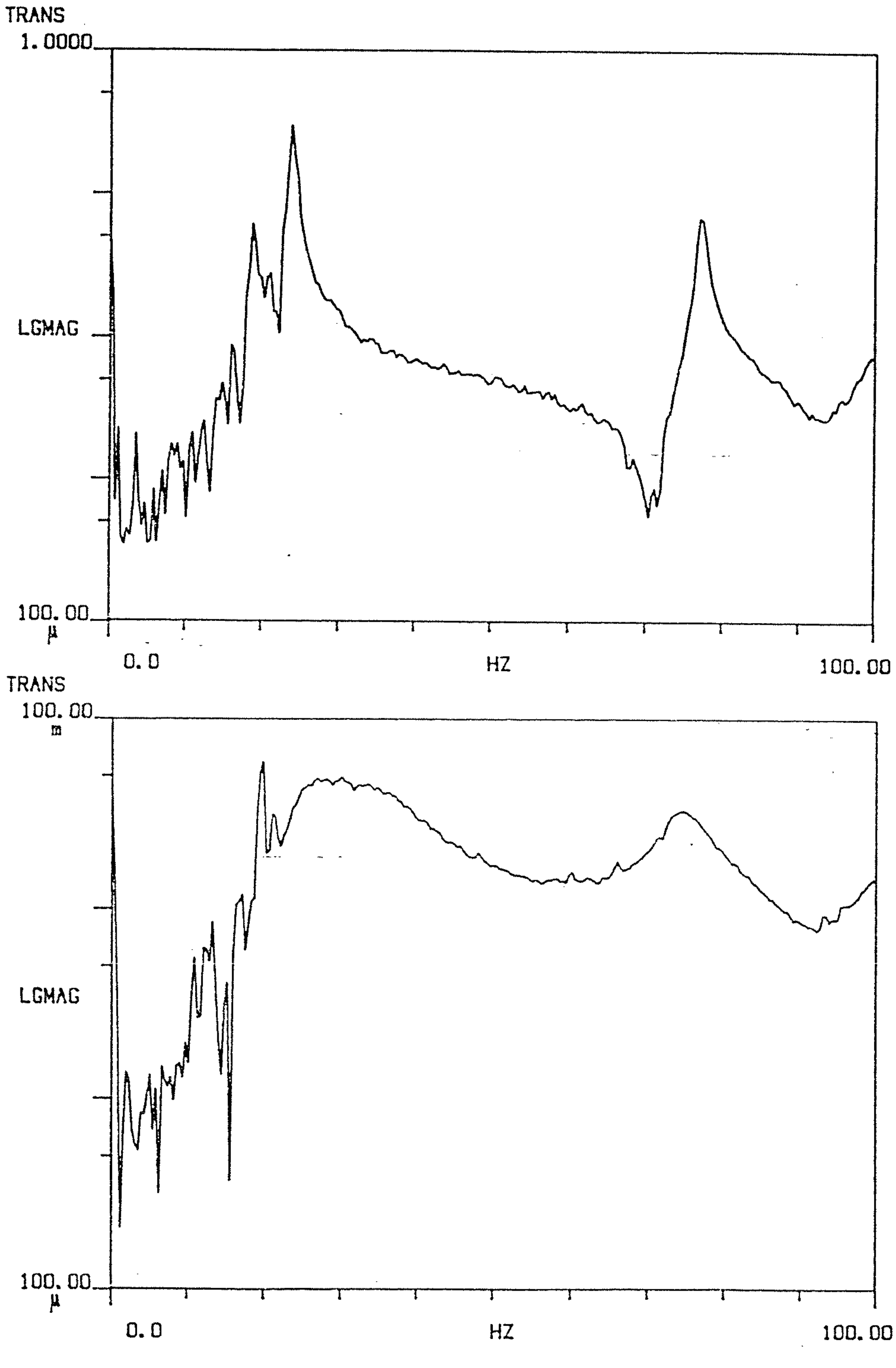


Figure 10: Open and Closed Loop Frequency Responses

was obtained on the ACTEX flight experiment. These data will be compared with both short and long term flight data as they becomes available.

Table 2: Ground Tested Damping

Mode	Open Loop		Closed Loop	
	Frequency (Hz)	$\zeta(\%)$	Frequency (Hz)	$\zeta(\%)$
Lateral Bending	21.0	1.1	20.9	16.3
Lateral Bending	23.9	0.8	27.0	22.0
Torsion	77.0	0.5	75.0	6.7

CONCLUDING REMARKS

The description of an advanced controls technology flight experiment has been presented herein. The experiment was designed within the tight constraints of being a secondary payload on a Navy spacecraft. The structure itself consists of an active tripod with piezoceramic sensors and actuators embedded in the graphite composite tripod legs. Digitally programmable analog electronics are used to drive and control the active members, giving a great degree of on-orbit flexibility for control design and for a demonstration of adaptive structures. Damping levels greater than 22% were observed during closed loop testing on the ground.

The flight experiment has been fully integrated with the host and has undergone system level environmental testing with the host spacecraft. A launch date sometime late in 1993 is expected. Results regarding the system identification performance, open and closed loop damping levels, degree of adaptivity, and lifetime/reliability data will be presented when they becomes available.

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REFERENCES

[1] Chen, G-S., Lurie, B.J., and Wada, B.K., "Experimental Studies of Adaptive Structures For Precision Performance", *Proceedings of the 30th Structures, Structural Dynamics, and Materials Conference*, Mobile, AL, April 1989, pp. 1464-1472.

[2] Doyle, J.C., "Analysis of Feedback Systems with Structured Uncertainties", *IEEE Proceedings*, Vol. 129, Part D, No. 6, Nov. 1982, pp. 242-250.

[3] Cross, E., "Piezoelectric and Electrostrictive Sensors and Actuators for Adaptive Structures and Smart Materials", *Adaptive Structures*, ASME AD-Vol. 15.
[4] Bronowicki, A.J., Mendenhall, T.L., Betros, R.S., Wyse, R.E., and Innis, J.W., "ACESA Structural Control System Design", Presented at the First Joint U.S./Japan Conference on Adaptive Structures, Maui, HI, November 13-15, 1990.
[5] Fanson, J.L. and Caughey, T.K., "Positive Position Feedback Control for Large Space Structures", *Proceedings of the 28th AIAA Dynamics Specialists Conference*, Monterey, CA, April 9-10, 1987, pp. 588-598.