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REVIEW ARTICLE

Design and application of solar sailing: A review on key technologies

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Abstract Solar sail technology has been proposed and developed for space explorations with advantages of low launch cost, no-propellant consumption, and continuous thrust, which has great potentials in earth polar detection, interstellar explorations and etc. The development of solar sail has made significant progress in structural design, manufacturing, materials, orbit transfer, and stability control in the past few decades, which makes meaningful contributions to astronomy, physics, and aerospace science. Technological breakthroughs of Solar Radiation Pressure (SRP) propulsion and interstellar transfer have been achieved in current solar sail missions. However, there are still many challenges and problems need to be solved. This paper attempts to summarize the research schemes and potential applications of solar sailing in space missions from the viewpoint of key technologies, so as to provide an overall perspective for researchers in this field. Analyses of the key technologies of solar sailing system design are provided. Finally, challenges and prospective development of solar sailing are discussed.

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1. Introduction

Space agencies such as NASA, European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA) have proposed their deep space exploration plans in the 21st century, aiming to maintain an advantage in the competition for space resources.[1–3] Deep space exploration missions are usually getting quite far away from the earth, so propulsion capability of spacecrafts has become an inevitable challenge. Therefore, a variety of new propulsion methods have been proposed, among which solar sailing that can provide continuous small thrust and infinite specific impulse has become one of the most promising in deep space exploration.

The solar sail is a type of spacecraft that uses the interaction of solar photons reflected from membrane with a large surface-to-mass ratio to accelerate.[4] Momentum transfer

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occurs when solar photons hit the membrane, and SRP is used to describe intensity (or flux) of the solar radiation. The solar sailing spacecraft has advantages over traditional chemical propulsion spacecraft, including light weight, low launch cost, no propellant consumption, and continuous thrust. Although thrust produced by the SRP on 1 m^2 sail is on the order of millinewtons, the continuous acceleration makes solar sails suitable for some special space exploration missions, such as solar polar exploration, asteroid detection, geomagnetic storm forecast, translational point detection, and interstellar travelling.[5].

In the 1920 s, Literature[6] first proposed that the thrust generated by SRP can be used for the spacecraft propelling. Until 1958, Garwin[7] published the first paper on solar sailing that led to a greater interest in this topic. In 1960, the ‘‘Echo-1″ probe balloon was launched by NASA, which measured the solar pressure for the first time.[8] Afterwards, the United States and Russia put forward schemes on the solar sailing, but most of them have been stranded due to a series of difficulties in solar sailing design, uncertainty about the mechanical properties required for membrane materials, and insufficient funding. Moreover, some schemes were terminated due to failure in deployment tests.[9] Until May 21, 2010, JAXA successfully launched the first solar sailing spacecraft "IKAROS". It successfully demonstrated an on-orbit spinning deployment, accelerated sailing and Venus fly-by. Since then, solar sailing technologies have been dramatically developed, and also many countries have taken the solar sailing as an important scheme for deep space exploration propulsion. Besides, increasing innovative designs and researches were presented in academic journals and authoritative conferences, such as AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA Spacecraft Structures Conference, etc.

In the past 30 years, the solar sailing had made a progress from concept to on-orbit demonstration, building on improvements in structural design, membrane materials, and its dynamics and control.[10–11] This paper reviews the development of solar sailing and summarizes key advances in key technologies.

This paper is divided into 5 parts. In Section 2, the main research schemes of solar sailing are summarized in chronological order. In Section 3, the key technologies and the applications of solar sails are summarized. In Section 4, the key technologies of solar sailing are classified and discussed in detail from the view of engineering. In Section 5, the current technology challenges and the future development about solar sails are presented and discussed. Finally, the paper is concluded in Section 6.

2. Development of solar sailing

This section reviews the fundamentals and development of solar sailing schemes. The contributions of the main research teams are also discussed.

2.1. Fundamentals of solar sails

The solar sail is a type of spacecraft propelled by SRP. It is of great importance to establish a proper mathematical model to evaluate the propulsion efficiency of the solar sail. Based on reasonable assumptions of parallel solar radiation rays, numerous works have been. done to build solar pressure models, which mainly can be divided into ideal SRP model (I-SRP) and optical SRP model (O-SRP).[12–17] Compared with I-SRP, the O-SRP model accounts for optical parameters of the membrane surface that determine the key feature of the SPR tangential force, which are ignored in I-SRP model. Therefore, the O-SRP force model is of significant value in analyzing solar sail dynamics, attitude control, and orbit transfer. For instance, a widely used O-SPR force model[12] is shown as

$$\begin{aligned}\boldsymbol{F}_{\text{tot}} = -PA(\boldsymbol{n}_{\text{s}}\cdot\boldsymbol{n})(\boldsymbol{\alpha n}_s + \alpha\tfrac{\varepsilon_{\text{b}}B_{\text{b}}-\varepsilon_{\text{f}}B_{\text{f}}}{\varepsilon_{\text{f}}+\varepsilon_{\text{b}}}\boldsymbol{n}\\ +2\rho_{\text{s}}(\boldsymbol{n}_{\text{s}}\cdot\boldsymbol{n})\boldsymbol{n} + \rho_{\text{d}}(\boldsymbol{n}_{\text{s}} - B_{\text{f}}\boldsymbol{n}))\end{aligned} \tag{1}$$

where $\boldsymbol{F}_{\text{tot}}$ is the total force on a flat sail, A is the surface area of the sail that receives the light pressure, P is SRP acting on the A surface, which refers to the surface reflectivityρ. The subscripts f and b are the front and back sides of the film. $\boldsymbol{n}$ is the surface normal unit vector and $\boldsymbol{n}_{\text{s}}$ is incident solar radiation direction. B is the Lambertian constant. α is absorption rate, and ε is surface emissivity. It is inferred the solar sails had better to be ultra-light, ultra-thin, highly reflective, high-temperature resistant and adaptability to high-altitude solar radiation.

2.2. Research schemes and hotpots in solar sailing

Mankind's initial application to solar pressure can be traced back to the 1970 s. From the 1990 s, solar sailing has become a research hotspot, and related researches have sprung up. In this section, research schemes of solar sailing spacecrafts are introduced.

(1) Znamyas.

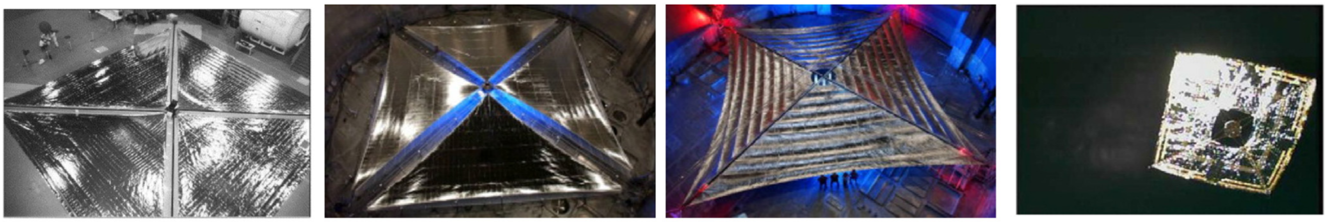
Znamya-2 was launched on February 4, 1993. It was not intended to act as a solar sailing spacecraft, but rather as a verification of the deployment technology and concept for large-scale space structures under the action of centrifugal force. The reflector, with a diameter of 20 m, was deployed successfully.[18] Znamya-2 proved the feasibility of on-orbit deployment for large-scale flat gossamer structures, which laid a foundation for later development of solar sails.[18] Later, Znamya-2.5 was developed and tested in 1999 in an attempt to deploy a 25 m diameter sail, but it failed due to the sail being caught and torn by the antenna.[8]

(2) ESA & DLR solar sail.

A ground test of a fully deployable light solar sail structure was carried out by ESA and German Aerospace Center (DLR) in 1999.[19–20] Notably, a gravity compensation system was used to simulate the microgravity environment during the ground tests. As shown in Fig. 1(a), the four Carbon Fiber Reinforced Plastic (CFRP) booms were deployed, and then four triangular sail sections were deployed and tensioned to form a plane. While three different materials, 7.5 μm Kapton film, 12 μm Mylar film and 4.0 μm Polyethylene naphthalate (PEN) film, were used as the sail membranes. The total sail area is 330.5 m^2.

(3) ATK & L'Garde solar sail.

At the beginning of the 21st century, two solar sail ground trials were undertaken by ATK and L'Garde on behalf of NASA. As shown in Fig. 1(b) and 1(c), every system had a side length of 20 m and was deployed using deployable booms equipped with high-precision control systems.[2,21–22] ATK built



(a) ESA & DLR solar sail[19] (b) ATK solar sail[2,15] (c) L'Garde solar sail[2,16] (d) IKAROS[24]

Fig. 1 Typical solar sailing schemes.

a sail with coiled truss arms and CP1 membrane, while L'Garde used inflatable booms and a Mylar membrane. The deployment and functional tests of the two systems in a vacuum environment were carried out in 2004.

(4) Cosmos-1.

Cosmos-1, designed by the Planetary Society, was launched aboard Wave carrier rocket on July 20, 2001, which intended to conduct a deployment test in suborbit. The launch vehicle took off from the submarine and ascended to high altitude successfully.[23] However, Cosmos-1 was not be separated from the third-stage rocket because of the separation instruction signal being not issued successfully. On June 22, 2005, a solar sail scheme also named Cosmos-1, was developed by Russia and the United States, failing to enter the intended orbit due to failure of the launch vehicle. The second Cosmos-1 weighs 50 kg and is composed of 8 triangular polyester films with a hypotenuse of 15 m. The total deployable area is 600 m^2.

(5) IKAROS.

IKAROS, launched by JAXA in 2010, is the first solar sailing spacecraft to complete deorbit missions successfully.[24–25] The total mass of the spacecraft is 307 kg and the deployable area is about 196 m^2.[26] As shown in Fig. 1 (d), the sails were deployed and tensioned through four tip points with a mass of 0.5 kg. Thin-film solar cells were installed on the sails to provide energy for the spacecraft. IKAROS successfully deployed on orbit on June 10, 2010, and the dynamic control was achieved by adjusting the reflectivity of 80 Liquid Crystal Display (LCD) panels on the outer edge of sails. Furthermore, IKAROS successfully demonstrated flyby to Venus. [25, 27]

(6) Nanosail-D.

Nanosail-D is a 3U Cubesat that was launched carrying Minotaur IV on November 19, 2010, and was deployed a 10 m^2 sail in Earth orbit successfully on January 17, 2011. The flight phase of this mission also demonstrated the effectiveness of drag-based deorbiting from Low Earth Orbit (LEO) using a sail. CP-1 with a thickness of 2.5 μm was used as the sail membrane. Nanosail-D was deployed using 2.5 m Triangular Rollable And Collapsible (TRAC) booms. After 240 days in orbit, Nanosail-D returned to the Earth's atmosphere on September 17, 2011.[28]

(7) Cubesail.

Cubesail is a solar sailing scheme relied on the 3U Cubesat, which was designed and constructed at the Space Center of University of Surrey. The total mass of the cubic sail is about 3 kg. The main purpose of this mission is to demonstrate deorbit using a drag sail.[29] The project was funded by the ESA ARTES 5.1 Program. The project ended in 2013, by which time a 5 × 5 m^2 solar sail had been developed and a series of ground tests were completed.[30] However, Cubesail has not been demonstrated in orbit.

(8) Sunjammer.

Sunjammer is a solar sailing mission proposed by Space Technology Mission Directorate of NASA in 2011. Sunjammer aims to deploy a 1200 m^2 solar sail and control the direction of the solar sail through the tip blades of booms, in order to approach and maintain the L1 balance point. Sunjammer spacecraft was designed by L'Garde as an experimental space weather buoy to detect solar coronal mass ejections.[31–33] However, NASA eventually terminated the project due to integration issues and schedule risks.

(9) Lightsail-1.

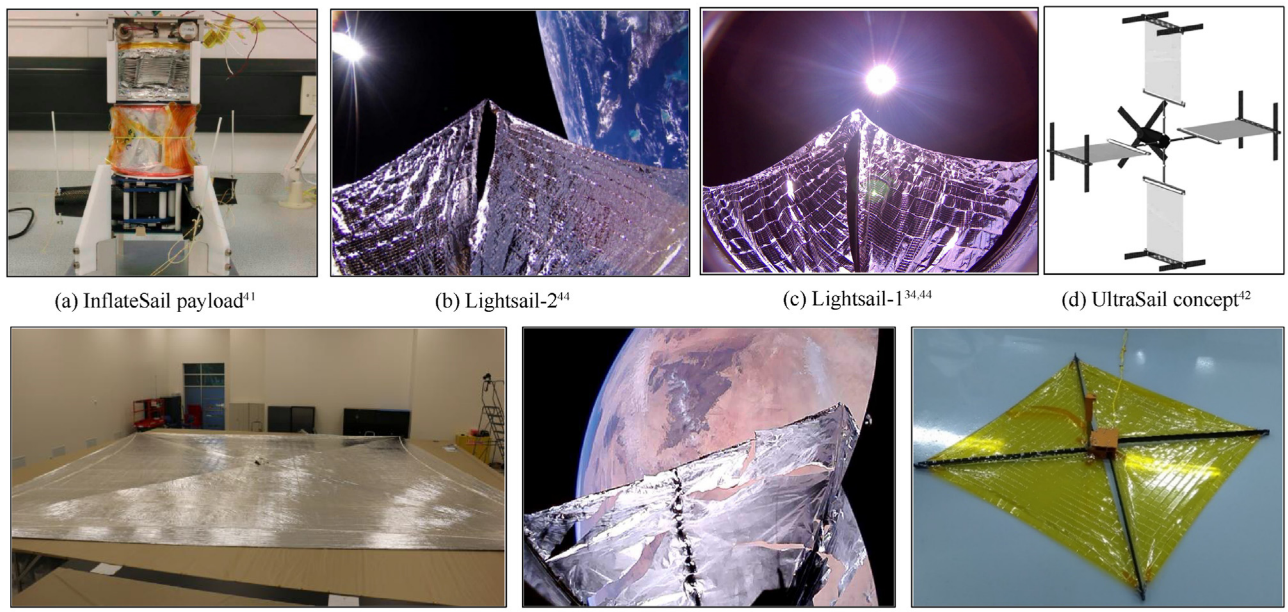
The Lightsail-1 project was initiated by the Planetary Society to advance solar navigation technology based on a 3U Cubesat. Lightsail-1 was a 32 m^2 sail, designed to be deployed in LEO. It was launched on May 20, 2015 and completed all missions in 5 weeks. The deployed sail is shown in Fig. 2 (c).[34–35].

(10) DeorbitSail.

The DeorbitSail project was a low-cost end-to-end space mission to demonstrate satellite deorbiting using a 5 m × 5 m sail deployed from a 3U CubeSat platform. Although not being designed as a solar sail, DeorbitSail shared many of same architectural features as typical solar sails. DeorbitSail was funded by the 7th framework programme of the European Community (FP7). DeorbitSail aimed to employ a low-cost, ultra-light sail as a drag sail to deorbit space debris, lowering the altitude of the spacecraft over time before eventual demise in the Earth's atmosphere. It was estimated that the DeorbitSail system was capable of deorbiting satellites with a mass of 20–500 kg from orbits up to 1000 km within 25 years. The Cubesat was successfully launched on board the PSLV-C28 vehicle in July 2015.[36–38] However, the sails were not deployed. The exact cause of this failure has not been determined.

(11) InflateSail.

The InflateSail 3U CubeSat, designed by the Space Centre of University of Surrey, was another drag sail with many features in common with typical solar sails. The InflateSail satellite was equipped with a 1 m long inflatable mast and a 10 m^2 deorbit sail. The main goal of InflateSail was also to demonstrate the effectiveness of drag sails in LEO. The InflateSail system (or one similar to it) could be installed on any LEO-bound satellite before launch, after which the satellite could be quickly removed from orbit at the end of its service life. In June 2017, InflateSail was launched on the PSLV-C38 carrier rocket and both the inflatable boom and drag sail were successfully deployed on orbit.[39–41] The InflateSail payload is shown in Fig. 2(a).



(a) InflateSail payload[41] (b) Lightsail-2[44] (c) Lightsail-1[34,44] (d) UltraSail concept[42]

(e) NEA Scout mission[45] (f) PW-Sat2 deorbit sail[9] (g) SIASAIL-I

Fig. 2 Solar sailing missions.

(12) UltraSail.

UltraSail was proposed by researchers in University of Illinois Urbana-Champaign (UIUC),[42–43] which could provide a high speed increment Δv and payload mass. The concept of UltraSail is shown in Fig. 2(d). The main innovation of this system is that support structures of sails are almost eliminated by connecting the top of each blade and the corresponding formation flying satellite. The UltraSail system has a hub satellite that contains most of payloads. Polyimide membranes with micro thickness that connect to the hub satellite, are deployed from storage scrolls with the help of formation flying satellites that located at the end of each blade. UltraSail was launched on an Electron launch vehicle on 16 December, 2018 from New Zealand. However, it hadn't work due to communication failure.

(13) PW-Sat2.

PW-Sat2 project was initiated by Warsaw University of Technology (WUT) in 2013, for developing deorbit technology.[9] The project test includes a 4 m^2 drag sail, a custom-made solar sensor, a solar array system and two cameras to observe the deployment process. In December 2018, PW-Sat2 was launched by Falcon 9 rocket of SpaceX. Unfortunately, the membrane was torn during the deployment process, as shown in Fig. 2(f).

(14) Lightsail-2.

Following Lightsail-1, Lightsail-2 was launched on June 25, 2019. It is the first spacecraft to be driven entirely by SRP in earth orbit. On July 31, 2019, the Planetary Society announced officially that the orbital altitude of LightSail-2 had been increased a measurable amount, which indicated that solar sails are a viable propulsion method for CubeSats.[44] Until now, Lightsail-2 (see Fig. 2(b)) is still in orbit, and the orbital height has been reduced from 730 km to 630 km.

(15) NEA Scout.

NEA Scout is a 6U Cubesat developed jointly between NASA's Marshall Space Flight Center and the Jet Propulsion Laboratory (JPL). As a robotic reconnaissance mission, NEA Scout plans to fly over a near-Earth asteroid and return data. A solar sail is designed as the main propulsion system of NEA Scout, which is used with other spaceborne systems to provide stable guidance for approaching a destination, including optical navigation, rotating and actuating the spacecraft to its intended destination.[45–46] The mission is planned to launch in 2022 and deploy an 80 m^2 sail.

(16) Others.

Some solar sailing and drag sailing missions have been attempted in China recent years. SIASAIL-I solar sail developed by the Shenyang Institute of Automation was launched carried by Xiaoxiang-1 07 satellite in 2019, and successfully deployed a 0.6 m^2 sail in orbit.[47] Fig. 2(g) shows the test prototype of SIASAIL-I. SIASAIL-I is only 0.5U volume including the deployment mechanism, the sail booms, the folded membranes and a spring-driven space steering device, which achieves an effective integration. In June 2022, a drag sail with 25 m^2 made by China Aerospace Science and Technology Corporation (CASC, we called it CASC-sail) was deployed successfully.[48] It is the first time that the drag sail is applied to the compartment of a launch vehicle aiming at reducing space debris.

(17) The future concepts.

More future solar sailing concepts have been proposed to further promote the development of solar sail technologies. Kelly, et al.[49] proposed the concept of TugSat, which provides propulsion for CubeSat through a high-performance solar sail to remove space debris. JAXA proposed a future solar sail mission OKEANOS, planned to launch in 2026, to explore a Jupiter Trojan asteroid.[50] Solar Cruiser mission is planned by NASA to study how interplanetary space changes in response to the constant outpouring of energy and particles from the Sun and how it interacts with planetary atmospheres.[51] It is currently planned to launch in 2025. Some standardized information of solar sailing schemes and missions have been listed in Table 1.

While solar sailing development has progressed since 1990 s, it appears to have entered a stage of rapid development in 2010, after which at least 9 sails have been demonstrated in orbit.[52] Solar sail technology is still in what would be classed as an experimental stage, with IKAROS being the only sail that has successfully completed a planetary exploration mission. Therefore, there is still a long way before solar sails can realize space applications.

Solar sail technology represents one of the hot topics in the aerospace field, with a series of technologies, such as materials, mechanics, machinery, testing, control, etc. Which in this paper we mainly summarize as system design, flexible structures, attitude control and orbital dynamics. Thrust vector control analysis, non-keplerian orbit, flexible solar sails are focused, which guides the future development of solar sailing.

3. Applications of solar sails

A series of orbital missions that are difficult for traditional spacecraft can be accomplished using solar sails.[53] Solar sailing has been regarded as an effective way to transmit payloads to planets, small bodies in the solar system, or solar polar orbits. We summarized the potential applications as follows:

(1) Special orbit dynamics.

Highly non-Kepler orbits can be realized by solar sails,[54] which are extensions of the classic two-body and three-body problems of orbital mechanics.[55] These special orbits have a wide range of applications, including earth observation, planetary science, and space-based geoengineering.[56] Offset orbits above the ecliptic can be formed using the continuous low thrust provided by solar sails, which are highly offset above the plane of ground events due to space weather.[57–58].

(2) Formation-flight of solar sails.

Formation flight is a new application of solar sails in space missions. Current research focuses on the application of solar sailing formation for deep space flight.[59–60] GeoSail formation flight is a potential application that is superior to ordinary spacecraft formation missions contributing from the propellant consumption and the duration of the Earth's magnetic tail. McInnes[6] demonstrated that formation flight of multiple solar sails on an inclined orbit was more efficient than a single solar sail in the Geo Sail mission. Mu, et al.[61] proposed a method for orbit and attitude control of solar sails flying in formation in the GeoSail mission. However, the formation flight of solar sails was difficult in low-Earth orbit,[62] because the earth gravity is dominated in comparison to SRP.

(3) Active space debris removal.

Active space debris removal tasks using solar sails is one of the current hotspots.[63] Solar sail / drag sail contributes to orbital transfer through air resistance on low orbits, or SRP on high orbits, so the space debris can be dragged into the atmosphere or into cemetery orbit.[64] The RemoveDEBRIS project, led by the University of Surrey,[65] has conducted preliminary on-orbit demonstration of debris removal using a dragsail.

(4) Earth polar exploration.

The application of solar sails in near-Earth space also includes the establishment of artificial balance above the ecliptic plane. The solar sail with a characteristic acceleration of 0.15 mm/s^2, can be placed on the polar axis of the earth during the summer solstice. The imager located in this artificially balanced position can provide real-time hemispherical views of high latitude regions and poles for climate science, although the spatial resolution is low due to the earth-spacecraft distance of approximately 3 million kilometers. Traditional polar-orbit spacecraft can only provide high spatial resolution, but the time resolution in high latitude areas is poor. Therefore, the images of many polar channels need to be stitched to provide full coverage of the North and South Pole.[66].

(5) Exploration mission of extrasolar planets.

A high speed (13 km/s) is required when using conventional chemical propulsion for transporting payloads to other planets. Solar sails can be used to complete high-energy missions in the solar system. For example, a solar sail with a large payload mass fraction and a characteristic acceleration of 0.25 mm/s^2 can deliver the payload to Mercury in 3.5 years, while a solar sail with doubled performance takes only 1.5 years.[67] Further, Macdonald, et al.[68] proposed to explore the Kuiper Belt and beyond, such as the Oort Cloud using solar sail.

Table 1 Solar sail missions in detail.

Missions	Operator	Time	Deployment method	Volume	Area	Other information
Znamya-2	Russia	1993	-	-	314 m^2	LEO
Cosmos-1	The planetary Society	2005.06	Inflatable tubes	-	600 m^2	Failed
IKAROS	JAXA	2010.05	Spinning	-	196 m^2	315 kg, Heliocentric orbit
Nanosail-D	NASA	2010.11	Bistable booms	3U	10 m^2	4 kg, LEO
Cubesail	Surrey Space Centre	2011	Bistable booms	3U	25 m^2	3 kg, TBD
Sunjammer	NASA	2013	Truss booms	-	1200 m^2	32 kg, canceled
Lightsail-1	The planetary Society	2015.06	Bistable booms	3U	32 m^2	LEO
DeorbitSail	EU	2015.08	Bistable booms	3U	25 m^2	Deployment failed, LEO
PW-Sat2	WUT	2018.12	Bistable booms	0.5U	4 m^2	Deployment failed, LEO
UltraSail	UIUC	2018.12	Formation flying	2 × 1.5U	20 m^2	Failed, LEO
InflateSail	Surrey Space Centre	2019.05	Bistable booms	3U	10 m^2	3.2 kg, LEO
Lightsail-2	The planetary Society	2019.06	Bistable booms	3U	32 m^2	LEO
SIASAIL-I	China	2019.08	Bistable booms	0.5U	0.6 m^2	LEO
CASC-sail	China	2022.06	Bistable booms	-	25 m^2	LEO, drag sail
NEA Scout	NASA	2022	Bistable booms	6U	85 m^2	14 kg, Heliocentric orbit

(6) Flybys and rendezvous of small celestial bodies.

Solar sails are possible to complete the missions of rendezvous or samples return from small celestial bodies regarding to potential unlimited Δv.[69] For example, a solar sailing spacecraft with a characteristic acceleration of 1 mm/s^2 can complete a mission of returning samples from Comet Encke within 5 years. Similarly, exploration of multiple asteroids using solar sailing spacecrafts[70] would be an attractive and cost-effective concept.

(7) Interstellar exploration.

An extremely high escape speed can be obtained from a small-mass nano-spacecraft with a large sail area and advanced sail membrane materials to fly to the sun at low perihelion. In less than 50 years, it is possible to arrive at the destination of hundreds of astronomical units outside the solar system.[71]

4. Solar sailing technologies

Solar sail technologies for realizing on-orbit applications are summarized in this section from the perspective of mission architecture. The key technologies are given in Fig. 3, which is divided into 6 aspects: system design, flexible materials, membrane dynamics, structure control, ground testing technology and control strategy. Discussions are carried out in details as follows.

4.1. System design for a solar sail

The current solar sail system design follows the design guidelines of miniaturization, modularity, economy, practicality, and reliability. The design methods and structural forms of solar sails are different, which mainly depends on different mission requirements of solar sails. In this section, the system components of solar sails are reviewed. Additionally, the design method of the deployment mechanism is introduced and discussed in details.

4.1.1. System composition

Overall design of the solar sailing system has many similarities with other spacecraft. For the purpose of achieving on-orbit operation and performing space missions, the system must be integrated including the following sub-systems: propulsion system, structural system, power supply system, measurement and control system, thermal control system, attitude and orbit control system, communication system and payloads. The structural system is the main body of the spacecraft, which provides structural support for other systems. The measurement and control system including telemetry, remote control, and tracking forms a closed loop for the solar sail. The attitude and orbit control system, and thermal control system can jointly maneuver and maintain the normal operation of the spacecraft.

For the spacecraft with fully passive propulsion, a solar sail is the propulsion system that can be constructed with deployment mechanism, sail membrane, etc. For instance, IKAROS is one of the carrying spacecraft in the H-IIA rocket, which is integrated with solar sail membrane, thin-film solar arrays, liquid crystal devices, the end mass, and the satellite control platform. In addition, IKAROS is equipped with a Gamma-Ray Burst Polarimeter to detect gamma-ray bursts, a Very Long Baseline Interferometry (VLBI) for high-precision orbit determination, a sun sensor, a three-axis gyroscope and 4 cameras to measure the main satellite and membrane movements. In the initial design of a solar sail spacecraft, the following

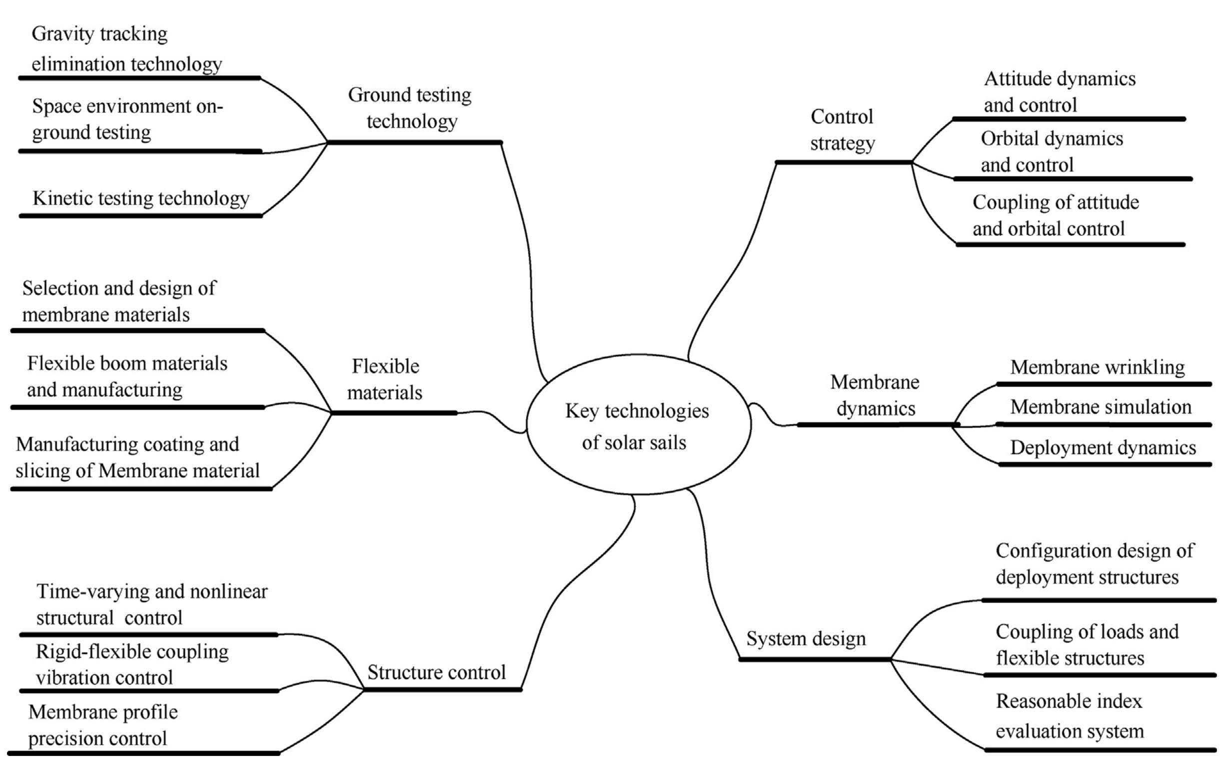


Fig. 3 Key technologies of solar sails.

characteristics should be considered:[72–73] (1) The sail area of a solar sail must be large enough so that the photons can generate a considerable thrust; (2) The overall mass of the spacecraft should be as small as possible in order to convert the thrust generated by the SRP into non-negligible acceleration. In general, the mass-area ratio is an important indicator to evaluate the performance of a solar sailing spacecraft.

4.1.2. Deployment mechanism design

Membrane deployment is the first step and crucial for solar sail to execute tasks normally. The deployment methods of solar sails are mainly divided into two categories:[74] (1) Sails exploit centrifugal force. The solar sail with this structure is spin-stabilized and deployed by the centrifugal force;[75] (2) Sails deployed by booms. This type of solar sail normally remains stable at three axes in-orbit, which has a high operating reliability. While the main component of the deployment system of solar sails is the deployment mechanism.

(1) Spinning solar sails.

Taking IKAROS as an example, the spinning deployment mechanism uses centrifugal force to deploy the membrane at a rotation speed of up to 25 rpm without any supporting structures. Eliminating the booms contributes to an easy and lightweight deployment mechanism, which is a major advantage of the spinning solar sail.[75–76] The spinning solar sail has only the central hub as its main structure, see Fig. 4. The central circular groove is used to store the membrane, and the 4 supporting cylinders protruding from the central circular groove are used to fix the membrane. The sail membrane is wound on the hub rotator and drawn out by the rotating rod when the hub rotates.[74,76] The deployment consists of 2 stages: the first stage is to draw out the sail to make it into cross shape, and the cross-shaped sail is released into fully deployed shape in the second stage.[24–25].

(2) Three-axis stable solar sails.

The deployment mechanism of three-axis stable solar sail is relatively complicated due to the supportive way of deployment. They are normally divided into three types according to different driven methods: (1) Inflatable deployment; (2) Mechanical deployment; (3) Elastic deployment. Similar design concepts (see Fig. 5) comprised of a central scroll, guide cylinders, motors, and composite booms are reviewed. Typically, a pinch device must be designed to prevent blossoming

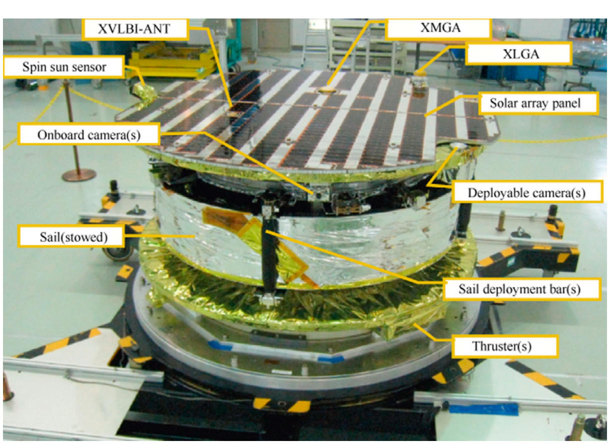


Fig. 4 IKAROS system[24].

of booms during deployment. For instance, the Gossamer sail research team has developed two deployment mechanisms according to the sail deployment booms. The rollers move radially inward when the boom is extended from central scroll.[77–85] The other one utilizes bistable Carbon Fiber Reinforced Plastic (CFRP) boom.[30,77] One is shown in Fig. 5(a), which uses 8 spring-loaded rollers to control Becu booms.[78] CFRP booms are fully bistable, which simplifies the deployment mechanism (see Fig. 5(b)). Four torsional springs are used to prevent the boom from blossoming. Similarly, Fernandez, et al.[79] designed a deployable module, as shown in Fig. 5 (c). The deployment mechanism consists of a fixed shaft connected to the satellite on which 4 bistable booms are coiled. Furthermore, NASA proposed a Composite-Based Solar Sail System (CS3) for the NEA Scout Mission aiming at deployment with hundred square meter class, as shown in Fig. 5(d).[85].

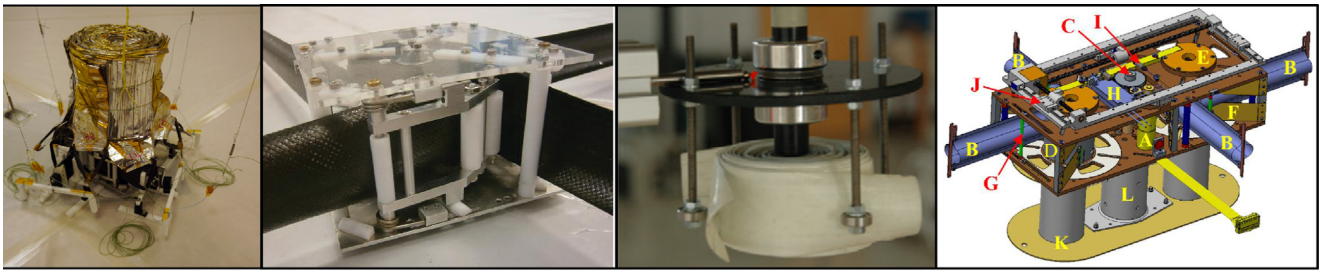
The reliability and stowage efficiency are indicators for evaluating deployment mechanisms, which determines the structure performance. For spinning solar sails, the deployment mechanism yields to high packing efficiency but is very complicated and easy to fail. Whilst the three-axis stable solar sails performing high reliability are very popular at present, but they yield limited ratio of the deployed area to stowed volume (m^2/m^3). Moreover, some other deployment methods are utilized to replace booms, such as petal-inspired deployable mechanism, Flasher,[80] deployment mechanism based on scissor unit,[81] etc. These deployment methods are usually used in the fields where special geometry is required, or the deployed area is not crucial, such as reflector antennas, solar arrays.[82] In general, the stowed sail volume determined the approach of sail deployment, and the two main types of deployment methods still need further investigation and breakthroughs to meet the packing requirements.

4.2. Flexible materials

Huge deployment area is essential to solar sails. While considering constraints of launch cost and stowage space in launch vehicles, flexible materials are only solutions to current solar sail spacecrafts. A solar sail mainly consists of flexible booms to support membranes and membranes to reflect solar radiation. This is the core part of a solar sail spacecraft.

4.2.1. Deployable booms

Booms play the role of deploying and supporting the sail membrane in three-axis solar sails. Many scholars discuss booms as a key component of the deployable mechanism. In literature, rigid space structures such as deployable trusses are used.[83] Brown[84] proposed a novel deployable compression element, the NRL Super-string mast, which enabled trusses to deploy to be extremely long. With the development of material technology, the booms tend to be bistable composite structures. The deployable booms have the advantages of light weight and small storage volume. For instance, NASA noted in the NEA mission that the bistable composite with a lightweight design of 16.5 g/m, can reduce the weight of a solar sail mission on a 6U CubeSat by approximately 10 %.[47,85] The deployment length of booms can reach 7 m. The deployable composite booms with four different cross-section configurations are given in Fig. 6, which are C-type boom, double C-type boom, deployable composite Triangle Rollable And Collapsible



(a) BeCu boom deployer[78] (b) CFRP deployer concept[77] (c) Stripped sail module[79] (d) CS3 for the NEA Scout mission[85]

Fig. 5 Deployment mechanisms for solar sails.

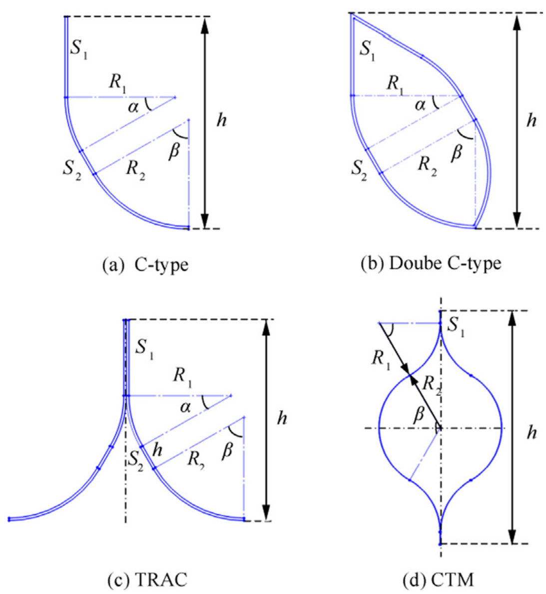
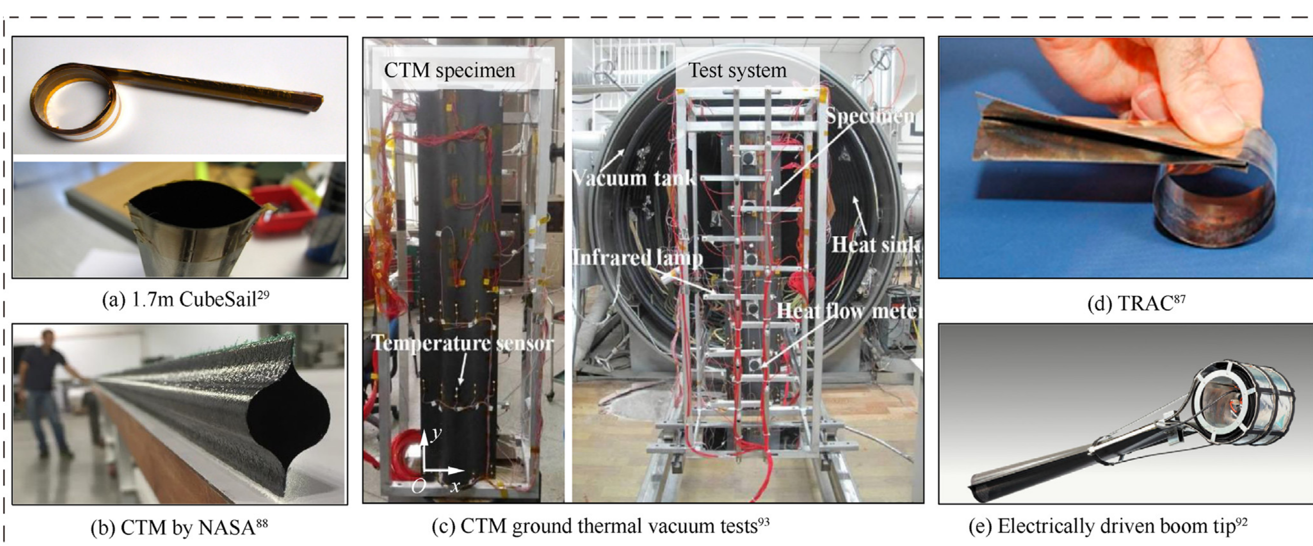


Fig. 6 Geometries of boom cross sections.

(TRAC) boom, and the Collapsible Tubular Mast (CTM). The C cross-section booms are easy to manufacture, and the transition between the two steady states is seamless, making it suitable for solar sails. However, the non-closed geometry of the cross section makes them prone to buckle. Therefore, TRAC and CTM get more attractive at present.[86]

In the Cubesail scheme, double C booms were used instead to improve the boom stiffness, as shown in Fig. 7(a).[29] The TRAC invented by Murphey et al.,[87–88] and developed by the Air Force Research Laboratory is consisted of two arcs (tape springs) connected along the edges, as shown in Fig. 7 (d), which has a higher bending stiffness and unfold-height ratio than CTM booms.[87] TRAC has been utilized on NanoSail-D,[89] LightSail-1[90] and LightSail-2[34] successfully. Leclerc and Pellegrino[91] studied the elastic buckle behavior of TRAC under pure bending. An autoclave manufacturing process of an ultra-thin composite boom was proposed, and the performances of three samples were experimentally studied.[92–93] The buckling instability moment is usually 4 times the initial buckling moment, which marks the end of a stable post-buckling state. For the CTM, DLR conducted early research and proposed the mechanism design shown in Fig. 7(e) to transfer weak transition zone from the root to end, which can offset the match of the highest load and the lowest stiffness.[91] NASA carried out further research on com-



(a) 1.7m CubeSail[29] (b) CTM by NASA[88] (c) CTM ground thermal vacuum tests[93] (d) TRAC[87] (e) Electrically driven boom tip[92]

Fig. 7 Related researches for booms.

posite CTM shown in Fig. 7(d), and thin-ply spread-tow composite materials are used to decrease the boom thickness. The flattened height of this boom is only 45 mm. The asymmetrical double layer [±45PW/0] layup was adopted. The shell thickness is only 0.115 mm, and the thickness of the bonded area is only 0.33 mm.[85].

Additionally, inflatable technology is attractive in space due to the characteristics of light weight and small storage volume. DLR proposed a concept of inflatable booms as shown in Fig. 8(a), a 12 μm airtight polymeric capsule is embedded in a CFRP boom. The inner tank acts as a pneumatic actuator to deploy the boom when pressurized.[92] Similarly, an inflatable extension arm was test in the InflateSail mission, which was used to push out the solar sail deployment device from CubeSat.[39] The inflatable extension arm is composed of aluminum polymer laminates, with Mylar bladder inside to improve air tightness, as shown in Fig. 8(b). A 1 m arm was

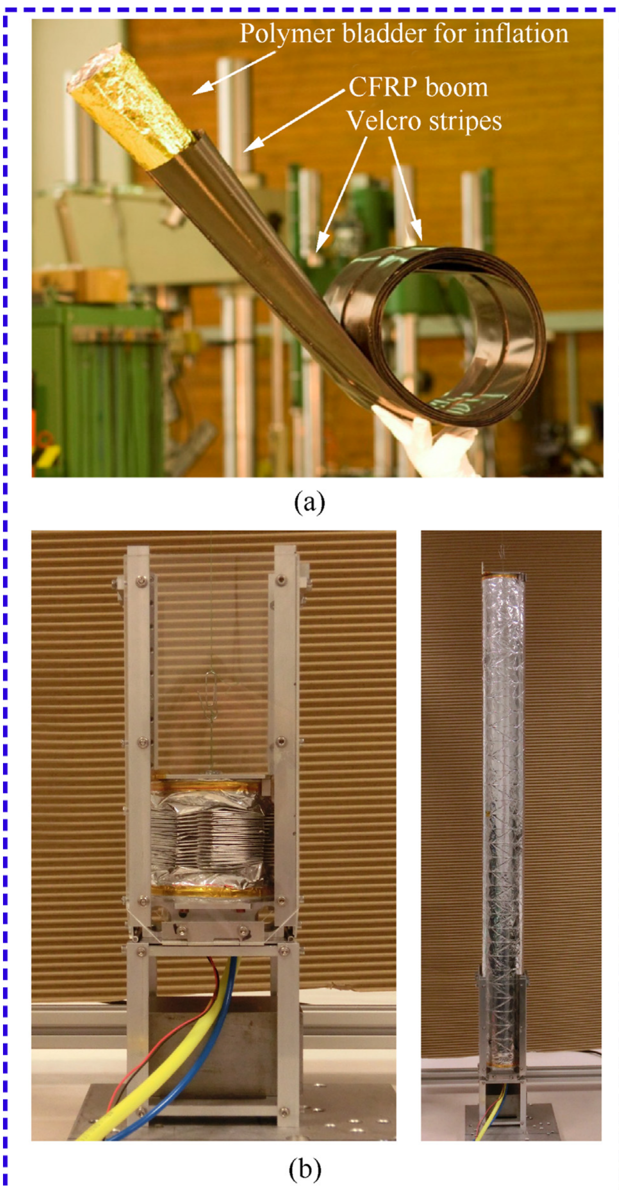


Fig. 8 Inflatable booms[92].

folded based on Miura origami, and the height of fully collapsed arm is only 63 mm. However, a fully space inflation system is not easy to construct, which increases the system complexity. Moreover, inflatable structures are susceptible to potential damage, which limits their on-orbit applications.

During the deployment of sail membranes, enough force must be provided by booms to extract sail and overcome frictions in the system. Whilst with the lengthening and thermal distortion of extended booms, the risk of instability will increase, making the booms easy to fail and the sail shape to be non-planar. In the future, how to develop extremely long and flexible booms with high mechanical performance and innovative deployment solutions will be major challenges in three-axis stabilized solar sails.

4.2.2. Membrane materials

Membrane is a functional component of solar sail system, and the material and reflectivity efficiency affect the performance of solar sailing spacecraft directly. ESA once set up a project called Solar Sail Materials (SSM) for the purpose of developing and testing future membrane technology, which mainly focused on 3 fields: (1) Membrane and coating materials, including membrane thickness reduction and large-scale assembly processes (2) Sail-to-Structure Interfaces (SSIF) (3) The correlation between 3D imaging and finite element simulation in different tension strategies.[94]

Many scholars have carried out research on the related technologies of solar sail membrane. Firstly, the selection of membrane material is critical to the mechanical and dynamic performance of solar sail, in which it must not only have excellent mechanical properties, but also be able to withstand high and low temperature cycling stability and various radiations in space. At present, advanced sail membrane materials with optical and infrared properties,[95] as shown in Table 2, are normally used for solar sails. The PEN has the lowest area density, but poor resistance to ultraviolet radiation. The PET has weak anti-ultraviolet radiation ability and cannot be exposed to sunlight for a long time, thus a double-sided coating is required. The Polyimide (PI) film has high radiation resistance, and can maintain excellent physical and mechanical properties in a wide range of temperature. The temperature at which polyimide undergoes phase change is about 680 K, and the maximum temperature for long-term safe operation of solar sails is generally believed to be between 520 K and 570 K. PI with its high adhesion to metalized films, tapes and adhesives has been considered as the prime candidate for solar sail membrane substrates.

Whilst for the purpose of achieving better reflection characteristics, the membrane substrate is normally covered with a metal coating that is reflective to the full spectrum. This coating has a suitable high melting point, the selection of which depends on the operating orbit and the closest distance from the solar sail to the sun. Some possible metal coating materials that can be penetrated and degraded by solar ultraviolet radiation are shown in Table 2. Kezerashvili[96] studied the minimum thickness of membrane substrate/coating that provided the maximum reflectivity and absorption capacity, and they demonstrated that aluminum and beryllium with much less thickness were suitable candidates for membrane coatings. However, the melting temperature of aluminum was found much lower than that of beryllium, and the processing and

Table 2 Candidates sail membrane materials with optical and infrared properties[95].

Material		Core Polymer	Coating	α	ρ	ε	ρ
Metallized PI	Reflective	Kapton®EN	Al/100 nm	0.1	0.9	0.03	0.97
	Emissive	5 μm	Cr/30 nm	0.54	0.46	0.48	0.52
Aluminized CP1	Reflective	LaRC™CP1	Al/90 nm	0.1	0.9	0.03	0.97
	Emissive	2.54 μm	-	0.17	0.83	0.29	0.71
Aluminized PET	Reflective	Mylar®	Al/100 nm	0.09	0.91	0.02	0.98
	Emissive	2.54 μm	-	0.14	0.86	0.25	0.75
Metallized PEN	Reflective	Teonex®Q72	Al/100 nm	0.1	0.9	0.03	0.97
	Emissive	2 μm	Cr/15 nm	0.57	0.43	0.6	0.4

Note:α: Absorptance, ρ: Solar Reflectance, ε: Emittance, ρ: Thermal Reflectance.

use of beryllium was potentially toxic. The reflectivity of aluminum was between 0.88 and 0.9, and addition of a layer of silicon oxide in front of the coating could slow down the reflectivity decline caused by oxidation of the reflective surface before emission.

Considering successful on-orbit missions of solar sails, DLR-ESA tested three kinds of polymer films: (1) polyester with a thickness of 12.0 μm and aluminum coated on the front surface; (2) polyimide film with a thickness of 7.5 μm and aluminum coated on both sides; (3) PEN membrane with a thickness of 4.0 μm and aluminum coated on both sides. The conventional polyimide was found difficult to seal when huge-area solar sails required. While IKAROS used two types of polyimides of commercial APAIL-AH and ISAS-TPH. ISAS-TPH had thermal adhesion and resistance to the space environment. The thickness of both films is 7.5 μm.[25] Nanosail-D utilized 2.0 μm thick Colorless Polyimide (CPI) film with 100 nm aluminum foil plated on the front surface enabling a wide operating temperature (from low temperature to 250 ℃) and high resistant to ultraviolet radiation.

As the most important functional component of solar sails, the optimization of membrane material properties and improvement of material degradation performance are always of importance. Innovative membrane materials with higher specific stiffness and strength, high temperature resistance, and stronger resistance to oxygen atomic erosion or ultraviolet radiation exposure and tear propagation will be persistent technical issues.

4.3. Membrane and structural dynamics

Flexible membrane exhibits complex mechanical behaviors, and their dynamics has always been difficult to predict. Current numerical simulation methods cannot effectively and quantitatively analyze motion and mechanical properties of membranes. In this section, the membrane folding patterns and their dynamics are discussed.

4.3.1. Folding patterns

For the consideration of transportation expense, solar sail membrane is normally folded to fit the storage space of the deployment mechanism. Folding and deploying techniques also have profound impacts on the force transmission path and surface flatness of deployed sail membrane.

In recent years, the principle of origami[97] has been studied well and utilized to fold solar sail membrane. The Z-fold (see Fig. 9(a)) also known as the accordion fold is the most commonly used folding and deploying method for a three-axis solar sailing,[98] which compresses a large plane horizontally or longitudinally folded into a small volume. In 1985, Miura[99] put forward the concept of using large-size folding inspired by origami for deployable space structures. This method was named Miura-ori (see Fig. 9(b)) and transformed the two-way folding problem of one plane into an infinite plane. The two-way elastic compression problem had evolved into a series of parallelogram folds in both vertical and horizontal directions. Miura-Ori became an important milestone in the real application of origami to space structures, and it is characterized by large packing efficiency, negative Poisson's ratio and anisotropic stiffness. Then, Tachi[100–101] proposed concepts such as rigid origami and origami inlays, and constructed a variety of models for aerospace,[102] construction, and medical fields.

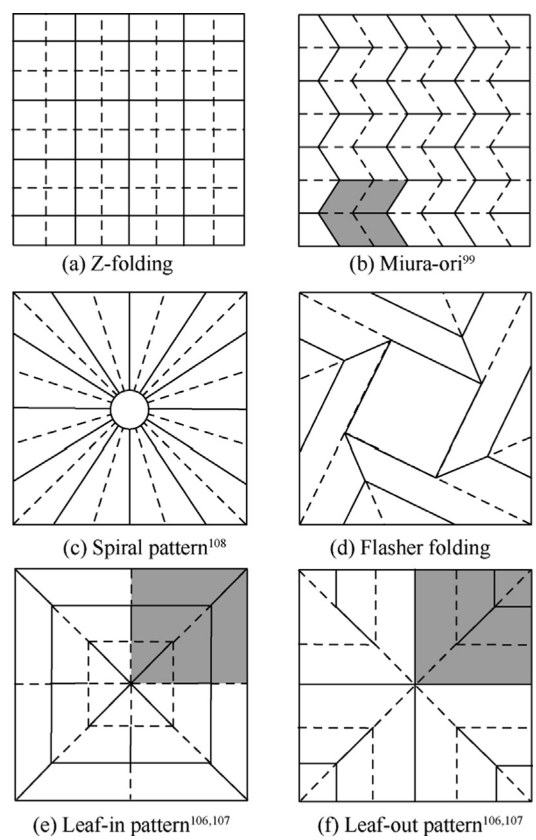


Fig. 9 Typical origami configurations.

Inspired by Miura folding, NASA Jet Propulsion Laboratory (JPL) developed a novel flasher folding model.[103–104] As shown in Fig. 9(d), this model mixed diagonal and rectangular folds, and could be quadrilateral, pentagonal or even polygonal folds. All folding surfaces were folded and gathered around the central axis direction, which was a 1-DOF deployed and suitable for spinning solar sails. Some rigid mechanisms based on flasher had been designed and analyzed.[105] Kobayashi, et al.[106–107] proposed a single leaf folding model (see Fig. 9 (e) and Fig. 9(f)) on the basis of bionic principle. Every unit (the part in grey) of single-leaf folding is connected and compatible with each other, and the whole structure can be folded and deployed from one or more driving points. IKAROS membrane adopted the leaf-in folding pattern (see Fig. 9(e)). In addition, the spiral-wound folding method is also widely used in baseline synchronous solar sails. Banik and Murphey[108] proposed an improved spiral folding model (see Fig. 9(c)) that could reduce the folding height by half.

The folding patterns and sail storage are important considerations in the design of solar sail, because long-term storage of the folded sail membranes result in stiction between adjacent folds, which makes membrane easy to be teared during deployment process. Also the direction of tension forces to deploy membrane in folded configuration and the residual creases in the sail should be carefully designed to achieve a planar sail shape.

4.3.2. Membrane dynamics

Successful deployment of sail membrane is the first step for solar sail missions. The solar sail membrane is typically a two-dimensional structure, and its thickness is much smaller than the transverse dimension, so the bending stiffness is insignificant compared with the stretching stiffness that mainly bears when deploying.

Researchers tend to analyze the membrane dynamics numerically, and some studies are shown in Fig. 10. Papa and Pellegrino[109] analyzed the mechanical behavior of the membrane structure with creases subjected to tension. Wang and Johnson[110] used LS-DYNA to model the deployment dynamics of an inflatable boom folded with Z and curl types, respectively. Vatankhahghadim and Damaren[111] analyzed the deployment dynamics of a simplified quadrant of solar sail composed of two Euler Bernoulli beams and a flexible membrane. While a coupled equation of motion describing the lateral displacement and in-plane motion of the system was obtained, and the tension field with linearly increasing stress on the additional boundary was simulated. Some simulation results are shown in Fig. 10(d). Zhang and Zhou[112] proposed a method to establish a geometric model by analyzing the deployment process of solar sail. On this basis, a Finite Element Method (FEM) of the solar sail built with continuous cables and sail membranes was established. The dynamic simulation of the second stage deployment process of the solar sail was carried out with nonlinear finite element software ABAQUS. Effects of different blade tip masses, initial speeds and control parameters on the rotation speed and out-of-plane motion of the hub were investigated. Some simulation results are shown in Fig. 10(a). Cai, et al.[113] numerically modeled the deployment process of Miura-Ori based membrane structure in ABAQUS (see Fig. 10(e)), and the variable Poisson's ratio model was used to modify the stress distribution of

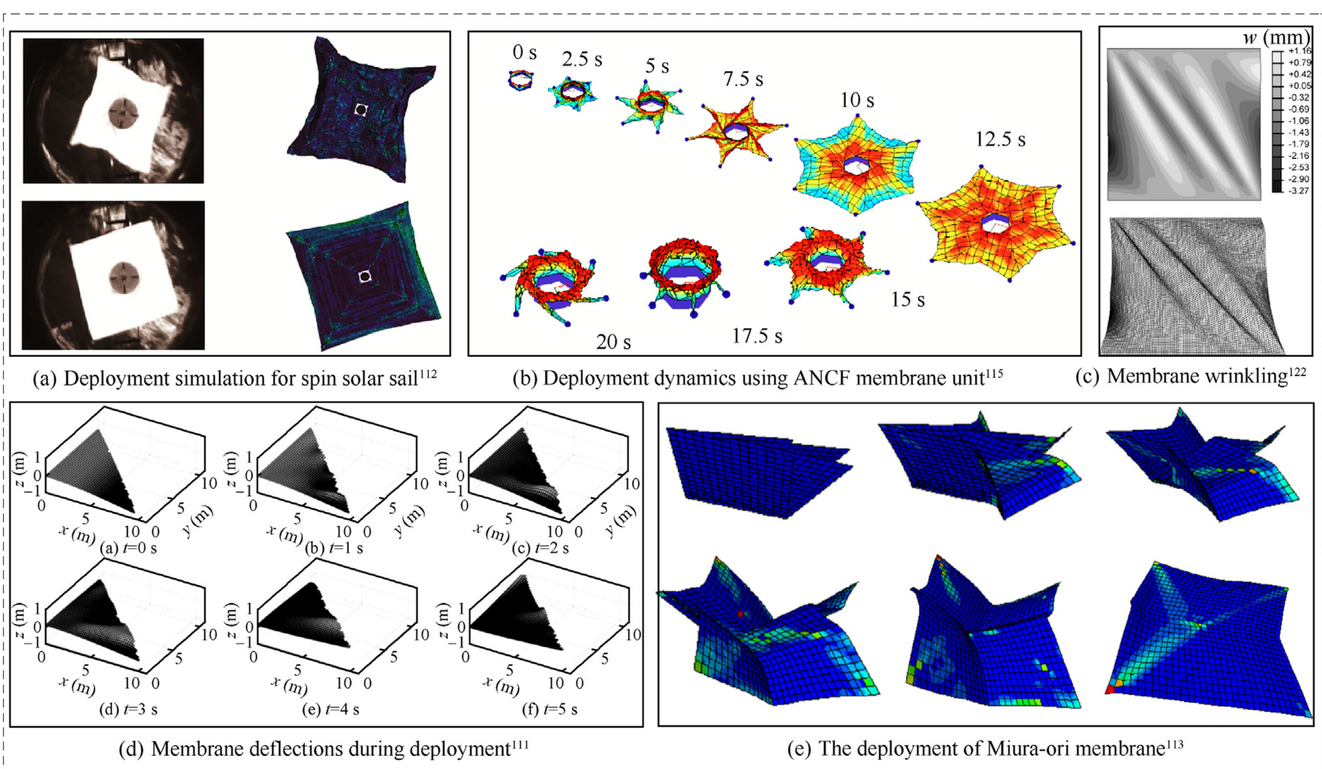


Fig. 10 Related researches for membrane dynamics.

membrane element. For the purpose of estimating the motion of flexible membrane, Chujo and Kawaguchi[114] applied the Multi-Particle Model (MPM) for numerical simulation, in which the membrane was modeled with masses, springs and dampers. Continuum and Eigenfunction were used to analyze the transient response of the rotating solar sail, demonstrating that the Eigenfunction analysis provided a suitable method to obtain approximate solutions in short computing time. Liu, et al.[115] and others proposed the Absolute Node Coordinate Formulation (ANCF) membrane element and integrated the wrinkle/relaxation criterion into the shell element based on ANCF to simulate the sail membrane (see Fig. 10(b)). Finite element simulation has been widely used,[116–117] but there is still no effective and authoritative method to accurately simulate the deployment process of flexible membrane or structures.

Additionally, the flexibility of membrane makes it easy to wrinkle. Most of wrinkling analysis uses a tension field to simulate mechanical properties of the membrane. It had been found that large amplitudes and long structural wrinkles usually lead to high stresses, and the bending effect and compressive stress could be completely eliminated by modifying the constitutive relationship.[118–121] Basic thin film theory could predict the basic load transfer and fold direction of film. However, it could not predict the out-of-plane fold shape, wavelength, and amplitude. Tessler[122] used the geometrically nonlinear Lagrangian shell theory to simulate the formation of membrane shrinkage deformation (seen in Fig. 10(c)). Two effective modeling strategies were introduced to promote the convergent solution of the fold equilibrium. Liu, et al.[123] simulated membrane shrinkage and deformation using the geometrically nonlinear updated Lagrangian shell formula.

Simulation has been taken as an effective way to predict the folding and deploying process of membrane, the force transmission path, and the mechanical behavior of the film tearing. However, the plastic deformation has already occurred at the crease of the folded sail membrane. Therefore, we cannot accurately predict the dynamic performance of solar sails with only elastic material properties of membrane materials, and the mechanical properties of the film at the plastic deformation state are required, which is difficult to accurately measure at current technical level.

4.3.3. Structural analysis of deployed solar sails

Once the solar sail membrane is deployed in orbit, its stability will be affected by SRP. Although the reaction force is actually tiny, the vast membrane structure will be perturbed significantly. Thus, the structural performance of solar sail is of great importance to analyze (mostly by using FEM). Sakamoto, et al.[124] used geometric nonlinear FEM to simulate the deformation of sail membrane under SRP. He pointed out that SRP could be approximated to uniform air pressure. A way of describing the surface deformation subjected to SRP in a numerical model was given. Boni, et al.[125] proposed a method to obtain the structural response of a classic square solar sail that was free-flying. He accounted for the effect of thermal loads on the reflective surface of sails, which significantly affected the sail deformation at certain altitudes. Wei, et al.[126] compared FEM with experimental tests to investigate the modal characteristics of square sails. Deng, et al.[127] evaluated the influence of SRP on the wrinkle patterns of a gossamer sail, indicating that the increment of the pressure perpendicular to the membrane surface would increase the amplitude and decrease the wavelength of wrinkles. However, the wrinkle pattern did not change until the applied pressure was much greater than the SRP experienced by gossamer sails. Fu et al.[128] studied the equilibrium shape of an unstretched film subjected to SRP. The steady-state surface yielded a zero Gaussian curvature produced by balancing radiation pressure and membrane tension.

A quantitative understanding of the mechanics is essential in characterizing the structural performance of deployed solar sails. Takao, et al.[129] proposed a method of using vibration to achieve active control of deformation of a spin-synchronized membrane structure. Shi, et al.[130] developed a reliable iterative membrane characteristic modeling method to study the nonlinear dynamic behaviors of typically large-space membranes that cannot be accurately described by natural frequencies and modes. Three different driving and sensing positions were compared and evaluated to obtain superior vibration suppression performance. Boni, et al.[131] also computationally studied the membrane performance of a square solar sail. The inertial release method was used to analyze the changes of solar flux on the sail surface of a free-flying spacecraft at different incident angles. Choi and Damaren[132] applied the geometric nonlinear elastic FEM to simulate the dynamic behavior of solar sails under airfoil altitude control. Gibbs and Dowell[133] generalized the classic asymptotic analysis of springs to study the structural stability of solar sails and to evaluate the stability performance of the sun jammer spacecraft.[134] Zhang[135] established an accurate and closed-loop analysis for stripped sails to identify buckling load and vibration of the entire solar sailing structure. Moreover, performance scalability of solar sails is of importance to understand due to difficulties in ground testing of full-scale flexible structure. Trofimov and Ovchinnikov[136] quantified both payload mass and payload-mass fraction to show how components of a given sail system should be safely scaled to obtain desired characteristic acceleration.

In summary, researchers tend to solve the membrane dynamics problems using FEM. Some other methods were proposed to solve some special problems such as crease problem, membrane wrinkling, buckling and vibration, etc. We reviewed these methods and problems that can be solved in Fig. 11.

Structural performance of the deployed solar sails is difficult to evaluate on ground. For instance, during assembly and testing, both the supporting booms and the sail membranes will withstand a series of deployment and stowing cycles, as well as gravity-induced deformations that is actually experienced in the micro-gravity space. While to offset the gravity, balloons, supporting lines and air bearings are used, but only limit to a small scale of solar sail structures. Additionally, the deployed solar sails are flexible structures, and their theoretical analytical models are deficient. How to understand and predict the structural performance of solar sails with very large deployed area still needs further investigation.

4.4. Ground testing technology

All spacecrafts undergo rigorous ground experiments before launching to ensure that they can complete the on-orbit missions. Conventional ground experiments include: high and

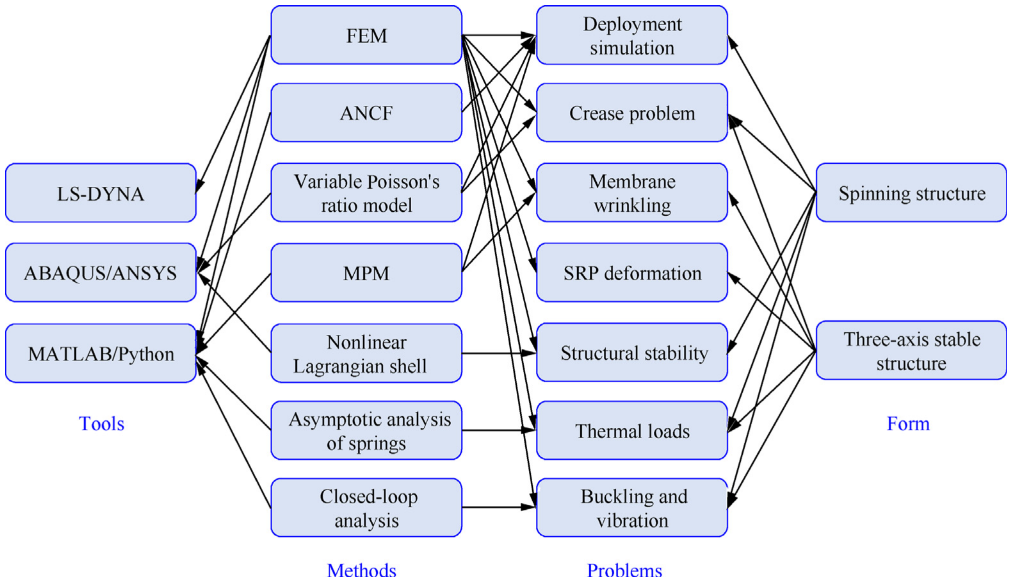


Fig. 11 Method classification for different problems of membrane dynamics.

low temperature experiments, thermal cycle experiments, flight parts vibration experiments, vacuum test, etc.

For the purpose of achieving better understanding of overall performance of the solar sails, normally experiments and mechanical performance tests on the booms, membranes and scaled model are conducted. Bai, et al.[93] used ground thermal vacuum tests (see Fig. 7(c)) and FEA to study the thermal behavior of thin-walled Deployable Composite Boom (DCB) in a space environment. Oberst and Tuttle[137] conducted a quasi-static bending test on a tape spring, which was emphasized on the instability caused by high disturbance sensitivity and inherent non linearity. As shown in Fig. 12, a vacuum test of a scaled inflate sail is complemented.[40] Hoskin, et al.[138] proposed a method that the strain energy in the booms and compression springs was used to estimate the tip force when blossoming.

Specially, solar sails must be deployed on orbit, and all of the conventional ground tests will be difficult to execute due to the extremely large deployed areas. Whilst deployed solar sails receive both external and internal disturbances, such as radiation, temperature difference, electromagnetic, and gravity. Moreover, internal disturbances caused by motors, control systems, and spring elements would produce unforeseen risks for solar sails. Additionally, the difficulty in gravity offset of flexible and large-scale gossamer structures is also challenging the ground testing.

4.5. Control strategy for solar sails

Solar sails with large deployed area are flexible structures, thus control strategy is a hot topic. Many researchers have carried out extensive researches. In this section, we categorize and summarize the latest researches on control strategies, as shown in Table 3.[140–163] This mainly includes structural control, attitude control and orbital dynamics. Control moment gyros, reaction wheels, and thrusters have been used for spacecraft attitude control for decades, but they are not ideal for passive propulsion of solar sails[12] due to very large torque required for

Fig. 12 Sail deployments in the SSC thermal chamber[40].

Table 3 Relevant researches on control strategy of solar sails.

Contributors	Research field	Model/Control method	Form	Major achievements/conclusions
Wie[139]	Structure vibration	Parameter identification	○	Higher computational efficiency than FEM
Boni, et al.[141]	Structure control	FEM	◇	Considered the deformation by SRP
Ono, et al.[142]		-	◇	Attitude dynamics model for a non-rotating momentum-biased spacecraft
Tsuda, et al.[145]	Structure stability analysis	-	◇	The girder must be 6 times heavier than the sail deployment device
Adonis, et al.[143]		Discrete-mass approach	△	Predict the onset of flutter and to thus achieve a better understanding of the system's stability regions
Juang et al.[144]		Single-blade fixed-speed heliogyro model	△	The flutter unstable frequency changed with SRP
Tsuda, et al.[145]		Generalized spinning sail model	△	Studied the effect of sail surface defects on the attitude control
Funase, et al.[146]	Attitude controller design	Reflectance control device resistant to radiation	○	This equipment was utilized in IKAROS and successfully verified on orbit
Hassanpour and Damaren[147]		2-DOF control tip vanes	◇	Solved non-collocated attitude control without spillover
Huang and Zhou[148]		-	◇	Proposed a mechanical structure that used a CubeSat as a movable mass to adjust the mass center
Baculi and Ayoubi[149]		Takagi-Sugeno fuzzy model	◎	A better effect than PID controller
Lian, et al.[150]		Anomaly adaptive sliding mode	◇	Established pitch dynamics of the solar sail in an elliptical orbit
Hu and Gong[151]	Attitude control	A hybrid method	○	Quantified the flexibility effect on passive station keeping
Liu, et al.[152]		-	◇	Considered large vibrations caused by the controlled motion of the actuator as additional constraints
Liu and Cui[153]		Von Karman nonlinear /Kelvin Voigt model	◇	Considered geometric nonlinearity and damping of the structure
Takao, et al.[154]		Shape control	◎	Proposed a completely propellant-free solar sailing method
Gong, et al.[155–156]	Special orbit design	-	◎	Presented a sun-synchronous frozen orbit and heliocentric elliptic displaced orbit
Zeng et al.[157]		-	◎	Heliocentric planar multireversal periodic orbits
Huang et al.[158]		Elliptic restricted three-body problem	◎	Proposed families of halo orbits
Vergaaij and Heiligers[159]	Orbital transfer	-	◎	Investigated optimal trajectories for an Earth-Mars cycler
Farrés[160]		-	◎	Studied transfer orbits to L4 in the Earth-Sun system
Shahid and Kumar[161–162]	Formation flying	High-order nonlinear sliding mode control	◎	Discussed spacecraft formation control by SRP at the L2 Sun-Earth / Moon collinear libration point
Mu et al.[16]		-	◎	Studied the use of reflectivity-controlled solar sail formations for magnetosphere mission
Wang et al.[163]		-	◎	Investigate the problem of solar sail formation flying around a heliocentric displaced orbit.

Note: ○Spinning structure, ◇three-axis stable structure, △Heliogyro configuration, ◎all configurations.

resisting solar radiation interference. For instance, Zhang et al.[140] pointed out that SRP interference torque for a 40 m × 40 m solar sail spacecraft might be hundred times larger than that of a geosynchronous communication satellite. Whilst, controlling the attitude of solar sail spacecraft differs from traditional spacecraft due to their large-scale thin-film sail surfaces. Attitude adjustment and vibration of the flexible structure will vary the magnitude and direction of thrust, which affects the spacecraft orbital maneuvers.[164] Regarding to control strategies for solar sails, a large number of research are published and discussed every year, but there are still many challenges that need to be further studied with respect to dynamics and control.

This review focuses on the design, materials and mechanics of solar sails. Therefore, only the research results in the past 3 years are summarized and discussed in the field of control. Some scholars such as Gong[165–166] have made more professional reviews and studies. We look forward to a more professional overview and discussion in this area.

5. Future of solar sailing

Solar sails have been developed for decades, but key technologies still limit their on-orbit applications. In this section, we briefly summarize challenges in compact structural design, membrane modelling and scalability analysis. Future technologies that can be further investigated in solar sails are also outlined.

5.1. Technology advances in solar sails

Solar sail is an emerging technology with interdisciplinary design, and it is still in the stage of technology development and on-orbit demonstration.[167] The current state of the art and technology advances are listed and discussed (see Fig. 13) on the basis of solar sailing missions. Obviously, each individual technology cannot represent the current state of solar sailing development, and some potential technological breakthroughs may bring subversive breakthroughs to solar sail technology, such as new deployment methods, new material technologies, etc.

5.2. Challenges in solar sails

Advances in flexible structural design, highly reliable deployment mechanisms, and ultra-light and multifunctional membrane materials have been studied. Moreover, ground testing, orbital design and control dynamics are also analyzed for scientific solar sailing missions. However, there are still technical challenges in the following areas.

(1) Compact structural design.

A relatively large characteristic velocity is normally required for a space mission in order to shorten flying time. Consequently, deployment area of solar sail membrane had to be extremely large to obtain more photons and to generate more thrust. Simultaneously, considering the launch cost and packing constraints, the area-to-mass ratio must be increased to the maxima. Thus, a very compact design of a solar sail system with a high-efficiency packing is of great challenge for the purpose of achieving a relatively large area-to-mass ratio and high deployment reliability under specific design constraints.

(2) Membrane materials.

Advanced thin membrane materials with long-term space environmental sustainability are essential for long-lived solar sails. Extremely that the materials degradation due to ultraviolet radiation exposure or atomic oxygen erosion will be an inevitable challenge to solar sail spacecrafts operating in deep space or low orbit. Meanwhile the techniques to splice thin films have to be developed to manufacture very large sail strips or membranes.

(3) Membrane modelling.

Modeling and analysis of solar sails are normally assumed that the deployed solar sail membrane is completely flat. However, the film cannot be a completely planar structure due to effects of folding creases, mechanism pretightening forces, errors from processing, manufacturing and assembly, etc. As already known that the folding creases will not only decrease mechanical properties of the membrane, but cause the photon to produce undesired force components. How to accurately describe the wrinkling and folding creases to predict the efficiency of the SRP propulsion and to analyse the overall structural and dynamic performances of sail membranes should be well considered.

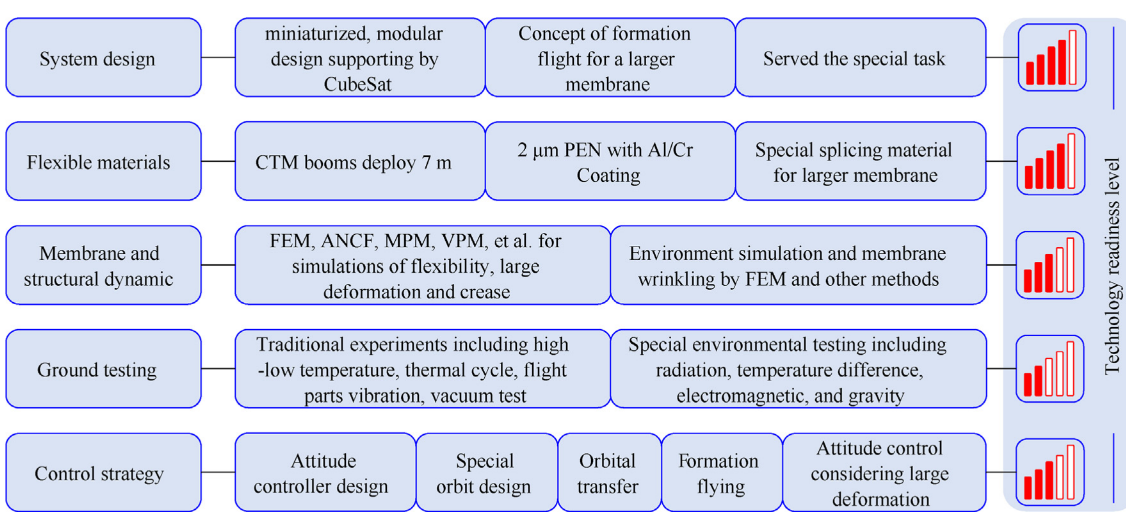


Fig. 13 Current technology advances of solar sails.

(4) Scalability analysis.

A fully deployed solar sail structure is huge and flexible, which makes its structural analysis and on-orbit deployment dynamics difficult to demonstrate both on ground testing and dynamic modelling. Moreover, scaling law is a big challenge in developing a solar sail with extremely large membrane and long flexible supporting booms. Therefore, development of accurate dynamic models and coupled numerical simulation techniques to predict the solar sail deployment process, as well as scalability analysis are of essence to improve the reliability and technology readiness level of solar sails in orbit.

5.3. Future solar sailing technologies

5.3.1. New concepts of solar sails

Innovative solar sail technologies including new sail concepts and thin membrane materials have been developed. Luo, et al.[168] proposed a new solar sail design concept named Solar Sail with Individually Controllable Elements (SSICE), which could be used in Halo orbit missions around Sun-Earth Lagrangian points or other interplanetary missions. Markhoos[169] used the point-like and spherical-like solar model to study the motion characteristics of the flat and spherical solar sails near the sun, respectively. Wu, et al.[170] presented an innovative method of using origami technique to convert a two-dimensional sail into a three-dimensional optical element structure with designable and steerable optical properties, as shown in Fig. 14(a). Firuzi and Gong[171] proposed a new type of photon propulsion method (see Fig. 14(f)), which was achieved by the refraction of light in a transparent array of micro prism films. The proposed refracting sail could interact with solar radiation and generate a large tangential radiation pressure even under normal radiation incidence. Achouri and Caloz[172] proposed a metasurface solar sail system shown in Fig. 14(b), which not only generated repulsive force, but also attractive force, lateral and rotational forces. The force acting on the metasurface sail could also be controlled by changing the polarization or wavelength of the laser beam. For the sail membrane, new membrane materials with improved mechanical and optical performance have been well developed. Li, et al.[173] developed a highly transparent and super-foldable polyimide composite film with a thickness of 23 μm has been developed. Zimin and Nerovnyi[174] investigated transmission coefficient variation of a large-scale switchable film material with its deformation value.

5.3.2. Self-deployment technologies

Self-deployment has been an attractive technology for solar sails. Sokolowski and Tan[175] stated that the cold-hibernated elastic memory (CHEM, see Fig. 14(c)) is one of structures with simple, reliable and low-cost characteristics. These lightweight structures were deployed by shape-memory and the elasticity of foam. Costanza and Tata[176–178] designed and manufactured a revolutionary self-deployment system based on nickel-titanium (Ni-Ti) shape memory wires, as shown in Fig. 14(d), which could be used on the kapton sail surface. Wu, et al.[179] proposed a self-folding polymer film (seen in Fig. 14(e)) capable of massive production and space applications. The film could transfer from a flat state to a load-bearing three-dimensional structure when it was heated by sunlight in space. Boschetto, et al.[180] studied the effect of Ni-Ti shape memory wire layouts on the flatness of sails that was examined using NextEngine 3D Laser Scanner. More intelligent materials can be further used to the self-deployment technology, so that solar sail spacecraft can be light weight, low-cost and highly integrated in the future.

6. Conclusions

Solar sailing has been developed for decades, and more than 20 solar sailing schemes have been proposed or demonstrated on orbit. However, they have not yet been applied in deep-space exploration due to technical difficulties. This paper reviewed the design and applications of solar sails, mainly on key technologies, to provide a systematic overview for researchers who are interested. The conclusions are as follows:

(1) Solar sailing has been identified as one of the most potential propulsion technologies for deep-space explorations and interstellar travelling, but it still cannot perform as a function unless the flight tests provide confidence in the technology.

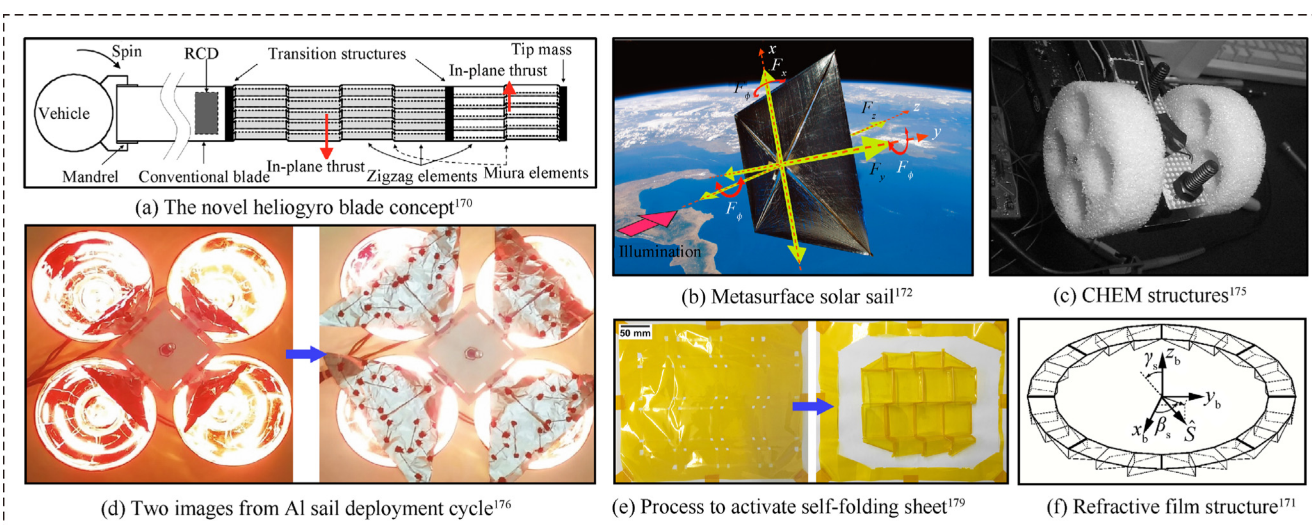


Fig. 14 Related researches for the future of solar sails.

(2) Key technologies related to system and structural design, flexible materials, membrane and structural dynamics, and ground testing have been reviewed. Advances and challenges in key technologies have been summarized.
(3) Renewal and advances in materials, mechanisms, mechanics and testing will benefit extremely large-scale and light-weight booms and membranes, so as to develop sufficiently large and efficient solar sails for deep-space explorations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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