SIMSAT: A Ground-based Platform for Demonstrating Satellite Attitude Dynamics and Control

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Abstract

A laboratory platform capable of demonstrating the attitude dynamics of an orbiting satellite was developed at the Air Force Institute of Technology. This simulation satellite (SIMSAT) floats on an air bearing and is free to rotate about all three axes. SIMSAT is composed of all the same subsystems that are present on an operational satellite: structure, attitude determination and control, command and data handling, and power. Students are able to observe and interact with SIMSAT in order to more effectively understand the engineering principles of spaceflight mechanics.

Introduction

The last three decades have seen an increased use of space as a resource. Individuals use the resources of space daily without ever realizing it. Satellites provide information for up-to-date weather reports, communications, and television programs. Space continues to play an important role in U.S. military operations as well--missile warning, global communications, and global positioning systems (GPS). Because of the value of space, the USAF has begun to move its focus from operating as an air force to becoming the premier air and space force by the year 2025. Accordingly, the Air Force Institute of Technology (AFIT) provides graduate programs in both space operations and astronautical engineering.

The introductory and intermediate spaceflight mechanics graduate courses are of core importance to the Space Operations and Astronautical Engineering programs at AFIT. These courses rigorously develop the fundamental principles of astrodynamics. Topics in both orbital mechanics (which deals with the trajectory of a point mass) and attitude dynamics (which deals with the motion of a satellite's orientation) are rigorously developed in these classes. The latter field is the most challenging for students to understand, since attitude dynamics is often counterintuitive. (Consider, for example, the behavior of a spinning top which appears to defy gravity.) Furthermore, the satellite dynamics cannot be exactly demonstrated in the classroom, since the classroom is not experiencing freefall as a satellite does. This misfortune leads to the universal difficulty of providing visual aids to teach astrodynamics. In a recent critique of the introduction to spaceflight mechanics course at AFIT, 5 out of the 10 students had written comments citing the lack of visual aids as an impediment to learning the material.

To more effectively pursue spacecraft educational and research objectives at AFIT, students in the Department of Aeronautics and Astronautics designed and constructed a simulation satellite (SIMSAT).[1] SIMSAT, see Fig. 1, provides AFIT with the capability to conduct practical experiments regarding attitude dynamics and control. SIMSAT is capable of fully rotating about its yaw and roll axes. Rotation about the pitch axis, however, is limited due to the air pedestal on which it rests. This air pedestal is used to simulate almost zero friction and prevents external torques from being applied to the system. Power or data cables attaching SIMSAT to ground station computers would also apply external torques. Accordingly, batteries and wireless communication systems are used to transmit and receive telemetry data.

SIMSAT improves classroom lectures by allowing students to visualize complex satellite attitude dynamics concepts and to gain hands-on experience with satellite control theory.[2] By adding to classic classroom instruction we hope to increase student interest in the course and to provide an invigorating learning environment. Studies have shown that students retain 25% of what they hear, 45% of what they see and hear, and almost 70% when they actively participate in the process.[3]

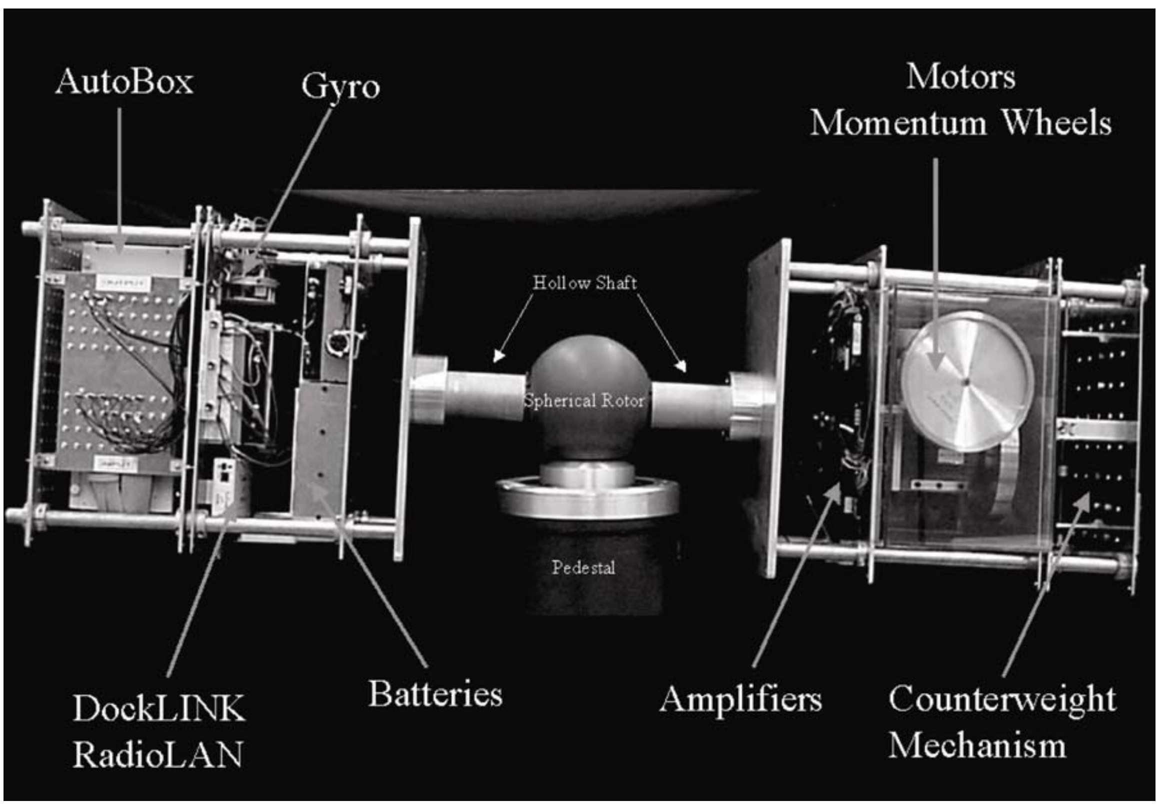

Figure 1. SIMSAT: A Ground-based Satellite Demonstrator

This increase in retention percentage is a result of the student using more than one style of learning. The three ways in which somebody "knows" something is enactive (through doing it), ikonic (through a picture or image of it), and symbolic (through some symbolic means such as language).[4] These three methods of learning something closely resemble a Chinese Proverb:

I hear and I forget. I see and I remember. I do and I understand.

While the traditional lecture is an effective way of presenting information to large groups in a short amount of time it is also the least effective method of promoting learning. To truly stimulate knowledge growth the students need to practice the taught skills and visualize the concepts presented in class.[5]

SIMSAT Platform

SIMSAT is a laboratory-based satellite simulator. This simulator assists instructors in teaching attitude control concepts. In addition, SIMSAT is capable of supporting several areas of research in attitude control and spacecraft stabilization. It is constructed out of several hardware and software components. Fig. 1 illustrates where some of these components are located.

The main subsystems of SIMSAT are the structure, attitude determination and control, command and data handling, and power. SIMSAT is a complex, interdependent system. The choice of components was interrelated. For example, the structure obviously has to support the remainder of the system; however, the amount of power affected the required strength, the inertia of the system impacted the size of the momentum wheels, the current draw of the electric motors helped size the batteries and the weight of the motors, wheels and batteries sized the structure. Hence design required an interdisciplinary system design approach involving tradeoffs between the various choices. This iterative approach to systems design and its application is detailed by Colebank et al.[1]

The structure of SIMSAT, shown in Fig. 2, supports individual components and acts as a skeleton for the entire system. The SIMSAT structure consists of the central sphere, hollow mounting shaft, and two box trusses which attach to each side of the mounting shaft. The central sphere and the mounting shaft are combined to form the air bearing assembly and has a mass of 19.32 kg (42.5 lbs). The box trusses are comprised of two baseplates, six mounting plates and eight mounting rods. These trusses house the various components on movable mounting plates. This allows SIMSAT components to be repositioned by the researcher to accommodate for emerging configurations and weight distribution. The movable mounting plates also provide easy access to various components.

The central sphere sits on an air bearing assembly. An air compressor supplies air at approximately 75 psi to the pedestal. This air is directed through six air jets positioned in the air bearing cup. The spherical rotor floats above the cup on a thin film of air measuring less than 0.0005 inches thick. The air bearing is capable of 360^o of yaw (rotation about the vertical axis), 360^o of roll (rotation about the horizontal axis), and 30^o of pitch (tilt in the vertical plane). The air jets are capable of levitating at least 372.5 lbs. SIMSAT weighs approximately 310 lbs when fully constructed. A portable crane is used to lift SIMSAT and place it on the air bearing cup.

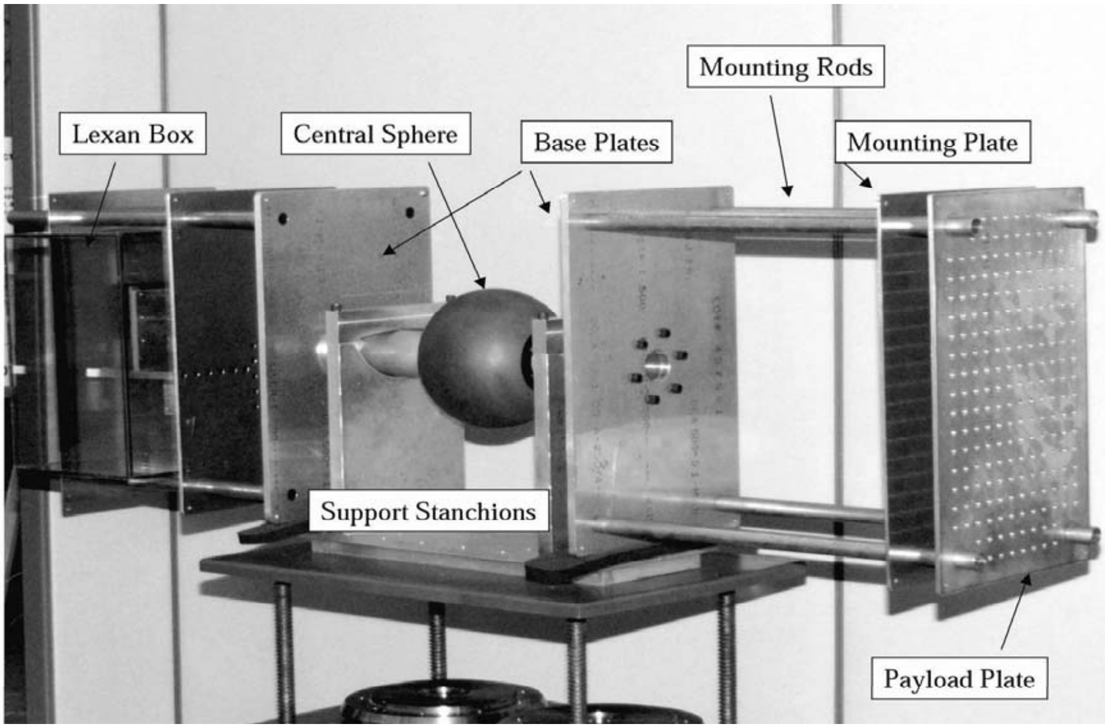

Figure 2. SIMSAT Structure

SIMSAT must be balanced about the air bearing in order to eliminate gravity torques. Gross balancing is achieved by attaching carbon steel blocks with masses of 5 kg and 1 kg to the mounting plates. Fine-tuning static balance is accomplished with a specially designed counterweight mechanism of small masses on adjustable threaded rods.

The attitude determination and control is responsible for sensing the orientation of SIMSAT and pointing it in the desired direction. Within this subsystem, there are two main functional components--gyroscope and momentum wheels. The Humphrey CF-75 Series Axis Rate Gyro provides rate and acceleration data from which SIMSAT's position can be calculated. Momentum wheels provide the means to maintain a desired position or change the vehicle's orientation.

The command and data handling system acts as both the controller and communication system for SIMSAT. Within this subsystem, there are three main functional components- an onboard computer, a transmitter/receiver package, and a ground station. The onboard computer is an AutoBox produced by dSPACE Inc. It contains the computer processors and software codes. The transmitter/receiver package is a wireless LAN connection that allows SIMSAT to interact with the ground station. The “ground station” is a desktop computer that is analogous to the station of a space operator; it communicates with the self-contained SIMSAT. The software run on the ground station was also developed by dSPACE Inc. It receives the telemetry, data on the state of SIMSAT, and sends the commands. An example is shown in Fig. 3. The middle window “EulerIn” always the user to send pitch, roll and yaw commands to SIMSAT by sliding the bar to the desired orientation. The window on the right, “EulerOut” tells the orientation of the satellite with three Euler angles which are determined onboard (see the Attitude Determination section below).

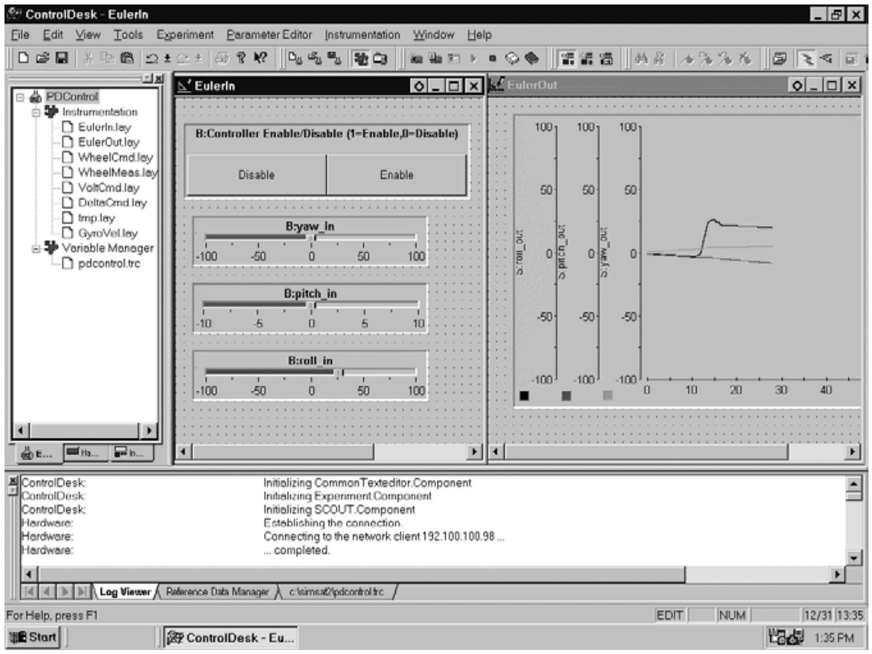

Figure 3. Ground Station

Within the power subsystem, there are four main components--power bus, batteries, undervoltage alarm, and the power interface for the experimental payload. The power bus includes the wiring and equipment necessary to provide a 12 VDC, 24 VDC, and 36 VDC power supply from the batteries to the vehicle. The batteries are the voltage source. The undervoltage alarm informs experimenters when the batteries are running low. Finally, a special power interface allows the user to attach the experimental payloads to the existing power system.

SIMSAT's Educational Role

SIMSAT is currently integrated into the lesson plans of both the Introduction to Spacecraft Dynamics and Intermediate Spacecraft Dynamics courses. These graduate-level courses treat various of topics of both orbital mechanics (the study of motion of point masses) and attitude dynamics (the study of the motion of the orientation of a body). The three topics with relevance to SIMSAT are torque-free motion, attitude determination, and attitude control. To demonstrate these concepts in actual practice, the students are brought to the laboratory during class. Fortunately, class sizes are generally less than a dozen people, which facilitates the logistics of this exercise.

Torque-free Motion

Torque-free motion deals with the attitude dynamics of a rigid body when it is not subjected to any external torques. The study of torque-free motion is of particular interest to astrodynamists because, in orbit, a typical satellite experiences torques less than 10^{-3} N-m.[6] For many satellite applications, this can be considered torque-free. The most difficult material to teach in this area is that of the spin-stabilized spacecraft. Spin-stabilization is a simple way of keeping the attitude of a satellite stable. If the spin-up of the satellite is not precisely executed or if there is a disturbance (e.g. a slight nudge from the upper stage that launched the satellite), then the spin axis of the satellite begins to cone. This is a classic problem, taught in both undergraduate and graduate dynamics classes. Solving the complicated equations governing the problem, we arrive at the coning motion of the spin axis that is depicted in Fig. 4. The plot of the left is the theoretical prediction, while the plot on the right is the experimental data taken from SIMSAT. Both display the classical coning behavior, giving the students visual reinforcement to the material. The exact nature of the coning is different between the two, for example the SIMSAT cone angle is about half that of the theory and it is also not constant (i.e. it does not trace out a perfect cone). This difference, however, can be pedagogically useful for pointing out the difference between the assumptions of the theory and the actual experiment. For example, to solve for the theoretical motion, the body is assumed to be rigid, but SIMSAT does bend enough to significantly alter the idealized motion.

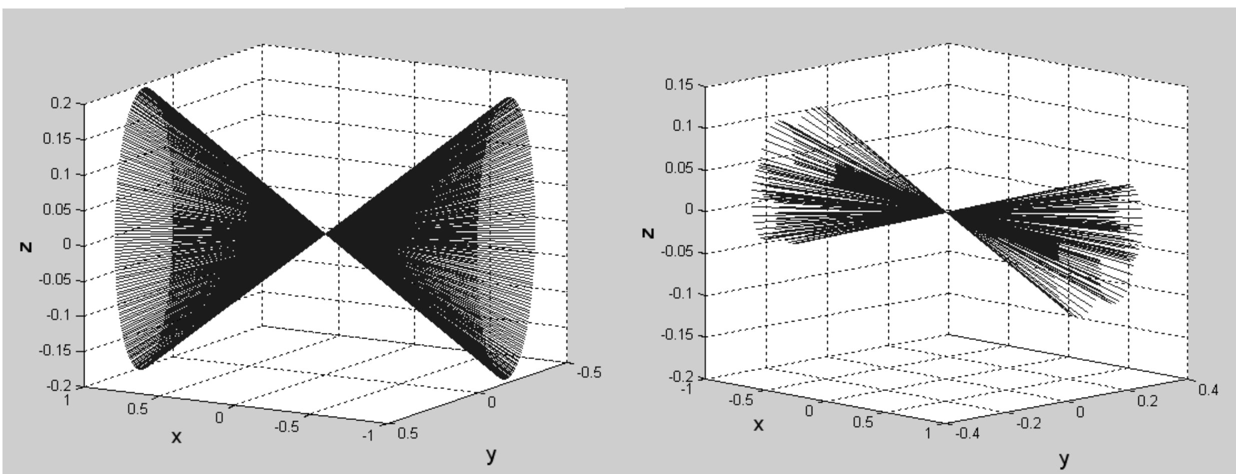

Figure 4. Spin Axis Precession of SIMSAT. Left – Theoretical Prediction, Right – Experimental Results

Attitude Determination

In order to perform their missions, nearly all aerospace vehicles must be able to sense their orientation, or attitude. Planes tell pilots the amount of bank or dive they are in, satellites must know where to point their antennas and camaras, and cruise missles must know their direction in order to arrive at their target. Attitude determination can be accomplished in a variety of ways, but the “strapdown” system used on SIMSAT has gained in popularity in recent decades. [7] A “strapdown” system uses gyroscopes attached to the vehicle to sense the rotation rate about at least three axes. This information is then used to arrive at an orientation with respect to a known reference. The equations relating the rotation rates to orientation angles are called the “kinematic equations.” There is no known analytic solution for these equations, so they must be solved by a microprocessor.

SIMSAT's attitude determination system is exactly like that of many missles, aircraft and spacecraft that are in use today. The kinematic equations are programmed into the onboard computer and a suite of three mechanical gyroscopes are mounted to the platform. This allows the students to see how such a system is implemented. The students can also physically move the satellite and then observe the change in the output from the onboard computer. Fig. 5 shows the results from this type of demonstration. The spacecraft was rotated several degrees about the pitch, roll, and yaw axes. SIMSAT senses its own motion and continually outputs its orientation which is shown in Fig. 6.

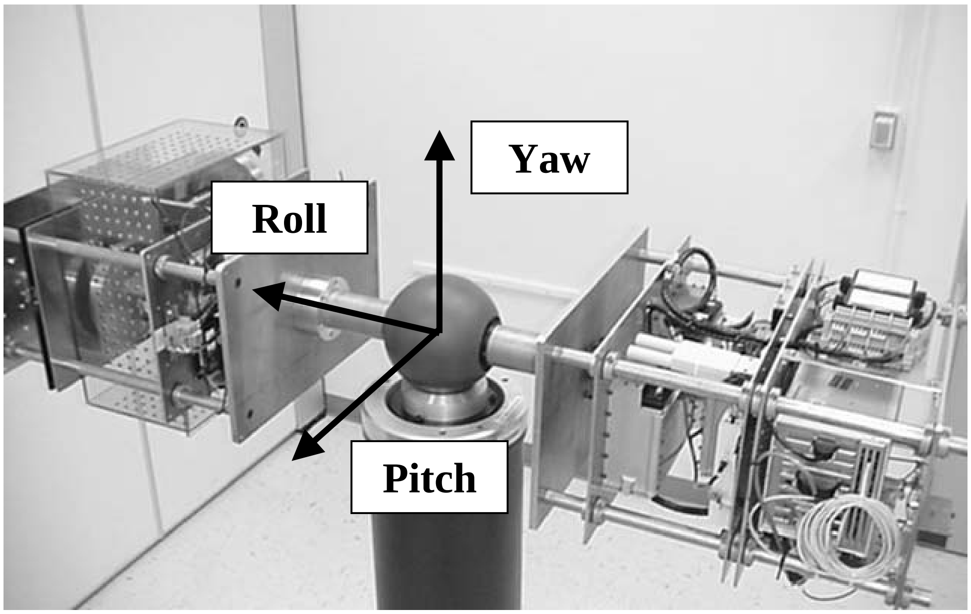

Figure 5. Yaw, Pitch, and Roll Axes

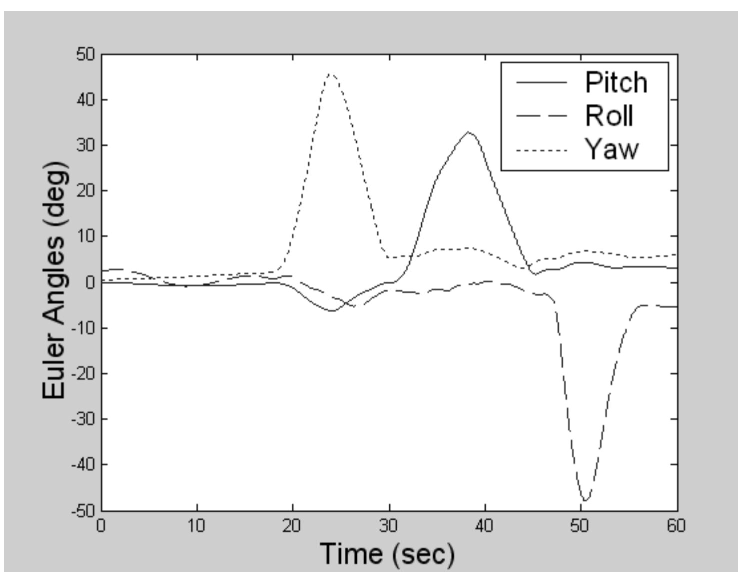

Figure 6. Experimental Results of Physically Rotating SIMSAT About Three Orthogonal Axes

Attitude Control

Once a satellite has determined its orientation, it generally must then control the direction in which it is pointing. Many satellites, for example, must remain oriented toward the Earth in order to send and receive signals. This can be done with thrusters, magnetic coils, control moment gyros, or reaction wheels. SIMSAT uses nine inch diameter reaction wheels, shown in Fig. 1, which are spun by a motor in one direction to effect a rotation of SIMSAT in the opposite direction. SIMSAT has a feedback control law programmed into its onboard computer that sends commands to the reaction wheels in order to bring about a desired orientation. The ground station controller commands a certain orientation via the interface shown in Fig. 3. Fig. 7 illustrates the results of commanding SIMSAT to rotate 50 deg of yaw (in the plane parallel to the floor). The maneuver takes a minute to complete, but this response is relatively fast compared to typical spacecraft operations. There is, however, some steady state error at the end of the maneuver. This error will be improved upon with better control law design.

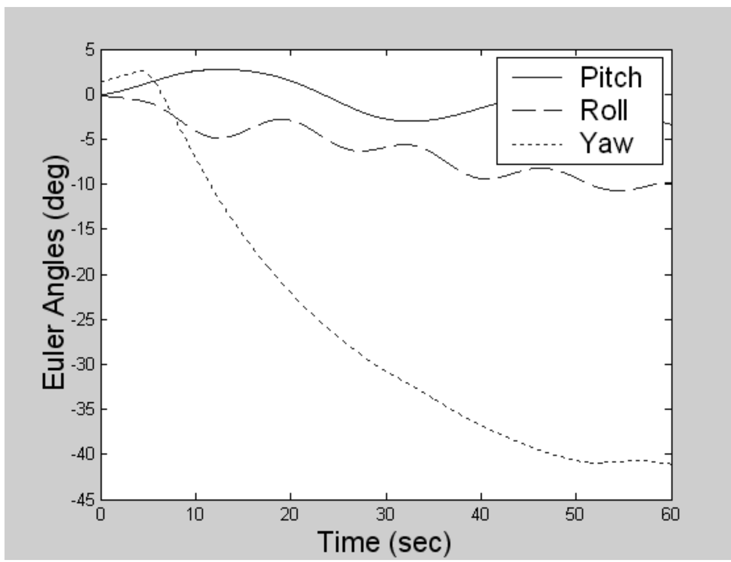

Figure 7. Experimental Results of a 50 deg Yaw Command

Assessment and Evaluation

The introduction of SIMSAT into the spaceflight dynamics courses at AFIT will occur in the Spring and Summer quarters of this year. Direct student feedback and course critiques will be used to evaluate the effectiveness of SIMSAT as an educational tool. Since student numbers are quite low in AFIT's graduate programs, statistical measures of effectiveness were not deemed to be appropriate. After assessing the usefulness of the platform, SIMSAT may also be incorporated into courses on linear systems, controls and inertial navigation.

Conclusion

A laboratory demonstration of satellite attitude determination, dynamics, and control has been successfully achieved with the SIMSAT platform at the Air Force Institute of Technology. This platform has tremendous potential to remedy the lack of hands-on experience that is inherent in the study of spacecraft dynamics and control. Using SIMSAT in the classroom is aimed at providing a more stimulating learning experience and making a more direct connection between the theory of the classroom and actual practice. SIMSAT also has potential research applications, such as demonstrating new advances in attitude control theory and investigating complicated dynamical behavior such as fuel slosh.

Acknowledgements

Six individuals deserve recognition for the work that came before on this project. James Colebank, Robert Jones, George Nagy, Randall Pollak, Donald Mannebach, and Mike Hanke began the work on SIMSAT as the initial design team. Working under the guidance of advisors Greg Agnes and Stuart Kramer, these individuals' hard work and systems expertise made SIMSAT possible.

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Biography

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