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Control System Development for an R-LEMA Testing Cubesat Experiment

Lucas Casaril[a], Bruno Lugnani de Souza[a], Luiz Felipe Pscheidt[a], Mairon de Souza Wolniewicz[a], Alexandro Garro Brito[a], and Gary B. Hughes[b]

[a]Federal University of Santa Catarina - UFSC, Joinville, Brazil
[b]California Polytechnic State University , San Luis Obispo, USA

ABSTRACT

This paper presents the general concepts related the control system design for a formation-flight cubesat experiment. The mission purpose is to analyze the mineral composition of asteroids, as well as to study the dynamic disturbance of a laser shot at the surface of such target. The present state-of-art of the system development, some results, future steps and challenges are discussed. The main idea is to give a general overview about the control demands and their links to the experiment requirements.

Keywords: space exploration, control systems, inertial navigation, cubesats.

1. INTRODUCTION

The Remote Laser Evaporative Molecular Absorption (R-LEMA) is a new methodology proposed to probe the molecular composition of cold targets in the Solar System through a cubesat orbiting around them. Such development is being supported by NASA Innovative Advanced Concepts Program (NIAC). To test the main concepts, a formation flight involving two cubesats was proposed. The main spacecraft includes the laser beam generator and the spectroscopy measurement. Another cubesat is used as target, simulating the shot at a real asteroid. This is a complex experiment, that blends many different tasks.

An important step on the experiment implementation is the control system development. The system shall be responsible for the individual cubesat orbital/attitude orientation, and a precise cooperative command execution as well. Due to these requirements, the control system design is an involving task which comprises many linked activities.

This paper aims to present the very initial steps for the control system implementation. The development comprises different, but highly connected, activities. They include:

1. The development of a complete orbital simulation environment. It is important to test and analyze all the control system demands during the flight, including the evolution of the satellite's flight;
2. The study of possible control actuators to be used. Two types of actuators are now under analysis: magnetorquers and reaction wheels. These are complementary systems to be used at the final prototype. However, each of them has specific demands, accuracy and implementation;
3. The implementation of an orbital dispersion simulation. Due to the laser beam impact over the target-ship, a dispersive effect is expected. It is crucial to know the magnitude of possible deviations on attitude and orbit, so that the control system can be designed to circumvent them;
4. The definition of the computational system and sensors to be used for inertial navigation. Initially, a low-cost on-board computer has been used. It is useful for the study of the main demands involving communication and computational charge issues. Then, the results will support a proper system specification. At the same time, a complete inertial navigation algorithm will be developed.

Further author information: (Send correspondence to Gary B. Hughes)
Gary B. Hughes: E-mail: gbhughes@calpoly.edu
Lucas Casaril: E-mail: lucascasaril@hotmail.com

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The paper is organized as follows. Section 2 presents the simulation environment of the satellite's flight. Section 3 presents the main ideas about the control system design and the actuator specification. Section 4 is devoted to discuss the orbital disturbance related to the laser beam impact over the target-ship. Section 5 presents the initial ideas about the navigation system and development. Finally, section 6 presents the paper conclusions.

2. ATTITUDE SIMULATION

Both modeling and simulating the orbit and attitude dynamics are crucial factors to evaluate the performance of the control techniques. The satellite's attitude is simulated by using models for aerodynamic, gravity gradient and magnetic effects. The magnetic effects can be credited to the interaction between the magnetorquers installed in the satellite's body and the geomagnetic local field experienced by the satellite in orbit. Figure 1 shows the implementation of the satellite's dynamic equations in the graphical modeling environment *Simulink*©.

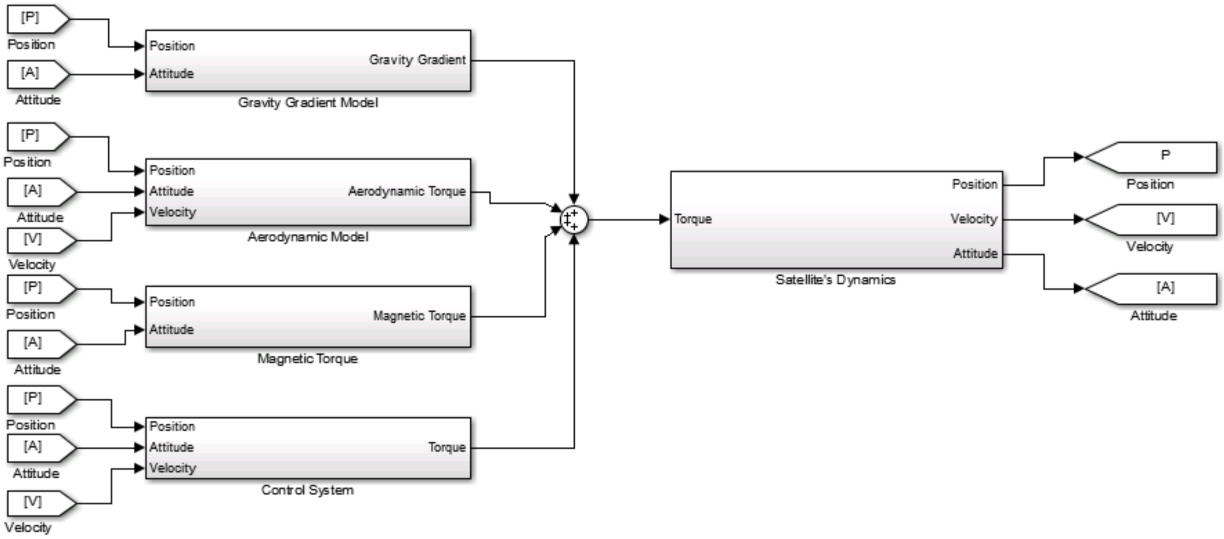

Figure 1. Simulation of Orbit and Attitude Dynamics

The satellite dynamics are defined in the 6-DOF block, which includes the following equations in body-frame coordinates.[1]

$$J \cdot \frac{d\vec{\omega}}{dt} + \vec{\omega} \times J \cdot \vec{\omega} = \vec{M}_{total} \tag{1}$$

$$\frac{d\vec{q}}{dt} = \frac{1}{2}(\vec{q}_4 \omega - \omega \times \vec{q}) \tag{2}$$

$$\frac{d\vec{q}_4}{dt} = -\frac{1}{2}\vec{\omega}^T \vec{q} \tag{3}$$

where J is the satellite inertia matrix, $\vec{\omega}$ is the body angular rate vector in body-frame, $\vec{M}_{total}$ is the total external torque vector in body-frame and $[\vec{q}\ \vec{q}_4]$ is the quaternion attitude vector in body-frame.

Such equations are used to describe and analyze the effect of several external torques that affect the satellite's attitude, through the inertia matrix. The rotational kinematic equations will specify the changes in the satellite's attitude angles as a function of the angular rates. The net torque over the satellite during its orbit is basically composed by four main factors: i)local gravity field; ii)atmospheric density; iii)local geomagnetic field; iv)control System.

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2.1 Gravity Gradient

The gravity gradient torque for an Earth-orbiting satellite is caused by differences in the distance to Earth across the satellite's body. The mass that is closer to Earth experiences higher gravitational attraction. For a given satellite geometry, the torque profile due to the gravity gradient is a function of the attitude.[1] This specific torque is a significant source of angular momentum for small satellites such as the cubesats. The gravity gradient torque is given by the following equation

$$\vec{M}_{gg} = \frac{3\mu}{R_0^3}\vec{u}_e \times J\vec{u}_e \tag{4}$$

where $\vec{M}_{gg}$ is the gravity gradient torque, $\vec{u}_e$ is the unit vector towards nadir, R_0 is the distance from the center of the Earth to the satellite, J is the inertia matrix, and μ is the geocentric gravitational constant. The vectors are expressed in body-frame coordinates.

2.2 Aerodynamic Torque

The atmosphere plays a major role in orbit decay and orbit life, mainly for low-orbit satellites. The translational forces, due to atmospheric drag, cause a decrease in velocity. This effect decreases the satellite's altitude, resulting in a premature reentry. However, the atmospheric drag also induces angular moments for an asymmetric spacecraft. The aerodynamic torque induced over the satellite's body can be expressed by the equation

$$\vec{M}_{aero} = \frac{1}{2}\rho V^2 C_d A(\vec{u}_v \times \vec{s}_{cp}) \tag{5}$$

where $\vec{M}_{aero}$ is the aerodynamic torque, ρ is the atmospheric density, V is the satellite's linear velocity, C_d is the drag coefficient, A is the satellite's effective area, $\vec{u}_v$ is the unit velocity vector, and $\vec{s}_{cp}$ is the vector from the center of pressure to the center of mass. Once again, the vectors are expressed in the body-frame.

2.3 Magnetic Torque

A known physical concept is that a magnetic dipole experiences an angular moment when immersed in a magnetic field. This is the kernel of a strategy for the control magnetic stabilization of a cubesat. The idea is to introduce magnetorquers within the satellite's body, which tends to align itself with Earth's local magnetic field during the orbital flight.

The torque experienced by the satellite due to the Earth's local magnetic fields is given by

$$\vec{M}_{magnetic} = \vec{m} \times \vec{B}_{Earth} \tag{6}$$

where $\vec{M}_{magnetic}$ is the magnetic torque vector, $\vec{m}$ is the magnetic dipole moment vector (provided by the permanent magnets), and $\vec{B}_{Earth}$ is the Earth's local magnetic flux density vector. All the vectors are in body-frame coordinates.

The Earth's magnetic field is modeled as a simple dipole (L-Shell Model). Each dipole value is obtained at a given instant, according to the satellite's position in orbit. The vector should be rotated to body-frame coordinates in accordance to the actual attitude of the satellite.

3. ACTIVE CONTROL

Analyzing the results obtained through the simulation, it is possible to design the control system that will be implemented in the cubesat. Such control system is in charge of meet the experiment's requirements. Considering the nature of the mission, a high-level of precision is necessary to achieve a successful experiment. Both spacecrafts must be aligned with each other with a precision level in the order of millimeters. Such accurate requirement demands an active control system, where the mother-ship must know, at any given time, the relative position of the target-ship. The position of the system relative to the Sun should also be known. This is because the sunlight can interfere in the spectrometer's reading.

Once the requirements are well defined, we can study the different strategies of active control. Two main types of control systems can be used to achieve the goals of the mission:

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- a propelled system, where a cold gas or a liquid fuel propellant is responsible for adjusting the satellite's attitude.

- a set of magnetorquers combined with reaction wheels.

By considering the internal space limitation into the spacecraft, the chosen strategy should achieve both the requirements of sizing and accuracy.

The magnetorquer based system consists in placing a set of three magnetorquers perpendicular to each other, one on each axis of the satellite's body. Once the magnetometer sensors get a real-time reading of the local magnetic field in three dimensions, the control system determines the resultant magnetic field vector. This is used to adjust the satellite's attitude. Then, the purpose of the control system is to correct the satellite's attitude by using a modulated internal magnetic field, which interacts itself to the Earth's field. Once the local magnetic field vector is known, the magnetorquers are activated separately and work in order to compensate the effect of the local field. Such system depends on a considerable energy supply, for it provides a relatively high torque to the system. The magnetorquer set is used to provide a raw correction on the satellite's attitude, due to its greater torque.[3]

The reaction wheels are used to actuate on the satellite once the magnetorquer system already provided a raw adjustment of the spacecraft orientation. By using the principle of angular momentum conservation, the reaction wheels are capable to provide a fine adjustment in the satellite's attitude, which is essential to the mission. The wheel system is also implemented as a perpendicular formation. However, a control strategy with an additional reaction wheel can be also considered for redundancy purposes.

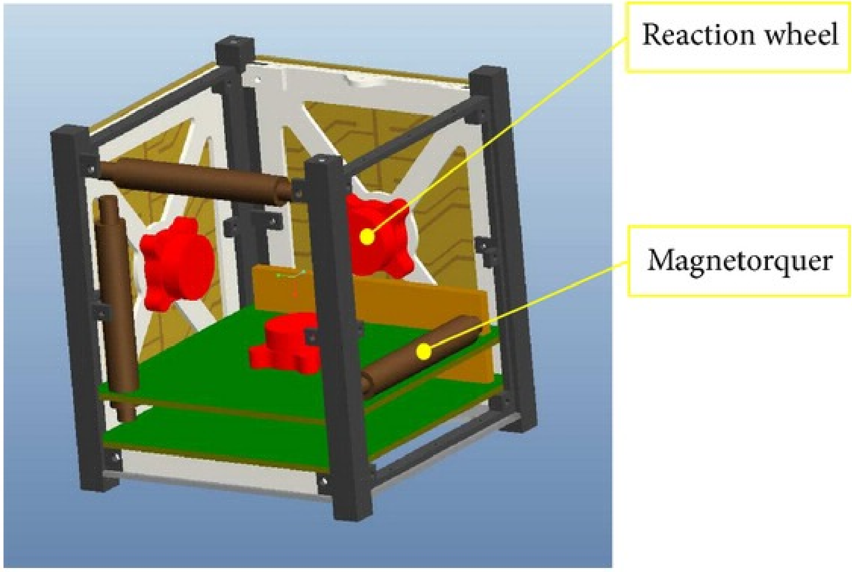

Figure 2. Example of implementation of an active control system

Both systems will be optimized based on the results of the simulation, as well as on other mission specifications.

4. ORBITAL DISTURBANCE

A laser shot at the target is necessary in order to analyze the composition of the mineral sample through spectroscopy measurement. When such laser beam hits the target sample, a resultant torque occurs on the target-ship. This torque can affect the satellite's attitude, as well as its orbit. For a better understanding of this phenomenon, a simulation was designed to study and predict the behavior of the target-ship's body. The

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ultimate goal is to determine how many shots can be fired before the satellite leave its orbit. Another aim is to determine the disturbance levels for the control system design.

Figure 3 shows a preliminary simulation of the orbit's disturbance result. The inner circle is the undisturbed orbit, and the outer circle is the orbit after the laser shot. In this case, it was used a resultant force of 10N to make the results more visible. Although this is a higher force than the possible in a real flight, it shows the influence of the laser shot force over the trajectory.

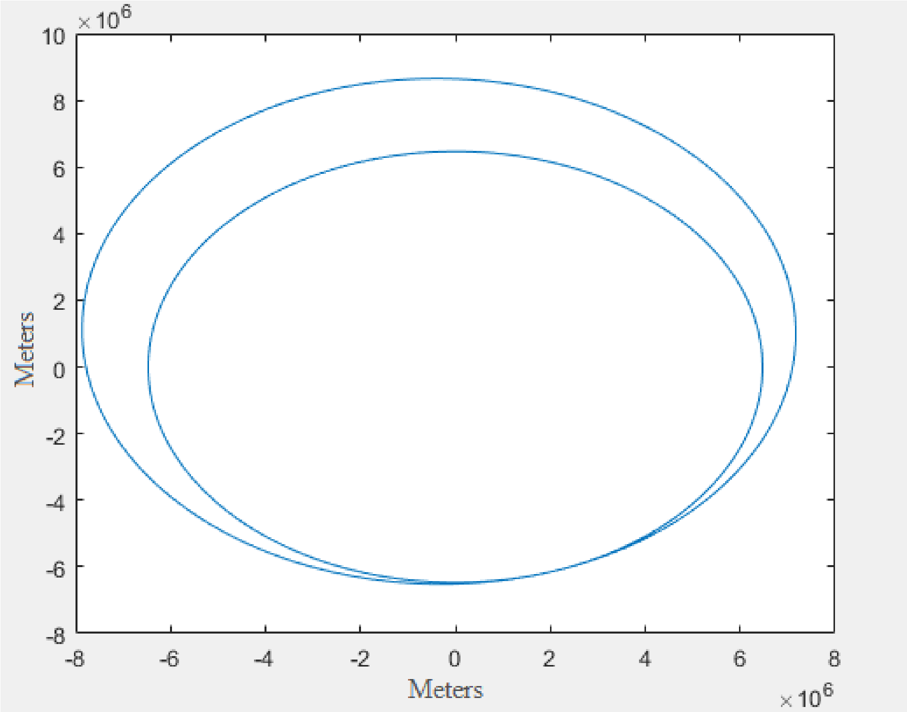

Figure 3. Preliminary orbit disturbance simulation

The idea is to develop a Monte Carlo[4] simulation aiming to study the disturbance of the satellite's orbit caused by the laser beam. A Monte Carlo simulation consists in repeating a simulation many times using random values to generate a statistic distribution of the results. For this experiment in particular, the parameter chosen was the different positions that the laser beam can hit the sample, as well as the different intensities that the laser can present.

The equations used to simulate the satellite's orbit were deducted from Newton's law of universal gravitation and Newton's second law of motion, as shown below.

$$\frac{d^2r}{dt^2} = \frac{F_r}{m} + r\frac{d\theta}{dt}^2 \tag{7}$$

$$\frac{d^2\theta}{dt^2} = \frac{1}{r} \cdot [\frac{F_\theta}{m} - 2\frac{dr}{dt}\frac{d\theta}{dt}] \tag{8}$$

A preliminary study was developed using *Simulink*©, to simulate the orbit of the target-ship, initially as a cube with a uniform mass distribution. Once the geometry of the target was defined, the disturbances caused by the laser shot were added to the equations. The applied force has arbitrary module and time interval. In order to optimize the simulation, using *matlab*©, the new code will present random values for the forces caused by the laser shot. It will calculate the disturbances and effects of the shot in the satellite's orbit. Once the results are known, the simulation will be responsible to determine exactly how many shots can be fired at the target, as well as the optimized intensity of each shot.

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The next step in the simulation is to include the real target-ship parameters. This considers the sample specification data, such as mass distribution and material density. The final task will be to make the simulation able to show a more complete information about the influence of the laser beam over the target-ship's trajectory.

5. INERTIAL NAVIGATION

The inertial navigation is very important for the mission purposes. Such system is responsible to provide the orbital and attitude orientation to the control system. Obviously, the accuracy is a major demand for such system. Two linked steps are necessary for a complete system specification: i) specification of the inertial system based on the mission requirements, and; ii) study and definition of a computational system for inertial data processing.

At this moment a low cost computer Raspberry Pi 3 is been used for the experimental studies. It is capable to send and receive data through I2C bus, and unlike same price microcontrollers like Arduino, a Raspberry Pi, it has a high processing power. This computer is useful for an initial analysis of the computational charge involved in inertial navigation. It also permits the software implementation and testing. Moreover, this computer is a reasonable solution for communication bus testing. Obviously, such computational system cannot be directly applied in a real flight. More trustful (and expensive) solutions are available for such application. However this general use onboard computer is an important tool during the system development.

The cubesat attitude is determined by inertial sensors, which measures the relative motion of the body. Due to occupied internal space and low cost technologies available, the best approach is an embedded IMU (Inertial Measurement Unity), composed by accelerometers and gyroscopes. The IMU is responsible for data acquisition, while the computer performs operations for correct attitude representation. The available IMU's provides serial bus communication (e.g. I2C and SPI).

The accelerometer[5] measures the inertial force imposed on it during discrete intervals of motion. In order to get the attitude as a function of velocity and position, a complex algorithm for data processing is necessary. The reason is the errors involved in acceleration measurement. A gyroscope is able to measure the angular attitude speed, which makes possible a frame rotation to an inertial frame in every time step.

Attitude is delivered in Euler angles form: yaw, pitch and row. This model can have a singularity error originated in $\pi/2$ and $3\pi/2$, which makes it essential to calculate motion using a quaternion system. A quaternion[6] is defined as a four dimension array, where the transformation of one frame to the other is made by rotating an angle Φ around a determined axis u, through a rotation vector. For every data sample, new quaternions are generated.

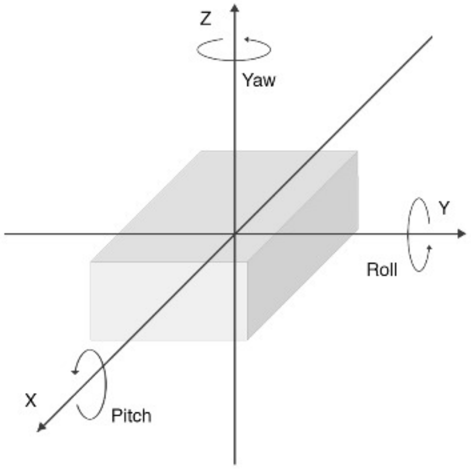

Figure 4. Satellite Axis and Euler Angles[7]

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Velocity increment in every step is calculated by integration of specific force transformed to the inertial frame. The velocity increment preserves the exact value for velocity in the presence of an acceleration change, instead of the instant acceleration.

One of the main inertial navigation problems comes through an accumulated error in the transformation matrix, determined by alignment process. However, autonomous alignment can be applied in a strap-down system. A first method applies coarse alignment based in gravity vector and Earth rotation rate vector. The fine alignment is calculated through Kalman filter,[8] based in statistics theory to estimate the body's state in the future. This information is used to correct the attitude in every iteration step, reducing the error.

Every data acquisition procedure will be initially processed by the Raspberry Pi, in software written in C. The Raspberry sends the data in real time, as it is acquired, to the attitude correction, which then proceeds to maintain the satellite's attitude as desired. The final development step will be the specification and implementation of the software at the chosen computation system to be used in the real flight.

6. CONCLUSIONS

This paper presented the initial activities related to the control system design for the R-LEMA experiment. The idea is to use two cubesats in formation flying to simulate an asteroid composition analysis. The main cubesat will have the laser beam generator and spectroscopy sensors. The target cubesat simulates a possible asteroid to be hit by the laser beam. This is a complex experiment from the control point of view, given the several pointing and positioning requirements that are involved. To permit a proper design, many steps are necessary for the control system specification. This includes, for example: i) development of a comprehensive orbital simulation, considering several environmental, physical and structural factors; ii) development and/or specification of the control system actuators and sensors; iii) implementation and testing of control system algorithms, and; iv) simulation of the target orbital disturbance due to the laser shot impact. The main ideas related with such activities are discussed herein.

The main paper aim is to discuss such control system design, by dividing important tasks in small packages. Although the state-of-art is still preliminary, the ideas presented in such paper will be the basis for the next development steps. All the control system specification will depend on the success of this initial step. The coordination of this project effort is necessary for the proposition of the final control system to be used in the experiment.

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