Attitude Control of the Sunjammer Solar Sail Mission

Ofer Eldad, E. Glenn Lightsey
Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin
210 East 24th Street Room 412D, Austin, TX 78712; (512) 704-4595
ofer.eldad@utexas.edu

ABSTRACT

Sunjammer is a NASA technology demonstration mission that will demonstrate the potential for solar sail propulsion using a 1200 m^2 sail. Attitude control of the sail is achieved by changing the four 15m^2 boom-tip vanes' orientation relative to the satellite-Sun vector. A control scheme has been developed that incorporates passive stability about two axes and utilization of equilibrium-trim angles alongside a proportional-derivative (PD) controller. The attitude control system employs predetermined trim vane angles to maneuver the vehicle to a desired attitude. By observing the command history of the PD controller that maintains the desired attitude, these predetermined vane angles are adjusted autonomously. This adjustment allows for errors in sail force and moment characterization to be conducted on-orbit and provides a reduction of the required control effort. This control scheme is shown to be well suited in handling experimentally derived sail force and moment coefficients that do not assume a simplified flat-plate model. System performance is evaluated using test reorientation maneuvers and robustness is checked against various modeling uncertainties. Through simulation, the attitude control algorithm is shown to achieve better than a 2 degree pointing accuracy in the presence of expected environmental disturbances.

INTRODUCTION

Solar sailing provides an alternative to rocket propulsion by utilizing the constant solar radiation pressure provided by the Sun. By exploiting the momentum carried by photons from the Sun, spacecraft that utilize solar sails have the potential of traveling to regions currently unreachable by conventional forms of propulsion. Controlling the orientation of the sail can increase, decrease, or change the direction of the spacecraft's angular momentum about the Sun, thus enabling diverse navigational possibilities and unique non-Keplerian orbits [1]. With the increased capabilities of smaller and smaller payloads [2], solar sails become an increasingly viable option for a variety of missions. Meaningful missions are becoming achievable with physically realizable solar sails.

Sunjammer is NASA's first solar sailing technology demonstration mission to fly in deep space and, once deployed, will be the largest solar sail flown to date. L'Garde is the prime contractor for this mission. Design and development of Sunjammer's flight software was tasked to Micro Aerospace Solutions and Alidyne Consulting with attitude determination and control algorithm development tasked to the authors. Sunjammer will fly towards the Sun-Earth L_1 point and demonstrate deployment of a $1200m^2$ sail. The mission objectives include executing a maneuver sequence requiring propellantless attitude control to an accuracy of better than 2°. Attitude control is achieved through the use of four reflective boom-tip mounted vanes shown in Figure 1, each with an area of approximately $15m^2$.

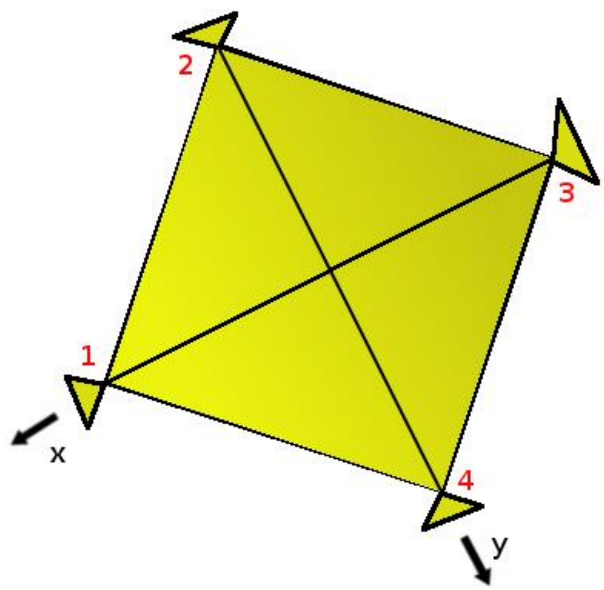

Figure 1: Sunjammer square sail with 4 boom-tip mounted vanes

The control vanes can be canted about the vane's y-axis twirled about the vane's x-axis shown in Figure 2, providing two degrees of freedom per vane.

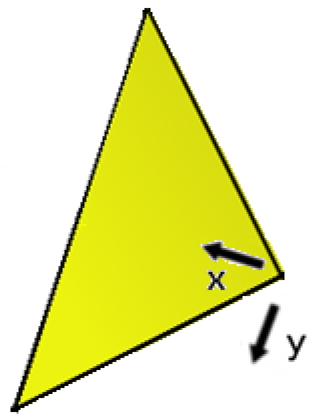

Figure 2: Control vane axes definition

The attitude control algorithm is based on the concept of trim angles developed by Derbes [3]. It has been extended to allow for closed-loop attitude control of the sail and accommodate uncertainties in the sail and vane force and moment model through autonomous adjustment of the trim angles. The use of trim angles allows for active control about a passively stable equilibrium point. On-board attitude determination and control is performed using attitude quaternions, however, in this paper attitude is described by 3 Euler angles: top angle, Sun-incidence angle, and flat-spin angle that represent a 3-2-3 rotation sequence relative to a Sun-pointing orientation [4]. Therefore, when the three angles are identically zero, the sailcraft surface normal is pointed directly at the Sun.

Throughout this paper, the various components of the controller are examined through the simulation of the typical attitude maneuver. This maneuver reorients the spacecraft from an initial Sun-pointing orientation to a desired orientation with a top angle of 10°, a Sun-incidence angle of 35°, and a flat-spin angle of 0°. This maneuver was chosen since it is one of the baseline reorientations that will be performed by the spacecraft during Sunjammer's mission. A Sun-incidence angle of approximately 35° maximizes the effect of the solar radiation pressure on the spacecraft's angular momentum [1], and so this attitude will provide the most propulsion to the spacecraft.

The simulation uses a model of the sensors and actuators chosen for the Sunjammer mission which incorporates the expected errors associated with each component. The spacecraft is modeled as a rigid body. Motion of the control vanes is limited to one command every 400 seconds and the control gains are chosen such that the spacecraft rotates slowly. Although a detailed structural analysis has not yet been completed, limiting the motion of the control vanes serves to induce fewer moments on the structure that may in turn induce flexible-body modes.

ATTITUDE DETERMINATION

Attitude determination is performed using the Sequential Optimal Attitude Recursion filter (SOAR), developed by Christian and Lightsey [5]. The filter combines measurements from a star tracker and Sun sensor to arrive at an estimate of the quaternion rotation relative to an ECI frame. The 1σ bound on the quaternion estimate is approximately 30 arc-seconds.

Direct measurements of the spacecraft's angular velocity are not available with the sensors that are provided, and angular velocity is therefore derived from the quaternion measurements according to Equation 1.

$$\hat{\boldsymbol{\omega}} = 2\dot{\hat{\tilde{\boldsymbol{q}}}} \otimes \hat{\tilde{\boldsymbol{q}}}_{\boldsymbol{avg}}^{-1} \tag{1}$$

Where $\dot{\hat{\tilde{\boldsymbol{q}}}}$ is the derivative of the quaternion estimate, $\tilde{\boldsymbol{q}}_{\boldsymbol{avg}}^{-1}$ is the inverse of the average quaternion, and $\otimes$ denotes the quaternion product operator.

Since the controller only requires the angular velocity estimate once every 400 seconds in the current implementation, there is some flexibility when calculating the derivative of the attitude quaternion which is measured twice a second. In the standard form of the derivative shown in Equation 2,

$$\dot{\hat{\tilde{\boldsymbol{q}}}} = \frac{\Delta \boldsymbol{q}}{\Delta t} \tag{2}$$

the time between measurements can be varied. A larger Δt allows for the attitude of the spacecraft to change enough such that the angular velocity is observable above the noise in the measurements. Naturally, taking this derivative over a longer time period to reduce noise is a tradeoff with a lag of the estimated angular velocity behind the true angular velocity.

The expected maneuvers during Sunjammer's mission require faster maneuvers about the spacecraft's y-axis than the x- and z- axes. Therefore, the chosen time interval used in the derivative process is 100 seconds for the y-axis and the full 400 seconds available between actuations for the x- and z- axes.

Using these values, the derived angular velocity was shown to be sufficiently accurate for use in the PD controller discussed below.

FORCE AND MOMENT MODEL

The sail forces and moments generated by the control vanes and main sail were experimentally derived and provided by L'Garde. They include effects of non-perfect reflection and shape-induced effects. The on-board controller therefore does not calculate forces and moments based on an analytical model, but instead employs a lookup table that is accessed according to each surface's orientation relative to the Sun. The moments and forces are stored as non-dimensional coefficients that are normalized by a reference area of the sail and represent forces and moments when the sail is located at a distance of 1 Astronomical Unit (AU) from the Sun as shown in Equation 3 and 4:

$$\boldsymbol{F} = c_f P A \tag{3}$$

$$\boldsymbol{M} = c_m P A^{1.5} \tag{4}$$

Where c_f and c_m are the force and moment coefficients, A is the reference area of the sail and P is the solar radiation pressure defined by Equation 5,

$$\boldsymbol{P} = \frac{W_E}{c}\left(\frac{r_E}{r_{/Sun}}\right)^2 \tag{5}$$

Where W_E is the energy flux measured at the Earth's distance from the Sun, c is the speed of light, r_E is the average distance between the Earth and the Sun, and $r_{/Sun}$ is the current distance between the spacecraft and the Sun.

Incorporating a non-idealized sail force model is essential in creating a useable solar sail control algorithm. An important feature of the imperfect sail is a restoring moment that is generated when the sail normal vector is not directly pointing towards the Sun.

TRIM ANGLES

In order to counteract the restoring moment generated by the sail while minimizing the required motion in the vanes, Sunjammer's attitude control system utilizes trim angles of the vanes. In the trim orientation, the net moment acting on the center of mass is zero. A trim table is calculated a priori based on the model of the forces and moments generated on the sail and vanes at each orientation of the main sail relative to the Sun. The trim orientation is used whenever the desired moment calculated by the control law is below a pre-determined threshold.

Utilizing trim angles allows the PD controller to operate about an equilibrium position. This removes the effects of the restoring moments caused by the CM-CP offset, the imperfect optical properties of the sail, and the deviation of the true sail shape from that of a flat plate under the effect of the solar radiation pressure. However, populating an a priori trim table requires a force and moment model sufficiently accurate to determine the equilibrium position of the vanes. During development of the controller, its performance was seen to be sensitive to small deviations of the trim table from the truth. Deviations are expected to occur due to static bending and twisting of the booms, wrinkling of the sail material, and other simplifications made in the modeling process.

AUTONOMOUS UPDATE OF THE TRIM CONDITION

To address the sensitivity of the controller to small errors in the trim table, the table is autonomously updated. The controller calculates a moving average of the commanded vane angle history and uses that average to determine what the true trim condition must be. The trim table thus converges on the true trim orientation and motion of the vanes is minimized.

Figure 3 shows this convergence from the a priori trim value for cant angle of vane 1 from 4° to the true orientation that minimizes moment about the y-axis of approximately -6°.

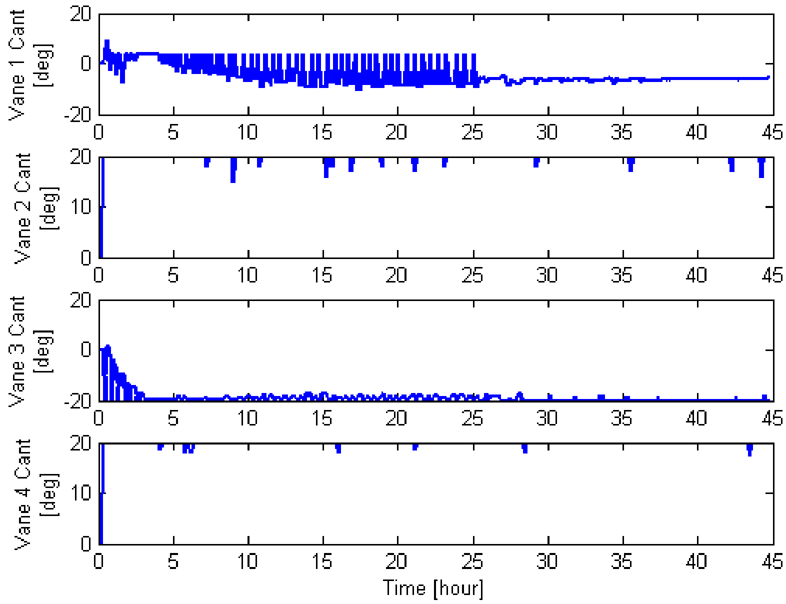

Figure 3: Vane angles following autonomous adjustment of trim angles

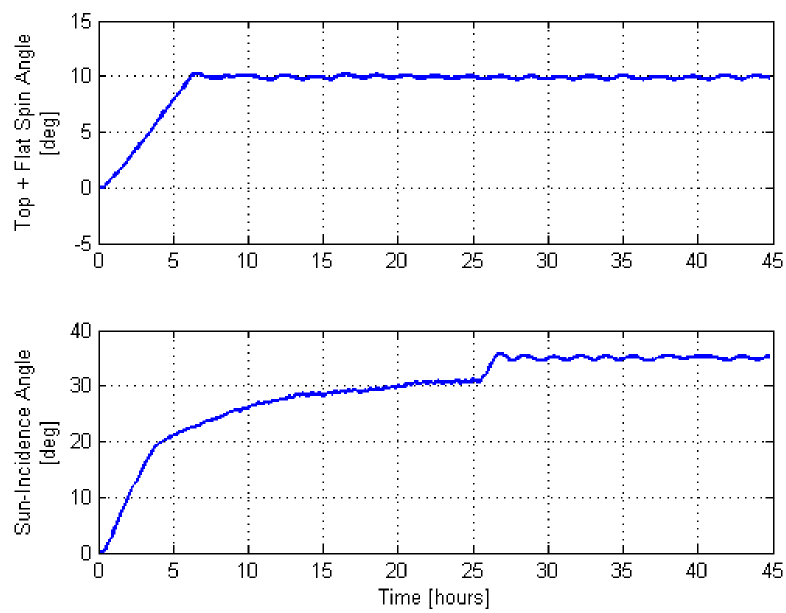

Figure 4: Resulting motion of the spacecraft with autonomous adjustment of trim angles

Adjustment of vane 1's trim angle begins at t = 25 hours in order to demonstrate the difference between the required control before and after the adjustment. The attitude of the sail is shown in Figure 4. It can be seen that using a trim angle that is initially incorrect by 10° results in a steady-state attitude error of about 5° in the Sun-incidence angle. Additionally, it is clear that the required vane motion in both vanes 1 and 3 is significantly smaller once operating about the true trim orientation of the vanes. Once the trim angles are autonomously adjusted, the attitude converges to within the desired error bound.

CONTROL LAW

The control law used to determine the desired moment about each axis is a traditional proportional-derivative (PD) controller with a saturation function on the proportional error designed to limit the angular velocity obtained by the solar sail during a re-orientation maneuver. The control law is described by Wie [6]:

$$\boldsymbol{u} = -Ksat(P\boldsymbol{q}_{err}) - C\boldsymbol{\omega}_{err} \quad (6)$$

Where K, P, and C are control gain matrices, $\boldsymbol{q}_{err}$ consists of the vector component of the quaternion rotating the spacecraft from the current orientation to the desired orientation, and $\boldsymbol{\omega}_{err}$ is the difference between the desired angular velocity and the current angular velocity of the spacecraft.

MOMENT ALLOCATION

If the desired moment calculated by the controller is above the threshold for the use of just the trim angles, the moment is allocated to the control vanes such that each axis is controlled independently. Moment around the x-axis is generated by canting vanes 2 and 4 about their y-axis. Similarly, moment around the y-axis is generating by canting vanes 1 and 3 about their y-axis. To generate moment about the roll, or z-axis, all 4 vanes are twirled about their x-axis by the same angle.

Generating the required moment about the x- and y-axes can be seen to have an infinite set of solutions due to the two degrees of freedom capable of generating this moment. The process of allocating moment is thus performed by first rotating the appropriate vane towards a more Sun-facing orientation. Where the appropriate vane is determined through equation 7 (using the y-axis as an example):

$$Controlled\ vane = \begin{cases} 1, & M_{y_{des}} - M_{y_{cur}} \geq \epsilon_{d_y} \\ 3, & M_{y_{des}} - M_{y_{cur}} \leq -\epsilon_{d_y} \end{cases} \quad (7)$$

Where $M_{y_{des}}$ is the desired moment about the y-axis, $M_{y_{cur}}$ is the current moment generated by the sail and vanes in the y-axis, and ϵ_{d_y} is the deadband utilized in the y-direction to reduce chatter in the vane control when the desired moment is sufficiently close to the current moment. If the difference in the moments is smaller than the pre-defined deadband, no change is made to the vane angles controlling the y-axis. Once the appropriate vane's surface normal vector is pointed in the direction of the Sun, no more moment can be generated about the y-axis. Therefore, if still more moment is required, the controller then moves the opposing vane incrementally away from the Sun until a predetermined limit has been set. At that point, the maximum amount of moment about the y-axis is generated and the controller is saturated. Appropriate selection of the control gains ensures that saturation is not encountered during normal operation. Furthermore, the impact of this saturation, namely, a slower than desired rotation rate, is not significant in the context of the Sunjammer mission plan. Moment about the x-axis is generated in an identical fashion utilizing cant of vanes 2 and 4. The moment allocation is summarized in Figure 5.

Once the appropriate cant angles have been calculated for all the vanes, the controller then changes the twirl of all 4 vanes in the appropriate direction to create the desired moment. Twirling of the vanes away from zero reduces the moment supplied by each vane. However, the sail force and moment model used for this development shows little moment biases about the z-axis and so the desired slow reorientation and attitude hold requires little twirl motion of the vanes. Therefore, the departure from the desired moment about the x- and y- axes caused by controlling the moment about the z-axis is infrequent and small in magnitude. This effect is further diminished since opposing vanes are twirled by an equal amount.

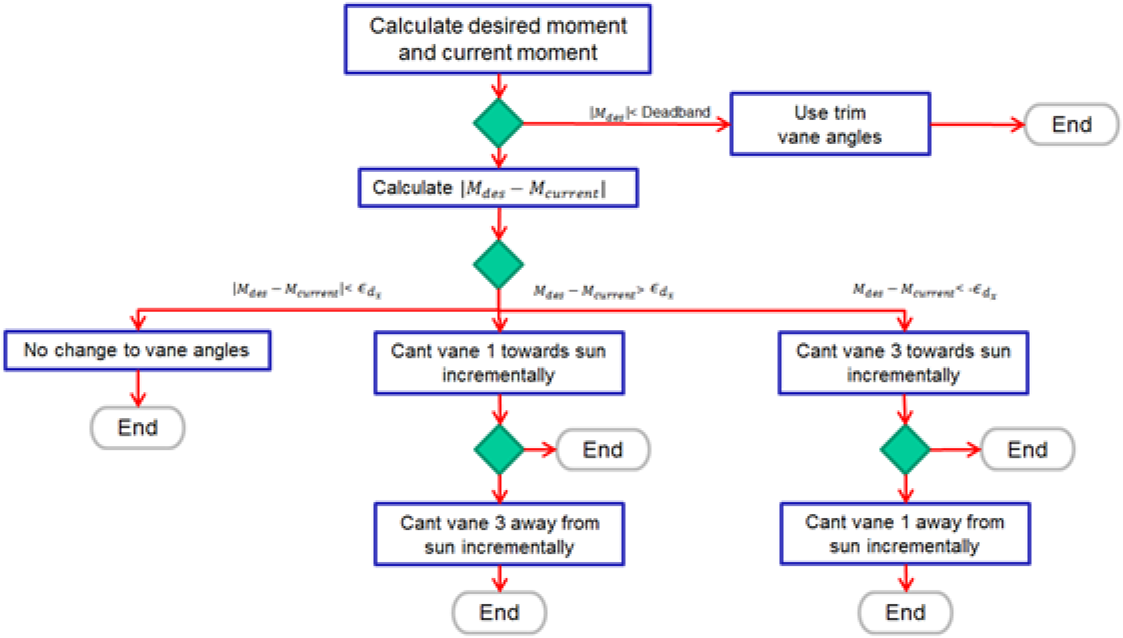

Figure 5: Schematic of the control scheme for generating moment about the y-axis

PASSIVE STABILITY

The current concept of operation of the Sunjammer mission involves reorienting the spacecraft to a given orientation and maintaining that attitude for long periods of time. To maintain an attitude for long periods of time with minimal motion of the vanes, the control algorithm takes advantage of passive stability about the x- and y- axes. The concept of solar sail passive stability has been discussed by Derbes [3] and is shown in Figure 6.

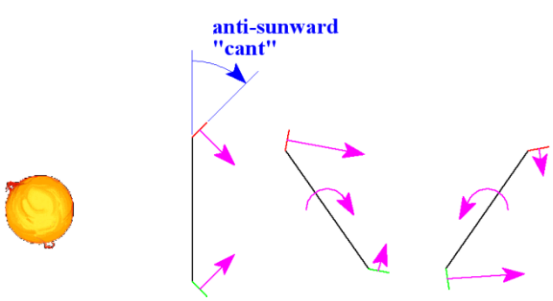

Figure 6: Passive stability in a Sun-pointing orientation. (Derbes 2004) [2]

Any motion away from a Sun-pointing orientation causes a restoring moment and maintains the sail in the Sun-pointing orientation. As discussed above, this restoring moment also exists due to an imperfect sail and the CM-CP offset; however, using these cant angles can increase the sail stability in this orientation. Furthermore, the same concept can be applied to other orientations relative to the Sun, which require opposing vanes to have different cant angles.

The control system is able to passively stabilize any orientation due to the fact that multiple control degrees of freedom are available to control a single rotational degree of freedom. For example, any orientation of opposing vanes will produce zero moment about the center of mass in a Sun-pointing configuration as long as both vanes' cant angle is the same. The vane cant angle chosen for passive stability on Sunjammer is 20°.

The effect of introducing passive stability about the x-axis is shown in Figures 7 through 10 where the sail is again performing the reference reorientation from a Sun-pointing orientation to an orientation with a Sun-incidence angle of 35° and a top angle of 10°.

The controller is able to maneuver the spacecraft both with and without passive stability as shown in Figures 8 and 10. However, convergence to the desired attitude occurs only after 25 hours in Figure 8 compared with 16 hours in Figure 10 with the use of passive stability. Furthermore, Figure 7 shows a significant amount of chatter in the motion of vanes 2 and 4 when compared to Figure 9. With passive stability, the attitude maneuver occurs without significant overshoot and with a much reduced required control effort.

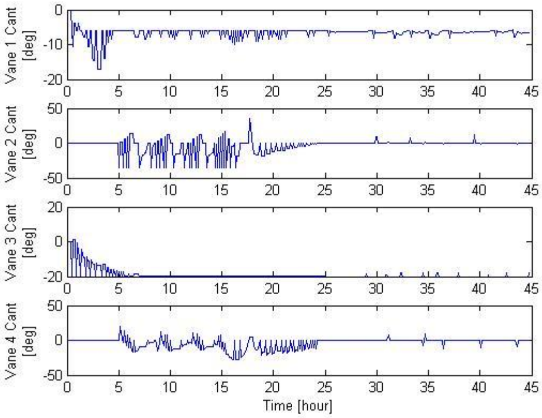

Figure 7: Cant angle without passive stability

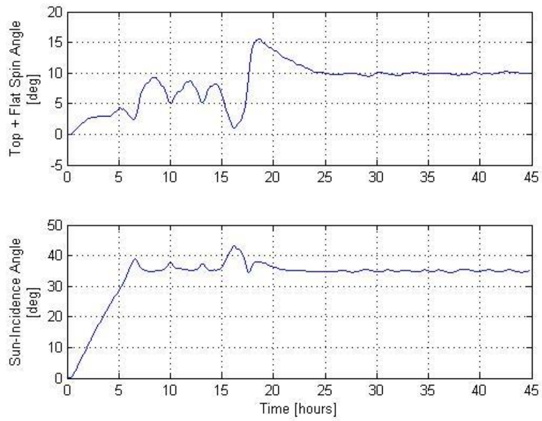

Figure 8: Spacecraft attitude without passive stability

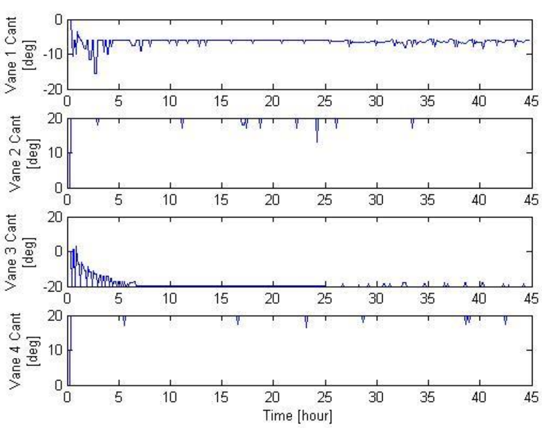

Figure 9: Cant angle with passive stability

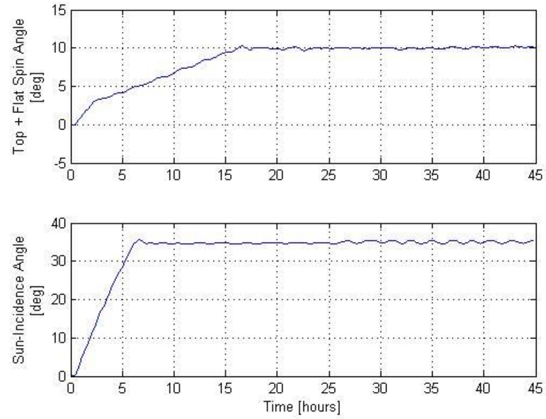

Figure 10: Spacecraft attitude with passive stability

UNCERTAINTY ANALYSIS

In order to analyze the performance of the control scheme in light of uncertainties, various modeling errors were introduced and simulated. These included error in the estimated inertia matrix, scale factor error in the moment and force coefficients, and un-modeled vane bend. Un-modeled vane bend had the most significant effect on the controller. When the vane bends away from the Sun by an unpredicted amount, the controller is no longer operating about the equilibrium vane orientation and the PD controller requires significantly more effort to reorient the spacecraft or maintain its attitude in light of the generated moment.

Figure 11 shows the attitude of the spacecraft during the same reference maneuver now with a moment scaling error of 10%, Inertia error of 10% and un-modeled vane bend of 10%.

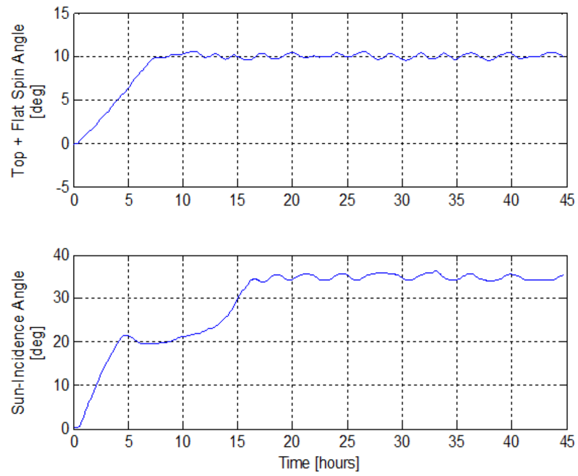

Figure 11: Spacecraft attitude with introduction of 10% error to the inertia matrix, force and moment coefficients, and un-modeled vane bend

The controller is still able to achieve the desired attitude due to the use of the autonomous adjustment of the trim angles; however, the errors are seen to have a significant effect on the system behavior.

CONCLUSION

The attitude determination and control scheme used by the Sunjammer solar sail has been presented. A dynamic model of the spacecraft was constructed and used to investigate the control algorithm. The controller was shown to benefit from passively stabilized attitude about two axes and autonomously adjusting trim angles. These adjustments were able to counteract significant un-modeled effects that may be encountered on orbit while maintaining the desired pointing accuracy of 2°. Further work will focus on a deeper investigation of the validity of the rigid body assumption used in this analysis as well as incorporation of updated force and moment models.

ACKNOWLEDGEMENTS

This work was supported by a contract from Micro Aerospace Solutions, LLC and L'Garde, Inc.

REFERENCES

1. McInnes, C.R., Solar Sailing Technology, Dynamics and Mission Applications, Springer-Praxis, London, UK, 1999.
2. Sandau, R., "Status and Trends of Small Satellite Missions for Earth Observation," Acta Astronautica, vol. 66, issues 1-2, January-February 2010.
3. Derbes, B., Lichodziejewski, D., and Veal G., "A Yank and Yaw Control System for Solar Sails," 14th AAS/AIAA Space Flight Mechanics Conference, AAS 04-100, Maui, Hawaii, February 2004.
4. Derbes, B., Lichodziejewski, D., Ellis, J., Scheeres, D., "Sailcraft Coordinate Systems and Format for Reporting Propulsive Performance," 14th AAS/AIAA Space Flight Mechanics Conference, AAS 04-284, Maui, Hawaii, February 2004.
5. Christian, J. and Lightsey, G., "Sequential Optimal Attitude Filter," Journal of Guidance, Control & Dynamics, vol. 33, No. 6, November-December 2010.
6. Wie, B., Space Vehicle Dynamics and Control, Second Edition, AIAA Education Series, AIAA, Reston, Virginia, 2008.