Attitude Determination and Control For LionSat (Local Ionospheric Measurements Satellite)

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Abstract

LionSat (Local Ionospheric Measurements Satellite) will carry two hybrid plasma probes to map plasma densities in the ram and wake directions of the vehicle's motion. This paper describes a proposed control law to reorient the spin axis and control the spin rate of the spin-stabilized satellite in LEO using two magnetic torque rods. Attitude determination will employ a three-axis magnetometer, sun sensors, and an extended Kalman filter to estimate angular velocities, which are then integrated to obtain attitude estimates. Initial estimates will be frequently updated using the TRIAD algorithm to remove accumulated errors. Sensing via the magnetometer is not possible while operating the magnetic torque rods, and attitude correction due to the control moment from the magnetic torque rods will be derived with only prediction of angular velocities. Simulation results show adequate performance for LionSat's scientific attitude control and attitude knowledge requirements.

Introduction

Penn State University's Local Ionospheric Measurements Satellite (LionSat) is a participant in the University Nanosat-3 program co-sponsored by the American Institute of Aeronautics and Astronautics (AIAA), the National Aeronautics and Space Administration's Goddard Space Flight Center (NASA/GSFC), the U.S. Air Force Office of Scientific Research (AFOSR), and the U.S. Air Force Research Laboratory Space Vehicles Directorate (AFRL/VS).

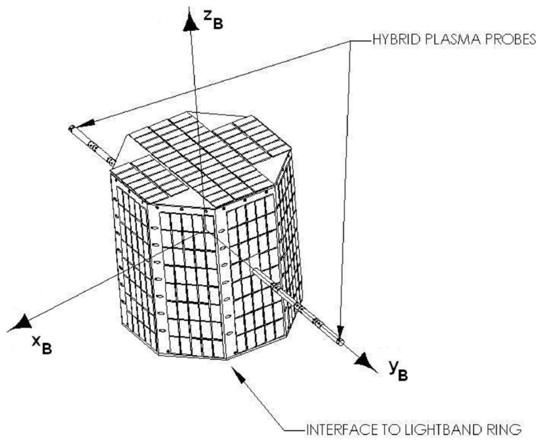

Figure 1: LionSat

As seen in Figure 1, the satellite has an octagonal shape with a height of 0.4 m., an average radius of approximately 0.2 m., and a mass of 30 kg. For purposes of making scientific measurements, the satellite is required to spin along its maximum moment-of-inertia axis, which will be designated as the z_B-axis. For an octagonal shape with uniform mass distribution, the moments of inertia have the relation $J_{x_B} = J_{y_B} > J_{z_B}$, which would make it a prolate spinner. In the case of spin stabilization with spin about the z_B-axis, energy dissipation would result in shifting its spin axis to a major moment of inertia axis (x_B or y_B). To prevent this, LionSat's mass will be distributed to make the spacecraft an oblate spinner, with a nominal inertia ratio of $J_{z_B} / J_{x_B} = 1.01$. For its scientific measurements, the satellite is required to rotate with a rate of 10 rpm, while maintaining its spin axis orbit-normal. The spin axis should be maintained within 5 degrees of the orbit normal direction, and azimuth angular position of the scientific probe should be known to within 10 degrees. To reduce complexity and to avoid problems with gyroscopic devices on spinning satellites, no gyroscopic instrument will be used. Instead, we are using three-axis magnetometer (TAM) measurements to find the angular velocity of the satellite. This angular velocity will be used to find the angular momentum vector of the satellite and will be integrated to get an attitude representation, in this case, quaternions. Since the angular measurements have some errors, the quaternions will also accumulate errors, therefore frequent updates will be applied with the TRIAD [1,2] algorithm using the sun vector and the geomagnetic field vector. We will use the term *measurement* to include collectively the physical sensing and the estimation of quantities based upon the sensed data.

Overview of Attitude Determination and Control System (ADCS)

The main goal of the attitude determination and control system is to maintain the satellite's attitude as desired at all times. Attitude sensors, algorithms to process the sensor output, control logic, and control hardware work together to achieve this.

The magnetometers provide vector measurements, and the sun sensors give an angle from a body axis with respect to the sun. Because the sun sensor is aligned with one of the body-fixed axes, the sun vector in the body-fixed coordinate frame is easily derived from the measured angle between the sensor and the sun. The ADCS makes two vector measurements each satellite rotation. These two vector measurements will be processed to find the attitude representation with respect to the inertial frame. Assuming we know the satellite's orbital elements, we can find the attitude representation of the satellite with respect to the orbit. Unfortunately, specific orbital elements will be defined by the primary payload of the launch vehicle, and because this satellite is a secondary payload, LionSat will have essentially the same orbit as the primary payload. During Earth eclipse, sun sensors will not be available, so we have only one measurement for the attitude information. We attempted to apply the magnetometer-only method [3] to determine its attitude; however, that method failed to meet the attitude determination requirements for LionSat. Instead, we use the magnetometer measurements to find angular velocities with an extended Kalman filter (EKF), and then integrate the rate into either Euler angles or quaternions.

Figure 2 shows a block diagram for the proposed ADCS system. Attitude control will generate commands for the control action, and these commands will be produced with attitude information from either the attitude determination or attitude prediction. Outputs from the attitude determination, $\hat{\vec{\omega}}$ and $\hat{\vec{q}}$, correspond to the updated angular velocity and quaternions, respectively, with data either from the sun sensor, the magnetometer, or from both. The angular velocity and quaternion ($\vec{\omega}^{-}$ and $\vec{q}^{-}$) from the attitude predictions correspond to projection ahead without data because either the sun is not available or the magnetometer is off due to magnetic torque rod operations.

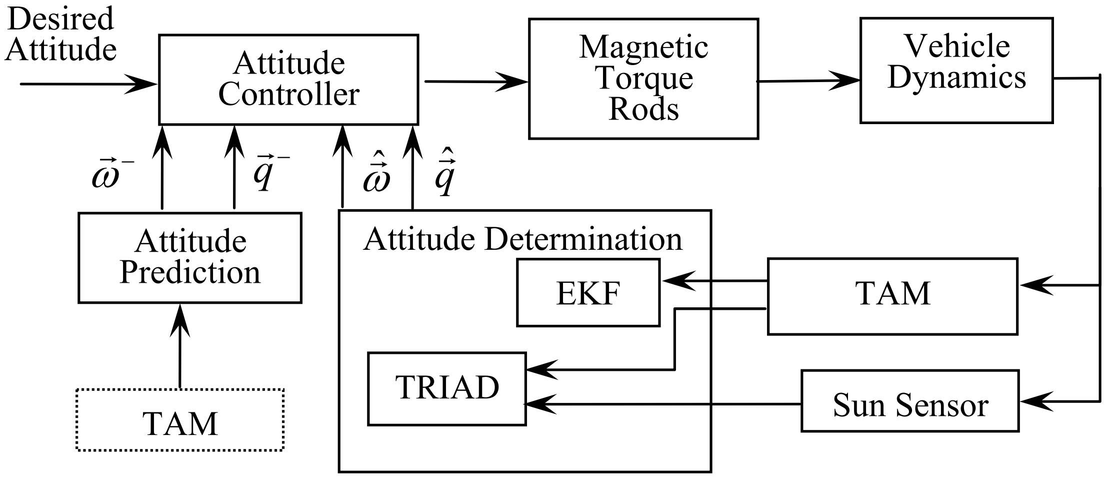

Figure 2: Attitude Determination

Control torque to change orientation will be provided with two independently-operated magnetic torque rods, which are installed parallel and normal to the spin axis. Simple control logic will turn the rods on and off, changing their polarities if necessary. The magnetic moment of the rods will interact with the geomagnetic field to generate the required torque.

Since the control hardware and sensors use the magnetic field, once the control hardware activates, no reliable measurements of the geomagnetic field can be made. Therefore, the control logic will use only propagated attitude and angular velocities, then periodically update the attitude as necessary, while keeping the control hardware off. From a computer simulation, the optimal time interval between updates will be determined.

Basically, considering the spin-stabilized attitude with the axisymmetric configuration, the spin axis will stay fixed in the inertia frame. Anticipated external or internal torque will cause precession of the spin axis, but not cause the spin axis to drift in the inertial frame. Therefore, the major reason the spin axis drifts from the desired orientation (orbit-normal) is the regression of the ascending node of the orbit due to Earth-oblateness. At 400 km altitude and 52 degrees inclination, we have a regression rate of 5 degrees per day. Program requirements dictate an initial deployment with the spin axis in the orbital plane; consequently, the ADCS must first reorient the vehicle by 90 degrees (Figure 3). Once the desired attitude is achieved after the separation from a launch vehicle, very little control action will be necessary. Therefore, for most of the time in the orbit, the magnetometer will be available to find the angular velocity and attitude.

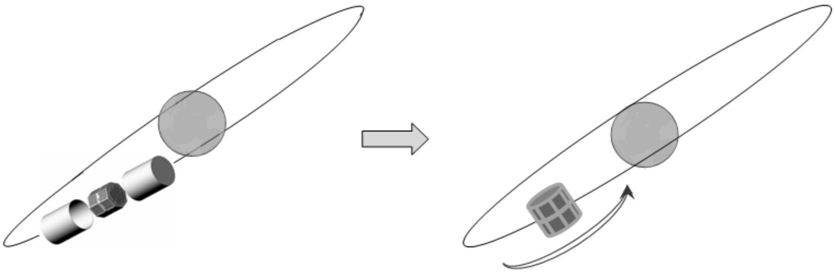

Figure 3: Spin Axis Reorientation

Angular velocity measurement

The most crucial task for the successful simulation depends on the accuracy level of the angular velocity measurements, which are used to project the quaternions ahead. Therefore, the accuracy level of the measurement of the angular velocity decides the accuracy of the attitude control. As mentioned before, angular measurements are done with the EKF, and to prevent any possibility of divergence of the EKF, it resets itself whenever it starts a new measurement right after the magnetic torque rods are used for attitude control. Thus, one can see damping periodically on a plot of angular velocity, such as in Figure 4, where ω_1 is the angular velocity about the x_B axis. Measurement errors for angular velocities about the transverse axes (x_B, y_B) fall within 0.05 degrees per second, while the error levels for spin rate (ω_3 about the z_B-axis) are found to vary from 0 to 0.2 degrees per second, with a worst case of 0.5 degrees per second. We use a modified version of the method described by Tortora and Oshman [4] to estimate the angular velocity.

Control scheme

Shiegehara [5], using the angular momentum vector as a control error function, proposed the control logic we are applying to LionSat. It permits spin rate and spin axis reorientation control with two magnetic dipoles. This control law uses a switching function to change the polarity of the dipoles to generate the desired torque. The switching functions are defined as

$$S_{orient} = \vec{E} \cdot \left(\hat{z}_B \times \vec{B}\right), \begin{cases} \vec{U} = \alpha^2 \hat{z}_B \text{ if } S_{orient} > 0 \\ \vec{U} = -\alpha^2 \hat{z}_B \text{ if } S_{orient} < 0 \end{cases} \text{(spin - axis orient. control)} \quad (1)$$

$$S_{spin} = \vec{E} \cdot \left(\hat{x}_B \times \vec{B}\right), \begin{cases} \vec{V} = \beta^2 \hat{x}_B \text{ if } S_{spin} > 0 \\ \vec{V} = -\beta^2 \hat{x}_B \text{ if } S_{spin} < 0 \end{cases} \text{(spin - rate control)} \quad (2)$$

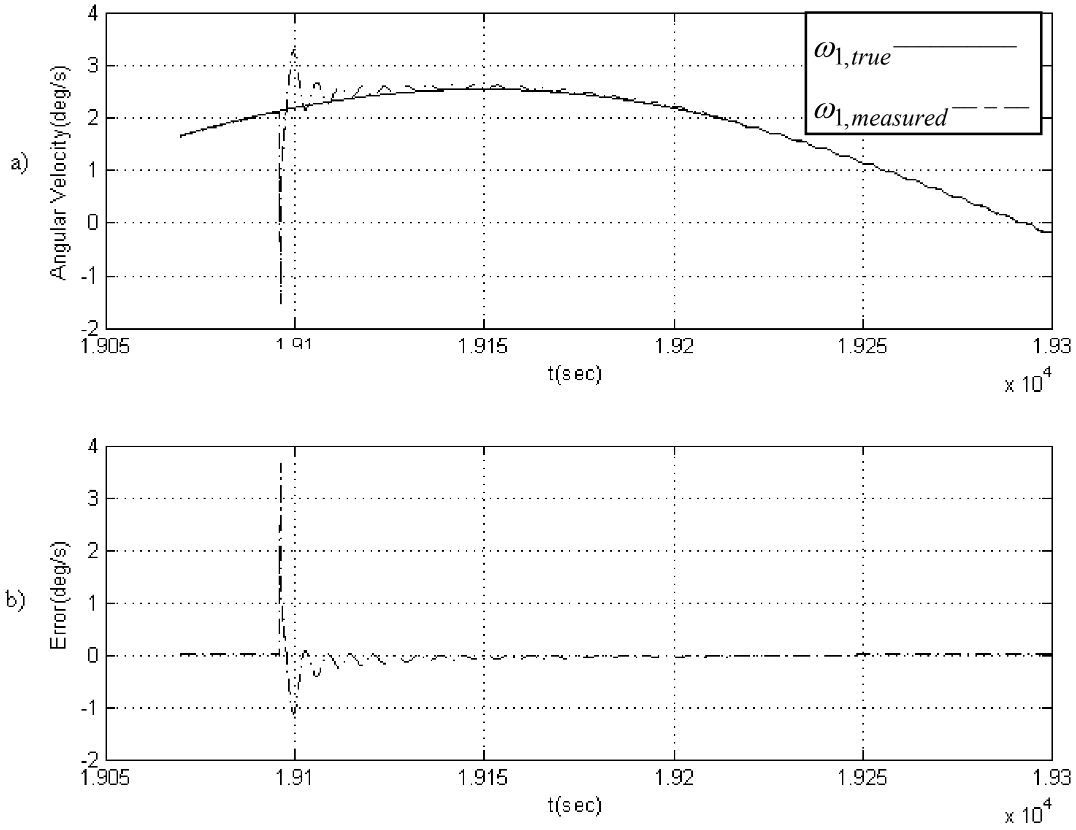

Figure 4: Angular Velocity Measurement

where $\vec{E}$ is the angular momentum error (difference between desired and actual), $\vec{B}$ is the geomagnetic field vector, $\hat{x}_B$ and $\hat{z}_B$ are unit vectors aligned with the respective body-fixed axes, and $\vec{U}$ and $\vec{V}$ are the magnetic moment vectors along the $\hat{z}_B$ and $\hat{x}_B$ axes, respectively, generated by the torque rods.

To have a nutation damping effect, the generated torque should have the opposite direction to $\vec{\omega}_{12}$ (the component of $\vec{\omega}$ in the x_B-y_B plane). For each nutation ($\vec{\omega}_{12}$ makes one revolution around the spin axis), the magnetic torque $\vec{U} \times \vec{B}$ can be assumed constant in magnitude and the angle ψ is the angular position of $\vec{\omega}_{12}$ in the x_B-y_B plane. Then, in order to act as a nutation damper, $\oint \left(\vec{U} \times \vec{B}\right) \cdot \vec{\omega}_{12} d\psi$ must have a negative value, which means that the net torque for each nutation has the opposite direction of $\vec{\omega}_{12}$. But since $\oint \cos\psi \, d\psi = 0$, it follows that $\oint \left(\vec{U} \times \vec{B}\right) \cdot \vec{\omega}_{12} \, d\psi = 0$, meaning that no damping effect can be expected while generating torque for spin reorientation. Therefore, an additional switching function used mainly for nutation damping is introduced, defined as

$$S_{damp} = \vec{\omega}_{12} \cdot \left(\hat{z}_B \times \vec{B}\right), \begin{cases} \vec{U} = -\alpha^2 \hat{z}_B \text{ if } S_{damp} \geq 0 \\ \vec{U} = -\alpha^2 \hat{z}_B \text{ if } S_{damp} < 0 \end{cases} \text{(nutation damping)} \tag{3}$$

This switching function doesn't involve the error vector used in Eqs. (1) and (2), but uses only angular velocity. This is important because nutation damping can be activated at any attitude, even when the error vector cannot be defined such that the angular momentum vector exactly matches the desired vector. This switching function will be used for both spin-axis reorientation and spin rate change. Once the magnitude of $\vec{\omega}_{12}$ reaches a predetermined maximum limit, for instance 3 deg/sec, S_{orient} and S_{spin} will be deactivated and the torque rod parallel to $\hat{z}_B$ will be controlled by S_{damp} to make $\oint \left(\vec{U} \times \vec{B}\right) \cdot \vec{\omega}_{12} \, d\psi < 0$. As $\left|\vec{\omega}_{12}\right|$ decreases to the lower limit, for example 0.3 deg/sec, the normal attitude correction resumes.

Simulation results

A simulation study of up to 8 orbits indicates that the proposed measurement and control schemes will permit LionSat to meet the scientific requirements. The vehicle is deployed into a 400 km. altitude circular orbit, with inclination of 52 degrees; at the time of deployment, the orbital plane is parallel to the sun vector.

Figure 5 shows the difference between the true x_B and the measured x_B axes, and the true z_B and measured z_B axes. Measurements for both cases can be made within a 1.5 degree error when the periodic TRIAD update can be made. For the case where the TRIAD update cannot be made (such as when the satellite goes in the eclipse or the torque rods start to operate) errors accumulate as seen in Figure 6.

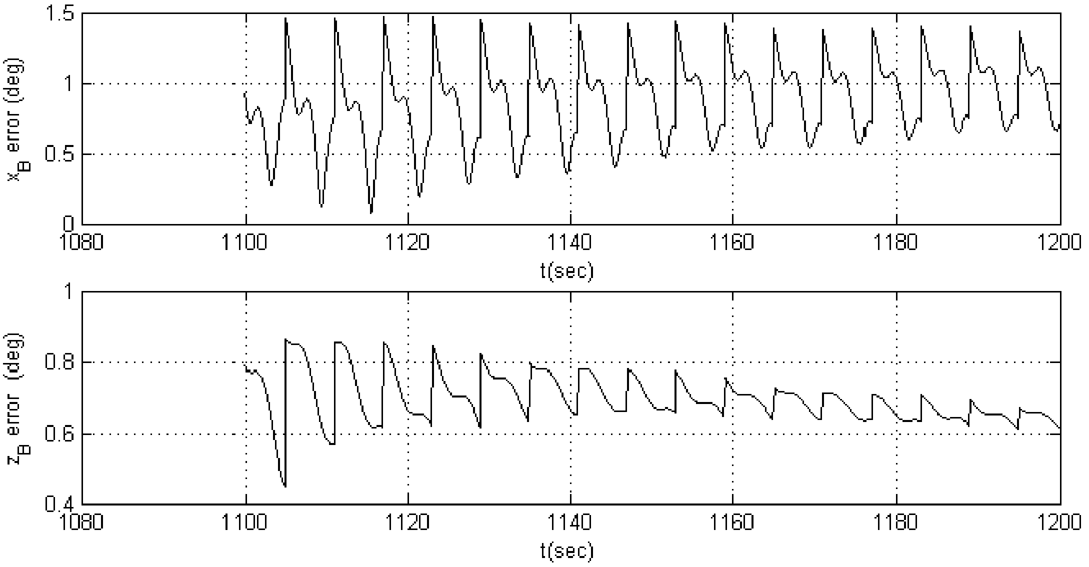

Figure 5: Attitude Accuracy With TRIAD

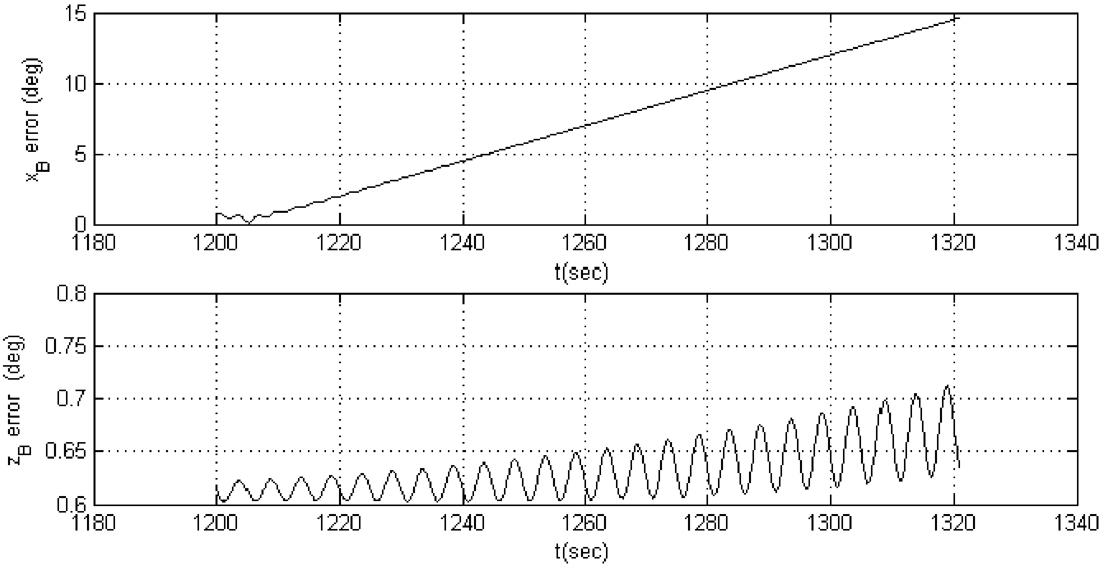

Figure 6: Attitude Accuracy Without TRIAD

For the initial reorientation manoeuvre, Figure 7 shows that the spin axis can be precessed to within 5 degrees of orbit-normal in approximately 4 orbits. Note that this manoeuvre includes intervals of eclipse, during which no control action occurs.

In the event that the deployment mechanism provides an initial spin rate of only 5 rpm, a spin-up manoeuvre will be required. Simulations for this mode (Figure 8) show that this can be accomplished in approximately 2 orbits.

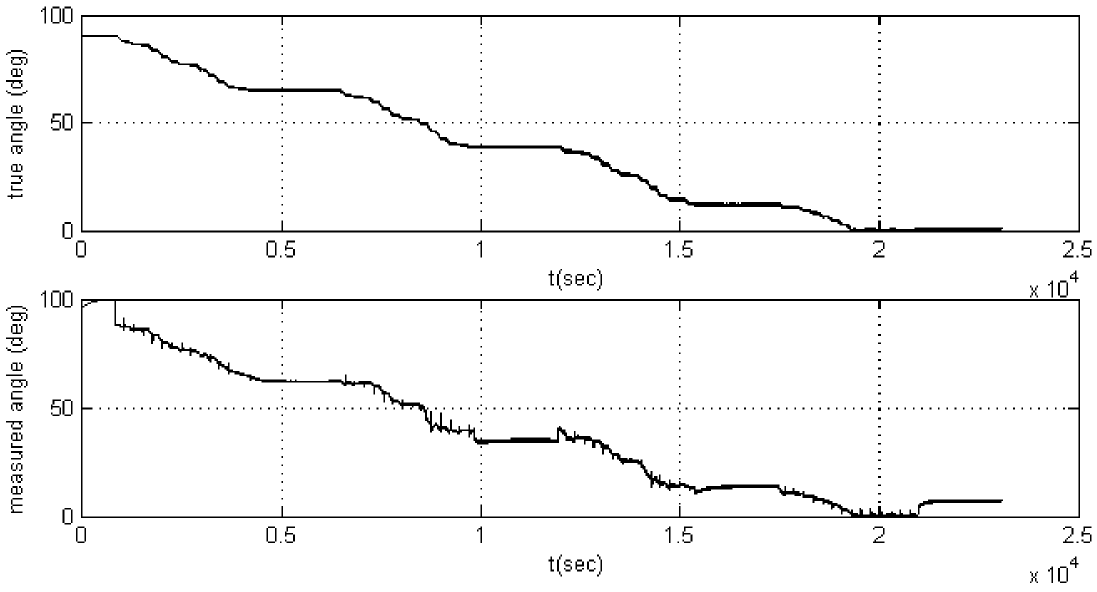

Figure 7: Angle Between z_B-axis and Orbit-Normal

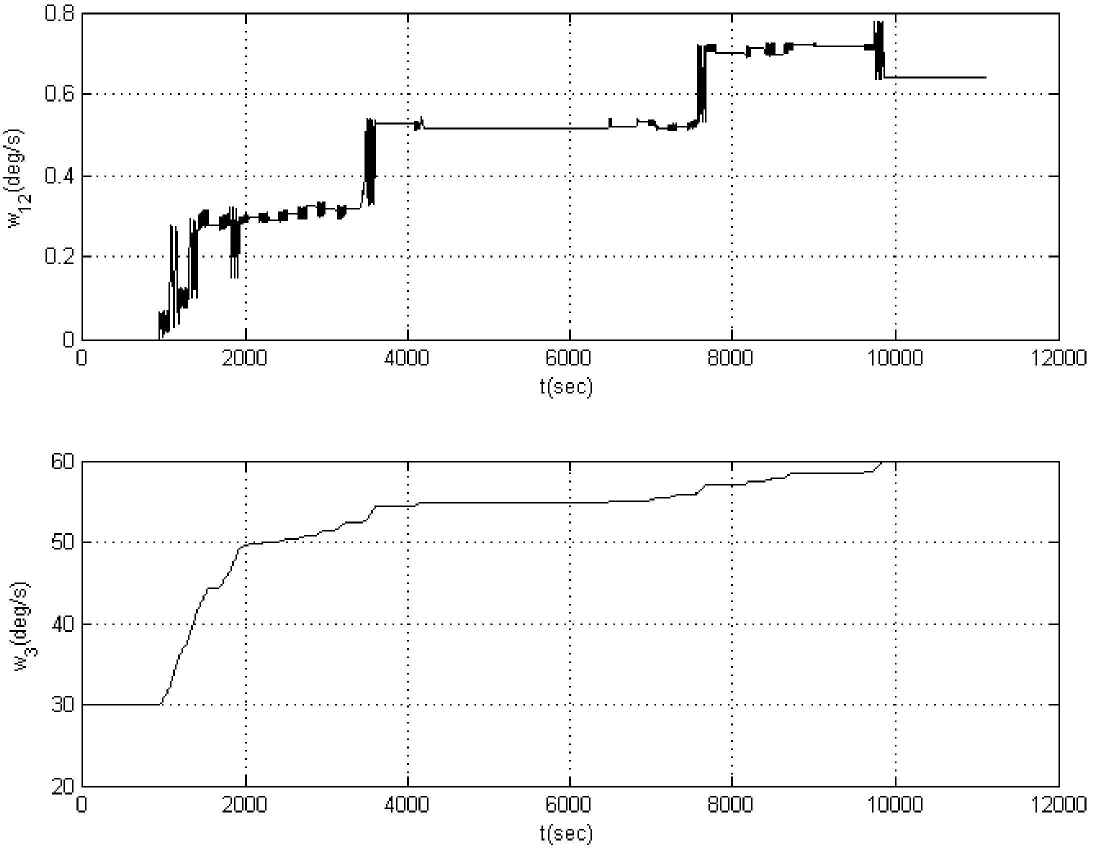

Figure 8: Angular Velocities During Spin-Up Manoeuvre

Finally, Figures 9 and 10 indicate the effects of omitting/including the nutation damping control mode. In this simulation, it is assumed that TRIAD updates are completed every 2 minutes (except during Earth eclipse). Clearly, omitting the nutation damping mode results in some divergence (with approximately equal inertias, and angular velocities of $\omega_{12} = 7$ deg/s, and $\omega_3 = 60$ deg/s after one orbit, the nutation angle is 7 degrees). Including the damping mode can drive that nutation angle down to 0.5 deg. in 1000 sec. during the sunlit portion of the orbit.

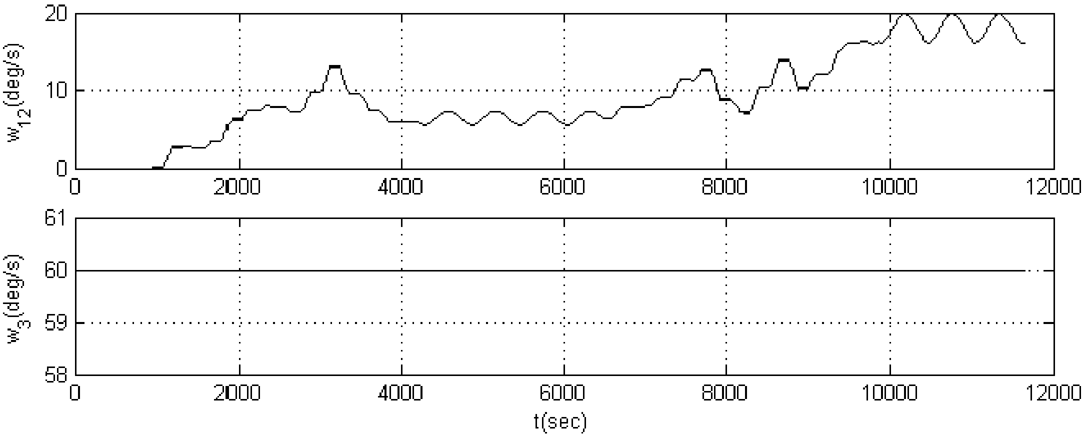

Figure 9: Angular Velocities Without Damping

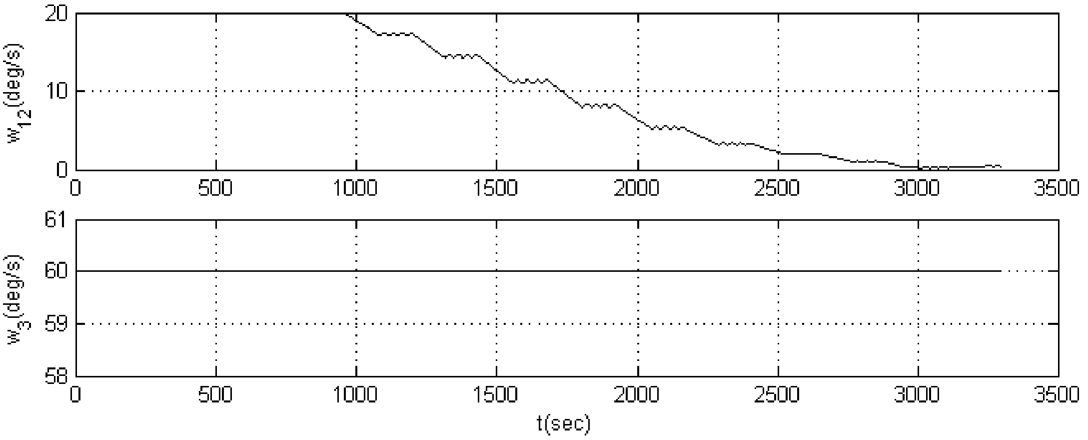

Figure 10: Angular Velocities With Damping

Conclusions

Attitude determination and control for a low-budget nanosatellite is possible using a combination of magnetic and sun sensors and an extended Kalman filter. In the particular application of LionSat, attitude sensing and control functions must be alternated to avoid magnetic interference; ongoing analysis and systems integration may reveal a similar need for alternating periods of scientific data acquisition and attitude prediction to preclude interaction between the plasma probes and the magnetometer.

Acknowledgment

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