Steering Concept of a 2-Blade Heliogyro Solar Sail Spacecraft

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To meet the requirements for relevant acceleration, solar sails require a large amount of areal coverage to convert solar photon pressure into thrust. Thus, when comparing conventional space vehicles of similar mass, solar sails require more maneuvering torque, created by the sail area, needed to overcome a larger moment of inertia. Currently, the approach to steer a solar sail spacecraft involves off-setting its Center of Mass (CM) relative to its Center of Pressure (CP). In the heliogyro solar sail configuration, the sail membrane is stowed as a roll of thin film that forms a blade when deployed. These blades can individually extend/retract/twist thereby changing the sail area and spin rate. This allows the deployment system to also serve as the navigation and propulsion systems. This paper introduces a simple concept to steer a 2-bladed heliogyro-configuration by extending/retracting the blades to adjust the spacecraft's CM with respect to CP. The solar sail area is varied by simultaneously alternating the extension/retraction of the blades, during each half rotation, thereby steering the spacecraft with respect to a defined turning axis by offsetting CM and CP. Assuming that the idealized spacecraft receives only solar photon pressure at incident angles to the sail blades at 1 astronomical unit (AU), does not orbit around other bodies in the solar system, the navigational calculations are performed. With the blades retracted/extended at 10–100 m from their original extended length of 2400 m, the time needed to turn the spacecraft at 10°- 40° relative to the sun-facing angle, and traveling on a new linear vector, are presented. The solar photon incident angles are assumed to be 1-50° with respect to the sails at 1 AU. These calculations predict that the times needed to turn the spacecraft at 10°, 20°, 30° and 40° are approximately 0.78, 1.10, 1.35 and 1.56 hours for the blade retraction/extension of 100 m with 1° solar photon incident angle.

Key Words: solar sail, interplanetary travel, Heliogyro, solar pressure, steering

Nomenclature

- F_n : force along the normal direction
- F_t : force along the tangent direction
- α : solar photon incident angle relative to the sun-line
- AU : astronomical unit
- P : solar pressure at 1 AU
- A : solar sail area
- $\hat{r}$: reflected photon off from the solar sail
- s : specularly reflected photon
- B_f : non-Lambertian of the solar sail front surface
- B_b : non-Lambertian of the solar sail back surface
- ε_f : front emissivities
- ε_b : back emissivities
- β : desired turning degree
- m_{B1} : mass of the solar sail blade 1
- m_{B2} : mass of the solar sail blade 2
- m_H : mass of the spacecraft non-sail mass
- M : total spacecraft mass
- X_{B1} : distances of the solar sail center of mass of blade 1
- X_{B2} : distances of the solar sail center of mass of blade 2
- X_H : distance of the center of mass of the spacecraft hull
- ω_{z1} : initial angular velocity of the spacecraft (with respect to the z-axis) when the two solar sail blades are fully extended
- ω_{z2} : new angular velocity of the spacecraft (with respect to the z-axis) when one solar sail blade extends and another retracts
- I_{z1} : spacecraft's initial moment of inertia about the z-axis when the two sail blades are fully extended at equal length
- I_{z2} : spacecraft's initial moment of inertia about the z-axis when one solar sail blade extends and another retracts
- D : distance of the new center of pressure to the new center of mass
- $\alpha_{x\beta}$: angular acceleration of the spacecraft in a function of the turning angle β with respect to the x-axis
- τ : resultant torque
- I_{x2} : instantaneous moment of inertia of the spacecraft with respect to the x-axis
- θ : instantaneous solar sail blade angle
- M_H : total hull mass
- M_B : solar sail blade mass
- L_B : tip-to-tip solar sail blade length
- L_H : hull length
- T_H : hull thickness
- H : distance from the solar photon center of pressure to the turning axis
- β_N : accumulated spacecraft out of plane turning angle
- β_{N-1} : accumulated spacecraft out of plane turning angle from the previous cycle

$\omega_{xo(N-1)}$: angular velocity of the spacecraft with respect to x-axis from the previous cycle

$\alpha_{x\beta(N-1)}$: instantaneous angular acceleration of the spacecraft with respect to x-axis in a function of the turning angle β from the previous cycle

t : total time to turn the spacecraft

1. Introduction

Solar sails can be classified into two groups based on their method of stabilization: 1) truss supported, and 2) centrifugally (spin) supported. The truss configuration requires masts or booms to deploy, support, and rigidize the sails [1,2] whereas the spin type uses the spacecraft's centrifugal force to deploy and stabilize the sails.[3] The truss-supported type sail has a scaling limitation because as the sail area gets larger, the sail is increasingly more difficult to make and stow: the masts and booms get heavier, occupying more volume, and have increased risk during deployment.[4, 5] This major disadvantage limits the size of the sail area. The spin type comes in two configurations, Fig. 1: 1) spinning square/disk sail [3, 6, 7] and 2) heliogyro sail. [4, 8-11] This spinning square/disk sail architecture suffers the same sail area limitation as the truss-supported sail.

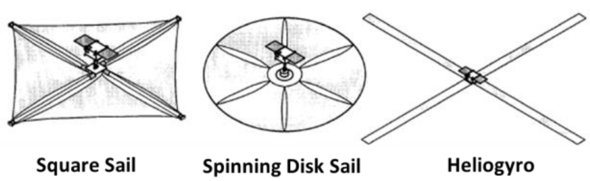

Fig. 1. Solar sail configurations. [12]

Steering Truss-Type Sails

The Team Encounter was a 76 x 76 m square sail having a constant pitch angle of 25 degrees with respect to the sun during the first 300 days after separation from the carrier spacecraft.[13] This 25 degree constant pitch is maintained by shifting the center of mass (CM) away from the center of pressure (CP) using a 3 kg payload mass tied to the side with a burnwire. After 300 days, an onboard timer would energize the burnwire to release the 3 kg payload. This 3 kg payload would then be moved back to the center of the spacecraft, bringing the sail to a zero degree trim angle with respect to the sun. This method is called a sliding mass, a trim control mass, or ballast mass. An idea was proposed to use sliding masses, along the mast lanyard, varying the CM relative to the CP, in order to control the attitude of the spacecraft.[14, 15] In addition to sliding masses along the mast lanyard, pulsed plasma thrusters (PPTs) [15, 16] and articulated control vanes [17] were proposed as a secondary attitude control system at the mast tips. Rotation of the articulated vanes at the spar tips can generate pitch, yaw and roll torque to control spacecraft. Angrilli and Bortolami proposed using a gimbal boom mounted at the center of the square sail (100 m x 100 m) hull to control the attitude of the spacecraft.[18]

Steering Spin-Type Sails

The spinning solar sail needs to be subjected to a bi-axial tension to be deployed and stabilized. This tension maintains sail rigidity and reduces wrinkling. The centrifugal force from the spinning spacecraft causes the sails to become taut in the radial direction, while bridges are needed to provide tension to the sail along the circumferential direction.[19] Studies from Onoda and Takeuchi,[19] found that the radial and circumferential tensions must be optimized to maintain rigidity, stability, solar pressure incident angles, and reduce sail waviness. As the sails get larger, additional supports are required along the radial and circumferential directions. This makes the spacecraft heavier, increases deployment complexity, and increases the chance to introduce stress concentration and intensities at the sail suspension structures.

The New Millennium Program Space Technology 5 (ST5) is a 76 x 76 m square spinning sail with proposed thrusters to spin-stabilize the spacecraft with a spin rate of 0.45 deg/s (0.075 rpm) to keep the angular momentum vector within 1 degree of the sun-line.[13] The concept of varying the CM relative to the CP method appears to be simple, but it requires challenging hardware implementation. The use of thrusters as a propulsion subsystem to counter balance solar pressure disturbance, and a large moment of inertia will impose challenges to implement. These propulsion subsystems contain consumable propellant, and are inadequate for longer extended missions wherein the fuel is spent. Therefore, steering methods without consumable propellant would extend the mission lifetime. The proposed New Millennium Program Space Technology 7 (ST7) has a 40 x 40 m square sail that articulates using a 2-axis gimbaled control boom, to change its CM location with respect to its CP, to control the spacecraft's attitude. [20] The sliding mass and the gimbal boom methods would require a complex control system. Articulated vanes could be used to steer the sail. However, the control equipment, such as wires that connect the central hull to the vanes would, add more weight and complexity to the existing masts.

So far, none of the methods described above allow the solar sail area to be varied or shifted, to control the spacecraft's attitude, counter balance disturbances from radiation pressure and gravitational gradient vectors, or allow the spacecraft to come to a full stop/start to remain/leave a stationary point if required. This is because the sail areas cannot be physically varied in truss-type and spin solar sail configurations described so far. In fact, the only method that varies the sail active area is IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) which imbalances the reflectivity of the sail area using a reflectivity control device (RCD) as a fuel-free attitude control system. [6, 7] The RCDs are thin-film type devices that electrically control their reflectivity, and can be used to generate an imbalance in the solar radiation pressure applied to the edge of the sail. [21] However, this method is limited by electrical control system area at the sail edges.

2. Steering Heliogyro-Type Sails

Similar to other methods, maneuvering of the Heliogyro solar sail can be controlled using sliding masses along the lanyard to adjust the CM relative to the CP of the sail. However, the complexity of this method is similar to the spin type sail. The sliding mass and the gimbal boom methods would be difficult to implement because, the sliding mass and the gimbal booms need to counter balance the sail blades as the sail spins. Having pulse plasma thrusters or articulated control vanes at the sail tips to locally control the blades may cause difficulties during deployment, reduce mission time due to consumable propellant to produce plasma. Additionally, controllability of the articulated vanes or plasma thrusters at distances up to kilometers from the spacecraft hull would add additional levels of complexity to the control system on the spacecraft. These limitations can be mitigated by manipulating the sail blade areas to readjust the CM and CP of the spacecraft, such as using RCD or extending/retracting the blade lengths. However, the RCD requires wires and control devices to actively control the reflectivity of the RCD and these control devices impose weight to the solar sail and possible issues during extension/retraction of the sail blade. The heliogyro solar sail has the ability to vary the solar sail area directly through extension and retraction of the blades without any extra control devices like the RCD.[4, 8)] The coning angle of the blades can be adjusted by varying spacecraft spin rates which govern the amount of blade tension.[10)] Extension and retraction of the solar sail blades can be used to vary the CM, offset the CP, and dynamically balance the craft without additional control mechanisms or adding any coning angle issues.

Summaries of proposed theoretical attitude/steering control methods of square/disc and heliogyro solar sail configurations for rigid and spin stabilized types in Table 1 suggest that heliogyro solar sail configurations enable a unique attitude/steering control method by extending and retracting the blades to re-adjust the CM and CP. The square/disc mast-supported solar sail configurations, that have a fixed area and shape, require the use of additional auxiliary control systems, as there is not yet a sail retraction/extension method applicable to these configurations. A Heliogyro solar sail configuration allows blades to be retracted and extended because there are no booms/spars or masts that restrain the blade areas from readjustment. Some other methods, such as articulated vanes, may be possible but are difficult to implement, and redundant as the blades can be articulated. This is a unique attribute that the heliogyro configuration provides, especially considering that a separate steering concept is not required.

This report proposes a simple method to model the steering of a long solar sail thin film membrane heliogyro solar sail spacecraft, using a two-blade heliogyro solar sail with a 6U CubeSat form factor as the working example. [4, 8, 22)] This heliogyro solar sail is comprised of 2 rolls of solar sail thin film stowed in the two external units of the spacecraft. When deployed, each roll forms a solar sail blade, and is capable of retracting and extending by means of a small electric motor. The method described in this paper explores the concept of altering the sail blade lengths to shift the spacecraft's CM and CP thereby estimating the time required to steer this spacecraft to any desired sun-facing (or sun-line) angle. These calculations assume that the idealized spacecraft receives only solar photon pressure at various incident angles to the solar sail blades at 1 astronomical unit (AU), and does not orbit around other bodies in the solar system. Any other forces that may affect the spacecraft, such as gravitational effects from other bodies in the solar system, are not accounted for. The electromagnetic interaction between the spacecraft and the Earth's magnetic field is not considered, and it is assumed that the blades are rigid and flat, with no modes of vibration, or out of plane bending or twisting.

Table 1. Proposed theoretical attitude and steering control methods of various solar sail configurations.

Attitude/Steering Control Methods	**Truss Type**	**Spin Stabilized Type**	
	Square	**Square/Disc Sail**	**Heliogyro Sail**
Sliding Mass	Y	N	N
Gimbal Booms	Y	N	N
PPTs	Y	Y	N
Articulated Vanes	Y	N	N
Reflectivity Control	Y	Y	Y
Blade Extend/retract	N/A	N/A	Y

Y = Yes: Demonstrated/Proposed.
N = No: difficult to implement, N/A = Not Applicable.

3. Heliogyro-Configured Solar Sail Spacecraft: 6U CubeSat Scale

A 1U CubeSat unit has the dimensions of 10 x 10 x 10 cm and a maximum weight of 1.33 kg (3 lbs. per U).[22)] This maximum weight was used for all calculations of the spacecraft total weight throughout this paper. A 6U CubeSat has three 2U CubeSat units attached together, where each 2U CubeSat unit measures 10 x 20 x 10 cm. Each of the 2U outer units of the 6U CubeSat contains a single solar sail blade roll, denoted as a solar sail unit. The solar sail deployment and propulsion unit [4, 8, 22)] is designed to be a stand-alone non-chemical in-space propulsion module that can be integrated into different spacecraft dimensions and configurations without altering major spacecraft design concepts. When the solar sail propulsion unit door is opened, a solar sail blade is deployed as shown in Fig. 2(a). The front and side views of the Heliogyro spacecraft are shown in Fig. 2(b) and (c), respectively. These views will be used throughout the paper. The front view of the spacecraft is where solar photons are reflected to provide thrust.

4. Solar Radiation Force on Solar Sails

The solar radiation pressure force model takes into account the imperfect solar sail film conditions by including three solar photon phenomenon which are reflection, absorption and re-radiation from the sail, assuming that the sail is flat.[11, 23, 24)] These parameters will be represented by coefficients which represent optical properties of the solar sail film.[11)]

The total force along the normal (F_n) and tangent directions (F_t), [11]

$$F_n = PA\left\{(1+\hat{r}s)(\cos\alpha)^2 + B_f\hat{r}(1-s)\cos\alpha + (1-\hat{r})\frac{\varepsilon_f B_f - \varepsilon_b B_b}{\varepsilon_f + \varepsilon_b}\cos\alpha\right\}\boldsymbol{n} \tag{1.}$$

$$\boldsymbol{F_t} = PA\{(1-\hat{r}s)\cos\alpha\sin\alpha\} \tag{2.}$$

The magnitude of the resultant force from solar photon is, [(11)]

$$|\boldsymbol{F}| = \sqrt{F_n^2 + F_t^2} \tag{3.}$$

The optical coefficients for square and heliogyro solar sails were analyzed and determined by JPL (Jet Propulsion Laboratory) [11)], are shown in Table 2, and are used throughout this paper.

Table 2. Optical coefficients for an ideal solar sail, JPL square and heliogyro solar sails.

Solar Sail	$\hat{r}$	s	ε_f	ε_b	B_f	B_b
Ideal Sail	1	1	0	0	2/3	2/3
Square Sail/ Heliogyro	0.88	0.94	0.05	0.55	0.79	0.55

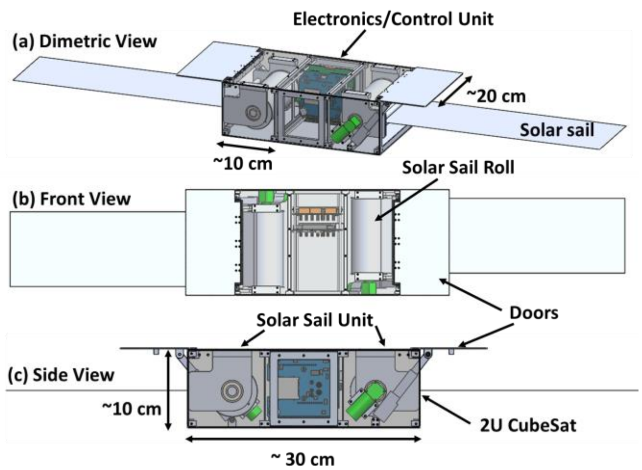

Fig. 2. (a) Extended solar sails with tip masses at end of each blade, (b) a front view of the Heliogyro spacecraft and (c) a side view of the Heliogyro spacecraft.

5. Steering Concept

This section explains a simple steering concept of a 2-blade heliogyro solar sail spacecraft using the spacecraft principal axes convention as shown in Fig. 3. The sail blades are varied to offset the (CM) and (CP). Here, the resultant solar photon force acts at the new (CP), generating torque about the roll axis to tilt the spacecraft to a desired β degree out of its spinning x-y plane, Fig. 4. When the spacecraft is turned using solar photon pressure to a desired β angle out of its spinning plane and remains flying at that β angle, the spacecraft will travel along a new straight path. The spacecraft can remain flying at a constant β angle by balancing the blade lengths to prevent offsetting of the CM and CP.

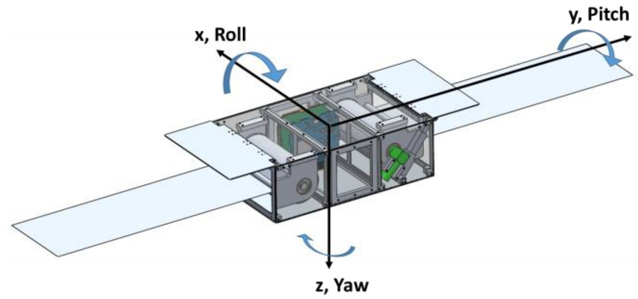

Fig. 3. Spacecraft axes and angles convention. The -yaw axis (-z axis) is the front view of the spacecraft as shown in Fig. 2(b) where the spacecraft receives solar photons. The blades are extended/retracted along the y-axis. The roll axis (x-axis) is the turning axis. The spacecraft turns making an angle β about the x-axis. The x-y plane is the spacecraft spinning plane.

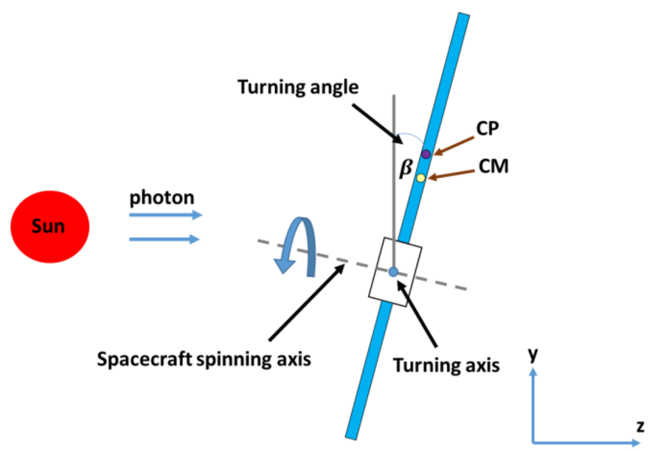

Fig. 4. A side-view of the spacecraft. Spacecraft turns, making a roll motion, due to shifted center of mass (CM) and center of pressure (CP) along the blade length. The locations of CM and CP are artificial and exaggerated. β is the desired turning angle. The spacecraft spins with respect to the z axis. The turning axis refers to the x axis.

The spacecraft can steer with respect to a defined turning axis by synchronizing the extension/retraction of the opposing solar sail blades every half a rotation (15 seconds for the spacecraft rotational speed of 2 rpm). This causes the CM and CP shift and these CM and CP remain in the same sector half of the spacecraft's rotational plane. Thus, maximum retracted blade length takes place at the complete opposite location of the maximum extended blade length for each revolution. This offsetting of the CM and CP, from the dynamically balanced center of the heliogyro, rotates the spacecraft with respect to the desired turning axis causing the spacecraft to turn as shown in Fig. 4. This turning angle and rate depends on the locations of the CM, CP, and the duration of the shifted positions. A step by step description of this steering method is explained as follows.

To initiate the steering cycle, as the spacecraft rotates 1/4 revolution (0° - 90°), the dotted blade extends while the white blade retracts the same length, simultaneously. The dotted blade reaches the pre-defined maximum extended length, and the white blade reaches its pre-defined minimum retraction at 90° and 270°, respectively, Fig. 5. The extended length of the dotted blade equals the retracted length of the white blade. It can be seen that the spacecraft's CP (denoted as black circles) move along the longer blade associated with the spacecraft rotation. The spacecraft's CM, (denoted as hollow circles) also follows this same path. The two blade designations, dotted and white, shown in Fig. 5, are used to distinguish between different blades for ease of understanding.

The CM and CP are farthest from their original locations when the longest blade (dotted blade) is at the 90° position and the shortest blade (white blade) is at the 270° position, Fig. 5. And Fig. 6. As the spacecraft continues to spin through the 2nd quarter sector of its revolution (past 90° towards 135°), the longer blade retracts, while the shorter blade extends simultaneously until the two blades are balanced at the horizontal axis at the 1/2 revolution point (0° / 180°). As the spacecraft continues to spin through 3/4 of its revolution (past 180° towards 225°), the blade that was at 0° (former shorter blade, denoted as the white blade) starts to extend, while the blade that was at 180° (former longer blade, denoted as the dotted blade), starts to retract. Simultaneous extension/retraction of blades continues until the two blades arrive at the vertical position (90° and 270°) where the former shortest blade (white blade) extends while the former longest blade (dotted blade) retracts, Fig. 6(right). As the revolution completes, both blades are in the horizontal position (0°/180°) and of equal length. The next revolutions repeat until the heliogyro is at the halfway point of its turning angle β, then the CM and CP are shifted to the other half sector, to decelerate the rotational turn, thereby arriving at the precise turning angle β with no turning momentum. It can be observed that the CM and CP of the spacecraft are always located in the sectors with the longer blade, except when the blades are at the same length then the CM and CP are located in the balanced center point of the spacecraft.

Illustrations of how the spacecraft's CM and CP change with this retraction/extension explained in Fig. 5 and Fig. 6 are shown in Fig. 7. When the CP is balanced with the CM, i.e., no blade extensions/retractions, the spacecraft's CM and CP stay at the same location throughout the rotation, seen as a solid circle, Fig. 7(a). When only one blade is fully extended while the other is fully retracted, the CM and CP are permanently shifted from the center of the spacecraft, Fig. 7(b).

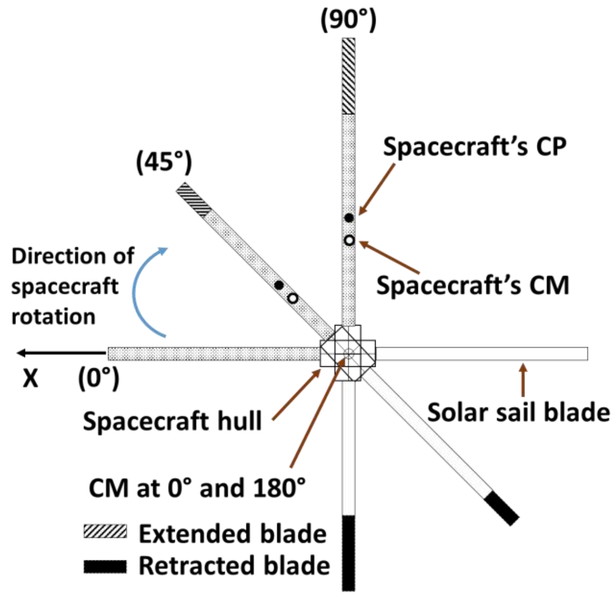

Fig. 5. Front view of the spacecraft. The Sun is out of the paper facing into the paper. Illustration of solar sail blades extension and retraction before the steering cycle starts. The spacecraft is balanced at a 0°. The dotted blade extends, while the white blade retracts simultaneously until the spacecraft orientation reaches 90°. At 90°, the dotted blade reaches its pre-defined maximum extension length while the white blade is at its pre-defined minimum retraction length at 270°. The hollow circles represent imaginary locations of spacecraft's center of mass. The black circles represent imaginary locations of spacecraft center of pressure. The locations of CM and CP are exaggerated.

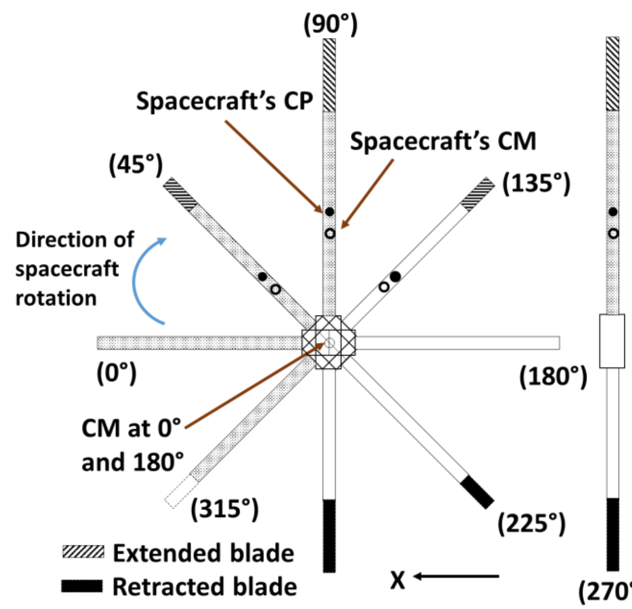

Fig. 6. Front view of the spacecraft. The Sun is out of the paper facing into the paper. Illustration of steering cycle starts where the blades are at 90° and 270°. After the blades extend and retract from the balance condition (0°) to 90°, the dotted blade is at pre-defined maximum extension length and the white blade is at its pre-defined minimum retraction length. As the spacecraft spins from 90° towards 270°, the dotted blade retracts while the white blade extends until at 270°, the dotted blade becomes the shortest length and the white blade becomes the longest length. The locations of CM and CP are exaggerated.

If smaller increments of rotation angles, Fig. 5, are compiled in the same plot, the CM and CP path will travel in circles located in the upper 2 quadrants of the x-y plot as shown in Fig. 7(c). As a result of the shifted CM and CP along the +y-axis, solar photon forces will create a torque about the x-axis, causing the spacecraft to undergo a roll rotation about the x-axis and make a rotation along the z-axis. To keep the CM and CP in the upper 2 quadrants of the x-y plot, the extension/retraction must be completed every half revolution. The path of shifted CP must be farther away from the shifted CM to allow solar photon resultant force to generate torque on the spacecraft about the x-axis, Fig. 7(c). To allow the steering cycle to start, where the pre-defined maximum extended blade is at 90° and the pre-defined minimum retracted blade is at 270°, these blades must extend to their maximum and the other blade must retract to its minimum within the first quarter revolution.

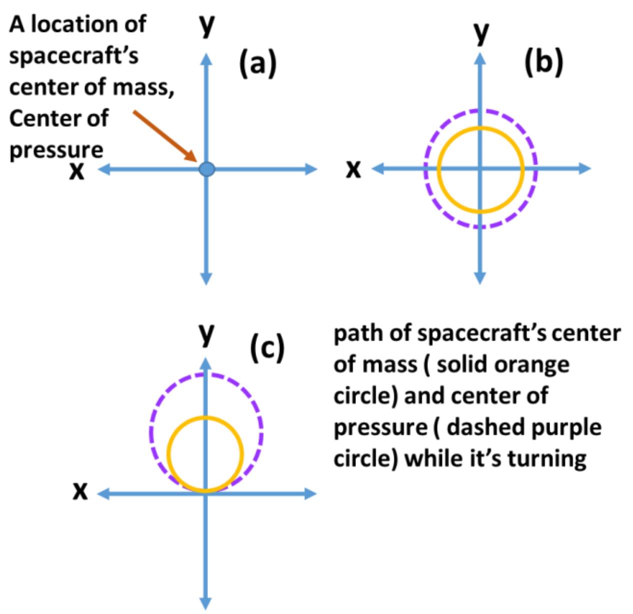

Fig. 7. Illustrates locations of the spacecraft's center of mass when viewed from the front of the spacecraft (-z axis). The x and y-axes refer to spacecraft's roll and pitch axes. Exaggerated center of mass and center of pressure locations of the spacecraft (a) when no blade extensions/retractions, (b) when only one blade extends while another blade is fully retracted and (c) when two blades are extended/retracted simultaneously every 0.5 revolution when assuming the spacecraft undergoes a turning about the x-axis. -z-axis is the spacecraft out of plane axis.

6. Steering Calculations

The moment of inertia of the spacecraft, when the two solar sail blades are fully extended, is determined with respect to the z-axis. In this study, the longest extended solar sail blade length is at 2400 m. When the blades are extended and retracted, the CM and CP of the spacecraft are shifted, this causes the moment of inertia of the spacecraft with respect to the z-axis to change. The new CM of the spacecraft is calculated using Eq. (4).

$$CM_{shifted} = \frac{m_{B1}x_{B1} + m_{B2}x_{B2} + m_H x_H}{M} \qquad (4.)$$

where m_{B1}, m_{B2} are masses of the solar sail blade 1 and 2, respectively, and m_H is the spacecraft non-sail mass. 'M' is the total spacecraft mass. X_{B1}, X_{B2} and X_H are measured from the reference axis, see Fig. 8.

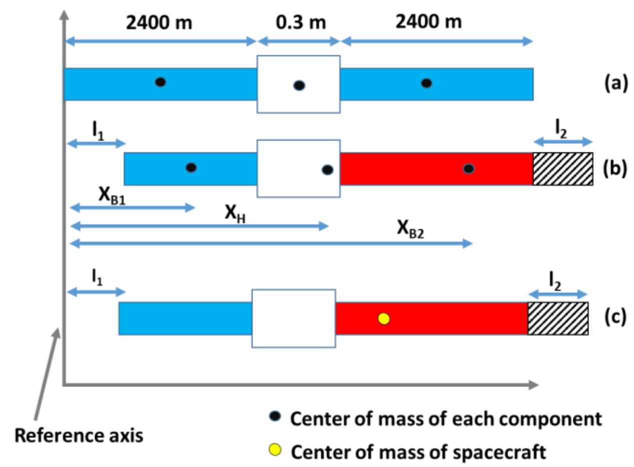

Fig. 8. A sketch of the center of masses of solar sail blade 1, 2 and the spacecraft hull with respect to a reference axis. (a) when the blades are fully and equally extended, (b) when one blade is extended at l_2 and another blade retracted at l_1. The new exaggerated location of spacecraft center of mass is shown in (c). The locations of CM are artificial and exaggerated.

Since the spacecraft CM has shifted, this causes the moment of inertia about the z-axis of the spacecraft to change. Thus, a new moment of inertia with respect to a z-axis must be determined. From the conservation of angular momentum, once the moment of inertia of an object changes, the angular velocity changes as shown in Eq. (5).

$$\omega_{z1} I_{z1} = \omega_{z2} I_{z2} \qquad (5.)$$

The solar sail blades are unbalanced when one extends and one retracts, therefore the spacecraft CP shifts from its original location, Fig. 9. Thus, the new CP is determined. Next, the distance from the new CM to the new CP is determined, followed by determining the CP distance from the turning axis. The spacecraft rotates about its instantaneous (new) CM during the angular shift that causes the spacecraft to rotate about the x-axis that passes through the new CM turning the spacecraft. These changes of the CM are taken into account shown as 'D' in Fig. 9 and Fig. 10. However, this shifting of the CM is very small even though the blade extends at 100 m.

From here, instantaneous solar sail blade angle (θ, Fig. 9) with respect to the spacecraft's turning axis can be determined from Eq. (6)

$$\omega_{z2} = \frac{\theta}{t} \quad (6.)$$

where ω_{z2} is the new spacecraft angular velocity (determined in Eq. (5), and 't' is the time increment it takes to rotate the spacecraft a set angle. Eq. (6) indicates that the spacecraft rotational speed changes as the blade movement is occurring and these changes are taken into account in the calculation.

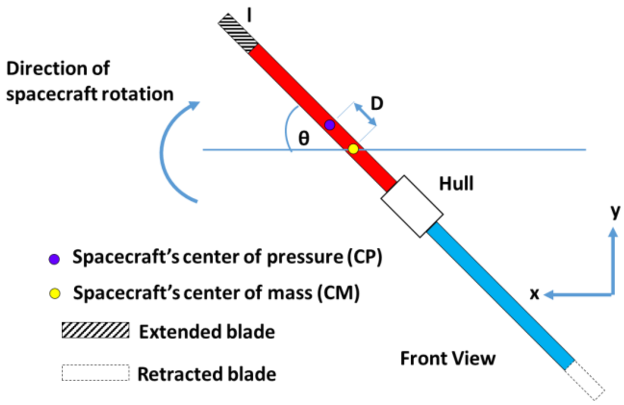

Fig. 9. Illustration of solar sail blade angle with respect to the spacecraft turning axis (x-axis). The distance 'D' is the new center of pressure to the new center of mass. The locations of the CM and CP are exaggerated. Θ is the instantaneous solar sail blade angle with respect to the spacecraft's turning axis.

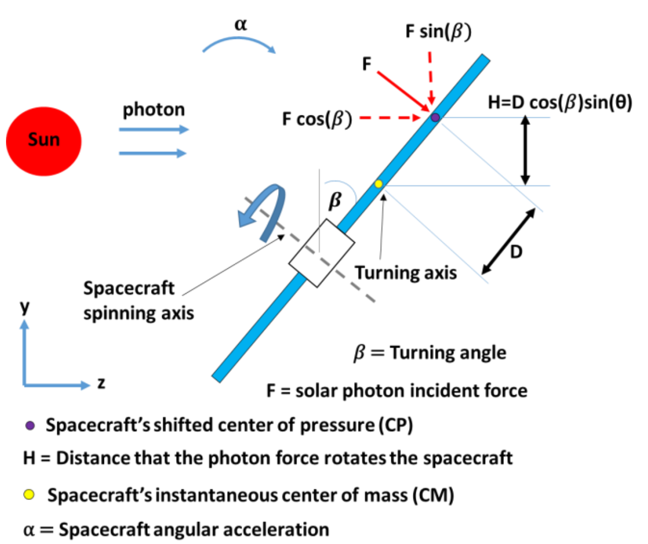

Fig. 10. Side view of the spacecraft with turning angle β. The locations of the CP is artificial and exaggerated. F is the solar photon force from Eq. 3. H is the center of pressure distance from the turning axis (x-axis).

The aim is to turn the spacecraft with respect to the roll axis to the specified turning angle, β, Fig. 10, thus, the angular acceleration of the spacecraft is a function of the turning angle β with respect to the x-axis and is determined from Eq. (7),

$$\alpha_{x\beta} = \frac{\tau}{I_{x2}} \quad (7.)$$

where τ is the resultant torque at the spacecraft and is generated by the resultant solar photon force about the spacecraft turning axis, Fig. 10. I_{x2} is the instantaneous moment of inertia of the spacecraft with respect to the x-axis by taking into account changes of solar sail blade lengths.

The instantaneous moment of inertia of the spacecraft, as a function of the instantaneous solar sail blade angle with respect to the spacecraft's turning axis (θ), when it rotates with respect to the x-axis is determined from,

$$I_{x2} = \frac{1}{12} M_B (L_B + L_H)^2 (\sin\theta)^2 + \frac{1}{12} M_H (L_H^2 + T_H^2) \quad (8.)$$

where M_B is the total solar sail blade mass, L_B is the tip to tip length of the solar sail, sin (θ) accounts for changes of the blade's length along the y-axis with respect to spacecraft instantaneous rotating angle θ. M_H is the total hull mass, L_H is the hull length and T_H is the hull thickness.

The torque resulting from the solar photon force acting at the shifted CP with respect to the turning axis is determined from,

$$\tau = F \cos\beta \cdot H \quad (9.)$$

where F is the total solar photon force determined in Eq. (3) and H is the distance from the solar photon CP to the turning axis (x-axis). This CP represents the location where the distributed solar pressure becomes a resultant point load, the sum of all the solar pressure acting on the solar sails and hull.

The distance from the solar photon CP to the turning axis, H, shown in Fig. 10, varies instantaneously with both the turning angle (β) and the spacecraft rotating angle (θ). To take this varying spacecraft rotating angle into account, the new H becomes

$$H = D \cos\beta \cdot \sin\theta \quad (10.)$$

Eq. (10) is the distance from the new CP to the turning axis. Substituting Eq. (8), Eq. (9) and Eq. (10) into Eq. (7) yields,

$$\alpha_{x\beta} = \frac{F \cos\beta \cdot D \cos\beta \cdot \sin\theta}{\frac{1}{12} M_B (L_B + L_H)^2 (\sin\theta)^2 + \frac{1}{12} M_H (L_H^2 + T_H^2)} \quad (11.)$$

Eq. (11) is the angular acceleration of the spacecraft as a function of the turning angle β with respect to the x-axis, taking into account the instantaneous moment of inertia of the spacecraft as it rotates with respect to the x-axis and the torque created from the solar photon force acting at the CP with respect to the turning axis.

7. **Determine time needed to turn the spacecraft to a desired turning angle, β**

The accumulated spacecraft out of plane tilt angles at various spacecraft rotational angles can be calculated from the rotational motions with constant angular acceleration,

$$\beta_N = \beta_{N-1} + \omega_{xo(N-1)} t + \frac{1}{2}\, \alpha_{x\beta(N-1)} t^2 \qquad (12.)$$

where β_N is the accumulated spacecraft out of plane turning angle, Fig. 10, N is the number of cycles the same solar sail blade appears at the same spacecraft rotation angle, θ, 't' is the total time to turn the spacecraft to β_N. Here,'t' increases as a function of β, 'N-1' is the spacecraft out of plane turning angle from the previous cycle, and $\omega_{xo(N-1)}$ is the initial angular velocity of the spacecraft with respect to the x-axis from the previous cycle. This $\omega_{xo(N-1)}$ indicates that the rotational speed of the spacecraft changes at each rotational cycle, and these changes are taken into account in the calculation. Since the blades extend and retract at different lengths while the spacecraft spins, the instantaneous angular acceleration of the spacecraft, $\alpha_{x\beta}$, with respect to the x-axis will be different at each rotational angle, θ, and at each β increment. To determine instantaneous spacecraft out of plane turning angles associated with the spacecraft rotational angle (0-180°), the instantaneous angular acceleration of the spacecraft with respect to the x-axis at each spacecraft rotational angle will be used, $\alpha_{x\beta(N-1)}$.

8. Results and Discussions

This section discusses the time needed to turn the spacecraft from 10° - 40°, β in Fig. 10, by varying the solar sail blades from 1 – 100 m. The study assumes that the spacecraft experiences solar photon incident angles from 1° - 50° with respect to the sun-line at 1 AU. The extension and retraction of blades within each cycle can be explained as follows. If the maximum length the solar sail blade needs to travel is from 1 meter extension to 1 meter retraction, then the total length the solar sail blade needs to travel is 2 meters. If the blade is initially extended to 2400 meters and has been extended 1 meter extra (i.e., 2401 meters), then the solar sail material in this blade needs to travel 2 meters when it is required to retract to 1 meter shorter than its initial extension (i.e., 2399 meters). The spacecraft input properties in this analysis are shown in Table 3. The times to make 0.25 and 0.5 revolution (i.e., 7.5 and 15 seconds, respectively) were calculated from the spacecraft spin rate of 2 rpm. The hours needed to turn the spacecraft are presented in Table 4 and Fig. 11 to Fig. 13. The horizontal axes of Fig. 11 to Fig. 13 represent extracted/retracted blade lengths, the vertical axes represent the desired spacecraft turning degrees (β). The black/white profiles represent the time needed to turn the spacecraft to any desired degrees (β) in functions of extracted/retracted blade lengths and solar photon incident angle. It can be observed that the hours are in a similar range for the solar photon incident angles between 1°-20° and the transition is at the solar photon incident angle of 30°. The hours needed to turn significantly increase when the incident angles are at 40°– 50°.

The average time increases when the blades make 10°, 20°, 30°, 40° and 50° incident angles when compared to incident angles of 1° are 1.5%, 6%, 15.3%, 30% and 55% regardless of the blade extension/retraction lengths. When the blade extension/retraction lengths are increased by 300% (from 10 m to 40 m), the time to turn the spacecraft will be reduced by 50% regardless of the incident angle. For example, the time to turn the spacecraft at 10° and 20° when the blades orient at 50° and extend/retract at 40 m (1.91 and 2.70 hours, respectively) is shorter than the time to turn at the same angle and at the same incident angle with extend/retract blade length of 10 m (3.82 and 5.39 hours, respectively), Table 4. By increasing the extension/retraction lengths by 600% (from 10 m to 60 m), the time will be reduced by 62% regardless of the incident angle. For example, the time to turn the spacecraft at 10° and 20° when the blades orient at 50° angle with respect to the sun-line and extend/retract at 70 m (1.44 and 2.04 hours, respectively) is reduced by 62% when compared to the same angle and at the same incident angle with extend/retract blade length of 10 m (3.82 and 5.39 hours, respectively). This number is reduced by 68% when the blades extend/retract at 100 m.

Table 3. Input Parameters for Analysis.

Input Parameters	**Values**
Solar Sail Roll Inner/Outer Diameters [meters]	0.01/0.08
Solar Sail Density [kg/m^3]	1360
Spacecraft Initial Spin Rate [rpm], [rad/s]	2, 0.2094
Solar Sail Blade Width [meters]	0.145
Spacecraft Hull Thickness [meters]	0.1
Spacecraft Hull Width [meters]	0.2
Spacecraft Hull Length [meters]	0.3
Solar Sail Thickness [micro-meter]	2
Solar Sail Blade Full Extended Length [meters]	2400
Fully Extended Solar Sail Area [m^2]	696
2 Solar Sail Blade Mass [kg]	1.894
Non-Sail Mass [kg]	6.086
Total Spacecraft Mass [kg]	7.98
Total Spacecraft Diameter With 2 Blades Extended Plus Spacecraft Hull Length [meters]	4800.3
Spacecraft Moment of Inertia When Blades are Fully equally Extended [m^4]	3.6 x 10^6
Time to Make 0.5 Revolutions [seconds]	15
Time to Make 0.25 Revolutions [seconds]	7.5

Table 4. Hours to turn the spacecraft to 10° - 20° by varying the solar sail blades from 1-50 m at solar photon incident angles of 1° - 50° at 1 AU. β is the spacecraft turned degree.

Hours to Turn the Spacecraft				
Incident Angle = 1				
	Extension/Retraction lengths			
β	**10**	**40**	**70**	**100**
10	2.47	1.23	0.93	0.78
20	3.48	1.74	1.32	1.10
30	4.26	2.13	1.62	1.35
40	4.92	2.47	1.87	1.56
Incident Angle = 10				
β	**10**	**40**	**70**	**100**
10	2.50	1.25	0.95	0.79
20	3.53	1.77	1.34	1.12
30	4.33	2.17	1.64	1.38
40	4.99	2.50	1.89	1.58
Incident Angle = 20				
β	**10**	**40**	**70**	**100**
10	2.62	1.31	0.99	0.83
20	3.70	1.85	1.40	1.18
30	4.53	2.27	1.72	1.43
40	5.23	2.62	1.98	1.66
Incident Angle = 30				
β	**10**	**40**	**70**	**100**
10	2.84	1.43	1.07	0.90
20	4.02	2.01	1.52	1.27
30	4.92	2.46	1.86	1.56
40	5.67	2.84	2.15	1.80
Incident Angle = 40				
β	**10**	**40**	**70**	**100**
10	3.21	1.61	1.22	1.02
20	4.53	2.27	1.72	1.43
30	5.55	2.77	2.10	1.76
40	6.41	3.21	2.42	2.03
Incident Angle = 50				
β	**10**	**40**	**70**	**100**
10	3.82	1.91	1.44	1.21
20	5.39	2.70	2.04	1.71
30	6.61	3.31	2.50	2.09
40	7.63	3.82	2.88	2.42

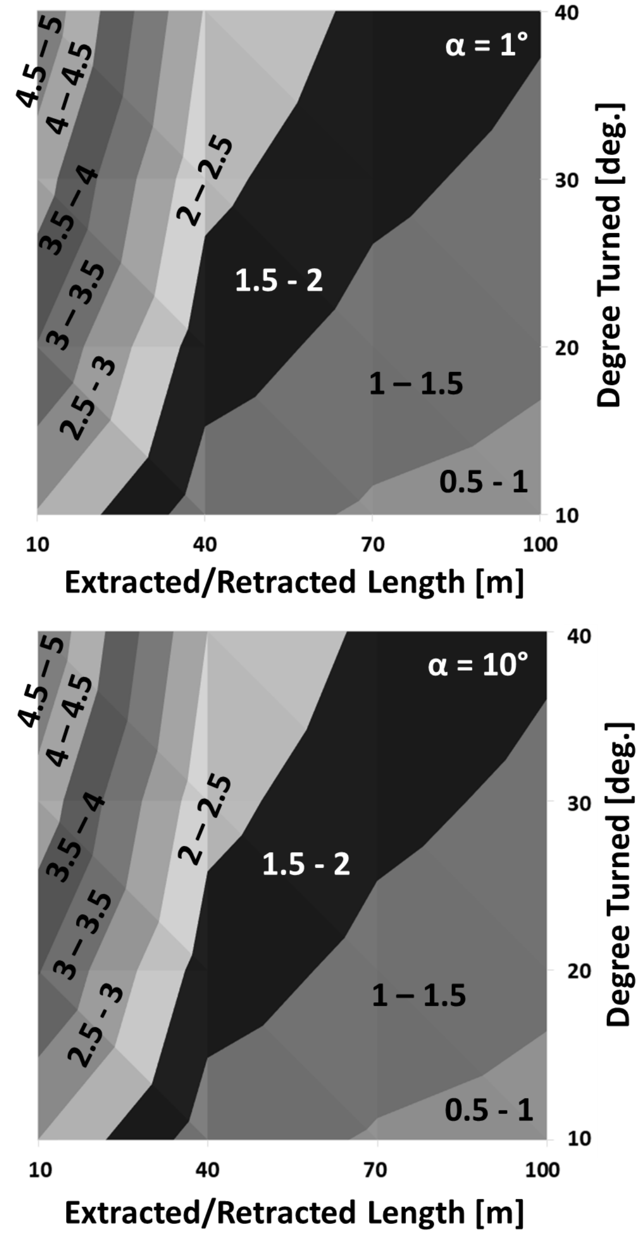

Fig. 11. Hours to turn the spacecraft to 10° - 40° by varying the solar sail blades from 1-100 m at solar photon incident angles α of 1° (top) and 10° (bottom) at 1 AU. Horizontal axes represent extracted/retracted blade lengths from 10 to 100 meters. Vertical axes represent desired spacecraft turning degrees (β). The black/white profiles represent time (hours needed to turn the spacecraft to any desired degrees) with indicated numbers.

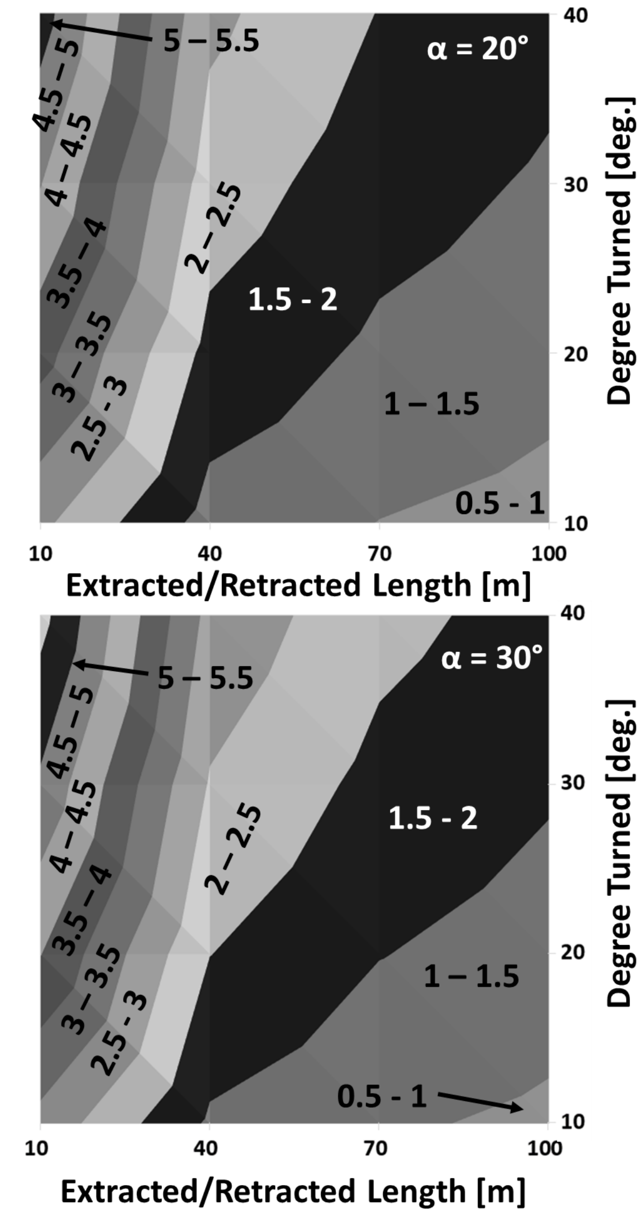

Fig. 12. Hours to turn the spacecraft to 10° - 40° by varying the solar sail blades from 1-100 m at solar photon incident angles α of 20° (top) and 30° (bottom) at 1 AU. Horizontal axes represent extracted/retracted blade lengths from 10 to 100 meters. Vertical axes represent desired spacecraft turning degrees (β). The black/white profiles represent time (hours needed to turn the spacecraft to any desired degrees) with indicated numbers.

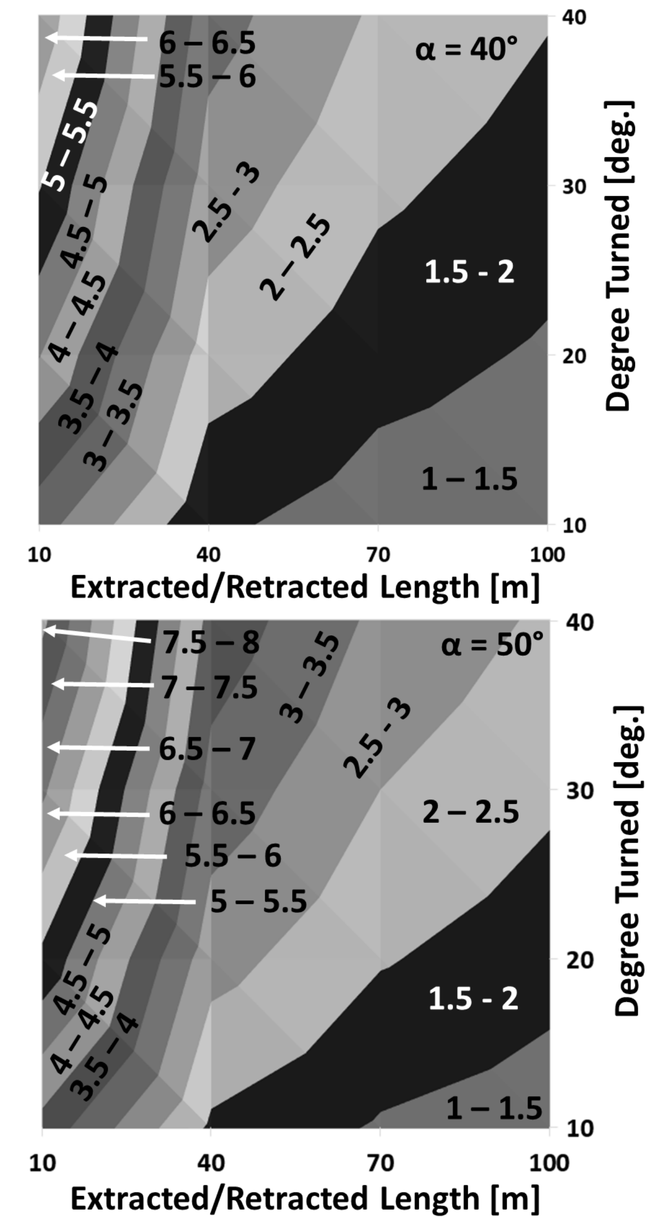

Fig. 13. Hours to turn the spacecraft to 10° - 40° by varying the solar sail blades from 1-100 m at solar photon incident angles α of 40° (top) and 50° (bottom) at 1 AU. Horizontal axes represent extracted/retracted blade lengths from 10 to 100 meters. Vertical axes represent desired spacecraft turning degrees (β). The black/white profiles represent time (hours needed to turn the spacecraft to any desired degrees) with indicated numbers.

9. Conclusions

This paper proposes a simple conceptual method to steering a 2-blade solar sail spacecraft using solely solar photon pressure (neglecting any other forces that may affect the spacecraft such as the gravitational force gradient and magnetic fields) to any desired turning degree within ±89° of the sun-line. A two-blade heliogyro solar sail spacecraft with a 6U CubeSat scale was used as the example. The spacecraft is steered by shifting the CM and the CP. This is achieved by periodically varying the offset of the solar sail blade lengths. The solar sail blades need to reach their extremum within a half revolution. These offsets of the CM and CP, as a function of blade extension/retraction lengths, result in changes of out of plane torque acting on the spacecraft due to the resultant solar photon force. This torque in turn tilts the spacecraft out of its spinning plane causing the spacecraft to turn. The times needed to turn the spacecraft to a desired turning degree between 10° and 20° were calculated. Sail blade extension/retraction lengths ranging from 1 – 100 meters and varying solar photon incident angles (1° – 50°) were discussed.

It was found that solar photon incident angles up to 20° do not have a large impact on the time needed to turn the spacecraft. Although, the desired turning degree and the blade extension/retraction lengths had a large impact on the turning times. When the blade extension/retraction length is 10 meters, and the solar photon incident angles are within 20°, the time needed to turn the spacecraft is close to 2.5 hours for turning degrees of 10°. For the shortest blade extend/retract lengths in this study (i.e. 10 m) and at the highest solar photon incident angle of 50°, the time needed to turn the spacecraft at the 40° is less than 8 hours. While the time needed to turn the spacecraft at 10° with 100 m solar sail blade extend/retract lengths at 100 m with almost no solar photon incident angle (i.e. 1°) is 0.78 hours (i.e. 47 minutes).

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