Low-Cost Attitude Determination and Control for Small Satellites

by

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Abstract

This paper addresses the need to develop small satellite technology which will enable small satellites to perform large satellite missions. The Center for Aerospace Technology (CAST) at Weber State University (WSU) has an 18 year history of small satellite innovation. Previous satellites include: NUSAT, WEBERSAT, and PHASE 3d. CAST is currently fabricating two new small satellites with advanced capabilities. CATSAT, a USRA program, will determine the origin of gamma-ray bursts and is a joint project with the University of New Hampshire and the University of Leicister in England. JAWSAT, a joint project with the U.S. Air Force Academy, will be the first payload launched by a converted minuteman missile. Both missions require active attitude determination and control previously unavailable for satellites of this class. In support of these two missions CAST has undertaken the task of developing satellite instrumentation designed specifically for small satellite applications. Size, weight, power consumption and cost minimization were incorporated into the design philosophy. New enabling technology includes the use of the State-Sampled Network for sensor integration, attitude determination and attitude control. The overall development history is chronicled with emphasis relating to issues of reliability and acceptance testing.

1. Introduction

It has always been the hope of smallsat enthusiasts to prove the worth of low cost, small satellites to perform useful space missions. However, few if any smallsat missions to date have been able to demonstrate this ability. The main obstacle is the lack of attitude determination and control. The Center for Aerospace Technology (CAST) at Weber State University (WSU) has taken on the task of developing flight hardware specifically designed for the next generation of small satellites.

Two small satellites with advanced capabilities including prototype attitude determination and control are being constructed. The Cooperative Astrophysics and Technology Satellite (CATSAT) is a joint project with the University of New Hampshire and Leicister University in England. CATSAT is designated as the third Student Education Demonstration Initiative (STEDI) and the first University Experiment (UNEX) sponsored by the University Space Research Association (USRA) and funded though NASA. The purpose of CATSAT is to use a low-orbit satellite, incorporating an array of gamma-ray and x-ray sensors, to determine the origin of gamma-ray bursts.

The Joint Academy Weber Satellite (JAWSAT), a joint project with the United State Air Force Academy, will be a test bed for the development of arc-jet propelled small satellite technology for a micro-explorer program with advanced mission capabilities. Sponsored by the Department of Defense out of Philips Laboratory, JAWSAT will be the first payload to use a converted Minuteman missile as a launch vehicle.

2. CAST History

The Center for Aerospace Technology (CAST) is a department within Weber State University's College of Applied Science and Technology. CAST's mission is to obtain and manage projects to enhance the practical education of the College's students. The major emphasis of CAST's projects is the development and operation of small, low Earth orbiting satellites.

2.1 Founding of CAST

Initial work on aerospace projects at Weber State University started in 1978 with the development of a small satellite to be used to demonstrate a method to characterize the Federal Aviation Agency's secondary radar systems. This satellite, called NUSAT 1 (Northern Utah Satellite), a joint project with Utah State University and local industry, was the forerunner in small, simple and low cost satellites for special applications. The educational and technological innovations were so successful that the Center for Aerospace Technology was created in 1982 as a separate entity to direct future small satellite work in Utah.

2.2 NUSAT

NUSAT was launched in April 1985 by the NASA space shuttle, Challenger. NUSAT was a 100-pound satellite which orbited the Earth once every 90 minutes until it re-entered the atmosphere in December of 1986. In addition to its primary mission of calibrating FAA radar it also served as a useful tool for enhancing student education

2.3 WEBERSAT

WEBERSAT is a joint project with AMSAT-NA, a scientific, non-profit organization of amateur radio operators that has been active in building small satellites for several decades. WEBERSAT is one of four amateur satellites launched in 1990 on a French Ariane rocket. Weighing 27 pounds, it is equipped with five radio receivers, two transmitters and a color video camera. This sun synchronous, polar orbiting satellite is still successfully performing worldwide educational and other scientific experiments.

2.4 PHASE 3d

PHASE 3d is an AMSAT international project to build a 1500-pound communication satellite to be launched on the next generation of the French Ariane rocket in 1997. CAST has the major responsibility of building the space frame for this satellite and is currently the only undergraduate university in the world working on this international project.

3. Small Satellite Missions

Recent changes in the federal budget have forced a drastic modification of the national space program. Many traditional programs have been reexamined in the light of reduced funding and reassessed as to their cost verses actual mission payoff. The federal government is no longer willing to fund billion-dollar space missions or to heavily subsidize commercial space ventures. For this reason, NASA is currently promoting a "faster, smaller, cheaper" mission philosophy but has had little success in redirecting main stream aerospace opinion to actually change business as usual. NASA is being told by its contractors that it is impossible to do "good science" with small, reasonably priced, spacecraft. An interesting consideration is that the Center for AeroSpace Technology at Weber State University has an 18 year history of designing, building and flying satellites capable of performing "good science" and, with the use of new proprietary technology, can accomplish the reportedly impossible task of "faster, smaller, cheaper" even beyond the current aspirations of NASA.

3.1 Defining the Small Satellite

Historically there has been a lack of precision in defining a “small satellite.” Size and weight parameters have been bandied about for years. The bottom line is that size and weight are only secondary considerations. The only true definition relates to total program cost ! If we had the finances to build and fly a ‘maxi’ satellite that could do everything, that would be our choice. As is, smaller and faster are the necessities of cheaper. The trick is to develop an inexpensive satellite mission which can accomplish true scientific discovery.

3.2 Identifying Missions

Under a Small Business Technology Transfer (STTR) contract with Philips Laboratory, CAST and its technology spin-off company, One Stop Satellite Solutions (OSSS), is researching the issue of scientific, commercial and military applications for small satellites. Current and near-future capabilities will be matched with specific mission specifications.

One obvious concern of smallsats as to the requirements for valid missions is attitude determination and control. Free tumbling spacecraft have few if any useful mission capabilities. Passive methods such as gravity gradient, solar and aerodynamic stabilization have been successfully used on small satellite missions but do not provide the needed accuracy to facilitate mainstream scientific missions. Low orbital altitudes result in high levels of magnetic and aerodynamic perturbations, thus requiring constant reorienting of the satellite.

To accomplish valid missions, currently manifested CAST satellites will be three-axis attitude stabilized. The base line is an active attitude control with better than one degree accuracy. Hot or cold gas thrusters can be used for short duration missions. However, once the working fluid has been expended, attitude control is lost. Active methods require the constant expenditure of energy. Solar powered attitude control is the attractive solution, using either magnetic torquing coils or reaction wheels.

4. **Current Missions**

4.1 JAWSAT

The JAWSAT mission is progressing with interest from amateur, academic and professional organizations. Much of the mission has yet to be defined, but it is apparent that JAWSAT will be a major step forward in educational satellite technology. Launch is planned for mid 1998. CAST and USAFA have undertaken this project as a co-venture using volunteer labor and donated materials as much as possible. CAST has agreed to perform the majority of the mechanical and electrical design and fabrication with USAFA using its Air Force connection to arrange for the ride into orbit. Each organization will provide experimental packages with primary ground stations at Weber State University in Ogden, Utah and USAFA, Colorado Springs, Colorado. Amateur satellite hobbyists as well as academic institutions around the world will be encouraged to utilize down link telemetry freely.

4.1.1 Mission Objectives

As a joint project, the Air Force Academy and Weber State University have a common goal of student and faculty education in the arena of aerospace technology. We recognize the need to train students in the newest fields of technology. Satellite design and mission planning have become current classroom activities. Designing an actual space mission with the related hardware creates excellent classroom teaching situations. After launch, ground station procedures, data reduction and daily satellite maintenance will be incorporated into class curriculum. This type of project not only enhances the education of students directly involved in the project, but improves the faculty and curriculum for future students.

The growing involvement of the Air Force in space activities makes it increasingly important to give future officers this experience as part of their education. This project will provide active involvement to hundreds of students and faculty in spacecraft design and satellite operations.

Graduates of the Air Force Academy who major in astronautical engineering or space operations will become immediately involved in DOD space activities and will eventually, command the Air Force's efforts in space. The experience and education gained through JAWSAT will have a positive impact on hundreds of these future Air Force leaders..

The JAWSAT satellite is assumed to be the first of a series of micro-explorer satellites with the capabilities to carry out several mission scenarios.

4.1.2 Propulsion

Perhaps the most significant innovation on JAWSAT will be the use of electric propulsion to perform orbital maneuvering. An arc jet using Teflon propellant was developed by Lincoln Labs more than a decade ago and has been provided to us by the Rocket Research Co. This engine, with some modification, will support orbital station keeping and orbit raising. A liquid fueled arc jet engine is currently being sought for future missions.

4.1.3 Experimental package

Although JAWSAT's primary mission will be the testing of propulsion and attitude control systems pursuant to future projects, additional scientific experiments will be conducted. The Physics Department at the Academy is interested in providing a particle sensing payload to investigate those portions of the earth's magnetosphere encountered during high inclination orbits.

Since amateur radio frequencies will likely be used for JAWSAT, a simple transponder will be carried along with the capacity to support 'store and forward' communications much like the currently operating AMSAT satellites. One advantage of using amateur radio frequencies for JAWSAT is that all results from any payload experiment will be readily available to anyone who wishes to listen. We expect that data formats and image processing algorithms will be made available to any interested non-commercial party.

One of the Academy's most important contributions to the JAWSAT project is the opportunity for a launch through the Department of Defense's MSLS program out of Philips Laboratory. JAWSAT was formally registered with the Space Test Program in January of 1993 and was briefed to the Air Force Space Experiments Review Board in March. It is currently manifested for the first orbital flight of a Minuteman launch vehicle in mid 1998.

4.2 CATSAT

For a detail description of the CATSAT structure and mission, see papers by Carl Wood, Weber State University, Ogden, Utah and David Forrest, University of New Hampshire, Durham, NH, presented in this same conference.

5. **Developing a Low-Cost AD&C System**

It is a primary goal of both CATSAT and JAWSAT programs to develop, test and 'space qualify' a complete attitude determination and control system specifically intended for low cost small satellite applications. Five low-cost attitude sensor units will be used to determine the attitude of the space vehicles. They include: magnetometer, GPS receiver, two-axis optical sun sensor, and two infra-red earth horizon detectors. Four reaction wheels in an equilateral tetrahedral geometry constitute the main attitude actuator. As back up actuators, magnetic torque coils will be included. These coils can also be used to de-spin the space vehicle after launch vehicle tip-off and desaturate the reaction wheels as needed.

All units of the attitude determination and control subsystem are self-contained with integral data translation and diagnostic capabilities. Each unit is interfaced to the main flight computer, which contains the main control algorithm, which is based on a state-sampled controller. This controller is capable of real-time, optimal, control requiring very little computer overhead.

'Space qualification' and flight reliability have always been of vital concern. To insure reliability, each new design and flight article will be rigorously tested to meet Military Standard 1540c as part of an ISO-9000 testing program.

5.1 Market Solutions

When CAST first contemplated the design of satellites needing active attitude determination and control, a call went out to the vendors which normally manufacture and supply such items. Industry has always been quite supportive of our program and we were in hopes of soliciting donations of equipment and technical expertise. Although still supportive, the aerospace industry was found to be fighting for its own economic life. Rather than donations, we were offered generous educational discounts which, although appreciated, still left costs too high for our typical satellite budget.

5.2 In-House Development

Without the availability of donated devices, CAST embarked on an in-house development effort to build our own attitude determination and control system. The main goal was to develop a system designed uniquely for small satellite missions taking into account size, weight, power and cost constraints.

A Phase 1, Small Business Technology Transfer (STTR) contract from Philips Laboratory, was recently awarded to CAST and its technology spin-off company, One Stop Satellite Solutions (OSSS), to develop engineering models of attitude sensors designed specifically for small, inexpensive, satellite missions.

5.3 AD&C System

The CATSAT and JAWSAT missions require a stable platform from which experimental data can be referenced. The specific requirements are attitude control in three-axes to within ±5 degrees of any given pointing vector and attitude determination to within ±1 degree of the actual pointing vector of the satellite.

AD&C subsystems are made up of seven units which for the purposes of design, manufacturing, testing, and function are viewed as independent items that are complete and separate. Four attitude sensor units are used to determine the attitude of the space vehicle. The three-axis magnetometer is a new design based on nonlinear magnetic materials. This one sensor has the capability of meeting the mission attitude determination requirements but has less resolution than the sun and horizon sensors which are also new designs based on low cost sensor technology.

Two sets of actuators, reaction wheels and magnetic torque coils, are incorporated into the AD&C subsystem. These torques are controlled by the flight computer to orient the space vehicle attitude (see Figure 1).

5.3.1 Reaction Wheels

Four reaction wheels in an equilateral tetrahedral geometry constitute the main attitude actuator. The reaction wheels design specifications are:

Maximum weight - 1 kg per wheel
Electrical - 12 volt DC ± 2 volts - 3 watt at 1000 rpm - 15 watts at 20,000 rpm
Working life - 10 year
Angular momentum - 0.57 kg m^2/s
Radiation - 100,000 rads total
Thermal -20° to 60 ° c

Modes: interrogation, set speed, set frequency, set duty cycle, shut down

Communications - RS 422 - 9600 serial - 6” pigtails

Redundancy - 4 Reaction wheels per satellite system

Software - error detecting / correcting software

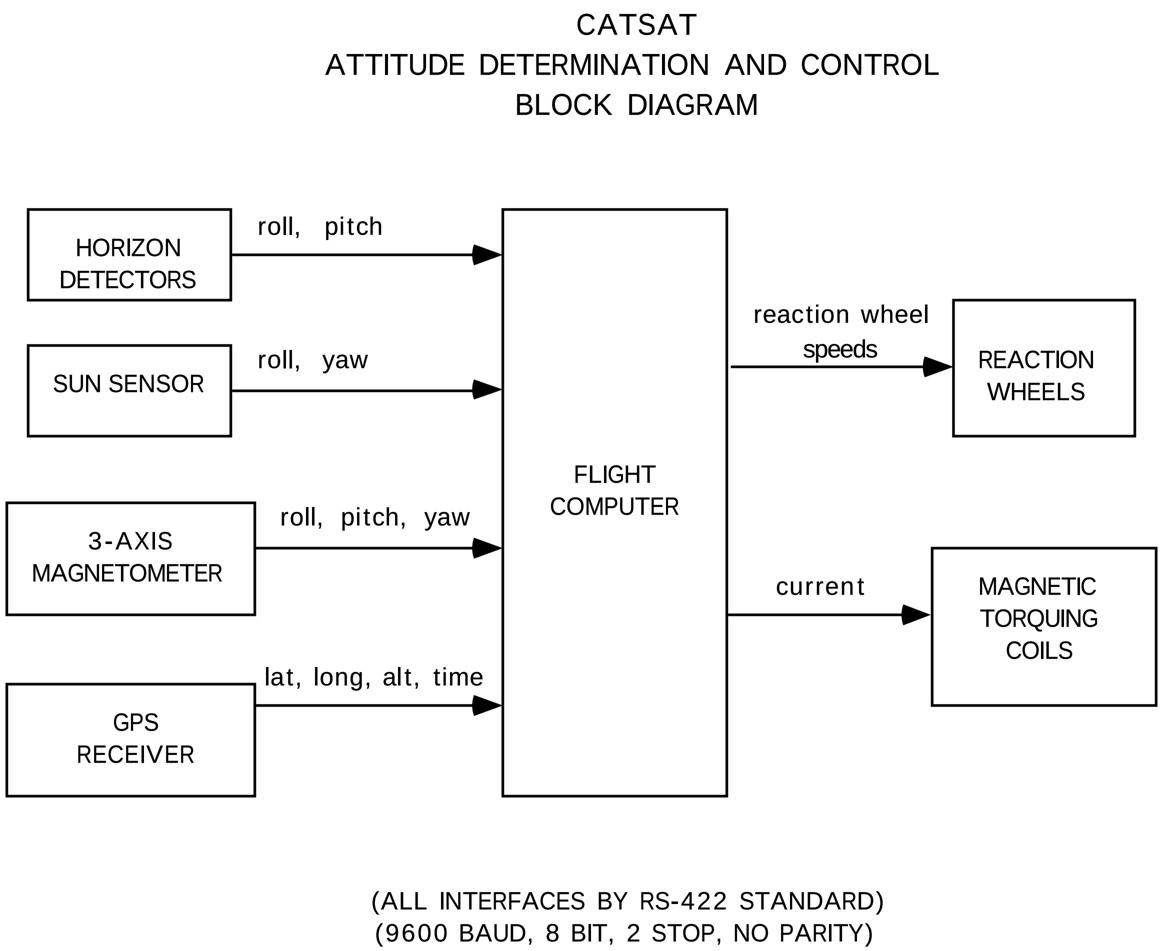

Figure 1 - CATSAT AD&C Block Diagram

5.3.2 Assembly and Quality Control

The reaction wheel design had to accommodate several considerations. A unit was needed that could maintain an internal pressure for a minimum of ten years to ensure no out-gassing of plastics, lubrication or other compounds inside. The induction motor needed to be mounted so as to reduce resonance problems during launch. Finally, ease of assembly was considered for possible future mass production.

Before assembly, parts were cleaned and inspected to ensure the least amount of contamination by oils and fine debris.

Surface mount components were selected to create an unit that could meet the design constraints set by the physical size of the satellites in which they will be placed. Solder paste was determined to be the best way to ensure reliable solder connections and maintain reasonable cleanliness. Each circuit board assembly was solvent cleaned and tested by interfacing with a Macintosh computer and placed in a hermetically sealed static bag to retain cleanliness and prevent damage from static electricity.

An inspection of all mechanical items was performed by a senior mechanical engineer to verify each part to be in tolerance The most important inspection was the inside surface of the lids and the grooves which retained the O-rings. A slight scratch in either of these areas would cause an improper seal. A microscopic inspection of each groove was conducted.

Circuit boards were microscopically inspected to insure 'best workmanship' of assembly techniques and potted with a space rated RTV compound. The two optical sensors on the motor side of the canister were aligned with the two holes of the canister. The circuit boards, plastic spacers and three mounting screws were placed inside the canister and the screws were tightened to an equal tension.

The induction motor was then inserted into the canister and the three wires, for each phase, were then connected to the circuit board. The three wires passed through the center of the circuit boards and were connected to P3. The six wires, which were previously epoxied through the feed-hole of the upper lid, were then soldered in place

The o-rings were lightly and evenly coated with a high-vacuum grease to create a better seal. The upper o-ring was placed in first and the upper lid was put carefully in place. All of the screws were then tightened on the perimeter of the upper lid. The lower o-ring was then placed in the groove of the lower part of the canister and the lower lid was carefully lined up with the center shaft of the motor. This shaft is keyed so that the motor can fit only in one position. The lid was then tightened down by the screws. The Reaction Wheel was then completely sealed except for the fill port located on the lower half of the lower lid.

The reaction wheel was placed in a vacuum to remove any moisture and air. With the fill port open, the reaction wheel remained in the vacuum for 30 minutes, after which re-pressurization atmosphere of dry Argon/Helium mixture (95% Ar, 5 % He) was introduced to an internal pressure of approximately 13 PSI. A pressure of 3 PSI is needed for more efficient operation. The fill port ball was next installed with a couple of drops of epoxy. The reaction wheel was then placed inside the bell jar with the bottom lip facing upward. The vacuum pump was set to 3 PSI. The vacuum was held until 3 PSI was attained on the internal pressure sensor. The vacuum was then removed and the set screw set in place. After this the unit was verified for proper operation.

5.3.2.1 Testing

Developmental tests were conducted to evaluate the design of the Reaction Wheel under a space environment. The testing parameters were based upon various sources of information. The NASA UELV User's Guide (Section 4) was used to determine the vibration characteristics of the expected payload. Other parameters such as the temperature range, reliability and leakage rate were determined by the Reaction Wheel team members. The radiation test was determined mathematically using the "Space Radiation" software package.

Qualification and Acceptance testing are in progress and follow the guidelines listed in the attitude determination and control subsystem test plan, section 8.0.

5.3.2.2 Milestones

To illustrate the steps and time required to develop the reaction the following milestone chart is included.

MILESTONES	WHO	TARGET	COMPLETED
Radiation Effects	Wise	7/7/95	Yes
Radiation Environment	Durand	7/7/95	Yes
Radiation Sheilding	Chapman	7/7/95	Yes
Connectors	Wise	7/7/95	Yes
Processor Choice	Smith	7/11/95	Yes
Documentation Standards	Smith/Clapp	7/11/95	Yes
Hermetic Can	Smith/Adams	7/18/95	Yes
Supply of Gyros	Wise	7/21/95	Yes
Motor Rewinding	Durand	7/21/95	Yes
Drive Circuit	Smith	7/18/95	Yes
Tach Circuit	Chapman	7/18/95	Yes
Temperature Circuit	Durand	7/18/95	Yes
Pressure Circuit	Wise/Chapman	7/18/95	Yes
Digital Interface	Smith	7/18/95	Yes
Circuit Boards Layout	Wise/Durand	7/26/95	Yes
Circuit Boards Construction	Wise/Durand	8/4/95	Yes
Software	Smith	8/4/95	Yes
Hermetic Can Fabrication	Nelson	8/4/95	Yes
Assembly	Wise/Durand	8/15/95	Yes
Thermal Vac Test	Wise/Durand	9/4/95	Yes
Shake Test	Wise	9/6/95	Yes
Life Test	Wise/Durand	9/7/95	Yes
Controlware	Smith	9/19/95	Yes
Sensors	Chapman	9/19/95	Yes
Create/Update Milestones	Wise/Durand	10/16/95	Yes
Update Contacts	Wise/Durand	10/16/95	Yes
Inventory Parts	Wise/Durand	10/16/95	Yes
Find Out Original Motor Rewind	Wise/Durand	10/16/95	Yes
Update Schematics	Wise/Durand	10/30/95	Yes
Order Parts	Wise/Durand	10/30/95	Yes
Documentation Rough Draft I	Wise/Durand	10/30/95	Yes
Complete Reaction Wheel Design	Wise/Durand	10/30/95	Yes
Pressure Circuit	Wise/Chapman	7/18/95	Yes
Digital Interface	Smith	7/18/95	Yes
Circuit Boards Layout	Wise/Durand	7/26/95	Yes
Circuit Boards Construction	Wise/Durand	8/4/95	Yes
Software	Smith	8/4/95	Yes
Hermetic Can Fabrication	Adams	8/4/95	Yes
Assembly	Wise/Durand	8/15/95	Yes
Thermal Vac Test	Wise/Durand	9/4/95	Yes
Shake Test	Wise	9/6/95	Yes
Life Test	Wise/Durand	9/7/95	Yes
Controlware	Smith	9/19/95	Yes
Sensors	Chapman	9/19/95	Yes
Hermetic Can Mounts	Adams	12/27/95	Yes
Fabrication of Four Cans	Adams/Wise/Durand	12/20/95	Yes
Testing of Four Cans	Wise/Durand	as needed	
Documentation	All	as needed	
Delivery of Complete System	All	as needed	

Reaction Wheel Milestone Chart

5.3.3 Magnetic Coils

As back up actuators, two magnetic coils will be included in the AD&C subsystem. These can also be used to de-spin the space vehicle after launch vehicle tip-off.

5.3.4 GPS Receiver

To determine the attitude of a spacecraft by use of a magnetometer, the geo-magnetic field at the vehicles position must be determined The position of CATSAT will be determined by use of a made-for-space GPS receiver with a backup provision of up-loading ground based orbital elements into the flight computer. After determination of the vehicles position, an appropriate geo-magnetic field model will be referenced.

5.3.5 Three Axis Magnetometer

The three-axis flux-gate magnetometer is being developed by Orchid Industries of Huntsville, Utah. This sensor design uses a new nonlinear magnetic material, and with the addition of proprietary software contained in the magnetometer unit, a resolution of 1.0 degrees with a dynamic range of ±2.0 Gauss can be obtained.

5.3.6 Sun Sensor

An experimental, optical sun sensor is being developed at WSU based on a new Hamamatsu silicon device. The expected resolution is better than 0.1 degrees in two axes.

5.3.7 Horizon Sensors

New manufacturing techniques have created a non-cooled infra-red sensor that is sensitive in the 12 micro-meter band. Two earth-horizon sensors using this technology have been designed. The expected resolution is better than 0.5 degrees.

5.3.8 Control Software

All units of the AD&C subsystem are interfaced to the main flight computer with RS-422 standard serial communication pathways. The flight computer also contains the control algorithm which is based on a state-sampled network. This software has been written and tested using a MATLAB simulation of the spacecraft characteristics.

5.4 The State-Sampled Network

A new type of trainable network technology was developed for this application. Trainable networks are interconnections of individual memory elements that can store information to create overall network characteristics. The "neural network" is the most popular of these trainable networks and has created much excitement in the arena of control engineering. Trainable networks are sometimes presented as almost magical in nature, creating controllers where little mathematical information of the system is known . This creates a difficult situation for the control engineer who desires the versatility of a trainable network but must also guarantee system performance based on mathematical analysis. Issues such as stability, observability, controllability, steady-state error, optimal design criteria, and dynamic characteristics are not well understood when typical networks are utilized for the controller. This is particularly true in the case of neural networks where the input/output relationships are masked behind the complexity of nonlinear functions. This lack of mathematical rigor in the design and analysis of trainable network controllers has generally kept engineers away from using this highly promising method .

The State-Sampled Network is similar to the CMAC network introduced by James Albus in 1975, but uses less memory, trains faster, and provides results based on spectral analysis of the desired control law as a function of state variables. The State-Sampled Network can be trained with supervised learning techniques and on-line adaptive algorithms. Classical mathematical methods such as using quadratic cost functions to define optimality are easily incorporated into the design procedure. The network itself can be shown by classical sampling theory to be of minimal size, requiring only the number of weights needed to match the dynamic response of the control law. Few computational iterations are required for on-line training and normal operation. It is therefore simple enough to be implemented in real time in hardware or software using a less powerful computer.

5.5 Software Simulation

The main purpose of developing the State-Sampled Controller was to create a three-axis attitude controller that would be suitable for a small satellite. Small satellites are defined not only by their small physical size but also by their limited computational power. This is usually incurred by a relatively meager financial base, a micro budget.

The on-board computer for CATSAT and JAWSAT satellites will be an 80186 which does not have the speed necessary to perform satellite ‘house keeping’ and implement control algorithms in real time. Deployment of solar panels and experimental structures along with fuel-mass consumption constitutes a time variation in mass properties, which creates difficulties with using a simple controller. Neural network controllers were considered but rejected for the reasons given earlier. The State-Sampled Controller was originally designed for use by these and similar small-satellite applications.

5.5.1 Design Procedure

The first step in creating a State-Sampled Controller is to define the state variables, their range, and their sampling intervals for the control function. This can be augmented by the knowledge of the underlying dynamic equations. Beyond this, some “trial and error” based on reasonable engineering experience can be utilized.

CATSAT and JAWSAT are designed so that the principal axes of the moments of inertia coincide with the principal axes of the geometry . This allows the use of Euler’s equations for a rigid body in their simpler form without extensive cross terms.

$$M_1 = I_1\dot{\omega}_1 + \omega_2\omega_3(I_3-I_2)$$

$$M_2 = I_2\dot{\omega}_2 + \omega_1\omega_3(I_1-I_3)$$

$$M_3 = I_3\dot{\omega}_3 + \omega_1\omega_2(I_2-I_1)$$

We note that these equations form three coupled nonlinear differential equations. The three state variables of angular rotation about each axis can describe the state of the system.

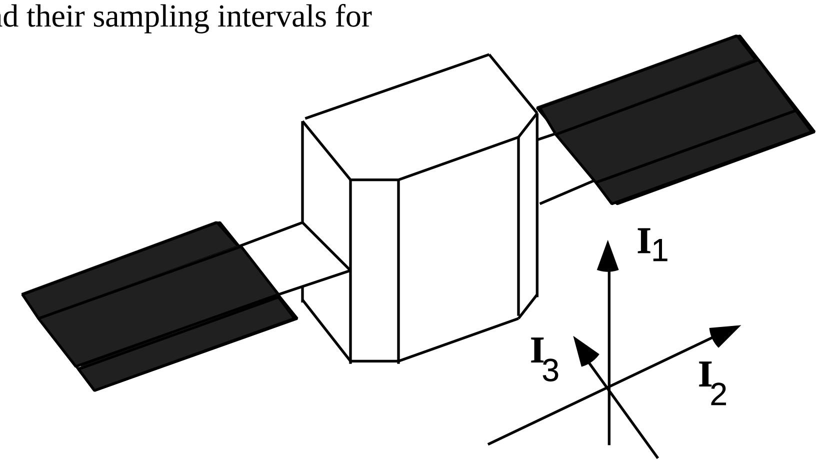

Figure 2 - JAWSAT satellite showing principal axes.

Angular position is the desired controlled variable and can be calculated by simple integration of the velocity with knowledge of initial conditions. Four reaction wheels are mounted in an equal-angular tetrahedron with the axis of each wheel offset 160.5° from the other reaction wheels of the satellite. The three angular position variables, the three angular speed variables, and the four reaction wheel speed variables constitute 10 state variables. A seven-point sampling of a tenth-order state space with four output variables would require a 4 x 710 or 1,129,900,996 weights or control constants. This staggering number of weights is of course too large for the fight computer. The ten-dimensional system can be partitioned into a number of smaller systems by recognizing that the differential equations are only in terms of velocities. Positions about each axis are independent of all state variables except for the velocity about the same axis. There are no cross position-velocity terms. The motor equations and their torque-to-voltage transfer functions are independent of the state variables of the satellite and therefore can also be viewed as independent controllers. As a result we can partition the controller into a 3-input, 4-output position controller, a 3-input, 4-output velocity controller, and four single-input, single output motor controllers. This yields:

$$4x7^3 + 4x7^3 + 4x7^2 = 2940 \text{ weights}.$$

For comparison, a CMAC controller would require:

$$4x256^3 + 4x256^3 + 4x256^2 = 134.5 \times 10^6 \text{ weights}.$$

Hash mapping could reduce the number of needed weights to 1.345×10^6, which is still almost 50 times more than is required by the State-Sampled Controller. A SIMULINK four-block model of the JAWSAT satellite is shown in Figure 3. The controller is partitioned into separate 3-input, 4-output position and velocity controllers as shown in Figure 4. Figure 5 shows the overall structure of the reaction wheel module with the four motors. Each wheel’s dynamics with a classical feedback controller are shown in Figure 6. Figure 7 shows the SIMULINK representation of the satellite dynamics based on the Euler equations.

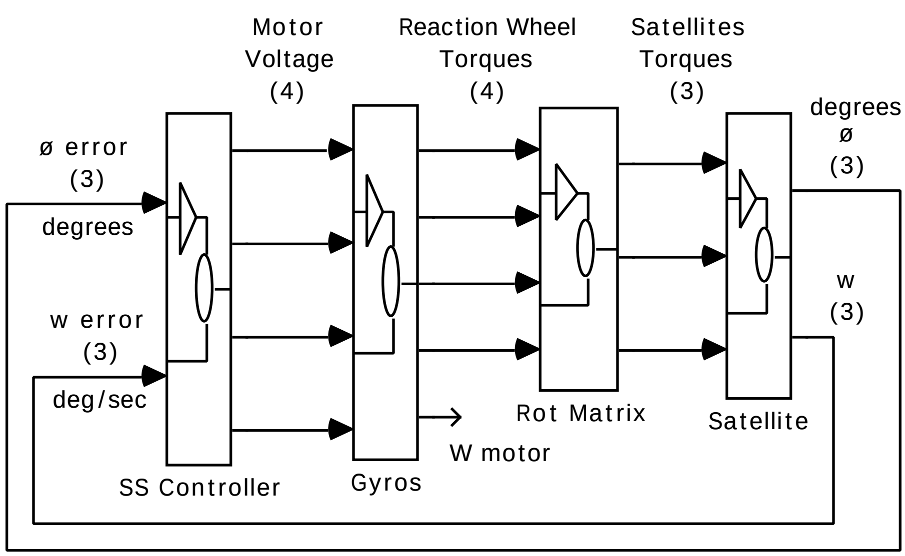

Figure 3 - SIMULINK model of the JAWSAT satellite.

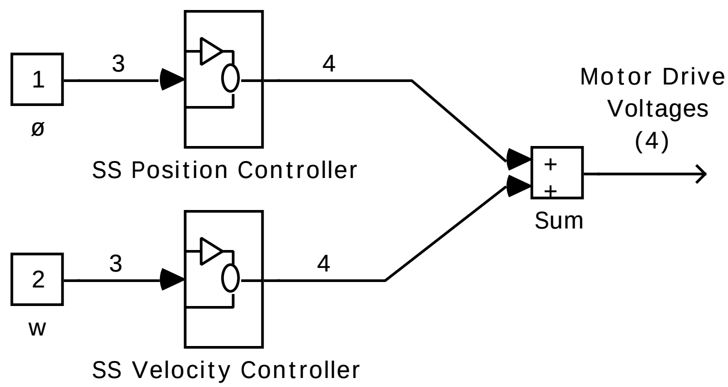

Figure 4 - Partitioning of the controller into position and velocity

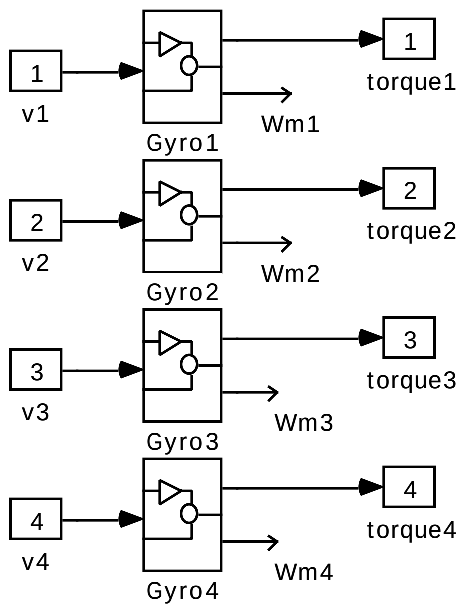

Figure 5 - Reaction wheel module with four motors.

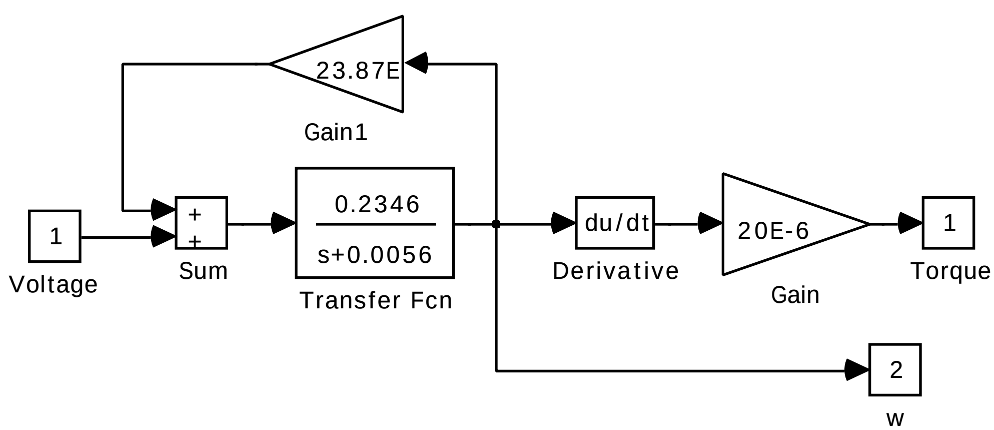

Figure 6 - Reaction wheels and drive circuit dynamic model.

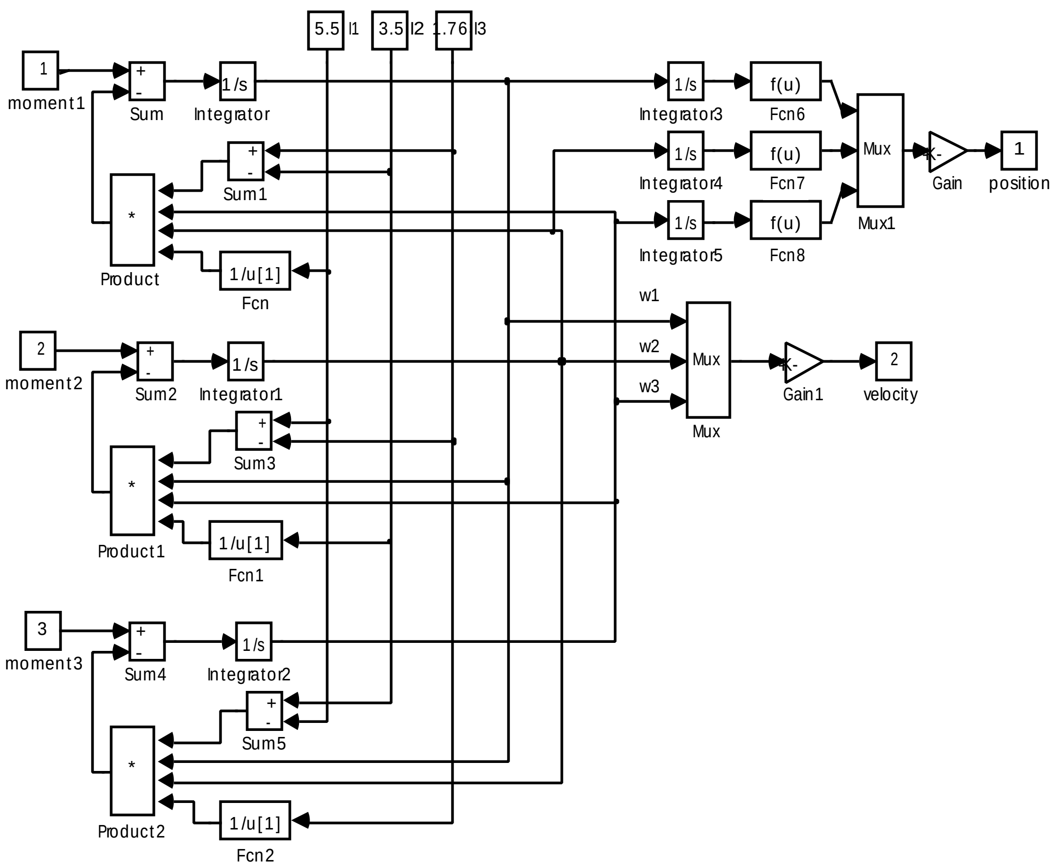

Figure 7 - Satellite dynamics based on Euler's equations.

The reaction wheels are placed in a regular tetrahedron so that the sum of equal torques on all four motors results in a net zero torque on the satellite. This helps ensure equal usage of each wheel during nominal operations. The relationship that maps the motor torque vectors into satellite coordinates is given by the rotation matrix of :

$$\text{Rotational Matrix} = \begin{bmatrix} -1.0000 & 0.3333 & 0.3333 & 0.3333 \\ 0.0000 & 0.9428 & -0.4714 & -0.4710 \\ 0.0000 & 0.0000 & 0.8165 & -0.8165 \end{bmatrix}.$$

The cost function for this controller is made up of several terms:

$$J = øPø' + wQw' + uRu$$

where ø = position error, w = velocity error, and u = reaction wheel drive. The first term is a penalty for error in angular position, ø scaled by matrix P. Next, any angular velocity (w) scaled by matrix Q is penalized. Third, in order to keep any one reaction wheel from saturating in speed, a penalty is placed on the absolute value of each of the four reaction wheel drive signals (u) scaled by matrix R.

5.5.2 Evaluation

The Lagrangian minimization algorithm was applied to train each of the above mentioned controllers. The results of step tests in velocity error are shown in Figure 8. The velocity controller corrects for errors of up to 2 degrees per second within 600 seconds (10 minutes) without exceeding reaction wheel capabilities. Step tests for positional errors are shown in Figure 9. This controller corrects for positional errors within 1200 seconds (20 minutes).

Under unusual circumstances, such as recovering from a partial control failure or power shutdown, the satellite may have a completely random position and rotation. A test of such is shown in Figure 10. After 1200 seconds (20 minutes) the satellite has completely recovered to zero error in rotational velocity and position. It should be noted that the settling time of the system could be modified by changing the weights of the cost function. The optimal criteria for each of the above performance tests was to reach a stable, minimal error state in a 10- to 20-minute time frame without expending any more control energy than needed. Differing control criteria would require a different cost function and would yield results optimized to other parameters.

6. CAST Test Plan

This section sets forth the testing requirements and procedures for the attitude determination and control (AD&C) subsystem which makes up a major functional block of the CATSAT and JAWSAT space vehicles. The intent of this document is to identify sections of the Military Standard Test Requirements for Launch, Upper-Stage, and Space Vehicles, 15 September 1994 (MIL-STD-1540c) which pertain to the development, qualification, and acceptance testing of the AD&C subsystem. Whenever possible, terminology and procedures contained in this document will be parenthetically referenced to the MIL-STD-1540c sections which apply.

6.1 Definitions

The following definitions are used in this documents for consistency with MIL-STD-1540c standard, section 3.1.

<u>Part</u>. A part is a single piece, or two or more joined pieces, which are not normally subject to disassembly without destruction or impairment of the design use. Examples: resistors, integrated circuits, relay, roller bearing.

<u>Subassembly</u>. A subassembly is an item containing two or more parts which is capable of disassembly or part replacement. Examples: printed circuit board with parts installed, gear train.

<u>Unit</u>. A unit is a functional item that is viewed as a complete and separate entity for the purposes of manufacturing, maintenance, or record keeping. Examples: hydraulic actuator, valve, battery, electrical harness, transmitter.

<u>Subsystem</u>. A subsystem is an assembly of functionally related units. It consists of two of more units and may include interconnection items such as cables or tubing, and the supporting structure to which they are mounted. Examples: electrical power, attitude control, telemetry, thermal control, propulsion.

<u>Space Vehicle</u>. A space vehicle is an integrated set of subsystems and units capable of supporting an operational role in space. Example: CATSAT.

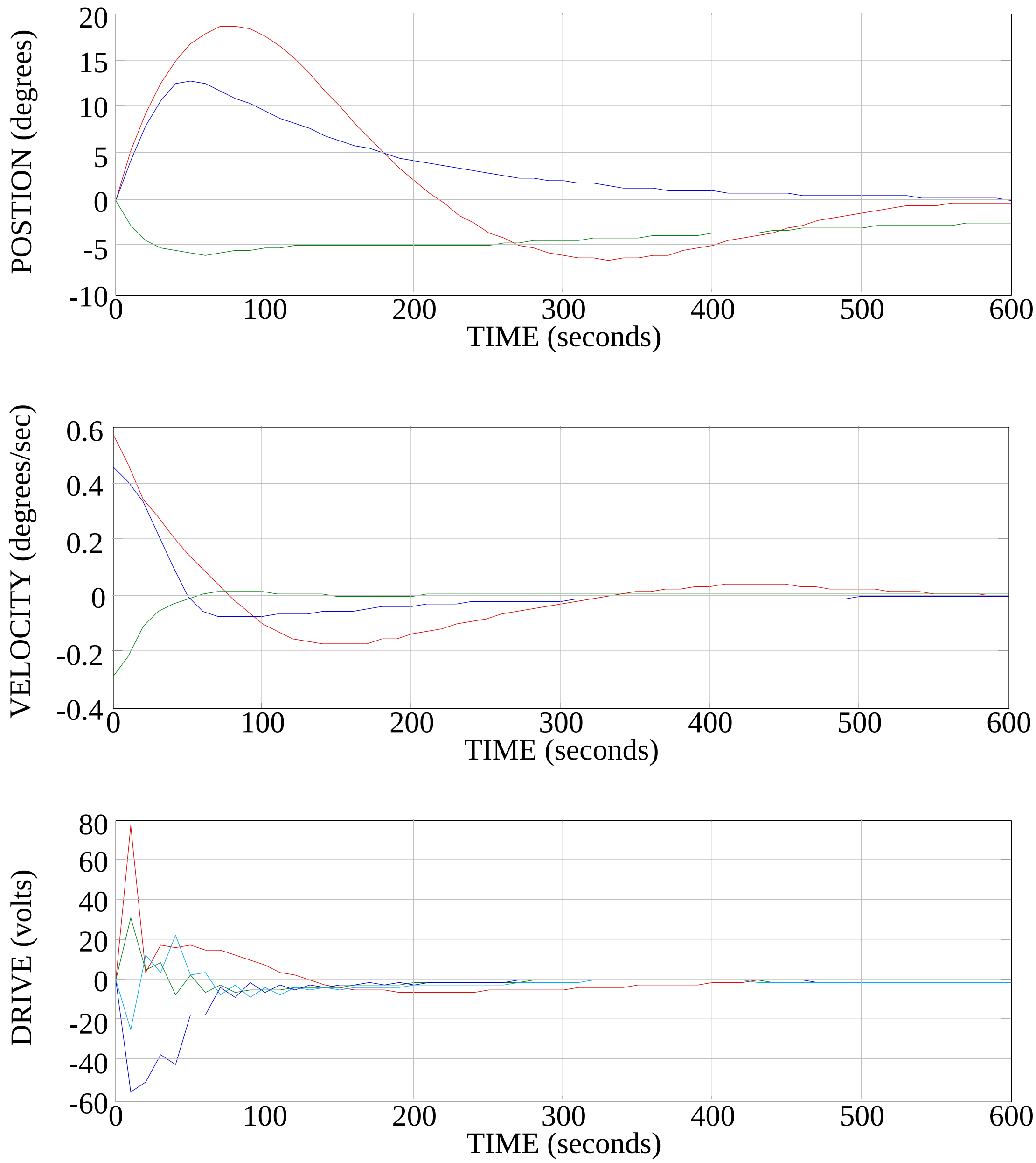

Figure 8 - Step test of velocity error.

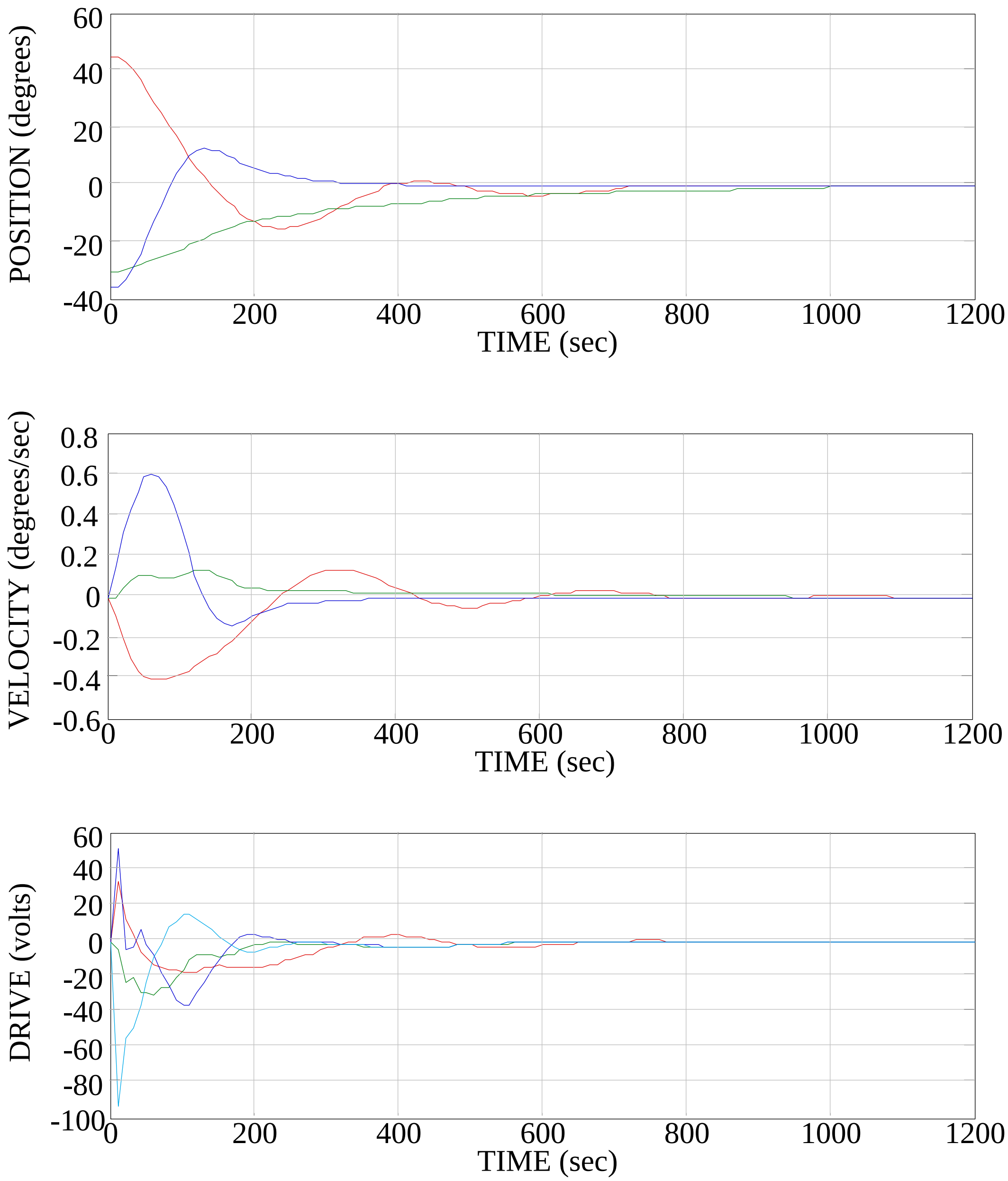

Figure 9 - Step test of position error.

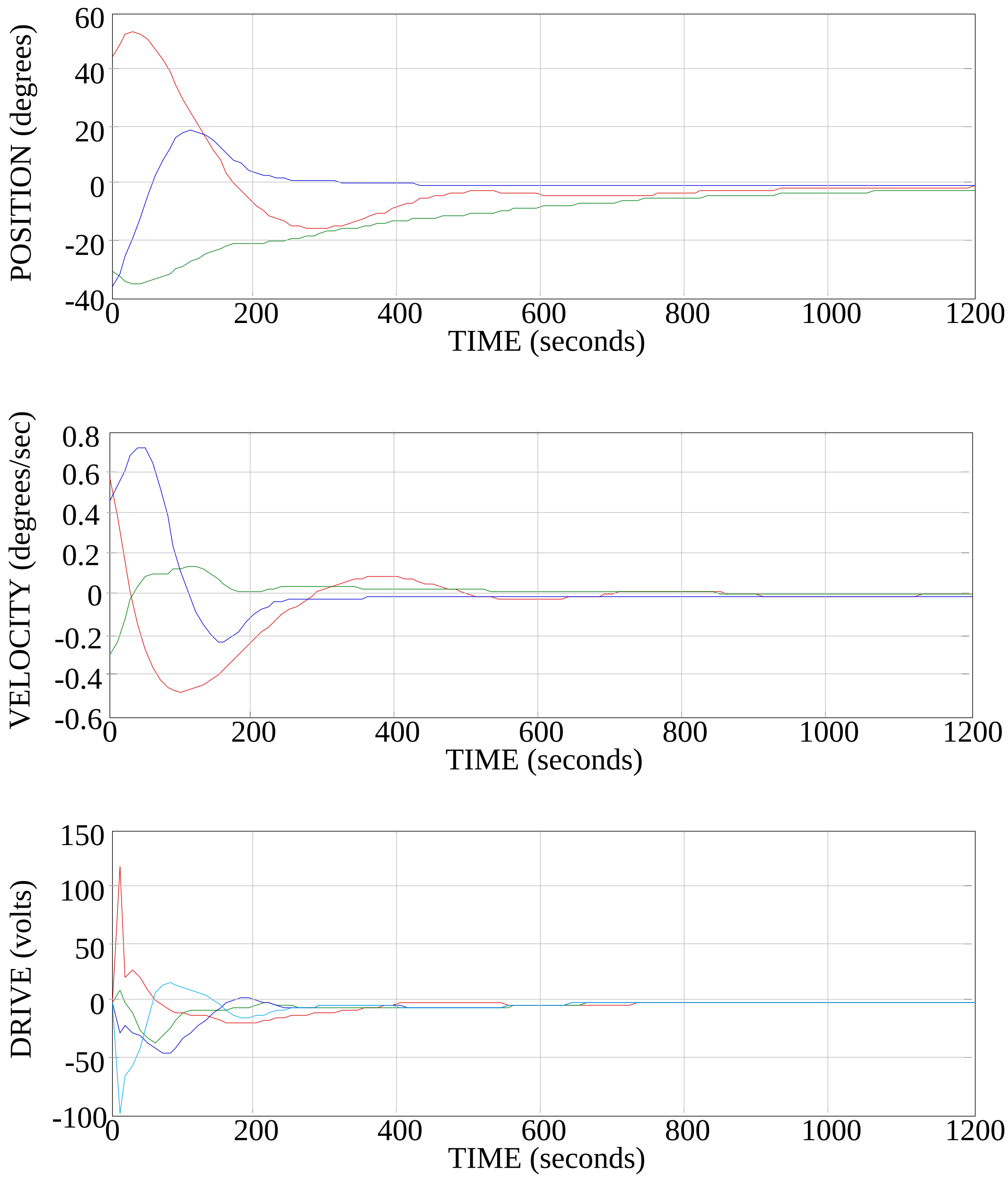

Figure 10 - Step test of random velocity and position errors.

6.2 AD&C Unit Testing

All AD&C units shall be given the same qualification and acceptance tests as described in the following sections.

6.2.1 Development Testing

These informal test procedures are performed during all phases of design and prototype construction. Development tests can be used at the engineer's discretion to validate existing design or identify design flaws which can be corrected before entering the final design phase (3.2.3), (5.1), (5.3), (5.4). Complete records of each development test will be entered into a standard engineering log book which will become part of the design history of the unit. After development, log books and other design documents will become the property of the Center for Aerospace Technology at WSU and will be archived for future reference.

6.2.2 Unit Qualification Test Plan (Section 6.4)

Qualification tests rigorously check randomly selected production units to certify the quality of design and workmanship against unit specifications. The AD&C unit qualification test procedures will require one set of subassemblies in each ten to be randomly selected for qualification testing. The subassemblies selected for qualification testing shall be produced from the same drawings, using the same materials, tooling, manufacturing process, and level of personnel competency as used for flight hardware (6.1.1). Modifications may be made to the selected subassemblies to facilitate testing where theses modifications are deemed necessary by the testing team and approved by the engineering team leader as not to affect the validity of the test as to critical perimeters. Subassemblies, parts and units selected for qualification testing will not be used as flight hardware. Qualification test procedures shall be conducted in the following order:

6.2.2.1 Inspection of Mechanical Parts

All mechanical parts shall be visually inspected by a senior mechanical engineer or trained specialist as to determine the meeting of mechanical tolerances and quality of workmanship. Qualification require all mechanical dimensions to be within the tolerances as defined by the most recently approved production drawing of the part.

6.2.2.2 Inspection of Electrical Subassemblies

All electrical subassemblies, mainly populated circuit boards, will be visually inspected by a senior electrical engineer or trained specialist as to determine the meeting of electrical assembly tolerances and quality of workmanship. Each solder joint will be visually inspected using a microscope to determine quality of workmanship. Qualification requires all part mountings and electrical connections to be of best commercial practice.

6.2.2.3 Inspection of Software

All software algorithms, flow charts and coded programs shall be inspected by a senior software engineer or train specialist. Qualification of software requires all elements and documentation to be of best commercial practice.

6.2.2.4 Functional Tests of Electrical Subassemblies

Functional tests for each electrical subassembly shall verify all operational functions as listed in the subassembly's approved specification sheet. Electrical tests shall include application of all expected operational voltages and signals. When a range of signals is expected, the signals shall be varied throughout their specification range and sequences expected in flight operation. The subassembly output shall be monitored to verify that the subassembly performs to specification requirements (6.4.1).

6.2.2.5 Thermal Cycling of Electrical Subassemblies

As per section 6.4.2 of the MIL-STD-1540c, electrical subassemblies shall be cycled as per Figure 1 page 56, for a total of 78.5 temperature cycles. The mission maximum and minimum temperatures as established by computer aided thermal analysis are 50°c and -10°c respectively. The qualification thermal cycle profile shall therefore have a range of 60°c to -20°c as shown in the following figure. As indicated in the figure, the subassemblies shall be powered nominally during the thermal cycling except for cold and hot restart tests as indicated.

6.2.2.6 Functional Tests of Electrical Subassemblies

Same as 2.2.4.

6.2.2.7 Assembly Inspection

After each subassembly is integrated into the unit assembly, a senior engineer or qualified specialist will visually inspect the assembled unit to identify any assembly errors or deficiencies in workmanship. Qualification requires all mountings and electrical connections to be of best commercial practice.

6.2.2.8 Mechanical Fit Check

The assembled unit shall be visually examined by a senior engineer or qualified specialist. The unit shall be test mounted in the space frame to verify mechanical clearances, electrical connections, and mounting hole alignment.

6.2.2.9 Functional Tests of Assembled Unit

Functional tests for each AD&C unit shall verify all operational functions as listed in the unit's approved specification sheet. (6.4.1)

6.2.2.10 Thermal Vacuum Test

The unit shall be thermal cycled a total of six cycles at a vacuum pressure below 133 millipascals (10^{-3} Torr) following the same temperature profile and function testing as section 2.2.5 (6.4.3).

6.2.2.11 Thermal Vacuum Leak Test

Among the AD&C units, only the reaction wheel has a hermetically sealed enclosure. The small volume and low pressure of this enclosure, precludes pressure vessel testing (3.4.11); however this enclosure shall be leak tested and qualified by pressurizing the enclosure to 3 psia absolute with dry nitrogen and 10% argon or helium content as required by the leak detection method. During thermal vacuum testing, the leak rate of the enclosure shall be measured. Qualification requires a verified leak rate of less than one half the total mass of the enclosed nitrogen mixture during a two year period in an ambient environment of 10^{-3} Torr with temperature cycling as per 2.2.10.

6.2.2.12 Functional Tests

Same as above.

6.2.2.13 Vibration and Shock Test

The unit shall be mounted to a fixture (6.4.4.5) through the normal mounting points of the unit. The same test fixture is to be used in qualification as well as acceptance testing. Attached wire cables shall be included as per the flight configuration. The unit shall be tested in each of 3 orthogonal axes. The sinusoidal, random, and shock spectrum signals shall be consistent with publish qualification requirements for both the Orbital Science Pegasus and Lockheed Launch vehicles. The test shall be conducted as per 6.1.4.2 requiring application of the qualification level spectrum for three minute per axis. (6.4.4.)(6.4.6)

6.2.2.14 Functional Tests of Unit

Same as above.

6.2.2.15 Disassembly and Inspection

The tested unit shall be disassembled and microscopically inspected as to any mechanical damage caused by testing.

6.2.2.16 Life Test

Among the AD&C units, only the reaction wheel has a limited life based on mechanical wear of the rotor bearings. After reassembly and repressurization of the qualification-test reaction wheel unit, an accelerated life test of 1,051,200,000 revolutions (2 years at 1000 rpm) shall be conducted (6.4.10). i.e. 876 hours (36.5 days) at 20,000 rpm. After completing the number of required revolutions, the unit shall be disassembled and the rotor bearings microscopically inspected by a senior mechanical engineer or trained specialist to determine that the bearings have an in-specification minimum operational life of 2 years at 1000 rpm.

6.2.3 Unit Acceptance Test Plan (Section 7)

To insure production standard and consistency of the product and identify any manufacturing defects.

6.2.3.1 Inspection of Mechanical Parts

Same as qualification test procedure.

6.2.3.2 Inspection of Electrical Subassemblies

Same as qualification test procedure.

6.2.3.3 Functional Tests of Electrical Subassemblies

Same as qualification test procedure.

6.2.3.4 Thermal Cycling of Electrical Subassemblies

Same as qualification test procedure except only 25 cycles at a maximum and minimum temperature range of -10°c and 50°c respectively (7.1.1).

6.2.3.5 Functional Tests of Electrical Subassemblies

Same as qualification test procedure.

6.2.3.6 Assembly Inspection

Same as qualification test procedure.

6.2.3.7 Functional Tests of Assembled Unit

Same as qualification test procedure.

6.2.3.8 Thermal Vacuum Test

Same as qualification test procedure except only one temperature cycle.

6.2.3.9 Thermal Vacuum Leak Test

Same as qualification test procedure.

6.2.3.10 Functional Tests

Same as qualification test procedure.

6.2.3.11 Vibration Test

Same as qualification test procedure except only one minute in each axis.

6.2.3.12 Functional Tests of Unit

Same as qualification test procedure.

7. Conclusions

7.1 Center of Excellence Program

CAST was originally proposed to create a focal organization in Northern Utah which could promote the growth of high technology aerospace industries and attract new industries. CAST has been eminently successful in fostering aerospace projects by bringing together students and local industries.

7.2 AD&C Development

With the emergence of new enabling technologies, small satellite will be able to compete for main stream science missions.

The following table represents the schedule for this design effort.

Product	Design	Prototype	Manufacturing Package
Reaction Wheels	done	done	Nov ‘96
Sun Sensor	Aug ‘96	Jan ‘97	June ‘97
Horizon Sensor	Aug ‘96	Jan ‘97	June ‘97
Magnetometer	Aug ‘96	Jan ‘97	June ‘97