The Development of a Small Satellite Attitude Control Simulator

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Abstract

Utah State University has developed an air bearing table to simulate the attitude dynamics of a small satellite. The Small Satellite Attitude Control Simulator (SSACS) table includes attitude sensors, a control computer, movable mass units and gas jet thrusters. This paper describes the design of the SSACS table and provides preliminary experimental results from 3 axis control tests.

1. Introduction

Satellite attitude controls is a major part of the aerospace engineering curriculum at Utah State University. USU currently offers courses in this area emphasizing the application of the basic principles of dynamics and controls to spacecraft related problems. The motion of the spacecraft represented by analytic and numerical solutions are often difficult for students to intuitively visualize. Many students wish to delve deeper into controller design topics. A testbed including hardware, sensors, software and actuators provides the students with an excellent learning platform.

Additionally, USU is involved in several spacecraft attitude controls research projects, ranging from replicating classical attitude control designs in hardware to implementing adaptive and neural network control concepts. The realistic evaluation of these algorithms requires a laboratory facility where experimental tests can be performed under repeatable conditions.

To satisfy both the teaching and research needs, the design of a Small Satellite Attitude Control Simulator (SSACS) was undertaken jointly by the Mechanical and Aerospace Engineering and Electrical Engineering departments at USU.

2. Previous Simulator Systems

Satellite Simulator platforms have been used for attitude control studies in academic, industrial and governmental laboratories. An air bearing based satellite motion simulator was developed in 1959 at Marshall Space Flight Center by Haeussermann and Kennel [1] capable of supporting a 900 lb platform. A similar air bearing platform was developed by NASA at the Langley Research Center for ground testing for the Solar Orientation

Control Systems Project reported by Fontana et al [2]. Tabata et al. [3] developed a Satellite Attitude Control System Simulator operating on a plate attached to an air bearing for the National Space Development Agency of Japan. The European Space Research Organization (ESRO) developed an air bearing test facility for control system studies, as described by Arbes et al. [4] in the early 1970's. Stanford University developed a Spinning Vehicle Simulator which was used for attitude control tests, e.g., Lorell and Lang [5]. Three D.O.F. control system test facilities continue to be developed and used, such as the Spacecraft Control Laboratory Experiment (SCOLE) currently in use at Langley Research Center[6].

3. Description of the SSACS Table

The SSACS table was designed as an experimental testbed to study spacecraft dynamics and attitude control. The table's configuration provides 3 axis pointing control as well as a single axis spin stabilized platform, using a gas jet thruster system. The overall design of the table is shown in Figure 1. Roll, pitch and yaw motions are defined about the X, Y and Z axes respectively.

The design of the table was driven primarily by system flexibility and cost. Flexibility was needed as a test facility to allow testing over a wide range of potential mission scenarios. Cost considerations affected the selection of components, especially instrumentation, available for the table. The design evolved as funding became available for higher quality onboard computers and sensors.

The table consists of an aluminum disk riding on a 4 inch diameter spherical gas jet bearing. The brass bearing uses twice-filtered compressed air regulated to 40 psi applied through six jeweled nozzles to provide a virtually frictionless bearing. The bearing has a maximum load capacity of 180 lbs and provides for ±45 degrees of motion about the pitch and roll axes, plus a full 360 degrees of rotation about the yaw axis.

The upper portion of the spherical bearing is attached to a 30 inch diameter aluminum table with helicoiled mounting holes placed at 2 inch intervals in a square pattern. The support stand for the lower (fixed) part of the bearing consists of a solid aluminum rod strengthened by 3 gussets welded to an aluminum base plate.

An attempt was made to measure the frictional characteristics of the bearing by spinning the table and monitoring the decay in the spin rate. With an initial spin rate of 5 rad/sec, the table was still spinning after three hours. We were unable to determine the drag characteristics due to energy transfer to other oscillatory modes. We expect that the aerodynamic drag of the table is greater than the drag induced by the bearing.

The table is coarsely balanced by manually adjusting the position and mass of six lead weights mounted on adjustable length standoffs to the table. Fine balancing can be accomplished in two ways: manual positioning of leadscrews or through the use of six computer-controlled mass movement assemblies (MMA's) to accurately position masses on the table. These assemblies are designed to be used to continuously balance the table during operation to compensate for losses of thruster propellent. The MMA's, shown

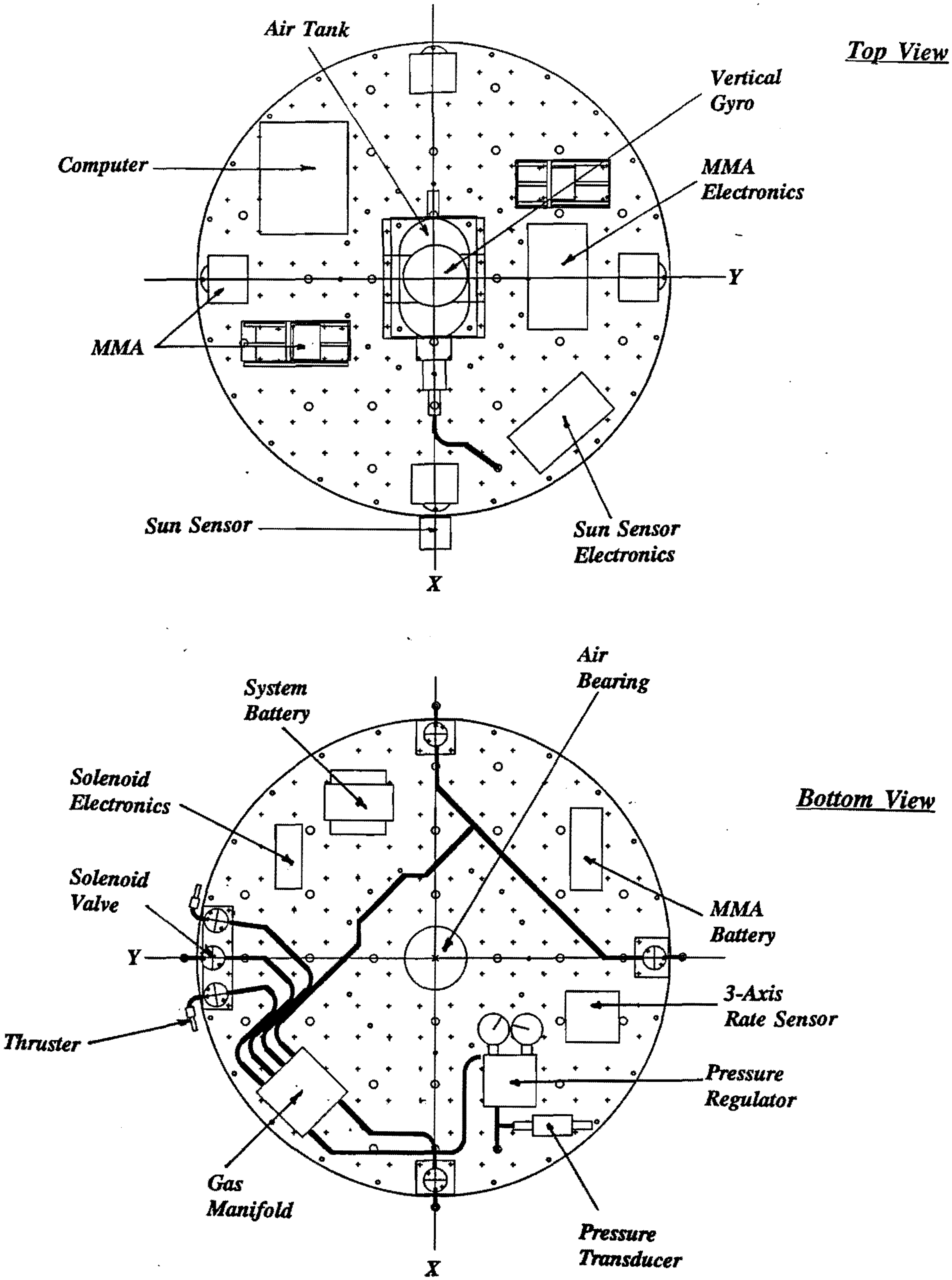

Figure 1. Configuration of the SSACS Table

in Figure 2a, consist of a stepper motor weighing 1.2 lbs. riding on a leadscrew travelling 0.05 inches per revolution, allowing positional changes of 0.000125 inches. The distribution of the MMA's on the SSACS table is shown in Figure 2b. Adjusting these masses also can be used to fine tune the inertia of the table.

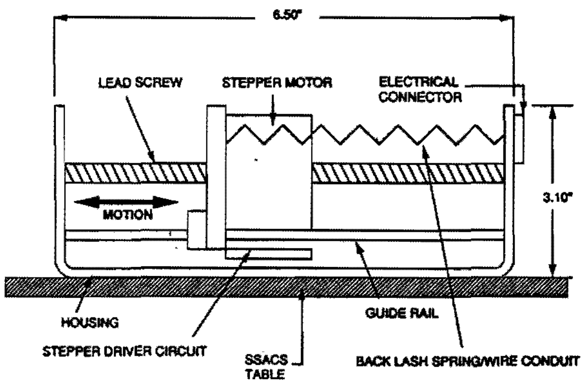

Figure 2a. Mass Movement Assembly

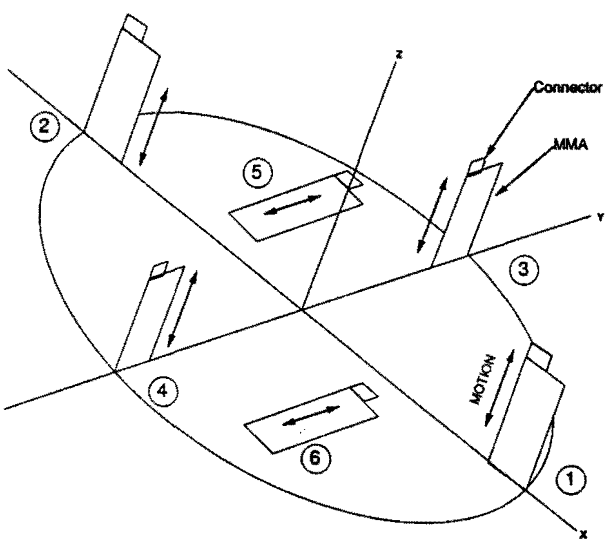

Figure 2b. Distribution of MMA's on Table

The inertia tensor of the SSACS table was measured using bifilar tests. A bifilar test was first performed on a solid rod of known dimensions, with the measured inertia differing by less than 2% from the calculated value of the rod. The bifilar test was then applied about each axis of the SSACS table to determine the moments of inertia. By rotating the attachment points for the cables, additional measurements were used to find the products of inertia. The inertia tensor for the table in it's initial configuration was found to be (lb sec^2 ft):

$$I = \begin{vmatrix} 1.20 & -0.033 & -0.048 \\ -0.033 & 1.25 & -0.029 \\ -0.048 & -0.029 & 1.86 \end{vmatrix}$$

Attitude control thrust is provided by six gas jet thrusters generating a torque of 17 ounce-inches each. Electronically actuated solenoid valves with rise times of under 0.015 seconds are used for actuation. Each thruster consists of a converging nozzle of 0.005 inch diameter, with compressed air exiting at sonic velocities. Compressed air is stored on the SSACS table at pressures of up to 2000 psi. This air is regulated to 500 psi and piped through a manifold to six solenoid-controlled nozzles. The thrusters are oriented to provide bi-directional thrust about the pitch, yaw and roll axes. The actual moment generated by the thrusters was measured using a six axis force/torque sensor. By simultaneously measuring the propellent pressure, a torque/pressure relationship was determined.

The orientation sensors on the SSACS table include a vertical gyro, a two axis sun sensor, a three axis magnetometer and a three axis angular rate sensor. The vertical gyro was a surplus aircraft gyro, providing pitch and roll measurements. This gyro was calibrated using a two axis indexing table, with pitch and roll measurements determined to be accurate to within 0.5 degrees.

The two-axis sun sensor is based around a two-axis, analog, position sensing photodiode. It measures the yaw and pitch angles of the SSACS relative to a light source. The sun sensor was calibrated over it's ± 30 degree field of view about two axes with the use of a precision rotary turntable. Data sets of angle and corresponding voltage for the yaw and pitch axes were curve fit to a third order polynomial surface using a least squares approach. The resulting calibration was accurate to under 1.0 degrees in pitch and yaw. Roll displacements effect the accuracy of this calibration, however.

The magnetometer is a 3 axis flux gate TAM7 magnetometer generously loaned to the project by Dowty Magnetics. Unlike an orbiting spacecraft, the SSACS table operates in a constant magnetic field, allowing the magnetometer to provide a constant vector which, when combined with the gravitational vector determined by the vertical gyro to uniquely determine the attitude of the SSACS table [7] . The magnetometer must be mounted on a 3 foot standoff to avoid magnetic interference from the table.

Angular rate was initially measured using a 3 axis fluidic rate sensor. However the repeatability of the null rate value on this sensor was poor. Three single axis micro-mechanical "Gyro-chips" were purchased for improved accuracy. These sensors were calibrated by placing them on a rotary indexing table accurate to 1 arc second. The chips were then rotated 90 degrees back and forth for ten minutes with the rate output sampled at 100 Hz using a data acquisition system. The rate output was then integrated offline and the resulting positional measurements were compared to the exact positions of the indexing table. The total error of the integrated position was under 0.5 degrees after 2 minutes and under 1.8 degrees after 10 minutes. Note that these integrated values were more accurate than those found from the other sensors for the first few minutes of operation. These values could be improved by using more sophisticated integration algorithms.

Angular spin velocities are measured by using an seismic accelerometer to measure the centripetal acceleration. Placing the 8 g piezoelectric accelerometer at a radius of 15.0 inches provides a measurement of spin speeds about the yaw axis of up to 2.28 revolutions per second.

Initial testing of the table used an offline data acquisition and control computer (Masscomp 5450) connected by an umbilical ribbon cable to the table. The controller software was developed in modular form in a high level language, allowing for flexible and rapid reconfiguration of the control system software to an onboard processor. An 8 bit microprocessor was also used for limited testing where an umbilical line would prohibit correct dynamics.

A 32 bit computer (Onset Model 7) based on a Motorola 68332 embedded controller is currently being installed for autonomous control. Circuitry built by USU for this processor provides for 32 channels of analog data input and can simultaneously control the six thrusters and six mass movement assemblies. Up to 20 Mbytes of experimental data can be recorded by the onboard disk drive. The controller software developed for the off-table controller is being modified for the embedded controller.

A telemetry system is also under development to transmit commands from a ground-based computer to the SSACS table, as well as down link data from the table to the ground station, allowing real time monitoring of the table's performance.

Power for the table is provided by two rechargeable battery packs. One pack runs at 28 VDC providing power for the instrumentation and controls. A second 8 VDC battery pack is used exclusively to drive the stepper motors on the MMA's.

4. Relationship to Actual Satellites

The SSACS table has many of the performance characteristics of a satellite in orbit. It exhibits virtually torque free motion; it has gas jet thrusters with a limited fuel capacity; it must operate autonomously; it requires instrumentation for attitude determination; and it requires a self-contained power source. The SSACS table also was designed with a limited size and budget, as are many small satellites.

Unlike a conventional satellite, dynamic balancing of the SSACS table is required to offset mass losses in propellent during operation. Aerodynamic friction effects on the angular momentum vector must be considered when using the table for spin stabilization tests. However, the table does not need to be designed for launch vehicle integration or survive the rigors of launch. Reliability requirements for the table are significantly less than those required for actual spacecraft, since we have easy access for repairs. Environmental references sun as the sun, stars and horizon of the earth often used for attitude determination must be simulated in the laboratory. The earth's magnetic field does not vary for the table, as it does for orbiting satellites.

5. A Sun Seeking Three Axis Controller

Under NASA - USRA (Universities Space Research Association) sponsorship, a USU student design team developed a preliminary design for a small satellite which would test a solar-powered, thermionic heat pipe element for an excore heat-pipe-thermionic space nuclear reactor power system [8]. To obtain adequate power for this system from the sun, a three-axis attitude control system was employed in this design to maintain the orientation of a solar collector on the satellite to within a tolerance of ± 0.75 degrees per axis. This project provided the motivation for the first experimental tests on the SSACS table.

The objective of this project, lead by Glen Peterson [9], was to implement a three axis attitude control system to point the SSACS at a light source emulating the sun to within ± 5 degrees about each axis. This rather crude pointing accuracy was selected because of uncertainties in the capabilities of the sensors and actuators available to the SSACS project at that time.

A dynamic rigid body model based on Euler's equations was developed using standard approaches [7,10]. A minimum time control law was chosen for each axis of an ideal system:

$$u = -U \, \mathrm{sign}[\, 2 U \Theta + I \dot{\Theta} \, | \dot{\Theta} | \,]$$

where sign is the signum function, u is the control moment command signal, U is the magnitude of the available moment about each axis, Θ is the angular position of the SSACS table, and I is the principal moment of inertia about a single axis. One controller was implemented for each of the principal axes of inertia. No effort was made to decouple the dynamics of each system.

The implemented design used the two axis sun sensor for pitch and yaw measurements and the vertical gyro for roll and a second pitch measurement. Gas jet thrusters were used for torque generation. At the time the experiments were performed, the rate sensors were not operational. Rate information in the controller was determined by digitally differentiating and low pass filtering the positional information. Due to the lack of an onboard computer at the time of testing, an umbilical was used to link the SSACS table to the control computer. Figure 3 shows the relationship between the table and the control computer hardware and software.

6. Single Axis Tests

Tests were conducted about each of the body fixed axes with all three single-axis controllers operating. First, testing was conducted about the yaw axis. This axis is affected the least by external gravitational torques acting on the small existing imbalance in the table. Figure 4 shows the transient response of angular position in yaw versus time and the corresponding thruster commands. This figure shows that the controller brought the SSACS from an initial displacement of -24 degrees to within the dead band of the controller (5 degrees) in approximately 6 seconds. The controller maintained the positional accuracy for the duration of the test.

A phase plane portrait of the yaw axis for this test is presented in Figure 5. Notice the placement of the switching line and the resulting limit cycle behavior. Dynamic coupling between motions also effects the shape of the limit cycle.

A longer duration test was conducted to observe the long term dead band response in all three axes. Figure 6 shows yaw position and thruster signal versus time. Again notice that the limit cycle amplitude oscillates in time, resulting from coupling with the motion of the other axes.

The transient response to an initial disturbance about the pitch axis along with the thruster signal are shown in Figure 7. After the initial transient, the velocity constraint was violated before the position constraint, keeping the limit cycle within the required positional limits. This axis is affected by gravitational torques due to errors in the balance of the SSACS presumably caused by changes in the position to the center of mass due to propellent losses. This produced oscillation about only one side of the dead band.

The response about the roll axis for initial conditions in roll is presented in Figure 8. The roll axis is also affected by gravitational torques. This figure shows that the first control maneuver brought the position only half way to the origin. Repeated maneuvers were required to satisfy the positional tolerance. Errors in the inertia value and coupling between axes are likely here. The velocity

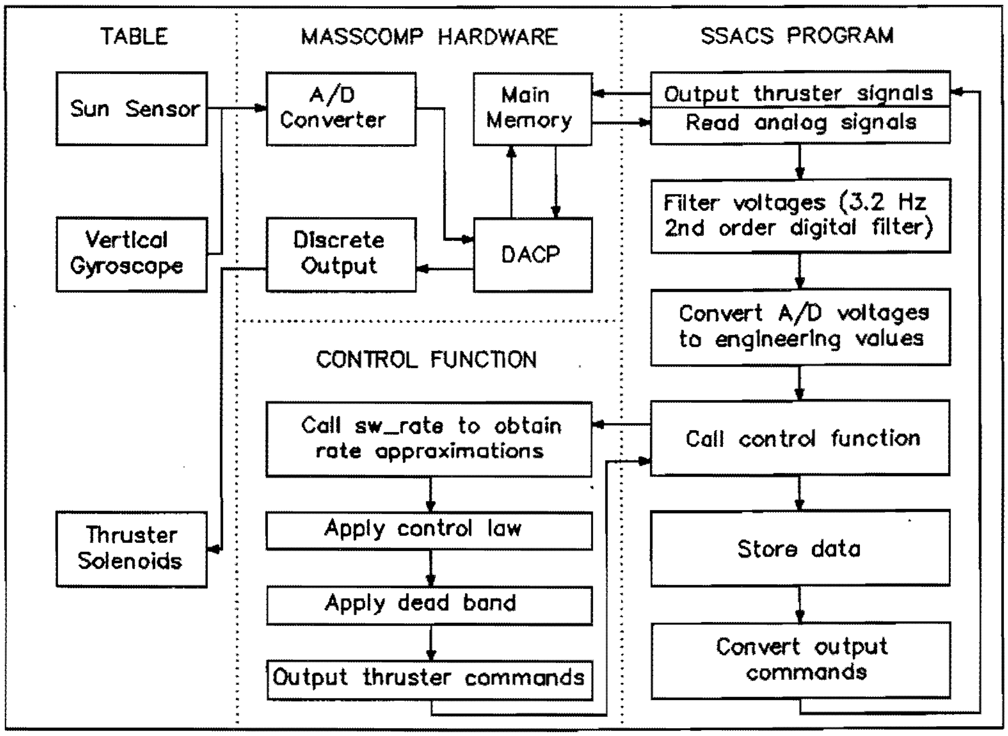

Figure 3. Block diagram of the SSACS hardware to software interfaces and software functions.

tolerance was only satisfied for short periods of time. The disturbance present in the initial seconds of this plot was due to faulty release.

7. Multi-Axis Tests

The control system was next tested with nonzero initial conditions about both the yaw and the roll axes. Figure 9 shows the position of the SSACS in yaw, pitch, and roll versus time. Note the large overshoot in the pitch axis during this test. This is due to gravitational effects about the pitch axis and coupling between axes. During the limit cycle the velocity signal noise is excessive.

Recall that the sun sensor was only calibrated in two axes (pitch and yaw). Therefore with significant roll of the SSACS the pitch and yaw readings are erroneous. Despite the incorrect signals in pitch and yaw the controller brought the system to within the dead band for each axis.

8. Summary of Initial Testing

The preliminary tests reported in this paper demonstrate the potential use of the SSACS table. Many of the hardware limitations of these tests were due to the early state of development of the table when these tests were performed. These limitations are currently being addressed. These tests also pointed out how easily the limited propellent resources can be exhausted if the control law does not account for this condition.

9. Developmental SSACS Projects

Many modifications are currently being addressed on the SSACS table. Most notably, a 32 bit embedded processor has been acquired for data acquisition and control onboard the table, eliminating the need for umbilical lines. Three very accurate "Gyro-chip" rate sensors have been purchased for improved rate detection. Finally, a 3 axis fluxgate magnetometer has been loaned to the project by Dowty Magnetics for positional measurement.

Several developmental projects are either under way or soon to begin. These include the development of a numerically accurate dynamic model of the table and sensors. This project is investigating improvements in estimates of the inertia tensor, improved calibration of the onboard sensors, and a more accurate determination of the moment vectors generated by the six thrusters.

The SSACS table has several redundant sensors for position and rate determination. A second project is investigating the integration of these sensors through a Kalman filter to provide the best possible estimate of the state of the table. The sensors are calibrated by mounting the table on a high accuracy (1 arc second) two axis indexing table, with the position of the index table and the sensor data simultaneously recorded.

An accurate spreadsheet program accounting for the mass distribution of the table is under development, with the results correlated with the bifilar inertial tests. This program will continually update the inertia tensor estimate as modifications are made to the table. This table will also help in relocating the table's mass to diagonalize the inertia tensor about the pitch, roll and yaw axes.

Improved balancing procedures using the stepper-motor-based MMA's will soon begin. The development of a software controlled mass adjustment algorithm to balance the table will both reduce the setup time for the table and improve the balance accuracy. Further, we hope to implement this algorithm during operation of the table to compensate for imbalances caused by the loss of thruster propellent.

The previously described positioning tests were based on minimum time algorithms, and are costly in terms of propellent. Additional tests will also be performed using control laws which attempt to conserve propellent, allowing for longer test runs.

10. Current and Future Research Projects

The SSACS table is supporting several current research projects. One project, led by Walter Holemans, is attempting to dynamically measure the inertia tensor of the SSACS table during spin stabilized motion, and then adjust the inertia tensor using the MMA's to fine tune the orientation of the spin axis.

A second project, developed by Tanya Olsen, intends on positioning the MMA's to adaptively balance and position the table using an adaptive algorithm similar to the Adaptive Computed Torque technique used in robotics control.

A recently completed thesis [11] by Jim Nottingham investigated using a neural network controller to reorient a small satellite to acquire the sun reference vector as the satellite emerges from the earth's shadow. This approach uses only light intensity data from simple solar cells and requires no inertial sensors.

Neural network methods are also being investigated for sensor fusion. This approach attempts to combine diverse sensor data from magnetometers, inertial platforms, horizon and sun sensors and CCD camera data through a neural net to provide accurate yet potentially inexpensive estimates of the attitude of a spacecraft. This project, led by Jay Smith, will use the SSACS table for experimental tests, with the techniques developed applied to data from the WEBERSAT satellite.

11. Conclusions

The SSACS table has three roles: to support university education, to be used to experimentally test attitude control designs destined for small satellites, and serve as a test vehicle for research work in attitude controls.

The SSACS table currently provides an effective demonstration tool for satellite dynamics. Further, the design, construction, calibration and testing of the SSACS table has already succeeded as a teaching tool. Over ten students have been involved directly with the SSACS table, learning considerably more by their experience than they would have otherwise.

When the current efforts to complete the development of the SSACS table are finished, the table will become an effective research tool for evaluating attitude control approaches for small satellites.

Acknowledgements

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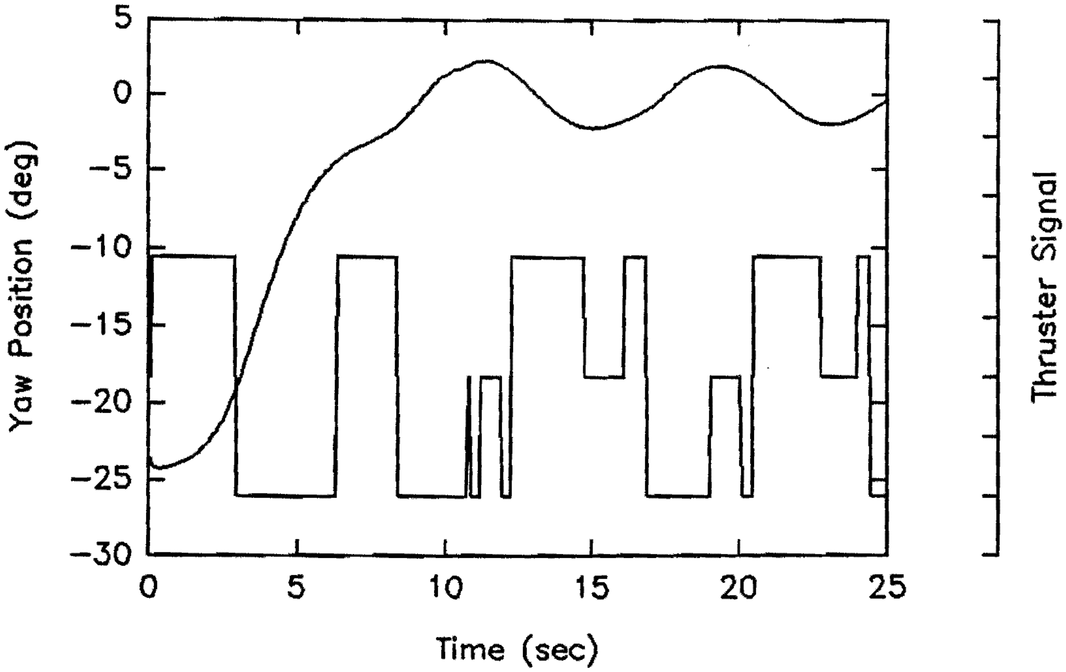

Figure 4. Actual yaw position and thruster signal versus time for initial conditions about the yaw axis.

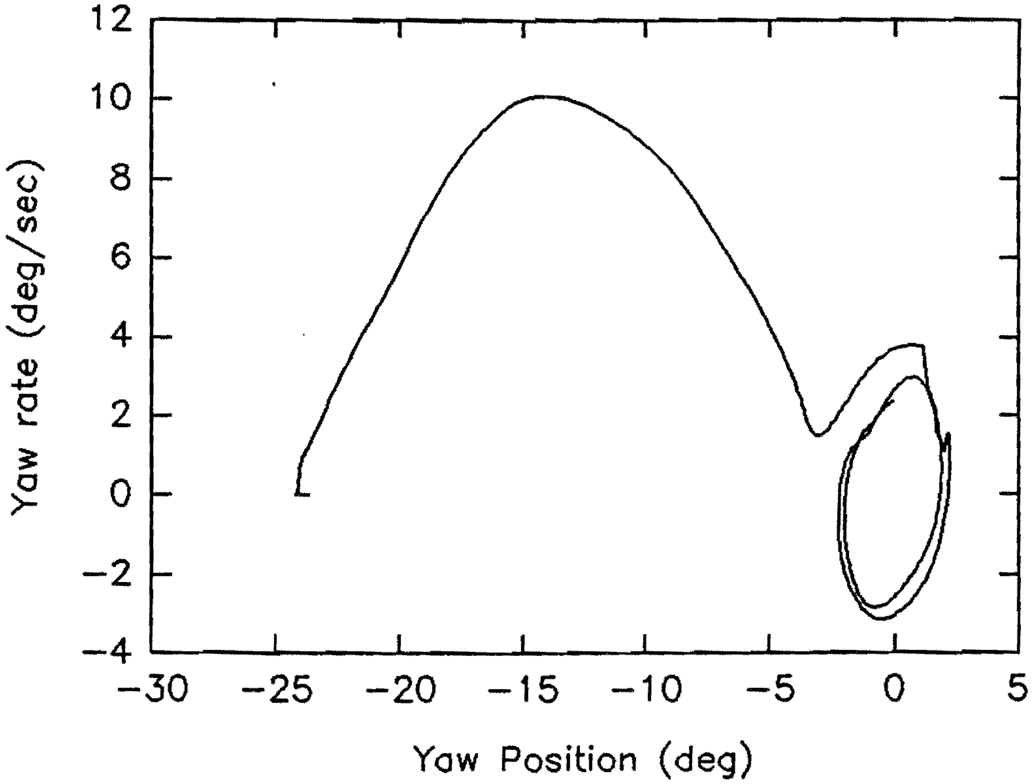

Figure 5. Phase plane portrait of the yaw axis for initial conditions about the yaw axis only.

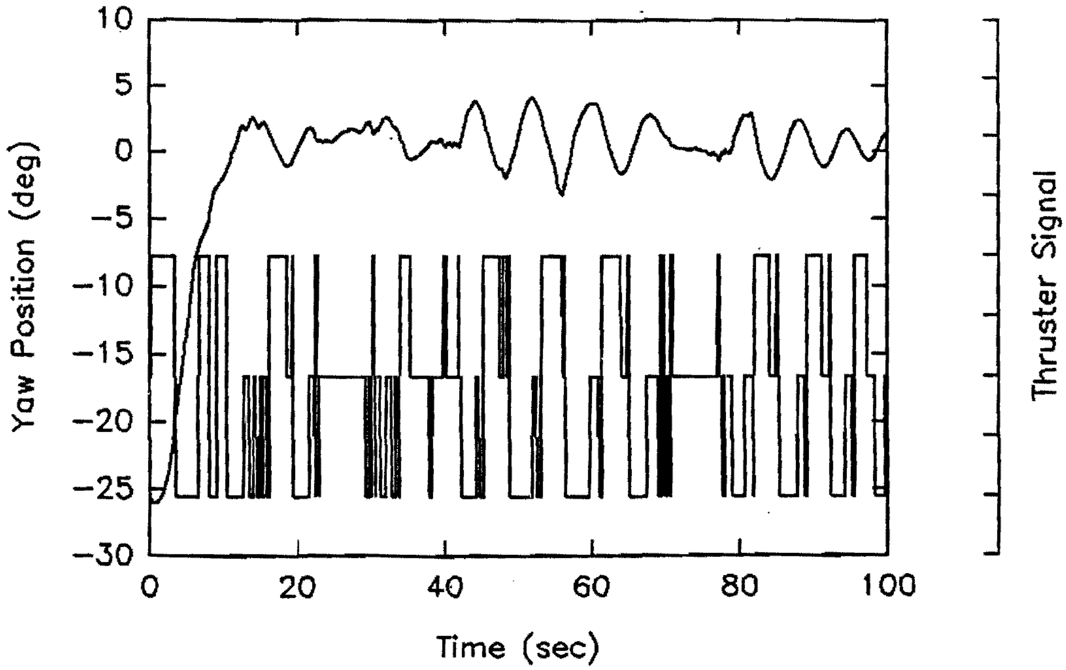

Figure 6. Long duration test showing yaw position and thruster signal for IN's about the yaw axis only.

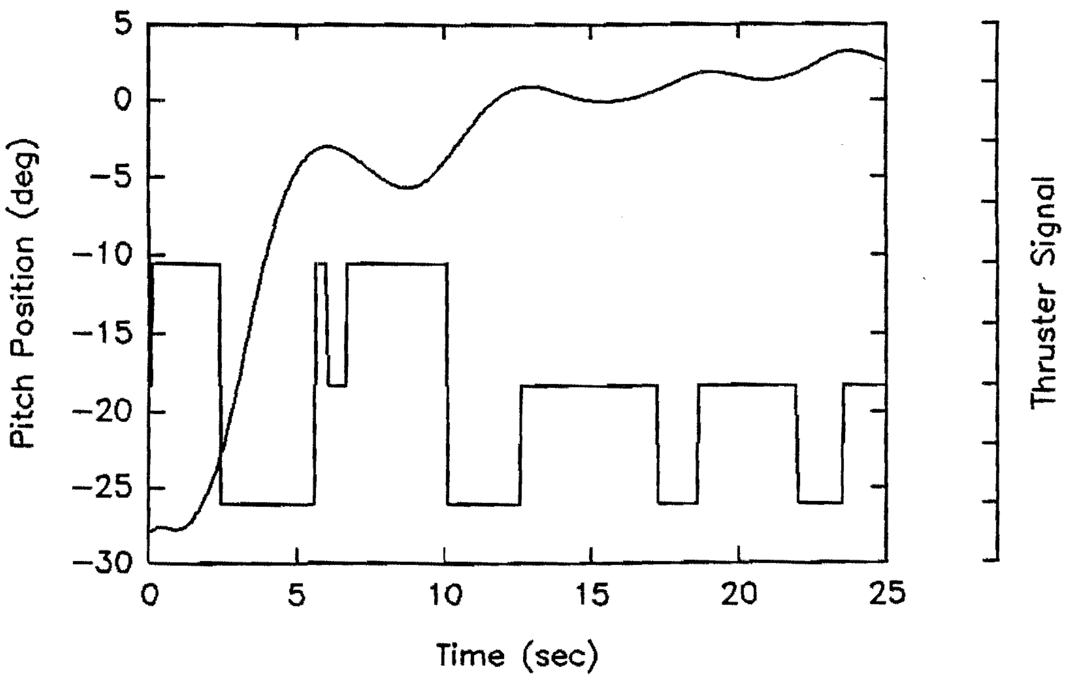

Figure 7. Pitch position and thruster signal versus time for initial conditions about the pitch axis only.

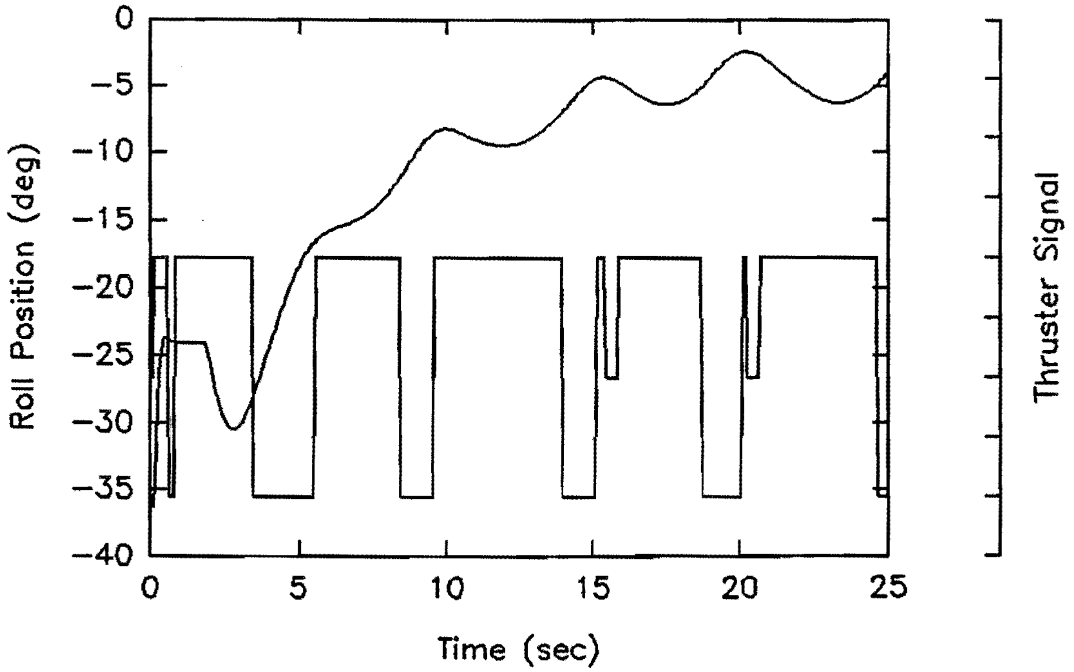

Figure 8. Roll position and thruster signal versus time for IN's about the roll axis only.

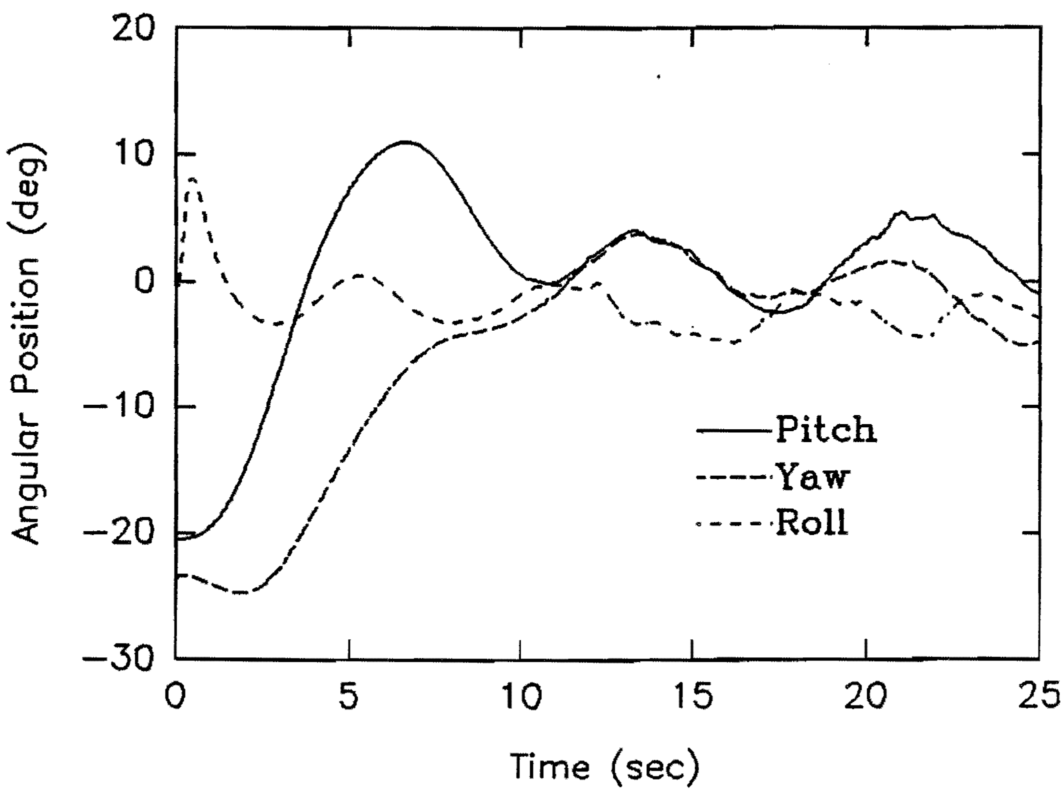

Figure 9. Yaw, pitch, and roll positions versus time for initial conditions about both the yaw and pitch axes.