Solar Sail Control Actuator Concepts

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I. Introduction

The thrust produced by a solar sail is a direct function of its attitude. Thus, solar sail thrust vector control is a key technology that must be developed for sailcraft to become a viable form of deep-space transportation.

The solar sail community has been studying various sail Attitude Control System (ACS) actuator designs for near Earth orbit as well as deep space missions. These actuators include vanes, spreader bars, two-axis gimbals, floating/locking gimbals with wheels, and translating masses. This paper documents the various concepts and performs an assessment at the highest level. This paper will only compare the various ACS actuator concepts as they stand at the publication time. This is not an endorsement of any particular concept. As concepts mature, the assessments will change.

II. Assumptions

This paper assumes that the mission requires the spacecraft bus to reduce launch vehicle separation and tip off rates, and hold the spacecraft in a power and thermally stable attitude. The bus is also required to hold for deployment, and recapture to a safe attitude due to an anomalous contingency. Body spin rate reduction and recapture can be accomplished with a reaction wheel / magnetic torquer bar combination or thrusters. Due to the impulsive nature of thrusters, sail deployment can best be accomplished by modulating wheel speeds to avoid exciting the resonant modes as the sail frequencies vary with time. Therefore, reaction wheels are assumed to be required on the spacecraft bus.

NASA imposes a requirement for spacecraft decommissioning. In the event that the sail technology suffers an anomalous condition, the spacecraft bus must be able to fulfill the decommission requirement. Due to continuing thrusting nature of the sail, an Earth orbiting mission would require an Earth re-entry maneuver or an Earth escape trajectory. Therefore, it is assumed that the spacecraft bus will carry a propulsion system as well as reaction wheels. The ACS sensor compliment is assumed to consist of a star tracker and a three-axis gyro package.

III. Sail Model

The current focus of NASA development efforts are on a three-axis stabilized square sail. Other concepts such as spinners and helio-gyros show promise but are not considered as mature. This paper focuses primarily on four-quadrant sails that consist of four booms and four quadrants (see Fig 1). Many of these concepts might apply equally well to square sails that do not have four quadrants, or even to circular sails, but current industry practice favors the four-quadrant square sail for structural and other reasons. An exception is the Cosmos-1 sail sponsored by the Planetary Society[1], which is a helio-gyro design.

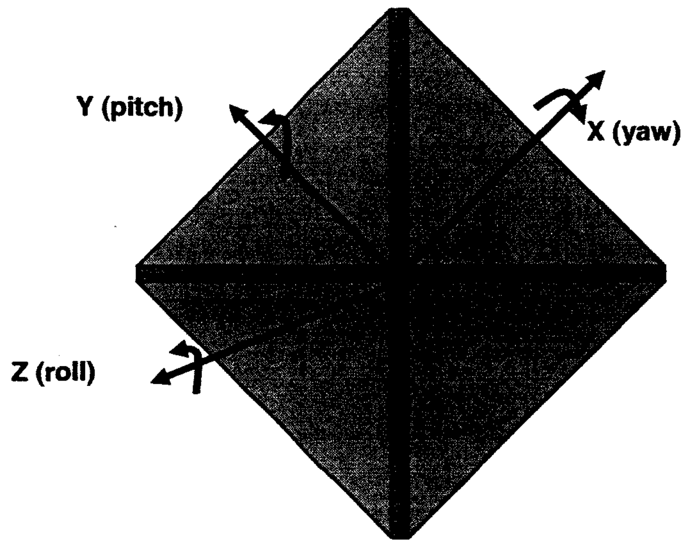

Figure 1 - Four Quadrant Sail Configuration

IV. Solar Sail Actuator Comparison

Table 1 compares the sail actuators in terms of controllability, the amount of hardware, total mass, power, heritage, reliability, cost, and fault tolerance. The sail control axes are defined in Figure 1. To avoid proprietary information, the mass power and cost were defined in relative terms. Heritage was defined as either flight proven, a redesign of a previously flown concept or no flight heritage.

The next several paragraphs go into more detail on each of the systems in Table 1.

Two-Axis Gimbal

This sailcraft ACS concept uses a control mass mounted on the end of a boom located near the Center of Mass (CM) of the entire sailcraft to shift the CM with respect to the solar photon Center of Pressure (CP). The difference in CM vs. CP generates a control torque from solar pressure. The uncertainty in CP vs. CM affects the two-axis boom design strongly. That uncertainty is a key parameter for any solar sail Attitude Control System (ACS) design. A two-axis gimbal is necessary for both Pitch and Yaw control. Roll control is not possible with the two-axis gimbal. Standard antenna drivers can probably be used to actuate the boom.

Floating Gimbal with Wheels

This JPL concept proposes the use of the bus reaction wheels and a relatively frictionless two-axis gimbal that can be locked at any angle[2]. The gimbal is attached to the geometric center of the sail and to a boom that extends to the spacecraft bus. When the gimbal is unlocked, the spacecraft wheels maneuver the bus and boom to a new position relative to the sail. The gimbal is locked and a new CM is created. The offset distance from the new CM to the sail CP generates a torque. By using a series of gimbal locking and unlocking in combination with maneuvering the bus relative to the sail, the sail can be rotated to various attitudes about two axes.

For this paper, the bus reaction wheels are considered essential to the deployment phase of the mission. The wheel mass and power are therefore not covered in the Floating Gimbal with Wheels budget, but covered by the spacecraft bus budget.

Table 1) Solar Sail Actuator Concepts

Actuator	Control Axes	Hardware List	Mass	Power	Heritage	Reliability/ Complexity	Cost	Fault Tolerance
Two Axis Gimbal	Y & Z	1 Two Axis Drive 1 Electronics Box	Med	Med	Flight Proven	Low Number of Failures	Med	No
Floating Gimbal with wheels	Y & Z	1 Two Axis locking mechanism 1 Electronics Box (wheels not included)	Light	Low	Partial Flight*	Varies By Component	Low	No
Spreader Bars	X	4 Bars 4 Stepper Motors 4 Potentiometers 4 Sets of Wiring 1 Elect. Box	Light	Low	None	Unknown	Low	Yes Can lose 1 or 2 bars
Running Masses	Y & Z	4 Masses 4 Stepper Motors 4 Potentiometers 4 Pulley Systems 1 Elect. Box	Med	Low	Some**	Unknown	Med	Yes Can lose 1 per axis
Tip Vanes	X, Y & Z	4 Small Sails 8 Booms 4 Deployment mechanisms 4 Stepper motors 4 Potentiometers 4 Wiring Harnesses Elect. Box	Med to Heavy	Low	None***	Unknown	Med	Yes Can lose 1 or 2 vanes
Pulse Plasma Thrusters	X, Y & Z	4 Thruster Sets 4 Wiring Harnesses Elect. Box	Med	High	New Redesign	Low No moving parts	High	Yes Can lose multiple thrusters

* The components are flight proven, but not the integrated actuator

** Scaled-down version for vernier adjustments to inertial properties

*** Trim tabs for solar panels to help control solar torques have flown; however they are not gossamer and do not provide full control

Spreader Bars

Spreader bars are a concept developed for a four-quadrant square sail as part of the ST6 JPL proposal for the New Millennium program[3]. The spreader bars are attached to the tips of the sail booms. As the bars are rotated, the sail quadrants "twist" with respect to the normal of the sail plane. Each quadrant twists, and each can be twisted in the same direction or in different directions as desired. This ACS concept is designed primarily to trim out the roll or "windmill torque" (the torque about the normal to the sail surface). The torque about this axis is small over short periods of time, but can be difficult to control if rates are allowed to build up. The spreader bars only change the angle of the sail quadrants a few degrees, but are sufficient to control the windmill torque.

Translating Masses

This concept is another way of varying the CM with respect to the CP that takes advantage of the sail boom geometry of a four-quadrant square sail. Masses are mounted on wires that extend along each boom. These masses can be translated along the length of the boom, thereby changing the CM of the sail in two dimensions. Even small changes in CM can provide a significant amount of control authority. Translating masses are currently being used by Gravity Probe B (GPB)to help stabilize the pointing of that spacecraft, although the translation rate is less stringent and the control authority requirement much less for GPB compared to what is needed for a sailcraft. The translating masses by themselves do not provide a complete 3-axis control authority and so must be combined with some other method.

Tip Vanes

Tip vane ACS actuation is a straightforward concept that works like an airplane control surface. The vanes are generally mounted at the tips of the booms to provide a long moment-arm. The vanes can be rotated along either one or two axes. The rotation of the vane to a different angle than the main body of the sail produces a torque in the same way that an elevator produces a pitch for an airplane. If there are four vanes with two-axis actuation, the problem is over-determined and the selection of the proper angles becomes somewhat of a design issue to avoid "vane chatter[4]". Vanes can be sized as needed for control authority and perhaps even used to modulate thrust. Control trim tabs to manage solar torques are quite common for communication satellites in geosynchronous orbits[5], so there is something of a flight heritage for vanes.

Pulse Plasma Thrusters

Recently Pulse Plasma Thrusters (PPTs) have been proposed for use with solar sails[6]. Although having thrusters to some extent defeats the great solar sail advantage of not needing propellant for thrust, PPTs mounted on the tips of the booms will provide a large moment-arm and so the propellant requirements need not be excessive. Currently, PPTs are envisioned as a backup to the primary ACS, but in theory could be used as the primary thrust vector control. They have the advantage of providing torque in any direction that is independent of the Sun angle. However, they do require power, so larger solar arrays and possibly more batteries may be required. The total impact still needs to be investigated. Another potential issue is that the PPT firings will also generate some translational thrust. This "PPT thrust" could be mitigated by mounting the thrusters in a way and designing the control system so that thrust firing are coupled and the translational effect cancel out, but the problem needs to be studied more. Contamination is also an issue for PPTs, as continued firings may degrade the sail surface reflectance leading to a loss of thrust. PPTs have flown, but are still a relatively new technology and the size of PPTs appropriate to solar sails may not exist in the current market.

Discussion

The two-axis gimbaled mass on a boom has been flown on any number of spacecraft, and so offers a low-cost flight-proven design, but has limitations in the number of axes it can control. The floating gimbals with wheels offer an intriguing new idea, and all its individual components are flight-proven. However, the combination of wheels and a locking mechanism has never flown. Spreader bars are a common application for terrestrial vessels, but have not been used previously with large gossamer structures in space. However, they are quite simple in design. The running mass type device has flown before, but for a less stringent set of requirements. Tip vanes have not flown, but similar trim tabs for solar panels have flown. Pulse plasma thrusters have flown, but must be scaled down to become efficient enough for use with solar sails.

Future studies will look at the trades between combinations of actuator sets for three-axis control. Overall, other than the two-axis gimbal, all of the actuators are relatively new designs. Therefore, as their details are developed, the table's impact to the decision making process will increase.

V. Conclusions

This brief survey has provided an overview of the state-of-the-art in sailcraft ACS actuator design and suggested areas of further study. The current state of solar sail ACS design is encouraging, but much work remains. For three-axis control, actuator combinations should be studied. Future work is also needed on the controllability and stability of new control systems using the listed sail actuators. Further studies should also include comparisons of off-the-shelf hardware metrics of estimated mass, cost, and reliability.

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