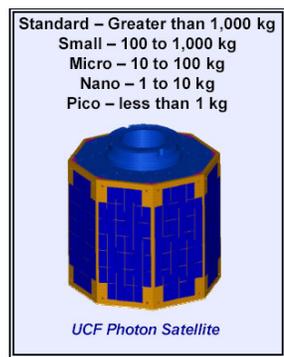# An Approach To Automated Health Monitoring & Control For Space Systems

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**ABSTRACT:** Modern satellites require a great degree of human attention to insure functionality. In this paper we discuss UCF's micro-satellite program aimed at designing automated satellite control systems with fault recovery and health monitoring capabilities designed to ease the operation of satellites. Three major topics are discussed: the organization of UCF's micro-satellite effort, work on health monitoring & autonomous control and finally work conducted on a satellite simulator.

## INTRODUCTION

UCF is currently developing a micro-satellite program. Figure 1 shows one of UCF satellite designs along with definitions of satellite classes. The UCF program is focused on designing and building inexpensive satellites capable of carrying a variety of different payloads.



Standard – Greater than 1,000 kg
Small – 100 to 1,000 kg
Micro – 10 to 100 kg
Nano – 1 to 10 kg
Pico – less than 1 kg

*UCF Photon Satellite*

**Figure 1**

It is also a goal to use these satellites to develop an on-board control system, which can autonomously control a satellite platform independent of a ground station. This project involves both graduate and undergraduate students working on different satellite systems. Work on the satellite is offered through thesis topics and an interdisciplinary senior design class for undergraduates.

Automated control systems are of particular interest to UCF's since when paired with an automated ground station management of groups of small satellites is possible with minimal human intervention. In addition to easing the management of large numbers of satellites there are also advantages in terms of reliability. By placing intelligence onboard the satellite the system retains the ability to react to unexpected failures and anomalies while not in contact with a ground station. This ability could easily be a mission saving feature for low earth orbit satellites that are not in contact with ground stations for a significant portion of their orbit. The micro satellite currently under development by UCF, for example, with an altitude of 350 km is only expected to provide 3-4 useful passes over it's ground station per 24-hour period. If an error was to occur onboard the satellite it could easily be several hours before the ground station gets notified and several more hours before corrective actions could be sent to the satellite. This delay may cause the satellite to be unrecoverable. For example, consider the case in which a satellite with directional solar panels is not correctly orienting itself with the sun due to a momentum wheel failure and is running on battery power alone. Clearly, this situation calls for immediate corrective action to insure that the system remains powered; otherwise the system may stop responding and contribute to the collection of space "junk" in orbit. Larger, more expensive sat-

ellites can afford to carry extensive power reserves and redundant equipment while smaller satellites cannot usually afford the added space and weight.

There are several key technologies needed to construct an autonomous satellite; a list of these items follows: The first of the components essential to create a truly automated satellite is the ability to sense and adapt to the environment. Health monitoring provides this capability in addition to providing information regarding the status of the satellite. Health monitoring also attempts to correct for measurement errors and anomalies in the data it provides though the use of filters and other intelligent algorithms. Health monitoring systems should also be able to identify corrective actions for recoverable failure conditions and pass these actions to the control system. Thus, health monitoring is a key piece in an intelligent control system, which allows a satellite to essentially take care of itself when failures occur. In order to implement an effective health monitoring system a filtering system is required to insure quality data is fed into the control system. Kalman filtering can provide extremely high quality filtering to data and therefore is a critical component in an automated satellite control system.

Finally, the control system must be built and tested extensively; this requires a simulation environment to rapidly test and validate new algorithms or configurations of the system. Several commercial software simulators are currently available for predicting satellite paths and designing control systems such as STK. However, none of these software options address all of the needs of this micro-satellite program. Therefore, to assist the development of the micro-satellite and ground station programs, a custom-built interactive, graphical simulator is currently being constructed at UCF.

## ORGANIZATION OF EFFORT

The micro satellite program involves several other closely related projects such as the ground station program and the sounding rocket programs at UCF. As part of UCF micro-satellite program a course is offered which allows interested students to work on satellite subsystems to meet their sen-

ior design requirements. The overall goal of the interdisciplinary course is to create an environment, in which Senior Design Students can work as an engineering team to enhance their comprehension in learning the design process for the design of a moderately complicated system of four to six subsystems. This kind of a project will require skills on each subsystem team as well as coping with multiple interfaces between each to insure a successful integrated outcome. The move from Senior Design as it is practiced today from the vantage point of each department, requires a change to an interdisciplinary allocation of student resources (across departments) to each team depending on the skills needed to design that subsystem. Laboratory support from engineering departments are shown in the Figure 2.
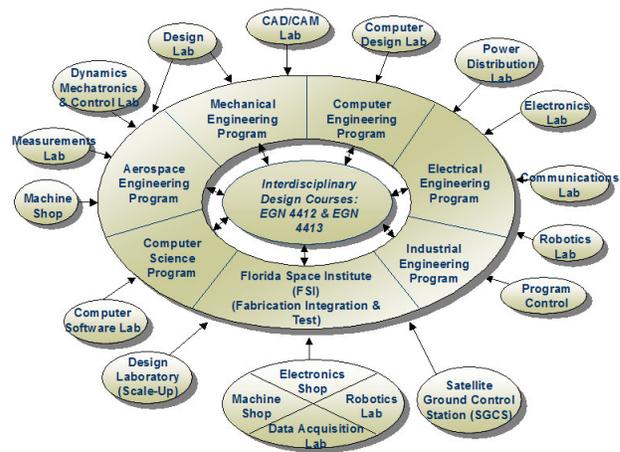


**Figure 2 – Departmental Support**

## AUTONOMOUS HEALTH MONITORING

Current spacecraft health monitoring capabilities cannot measure the dynamic behavior of a spacecraft system in real-time. Abnormal dynamic parameters are indicators of an out-of-tolerance performance of the system leading to impending failures in those systems. The proposed feature adds a new dimension to existing control mechanizations that will greatly enhance the visibility of the "system state" which, in turn, increases the reliability of the test and evaluation process and autonomous operations over those currently in use. This processing technique also promises the real-time detection of abnormal data flow conditions and the

automatic identification of the specific area (component/subsystem) causing the fault condition. This attribute speeds up diagnostic analysis to near real-time and provide enough time to stabilize the system by reconfiguration and parameter correction. Requirements for a new set of projects/systems calling for "autonomous" operations for long unattended periods of time are emerging. Hence, this approach is potentially a reality. The sensor measurements and actuator elements must now be analyzed to understand how the increased "reliability" and "parameter correction" requirements can be implemented into the systems to support autonomous operations.

The high fidelity, model of the non-linear system with the model of the actuator dynamics is incorporated in the simulation block diagram Figure 3. Mathematically the non-linear dynamics are given by the following differential equations:

$$\dot{x} = f(x,t) + B(x,t)[\Delta f(x,v_x,t) + z]$$
$$\text{and } \dot{z} = g(z,t) + \Delta g(z,v_z,t) + u \qquad (1)$$

where x(t) is the state of the system and z(t) is the state of the actuator and u(t) is the control to be designed and v(t) denotes the vector of unknowns/uncertainties, f(x,t), g(z,t) and B(x,t) are known parts of the system dynamics and $\Delta f(x,v_x,t)$ and $\Delta g(z,v_z,t)$ are uncertainties in the system dynamics and actuator dynamics respectively. Due to the presence of unknowns/uncertainties, a successful control must be robust. For the purpose of designing a fault tolerant control, potential failures of the actuators are considered. To this end, we are going to measure the output of the actuator and detect any failures in the actuators. If any failure is detected, the robust control should shift to the redundant actuator and recover the failed actuator (if possible) [12].
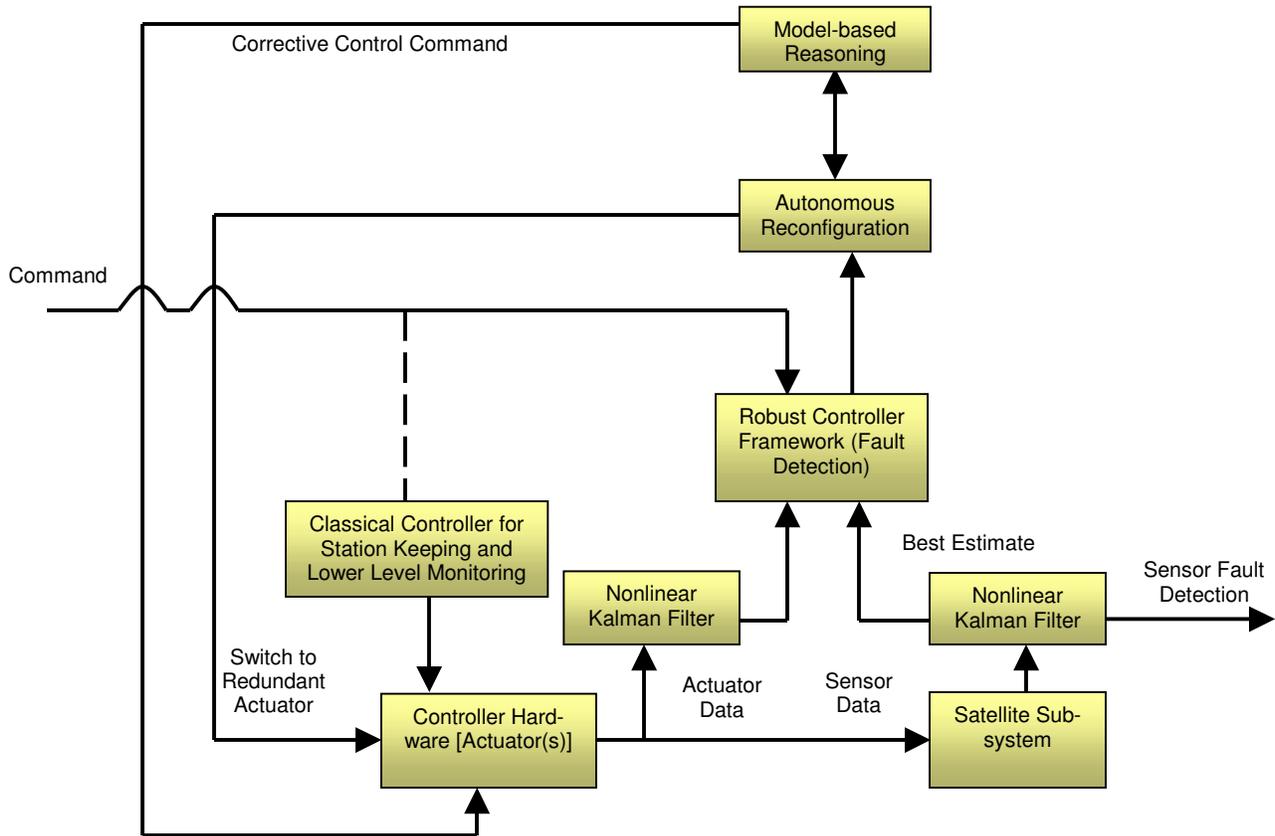


**Figure 3 – System Description**

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## FAULT DETECTION

The non-linear subsystem considered in this paper can be mathematically given by the following differential equations:

$$\dot{x} = f(x,t) + B(x,t)z \quad and$$
$$\dot{z} = g(z,t) + u \tag{2}$$

Fault diagnosis and fault tolerant control have been studied primarily on linear systems, but in the non-linear systems, the fault tolerant control is much more complicated and the presence of uncertainties in the systems makes the diagnosis more difficult. To overcome these difficulties, we derive the robust fault-detection measures to design robust control strategies using the Lyapunov direct method. When an actuator failure is detected, a Kalman Filter is used to compute the best estimate of the state. The Kalman Filter, in essence, is monitoring the redundant sensors and statistically setting the optimal gain based on the weighted average of the covariance matrix. For example, to illustrate the fault tolerance robust control, the following dynamics of the satellite along with the actuator dynamics (a rate gyro) is considered:

$$\dot{\theta}_1 = \{(\frac{1}{I_y})[-3\omega_0^2(I_x - I_z)\sin\theta_1]\} - 6\theta_1 - 10\theta_2 \quad ; \quad \dot{\theta}_2 = -0.1\theta_2$$

$$\dot{\phi}_1 = \{(\frac{1}{I_x})[-4\omega_0^2(I_y - I_z)\sin\phi_1]\} - 6\phi_1 - 10\phi_2 + \frac{I_z}{I_x}\omega_0\psi_2 \quad ; \quad \dot{\phi}_2 = -0.5\phi_2$$

$$\dot{\psi}_1 = \{(\frac{1}{I_z})[-\omega_0^2(I_y - I_z)\sin\psi_1]\} - 6\psi_1 - 10\psi_2 + \omega_0\phi_2 \quad ; \quad \dot{\psi}_2 = -0.1\psi_2$$

In the cases we have considered, the output of the faulty actuator jumps from its current value to its maximum value and stays there indicating the worst type of fault for stability. The uncertain dynamics are chosen to be:

$$\Delta f(x,v_x,t) = 0.04 \sin(\theta_1) + 0.03 \sin(2\theta_1)$$
$$\Delta g(z,v_z,t) = 0.0045 \theta_2 + 0.01 \cos(\theta_2) + 0.1 \sin(2\pi t)$$

Lyapunov functions are:
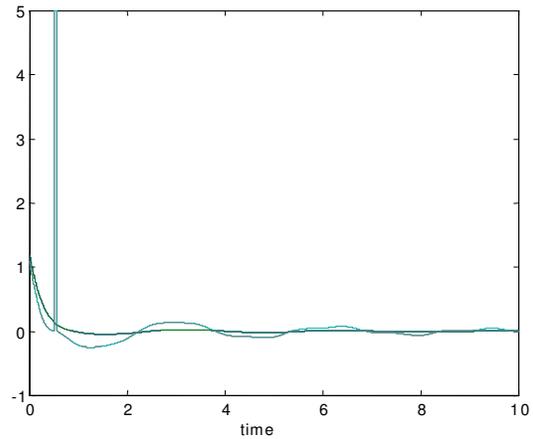$$V(\theta_1,t) = 0.5 [\theta_1 + \phi_1 + \psi_1]$$
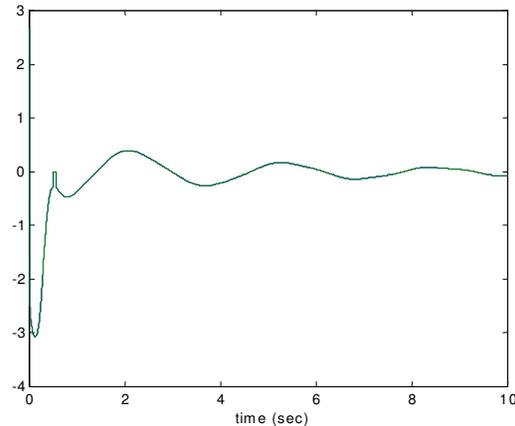$$L(\theta_2,t) = 0.5 [\theta_2 + \phi_2 + \psi_2]$$

Figures 4 through 6 show the results of a simulation of the pitch axis actuator.
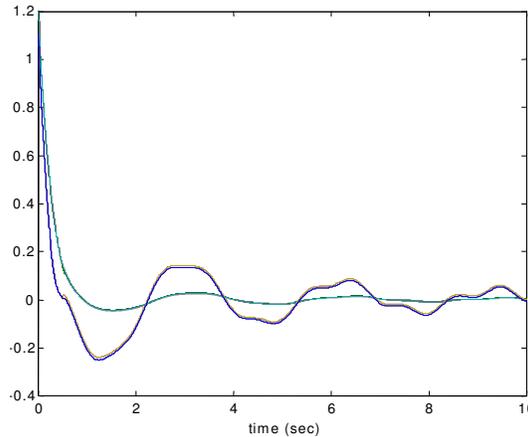


**Figure 4 - The state and estimated (x-solid,x-estim-dashed,z-dot,z-estim-dashed dot)**



**Figure 5 - Actuator Signal**



**Figure 6 - Control**

There is an actuator failure and depending upon the sequence of the failure, the proposed robust control law is energized. Thresholds can be

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placed on uncertainties to automatically detect whether actuator failures have been detected and/or corrected which in turn makes it possible for the fault tolerant control to restore its operation and ensure system performance. Figure 4 shows the actual states of the system and also of the actuator and the estimated states of the system as well as the actuator. Figure 5 is another plot that shows the fault detected in the actuator at 0.5 sec and the recovery made at 0.55 second. Finally Figure 6 shows the robust control acting at 0.5 second as soon as the actuator 1 fails and recovers it at 0.55 second. During that brief period of 0.05 second, the robust control shifts to actuator 2 from actuator 1 so that the overall system is still stable. In this simulation, all the actuators (roll, pitch and yaw) are designed to fail at the same time. The robust fault tolerant controller is applied to all the actuators at the same time and the reconfiguration to the redundant actuators occurs at 0.55 seconds on all the three axes.

## SIMULATOR EFFORT

As stated above, there are several goals in building a simulator for the satellite. The simulator is primarily an experimentation and learning tool. This aspect is particularly important at UCF since its micro-satellite involves several new students each year, many of which are unfamiliar with satellites.

The satellite simulator design is divided into four major pieces, the physics engine, the satellite control engine, the graphical rendering engine, and the user interface.

The physics engine of the simulator is based on a Newtonian physics model with the position of the satellite stored as an 3 element vector, a quaternion representing the satellite's orientation, and three variables representing the satellites pitch, yaw, and roll rates. For each time step in the simulation the satellite computes a net force vector based on gravity and any other perturbations included and changes its velocity accordingly. A satellite can be created by providing a position and velocity in inertial Cartesian coordinates. It is also possible to specify an orbit in Kepler parameters such as altitude, inclination, etc…
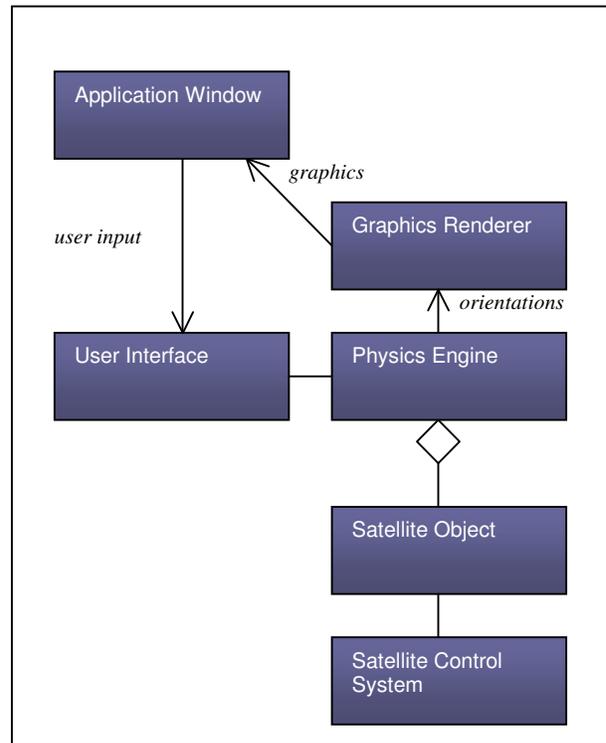


**Figure 7 - Satellite Simulator Class Diagram**

The graphical component of the simulator is the most visible to the user; it provides two views of the satellite, one up-close view showing the body axis and one view from a considerable distance away showing the complete earth and the satellite's orbit path around the earth. Graphical elements are implemented through OpenGL, an industry standard software interface with hardware acceleration on most platforms. This approach has the advantage of providing excellent performance and is portable.

The user interface is also a very visible aspect of the simulator to the user. The critical design element for the user interface is friendliness to the user. To achieve this requirement feedback to user from the simulator is provided both in graphical and raw data formats to the user. User interaction with the simulation is accomplished through a custom designed user interface. The interface contains a variety of controls and automated control techniques for the satellite with familiar "windows-like" widgets.

It is also important to be able to add new functionally to the simulator for later experiments, there-

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fore the satellite will be designed in a modular format with control modules.

It is planned in the near future to implement a system in which the user can design new control modules for the simulator. The simulator which also implement algorithms which keep track of how much memory and computing time is required to implement a given control technique; this will assist with hardware selection and planning.
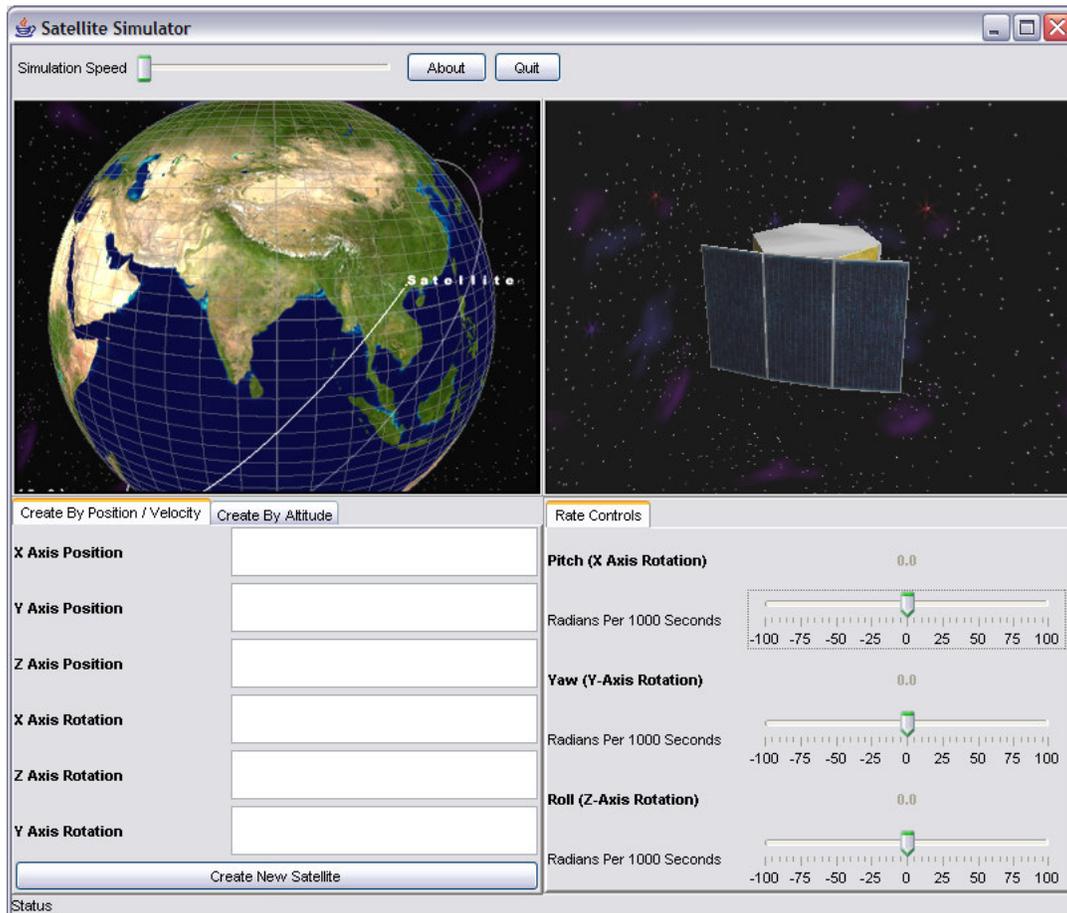


**Figure 8 – Simulator User Window**

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