# Model-Based Design of a Satellite with Orthogonal Spinning Sensors

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**Model-Based Design of a Satellite with Orthogonal Spinning Sensors**


by

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Professor Claire Tomlin
Professor David Auslander

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## Abstract

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Simulation models of mechanical systems are typically difficult to construct due to the presence of constraints and non-linearity. A systematic tool suite has been developed to integrate simulation into the mechanical design cycle using Autodesk Inventor, Modelica, and LabVIEW. To validate the tool suite, we present a case study for the design of a satellite with unique dynamics.

The design process begins with a detailed 3D solid model of the satellite which encapsulates the kinematics and mass properties of the system. Then, dynamical models are developed to simulate the behavior of the satellite under various control strategies. Once the simulations provide satisfactory results, the satellite is manufactured and tested against the models using the same control algorithms.

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# Acknowledgments

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I would also like to acknowledge Space Sciences Lab (Forrest Mozer, David Pankow, John Bonnell, John Sample) for their novel satellite concept (Grotifer/Eggbeater), encouragement, and feedback. I hope to see the satellite launched in the future.

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# Chapter 1

# Introduction

## 1.1 Overview

Current mechanical systems are becoming more complex and often require integration of technology from multiple disciplines with a blend of mechanics, electronics, and computer software. These cyber-physical systems (CPS) are used in robotics, autonomous vehicles, manufacturing, and more. Traditional design approaches are unable to handle the full complexity of current systems [1]. The thesis investigates challenges in designing, modeling, and controlling mechanical components in cyber-physical systems.

This thesis applies model-based design techniques to the development of a satellite with unique dynamics [2, 3, 4]. Model-based design approaches allow engineers to test and optimize control strategies at early stages of development without physical hardware using system-level simulation. The models provide a holistic view of a system and can be used to drive the design of the system with continuous verification and validation.

There is a lack of documented examples of model-based design applied to real engineering systems. The thesis describes each step of the design process for a satellite with unique dynamics. First, we create a 3D model of the proposed satellite that encapsulates the kinematics of the system. Then, we develop a dynamical model of the system from the constraints encapsulated in the 3D model. Finally, we manufacture the satellite and validate the dynamical model using lab experiments, comparing the operation of the mechanical components in real time with their behavior in simulation.

### Model-Based Design Methodology

In traditional engineering workflows, engineers typically cannot test and validate control systems until late in the development cycle when the mechanical system is finalized. Fixes for unexpected bugs that are discovered during system integration often require costly, dif-

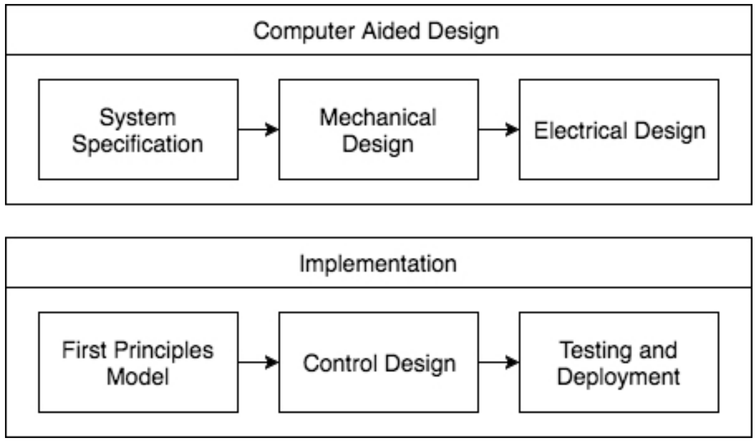


Figure 1.1: Model-Based Engineering Workflow

ficult, and time-consuming changes to the mechanical system.

To solve this problem, model-based design substitutes the real system with a mathematical model and uses simulation to design and virtually test every part of the system [5]. This method of design provides an opportunity for rapid prototyping and continuous verification processes via offline and real-time simulation.

In a typical model-based design framework, mechanical and electrical designs of the system are developed from system specifications and are separated from control system design. Control system design is developed from first principles mathematical models, while testing and validation is done using simulation of the controller on the first principles model. This is expressed in Figure 1.1.

## 1.2 Integrated Tool Suite Workflow

The Integrated Tool Suite was developed by Autodesk, National Instruments, and UC Berkeley and builds on model-based design methodologies, where simulation is used to define system parameters and develop control algorithms with less experimental work and physical manufacturing. In particular, the Integrated Tool Suite bridges CAD solid modeling and control system design software tools using a multi-domain modeling language, Modelica [6].

The advantage of the Integrated Tool Suite over typical model-based design approaches is that models are developed from mechanical and electrical designs rather than from first principles. Also, engineers can use simulation to iterate on system specifications, mechanical designs, and electrical designs. New designs can be simulated without the need for hardware. This workflow is expressed in Figure 1.2.

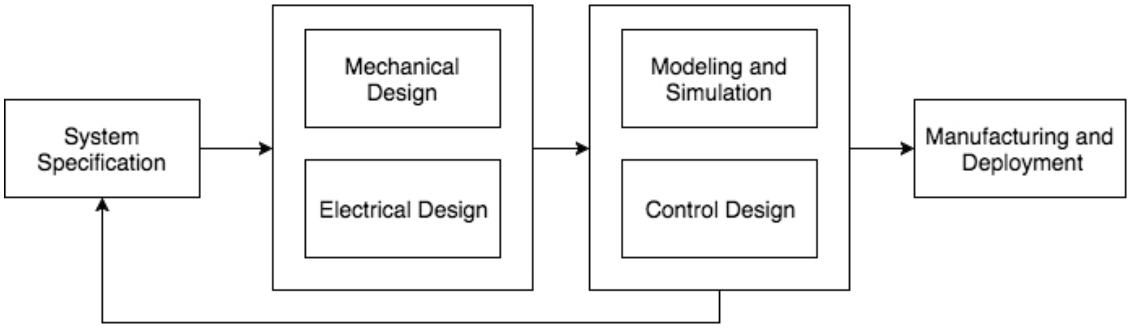


Figure 1.2: Integrated Tool Suite Engineering Workflow

Figure 1.3: Integrated Tool Suite Software Environments

### Software Tools

In this paper, we will be using Autodesk Inventor for 3D solid modeling, open source implementations of Modelica (JModelica [7] and OpenModelica [8]) for modeling mechanical systems, and National Instruments LabVIEW and RIO platforms for control and simulation.

The majority of CAD tools and simulation tools can be adapted into the workflow as it provides a framework that is not tool-dependent and an opportunity for software companies to release fully integrated solutions for consumers.

## 1.3 Application to the Design of a Unique Satellite

Extensive simulation and real-world testing are needed to show the feasibility of a new satellite design prior to manufacturing and deployment [9]. The proposed satellite is an example of a high-value mechanical system that would benefit from simulation prior to manufacturing and deployment. The Integrated Tool Suite provides a systematic approach to design and ultimately allows us to trace desired specifications to the model.

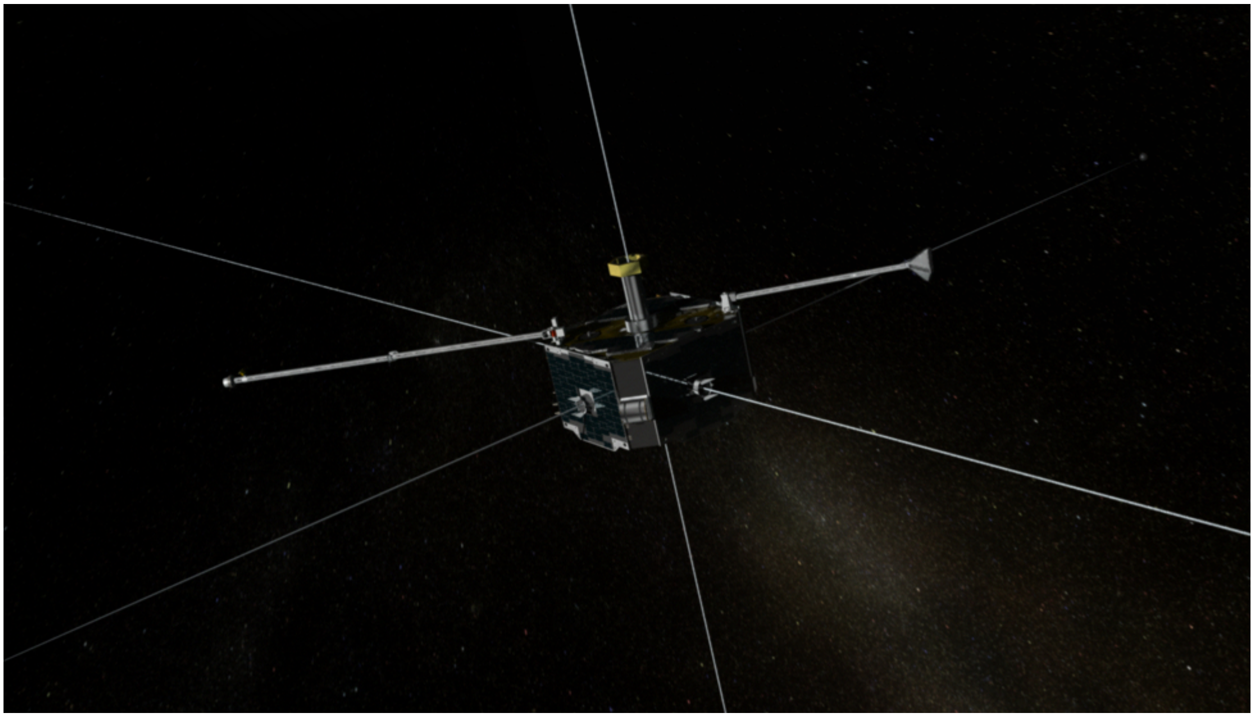

Figure 1.4: THEMIS Spacecraft Fully Deployed (Source: NASA/Goddard Space Flight Center, Conceptual Image Lab)

### Existing Measurement Satellites

Currently, several measurement spacecrafts navigate the Earth's upper atmosphere for space plasma physics research. Plasma is one of the four fundamental states of matter and consists of electrically charged particles with strong electrostatic and electromagnetic interactions. The inhomogeneous spacial scale of plasma in the terrestrial magnetosphere has pushed the need for more complete and high-quality field and plasma measurements.

Existing satellites such as the THEMIS probe and the Cluster II are spin-stabilized and release long wire measurements probes along the spin plane and shorter wire measurement probes along the spin axis for a complete measurement of the electric and magnetic field [10]. This design suffers from inaccurate measurements along the spin axis. To resolve this, identical measurement satellites are often placed nearby in different orientations, but this creates additional interference from spacecraft obstacles and near-spacecraft electric fields.

### Satellite with Orthogonal Spinning Sensors

To further improve the accuracy of field measurements, we investigate a design for a spacecraft configuration with spinning probes on two orthogonal planes [11, 12]. The design

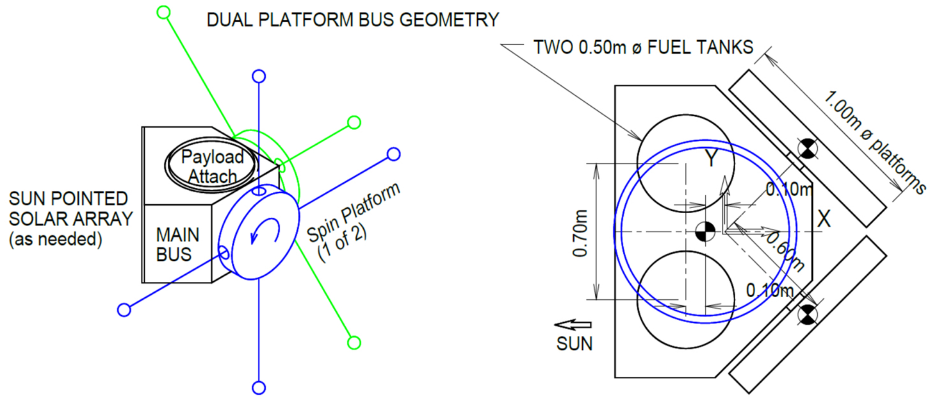


Figure 1.5: Satellite with Orthogonal Spinning Sensors Wire-Frame Concept Drawing [12]

provides a novel approach to instantaneously obtain measurements of the three-component electric and magnetic fields and the full distribution function of the plasma.

The satellite consists of two main semi-independent systems: a traditional attitude control system and a coordinated sensor system. The attitude control system stabilizes and adjusts the satellite's angular position after deployment. The coordinated sensor system ensures that the orthogonal spinning sensors rotate with the right speed and do not collide.

The original design provided a preliminary breakdown of the hardware specifications necessary for a viable mission using examples from past missions and early simulation results; however, the satellite designed in this paper is not meant for scientific missions. Instead, the physical prototype will help validate control algorithms and simulation models prior to launching. Dynamical models which accurately predict the behavior of a proto-flight vehicle may assist in predicting the behavior of an actual satellite.

## Integrated Tool Suite Workflow

The process begins with a detailed 3D model of the satellite which encapsulates the kinematics and mass properties of the system. Then, dynamical models are developed to simulate the behavior of the satellite under various control strategies. Once the simulations provide satisfactory results, the satellite is manufactured and tested against the models using the same control algorithms to verify the accuracy of the models.

## 1.4 Contributions

This thesis applies an model-based design approach to prototype a satellite with unique dynamics and provides the following contributions. First, the thesis provides an example of a real-world application of an integrated tool suite between CAD and control system design. Second, it provides evidence that the satellite concept is feasible and should be launched. Third, it presents an opportunity to investigate more complex design and simulation processes for satellite development.

### Integrated Tool Suite Test Case

The first contribution of the thesis is highlighting the effectiveness of an Integrated Tool Suite, which bridges the gap between 3D modeling and control system design. It provides an explicit example of a real engineering system and uses multiple software tools and interfaces in the design process.

### Feasibility of Satellite Concept

The second contribution of the thesis is to demonstrate the feasibility of a satellite with orthogonal spinning sensors. The models and proto-flight vehicle show the control of the vehicle with the presence of orthogonal spinning booms. Although our work provides evidence of a working attitude determination and control system, there are still many design challenges ahead before the satellite can be flown.

### Satellite Simulation and Future Development

The third contribution of the thesis is towards the development of more sophisticated satellite systems. The majority of satellites are built using off-the-shelf components with limited dynamics. Model-based development may enable satellites with customized components for a wider range of dynamics while still adhering to rigorous system specifications.

## 1.5 Organization

The remainder of the thesis is organized as follows. Chapter 2-3 investigate the dynamics and mechanical design of the satellite. Chapter 4-6 describe dynamic modeling and control system design within simulated environments for rapid prototyping. Chapter 7 presents the manufactured proto-flight vehicle and results of several experiments.

# Chapter 2

# Satellite Dynamics

## 2.1 Overview

In this chapter, we briefly describe how satellites operate and the purpose of an attitude determination and control system. Then, we derive a simplified dynamical model of the satellite to gain intuition about models used in later chapters.

## 2.2 Launch and Operational Environment

Satellites are objects which have been placed into orbit - most commonly around Earth. Placing a satellite in orbit requires a launch vehicle such as a rocket, and the specific orbit may depend on the satellite's application. Once the launch vehicle reaches a target altitude, the satellite is ejected away and tumbles out in space. From then on, it is the satellite's responsibility to generate and maintain power, maneuver itself in orbit, and communicate with ground stations.

While in orbit, satellites experience microgravity and can freely rotate without restoring forces. We will describe the satellite's flight dynamics and analyze its six degrees of freedom in a three-dimensional space [13, 14]. Specifically, we will model the satellite as a rigid body which can translate in and rotate about three orthogonal axes. In the thesis, we implement a control system to manipulate the satellite's orientation or angular position.

## 2.3 Attitude Determination and Control System

An attitude determination and control system (ADCS) is a specific subsystem of a spacecraft that is responsible for controlling the orientation of a satellite [15]. Without this subsystem, the satellite would continue to tumble in space after deployed. Often, an attitude control system is required for the satellite to accomplish its mission. For example, satel-

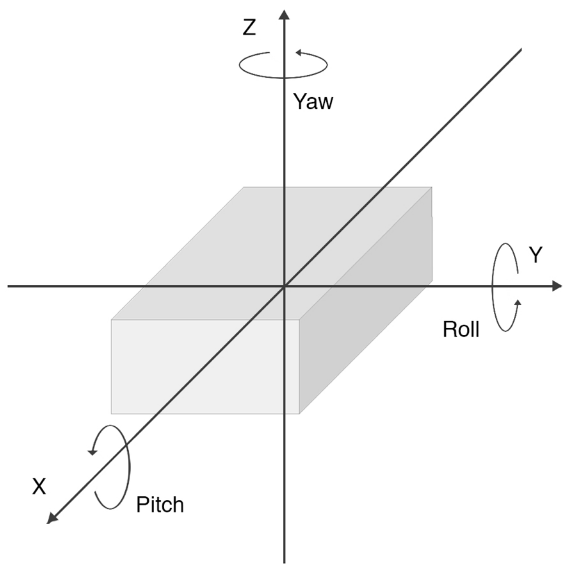


Figure 2.1: Satellite Coordinate System: Axes and Euler Angles

lites may require sensors pointed in a certain direction for optimal sensing, power generation, and/or communication bandwidth.

There are three main components of an attitude determination and control system. The first is a sensor system which measures the orientation of the spacecraft. The second is an actuation system which is able to exert torques to change the orientation of the spacecraft. The third is the controller which manipulates the orientation of the system to track a trajectory or stabilize against external disturbances using the measurements and actuators.

## Measuring Attitude

To accurately stabilize and adjust its angular position, the satellite must measure its rotation with respect to pre-defined non-rotated positions [16]. Traditionally, satellites use a combination of sun sensors, horizon sensors, star trackers, and/or inertial measurement units (IMUs) to estimate their angular position.

The prototype will use an IMU with accelerometers, gyroscopes, and magnetometers. Accelerometers measure linear acceleration and can provide a rough estimate of pitch and roll. Gyroscopes measure angular velocities about three axes. The estimates are used as first-order derivatives of the orientation estimate. Magnetometers measure the Earth's magnetic field and compare the measurements to an International Geomagnetic Reference Field (IGRF) [17].

Each sensor provides a rough estimate of the true orientation. Sensor fusion algorithms are

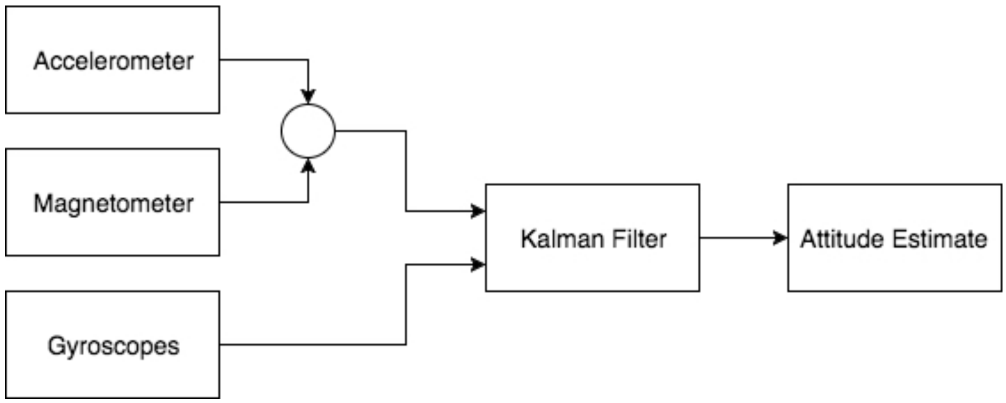


Figure 2.2: IMU Sensor Fusion Block Diagram

needed to provide higher accuracy estimates and minimize specific errors from individual sensors. Extended Kalman filters (EKF) are often used in IMUs to provide more precise attitude estimation [18].

## Controlling Attitude

Manipulating the satellite's angular position requires actuators that can torque the vehicle about specific axes. In large satellites, attitude control is accomplished with propulsion, control moment gyros (CMGs), and large reaction wheel sets. Smaller satellites do not have the appropriate volume for such systems and depend on actuators that are small enough to fit within the vehicle. Common actuators for small satellites include momentum wheels and magnetic torquers (torque rods) because they do not require expendable propellant [19]. Instead, they are often powered by battery packs, which are charged using solar arrays.

Momentum wheels come in a set of at least three for full 3D attitude control. A brushless motor is attached to the flywheel and exerts torque on the satellite by accelerating in the opposite direction. The system works by the conservation of angular momentum in which momentum of the satellite in transferred into the spinning wheels. One common problem with reaction wheels is they saturate and reach their top speed, and desaturating reaction wheels, or dumping momentum, often requires additional hardware and complex maneuvers. Magnetic torquers exert torque by reacting with Earth's magnetic field in Low-Earth Orbit (LEO). They apply current through a rod or coil to induce a magnetic flux and cause a torque. Torque rods are used to desaturate actuators with accumulated momentum due to disturbance torques like atmospheric drag, solar wind, and gravity gradients.

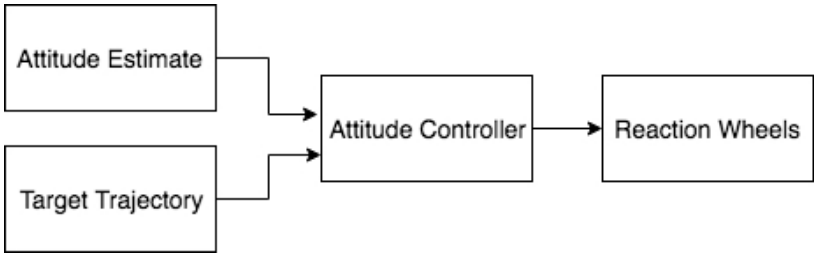


Figure 2.3: Attitude Determination and Control Block Diagram

## 2.4 Flight Dynamics

### Orientation

There are several ways to describe the orientation of a rigid body in three dimensions. The most common representation is described by three rotations with respect to a fixed coordinate system about an object's center of rotation. The value of the three rotations are called Euler angles and will be referred to as yaw, pitch, and roll respectively.

$$\boldsymbol{r}_{fixed} = \begin{bmatrix} \phi & \theta & \psi \end{bmatrix}^\top \tag{2.1}$$

The angular velocity with respect to a fixed reference frame can be found by differentiating angular position with respect to time; however, if the reference frame moves with the object, angular velocity must be written in the new basis.

$$\boldsymbol{w}_{fixed} = \begin{bmatrix} \dot{\phi} & \dot{\theta} & \dot{\psi} \end{bmatrix}^\top \tag{2.2}$$

$$\boldsymbol{w}_{moving} = \begin{bmatrix} \dot{\phi} sin\theta sin\psi + \dot{\theta} cos\psi \\ \dot{\phi} sin\theta cos\psi - \dot{\theta} sin\psi \\ \phi cos\theta + \dot{\psi} \end{bmatrix} \tag{2.3}$$

A problem that occurs with representing orientation and rotations using Euler angles is gimbal locking. Gimbal locking restricts the system's degrees of freedom when two axes in a three-gimbal system align. A solution is to use alternative representations of orientation: rotation matrices and quaternions.

Elemental rotations about axes of a fixed coordinate system can be written in matrix form. The following equations are used to represent or rotate a rigid body in a 3D Euclidean space using the right-hand rule. An orientation or rotation matrix can be written as a matrix multiplication of elemental rotations.

$$\boldsymbol{R}_\psi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\psi) & -sin(\psi) \\ 0 & sin(\psi) & cos(\psi) \end{bmatrix} \tag{2.4}$$

$$\boldsymbol{R}_\theta = \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix} \tag{2.5}$$

$$\boldsymbol{R}_\phi = \begin{bmatrix} cos(\phi) & -sin(\phi) & 0 \\ sin(\phi) & cos(\phi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.6}$$

$$\boldsymbol{R} = \boldsymbol{R}_\psi \boldsymbol{R}_\theta \boldsymbol{R}_\phi \tag{2.7}$$

Rotation quaternions are based on Euler's rotational theorem which states that the relative orientation of two coordinate systems can be described as an angle about a fixed axis. Quaternions provide a non-singular orientation representation and are more compact than matrices. The corresponding angular velocity and acceleration of the rigid body can be found by differentiating angular position.

$$\boldsymbol{r}_{quaternion} = \boldsymbol{q} = \begin{bmatrix} q_1 & q_2 & q_3 & q_4 \end{bmatrix}^\top \tag{2.8}$$

$$\boldsymbol{\omega} = 2\frac{d\boldsymbol{q}}{dt}\boldsymbol{q}^{-1} \tag{2.9}$$

$$\boldsymbol{\alpha} = 2\frac{d^2\boldsymbol{q}}{dt^2}\boldsymbol{q}^{-1} + 2\frac{d\boldsymbol{q}}{dt}\frac{d\boldsymbol{q}}{dt}^{-1} \tag{2.10}$$

If $\boldsymbol{q}$ is a unit quaternion for the rotation from one frame to another, the rotation matrix corresponding to the quaternion is:

$$\boldsymbol{R}(\boldsymbol{q}) = \begin{bmatrix} q_1^2 + q_2^2 - q_3^2 - q_4^2 & 2(q_2q_3 - q_1q_4) & 2(q_1q_3 + q_2q_4) \\ 2(q_2q_3 + q_1q_4) & q_1^2 - q_2^2 + q_3^2 - q_4^2 & 2(q_3q_4 - q_1q_2) \\ 2(q_2q_4 - q_1q_3) & 2(q_1q_2 + q_3q_4) & q_1^2 - q_2^2 - q_3^2 + q_4^2 \end{bmatrix} \tag{2.11}$$

The quaternion representation can be solved from a given rotation matrix using the following transformation:

$$\boldsymbol{q} = \begin{bmatrix} \frac{1}{2}\sqrt{1 + \boldsymbol{R}_{11} + \boldsymbol{R}_{22} + \boldsymbol{R}_{33}} \\ \frac{\boldsymbol{R}_{32} - \boldsymbol{R}_{23}}{4b_1} \\ \frac{\boldsymbol{R}_{13} - \boldsymbol{R}_{31}}{4b_1} \\ \frac{\boldsymbol{R}_{21} - \boldsymbol{R}_{12}}{4b_1} \end{bmatrix} \tag{2.12}$$

## Rotational Dynamics and Angular Momentum

Newton's second law of motion for rotation states that the angular acceleration $\boldsymbol{\alpha}$ is proportional to the net torque $\boldsymbol{\tau}$ and inversely proportional to the moment of inertia $\boldsymbol{I}$. The relationship is often written in the form presented below.

$$\boldsymbol{\tau} = \boldsymbol{I}\boldsymbol{\alpha} \tag{2.13}$$

The moment of inertia of a rigid body is a tensor that determines the torque needed for a desired angular acceleration about a rotational axis. The moment of inertia depends on the distribution of mass of the rigid body and reference coordinate system chosen.

$$\boldsymbol{I} = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} \tag{2.14}$$

Angular momentum is the measure of angular motion in a system relative to its center of rotation. It is proportional to the moment of inertia $\boldsymbol{I}$ and angular velocity $\boldsymbol{\omega}$.

$$\boldsymbol{L} = \boldsymbol{I}\boldsymbol{\omega} \tag{2.15}$$

Angular momentum is important because it is a conserved quantity, and the angular momentum of a system remains constant unless there is an external torque. To analyze the angular momentum of a satellite, we define a corotational basis $\{\boldsymbol{e}_x, \boldsymbol{e}_y, \boldsymbol{e}_z\}$ that rotates with the body of the satellite. The total angular momentum of the system relative to its center of mass can be written explicitly as follows.

$$\boldsymbol{L} = \begin{bmatrix} \boldsymbol{L} \cdot \boldsymbol{e}_x \\ \boldsymbol{L} \cdot \boldsymbol{e}_y \\ \boldsymbol{L} \cdot \boldsymbol{e}_z \end{bmatrix} = \begin{bmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega} \cdot \boldsymbol{e}_x \\ \boldsymbol{\omega} \cdot \boldsymbol{e}_y \\ \boldsymbol{\omega} \cdot \boldsymbol{e}_z \end{bmatrix} \tag{2.16}$$

## Angular Momentum of the Satellite with Momentum Wheels

Now we continue our analysis by adding three momentum wheels aligned with the axes. Each momentum wheel has a corresponding position $\boldsymbol{r}_{mw_i}$ relative to the center of mass of the satellite. It also has an angular velocity $\boldsymbol{\omega}_{mw_i}$ with components about its axis of rotation.

$$\boldsymbol{r}_{mw_i} = r_{mw_i,1}\boldsymbol{e}_1 + r_{mw_i,2}\boldsymbol{e}_2 + r_{mw_i,3}\boldsymbol{e}_3 \tag{2.17}$$

$$\boldsymbol{\omega}_{mw_i} = \omega_{mw_i,1}\boldsymbol{e}_1 + \omega_{mw_i,2}\boldsymbol{e}_2 + \omega_{mw_i,3}\boldsymbol{e}_3 \tag{2.18}$$

The angular momentum of each flywheel is proportional to its moment of inertia and angular velocity with relative to its center of mass.

$$\boldsymbol{L}_{mw_i} = \boldsymbol{I}_{mw_i}\boldsymbol{\omega}_{mw_i} \tag{2.19}$$

We define the center of mass of the satellite as the point $O$. The flywheel's angular momentum relative to the center of mass of the satellite frame can be written as follows where $m_{mw_i}$ is the mass of the $i$th momentum wheel.

$$\boldsymbol{L}_{O,mw_i} = \boldsymbol{L}_{mw_i} + \boldsymbol{r}_{mw_i} \times m_{mw_i}(\boldsymbol{\omega}_{mw_i} \times \boldsymbol{r}_{mw_i}) \tag{2.20}$$

A similar analysis can be done for the orthogonal spinning sensors, and the total angular momentum of the system can be expressed by the sum of the angular momentum of each component in the system.

$$\boldsymbol{L}_{sys} = \boldsymbol{L}_{satellite} + \sum_{i=1}^{3} \boldsymbol{L}_{O,mw_i} + \sum_{j=1}^{2} \boldsymbol{L}_{O,sensors_j} \tag{2.21}$$

Finally, to obtain the equations of motion, we take the derivative of the angular momentum of the system with respect to time, where $M_{ext}$ is the external moments on the system.

$$\dot{\boldsymbol{L}}_{sys} = M_{ext} = \dot{\boldsymbol{L}}_{satellite} + \sum_{i=1}^{3} \dot{\boldsymbol{L}}_{O,mw_i} + \sum_{j=1}^{2} \dot{\boldsymbol{L}}_{O,sensors_j} \tag{2.22}$$

# Chapter 3

# Satellite Mechanical Design

## 3.1 Overview

In this section, we introduce engineering specifications and describe the main mechanical components of the satellite. Then, we prototype the spacecraft using solid modeling tools to create high resolution 3D models, which will be used for creating dynamical models, simulation, and manufacturing.

## 3.2 Engineering Specifications

Early in the design cycle, designers must gather relevant information about the product and its functional requirements into a well-documented formal specification for performance and testing protocols [20]. Engineering specifications specify how a design will be implemented and clarify design goals and methods. These procedures are especially important in high-value applications such as satellites, where there is a significant risk of failure.

A satellite must pass a long list of qualitative and quantitative functional performance requirements prior to launch, but explicit system requirements are often not completely known ahead of time. Modeling and simulation is one tool for experimentation and quantifying desired system specifications.

The prototyped satellite presented in this thesis is not meant for flight so there is more flexibility in terms of hardware selection and system requirements. There are a few high level goals for the prototype. First, the volume of the satellite should be minimized to allow for testing in the lab and development into a potential CubeSat. Second, the sensing instrumentation must run at a minimum angular velocity of 5 RPM without collision. Third, the satellite should be able to remain stable when accelerating the spinning sensors. This work will develop models to help with future development of a flight vehicle.

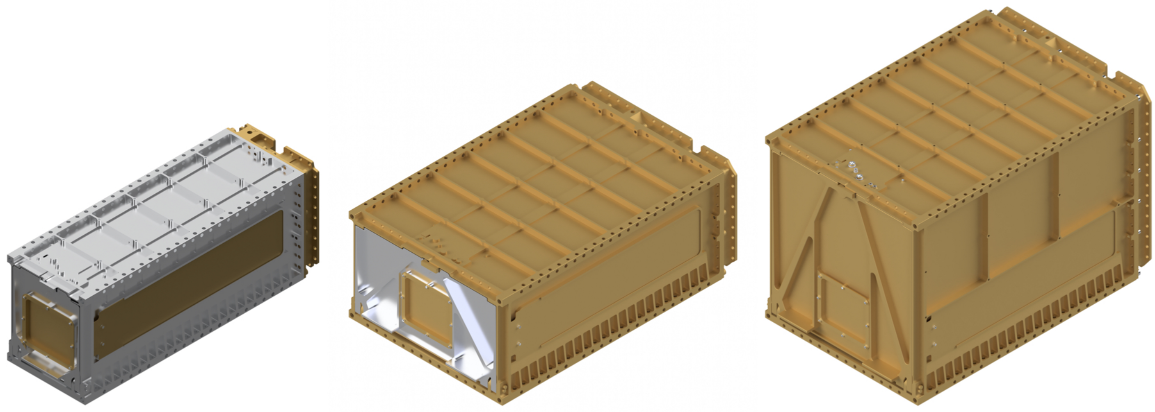

Figure 3.1: 3U, 6U, 12U CubeSat Dispensers by Planetary Systems Corporation

## 3.3 CubeSat Standard

The CubeSat standard is a set of design specifications for picosatellites and nanosatellites (1.5 - 12 kg) that reduces cost and development time, increases accessibility to orbit, and sustains frequent, repeated launches [21, 22]. CubeSats are often used to demonstrate satellite technology that present questionable feasibility and are unlikely to justify costs of a larger satellite. This makes it a potential platform for deploying a satellite with orthogonal spinning sensors.

CubeSats are categorized by volume, and each unit (U) is designed to provide 10x10x10 cm or 1L of useful volume. During launch, CubeSats are contained to protect the launch vehicle using customized dispensers and typically launched as secondary payloads [23]. Dispensers for 3U, 6U, and 12U CubeSats are shown in Figure 3.1. There are two types of designs for CubeSat dispensers: a railed system and a tabbed system. These mechanical differences will alter the final flight-ready design of the CubeSat.

Although preceding designs for the satellite were done for a much larger system, the new proposed spacecraft is designed within existing CubeSat 6U envelope dimensions in order to accommodate further development into a fully functional CubeSat. The 6U CubeSat configuration (100x200x300 mm, 12 kg) is large enough to contain the hardware needed for the system.

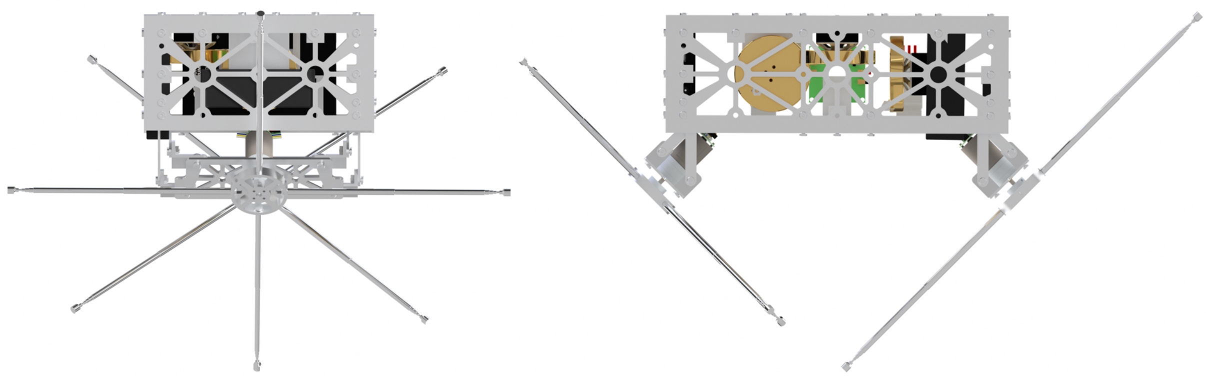

Figure 3.2: Satellite CAD Model: Four-Bar Deployment Mechanism and Orthogonal Spinning Sensors

## 3.4 Coordinated Orthogonal Spinning Sensors

The novelty of this satellite lies within the orthogonal long measurement probes. The proposed satellite uses two orthogonal spinning platforms, which houses four long wire booms, two shorter magnetometer booms, and plasma detectors. The platforms are stowed for launch and deployed using a four-bar mechanism. Long wire measurement probes, which remain taut by the resulting centrifugal force from their rotation, are preferred since they minimize interference from near-spacecraft electric fields. Instead of using long wire sensors, which cannot operate properly under gravity and may tangle in space, the prototype satellite uses rigid rods for sensing. This is a likely candidate for early missions because it minimizes the potential risk of failure.

In the original design, the satellite used a gearing mechanism to coordinate the two platforms to spin out of phase. To avoid potential challenges with a gearing mechanism, the prototype is designed with two independently controlled motors instead. This allows for a more flexible mechanical design with less weight and volume.

Weight and volume are important for the final design of the satellite because the spinning sensors must be stowed during launch. Once the satellite is deployed to its desired orbit by the launch vehicle, the satellite stabilizes itself and releases the sensor probes using four-bar mechanisms. The linkages guide the platforms to their final orthogonal position. The four-bar mechanisms and substitute orthogonal spinning sensors are shown in Figure 3.2.

Figure 3.3: Satellite CAD Model: Mutually Orthogonal Momentum Wheel Configuration

## 3.5 Momentum Wheels

Small satellites often use a configuration of magnetic torquers and momentum wheels for attitude control. After detumbling, the actuators help the satellite do two things: stabilize or slew (rotation maneuvers). To stabilize, the momentum wheels adjust to counteract disturbance torques on the vehicle. To slew, the momentum wheels will adjust to rotate to a desired attitude or track a trajectory to accomplish its mission.

There are a few key differences between the momentum wheels and magnetic torquers. Momentum wheels can exert larger torques than magnetic torquers, but require moving parts and are less reliable. There is also a limit on the amount angular momentum the wheels can provide as they reach their top speeds. Magnetic torquers are often used to help dump momentum and desaturate the wheels. The two sensors are often paired together for low Earth orbit attitude control systems.

The proposed satellite used one momentum wheel and two magnetic torquers for attitude control. The prototype in this case study uses three momentum wheels instead to simplify the testing on Earth. The momentum wheels are placed in mutually orthogonal positions as shown in Figure 3.3. They are axis-aligned with the satellite to simplify the controller.

The momentum wheels are designed around commercial off-the-shelf (COTS) motors. Brass flywheels are mounted onto brushless DC motors, which provide high speeds and low friction. The brushless motors are controlled using integrated electronic speed controllers (ESC) which provide tri-phase AC power from a DC power input.

## 3.6 3D Solid Modeling

Solid modeling is a technique for representing solid objects for design, analysis, and assembly. Common 3D solid modeling tools include Autodesk Inventor, Catia, Creo, NX, and SolidWorks.

Components are made by sweeping 2D sketches to create 3D features. Each component is assigned a material from common databases of standard material properties. Materials contribute to estimating mass properties of a component: mass, center of mass, and moments of inertia.

In addition to modeling individual 3D components, solid modeling software often also allow the addition of constraints between components to produce kinematic assemblies. Constraints are added as joints and limit the degrees of freedom of an object. The resulting assembly describes the motion of a system with rigid body components.

### Satellite 3D Model

The purpose of a CAD model is to present and iterate on designs, extract information for the simulation models, and provide a clear path to manufacturing. Design is an iterative process and begins with low fidelity models. Higher resolution 3D models are made as system specifications and hardware are finalized. The following baseline satellite design is shown in Figure 3.4 and is used to manufacture and assemble the final prototype.

The 3D model includes the core components of the satellite with the appropriate mass properties, but features such as wires and connections were not included. The majority of parts used in the design were off-the-shelf components with readily available 3D models. Customized components were designed for manufacturing based on readily available tooling. The selection of electronic components will be described in Chapter 6.

In the final assembly, components of the system with no relative movement together are constrained together for kinematic and dynamic analysis. With the four-bar mechanism released and fixed, the system reduces to six dynamic rigid body components: the frame, three flywheels, and two orthogonal sensors. Composing the CAD model in this way provides mass properties of each subassembly for dynamic analysis and simulation. The dynamical model developed from the assembly is described in the next chapter.

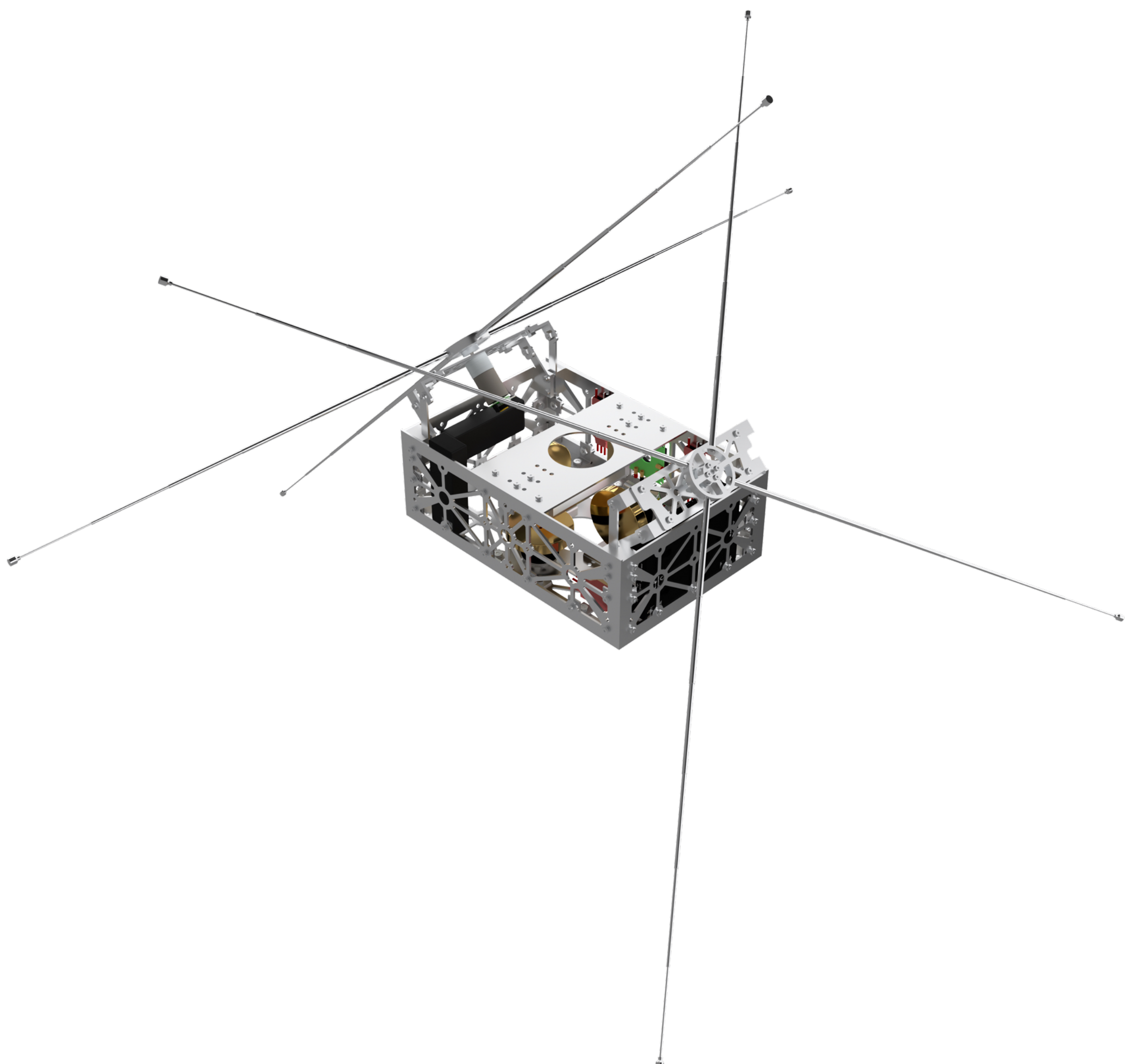

Figure 3.4: Satellite CAD Model: Fully Extended Spinning Sensors

# Chapter 4

# Dynamic Modeling

## 4.1 Overview

In Chapter 2, we derived a simple mathematical model of the satellite from first principles. In this chapter, we introduce the Modelica system modeling language and leverage the high resolution CAD model to create a more detailed dynamical model of the satellite. The model will be described by differential, algebraic, and discrete equations with mass properties and constraints derived from the CAD model.

## 4.2 Modelica Modeling Language

Modelica is a unified object-oriented language for modeling complex physical systems [6, 24, 25] . It differs from traditional simulation languages in that it describes the dynamics of mechanical systems using acasual differential, algebraic, and discrete equations. Modelica opens up opportunities for simulation, direct controller design, and hardware-in-the-loop testing. There are many open-source and commercial Modelica simulation environments, which may include different libraries and tools, but each use the same underlying modeling language. There are two main methods of creating Modelica models: scripting explicit equations and graphically manipulating components.

Models can be written as explicit equations. For example, a model for a DC motor can be derived from first principles as the following differential equations:

$$I(t)K_t - B\frac{d\theta}{dt} = J\frac{d^2\theta}{dt^2} \tag{4.1}$$

$$V(t) - K_{emf}\frac{d\theta}{dt} - RI(t) = L\frac{dI}{dt} \tag{4.2}$$

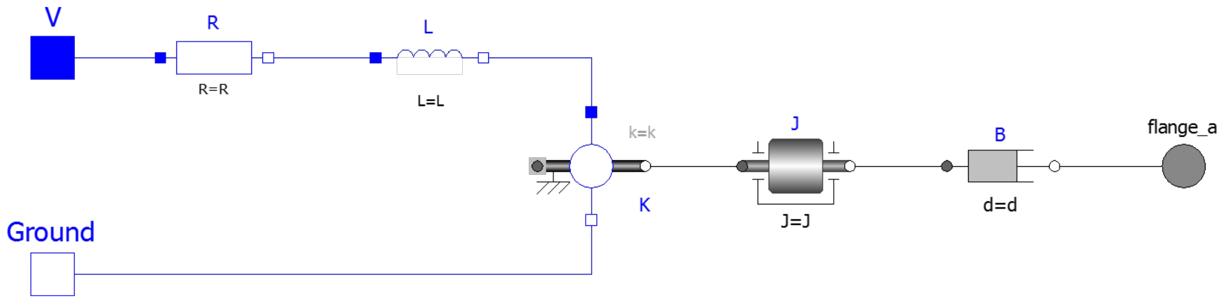


Figure 4.1: Modelica Model: Graphical Construction of a DC Motor

where $t$ is the independent variable for time, $V$ is the applied voltage, $I$ is the armature current, $R$ is the resistance of the circuit, $L$ is the inductance of the circuit, $\theta$ is the angular position of the motor, $B$ is the viscous friction coefficient, $J$ is the rotor inertia, and $K$ is the electromotive force and motor torque constant.

The differential equations can be written explicitly in Modelica, but users can leverage extensive libraries of available components to produce more complex models. For example, a DC motor can be created graphically using electronic components from the Modelica Standard Library as shown in Figure 4.1. Each icon represents a physical component (resistor, inductor, rigid body) and each connector represents a physical connection (electrical line, mechanical connection, heat flow). Note that connections in Modelica are acasual: the connection represents a coupled constraint between two objects unlike inputs and outputs in traditional graphical software environments.

To simulate a Modelica model in discrete environments, the model must be reduced to a numerically solvable system. Modelica translators can be used to convert Modelica object-oriented models into flattened models, which removes the object-oriented structure of the models using symbolic transformation techniques. Three types of systems can result from the translation of a Modelica model: ordinary differential equations (ODEs), differential algebraic equations (DAEs), or hybrid differential algebraic equations (Hybrid DAEs).

ODEs are differential equations containing functions of one independent variable. A general first-order differential equation can be written in the following form:

$$\dot{x}(t) = f(t, x(t)) \tag{4.3}$$

where $x(t)$ is the vector of state variables of the model, $\dot{x}(t)$ is the differentiated vector of state variables of the model, and $f$ is the function that defines the differential equations.

DAEs are a generalized form of differential equations with the addition of algebraic constraints. They have the following semi-explicit form:

$$\dot{x}(t) = f(t, x(t), y(t)) \tag{4.4}$$

$$0 = g(t, x(t), y(t)) \tag{4.5}$$

where $y(t)$ is the vector for algebraic constants and $g$ is the function that defines the algebraic equations of the system of equations.

Hybrid DAEs are generally described by a collection of continuous subsystems, a collection of discrete subsystems, and the possible interactions between them. Switched systems appear in many mechanical systems with friction or collisions.

Mechanical systems are frequently modeled as DAE systems because of their constraints. The resulting mathematical models are difficult to solve analytically but can be solved using numerical methods. The default solver used by several Modelica environments is the DASSL DAE solver which has proven to be reliable for most DAE problems. However, there are many other numerical methods which may perform better depending on the structure of the problem.

## 4.3 Dynamic Models from Mechanical Assemblies

Using the Modelica modeling language, we can develop a detailed mathematical model of the satellite directly from the 3D assembly described in the previous chapter. The new model will include mass properties of each component, joints between each component, and multimedia elements such as sensors and actuators.

We will use model components and standard component interfaces from the Modelica Standard Library to simplify the development process. The library includes a wide range of components to model mechanical, electrical, thermal, fluid, control systems and hierarchical state machines. We will primarily use the Electrical and MultiBody libraries to model the dynamics of the satellite.

### Translating Assemblies into Modelica Models

First, a global coordinate system is specified at the center of mass of the complete satellite assembly. The position and mass properties of each component are measured relative to the origin of the coordinate system. Joints between components are expressed by degrees of freedom along the axes of a relative coordinate system.

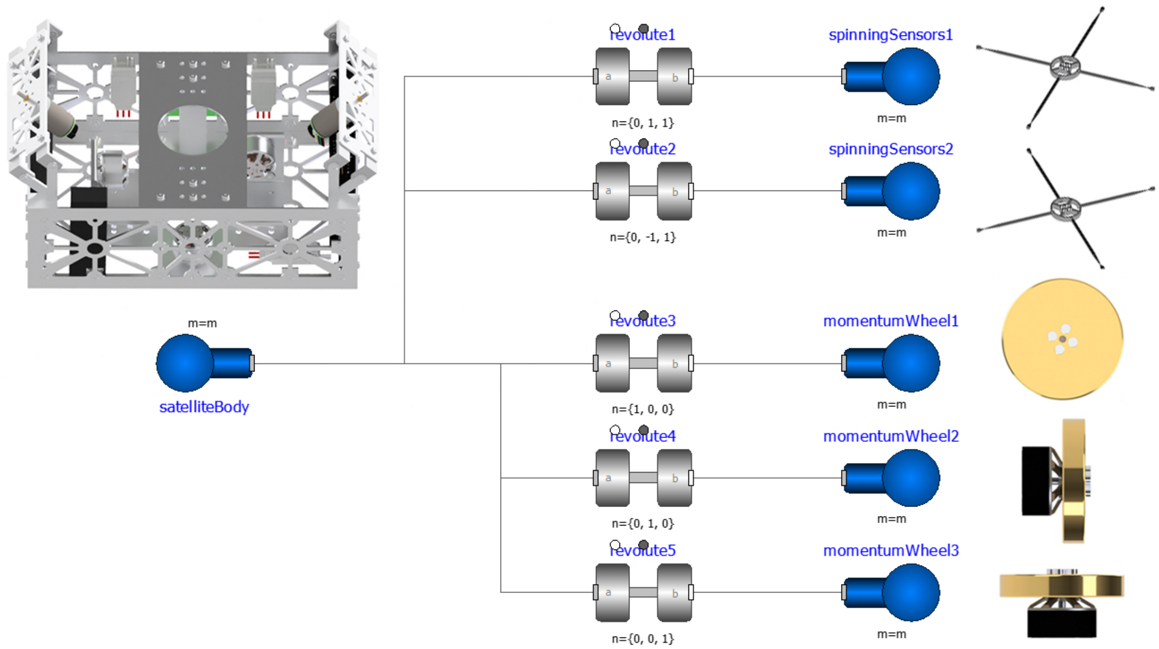


Figure 4.2: Modelica Model: Graphical Decomposition of Satellite Components

There are six rigid body components in the satellite assembly: the frame of the satellite, three flywheels, and two spinning sensors. Each component is kinematically constrained relative to another component. For example, the flywheels are fixed onto the body of the satellite and constrained to rotate about a given axis. These constraints are modeled as revolute joints. The revolute joint establishes a rotational framework that is common for motor-driven mechanical systems, and establishes a one-dimensional environment within the three-dimensional model space. Five revolute joints constrain the flywheels and the spinning sensors.

This procedure generates a kinematic model of the satellite from the assembly. A graphical view of the model is shown in Figure 4.2. Next, we add additional properties of mechanical systems, multimedia elements, and interfaces for control system design.

## Friction

Friction occurs in all mechanical systems but is very challenging to accurately model. Experiments show that friction is dependent on a variety of parameters, including material properties, relative velocity, surface area, load, and more. The complexity of interactions which contribute to friction forces makes it impractical to model from first principles. Instead, friction models rely on real-world experimentation and analysis [26, 27].

The system model and friction model are fundamentally coupled. If the components are readily available to test, the models can be tuned together such that the simulation closely approximates real-world behavior. If components are not readily available to test, friction may be estimated from the dynamics of the system, surface area, and material properties.

Fortunately, the effects of friction on the prototype satellite are minimal, and the system model does not require a detailed model of friction. Motors used in spacecrafts are also manufactured with very low friction for reliability purposes; however, friction has caused significant failures for attitude control systems in satellites after long periods of time. In 2012 and 2013, two of the four momentum wheels in NASA's Kepler telescope malfunctioned, causing erratic and intermittent friction. As a result, the Kepler telescope could no longer be pointed accurately and its mission was altered. This failure highlights the importance of accurate friction models in high value applications.

## Sensors and Actuators

CAD models typically only describe purely mechanical components and do not describe electromechanical components such as motors, pumps, etc. The non-mechanical properties of these components are essential to the simulation of mechatronic systems. Fortunately, Modelica provides a means of modeling non-mechanical, multimedia components of a system. Libraries of components can be used to augment the mechanical model with additional properties. For the satellite, we add brushless motors for the flywheels, brushed DC motors for the orthogonal spinning sensors, and sensors for the orientation of the vehicle.

The brushless and brushed DC motors are pulled from existing Modelica libraries. The two models are similar and convert signals into a rotational framework by connecting to the flanges on the revolute joints. Motor properties are initially estimated, later taken from manufacturer specifications, and finally tuned against physical hardware when available. Angular position sensors are placed at the revolute joints for the spinning sensors to model encoders used for feedback control.

A key component in attitude determination and control is measuring the current orientation of the vehicle. Each rigid body from the Modelica Standard Library contains a frame with the orientation of the object. The orientation can be obtained as Euler angles, a transformation matrix, or a quaternion.

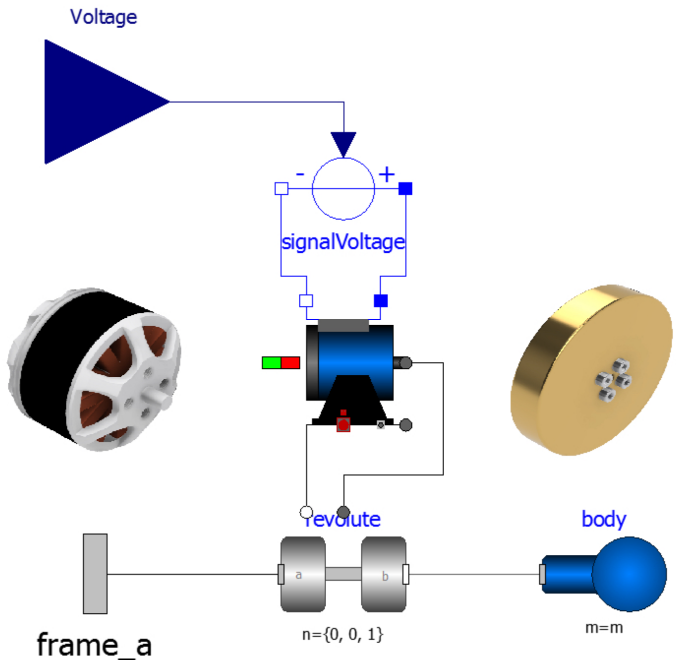


Figure 4.3: Satellite Modelica Model: Graphical View of Satellite Momentum Wheels

## Environment and Disturbances

In many mechanical systems, it is useful to model the effects of the environment on the system. A common way to capture the effects of external disturbances on the system is to include a disturbance vector in the mathematical model:

$$\dot{x}(t) = f(t, x(t), d(t)) \tag{4.6}$$

where $d(t)$ represents the effect on the rate of change of the state by external disturbances.

For small satellites, there is a wide range of potential external disturbances on the system. For example, magnetic, gravity gradient, and aerodynamic torques can cause a satellite to drift and tumble over time. To account for this, the satellite model may be simulated with a realistic disturbance torque profile to see if the system can maintain desired pointing requirements.

### Inputs and Outputs

The system model should provide the appropriate inputs and outputs as real-time target system so the same control system designed using the model can be applied to control the target system. This interface depends on the sensors and actuators in the system.

The brushless and brushed DC motors in the satellite can be controlled by sending pulse-width modulation (PWM) signals to the electronic speed controllers (ESCs) and H-bridges, respectively. The encoders on the brushed DC motors provide angular position to the controller as incremental counts.

The satellite's attitude determination and control system will use observations of the vehicle's orientation and apply corrective inputs to the momentum wheels. The interface for inputs and outputs of actuators and sensors is added to the Modelica model. An input-output model is required to connect the plant model with traditional simulation tools and design a controller.

## 4.4 Functional Mock-up Interface for Model Exchange and Co-Simulation

To bridge the gap between simulation and deployment to real-time hardware, we use the Functional Mock-up Interface (FMI), a tool-independent standard that supports model exchange and co-simulation using a combination of XML files and compiled C code [28, 29]. The models generated by FMI are known as Functional Mock-up Units (FMUs). This standard simplifies the exchange of Modelica system models between different software tools. By exporting the dynamical model to a control system design environment, the end user needs to only design a controller once using the Modelica model to verify behavior prior to deployment to real-time hardware.

We will be using the FMI Standard 2.0 to simulate the satellite model in different software environments. There are two options available when exporting a Modelica model: model exchange or co-simulation. Model exchange describes the dynamic system using flattened differential, algebraic, and discrete time equations while co-simulation contains both the model and the solver and is able to perform real-time data transfer between software environments.

The FMI standard provides a promising means of combining models from various software tools into a unified simulation environment, allowing us to reuse Modelica models in different applications.

# Chapter 5

# Control System Design

## 5.1 Overview

In this chapter, we describe the control systems required on a typical satellite, and design and implement closed-loop feedback control of the orthogonal spinning sensors and attitude of the spacecraft. We simulate the spacecraft by applying the control algorithms to the dynamical model of the satellite. Using the NI LabVIEW architecture, the same control algorithms are run on real-time hardware.

## 5.2 Satellite Modes of Operation

Small satellites with attitude control systems generally have four unique states: detumble, slew, stabilization, and safety mode [9]. The state of the satellite can be controlled by the ground or autonomously when desired conditions are met. In detumble mode, the satellite reduces its angular velocity until it can maneuver itself. In slew mode, the satellite rotates towards a target attitude. In stabilization mode, the vehicle maintains its position and begins to accomplish its mission. If the satellite detects any anomalies internally or in the environment, it may enter a safety mode and await further instructions from the ground.

### Detumble Mode

Once the satellite is ejected from the launch vehicle, it may tumble at rates up to 10 degrees per second. When ground command has secured connection with the satellite, it may initiate the satellite's attitude control system and enter the detumble mode. In this mode, the satellite measures its angular velocity using gyroscopes and magnetometers and uses the satellite's magnetometers to dump angular momentum and stabilize the vehicle. When the satellite has stabilized its angular rate, the satellite may autonomously enter a slew mode.

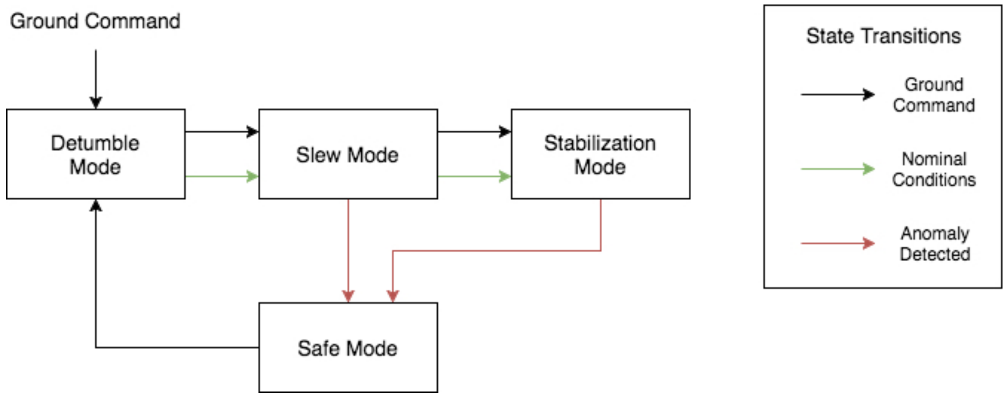


Figure 5.1: Satellite Modes of Operation

## Slew Mode

After the detumble mode, the satellite has stabilized in a random orientation. In slew mode, the satellite transitions from a given orientation to a target orientation. For example, the satellite may need to point its solar arrays in an optimal position or communication devices at ground command. The satellite uses the momentum wheels to apply a control torque and rotate the vehicle and the magnetic torquers to dump excess angular momentum.

## Stabilization Mode

Once the satellite has reached its target position, it stabilizes and begins its mission. In this mode, the satellite rotates its spinning booms and collects data. The satellite maintains this position for as long as possible, resisting disturbances and dumping excess angular momentum that builds up. Ground command may set new target positions if the satellite's current mission is altered or completed.

## Safety Mode

The safe mode is where the satellite observes unexpected behavior and shuts down all nonessential functions. Often, attitude control is maintained for optimal power generation and communication. At this stage, ground command may review telemetry data to determine the best course of action and how to recover the satellite.

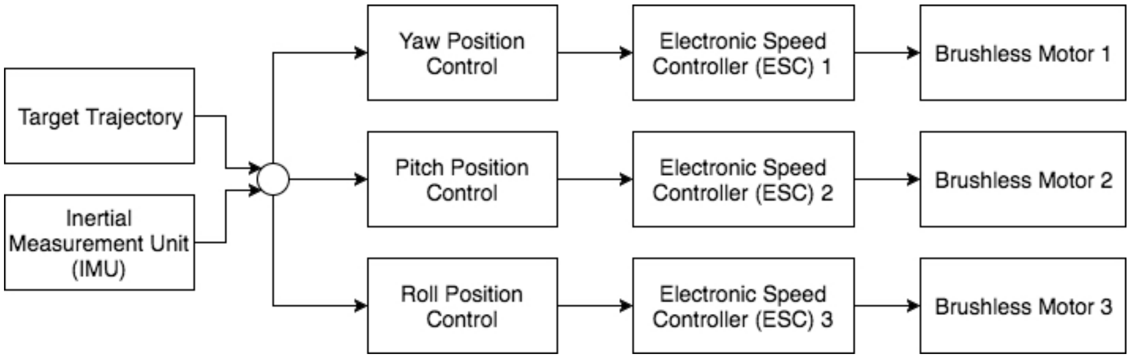


Figure 5.2: Attitude Control Block Diagram

## 5.3 Attitude Control

Closed-loop attitude control is done using a simple proportional-integral-derivative (PID) control law given by:

$$u = k_p(r - y) + k_i \int_0^t ((r(\tau) - y(\tau))d\tau + k_d(\dot{r} - \dot{y}) \tag{5.1}$$

where $u$ is the PWM for the brushless motor, $(k_p, k_i, k_d)$ are the proportional, integral, and derivative gains for the PID controller, $r$ is the desired orientation of the satellite, and $y$ is the measured orientation of the satellite.

This control law is applied to each of the three motors and degrees of freedom as shown in Figure 5.2. The three controllers convert measurements from an IMU and a reference trajectory to PWM signals for the brushless motors. The desired trajectory is adjusted for stabilization and slew modes.

To stabilize the satellite, the desired orientation, $r$, is fixed. This allows the satellite to resist small disturbance torques from the environment or the orthogonal spinning sensors. To navigate to a new orientation, we manipulate the target orientation. Large setpoint changes are generally undesirable in a control system because of actuation saturation can hurt the system, but we can ramp the setpoints to prevent the actuators from saturating.

The basic control calculations are done using Euler angles. Typical attitude control systems use quaternion based systems to avoid geometric singularities with Euler Angles and coupled differential equations with transformation matrices. This problem is not a large concern because the prototype satellite designed in this case study has limited degrees of freedom. Investigating more complex control strategies using the Integrated Tool Suite for a flight-ready vehicle is left as future work.

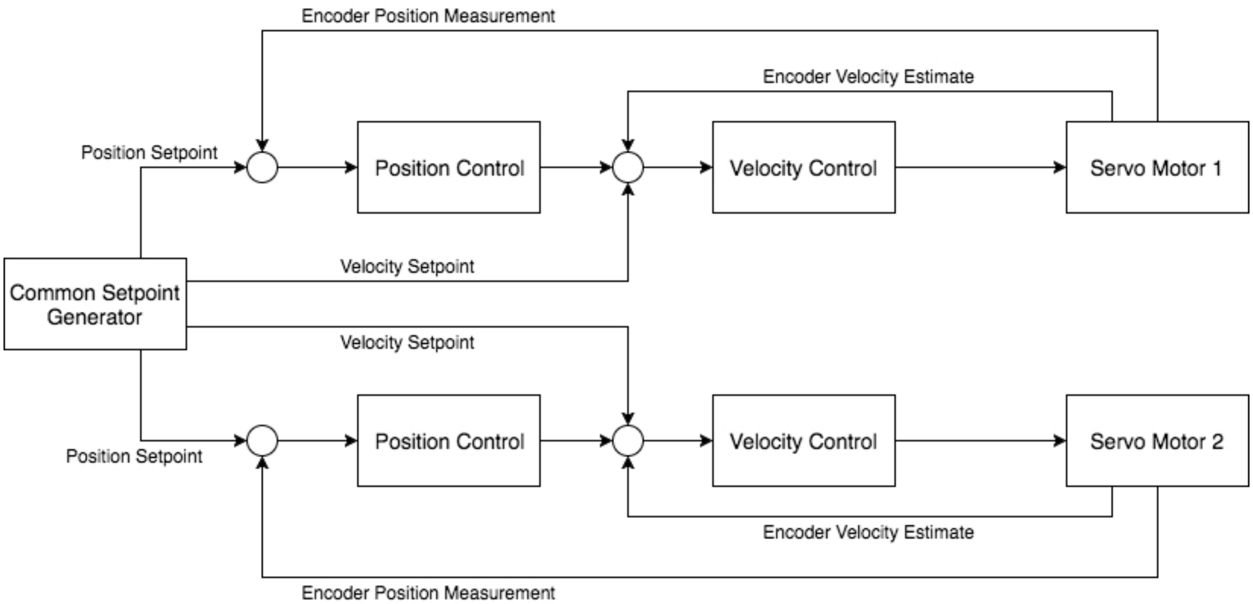


Figure 5.3: Coordinated Motion Control Block Diagram

## 5.4 Orthogonal Spinning Sensors

The orthogonal spinning sensors on the satellite are coordinated and controlled 45 degrees out of phase so they do not collide. Control of the two motors is done through a cascade position control with a common set point generator to maintain the proper phasing. Cascade control is a commonly used technique in which separate control loops are used for velocity and position with the output of the position loop being used as the set point for the velocity loop. Saturation limits are placed on the velocity and duty cycle outputs to avoid exceeding the system's actuation limits.

The common set point generator provides continuously changing position set points corresponding to the appropriate rotational motion. Position control is used rather than velocity control because any errors in velocity control would eventually integrate to large position errors. This type of control is often called electronic gearing or electronic line shaft in the motion control industry.

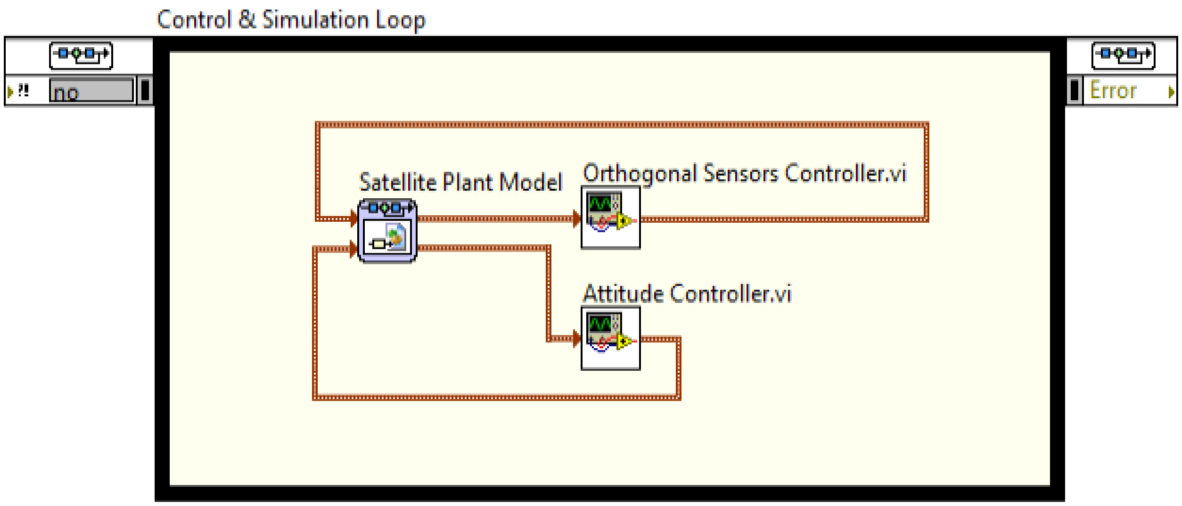


Figure 5.4: LabVIEW Model-in-the-Loop Satellite Simulation Block Diagram

## 5.5 Model-in-the-Loop Simulation

LabVIEW is used to test control algorithms in a virtual environment prior to manufacturing or selecting hardware. LabVIEW is a system-design platform commonly used for data acquisition, instrument control, and industrial automation. The LabVIEW Control Design and Simulation Module supports model exchange through FMI.

The Modelica model is converted into a LabVIEW plant model. The process automatically generates system parameters, dynamic relations, and input/output terminals based on the construction of the FMU. Bringing the model into LabVIEW enables Model-in-the-Loop (MiL) simulation where the same simulation environment is used to simulate the plant and the controller. This process is used to evaluate and optimize controllers without having physical hardware.

The LabVIEW Control and Simulation Loop is shown in Figure 5.4. The orthogonal sensors controller converts encoder counts into PWM signals to control the spinning sensors. The attitude controller receives orientation measurements and actuates the momentum wheels accordingly.

# Chapter 6

# Rapid Prototyping Using Simulation

## 6.1 Overview

In this chapter, we apply simulation as a tool to guide the design of the satellite. Simulation allows us to quantify system performance and implement and test the effectiveness of control algorithms prior to manufacturing. Even after manufacturing, simulation can be used to optimize controllers and iterate on new designs.

## 6.2 Simulation

Simulation is a well-established tool for control engineers to develop, test, and optimize their algorithms without access to the full system. Simulation provides a flexible platform for analyzing complex models, rapid prototyping, iterating on designs, and validating and verifying properties of systems.

Although simulation may not require physical hardware, often individual hardware components are necessary to calibrate and tune specific parameters of the model. Models are only useful if they are validated relative to analogous real-world systems. With an accurate plant model, we can more confidently predict the behavior of the real system.

After the models are calibrated, we can verify, validate, and test designs early and continuously throughout the process. Verification is used to check if the model accurately implements the description of the real-world system and the desired solution. Validation is used to determine if the model is an accurate representation of the system and its intended usage. Testing is used to examine error, accuracy, uncertainty, and sensitivity of the simulations. Together, these processes provide evidence of the utility of simulation results.

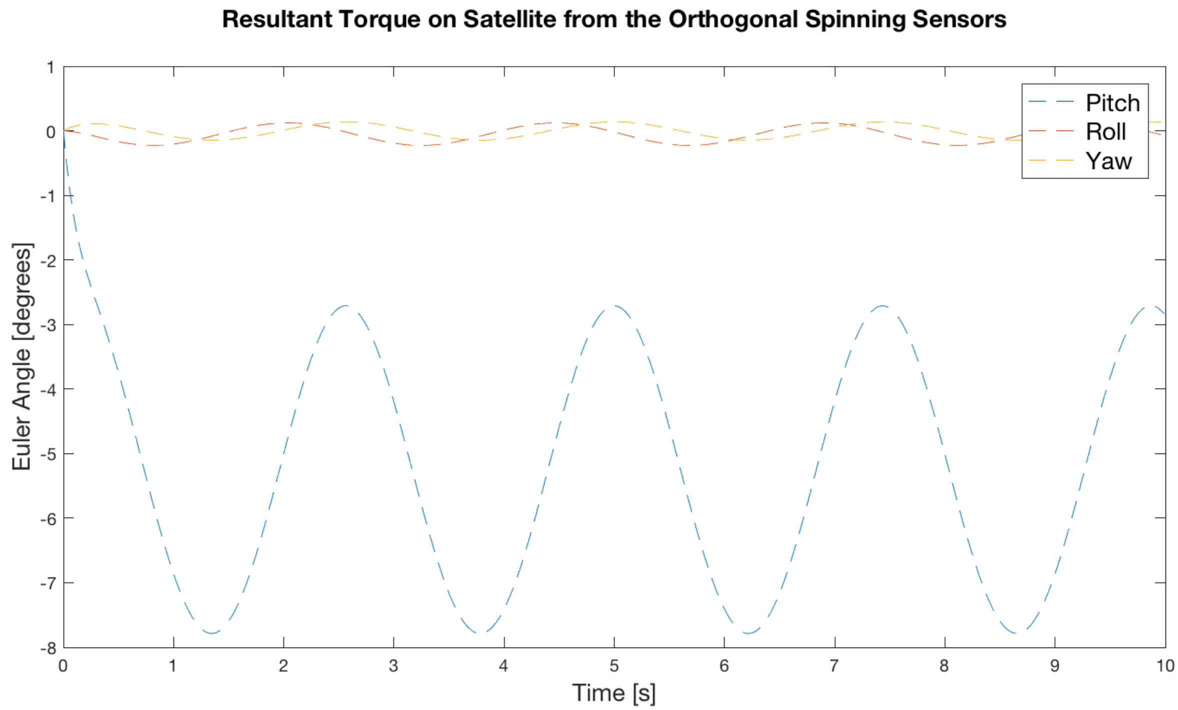


Figure 6.1: Satellite Simulation: Resultant Torque on Satellite due to Orthogonal Spinning Sensors

## Simulating the Resultant Torque from the Orthogonal Spinning Sensors

Using LabVIEW and the Modelica plant model, we can simulate the resultant torque on the vehicle due to the orthogonal spinning sensors. We implement the cascade position control scheme as described in the previous chapter. The orthogonal spinning sensors are initialized out of phase, and a graph of the resulting orientation of the vehicle is shown in Figure 6.1.

The spinning sensors are simultaneously ramped up to a constant angular velocity and kept out of phase to avoid collisions. The graph of the orientation of the vehicle shows that yaw remains constant but pitch and roll oscillate from the resultant torque. This is expected since the axis of rotation of the orthogonal spinning sensors rotates about the pitch and roll axes.

At this stage, the simulation provides insight into the dynamics of the satellite but does not accurately model the target system yet because hardware has not yet been reviewed, purchased, or selected.

## 6.3 Satellite Mechanical Design and Hardware Selection

### Mechanical Design

With simulation, we can easily test small changes to the design of the plant. Traditionally, parameters in the plant model are adjusted until simulations provide satisfactory results. Then, the mechanical design is adjusted until parameters match the modified plant model. In the workflow, the process can instead be done by directly modifying the CAD model and updating the model's mass properties and dynamic constraints. This changes the simulation results accordingly as provides a means of optimizing the mechanical design a system.

This process allows designers to experiment with different materials, 3D geometries, and dynamic constraints without the costs associated with prototyping real hardware. We can apply this process to the design of the satellite's momentum wheels. For example, the mass and moment of inertia of the flywheels can be changed by applying different materials or altering its geometry. The dynamic constraints of the assembly can be changed by aligning the momentum wheels in different positions or adding additional units for redundancy.

### Hardware Selection

A common challenge with the design of electromechanical systems is in sourcing the appropriate electronics to use. For example, matching a motor to a specific application is not easily accomplished by trial and error and often purchasing and testing is wasteful and time-consuming. As a result, it is common to use simple mathematical models early in the design process to determine basic functional requirements and design parameters of a system. After determining these requirements and parameters, engineers will source or manufacture components that will work for their application.

It is easy to model ideal components such as sensors and actuators, but these components may not be available or cost-effective. Instead, simulation can be used to more accurately predict the performance of the system given existing hardware specifications. Existing hardware specifications are added to the model prior to assembly to improve confidence that the system is feasible. The following sections describe hardware used for the prototype satellite: motors, sensors, and microcontroller.

## Brushless Motors for Momentum Wheels

A brushless motor with high torque and maximum angular velocity was selected for the momentum wheels. The manufacturer's specifications are shown in Table 6.1. Electronic speed controllers control the speed of the brushless motors by providing an electronically generated three-phased voltage source. The phase varies with the rotation of the motor which is estimated from the back EMF.

| Brushless Motor Specification | Value |
|---|---|
| KV | 470 RPM/V |
| Idle Current | 0.3 A |
| Voltage | 22.2 V |
| Max Continuous Current | 15 A |
| Max Continuous Power | 330 W |
| Max Efficiency Current | (2-8A) > 84% |
| Max Speed | 10340 RPM |
| Torque Estimate | 305 mNm |

Table 6.1: Brushless Motor Parameters

## DC Brushed Motor with Encoder

A simple gearmotor with an encoder was selected to control the position of the spinning booms. The gearmotor is a low-powered, 6 V brushed DC motor with a 48 CPR quadrature encoder on the motor shaft. An absolute encoder is preferred but an incremental encoder is used to reduce cost. The motor is controlled using an H-bridge via PWM. Motor parameters shown in Table 6.2 were taken directly from the manufacturer.

| DC Motor Specification | Value |
|---|---|
| Gear Ratio | 171.79:1 |
| Free-run speed @ 6 V | 34 RPM |
| Free-run current @ 6 V | 250 mA |
| Stall Current @ 6 V | 2400 mA |
| Stall Torque @ 6 V | 200 oz-in$^2$ |
| Resistance | 2.5 Ohms |

Table 6.2: DC Brushed Motor Parameters

## Inertial Measurement Unit (IMU)

To measure orientation, the satellite uses a 9DOF IMU, which incorporates three axis measurements from three sensors to obtain nine degrees of inertial measurement. Sensor fusion algorithms combine measurements from multiple sensors to improve the quality of the final output.

- ITG-3200 (MEMS triple-axis gyroscope)
- ADXL345 (Triple-axis accelerometer)
- HMC5883L (Triple-axis magnetometer)

The outputs of each sensors is processed by an on-board ATmega328 and outputted over a serial UART interface. The firmware can be programmed to stream accelerometer, gyroscope, and magnetometer measurements. Orientation estimates can be streamed as Euler angles or quaternions.

## myRIO Embedded System Platform

The NI LabVIEW RIO architecture combines four key components for designing advanced control systems: a real-time processor, a programmable FPGA, modular I/O, and a complete software tool chain. The National Instruments myRIO-1900 is a RIO device that is specifically geared toward student projects in mechatronics. It has a dual-core ARMÂő Cortex-A9 real-time processing and Xilinx FPGA customizable I/O. It also provides digital I/O, power output, and WiFi communication in a compact device.

The RIO architecture is directly integrated with the LabVIEW Control and Simulation environment, allowing us to deploy control designed using simulation to real-time hardware. This significantly simplifies the development process. Control code is only written once for both the dynamical model and the real-time system.

We used the NI myRIO-1900 Expansion Port (MXP) connectors to control the brushless motors and read orientation data from the IMU. We also used the Motor Adapter for NI myRIO to control two DC gearmotors for the orthogonal spinning sensors. The breakout board provides two 1.5A full h-bridge outputs and two quadrature encoders.

## On-Board Power Supply

To power the electronics in the satellite, we use conventional lithium polymer (LiPo) battery packs. Each pack consists of three cells with a total capacity of 2200 mAh and a voltage of 11.1 V. A single battery pack can power the system for approximately 20 minutes. A power distribution board is used to distribute power to each component.

## 6.4 Dynamic Visualization

Simulation tools often focus on accurately computing solutions to models and provide results in the form of raw data, which is often challenging to interpret. To solve this, simulation tools are often coupled with visualizations for animations to quickly validate the results. Visualization tools enable designers to communicate their designs and examine a graphical representation of a system prior to manufacturing and real-world testing.

The Modelica MultiBody library includes built-in animation properties which can be used to visualize the system with basic primitive shapes, but these tools are not provided in all control system design environments. Since the models developed using the Integrated Tool Suite come from detailed 3D models, system trajectories from simulations can be imported into the 3D modeling environment for high quality visualizations.

### Interactive Simulations

Recent advances in virtual and augmented reality have enabled engineers to visualize mechanical systems to scale in simulated and real-world environments. These interfaces typically allow users to interact with and manipulate their designs with natural hand gestures. Combined with accurate dynamic simulations, these tools will provide a wide range of applications in the design of mechanical systems.

# Chapter 7

# Manufacturing and Real-World Testing

## 7.1 Overview

Once behavior of the satellite in simulation is satisfactory, we manufacture the satellite and use NI LabVIEW RIO architecture to control the system in real time. In this chapter, we describe manufacturing challenges and the results of several experiments to illustrate the dynamics of the satellite and the attitude determination and control system.

## 7.2 Manufacturing

Mechanical designs are constrained by manufacturing resources and capabilities, and the manufactured system will differ from the mechanical design. Design for manufacturing (DFM) techniques are applied to improve quality and reduce manufacturing costs for the end product.

Since the prototype satellite is not meant for flight, many substitute off-the-shelf components are used to minimize design time and manufacturing costs. A handful of custom components are machined from stock materials. For example, the frame was cut from sheet aluminum and the brass flywheels were turned on a lathe. The prototype satellite was tested using a custom spherical air bearing that was made by 3D printing and casting.

Flight-ready satellite components must be carefully designed and manufactured to assure proper operation over the vehicle's expected life. Satellites intended for flight are also assembled in clean rooms because tiny imperfections with the hardware can cause catastrophic mission failures. Ultimately, satellites must be able to withstand the harsh environment of space with no opportunity for repairs.

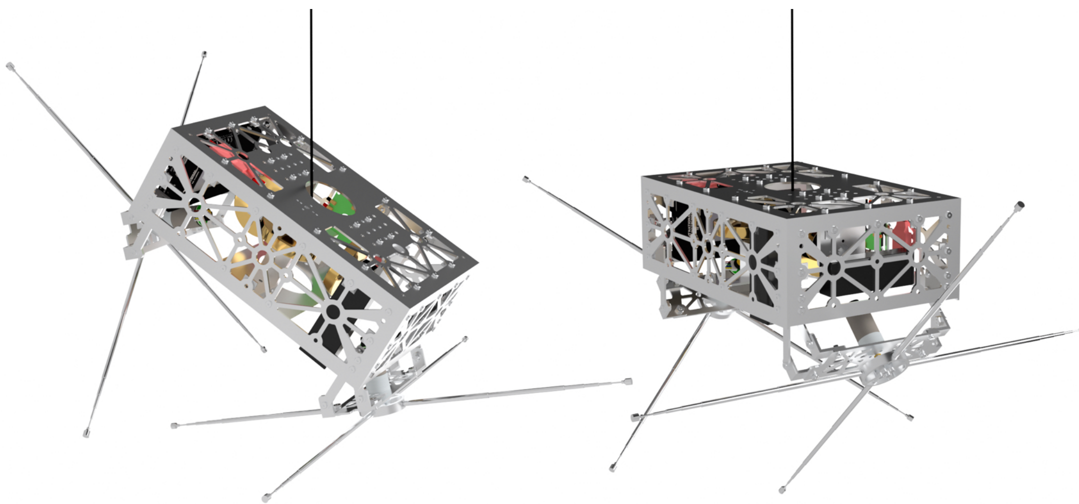

Figure 7.1: Tethered Satellite Test Configuration

## 7.3 Test Configurations

Prior to launch, the engineering team must show that the satellite is likely to accomplish its mission. Detailed tests are used to discover bugs and unexpected behavior that may jeopardize the mission. The tests should cover the range of potential scenarios the satellite may experience, but it is challenging to replicate a microgravity environment on Earth.

The majority of ADCS tests for larger satellites are done exclusively in simulation because their size makes testing inconvenient and impractical. Small satellites are easier to manipulate and can be tested on Earth to an acceptable level in a few different ways [30, 31]. Given the resources available, we examined two methods for attitude control testing: suspending the vehicle by a tether and placing the vehicle on a spherical air bearing.

### Tethered Satellite

Suspension is a simple way of testing uniaxial attitude control. The satellite can be tethered at or directly above its center of mass. Suspending the satellite from its center of mass conceptually allows for three limited rotational degrees of freedom about that point, and suspending the satellite directly above its center of mass allows for one rotational degree of freedom about the axis perpendicular to gravity.

The tethered test configuration suffers from the presence of a restoring torque on the satellite by the string. Also, hanging a satellite from its center of mass requires open access to the vehicle which is typically not possible. Despite these challenges, tethering a satellite is a quick and easy method of testing attitude control systems in one dimension.

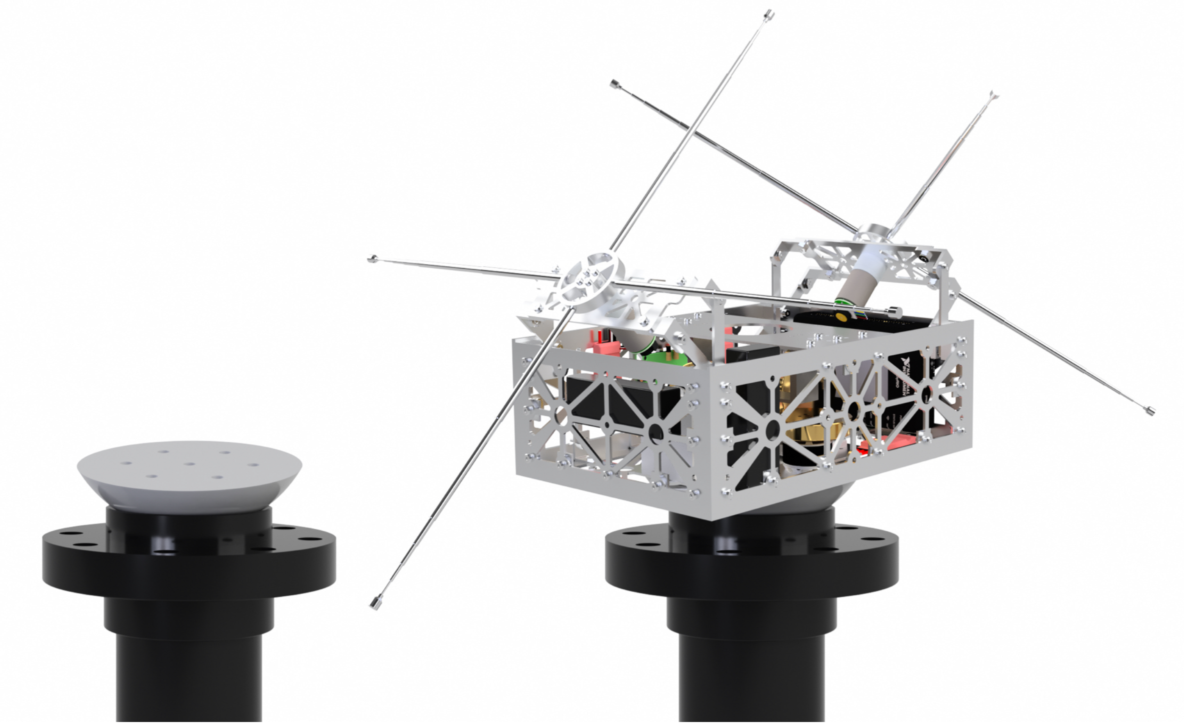

Figure 7.2: Spherical Air Bearing Test Configuration

## Spherical Air Bearing

The majority of attitude determination and control system tests for small satellites and weather balloons are done using air bearings. A spherical air bearing provides three rotational degrees of freedom. An external pressure supply routes compressed air through tiny orifices into the bearing gap, and the bearing supports a hemisphere on a thin layer of air. Air bearings have very low friction, which makes them a good method for simulating weightlessness.

There are several different ways of using a spherical air bearing for testing attitude control. The following tests place the satellite directly on top of the hemisphere. For full three axis attitude control, the center of mass of the hemisphere and satellite must be at the center of rotation or hemisphere to minimize torque due to gravity.

The movement of the orthogonal spinning sensors does shift the location of the center of mass of the satellite. To accommodate this, the sensors were replaced with disk with the same mass and moment of inertia. This provides the same vehicle dynamics but maintains the location of the center of mass.

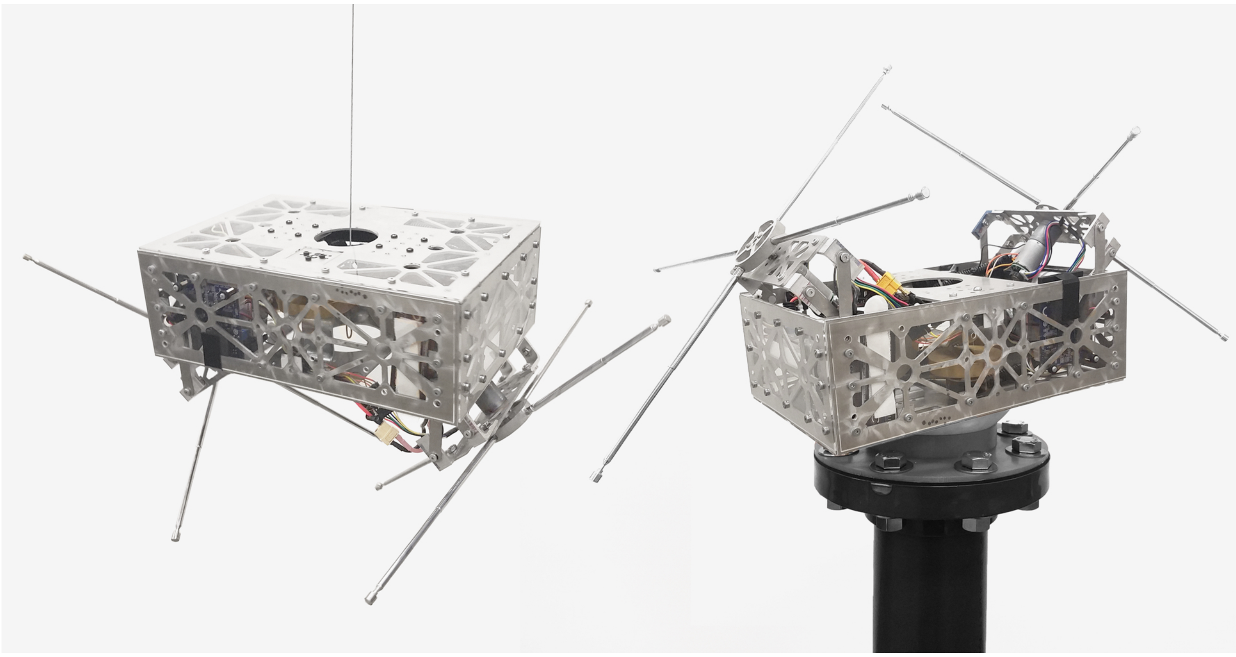

Figure 7.3: Satellite Physical Prototype Suspended by a Tether and Placed on a Spherical Air Bearing

## 7.4 Prototype Flight Vehicle

The manufactured prototype flight vehicle is shown in two test configurations in Figure 7.3. The two configurations provide similar range of motion and were equally challenging to set up. Counterweights were strategically placed on the vehicle to shift the center of mass to the center of rotation.

Tests were done for the coordinated spinning sensor system and the attitude determination and control system. In the next section, we compare the behavior of the satellite in simulation with the behavior of the satellite in real-time to verify the accuracy of our simulation models and the ability to design control systems using Modelica plant model. We also test if the momentum wheels have enough torque authority for attitude control.

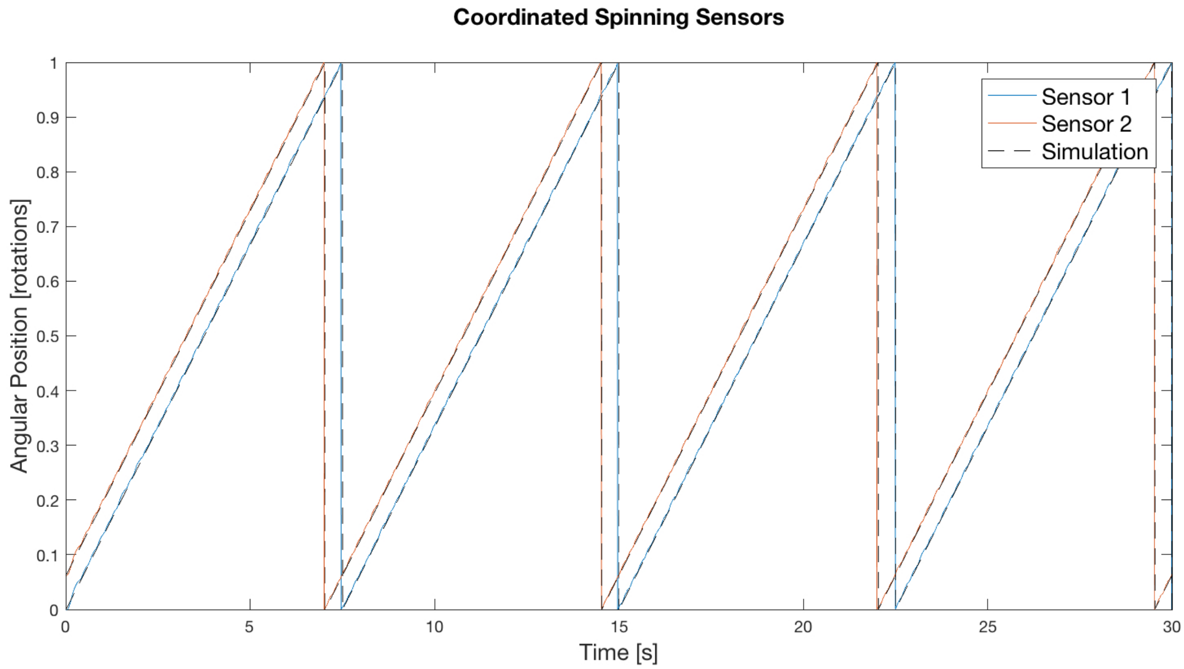


Figure 7.4: Coordinated Orthogonal Spinning Sensors Running at 8 RPM

## 7.5 Coordinated Spinning Sensors Results

The cascade position control technique described in Chapter 6 is implemented in a simulated environment using Modelica models of the sensor platform and gearmotor. The algorithm coordinates the two spinning sensors out of phase at 8 RPM.

The same control system designed using the model is applied to the real system. The simulated and measured angular position of the orthogonal spinning sensors is shown in Figure 7.4. We observe that the measured trajectories are nearly identical to the simulated trajectories. Subtle discrepancies between trajectories are likely caused by the resolution of the encoder.

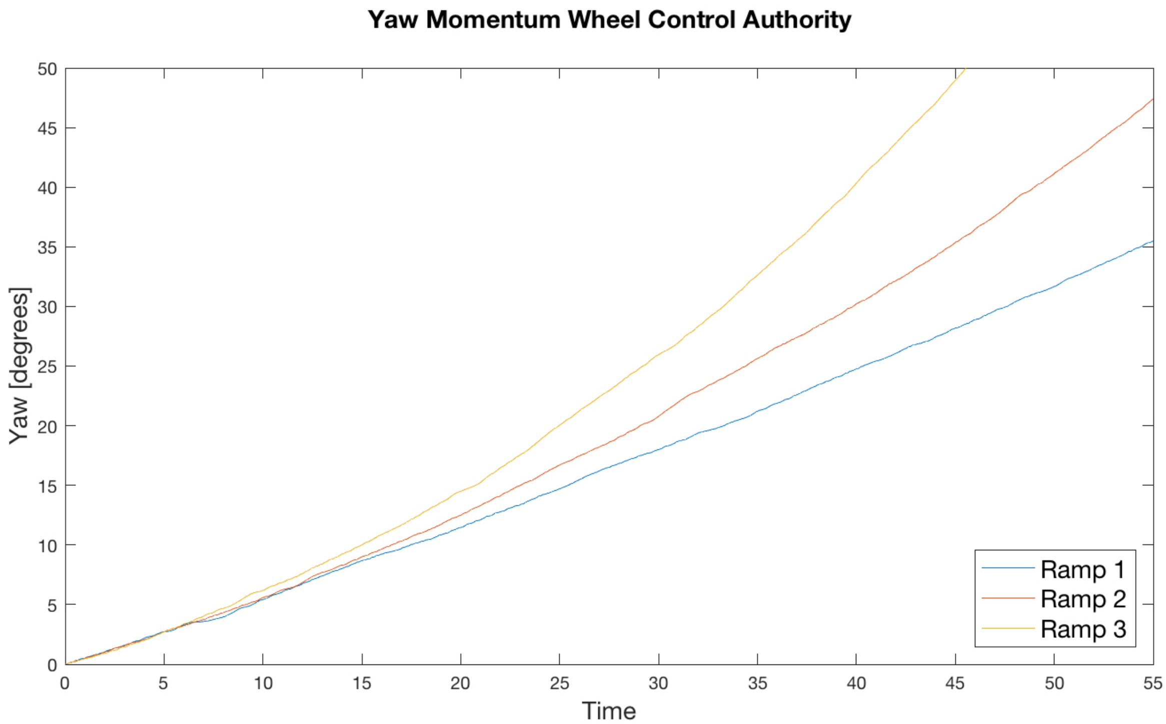


Figure 7.5: Momentum Wheel Torque Authority Analysis with Varying Ramp Rates

## 7.6 Attitude Determination and Control Results

### Open Loop Control Experiments

Prior to implementing control algorithms, it is important to check if the momentum wheels have the sufficient torque authority to counteract disturbance torques from the test configuration. Since the momentum wheels are controlled using the ESCs, the input to the brushless motor is a desired velocity. Acceleration is the derivative of velocity, so the speed of the motor is ramped with a constant slope to exert a torque.

Figure 7.5 shows a graph of the orientation of the satellite with different ramp rates, with Ramp 3 > Ramp 2 > Ramp 1. Unfortunately, the momentum wheels aligned with pitch and roll axes were unable to produce a consistent result. Further analysis of the ESCs and manipulation of the test configuration are needed for complete three axis attitude control.

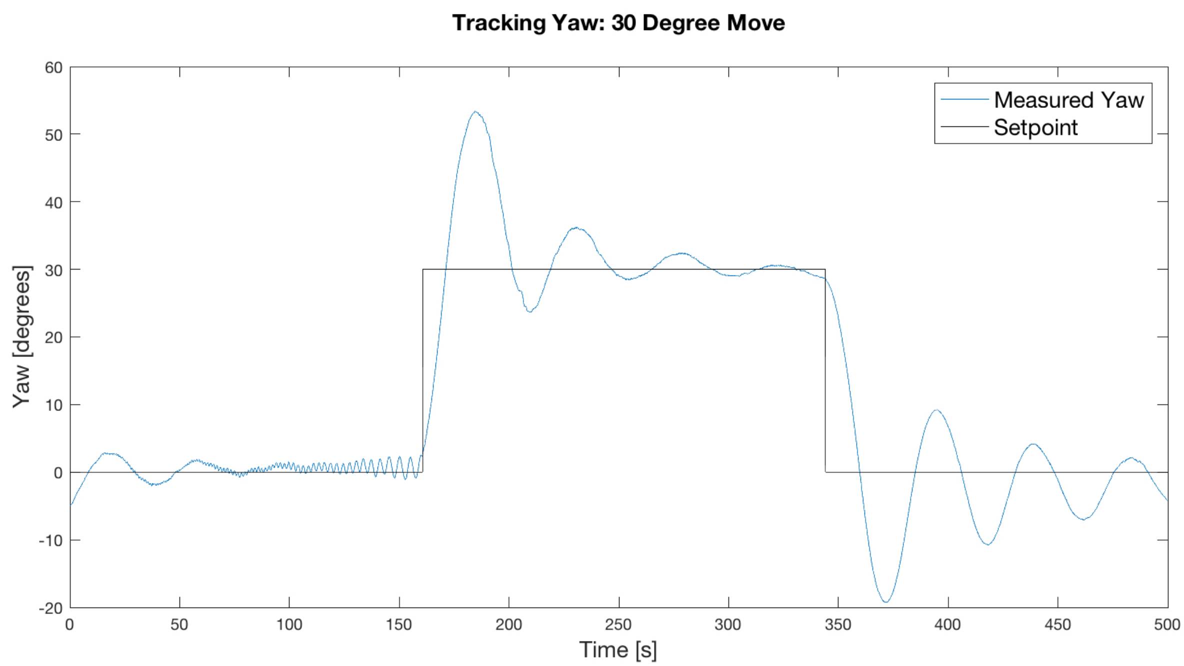


Figure 7.6: Satellite Tracking a 30 Degree Angle

## Closed Loop Feedback Control

A simple proportional position control system was applied to control the orientation of the satellite in one dimension. The satellite tracks a 30 degree pulse reference signal, and the result is shown in Figure 7.6.

The graph shows the satellite converging on the desired positions over time. Although there is significant overshoot and a long settling time, this response is actually better than expected. A proportional controller on a harmonic oscillator would not converge. This result shows that there is damping in the system from the test configuration which would not be present in space.

# Chapter 8

# Conclusion

## 8.1 Summary

This thesis shows a detailed model-based design process for a unique satellite system. We started with a concept, developed a CAD model, constructed a plant model for simulation, and tuned a control algorithm using the plant model. Then we manufactured the system and tested it with the same control algorithm developed using simulation. This case study demonstrates that the workflow simplifies the creation and use of dynamic simulations in the mechanical design process.

## 8.2 Extrapolation to Flight Vehicle

Despite the increase in the frequency of launches, it is still very expensive and difficult to send satellites to orbit. The prototype allows us to explore the main control challenges with the satellite concept and simulate the dynamics of the vehicle.

For a flight-ready vehicle, there will be more emphasis on formal requirements and specifications of the vehicle. Hardware selection must be adequate for flight. Small satellites rely on off-the-shelf components for more aggressive price points; however, each part used still requires pragmatic selection and screening. The work done here provides a first step in proposing those more expensive tests and in-depth analysis.

## 8.3 Integrated Tool Suite Development

Overall, the test suite proved very useful to the development of the prototype satellite. Each design iteration produced higher quality models and control algorithms. The project completed with a refined CAD model, dynamical model, control code, and prototype hardware. A typical prototype may not have as many elements and the end results show the benefits of a systematic Integrated Tool Suite.

Although we were able to show the entire Integrated Tool Suite workflow from CAD to control and deployment, we identified a few areas for future improvement. These areas include standards and interfaces between software tools, libraries of multimedia elements, and integration with manufacturing.

## Interfaces Between Software Tools

The workflow used shows that mechanical design often involves multiple software tools. Navigating designs through software tools is a common challenge for engineers. There are two interfaces involved in the Integrated Tool Suite: CAD to dynamics modeling and modeling to control system design.

There are three options for exchanging CAD data: direct model translation, file exchange, and third-party translators. These interfaces allow users to transfer solid models but typically do not transfer dynamic constraints between components. Because there is not a standard for CAD assemblies, it is difficult to develop a generalized translation tool from CAD to Modelica.

Functional Mock-up Interface provides a standardize means for model exchange and co-simulation of dynamic models. Many modeling and simulation tools support FMI which makes it a optimistic approach for a unified simulation environment.

## Multimedia Elements

Traditional CAD software tools do not retain detailed information about non-mechanical components of the system. These components include sensors and actuators such as the IMU, camera, and brushless motors. These components were modeled separately within the Modelica environment.

The properties of these components must also be translated into the models. This is a time-consuming process which requires relying on manufacture specifications or system identification using experimental results. There is an opportunity for manufacturers to develop models for their products specifically for users of similar design workflows.

## Direct Manufacturing

Recently, CAD solid modeling tools have been integrating computer-aided manufacturing (CAM) tools to simplify the manufacturing process. By integrating design and manufacturing, design tools can produce more accurate models of the physical component. This presents an opportunity to integrate tolerances on components and add uncertainty to the dynamical models accordingly.

## 8.4 Future Work

There are many potential directions for future development for the Integrated Tool Suite, prototype satellite with orthogonal spinning sensors, and satellite dynamic simulation tools.

The satellite developed in this case study requires many additional studies prior to being deployed. The Integrated Tool Suite can be applied to mechanical systems with more immediate use cases to showcase benefits of model-based design for rapid prototyping.

This study provides detailed analysis of the dynamics of a satellite with orthogonal spinning sensors, but we used relatively simple models and control algorithms. There are still many open questions specific to the satellite design. The current results will assist with future proposals for the development of a flight-ready vehicle.

Finally, model-based design provides an opportunity to explore more complex satellites without having flight-ready hardware. Engineer can now investigate satellites with a wider range of dynamics using simulation.

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