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Air Bearing Based Satellite Attitude Dynamics Simulator for Control Software Research and Development

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ABSTRACT

A Satellite Attitude Dynamics Simulator (SADS) has been developed to facilitate the research and development of spacecraft flight attitude control software at the Naval Postgraduate School in Monterey, CA. The simulator provides a real-time 3 degree of freedom (3DOF) synthetic spacecraft hardware-in-the-loop environment, that includes realistic angular motions, sensor-effector delays, and control torque profiles. Control software, entered into a notebook PC mounted on the equipment platform, is input as high level object oriented code, allowing rapid code development and thorough post-test analysis. Three flight-like reaction wheels and eight cold-gas thrusters that are mounted to the SADS equipment platform provide motion simulation torque. The equipment platform is suspended in air by a spherical segment air bearing. This virtually frictionless suspension allows free rotation of the equipment platform about any rotation axis. Three separate sets of sensors, three single-axis rate gyros, a three-axis magnetometer, and a two-axis sun sensor monitor SADS platform motion. This paper discusses the SADS design, and the practical uses of this simulator for satellite attitude control system software research and development.

Keywords: Air bearing, Flight dynamics, simulator, Attitude control, Hardware-in-the-loop, testing, Real-time, 3 degree-of-freedom, spacecraft motion, modeling

1. INTRODUCTION

An air bearing based attitude dynamics simulator has been developed to facilitate academic research into improving techniques for the attitude control of flexible spacecraft. This simulator is designated as the Satellite Attitude Dynamics Simulator (SADS) by the manufacturer, Guidance Dynamics Corporation (GDC), and the Three Axis Simulator (TAS) by the customer, the Naval Postgraduate School. Weightless attitude maneuvering of a spacecraft, or satellite is aided by the use of flight-like sensors, data processing and control electronics, and torque producing elements mounted to a platform, which in turn, is supported by a spherical segment air bearing. The spherical segment air bearing allows frictionless angular rotation of the equipment platform about three principal platform axes; the pitch, yaw, and roll angular rotation axes. Platform angular maneuvering is accomplished by real-time, closed-loop actuation of a combination of three orthogonally-mounted reaction wheels and eight cold-gas attitude control thrusters. Three sets of sensors, consisting of a sun sensor, a magnetometer, and three rate gyros provide attitude and rate data to the platform control processor, a Pentium II notebook PC. The notebook PC, using graduate student generated Matlab® Simulink® control algorithms running real time, using Matlab's® Real-Time Windows Target®, generates closed-loop control commands to the reaction wheels and/or thrusters. The simulator offers a low-cost alternative to the use of motor-driven gimballed motion systems, and allows full, real-time hardware-in-the-loop testing of small spacecraft and missile attitude control systems, in situations where only digital simulation had been considered practical.

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2. HISTORY & BACKGROUND

Simulation Background at the Naval Postgraduate School

The Spacecraft Attitude Dynamics and Control Laboratory (SADCL) at the Naval Postgraduate School (NPS) is used to perform research on developing improved control techniques for attitude control of flexible spacecraft. The emphasis of the research has been to develop improved control laws for fast slew maneuvering of flexible spacecraft, while minimizing the vibration and settling time at the end of slew maneuver. The development of this laboratory was initiated in 1989. The first simulator for attitude control was a single-axis Flexible Spacecraft Simulator (FSS). The FSS simulates attitude motion in the pitch axis only, of a flexible spacecraft. It consists of a central rigid body representing the spacecraft central body, and a flexible appendage, which represents a reflector with a flexible support structure. The system is floated on air pads over a granite table to simulate a micro-gravity environment. The actuators are cold-gas thrusters and a single reaction wheel. The sensors are Rotational Variable Differential Transformers (RVDT), a rate gyro and an overhead camera as a position sensor. A dSpace® system is used for the real time controller.

The FSS has been used by graduate students (MS and Ph.D.) and faculty to develop new control techniques. However, this simulator is limited to motion in only one axis. Interaction between actuators and sensors during multi-axis control could not be simulated by the FSS. In 1995, the effort was initiated to develop a Three-Axis attitude control Simulator (TAS). Due to financial constraints, the development was done in stages. As a first step, a spherical air bearing was bought from Team. Next, major components such as wheels and rate gyros were bought. Finally, Guidance Dynamics Corporation was given a contract to add the thruster system and additional components and make it operational.

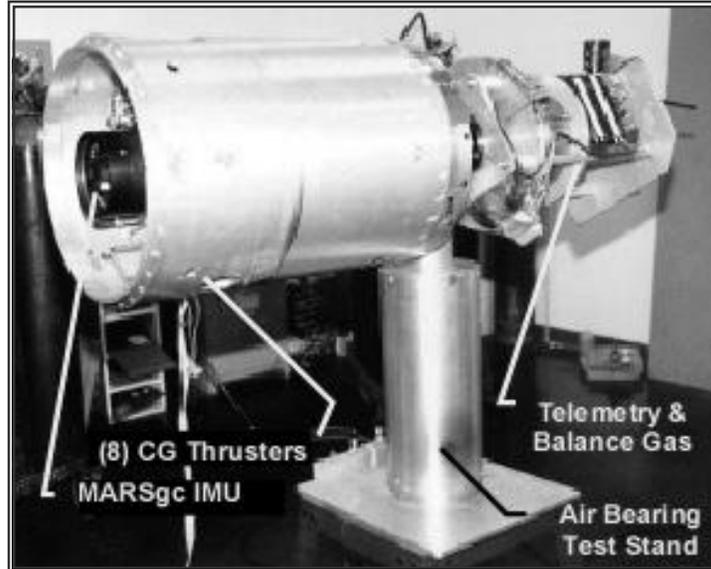
Simulation Applications at the NPS SADCL

Currently, the three-axis-attitude control simulator will be used on two NPS projects. The first project is to develop reaction wheel torque profiles for slew maneuver, such that at the end of slew, vibrations are eliminated or minimized, and settling time is reduced. The second project is to develop fine acquisition, tracking and pointing control to assist the utilization of beam control optics technologies for the Bifocal Relay Mirror spacecraft. The Bifocal Relay Mirror spacecraft is composed of two optically coupled telescopes used to redirect the laser light for ground based, aircraft based or spacecraft based lasers to distant points on the earth, or in space for DoD applications. This is a very challenging project. A fast steering mirror will be mounted on the simulator, and control laws for the fast steering mirror and the spacecraft bus will be developed and tested.

History of Air Bearing Based Flight Dynamics Simulation

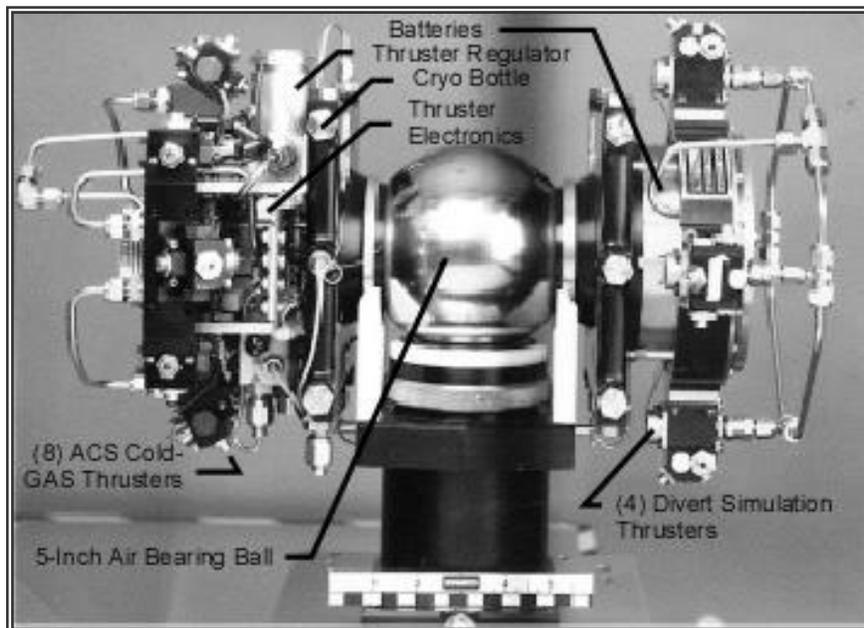
Spherical air bearings have been used to simulate a weightless environment since the early days of rocketry. A thin film of compressed gas, or air, is injected between a spherical segment, or ball and a mating spherical cup. This thin film of air creates an essentially frictionless lubrication layer between the ball and cup. When test articles, mounted to the ball segment are balanced, such that their aggregate center of gravity corresponds with the rotational center of the ball, rotational motions of the ball and test articles match those of an object with similar inertial properties free falling through space. Air bearing supported “couches” and floors were used during the Mercury manned space program to test astronaut responses in a weightless environment. Air bearing test stands have also been used for many years to test sounding rocket attitude control systems (Figure 1). Cold-gas thrusters maneuver flight-scaled sounding rocket test payloads through flight missions, often acquiring simulated targets, such as the Sun, stars, or other sources of electromagnetic radiation. These simulations allow integrated real-time hardware-in-the-loop testing of thrusters, rate gyros, inertial and optical sensors, telemetry links, and control electronics. Later, as analog control was replaced by digital flight computers and flight control software, these test platforms played a vital role in attitude control software algorithm development and testing. Spherical air bearing test fixtures still play an important role in the development of control systems for manned and unmanned spacecraft. This is evidenced by ongoing test programs at the NASA’s Wallops Flight Facility, Wallops Island, VA, the ASTREX test platform at the Air Force Research Laboratory in Albuquerque, NM, and at the Flight Robotics Laboratory at NASA Marshall Space Flight Center in Huntsville, AL.

Figure 1. GEMINI Air Bearing Attitude Control System Testing at GDC



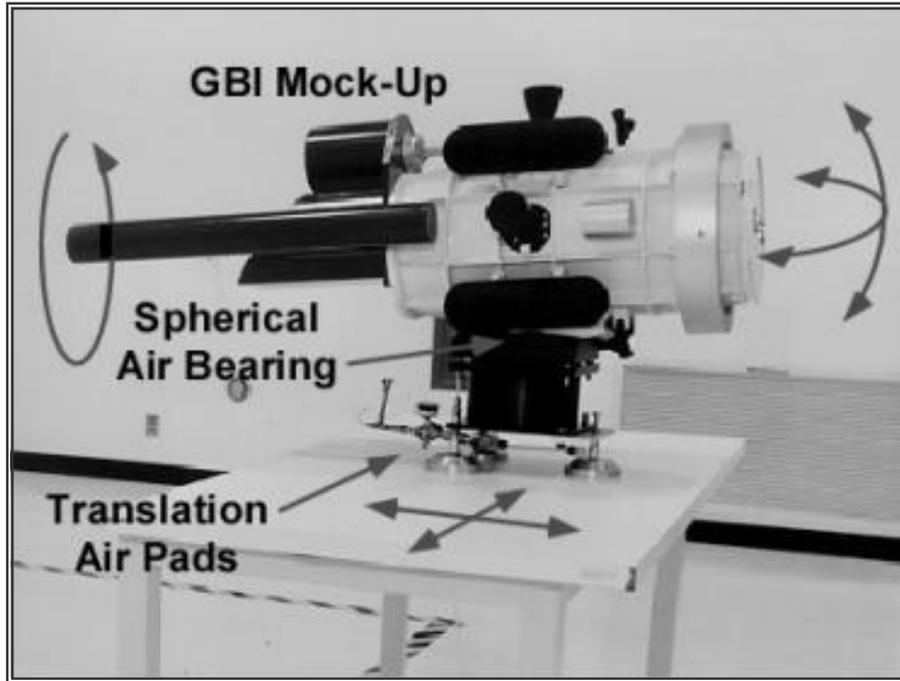
In the 1980s and 1990s air bearing test platforms were used to demonstrate the “hit-to-kill” capabilities of Kinetic Kill Vehicles (KKV) being developed for the Strategic Defense Initiative Organization (SDIO), and later the Ballistic Missile Defense Organization (BMDO). Air bearing based Flight Dynamic Simulators (FDS) were used in support of the Army and Navy Lightweight ExoAtmospheric Projectile (LEAP) (Figure 2), Air Force Brilliant Pebbles, and BMDO Ground Based Interceptor (GBI) programs. These test platforms were desirable because of their capabilities to simulate real-time, high angular accelerations and rates over relatively large angular displacements, while supporting bulky, heavyweight prototype seekers, flight processors and inertial measurement sensors. The use of actual flight prototype and electro-mechanically-simulated components resulted in higher fidelity simulations, especially when testing for closed-loop control software execution timing conflicts.

Figure 2. Army Lightweight ExoAtmospheric Projectile (LEAP) Air Bearing Test Fixture



To demonstrate divert maneuvering “hit-to-kill” control capabilities of KKV’s, additional degrees of freedom were added to laboratory test platforms. A concept demonstration for the GBI KKV used five degrees of freedom: three rotational, using a spherical segment air bearing, and two translational via three air bearing support pads (Figure 3).

Figure 3. GBI Mock-Up on a 5 Degree Of Freedom Air Bearing Test Platform



Recent interest in air bearing based flight dynamics simulators have focused on small spacecraft control systems. Academic and military research into such areas as the pointing and control of flexible space structures, small satellite formation flying, sensor and effector fault tolerance, and flywheel attitude control/energy management, exemplify some of the attitude control issues that are being investigated with the aid of air bearing based FDS. The following section describes a recent application of air bearing based flight dynamics simulation to small spacecraft attitude control research.

3. SATELLITE ATTITUDE DYNAMICS SIMULATION

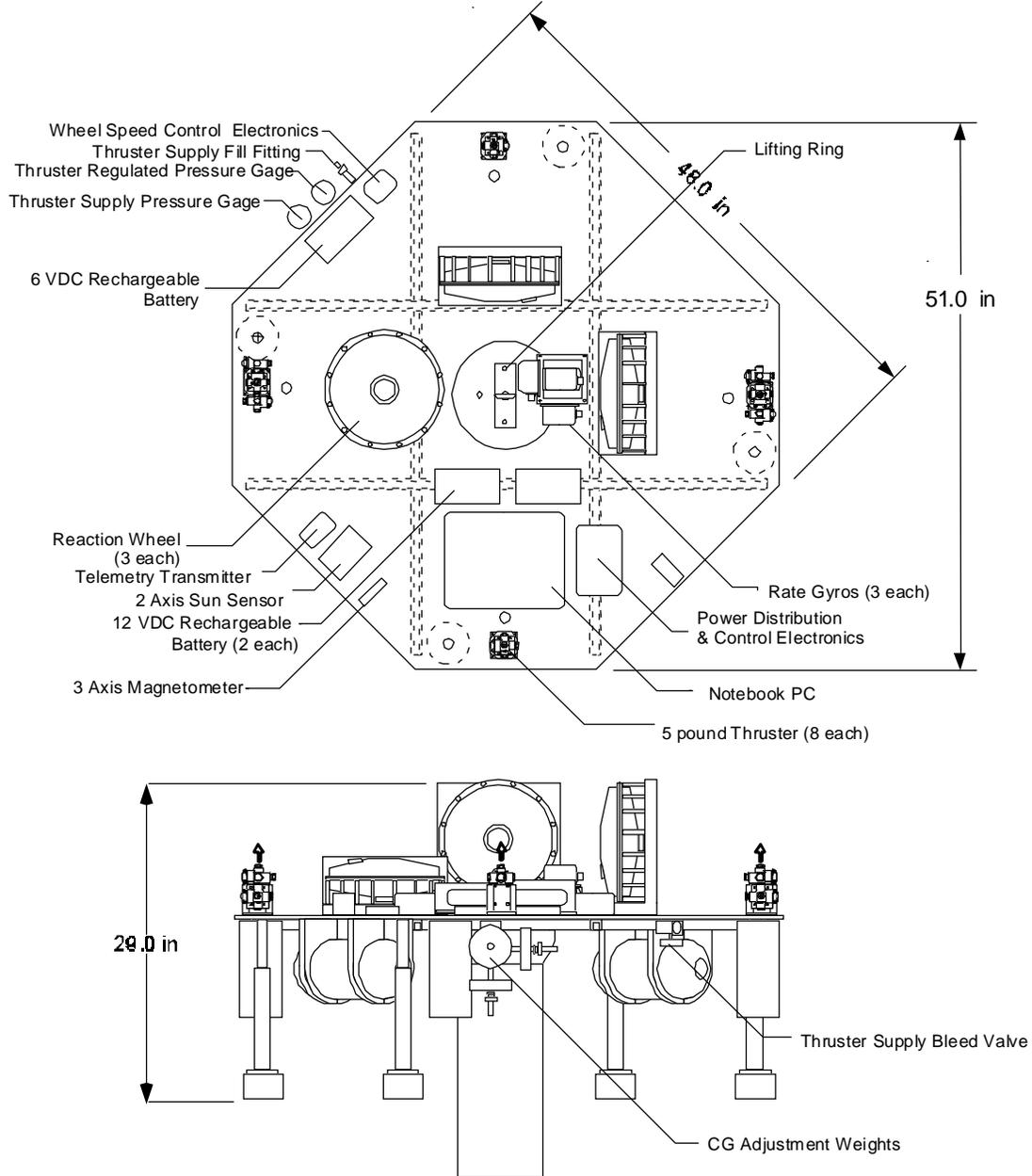
The Satellite Attitude Dynamics Simulator (SADS) (Figures 4, 5, 6 & 7) is a custom designed, fully integrated air bearing based flight attitude dynamics simulator. It has been developed by Guidance Dynamics Corporation for the Naval Postgraduate School in Monterey, CA to support the research into, and development of, control algorithms that improve the maneuvering and pointing of flexible spacecraft structures. The SADS is divided into two main elements: the spherical segment air bearing that provides 3 degree-of-freedom floatation for the spacecraft simulator, and the simulator itself. The simulator consists of sensors, torque-producing effectors, data processing/control electronics and software, and energy storage, all interconnected and supported by a structural platform. Table 1 describes the major active elements of the simulator, and summarizes the critical specifications of each element.

The SADS electronics (Figure 7) is an integration of four electronics boxes, and one notebook computer on the air bearing platform. A battery charger and a desktop computer are located off of the platform. The electronics boxes on the platform consist of a sun sensor, a RF Modem, a reaction wheel controller, and power distribution and control electronics. Power for the electronics is supplied by three rechargeable gel-cell type batteries, which are mounted to the top of the equipment plate.

The SADS sensors consist of a three-axis fluxgate magnetometer, three orthogonally mounted single-axis rate gyros, and a two-axis CCD sun sensor. These sensors are interconnected to the electronics boxes, and all are mounted to the top surface of the equipment mounting plate. Three 20 Nms reaction wheels are also orthogonally mounted to the top surface of the equipment plate. Control torques can also be applied to the SADS via eight five-pound cold-gas thrusters. The thrusters themselves, are mounted orthogonally on the top of the equipment plate to maximize thruster lever arms, and minimize cross coupling, while the gas storage, regulation and distribution plumbing for the reaction control system (RCS) is located on the underside of the equipment plate. Associated support equipment includes a fill port and gages for charging the RCS storage tanks, a charging port for the batteries, a lifting ring for removal/emplacement of the simulator off and onto the air bearing, support legs for servicing, and adjustable weights for platform center of gravity (CG) balancing.

Figure 6. Outline Drawing - Satellite Attitude Dynamics Simulator

Layout - Satellite Attitude Dynamics Simulator



The complete SADS simulator platform, including the spherical segment air-bearing ball weighs approximately 450 pounds. A summary of the SADS mass properties, and resultant angular acceleration capabilities is shown in Table 2. While the maximum SADS thruster and reaction wheel angular acceleration capabilities are 40 and 0.45 degrees per second squared respectively, thrust level adjustability, thruster pulse width modulation, and reaction wheel torque control allows for a wide range in acceleration levels and ratios between thruster and reaction wheel torques.

Figure 7. SADS Functional Block Diagram

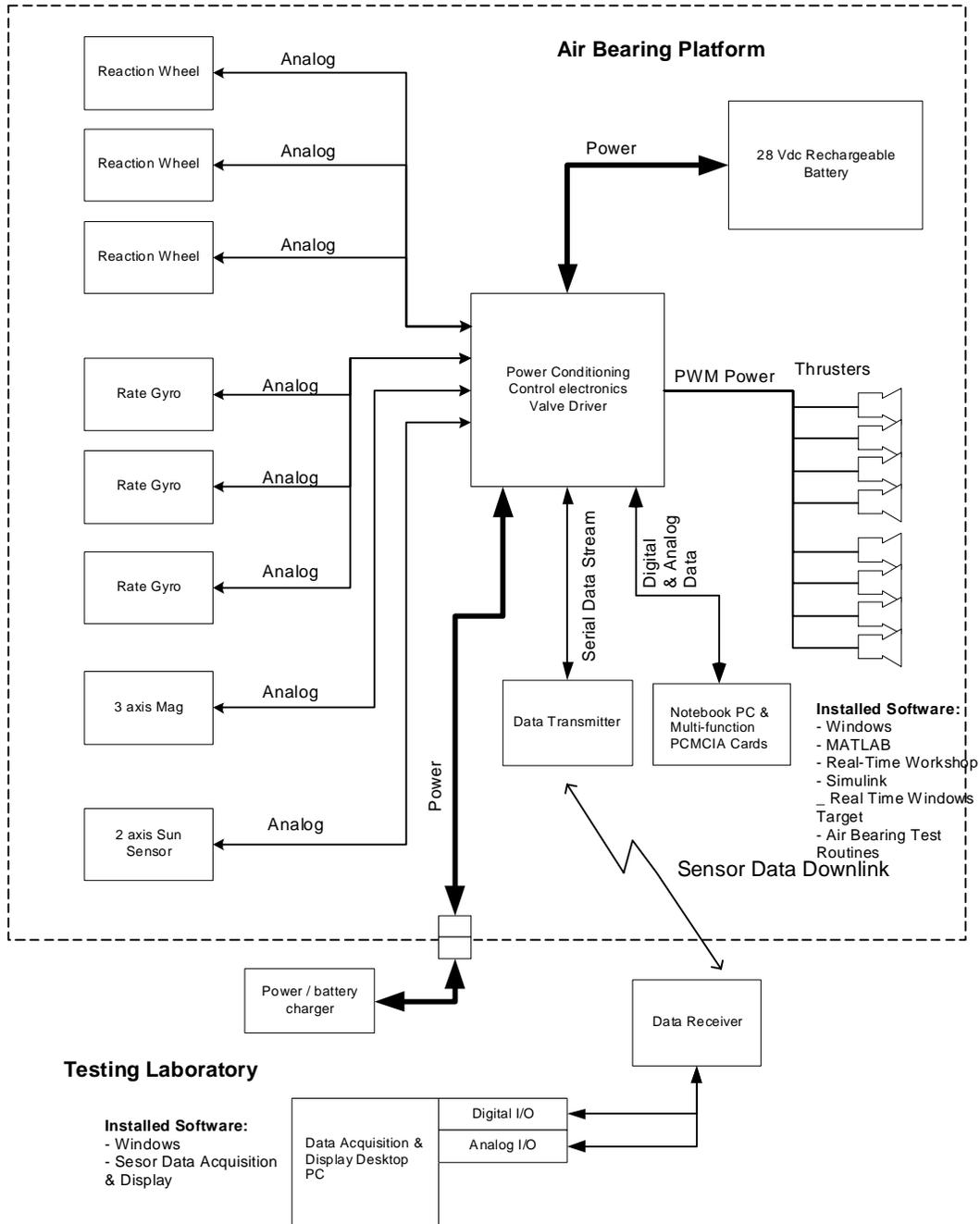


Table 1. SADS Major Elements & Key Specifications

| Qty | Instrument | Technology | Key Specifications | |
|---------------------------------|----------------------------|---|--|---|
| Sensors | | | | |
| 1 | Magnetometer | 3-Axis Fluxgate | Absolute Accuracy: Axis Matching: Max. Alignment Deviation: | 2% 0.20% 0.5 deg to ref surfaces 0.3 deg mutual axis |
| 3 | Rate Gyro | Spring Restrained Spinning Inertia | Rate Threshold: Rate Resolution: Acceleration Bias: | 0.01 deg/sec 0.01 deg/sec 0.1 deg/sec/g |
| 1 | Sun Sensor | 2 Axis CCD Spot Centroiding | Accuracy: Sample Rate: | 0.5 deg 5Hz |
| Torque Producing Devices | | | | |
| 3 | Reaction Wheel | Variable Speed Spinning Inertia Wheel | Angular Momentum: Wheel Speed Range: Reaction Torque: | 20.3 Nms +/- 2500 rpm +/- 162 mNm |
| 8 | Thrusters | Pulse Width Modulated Adjustable Cold Gas | Thrust Range: Min. Open Close Response: Repeatability: Max. Op. Pressure: | 0-5 lbs 0.010 sec 0.5% 600 psi |
| Data Processing | | | | |
| 1 | Attitude Control Processor | Pentium II Notebook PC | CPU Speed: RAM Storage: Hard Disk Storage: | 366 MHz 128 Mbytes 10 Gbytes |
| 2 | Data Acquisition & Control | 12-bit Analog and Digital I/O | Analog Input: Analog Output: Digital I/O: Counters/Timers: | 8 SE, 4 Diff 2 Ch 12-bit 24 (5V/TTL) Ch 3 16-bit |
| 1 | RF Modem | | Speed: | 9600 Baud |
| Software | | | | |
| 1 | Windows 98 | Operating System | Key Features | |
| 1 | Matlab | Matrix Math Programming Language | Widespread Usage & Stable Code | |
| 1 | Simulink | Graphical Modeling, Simulation & Analysis | Widespread Usage Graphical Construction Extensive Libraries | |
| 1 | Real-Time Workshop | Real-Time Code Compiler | Widespread Usage & Stable Code | |
| 2 | Real-Time Windows Target | Real-Time Hardware Interface for Windos PCs | 10 KHz Sampling Compatable with many DACs | |

One of the most significant elements of the SADS system is the utilization of a flexible, user-friendly, widely accepted, and therefore stable, data processing and control environment for research and development of innovative control system algorithms. SADS uses a 366 MHz Pentium® notebook computer running Mathwork's Matlab®, Simulink®, Real-Time Workshop® and Real-Time Windows Target® to facilitate the development, simulation, testing, analysis and documentation of attitude control system software. Extensive graphical libraries are available for the creation of control system block

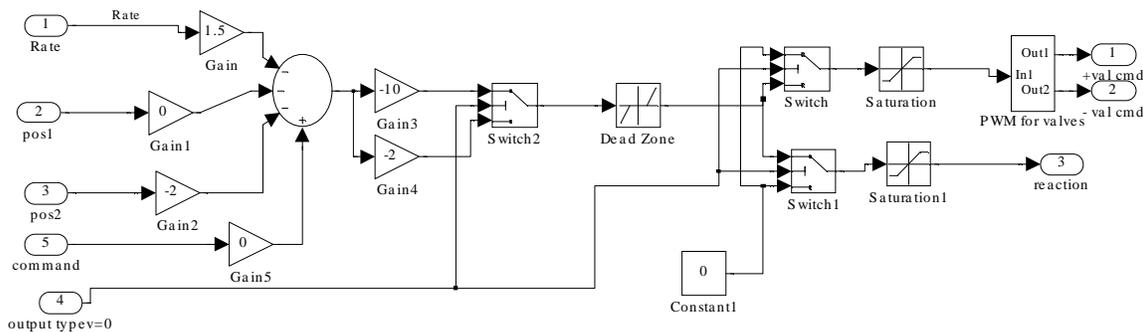
diagrams. Custom control blocks are also relatively easy to construct. Standard, tested control system sub-blocks can be established as part of the library of tools easing the development of larger, more complex control systems. Figure 8 shows a typical servo control system sub-block that formed part of the SADS delivery demonstration software.

Table 2. SADS Mass Properties and Angular Acceleration Capabilities

| SADS Weight | lxx | lyy | lzz | | | |
|------------------------------|------------------------------|------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| (lbs) | (slug-ft ²) | (slug-ft ²) | (slug-ft ²) | | | |
| 453.4 | 28.18 | 15.27 | 15.27 | | | |
| Max. Thrust Level | Thruster x Torque | Thruster y Torque | Thruster z Torque | Thrust Accel x | Thrust Accel x | Thrust Accel x |
| (lbs) | (lb-ft) | (lb-ft) | (lb-ft) | (deg/sec ²) | (deg/sec ²) | (deg/sec ²) |
| 5 | 20.00 | 10.00 | 10.00 | 40.66 | 37.53 | 37.53 |
| Max. x Reaction Wheel Torque | Max. y Reaction Wheel Torque | Max. z Reaction Wheel Torque | Reaction Wheel Accel x | Reaction Wheel Accel x | Reaction Wheel Accel x | |
| (lb-ft) | (lb-ft) | (lb-ft) | (deg/sec ²) | (deg/sec ²) | (deg/sec ²) | |
| 0.119 | 0.119 | 0.119 | 0.243 | 0.448 | 0.448 | |

Once constructed, the control system can be run entirely on the PC, using simulation models for sensors, effectors, SADS and/or intended spacecraft inertial properties and the dynamic environment. Much experience can be gained on the control system before ever running it with the SADS hardware-in-the-loop (HIL). The transfer of simulation software to the HIL environment is seamless, simulated elements being simply replaced with actual hardware elements via the DAC cards and Real-Time Windows Target® software, while the identical control system software used in simulation, processes real data and issues the appropriate SADS effector commands.

Figure 8. SADS Demo Software Servo Control System Sub-Block Diagram

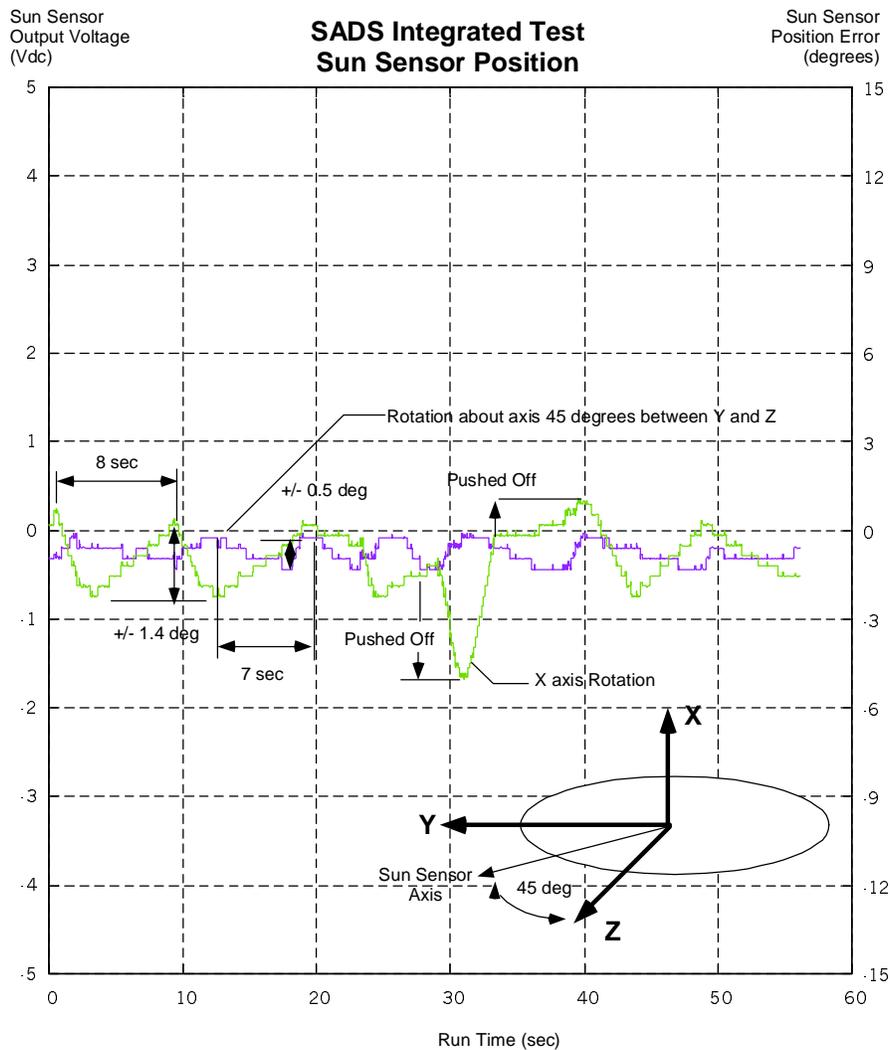


To operate the SADS in HIL mode, the SADS RCS storage tanks must be filled to a maximum of 4000 psig with clean dry gaseous nitrogen. The 450 cubic inches of storage at maximum working pressure will, depending upon the required thruster maneuvers, allow at least two, thirty minute test runs. After pressurization and verification that the electronics supply

batteries are fully charged, the center of gravity balance may be verified by placing the SADS in a floating state. Compressed air is supplied to the SADS air bearing via a small remotely located AC-powered air compressor. The 10-inch diameter air bearing ball segment only requires approximately 40 psig to float the 450-pound SADS platform.

Once floating and balanced, the SADS electronics are powered up. This involves a quiescent time period to allow the rate gyros to fully spin up. Power to the torque producing elements are inhibited by an isolation switch to, prevent inadvertent motion and/or thruster firing prior to the intended start of the test run. The test run is initialized by connecting the Simulink® control application to the SADS electronics by running the Real-Time Target® software, then running the appropriate mission sequence file. During a test run any system parameters of interest may be displayed graphically, in engineering units, on the notebook PC screen as viewing scopes. Control parameters, such as gains and system variables, may be altered mid test via the notebook keyboard, and the effects observed in real-time. All parameters of interest may also be saved to a data file for post-test display and analysis. In addition, the SADS telemeters a data stream of all critical control system parameters, via a RF modem, to a desktop PC located remotely in the testing laboratory. The sun sensor error data from a typical demonstration test run is shown in Figure 9.

Figure 9. Typical SADS Sun Sensor Position Data Telemetered During Demonstration Test Run



4. SUMMARY

SADS, a low-cost, real time, hardware-in-the-loop (HIL) spacecraft attitude control system simulator offers an alternative to digital only verification of control system software. It is an important part of an overall process for developing and testing attitude control system algorithms, and as such, it may find many applications in ongoing research into innovative control of flexible spacecraft structures, formation flying of small spacecraft, flywheel energy management and attitude control consolidation, and fault tolerance to instrument and effector failure. Applications to other flight control system development is anticipated. The use of graphics-based control system software development, integrated with HIL, will allow faster, more flexible development of fully tested control software. Air bearing based flight dynamics simulators can play a beneficial role in developing the next generation of small, smart attitude control systems.