11

Designing a Solar Sail

As with most engineering challenges, even for solar sails there is no single "best" design solution which will meet all potential needs and mission scenarios. This chapter is divided into two major sections. First, we will discuss the most viable solar sail design options and the pros and cons of each, including the problem of controlling the orientation of a sail in space. Then we will deal with technological aspects in building a sailcraft.

TYPES OF SOLAR SAILS

Sail Physics Requires Some Design Commonality

Before we discuss the myriad options available to solar sail designers, it might be useful to review some basics. First of all, a solar sail must contain a lightweight surface that efficiently reflects light (at least until we discover a way to "virtually" reflect light, which is currently beyond the realm of realistic engineering possibility). There is usually some sort of material under the reflector to provide structural strength and stability as well as to help balance any thermal issues. Current technology requires these lightweight materials to be deployed or suspended from some sort of boom, similar to the mast of a seventeenth century sailing ship, or to spin and have the deployment and deployed configuration maintained by the resultant centripetal acceleration. Building on these basic requirements, creative engineers and scientists have developed several options to consider as we begin solar sailing.

Three-Axis Stabilized Solar Sails

A three-axis stabilized solar sail most resembles a kite. Like a kite, booms support the solar sail material in three dimensions—the two dimensions that form the plane of the sail (left/right and top/bottom) as well as the dimension perpendicular to the plane of the sail (up/down). Like an airplane or a rocket, the sail must be stable in all three dimensions to allow the precise pointing required to control the Sun-provided thrust (pitch, roll and yaw), thus allowing the sail to carry a payload where we want it to go. The sail must also be supported in these dimensions to prevent it from going slack or collapsing on itself in any direction. Just imagine trying to fly a kite that has no supporting structure, and you will understand why a solar sail requires booms.

G. Vulpetti et al., *Solar Sails,* Springer Praxis Books,
DOI 10.1007/978-1-4939-0941-4_11

What characteristics must these booms have? First of all, given the overall size of a solar sail (typically greater than 20–40 m on a side) and the relatively small size of today's rocket fairings (typically less than 5 m in diameter), the booms must be deployable from some sort of spacecraft. There is no rocket known that can loft a pre-deployed, 20 m diameter solar sail. These deployable booms must also be very lightweight. Recall that a key technology driver for a solar-sail propulsion system is (low) mass. The push from sunlight is slight, and if the sail or its support structures are heavy, the sail will not perform well.

Centripetal acceleration is the acceleration that causes any rectilinear path to become curved. It is a pure kinematical concept, which is not limited to circular motion. For instance, an object at the end of a rope, rotating about a vertical axis, undergoes a centripetal acceleration *caused* by the cord's tension acting toward the rotation axis. When one writes Mass × Centripetal Acceleration = Tension, this means that the active force (or the motion cause) is the cord's tension, whereas the centripetal acceleration is the kinematical manifestation of this force. This is only a particular case of the general equation Force = Mass × Acceleration.

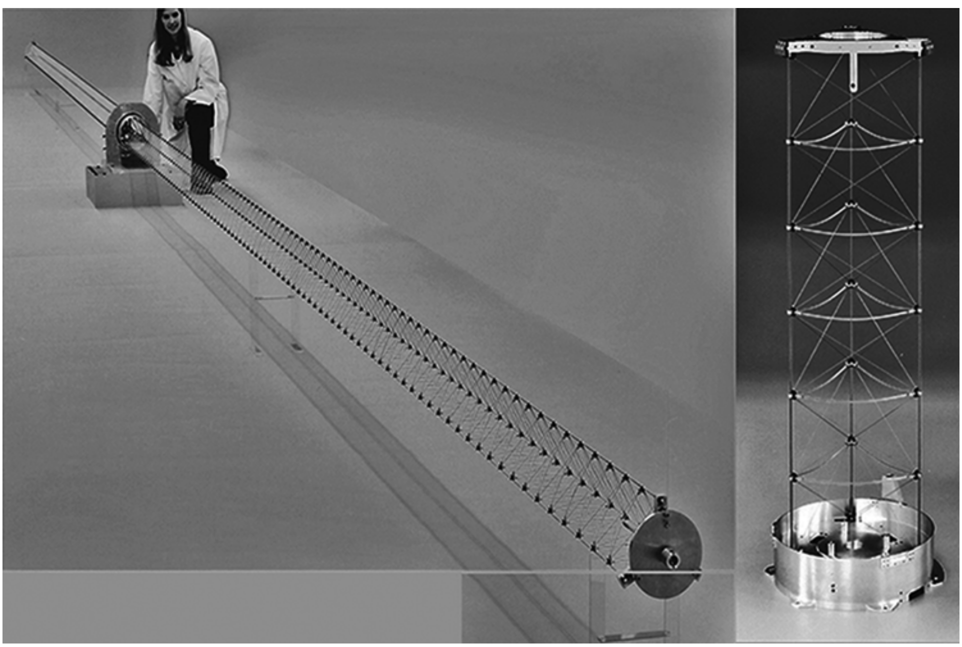
Do not confuse *centripetal* acceleration with *centrifugal* acceleration, even though they have the same magnitude. The latter is sensed by a body in a rotating frame; for example, think of what you sense when you are steering your car along a highway curve. The centrifugal acceleration is directed outward with respect to the curve, as its name indicates. An observer on the highway (or on the other side of the police television circuit) has a different view by watching you and your car curving because of centripetal acceleration. In this case, such acceleration is the consequence of the car engine, wheels, and road–wheel friction.

In contrast, in a general rotating frame, any body undergoes three different accelerations (all independent of its mass) for the mere reason that it is rotating; namely, they are not caused by force. (The true explanation of that can be provided in a postgraduate course for physicists.) Here, with regard to solar sails, it suffices to mention that a body in a rotating structure senses (besides the centrifugal acceleration, which is proportional to the distance from the rotation axis) a second acceleration that depends on the body's relative speed (the Coriolis acceleration, which is also very important in air and ocean circulations). The third acceleration occurs when the frame rotates at a nonconstant angular speed. (This last term may be included in a more general definition of centrifugal acceleration.) Generally, the directions and the magnitudes of such accelerations differ from each other.

NASA tested two design options for a long, lightweight deployable solar sail boom in 2004 and 2005. The first option most resembled a sail ship's mast of days gone by in that it was a solid, mechanical boom. Made from state-of-the-art composite materials, a rigid mechanical boom (developed by ATK Space Systems of Goleta, California) was used to deploy and test a 20 m solar sail developed for NASA. The boom and sail worked well in both ambient testing (room temperature and in air) as well as in thermal vacuum testing at NASA's Glenn Research Center Plum Brook Station (Sandusky, Ohio). The ATK booms, when stowed, resemble a spring under tension. They collapse to a mere 1 % of their fully deployed length and, when deployed, are capable of suspending a large sail even under the effects of Earth's gravity, which they will not have to sustain during operation in space. Figure 11.1 is a picture of the mast during development testing by NASA and ATK.

NASA's efforts in this area were preceded by Germany's Deutschen Zentrum fur Luft-und Raumfahrt (DLR), which used booms made from carbon fiber reinforced plastic to deploy a 20 m three-axis stabilized solar sail in 1999 (Fig. 11.2).

NASA also worked with L'Garde, Inc. (Tustin, California) to develop lightweight inflatable boom technology (Fig. 11.3). As the term implies, an inflatable boom is stowed onboard the central spacecraft structure until its deployment is initiated by blowing it up like a balloon. Nitrogen gas is expelled into the balloon-like boom until it is fully deployed. The boom is made from a material that quickly becomes rigid after exposure to the cold temperatures of deep space, thus obviating the need for the gas to remain within it. The benefits of this approach are twofold. First, the inflated boom is mechanically simple with few moving parts. Second, it is very lightweight and can be scaled to larger sizes without a significant increase in overall mass density. Since having low mass is critical for a solar sail propulsion system, this approach holds much promise.



11.1 Capable of supporting a solar sail in space, this boom, developed by ATK Space Systems, was tested by NASA both in air and in space-like vacuum conditions (Courtesy of ATK Space Systems)

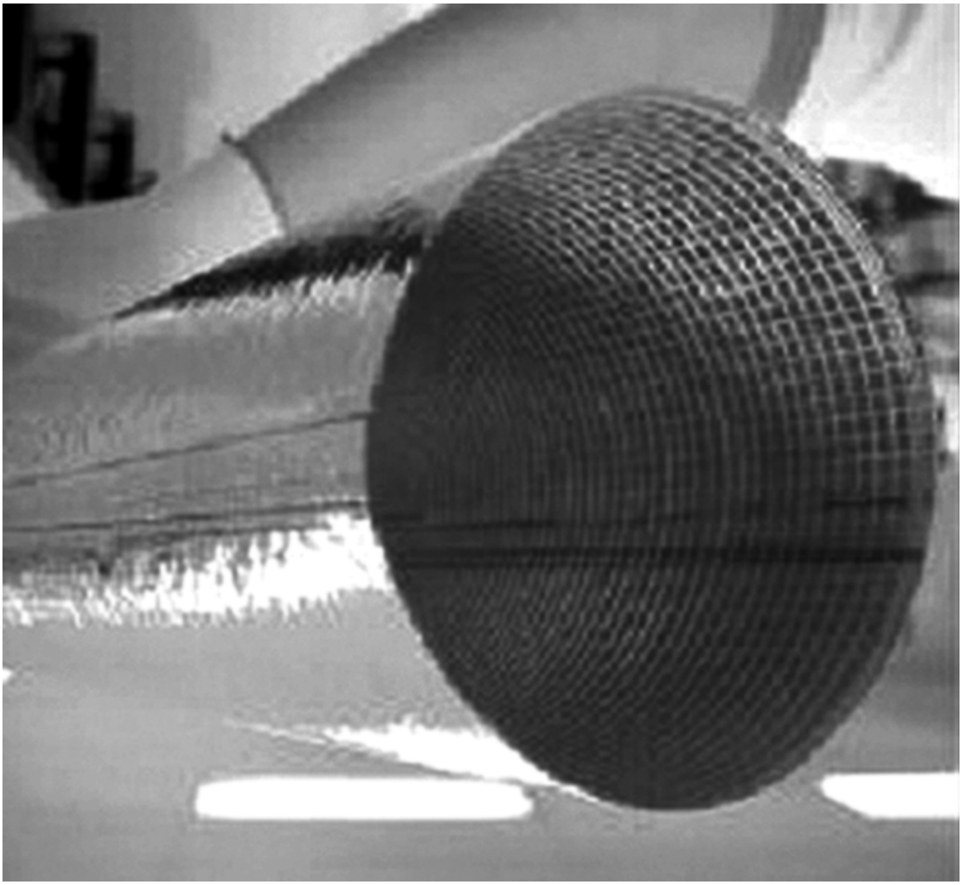
11.2 This rigid boom was used by DLR to deploy its solar sail during ground testing in 1999 (Courtesy of DLR)

Spin-Stabilized "Solid" Solar Sails

An obvious question to ask when designing a lightweight solar sail is how does one reduce the amount of mass required? One answer is to eliminate the mass of the booms (described previously) used to deploy and stabilize the sail. Fortunately, nature provides us with a proven and easily implemented solution—we can spin the sail to get rid of the booms. The centrifugal acceleration experienced by the sail due to its rotation (as mentioned in the box above, the system of the sail's molecules, as with any rotating object, senses its own rotation point by point) puts the sail material under tension, keeping it flat as sunlight reflects from it, thus eliminating the need for any booms. This may require that the sail be strengthened with tension-bearing lines, but the mass required for these lines is much less than that of a boom system. Since the sail system is spinning, it behaves like a large gyroscope, providing stability in pointing that would otherwise have to be achieved in some other way.

In addition to providing pointing stability, keeping the sail flat, and under tension, a spinning sail can be easily deployed. The rotation acceleration that keeps the sail taut can be used to gently pull the sail outward from the spacecraft during deployment. One should note that during the deployment process, the sail moves (slowly) with respect to the rotating structure. Such a deployment would work like this:

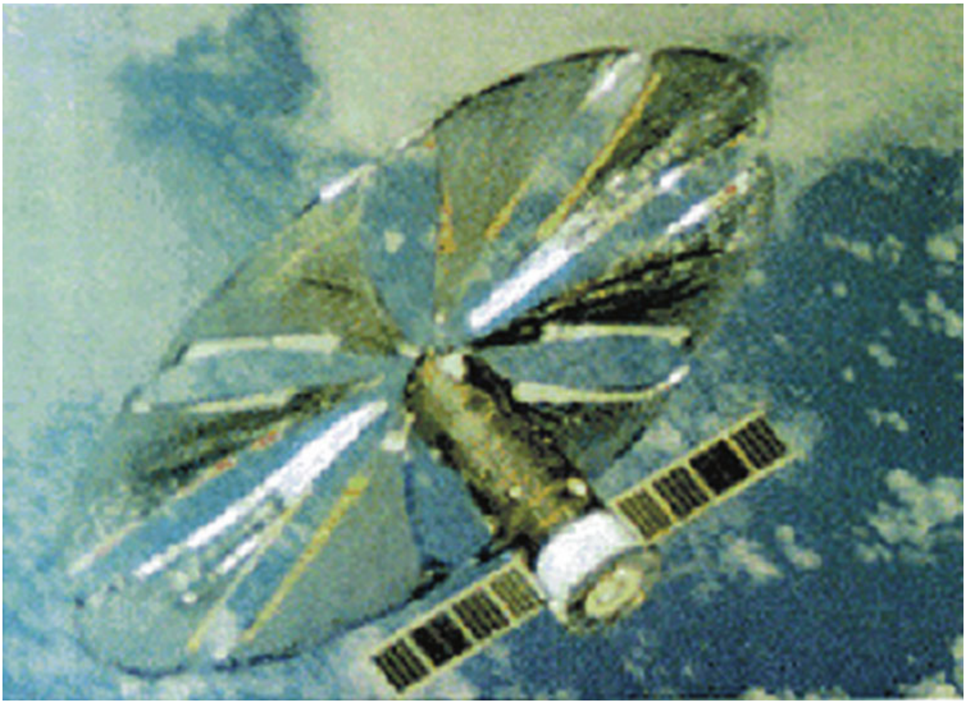
1. The sail is stowed aboard a small spacecraft and is launched into space.
2. The spacecraft begins to spin.



11.3 Shown here is deployment testing of L'Garde's inflatable boom for a solar-sail propulsion system (Courtesy of NASA)

3. The folded or packaged sail is released from the spacecraft, slowly unfurling due to the centripetal acceleration produced by the spinning spacecraft.
4. The fully deployed sail is kept taut by maintaining a slow rotation about an axis perpendicular to the plane of the sail.

The Russians successfully demonstrated this technique in space with their Znamya mirror experiment flown in 1993 (Fig. 11.4). Deployed from an unmanned Progress spacecraft following its resupply of the Mir Space Station, a 20 m circular sail-like reflector was unfurled. Its stated purpose was to demonstrate the technologies required to use large mirrors to illuminate cities at night, though most of the technologies on Znamya were directly applicable to solar sailing. A follow-up experiment in 1999 was to have deployed a 25 m diameter sail from another Progress vehicle during space operations. Unfortunately, this test failed due to the accidental extension of an antenna into the area occupied by the unfurling sail—the antenna caused the sail to crumple, ending the experiment.

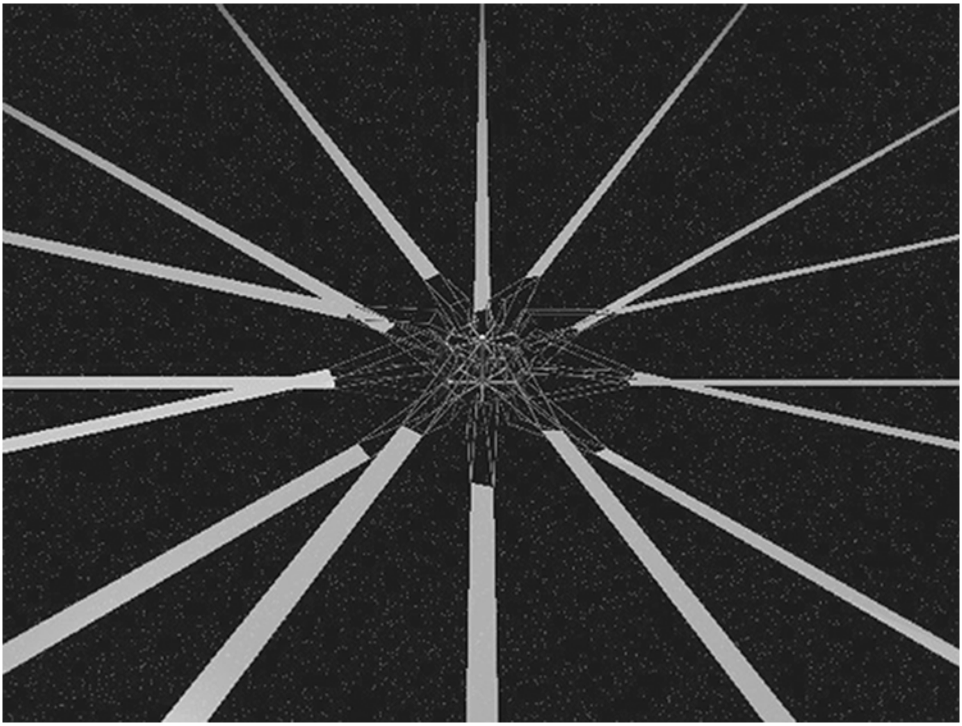


11.4 The Russians were the first to deploy a spinning, solar sail–like structure in space. This is an artist's concept of Znamya-2 (Courtesy of Russian Space Agency)

Spin-Stabilized "Heliogyro" Solar Sails

The heliogyro is another class of spin-stabilized solar sail. Heliogyro sails are also stabilized by centripetal acceleration, but they take on a totally different character in that they are composed of several separate vanes that deploy because of the spinning motion of the centrally located spacecraft. Instead of appearing as a solid, or near-solid, circular reflector, they look more like a windmill. An artist's rendering of a heliogyro solar sail is shown in Fig. 11.5.

This list is by no means exhaustive. In addition to the varieties of sails mentioned in this chapter, there have been various studies and technology efforts by the world's space agencies, universities and private organizations that result in a myriad of design options. Some show the benefits of triangular three-axis stabilized sails versus square ones. Others show the superiority of inflated booms over rigid mechanical booms, and vice versa. One thing is certain when comparing the various sail design options: no one option is superior for all mission applications or time frames. A near-term mission to study the Sun in the inner solar system will likely utilize a very different sail technology than that which will be used for our first missions into interstellar space. Engineers, keep innovating!



11.5 Shown here is an artist's rendering of a heliogyro solar sail composed of multiple vanes deployed and stabilized by the spinning motion of the central spacecraft (Courtesy of B. Diedrich)

HOW TO MANEUVER A SAILCRAFT

What Is Spacecraft Attitude?

Let us begin by explaining spacecraft attitude. This concept is not limited to space vehicles or other bodies outside our planet. The classical astronomical observations of the celestial bodies have been done from ground by (automatically) projecting them onto a sphere of very large, but indeterminate, radius. Such a sphere is called the **celestial sphere**; it is a mental construct, but quite useful. This concept does not depend on the specific planet or other body one is considering. Thus, the direction of a star is simply the observer-to-star line. The intersection of such a line with the celestial sphere is a point that is completely determined by two angles, like the longitude and the latitude pair, at a given instant. In other words, a point on the celestial sphere represents a direction.

Now, let us suppose that you want to tell somebody how, for instance, a large hardcover book is oriented in your study room. The first thing to do is to define some frame of reference in your room walls. Recalling analytic geometry and the three Cartesian axes: x, y and z, the frame of reference can be X-Y-Z along three edges convergent in one of the vertices (you may call the *origin* [O]) of the room. Because your book can take a lot of (infinite, in principle) orientations with respect to the frame O-XYZ, you can repeat the same logical process for the book. Thus, you have constructed another frame, say, o-xyz, *attached* to three edges emanating from a vertex of your book. (It is not mandatory that the two frames are Cartesian, in reality, but it's very useful.) At this point, the orientation of your book is quite determined once you decide the directions of the axes x-y-z with respect to the room frame XYZ. (Note that, as far as orientation is concerned, you don't need to know the position of the o-point with respect to the O-point.) In practice, you have to know the angles that x-y-z form with X-Y-Z. Six of the nine possible angles are sufficient. Thus, you have determined the **attitude** of your book with respect to your room. If you rotate the book in some way, you can repeat the same steps for determining the new attitude.

In space, we don't have a pretty room for orienting a spacecraft. The role of your room can be replaced by the celestial sphere *centered* on the spacecraft. However, we need again three axes x-y-z bonded to the spacecraft's main structure; the origin of the axes may be coincident with the spacecraft's center of mass or some other suitable point. Quite similarly to the book example, the three directions of x, y and z represent the orientation or the attitude of the space vehicle.

To specify angles on the celestial sphere, we need to define a great circle acting as a reference, and a special point (E) on it. (A **great circle** on the sphere is a circle with its center coincident with the sphere center.) In turn, this reference plane defines its own **north and south poles**, namely, the intersections between the sphere and the orthogonal-to-circle line passing through the sphere center (C). Usually, the north pole (N) is adopted as the second reference point. Thus, the CE line is taken as the x-axis, whereas the line CN is taken as the z-axis. Hence, the y-axis is automatically fixed. The two special points, E and N, are utilized to measure the angles defining a direction. Historically, the great circle of reference was Earth's equator at some date and the E-point was the east intersection of the ecliptic with the equator (the March equinox). Nowadays, the equatorial system of coordinates has been replaced by the highly accurate frame known as the International Celestial Reference Frame (ICRF, or its idealization ICRS), which is strictly inertial. The ICRS orientation, though, is close to that of the old system taken at J2000 (this abbreviation stands for the date 2000-01-01, 12:00:00, terrestrial time). The interested reader can be introduced to or find technical readings on such basic topics at http://www.iers.org/.

Of course, the attitude of a spacecraft may change with time. The spacecraft can rotate about some axis of symmetry; thus, at a given time, one must also measure the rotation angle to get the complete attitude. The examples are manifold because any spacecraft may have rotating parts, flexible appendages, long booms, independent steerable pieces, damping internal systems, etc.

Classifying Attitude Analysis Items

The general spacecraft attitude analysis may be categorized mainly as attitude determination, attitude prediction and attitude control.

Attitude **determination** is the process of computing the spacecraft orientation, with respect to an inertial frame of reference of Earth, the Sun or another celestial body, starting from the measurements of sensors onboard the spacecraft.

Attitude **prediction** consists of forecasting the future evolution of spacecraft orientation via algorithms, where both the spacecraft and the environment are modeled.

Attitude **control** is the process that enables us to get the desired attitude in a certain period of time for different purposes (e.g., thrust activation, spacecraft safety, scientific payload requirements, perturbation compensation, etc.). There are two main areas: attitude **stabilization** and attitude **maneuver**. The former concerns a process aiming at keeping the spacecraft attitude for a certain time interval. The latter concerns the problem of changing the spacecraft attitude, especially for allowing the spacecraft to follow the right trajectory to the mission target.

Classically, celestial mechanics is the area of dynamics and astronomy that addresses the motion of celestial bodies under their reciprocal gravitational influence. Astrodynamics is the study of the motion of artificial objects in space. The big difference between astrodynamics and celestial mechanics consists of propulsion and its control. In turn, astrodynamics has two major partitions: trajectory (or orbit) dynamics, and attitude dynamics. The former addresses the motion *of* the center of mass, or the barycenter, of spacecraft (i.e., the translational motion), whereas the latter is concerned with the motion of the spacecraft *about* its barycenter (i.e., the rotational motion).

When a force (either internal or external) applies along a direction that does not pass through the barycenter, the so-called moment of the force or the **torque** (about the barycenter) is generated. Internal and external torques can affect the rotational motion of parts of spacecraft with respect to others. However, only the external torques act upon the *overall* rotational motion (e.g., with respect to an inertial frame) of the spacecraft.

A fundamental property of spacecraft motion is that its trajectory and attitude histories are strongly connected. Conventionally, propulsive devices for trajectory control are called the main engines or thrusters, whereas the devices providing spacecraft with the control torques for orientation maneuvers are often referred as the control hardware or the **actuators** (which therefore represent a component of the whole attitude control system).

Finally, any spacecraft may be categorized in two large classes with respect to the attitude stabilization: (1) spin-stabilized spacecraft, and (2) three-axis stabilized spacecraft. The second class requires more complex active control of the vehicle attitude, which otherwise would drift uncontrolled under the action of external torques that may continuously perturb the spacecraft.

Sail Attitude Control Methods

In general, there are two major external torques on any spacecraft: (1) the **disturbance torques**, caused by the space environment the spacecraft interacts with, and (2) the **control torques**, induced intentionally by means of attitude actuators. The latter are of utmost importance because it is through attitude evolution that the main propulsion system, whatever it may be, forces the spacecraft to follow the planned trajectory to the final target.

A general rigid body rotating freely (no torque) in space has a rather complicated motion, with angular velocity constant in magnitude, but variable in direction (i.e., something roughly like the uniform circular motion). If we want to change both the magnitude and the direction of the angular velocity, and then to affect the attitude angles, we have to apply torques.

In Chaps. 5 and 7 we stated that two points, normally inside the volume occupied by the whole sailcraft, are given special importance in sailcraft dynamics: the center of mass of the spacecraft and the sail system, and the center of pressure of the sail system. Since the sail system is much larger than the spacecraft, one can define the vector position of the spacecraft (as a point-like system) with respect to the sail. In addition, the solar pressure thrust vector has a major component along the sail axis and a (nonnegligible) component along the mean plane of the sail (see Chap. 16 for more precise explanations). Normally, the sail axis is not aligned with the (local) Sun-sail line and there is the need to change the attitude sail systematically for controlling the sailcraft trajectory. Let us describe some methods envisaged for attitude control.

Method 1: Relative Displacement between Barycenter and Center of Pressure

One can think of shifting the sail laterally by acting on the sail structure directly. This sail shifting should be easier to implement if the sail were like a one-block structure. If the full sail is sectioned into subsails or panels, then one or two symmetrical sections may be translated with respect to the others. In any case, a torque arises with respect to the barycenter. Such torque can affect only two of the three sail directions; it is not possible to control the motion of the sail about its orthogonal axis. That may cause problems to the attitude control of some scientific instruments of the spacecraft payload, if a three-axis control is required by the mission objectives.

Since it is the relative displacement that matters, one could shift a ballast mass (in the spacecraft) by some device consuming electric energy. The physics of control does not change, of course: the induced torque allows two-axis control, as above. However, the towing device may be much simpler and lighter, especially when the sail is very large.

The so-called control authority is strongly related to the sail attitude itself; in other words, if the sunlight impinges on the sail with a large incidence angle, not only does the thrust acceleration decrease, but also the torque that one wants to use for controlling the sail lessens. Furthermore, the spacecraft has to be located between the Sun and the sail, a constraint that would cause many problems in missions for which the sailcraft trajectory is close to the Sun.

There is another general risk. A number of non-ideal effects may induce the barycenter and the center of pressure to be offset by some unwanted (and unmeasured) position vector:

hence, emerges **bias** or **unbalanced force moments**, which act as disturbance torques. As they may be comparable to the attitude-maneuver-required torques, they need to be trimmed down to zero (nominally). This can be done by an active attitude stabilization device; namely, by increasing the mass and complexity of the sailcraft.

Method 2: Using Pairs of a Segmented Sail

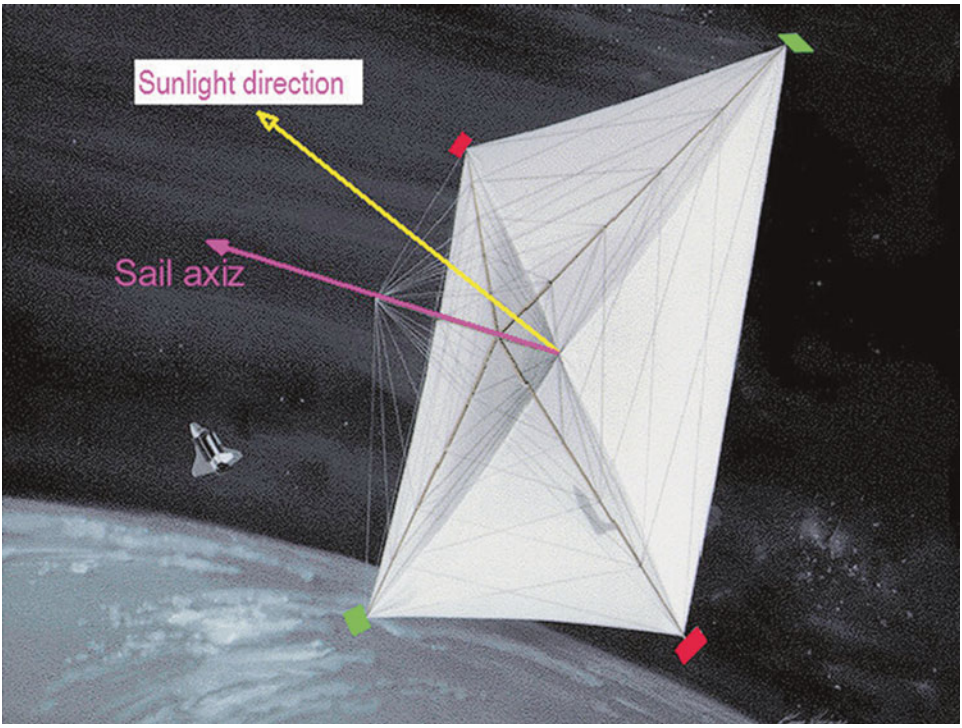
In contrast to the above-mentioned subsail pair (which was translated), this technique would use the rotation of two opposite panels. To do so, the sail has to have each attitude panel supported by two articulated booms, which gimbal at the sail mast structure. In addition, at the boom tips, the panels may be attached to small movable spars; thus, panel edges can be independently raised or lowered with respect to the boom's plane. By such a method, full sail controllability can be achieved. However, the hardware that enables panel movements should be rather massive. For redundancy, at least two panel pairs have to be equipped as described, thus increasing the sailcraft mass-to-sail area ratio. As a result, the solar pressure thrust decreases, and fast missions would not be allowed.

However, for other mission types, this control technique exhibits two additional advantages: (1) Attitude control is still possible when, in some mission phases, the sunlight is grazing the sail's mean plane; namely, when thrust is almost zero, (2) A priori, the spacecraft is not constrained to be put between the Sun and the sail, unless otherwise required.

Method 3: Utilizing Small Sails Located at the Boom Ends

In recent years, this method has been investigated considerably with regard to four-panel squared sails, like those experimented on the ground by NASA and ESA. Figure 11.6 visualizes the concept for a squared sail typically assumed for the first missions. One attaches small sails, or vanes, at the end of the booms of the mainsail frame. Each vane is a complex structure quite similar to the sail system. A vane may have either a triangular or rectangular shape. Every vane frame is gimbaled to the boom tips in such a way as to have one or two independent rotational movements. Thus, a full control authority of the mainsail could be achieved, even for real sails with construction asymmetries, beam bending and billowing. Each pair of opposite vanes can be given a different task; for example, following Fig. 11.6, the red pair of vanes (the **fore** and **aft** vanes) is more or less aligned with the sailcraft velocity. It can be used for getting and stabilizing a desired value of the angle between the sail's normal (the ideal sail axis) and the sunlight direction. The green pair of vanes (the **starboard** and **port** vanes) can be utilized for maneuvering and performing an active stabilization about the current sunlight direction. By sequencing the two maneuvers in either order, one can get the desired attitude of the sail and stabilize it for a certain time, until a new attitude is required.

This technique of sail attitude control seems difficult to apply to circular sails. The circular "rigidized" beam that keeps the sail open (see Chap. 7) would be too small for a strong joining to complex structures like vanes.



11.6 Solar sail controlled in attitude by small sails located on the boom-tips (Courtesy of NASA, adapted by author Vulpetti)

Method 4: Very Small Rockets

This is an obvious and well known technique. Depending on the mission duration and goals, one may employ microchemical engines or microelectric thrusters. On the balance scale pans, one has two main conflicting "weights:" the consumption of propellant and the independence of the sailcraft distance from the Sun. As a point of fact, the previously mentioned methods utilize the solar pressure, which acts on the attitude control surfaces as well. However, in missions to distant planets, a spinning sail is not appropriate for (long) rendezvous maneuvers. Thus, full sail control would be necessary, but this gets complicated because of the weakness of the solar pressure with the increasing Sun-sail distance. On the other side, using micro-rockets as primary devices for attitude control for the whole mission may result in an unfavorable mass, especially for large-sail missions.

Method 5: Changing Sail Reflectance

This method may appear doubly strange. Let us first describe qualitatively what the principle it is based on is. If the sail reflective layer is made of two different materials, one that reflects sunlight in a unchangeable way (e.g., once aluminum is chosen as the reflecting material and vaporized on a plastic support, there is no way to vary its mode of reflecting the light), and another one that can be *controlled* in reflection. Then, if we find a way to drive the amount of the reflected light, then we are able to get thrust and torque without using any of the above methods. This could appear a very difficult task; however, the first oddity is that a small version of such attitude control has been already demonstrated in space by JAXA's IKAROS. Its reflection capability was due essentially to a layer of aluminum vaporized on a special type of polyimide resin patented by JAXA. IKAROS's sail designers placed long strips of reflection-variable material loaded near the rims of the sail membrane; they selected liquid crystal films (LCF), the reflection of which could be varied by applying on/off voltage to the strips. Thus, reflection was changed from the (quasi-) specular to the diffuse mode, or vice versa, resulting in a torque and changing the sail orientation. This experiment can be turned into a conceptual advancement awaiting a confirmation via future sailcraft. This idea was not new.

In his book, J.L. Wright considered (very qualitatively) that "Attitude control is provided by changing the center of mass or the center of pressure of a ship. This can be done through the use of vanes, mass movement, sail movement, sail deflection and possibly reflectivity modulation" [1]. In his 2004 paper, C. McInnes suggested using sails with variable morphology (e.g., in configurations like a solar concentrator or like a large antenna for data returns) [2]. On July 13, 2010, JAXA performed a change of reflection in the IKAROS sail LCF and got an attitude control torque—a very meaningful experiment indeed. Later, in August of 2012, author Vulpetti proved mathematically that there exist *five* types of sailcraft thrust maneuvering. The fifth type allows getting a change of magnitude and/or thrust direction *without* varying the sail orientation in the sailcraft frame [3]. In the 3rd International Symposium on Solar Sailing, A. Borggräfe proposed a sail with continuous reflection variation for getting thrust and torque [4].

The concept of thrust maneuvering for solar-photon sail is therefore more general than sail attitude control via mechanical actuators of conventional and/or advanced type. The above-mentioned experiment on IKAROS appears as a special device opening a new "seam" of very advanced sailcraft. At the time of this writing, in the Astronautical Department of Rome University 'La Sapienza,' some graduate students (who started from the preliminary theory developed by author Vulpetti in his book of 2012) have been researching how thrust vectoring of the fifth type could affect sailcraft trajectories in practice. One of the key points is a very realistic thrust model based on vector theories of diffraction. Results are very encouraging and will be published in 2015 on a technical journal.

CONCLUSION

The first solar sail missions in the near term, in particular the flights of technology demonstration, may use one of the techniques described above. Subsequently, as experience accumulates and the mission complexity increases in terms of goals, transfer trajectory and operational orbit, a multiple attitude control system may turn out to be the most efficient choice. For instance, methods (1) and (3) would entail an excellent propellantless control, while method (4) (e.g., via pulsed plasma-jet micro-rockets at the sail mast tips) guarantees a backup attitude subsystem independent of the solar pressure. In this case, all three methods would make up the full attitude control (and stabilization) system. However, method (5) deserves further and accurate investigations, which may open new ways of designing high-performance and impressive sailcraft.

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