Experimental Tests of Various "Bang-bang" Controllers on the Small Satellite Attitude Control Simulator

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ABSTRACT

Various three axis "bang-bang" control laws were implemented on the Small Satellite Attitude Control Simulator (SSACS) table. The optimal time control law's experimental results demonstrated excellent correlation with the desired switching curve. Approximately 55.6% less fuel will be used for a given maneuver if the optimal time control law is modified to shut the thrusters off when the magnitude of the angular velocity reaches 1 deg/sec in the appropriate region; however, the time required to perform the maneuver increases. These results demonstrate the SSACS table's capability to simulate the attitude dynamics of small satellites.

1. INTRODUCTION

The declining budget of the United States's space program has forced mission planners to look at small satellites for both scientific and commercial use. These satellites will be required to fit into smaller shrouds or for piggy back payloads whatever space is available, requiring unusual design configurations. The dynamics of these satellites will not likely fit conventional models. The Small Satellite Attitude Control Simulator (SSACS) table offers a platform where the control systems for these satellites can be tested, verifying any assumptions that have to be made about the spacecraft's dynamics or control algorithms.

The SSACS table also provides students at Utah State University (USU) with a learning platform to explore spacecraft dynamics and attitude control. It has been the experimental testbed for several master's thesis projects for students of both Mechanical and Aerospace Engineering and Electrical Engineering at USU. These thesis projects as well as other projects using the SSACS table have ranged from replicating classical attitude control designs in hardware to implementing neural network control concepts [1,2,3].

The SSACS table has the potential to test commercial or scientific satellites. It is currently being configured to test the attitude dynamics and control algorithms of SKIPPER[4], a joint US/Russian satellite to study upper atmosphere chemistry to be flown in Summer 1995. The entire attitude control system of SKIPPER(flight hardware and software) will be mounted on the SSACS table to test the control system.

Also, intelligent control systems such as adaptive control, neural networks, and fuzzy logic are being designed to be tested on the SSACS table. This will allow verification of the effectiveness or ineffectiveness of these non-conventional control systems without the expense of flight tests.

In addition, the budget of many small satellites battles the cost of the control system needed to obtain the pointing requirements of its mission. Conventional sensors cause the cost of the control system to become a major portion of the satellite's budget. Intelligent control offers the possibility of using inexpensive, simpler sensors while offering the same control performance as more expensive sensors.

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2. DESCRIPTION OF THE SSACS TABLE

The development and description of the SSACS table was presented by Fullmer R., et al.[1]. The SSACS table is a 0.762 meter (30 inch) aluminum platform mounted on a 0.102 meter (4 inch) spherical air bearing. A photograph of the SSACS table is shown in Figure 1a, and the configuration of the SSACS table is shown in Figure 1b. The air bearing is capable of loads up to 81.82 kg (180 lbs). The configuration of the SSACS table allows for 3 axis maneuverability with 360 degrees of freedom about the Z-yaw axis and 45 degrees of freedom for the x-roll and y-pitch axes. On/off gas thrusters regulated to 2400 kPa (350 psi) are mounted to provide bi-directional thrust on each axis.

Figure 1a: Photograph of SSACS table.
Figure 1b: Configuration of SSACS table.
The mass movement assemblies (MMA's), used for automatic balancing, sun sensor, vertical gyro, and magnetometer are also available on the SSACS table but were not used for these experiments.

A 32 bit onboard computer (Onset--Tattletale Model 7) is mounted on the SSACS table for implementing control laws and data acquisition. Three single axis "Gyro-chips" provide angular velocities in the body fixed coordinate system. Angular positions are obtained by direct integration of the angular velocities. Euler transformations are used to determine the inertial attitude of the SSACS table.

The torque to inertia ratios of each axis were obtained from the dynamical relation \( T/I = d^2\theta/dt^2 \) where \( \theta \) is the angular position, \( T \) is the torque, and \( I \) is the inertia corresponding to appropriate axis, assuming the off axis inertia terms are negligible. The angular acceleration, \( d^2\theta/dt^2 \), was determined from experimental data. This ratio was then compared to the ratios calculated from the inertia tensor obtained using a bifilar pendulum test[5] and the nominal torque of the gas jets-- 0.085 N-m (12 ounce-inch) each. The calculated ratios agree with the ratios obtained from experimental data. Then, the ratios were adjusted to provide the best control performance of the "bang-bang" controller.

The table was balanced by adjusting six lead weights suspended from the table. The mass and position of the weights were adjusted to place the center of gravity at the center of the air bearing, minimizing the gravitational effect thus simulating a space environment. The balancing was fine tuned by adjusting leadscrews at different positions on the table.

Also, some aerodynamic drag and frictional drag of the air bearing were observed, but the effects were small enough to be included into model of the SSACS table as external noise.

3. IMPLEMENTATION OF "BANG-BANG" CONTROL

The "bang-bang" optimal time control law [6] for a single axis is given by

\[
\frac{u}{I} = -\frac{T}{I} \text{sgn}(2T/I\theta + (d\theta/dt)\theta)
\]

where \( \theta \) is the angular position, \( T \) is the torque, \( I \) is the inertia corresponding to appropriate axis, and \( \text{sgn}() \) is the signum function. The position dead band for each axis was set at \( \pm 0.5 \) degrees, and the velocity dead band was set at \( \pm 0.573 \) deg/sec., as shown in Figure 2a. Ratios of torque to inertia of 0.031, 0.050, and 0.052 were used for the yaw, pitch and roll axes respectively. This control law was implemented for each axis, assuming no significant coupling, to test the software. Then, simultaneous three axis control was applied. The angular velocity was sampled every 15 msec, and the angular position was obtained by discrete integration of the angular velocities.

However, because the optimal time control strategy maximizes the propellant used, it is not practical for use in spacecraft attitude control. Therefore, the control law was adjusted to save propellant by shutting off the thrusters when a given angular velocity was reached in the appropriate region, as demonstrated in Figure 2b. The battery packs for the table were also changed, and the torque to inertia ratio values were changed to 0.030, 0.044, and 0.044 for the yaw, pitch, and roll axes, respectively to compensate for the change in inertia.
Figure 2: Bang-bang control laws: (a) Optimal time, (b) Modified.

4. RESULTS AND DISCUSSION

The optimum time controller was implemented first. The position vs. time for yaw, pitch, and roll axes using the optimum time controller is shown in Figure 3. The controller was able to maneuver the table from a given non-zero orientation to the zero state. Moreover, it moved the table back to the zero state after an external disturbance was applied.
Figure 3: Time history of the yaw, pitch, and roll axes using the optimal time controller.

The phase plane plots for the yaw, pitch, and roll axis are compared with the switching line of the control law in Figures 4a, 4b, and 4c, respectively. The phase plane trajectories followed the switching line exceptionally well. The limit cycling in the dead band is approximately within the limits placed on it by our control law. However, some overshoot was observed in the roll axis possibly caused by the inaccuracy of the torque to inertia ratio.

Figure 4a: Yaw axis response and switching curve for the optimal time controller in the phase plane.
The control law was then adjusted as shown in Figure 2. Three separate tests were run where $v_{off}$, the switching value, was set equal to 3, 2, and 1 deg/sec. Figure 5a, 5b, and 5c compare the phase plane diagrams of the yaw, pitch, and roll axes for different values of $v_{off}$. The slight overshoot of $v_{off}$ by the angular velocities

Figure 4b: Pitch axis response and switching curve for the optimal time controller in the phase plane.

Figure 4c: Roll axis response and switching curve for the optimal time controller in the phase plane.
is caused by the effect due to a finite sampling rate. The drift in the angular velocities of the pitch axis may be caused from improper balancing of the SSACS table or sensor drift. The time history for the yaw axis is compared for all cases in Figure 6. As \( v_{\text{off}} \) decreased, the rise time increased, which is the price we must pay to save propellant.

Figure 5a: Comparison of yaw axis phase plane trajectories for 3 values of \( v_{\text{off}} \).

Figure 5b: Comparison of pitch axis phase plane trajectories for 3 different values of \( v_{\text{off}} \).
Figure 5c: Comparison of roll axis phase plane trajectories for 3 different values of $v_{off}$.

Figure 6: Time history of yaw angle using different control laws.

The time histories of thrust signal for the yaw axis are displayed in Figure 7(a-d) using the different control laws. The thrusters are on for the longest amount of time with the optimal time controller. By shutting off the thrusters at $v_{off}$ equal 3, 2, and 1 deg/sec, fuel savings, as a percentage of the fuel used by optimal time controller, of 18.0, 35.4, and 55.6%, respectively, can be achieved. Fuel usage was calculated by summing the time the thrusters were on during the maneuver from the initial orientation to the zero state. We assumed that the time the thrusters were on was directly proportional to the fuel used.
Figure 7a: Yaw axis position and on/off thrust signal for the optimal time controller.

Figure 7b: Yaw axis position and on/off thrust signal for $v_{off} = 3$ deg/sec.
Figure 7c: Yaw axis position and on/off thrust signal for $v_{off} = 2$ deg/sec.

Figure 7d: Yaw axis position and on/off thrust signal for $v_{off} = 1$ deg/sec.
5. CONCLUSION

The results of the classical "bang-bang" controller on the Small Satellite Attitude Control Simulator (SSACS) table demonstrate its ability to simulate the dynamics and control of small satellites in a space environment. By modifying the optimal time control law, significant fuel saving can be achieved which is essential for space applications. The SSACS table's ability to effectively test satellite models will provide valuable information, enabling successful control design and mission accomplishment. In addition, future research of intelligent control algorithms can be tested on the SSACS table with the possibility of using less expensive technology, allowing small satellites to remain within their budgets and accomplish their commercial and/or scientific objectives.

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