ISSS 2023

Program and Book of Abstracts

THE 6TH INTERNATIONAL SYMPOSIUM ON SPACE SAILING

JUNE 5-9, 2023

City Tech, CUNY
New York, USA

NEW YORK CITY COLLEGE OF TECHNOLOGY CITY TECH

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The 6th International Symposium on Space Sailing (ISSS 2023) will take place on June 5-9, 2023, in New York City, USA and hosted by the New York City College of Technology, City University of New York.

Since its inauguration in Herrsching, Germany, in 2007, the ISSS has been held in New York, USA in 2010, Glasgow, UK, in 2013, Kyoto, Japan, in 2017 and then in Aachen, Germany, in 2019.

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For each talk is allocated 25 minutes and 5 minutes for questions and discussion

Symposium Schedule

June 5, Monday

8:00 am – 9:45 am Registration		
9:45 am Welcome Remarks		
Time	Presenter	Title
10:00 – 10:30 am	Pekka Janhunen	Coulomb drag propulsion
10:30 –11:00 am	Osamu Mori	New Solar Power Sail Program in the Post-OKEANOS Era
11:00 - 11:30 am Coffee Break		
11:30 am –12:00	Les Johnson	The NASA Solar Cruiser Solar Sail System – Ready for Heliophysics and Deep Space Missions
12:00 – 12:30 pm	W. Keats Wilkie	Advanced Composite Solar Sail System Mission Update
12:30 –1:00 pm	Piotr Fil	Research for and Early-Stage Development of the First Interstellar CubeSat Powered by Solar Sailing Technology
1:00 – 2:00 pm Lunch		
2:00 – 2:30 pm	Bruce Betts	LightSail 2 Image-Based Engineering Assessment
2:30 –3:00 pm	Justin Mansell	LightSail 2 Orbit Evolution and Attitude Control Performance
3:00 – 3:30 pm	Andrew Nutter	Objectives, Design and Initial Test Results of the Upcoming GAMA-β Solar Sail In-Orbit Demonstration
Coffee Break 3:00- 3:30 pm		
3:30 – 4:00 pm	Andrew Heaton	Near Earth Asteroid Scout Solar Sail Mission Overview
4:30 – 5:00 pm	Andres Dono	ACS3 – Flight Dynamics for a Solar Sail Technology Demonstration Mission
6:30 – 9 pm Reception		

June 6, Tuesday

Time	Presenter	Title
9:00 – 9:30 am	Giovanni Vulpetti	Sailcraft Helianthus: a Solar-Photon Sail for Geostorm Early Warning
9:30 – 10:00 am	Yuki Takao	A Rendezvous Mission to Outer Solar System Bodies Using a 100-kg-class Solar Power Sail
10:00 – 10:30 am	Greg Matloff	Breakthrough Sun Diving: The Rectilinear Options
10:30 – 11: 00 am	Iain Moore	SOLSPACE Solar Reflectors: Commonalities with Solar Sailing
11:00 - 11:30 am Coffee Break		
11: 30 am – 12:00	Juan Fernandez	Scalability of Solar Sail Designs using Deployable Thin-Shell Composite Booms
12:00 – 12:30 pm	Marco Straubel	Modular and Scalable Boom Deployment Mechanism for Deployment and Retraction of up to four CTMs
12:30 – 1:00 pm	Roman Kezerashvili	Ways to Deploy a Large Size Solar Sail
1:00 – 2:00 pm Lunch		
2:00 – 2:30 pm	Zachary McConnel	Test of a Full-Scale Quadrant for the 1,653 m^2 Solar Cruiser Sail
2:30 – 3:00 pm	Kirk Maddox	Development of a Flight-Like Solar Sail Quadrant for NASA's Solar Cruiser
3:00 – 3:30 pm	Andrew Heaton	Reflectivity Control Device Roll Momentum Management for Solar Cruiser and Beyond
3:30- 4:00 pm Coffee Break		
4:00 – 4:30 pm	John Inness	Momentum Management Strategies for Solar Cruiser and Beyond
4:30 – 5:00 pm	Amber Dubill	Next in Solar Sail Technology: Diffractive Solar Sailing

June 7, Wednesday

9 – 9-30 am	Bernd Dachwald	Optimal Capture of an Interstellar High-Velocity Photon Sail in the Alpha Centauri System
9:30 – 10:00 am	Elena Ancona	Mission to Sedna with a Solar Sail Exploiting Thermal Desorption of Coatings
10:00 – 10:30 am	Tim Rotmans	Photon-sail Trajectories to Exoplanet Proxima b Using Heteroclinic Connections
10:30 – 11: 00 am	Bakhyt Alipova	Long-term Mission of The Spacecraft with a Degrading Solar Sail into the Asteroid Belt
11:00 - 11:30 am Coffee Break		
11: 30 am – 12:00	Matteo Ceriotti	Advances in Preliminary Solar-Sail Trajectory Design
12: 00 – 12:30 pm	Alesia Herasimenka	Controllability of Solar Sails
12:30 – 1:00 pm	Christian Bianchi	Blended Locally-optimal Control Laws for Space Debris Removal in LEO Using a Solar Sail
1:00 – 2:00 pm Lunch		
2:00 – 2:30 pm	Livio Carzana	Solar-sail Steering Laws to Calibrate the Accelerations from Solar Radiation Pressure, Planetary Radiation Pressure, and Aerodynamic Drag
2:30 – 3:00 pm	Benjamin Gauvain	A Solar Sail Shape Modeling Approach for Attitude Control Design and Analysis
3:00 – 3:30 pm Coffee Break		
3:30 – 4:00 pm	Grover Swartzlander	A Comparison of Diffractive Films for Solar Sailing
4:00 – 4:30 pm	Hanseong Jo	Advanced Approaches to Solar Sailing
Poster Session **See Pages 48 – 52**		

June 8, Thursday

9 – 9-30 am	Miroslav Rozhkov	Cyclic Interplanetary Motion of a Cargo Solar Sail
9:30 – 10:00 am	Benjamin Diedrich	Solar Sail Torque Model Characterization for the Near-Earth Asteroid Scout Mission
10:00 – 10:30 am	Patric Seefeldt	Highly Efficient Membrane-based Photovoltaic Array for Solar Sailing Missions
10:30 – 11: 00 am	Ryan Caverly	Solar Sail Attitude Control Using Shape Modulation: The Cable-Actuated Bio-inspired Lightweight Elastic Solar Sail Concept
Coffee Break 11:00 - 11:30 am		
11:30 am – 12:00	Les Johnson	Planetary Sunshades for Solar Radiation Management: A Noninvasive, Feasible, and Affordable Climate Emergency Insurance Option
12:00 – 12:30 pm	Livio Carzana	A New Model for the Planetary Radiation Pressure Acceleration for Optical Solar Sails
12:30 – 1:00 pm	Bruce Campbell	Factoring Force Uncertainty into Solar Sail Mission Planning
1:00 – 2:00 pm Lunch		
2:00 – 2:30 pm	Jin Ho Kang	Space Environmental Damage Assessment on Sail/Deorbit Materials in Low Earth Orbit
2:30 – 3:00 pm	Erik Klein	Solar Sail Propulsion Limitations Due to Hydrogen Blistering: Progression of Reflectance Decrease
3:00-3:30 pm	Ilhan Tuzcu	A Reduced-Order Model for the Dynamics of a Flexible Solar Sail
3:30 - 4:00 pm Coffee Break		
4:00 – 4:30 pm	Zitong Lin	Adaptive Terminal Sliding Mode Control for Asteroid Hovering by Solar Sailing: Application to 433 Eros
4:30 – 5:00 pm	Joshua Umansky-Castro	Development of Gram-Scale Flight Computers for Free-Flying Light Sail Demonstration in LEO
7:00 – 9:00 pm Symposium Banquet		

June 9, Friday

9 – 9-30 am	Yuki Takao	Constellation Around Small Bodies Using Spinning Solar Sails Under Simultaneous Orbit-Attitude-Structure Control
9:30 – 10:00 am	Juan Garcia-Bonilla	Uncertainty quantification for solar sails in the near-Earth environment
10:00 – 10:30 am	Daniel Stelzl	The ADEO Space Sail Products
Coffee Break 10:30 –11:00 am		
11: 00 am – 11:30	Gyula Greschik	A New Tethered Sail Architecture: the Solar Kite
11:30 am – 12:00	Gregor MacAskill	Design and Analysis of a Quasi-Rhombic Pyramid Drag Sail for Passive Attitude Control and De-Orbit of OirthirSAT
12:00 – 12:30 pm	Lorenzo Niccolai	Optimal Deep-Space Heliocentric Transfers with An Electric Sail and an Electric Thruster
12:30 – 1:00 pm Panel Discussion Symposium Closing		

Coulomb Drag Propulsion

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Coulomb drag propulsion means deflecting a natural plasma stream by the electric field of a thin charged tether, and thereby tapping momentum from the stream. The tether can be positively or negatively charged. The plasma physics is different, but both result in momentum extraction.

The electric solar wind sail (E-sail) [1] applies Coulomb drag propulsion to obtaining interplanetary propulsion from the solar wind. A positive tether voltage of order 10-40 kV is used, because negative voltage of that magnitude would cause field emission of electrons from the thin metallic tether wires. The positive tether voltage is maintained by an electron gun that continuously pumps out negative charge from the system.

For outgoing missions, the E-sail thrust decays slower than that of photonic sails or solar electric propulsion. The reason is that the effective sail area increases as the plasma density goes down, due to increase of the plasma Debye length.

The E-sail is applicable outside of Earth's magnetosphere where the solar wind blows. E-sails spin, i.e., they use the centrifugal force for keeping the tethers stretched. Thrust vectoring can be done by inclining the spin plane, and thrust magnitude can be controlled by changing the current and voltage of the electron gun. A single-tether E-sail works for a cubesat, larger spacecraft must use multiple tethers. Multi-tether E-sails have also auxiliary tethers that connect together the tips of the main tethers. For multi-tether E-sails, differential voltage control of the main and auxiliary tethers allows spin plane turning and spin rate modification independently from each other. An inclined E-sail experiences a secular spin rate change effect, which is due to the Coriolis force. In missions that make one or more revolutions around the Sun, the secular spin rate change must in general be counteracted. The multi-tether variant is capable of doing that by using the E-sail effect alone. The single-tether variant needs auxiliary propulsion for that purpose.

The Plasma Brake applies Coulomb drag propulsion in low Earth orbit for deorbiting a satellite or for controllably lowering its orbit. The plasma stream is the ionospheric ram flow that is due to the satellite's orbital speed. To balance the ion current that the negatively charged tether collects, an electron gathering surface is used. The electron gathering surface can be the body of the satellite itself, or it can be a 30-100 m long metal-coated tape tether. The Plasma Brake tether is by default gravity gradient stabilized. There is an ongoing ESA project to develop a Plasma Brake module at TRL 4 for deorbiting a telecom satellite such as Starlink.

Free travel in the solar system for small and moderate size probes and solving the problem of orbital debris - those are the two main attractions of Coulomb drag propulsion technology.

References

[1] P. Janhunen, et al., Electric solar wind sail: toward test missions, *Rev. Sci. Instrum.* **81**, (2010) 111301.

New Solar Power Sail Program in the Post-OKEANOS Era

Osamu Mori[1]*, Masanori Matsushita[1], Ahmed Kiyoshi Sugihara[1], Yuki Takao[2], Toshihiro Chujo[3], Yasuyuki Miyazaki[1], Yasutaka Satou[1], Nobukatsu Okuizumi[4], Hiraku Sakamoto[3], Ryu Funase[1], Naoya Ozaki[1], Yuki Kubo[1], Akihito Watanabe[5]

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Solar power sail is original Japanese concept. It can be accelerated by solar radiation pressure and generate electricity by thin-film solar cells on the sail membrane. JAXA developed the world's first solar power sail-craft IKAROS. By deploying a large sail using the centrifugal force of spin, IKAROS demonstrated both its photon propulsion and thin-film solar power generation during its interplanetary cruise. Solar power sail can generate sufficient power by large area thin-film solar cell to drive high-Isp ion engine in outer planetary region. We proposed solar power sail-craft OKEANOS. OKEANOS will rendezvous and make a round trip to Trojan asteroid. Solar power sail is the only current solution for sample return from Trojan asteroid. However, OKEANOS has not selected for JAXA project due to cost issues. We believe that the solar power sail can also contribute to the other exploration missions. Thus, we propose a new concept to make solar power sails useful in various missions.

1) Changing from spin-type sail to boom-type sail, the sail-craft can perform the attitude control for 3-axis stabilization instead of spin stabilization. It is advantageous for observation. The size of the sail is less than 100 m^2 due to the limit of boom extension, but even this size is sufficient for small or micro spacecrafts.

2) If gimbal mechanisms are added to a boom-type sail, it becomes a reorientable boom-type sail. Controlling the orientation of the sail using gimbals (motors), the orbit and attitude can be controlled simultaneously using solar radiation pressure.

3) Attaching various devices to a boom-type sail, high functionality can be achieved. For example, thin film solar cell (for ultra-light solar paddle), array antenna (for high-capacity communication), interferometer (for high-resolution observation) and reflective sheet (for deployable target marker).

Based on the above, this paper presents a new program for solar power sail including outer solar system exploration mission to replace OKEANOS.

The NASA Solar Cruiser Solar Sail System – Ready for Heliophysics and Deep Space Missions

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Solar Cruiser is a Small Satellite Technology Demonstration Mission (TDM) to mature solar sail propulsion technology and enable near-term, high-priority breakthrough science missions as defined in the Solar and Space Physics Decadal Survey, future operational missions increasing space weather warning times, and supporting national security needs. Solar Cruiser will demonstrate a "sailcraft" platform (using a 2.5 micron thick sail measuring 1,653 m^2 (17,793 ft^2) with pointing control and attitude stability comparable to traditional platforms, upon which a new class of Heliophysics missions may fly. Once flown, it will show sailcraft operation (acceleration, navigation, station keeping, heliocentric plane change) scalability of sail technologies such as the boom, membrane, and deployer to enable more demanding missions, such as high inclination solar imaging. The Solar Cruiser sailcraft system demonstrated system-level TRL-5 in 2022 and is funded to complete TRL-6 testing in 2023, making it ready for flight as early as 2026.

With a characteristic acceleration of > 0.11 mm/s^2, Solar Cruiser will immediately enable sustained in-situ observations of the Earth's bow shock and magnetotail by allowing the sailcraft to artificially precesses the apse line of its orbit to position the sailcraft within the geomagnetic tail. Solar Cruiser itself (or an identical follow-on mission) can accommodate solar wind plasma and magnetic field sensors. This would address compelling science questions regarding the evolution of the solar wind inside L1 and its degree of correlation with solar wind observations at L1 and at Earth. Results of such an investigation would determine the forecast efficiency of sub-L1 observations for operational NOAA space weather predictions. The system immediately enables sustained in-situ observations off the Sun-Earth-Line (SEL), including imaging coronal mass ejections (CMEs) between the sun and Earth and in-situ measurements of solar wind streams in the vicinity of L5 before they rotate into Earth. It can create artificial equilibria and indefinite station keeping at locations at any desired offset from the SEL leading or trailing the Earth in its orbit. The system can also provide high ΔV propulsion in cis-lunar space, allowing for strategic repositioning of assets at will (with maneuvers between EM Lagrange Point within 4-6 days) and without concern about using propellant or needing resupply

The Solar Cruiser sailcraft, concepts of operation, and future missions enabled will be described as well as the project's programmatic status regarding spaceflight.

Advanced Composite Solar Sail System Mission Update

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The Advanced Composite Solar Sail System (ACS3) will be the first practical solar sail for the National Aeronautics and Space Administration. [1] ACS3 will also be the first spaceflight demonstration of NASA compact deployable composite boom technology [2]. The primary mission objective of ACS3 will be to deploy and characterize an 80-m^2 composite boom structure solar sail technology in low Earth orbit. Extended mission goals will be to demonstrate controlled solar sailing flight via a series of orbit raising and lowering maneuvers. Target mission orbit is a 1000 km x 1000 km midnight-noon sun-synchronous orbit. Launch of ACS3 is scheduled for July 2023 with sail deployment in September 2023. Mission duration is expected to be six to nine months. The ACS3 solar sail vehicle is a 12U Cubesat consisting of a bus module, containing flight and solar sail control avionics, and a solar sail module, containing the composite booms and metallized polymer solar sail membranes of the solar sail structure stowed within a boom deployer mechanism. A four-camera instrument suite for 360-degree imaging of the ACS3 solar sail during and after deployment is also housed within the bus module. The ACS3 80-m^2 solar sail design is a sub-scale version of an intermediate-size 500-m^2 solar sail using NASA deployable composite boom technology. The sail consists of four metallized 2-μm thick polyethylene naphthalate (PEN) 20-m^2 triangular quadrants supported by four 7-m long lenticular cross-section composite booms. Booms are flattened and co-coiled for stowage within a tape-spool driven deployer mechanism. The total mass of the ACS3 space vehicle including solar sail is 16 kg. An overview of the ACS3 mission and mission systems will be provided in this presentation. This overview will include descriptions of the solar sail structures and materials technology used with ACS3, and discussion of the scalability and extensibility of the ACS3 solar sail to future larger-scale solar sailing mission requirements. An update on progress towards the launch of ACS3 in July 2023 will also be provided.

References

[1] https://www.nasa.gov/directorates/spacetech/small_spacecraft/ACS3
[2]https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/dcb

Research for and Early-Stage Development of the First Interstellar CubeSat Powered by Solar Sailing Technology

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Project Svarog is a student-led initiative aiming to reach the heliopause using a solar sail [1]. The sail is set to be passively stabilized and does not require gravity assists unlike previous interplanetary missions, thus making deep space exploration more feasible and flexible. Previous feasibility studies have been performed, demonstrating the potential of the mission and highlighting research focus. A high-fidelity orbital model has been developed for proving the feasibility of the trajectory and studying initial conditions. Currently, Scientific Machine Learning [2] is being implemented to study the optimal initial conditions, parameters, and the sensitivity of the trajectory with respect to those properties of the system. Initial studies show that the escape trajectory is feasible for a mass to area ratio of 12 g m^{-2}. Given the repeated close passes to the Sun, the long duration of the mission, and its sensitivity to solar events, understanding and modelling the space environment for the duration of the mission is paramount. So far, preliminary simulations of radiation dose received by the spacecraft using GRAS [3] coupled with data driven model of solar activity have been performed. Structural simulations from an in-house code which uses multi-particle model have been compared with commercial packages and paired with vacuum chamber testing for validation. Following the IKAROS team research and analysis [4], we have now developed non-dimensional analysis which will enable scaling of sail dynamics to reduce number of required simulations and enable conducting experimental validation of sail behaviour under influence of gravity. Mechanical and electronic design and prototyping have been undergoing in parallel with the research endeavours. These have made testing of deployment methods and communications architectures possible. A motor-controlled boom deployment is being studied in parallel with the flight proven spinning method [5]. Should these technologies be successful, the Svarog system could serve as a low-cost enabler for the testing of new technologies and research opportunities in deep space, piggybacking of the increasing number of interplanetary missions and fostering deep space exploration.

References

[1] P. Fil, F. Szczebak, D. Sengupta, I.R. Riesco, B.S. Tortosa, B. Krawczyk, et al. Mission Concept and Development of the First Interstellar CubeSat Powered by Solar Sailing Technology, Journal of the British Interplanetary Society, ISSN: 0007-084X, 2023.

[2] C. Rackauckas, Y. Ma, J. Martensen, C. Warner, K. Zubov, R. Supekar, et al. Universal Differential Equations for Scientific Machine Learning, arXiv.org, 2021 Nov 2.

[3] G. Santin, V. Ivanchenko, H. Evans, P. Nieminen and E. Daly, GRAS: a general-purpose 3-D Modular Simulation tool for space environment effects analysis, IEEE Transactions on Nuclear Science, vol. 52, no. 6.
[4] Y. Shirasawa, O. Mori, Y. Miyazaki, H. Sakamoto, M. Hasome, N. Okuizumi, et al. Analysis of Membrane Dynamics using Multi-Particle Model for Solar Sail Demonstrator IKAROS.
[5] H. Sawada, Y. Shirasawa, O. Mori, N. Okuizumi, Y. Miyazaki, S. Matunaga, et al. On-orbit Result and Analysis of Sail Deployment of World's First Solar Power Sail IKAROS.

LightSail 2 Image-Based Engineering Assessment

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The Planetary Society's LightSail 2 solar sail mission showed the enormous value of cameras to image the sails for engineering assessment and public outreach. LightSail 2 was the first mission to demonstrate controlled solar sailing in a small spacecraft, in this case, a 3U CubeSat [1]. It orbited Earth from June 2019 to November 2022. Four triangular sail segments of aluminized Mylar were deployed to 32 m^2 of sail area using four Elgiloy metal alloy booms. Two fisheye cameras were mounted on opposite sides of the spacecraft and were positioned to image most of the sail as well as Earth and/or space beyond the sail. This allowed detection and assessment of anomalies during the mission. Anomalies detected included the incomplete deployment of a solar panel, which was then compensated for, as well as a bent boom that showed some variation early in the mission but then stayed relatively stable. In addition, cameras enabled an engineering assessment of sail deployment, evolution of the boom and sail shape, and sail degradation with time. Images of sail deployment captured dynamics of the process, and allowed for rapid verification of successful deployment. Over the course of the mission, several sail degradation processes were observed, likely mostly caused by atomic oxygen at the approximately 700 km altitude of most of the mission. Wrinkles developed within days to weeks then stabilized. Small areas of aluminum delamination and the development of small holes occurred over months to years. Over time, the angle of the plane of the sail shifted systematically. Small variations in boom position were also noted on timescales of minutes, likely due to thermal expansion and contraction of the Elgiloy booms. Images have also been extremely valuable for sharing the mission with the public. Stunning pictures raised awareness and developed interest in solar sailing from the public, the technical community, and space agencies. Hundreds of images were acquired, many with the beautiful backdrop of Earth over the shiny sails. Based upon the experiences with LightSail 2, inclusion of cameras that can image the sail is very strongly encouraged on future missions. Note that another abstract submitted to this symposium covers LightSail 2 Orbit Evolution and Attitude Control Performance [2].

References

[1]. D. Spencer, B. Betts, J. Bellardo, A. Diaz, B. Plante, J. Mansell,: The LightSail 2 Solar Sailing Technology Demonstration. Advances in Space Research (ASR), Vol. 67, Issue 9, (2021), pp. 2878-2889.

[2] J.R. Mansell, J.M. Bellardo, B.H. Betts, , B. Plante, D.A. Spencer, Orbit Evolution and Attitude Control Performance, Abstract Submitted to ISSS, Jun. 5-9, 2023, New York, NY.

LightSail 2 Orbit Evolution and Attitude Control Performance

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The Planetary Society's LightSail 2 solar sail deorbited on November 17th, 2022, concluding a nearly 3-and-a-half-year mission during which the 3U CubeSat demonstrated the first controlled solar sailing in Earth orbit. Its 32 m^2 aluminized Mylar sail was deployed in a 709x726 km altitude orbit on July 23rd, 2019, and the spacecraft immediately proceeded to enact an "On-Off" attitude control strategy. This strategy commanded two 90-degree slews each orbit to harness solar pressure on the sail while moving away from the Sun and minimize it while moving towards. As the team experimented with several momentum management strategies, on-orbit performance of the On-Off strategy was refined, and a measurably reduced orbit decay rate was observed by the end of 2019 [1]. Attitude control performance subsequently degraded throughout 2020, but in 2021 a method of recalibrating LightSail 2's primary gyros on-orbit was devised and implemented. The recalibrations improved attitude knowledge and control performance to levels beyond even the start of the mission. The result was that during the summer of 2021, LightSail 2 overcame atmospheric drag and demonstrated a sustained period of orbit raising with semi-major axis increases exceeding 100 m/day. Increasing solar activity ultimately reversed these gains. However, the on-orbit lifetime of the mission was significantly increased by solar sailing compared to simulations of an uncontrolled sail. LightSail 2 was still operating on the last tracking pass before deorbiting. The final pass showed rotation rates exceeding those predicted by rigid body simulations, suggesting that the sail may have already collapsed. Thus, the results of the mission are of interest to future drag sails as well as solar sail missions.

Our presentation will review LightSail 2's attitude control performance throughout the mission and correlate changes in the orbit with both On-Off control and solar activity. The recalibration of the gyros and other operational lessons will be discussed. Finally, deorbit simulations will be compared to mission results to highlight the effect of solar sailing and gain insights relevant to drag sail spacecraft. Note that this presentation complements another abstract submitted to this symposium covering an image-based assessment of LightSail 2's solar sail [2].

References

[1] J. R. Mansell, D. A. Spencer, B. Plante, M. Fernandez, C. T. Gillespie, J. M. Bellardo,

A. Diaz, B. Betts, and B. Nye, “Orbit and Attitude Performance of the LightSail 2 Solar Sail Spacecraft,” 2020 AIAA SciTech Forum, AIAA 2020-2177, Jan. 6-10, 2020, Orlando, FL.

[2] B.H. Betts, J.M. Bellardo, J.R. Mansell, B. Plante, D.A. Spencer, LightSail 2 Image-Based Engineering Assessment, Abstract Submitted to ISSS, Jun. 5-9, 2023, New York, NY.

Objectives, Design and Initial Test Results of the Upcoming GAMA-β Solar Sail In-Orbit Demonstration

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GAMA will launch a solar sail spacecraft, Gama Beta, to demonstrate control and navigation in a high LEO orbit. The primary objective is to realize a controlled and precise change of orbit that increases the semi-major axis, using only the solar sail and photonic pressure. The secondary objectives include qualification of systems to navigate in deep space.

The mission Con-Ops are initial orbital insertion between 500-600 km altitude, using an Orbital Transfer Vehicle to reach our minimum required altitude of 1000 km, above the Earth's atmosphere. Once commissioned, Gama will deploy the solar sail, actuate the spacecraft to follow the optimal steering law to achieve our primary objective. Mission disposal will use the solar sail to deorbit, using thrust and subsequently the drag properties as the spacecraft re-enters the atmosphere.

Gama Beta will be the second demonstrator flight, prior to our first deep space scientific exploration mission. Many technologies will be qualified, including the sail deployment using GAMA's sail membrane and sail hub technology as well as DLR's deployable booms and boom deployment mechanisms. GAMA has already carried out initial ground-based membrane small scale deployment tests and exhibit force profiles that are compatible with the structural properties of the carbon fibre booms. DLR will conduct first deployment tests and limit load determination of the tailored boom deployment system in April/May 2023 to prepare the planned joint tests of membrane and booms in late summer of the same year. The launch of the FM is scheduled for early 2025.

The proposed talk will introduce GAMA's staged approach to technology maturation due to a set of consecutive missions with rising complexity and sail size. Exemplary, the overall spacecraft and mission concept of Gama Beta as well as the mentioned first test results will be presented.

Near Earth Asteroid Scout Solar Sail Mission Overview

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Near Earth Asteroid (NEA) Scout is a mission to a near Earth asteroid that launched as a secondary payload on Artemis 1 on November 16, 2022. Its goal was to rendezvous with and image a near Earth asteroid. The asteroid targeted was a function of launch date, and for the launch date achieved, the selected target was the asteroid 2020 GE. NEA Scout was supposed to deploy from the Space Launch System (SLS) Interim Cryogenic Propulsion Stage (ICPS) roughly 4.5 hours after launch, and may have. But to date, no contact has been established with NEA Scout and it is highly likely that the mission is lost. However, for posterity we would like to document some key segments of the planned mission timeline which was challenging and included several events particular to solar sail technology. Specifically, this was to be the first deep space solar sail deployment by NASA, the first deep space mission with a scientific target for rendezvous, the first solar sail mission to use a moving mass to manage momentum and the first NASA solar sail to be under full 3-axis control. Additionally, there were several hardware challenges that had to be addressed with early-mission calibrations, including calibrations of the Adjustable Mass Translator, the Reaction Control System, and the sail disturbance torque model. NEA Scout also had to perform a critical maneuver early in the mission to target a Lunar Gravity Assist so that the departure from the Earth-Moon system could be altered from the disposal trajectory of the ICPS, which was targeted to no specific destination in heliocentric space. In this paper we present an overview of the mission timeline including the plans for calibration, sail deploy, solar sailing to the target asteroid and the plan for the asteroid rendezvous to inform and benefit future solar sail missions.

ACS3 – Flight Dynamics for a Solar Sail Technology Demonstration Mission

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The NASA's Advanced Composite Solar Sail System (ACS3) mission consists of a spacecraft that will deploy an 80 m^2 solar sail in Low Earth Orbit (LEO). The main objective of the mission is to demonstrate that the solar wind can propel the spacecraft to change the semimajor-axis and obtain a different orbit altitude. The sail will be composed of a combination of composite materials and it will be deployed with lightweight booms from a 12U CubeSat bus, developed by NanoAvionics. The spacecraft will be launched aboard an Electron launch vehicle from Rocket Lab Launch Complex in New Zealand in 2023.

This paper covers the orbital mechanics and navigation developments to support the mission, from the solar sail trajectory model to the elements of ground software that provide the orbit determination analysis prior to flight. First, we introduce a description of our high-fidelity propagation that accounts for the solar radiation pressure to produce predictive ephemeris of the solar sail performance with several spacecraft attitude modes. As part of our results, we present plots of the expected altitudes achieved by the spacecraft once the solar sail is deployed under various assumptions of the space weather. In addition, we present a full description of our orbit determination process which relies in GPS state vectors for accurate estimation of the orbit solution and its uncertainty at a frequent cadence during the mission. The outcome of this estimation process will be critical to achieving the objective of determining effective altitude change produced by the solar sail.

References

[1] K., Wilkie. "The NASA Advanced Composite Solar Sail System (ACS3) Flight Demonstration: A Technology Pathfinder for Practical Smallsat Solar Sailing". 35th Annual Small Satellite Conference, Logan, Utah. 2021.

[2] Wilkie, W. K., Fernandez, J. M., Stohlman, O. R., Schneider, N. R., Dean, G. D., Kang, J. H., Warren, J. E., Cook, S. M., Heiligers, J., & More Authors (2021). overview of the nasa advanced composite. In AIAA Scitech 2021 Forum (pp. 1-23). [AIAA 2021-1260] (AIAA Scitech 2021 Forum; Vol. 1 Part F). American Institute of Aeronautics and Astronautics Inc. (AIAA). https://doi.org/10.2514/6.2021-1260.

Sailcraft Helianthus: a Solar-Photon Sail for Geostorm Early Warning

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The sailcraft-Helianthus concept is a project aimed at realizing a sailcraft for a geostorm early-warning mission with warning times longer than 100 minutes as the response to solar *fast streams* (typical speed about 800 km/s), or longer than 200 minutes for the usual *slow wind*.

The concept of mission Helianthus has some key features that have been considered as astrodynamical and technological advances to be achieved by the Italian Space Agency (ASI) in the framework of an interplanetary solar-photon full *in-space* propulsion (i.e., with no rocket add-on) development program. The related preliminary investigation - which involved Italian universities, laboratories, and a few companies - of the main sailcraft's systems and subsystems began in Nov-2019 and ended in Dec-2022. The key features of the reference mission can be summarized as follows:

1. Sailcraft Helianthus should perform heliocentric transfer orbit and heliocentric station keeping by solar-photon irradiance only, sail attitude control included;
2. The sailcraft lightness number should be as close to 0.1 as possible, by allowing Helianthus to operate well below the point L1 of the Sun-Earth gravitational system. If Helianthus were put around L1, like spacecraft ACE, the fast-streams warning time would amount to about 31 minutes;
3. Helianthus' systems and subsystems should exhibit comparable sail loading such that the overall sailcraft sail loading amounts to less than or equal to $15\,\mathrm{g/m^2}$;
4. In addition to the overall sail-system behavior, the boom subsystem and the sail attitude control have been investigated with innovation; the idea is to develop a technology appropriate to achieve very light photon-induced devices working onboard Helianthus;
5. Helianthus should operate on a range of orbits quasi-synchronous with the Earth-Moon Barycenter (EMB); this goal could be reached by four maneuvers per year by offsetting the initial orbital errors, the sail wrinkles perturbation, and the Earth-Moon system's gravitational disturbance;
6. Challenging payload instruments are in progress for (*a*) in-situ measuring the heliocentric magnetic field, (*b*) counting solar protons, and (*c*) imaging solar-corona, all in all not-heavier than 5 kg;

7. A focus on the orbital analysis has carried out a considerably-detailed propulsive acceleration model – through the sailcraft-frame Lightness Vector theory – including many effects compliant with electromagnetic theory and quantum aspects of the sail-membrane's metal reflective layer;
8. The investigation has been continuing experimentally for the sail-surface wrinkles distribution, the sail folding problem and deployment configurations.

Owing to the preliminary nature of this research, some hardware samples were delivered to ASI; in contrast, the astrodynamical feasibility of the Helianthus concept has been established extensively.

Acknowledgements

This work is performed jointly under the Implementing Agreement between the Italian Space Agency and DIAEE – University of Rome "La Sapienza" n. 2019-28-HH.0 - CUP n. F84I19001070005 related to R&D activities on solar photon propulsion. The Implementing Agreement is based on the Framework Agreement between ASI and "La Sapienza" n. 2015-1-Q.0.

A Rendezvous Mission to Outer Solar System Bodies Using a 100-kg-class Solar Power Sail

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Historically, solar sails have evolved in a form in which physical interaction between solar photons and a thin reflective sail is exploited. Other types of space sails, such as electric sail, magnetic sail, and drag sail, are also propelled by external forces exerted on the sailcraft. By contrast, Japan has addressed another form of space sail that collects and converts sunlight into electricity to produce thrust by means of solar electric propulsion. The sailcraft is made of a deployable membrane covered with flexible solar cells. This concept, called a solar power sail, makes it possible to generate a large amount of power in a lightweight spacecraft system. Solar power sails are capable of driving high-specific-impulse ion thrusters even in the outer solar system, allowing for challenging missions such as sample return from Jupiter Trojans, as was planned by JAXA's OKEANOS mission [1].

Although OKEANOS was a medium spacecraft of 1.4-ton wet mass, recent studies revealed that solar power sails are also effective for micro- to small spacecraft [2]. Small-class spacecraft are advantageous because of their low cost and short period of development, while their functions tend to be strongly constrained due to limited resources available. To reach regions beyond Jupiter using conventional spacecraft, large solar array panels and a large amount of propellant are needed, thus making the total spacecraft system heavy; consequently, a powerful launch vehicle is required. Because solar power sails offer the abilities of power generation and efficient propulsion with less mass resources, exploration of the outer solar system by a small spacecraft becomes possible. The requirement for launch vehicle can also be reduced.

This study presents a rendezvous mission to outer solar system bodies, such as Jupiter Trojans and Centaurs, using a 100-kg-class solar power sail. The Epsilon launch vehicle, which is a solid-fuel rocket of Japan dedicated especially to small satellites and nanosatellites in the near-Earth region, is assumed. Based on existing products of flexible solar arrays and ion thrusters that have been developed in JAXA, a rough design of the spacecraft is presented first. To increase the orbital energy of the spacecraft in order to reach the outer solar system, a method called V-infinity leveraging is used. Considering that outer solar system bodies tend to have large orbital inclination with respect to the ecliptic plane, a Jupiter gravity assist is performed to change the inclination efficiently. The Earth-Jupiter-Asteroid trajectory is designed using a global optimization method based on heuristics.

Results demonstrate that a rendezvous mission to outer solar system bodies can be accomplished with feasible design parameters such as propellant consumption and ion thrusters' operation time.

References

[1] O. Mori, J. Matsumoto, T. Chujo, M. Matsushita, H. Kato, T. Saiki, Y. Tsuda, J. Kawaguchi, F. Terui, Y. Mimasu, G. Ono, N. Ogawa, Y. Takao, Y. Kubo, K. Ohashi, A.K. Sugihara, T. Okada, T. Iwata, H. Yano, Solar Power Sail Mission of OKEANOS, Astrodynamics **4.3** (2020) 233–248.

[2] Y. Takao, O. Mori, M. Matsushita, A.K. Sugihara, Solar Electric Propulsion by a Solar Power Sail for Small Spacecraft Missions to the Outer Solar System, Acta Astronautica **181** (2021) 362–376.

Breakthrough Sun Diving: The Rectilinear Option

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A near-term possibility for utilization of Breakthrough Initiatives Project Starshot technology is application of the Sun Diving Maneuver as a replacement for Laser acceleration of highly miniaturized photon sails to interstellar velocities. This possibility was discussed during the June 2022 Breakthrough Discuss meeting in Santa Cruz California. Here, we consider application of Statite-type photon sail probes to achieve rectilinear trajectories to explore outer solar system and near-interstellar destinations. Statute-Type solar photon sails sufficiently thin and reflective that solar radiation-pressure force on the sail exactly balances solar gravitational force. In such a force-free environment, the spacecraft exits the solar system at its pre-sail-deployment solar-orbital velocity. Here we consider departures from a circular 1-AU solar orbit, the perihelion of a 0.7-1 AU elliptical solar orbit and the perihelion of a 0.3-a 1U solar orbit. Possible outer-solar-system destinations of possible interest to Breakthrough initiatives extraterrestrial-life/artifact -search researchers include Europa, Titan, Enceladus, and Arrokoth. More distant possible objectives are Oumuamua and the Sun's Inner Gravitational Focus. To achieve a rectilinear trajectory, the sail must be oriented normal to the Sun and spacecraft areal mass thickness is 1.46×10^{-3} kg/m^2. Current sail technology is reviewed to determine whether it can achieve the required areal mass thickness.

SOLSPACE Solar Reflectors: Commonalities with Solar Sailing

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There are several key technologies for clean and sustainable energy solutions, with solar photovoltaic (PV) farms providing one such solution. However, the operation of PV farms is limited to daytime use. The SOLSPACE project proposes the use of large orbiting reflectors in polar orbit to enhance the energy output of these farms, particularly at dawn and dusk, when output is low but energy demand is high [1]. The reflectors would project an image of the solar disk onto the PV farms to augment their energy output. SOLSPACE is investigating the engineering challenges of energy from space, as well as the economic and regulatory challenges such a venture would entail.

There are many commonalities between these solar reflectors and solar sails. In terms of their structure, the reflector would be susceptible to the same flexible modes as those of a solar sail, as well as wrinkling of the reflective film. The proposed solar reflectors are hexagonal in shape, with a side length of 250 m and total mass of order 3000 kg [2]. Given their large inertia, attitude control requires a capable actuation system [3] to perform slew maneuvers to direct sunlight to the PV farms. Due to the coupling between the reflector attitude and orbital dynamics, the targeting of slew maneuvers also requires orbit control to maintain a nominal ground track. These attitude control considerations share similarities with solar sailing, which has pointing requirements for orbit transfer, rather than only for orbit station-keeping.

This presentation will provide an overview of the SOLSPACE project, detailing the commonalities between the proposed solar reflectors and solar sails. Potential synergies between solar reflector and solar sail development will be discussed, which can offer benefits for both systems. In addition, this presentation will explore applications where the solar reflectors can be used as a solar sail to provide an adaptive platform for secondary missions. Given the large area-to-mass ratio, the reflector could operate as a high-performance solar sail with characteristic acceleration of up to 0.49 mms^{-2} for an ideal reflector. Such a solar sail would provide a capable primary propulsion option for future science missions where the addition of a science payload would not excessively compromise the sail performance. Towards the end of their life in Earth-orbit for energy delivery, it would also be possible for the solar reflectors to transit to a lunar orbit to continue operating as solar reflectors to support future Moon-based infrastructure [4].

References

[1] Çelik, O., Viale, A., Oderinwale, T., Sulbhewar, L. & McInnes, C. R. (2022). Enhancing terrestrial solar power using orbiting solar reflectors. Acta Astronautica, 195, 276-286.

[2] Viale, A., Çelik, O., Oderinwale, T., Sulbhewar, L., & McInnes, C. R. (2023). A reference architecture for orbiting solar reflectors to enhance terrestrial solar power plant output. Advances in Space Research (under review).
[3] Viale, A., & McInnes, C. R. (2023). Attitude control actuator scaling laws for orbiting solar reflectors. Advances in Space Research, 71(1), 604-623.
[4] Çelik, O. and McInnes, C.R., 2022. An analytical model for solar energy reflected from space with selected applications. Advances in Space Research, 69(1), pp.647-663.

Scalability of Solar Sail Designs using Deployable Thin-Shell Composite Booms

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The NASA Deployable Composite Booms (DCB) project has developed a series of thin-shell composite Collapsible Tubular Mast (CTM) booms for solar sail and other large space structures [1]. The Advanced Composites Solar Sail System (ACS3) mission that will launch in 2023 will be the first technology demonstrator of this compact, lightweight boom technology to deploy and support a solar sail [2]. The four miniaturized, 7-m-long ACS3 booms were designed to fit in a 12U CubeSat spacecraft and are 40% scaled down by length of the 16.5-m-long booms developed to fit in a 27U CubeSat form factor to enable future missions with a 500-m^2-class solar sail. Larger cross-section size booms fabricated using a new continuous manufacturing method are currently under development to enable much larger boom-supported solar sails of up to 5,000 m^2 in effective area. This paper will discuss the scalability of this type of boom technology to determine performance limits that warrant the use of other deployable technology. A preliminary boom sizing methodology for solar sail applications will be presented to derive boom designs compatible with small satellites. First, the simplified operational loads that typical solar sail missions impose on the booms will be presented and structural and thermal requirements will be derived. These component-level requirements will all converge into boom stiffness requirements typically used to size the boom cross-section and evaluate composite laminates of interest compatible with rolling of the structure into small volumes. The CTM boom architecture will be the focus of study but other alternative thin-shell designs also compatible with the volume limitations of small satellites are also possible. Typical performance metrics at the spacecraft level (lightness number and characteristic acceleration) and solar sail system level (sail loading) achievable with these boom systems and small satellite platforms will be reported in an effort to guide future mission designers and identify technology areas for improvement to increase performance. Finally, the paper will introduce concepts under development for large booms and associated deployment mechanisms that are traceable to the scalability analysis presented.

References

[1] J. M. Fernandez, S. A. Krizan, and E. R. Dyke, E. R., "Thin-shell Composite Booms for Solar Sails: Design, Manufacturing, and Qualification," in 5th International Symposium on Solar Sails, Aachen, Germany, 2019.
[2] W. K. Wilkie, et al., "Overview of the NASA Advanced Composite Solar Sail System (ACS3) Technology Demonstration Project," AIAA Scitech Forum, AIAA 2021-1260, Virtual, January 2021.

Modular and Scalable Boom Deployment Mechanism for Deployment and Retraction of up to Four CTMs

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As a result of its many years of experience in deployable masts and their deployment control mechanisms, DLR has developed a new generation of deployment mechanisms for its in-house manufactures CTMs (Collapsible Tubular Masts). These mechanisms are characterized by a modular setup and geometric scalability. This allows for the realization of 4-mast deployment modules for solar sails as well as 2-mast modules for solar arrays or a 1-mast module for Magnetometer-booms with the very same basic concept.

The modularity is achieved by a central boom hub including integrated drive and sensors (*core-module)*. This hub can accommodate up to four masts, each of which then requires an attachable *guide-module*. By using different mast cross-sections and lengths, core and guide modules can easily be adapted to different size requirements.

Furthermore, the new concept has a very rare feature: it can not only extend the masts but also retract them in a controlled manner. This allows for different mission approaches, offers more possibilities for mitigation of deployment errors in orbit and simplifies the testing and integration of the systems on ground.

The new concept and first test results from the prototype will be part of the planned presentation. Therefore, deployment and retraction behavior as well as load carrying capability of the combination of booms and mechanism will be given.

Ways to Deploy a Large Size Solar Sail

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A solar sail presents a sheet of low areal density membrane and is a propellant-less propulsion system for future exploration of the Solar System and beyond. One of the important aspects of using a solar sail is the mechanism for the deployment and stretching of large membranes in space.

Today all launched solar sails have a square shape and such design is related to the deployment mechanism. The world's first interplanetary solar sail, the IKAROS, successfully deployed its 196 m^2 sail in 2010. NASA's first solar sail deployed in low earth orbit was NanoSail-D which had 9.3 m^2 of light-reflecting catching surface and the LightSail-2 on July 23, 2019, deployed its 32 m^2 solar sail.

In this work we present a comparison of two novel concepts to deploy and stretch the large size circular solar sail based on:

i. the superconducting current loop attached to the sail membrane [1,2],
ii. the inflatable toroidal shell attached to the sail membrane [3].

In the framework of a strict mathematical approach based on the theory of elasticity, elastic properties of a circular solar sail membrane, inflatable toroidal shell, and superconducting wire loop are analyzed. Within classical electrodynamics it is predicted that the magnetic field induced by the Bi–2212 superconducting wire with engineering current densities achievable today can deploy and stretch the large membrane. The formulas for the superconducting wire and sail membrane stresses and strains caused by the current in the superconducting wire are derived.

Numerical calculations for the sail of radius of 5 m to 150 m attached to a superconducting wire with the cross-section radius of 0.5 mm to 10 mm are performed. Our calculations show that the sail of ∼1963 m^2 area (25 m radius) with the attached wire of 5 mm cross-section radius is expected to be deployed by the current in the wire of the engineering density 750 A/mm^2.

It is predicted that by introducing the gas into the inflatable toroidal shell one can deploy and stretch a large size circular solar sail membrane. The formulas for the toroidal shell and sail membrane stresses and strains caused by the gas pressure in the toroidal shell are derived. Calculations for the sail membrane attached to the toroidal shell with the varied cross-section radius are presented. For example, in the case of CP1 Polyimide film the sail membrane of 51 m radius attached to the toroidal shell of 0.1 m radius inflated by 0.75 kg of hydrogen is the optimal fit.

The normal transverse vibration modes of the sail membrane under tension caused by gas pressure in the shell are calculated.

The analytical expressions obtained for both types of the deployment mechanism can be applied to a wide range of solar sail sizes. Numerical calculations for the sail of radii up to 100 m (10000 m^2) made of CP1 membrane are presented.

We demonstrate the feasibility of deployment and stretching of a solar sail with a large size circular membrane attached to superconducting wire loop or the inflatable toroidal shell.

References

[1] V. Ya. Kezerashvili and R. Ya. Kezerashvili, On deployment of solar sail with superconducting current-carrying wire, Acta Astronautica **189** (2021) 196–198.

[2] V. Ya. Kezerashvili and R. Ya. Kezerashvili, Solar sail with superconducting circular current- carrying wire, Advances in Space Research **69** (2022) 664–676.

[3] V. Ya. Kezerashvili, R. Ya. Kezerashvili, and O. L. Starinova, Solar sail with inflatable toroidal shell, Acta Astronautica **202** (2023) 17–25.

Test of a Full-Scale Quadrant for the 1,653 m^2 Solar Cruiser Sail

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NASA Marshall Space Flight Center (MSFC), in collaboration with Redwire and NeXolve, is advancing the design of a 1653 m^2 Solar Sail System (SSS) for the Solar Cruiser mission; a technology demonstration mission to enable missions to high solar inclination orbits, sub-L1 halo orbits, non-Keplerian solar and other planetary orbits. Since 2019, the program has been developing key components, including: the Sail Deployment Mechanism (SDM), high strain composite Triangular Rollable and Collapsible (TRAC) booms, and the ~ 413 m^2 thin film sail quadrants. This effort has culminated in the successful ground deployment demonstration of a flight-scale prototype quadrant in late 2022. This paper provides an overview of the results from this test. This paper also outlines critical lessons learned that will inform ongoing efforts to further develop the technology towards flight.

Development of a Flight-Like Solar Sail Quadrant for NASA's Solar Cruiser

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In 2021 and 2022, NeXolve successfully collaborated with their NASA Solar Cruiser (SC) partners, NASA Marshall Space Flight Center (MSFC) and Redwire Space, to design, develop, fabricate, package, and conduct a ground deployment test a flight-like Prototype Sail Quadrant (PSQ) designed for NASA's Solar Cruiser solar sail mission. The Solar Cruiser solar sail system includes 4 right triangular quadrants, deployed radially from a central spool by 4 equally spaced deployable booms. The total SC sail area is 1653 m^2, with each quadrant having a design area of 413.25 m^2.

NeXolve was responsible for the PSQ design, development, manufacturing, and packaging as well as support during the ground-based deployment test of the PSQ at NASA MSFC. NeXolve developed all manufacturing process and mechanisms to support the PSQ manufacturing flow [1] which enables NeXolve to design and build solar sails, or sail quadrants, with a larger footprint than the facility in which they are manufactured. This is successfully accomplished by a delicate process of sail fabrication while also folding the sail simultaneously. The PSQ is made from NeXolve's 2.5-micron thick CP1 polyimide film with a 1000Å VDA (vapor deposited aluminum) coating [2]. The PSQ has sail surface features including edge and corner reinforcements for structural loading, electrical jumpers for continuity, rip-stops for tear-propagation, and seams that join the 60-inch-wide rolls of material alongside one another. These features are installed by way of a resin bonding process developed by and propriety to NeXolve. Following sail manufacturing and packaging onto the deployment spool at NeXolve facilities, the PSQ was ascent vent tested at NASA MSFC and then deployed at NASA MSFC. Following deployment, the PSQ deployed footprint was measured and compared to the design footprint. The PSQ corner to corner resistance measurements were also taken and show that the current grounding system will bleed electrical charge from the sail surface to the deployer.

References

[1] "Packaging and Manufacturing Processes to Enable Production of Very Large Solar Sails for Next Generation Missions", final report, NASA contract #: 80NSSC19C0200, 8/13/19- 9/27/22

[2] https://nexolve.com/wp-content/uploads/2021/10/TDS_CP1_Clear.pdf

Reflectivity Control Device (RCD) Roll Momentum Management for Solar Cruiser and Beyond

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Reflectivity control devices (RCDs), thin film optical devices that are actuated (by application of a voltage across the device) to control the reflection of sunlight on their surfaces, can effectively enable roll momentum management (MM) of a solar sail operating in deep space, outside any magnetic field. This enables solar sails to maintain adequate attitude control in these challenging environments without sacrificing mission life by using expendables. They were planned and developed for use on Solar Cruiser, operating sunward of the Sun-Earth Lagrange Point 1 (sub-L1) in a propulsion-intensive artificial halo orbit. Located in pairs of panels near the distal end of each of four booms, each articulated at a slight angle out of the sail plane to produce a force tangent to the sail at a large moment arm, the RCDs provide roll torque capabilities by using simple switching logic to determine which panels should be activated (voltage applied) to produce torque in the desired direction. The performance capabilities and constraints of these devices across a range of operating conditions, namely sun-relative attitude, is well characterized, granting designers insight on how to properly size the system and optimize the system and component designs to maximize roll torque per unit area. With an informed design, RCDs can be very effective actuators for managing roll momentum with minimal detrimental system impacts (mass, power, complexity, etc.) on Solar Cruiser and other future deep space solar sail missions.

Momentum Management Strategies for Solar Cruiser and Beyond

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Solar Cruiser is a small (ESPA-class) satellite Technology Demonstration Mission (TDM) to mature solar sail propulsion technology using a solar sail larger than 1600 square meters, demonstrating performance both as a propulsion system and a stable pointing platform for science observations in an artificial halo orbit sunward of the Sun-Earth Lagrange Point 1 (sub-L1). To ensure attitude control throughout the mission, momentum accumulated on the reaction wheels (RWs) used for attitude control must be managed such that the sailcraft does not lose control due to RW momentum saturation. Momentum builds up on the wheels from environmental disturbance torques caused by solar radiation pressure combined with a center of mass (CM)/center of pressure (CP) offset, deformed sail shape, and an off-sun pointing angle, plus other factors. Solar Cruiser mitigates this momentum build up by utilizing an Active Mass Translator (AMT) that maintains pitch and yaw momentum by trimming the CM/CP offsets, and thrusters to maintain roll momentum. A survey was conducted by the Solar Cruiser team to assess the feasibility and tradeoffs of novel momentum management concepts such as Reflectivity Control Devices (RCD's), different thruster configurations, and control vanes and other articulated control surfaces. In addition, techniques to reduce disturbance torque buildup, such as reducing boom tip deflections and clock angle control, were assessed. Similar sailcraft momentum management strategies can be used for future missions such as space weather monitoring and Earth magnetotail science missions.

Next in Solar Sail Technology: Diffractive Solar Sailing

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Presently, the law of reflection has traditionally governed solar sailing technology, but continuation of NASA Innovative Advanced Concepts (NIAC)-funded research gives promise the law of diffraction provides significant enhancements to future solar sailing applications.

Due to the higher efficiency and unique maneuverability options diffractive solar sailing can theoretically provide, it can allow spacecraft to attain novel observational orbits such as high solar inclination angles above the ecliptic. We expand the original concept of a singular solar polar orbiter by means of diffractive solar sailing, to an entire 4pi steradian constellation which corresponds to the heliophysics community's interests of multi-view, simultaneous observations of the Sun.

In order to capitalize on the mission architecture benefits that diffractive solar sailing can provide, further development in space qualified diffractive sails is imperative. We explore options for unique diffractive sail optical designs and space environment resistant materials in the scope of efficiency and manufacturability by means of analysis and experimentation.

Optimal Capture of an Interstellar High-Velocity Photon Sail in the Alpha Centauri System

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With the increased interest in interstellar exploration following the discovery of exoplanets and the proposal of the Breakthrough Starshot project [1] to perform a fly-through mission of the Alpha Centauri (α Cen) binary star system to capture the first images of an Earth-like exoplanet [2], this work investigates the optimization of photon-sail capture trajectories within the α Cen system. The main goal is to find the optimal steering strategy for a photon sail to be captured around one of the stars after a minimum-time transfer from Earth. By extending the idea of the Breakthrough Starshot project to include a deceleration phase at arrival, the scientific return of the mission will be increased. As a secondary objective, transfer trajectories between the stars and orbit-raising maneuvers to explore the habitable zones of the stars will be investigated. All trajectories will be optimized for minimum flight time using the low-thrust trajectory optimization software InTrance [3]. Our results show that a considerable increase in technology development is required to achieve a feasible flight time of less than one century, using a double-sided reflective sail. The optimized flight time from our solar system to a capture in the α Cen system ranges from 20,000 years for current sail technology to less than 80 years for a futuristic graphene-based ultralight sail. The latter allows a maximum arrival velocity at the α Cen system of 5.5% of the speed of light. The results in this work furthermore show an average improvement of 30% in terms of time of flight for lightness numbers smaller than that of a graphene-based sail obtained in previous work [4]. However, a sail like the one proposed by the Breakthrough Starshot project would take over 2000 years to travel from our solar system to a capture about the smaller star of the binary system, α Cen B. Significant technological developments are therefore required to reach and be captured in the α Cen system in less than a century. Thus, a fly-through mission probably remains the only option for a first exploratory mission to α Cen, but the results obtained in this work provide perspective for future long-residence missions to our closest neighboring star system.

References

[1] https://breakthroughinitiatives.org/initiative/3, retrieved 10 Mar 2023.
[2] G. Anglada-Escudé et al., A Terrestrial Planet Candidate in a Temperate Orbit Around Proxima Centauri, Nature, **536** 437–440, 2016.
[2] B. Dachwald, Optimization of Interplanetary Solar Sailcraft Trajectories Using Evolutionary Neurocontrol, Journal of Guidance, Control, and Dynamics, **27** (1) 66–72, 2004.
[3] R. Heller, M. Hippke, Deceleration of High-velocity Interstellar Photon Sails into Bound Orbits at α Centauri, The Astrophysical Journal Letters, **835** L32, 2017.

Mission to Sedna with a Solar Sail Exploiting Thermal Desorption of Coatings

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Missions to the Kuiper Belt region and beyond, the Oort Cloud, the gravitational focus of the Sun, and even the Alpha-Centauri system [1] are considered the next breakthrough for space exploration. Among various suggested destinations, the trans-Neptunian object Sedna (90377) has recently gained more and more interest from the scientific community. Sedna, orbiting the Sun in a highly eccentric orbit, is currently on the way to its perihelion (around 76 AU from the Sun), and recent studies consider this an extraordinary opportunity to get to know more about deep space, being its aphelion at about 936 AU. Given the orbital period of 11 thousand years, scientists have been proposing missions for launch in the next few years (around 2030), including gravity assist that would allow to reach Sedna in time for its closest approach [2].

In this study, we recommend using a solar sail that takes advantage of thermal desorption of its coating as an additional propulsion mechanism, beside its conventional acceleration. Thermal desorption can provide supplementary thrust as heating liberates atoms, embedded on the surface of the solar sail [3, 4]. To enhance this feature, the solar sail would first get closer to the Sun, and only then be deployed. The heliocentric distance to target would be given by the desorption temperature of coating materials' properties. As a result of heating by solar radiation at the specific heliocentric distance, the sail would benefit from a further thrust component. During the process of the thermal desorption one can neglect the acceleration due to solar radiation because this acceleration is an order of magnitude less than the one due to thermal desorption.

We considered a perihelion of 0.3 AU and the desorption effects on the cruise speed of the solar sail. Application of this technology with state-of-the-art sails can result in solar-system exit velocities in excess of 100 km/s, as mentioned in previous studies targeting Kuiper Belt Objects [5].

References

[1] P. Lubin, A Roadmap to Interstellar Flight, JBIS **69** (2016) 40-72.
[2] V.A. Zubko, A.A. Sukhanov, K.S. Fedyaev, V.V. Koryanov, A.A. Belyaev, Analysis of mission opportunities to Sedna in 2029–2034, Advances Space Research, **68**, 2752-2775 (2021).
[3] G. Benford., J. Benford, Acceleration of sails by thermal desorption of coatings", Acta Astronautica **56** (2005) 593–599.
[4] E. Ancona and R. Ya. Kezerashvili, Extrasolar space exploration by a solar sail accelerated via thermal desorption of coating, Advances Space Research **63** (2019) 2021–2034.
[5] E. Ancona, R. Ya Kezerashvili, G L. Matloff, Exploring the Kuiper Belt with sun-diving solar sails, Acta Astronautica **160** (2019) 601–605.

Photon-Sail Trajectories to Exoplanet Proxima b Using Heteroclinic Connections

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Now that a rocky planet is confirmed to orbit in the habitable zone of our closest stellar neighbor Proxima Centauri (one of the three stars in the Alpha Centauri system), the interest in visiting that system is growing; especially since Breakthrough Starshot proposed a fly-through mission of the Alpha Centauri system by sending a swarm of laser-driven photon sails. While many engineering problems still need to be solved for such a mission to succeed, research has shown that futuristic, theoretical photon-sail configurations can reach the Alpha Centauri system within 75-80 years while also getting captured in a bound orbit about one of the binary stars in the center of Alpha Centauri. This paper investigates trajectories from the binary star system towards planet Proxima b. A mission to Proxima b is scientifically grounded since measurements or pictures could help us better comprehend the evolution of rocky planets and potential life-formation in our Universe. The classical Lagrange points in the binary system (AC-A/AC-B) and the system Proxima Centauri-Proxima b (AC-C/Proxima b) are used to find possible trajectories towards Proxima b. The transfer is divided into a departure phase from AC-A/AC-B and an arrival phase to AC-C/Proxima b. Heteroclinic connections are then exploited using a patched restricted three-body problem method to connect the two phases. A grid search is applied on the optimization parameters to explore the design space, after which a genetic algorithm is applied to further optimize the link, focusing on minimization of the position, velocity, and time error at linkage. Four different futuristic, graphene-based sail configurations (carrying a payload of 10 grams) are used: two sails with a reflective coating on one side (β = 100 and β = 1779) and two sails with a reflective coating on both sides (β = 100 and β = 1779). The design space exploration shows that a double-sided sail provides little improvement over a one-sided sail, mainly due to the constant sail attitude along the trajectories. Results from the genetic algorithm show that a transfer from the L_2-point in the AC-A/AC-B system to the L_1-point in the AC-C/Proxima b can be accomplished with a transfer time of 235 years for the one-sided reflective sail and a lightness number of β = 1779. A transfer from the L_2-point in the AC-A/AC-B system to the L_3-point in the AC-C/Proxima b system for the smaller one-sided sail with a lightness number of β = 100 results in a transfer time of 1025 years. For both transfers, the position error at linkage is kept below 1% of the total travel distance, the velocity error below 1% of the velocity at linkage, and the time error below 1% of the total transfer time.

Long-term Mission of the Spacecraft with a Degrading Solar Sail into the Asteroid Belt

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The Mars-Jupiter asteroid belt remains one of the least explored regions of the solar system. The use of the Solar Sail Spacecraft (SSSC) will enable a long-term mission into the asteroid belt. We propose the following ballistic scheme for the mission: (1) at the first stage, the upper stage of the launch vehicle takes the SSSC out of the Earth's action sphere and imparts to it the necessary hyperbolic excess velocity; (2) the SSSC makes an Earth-Earth flight, ending with a gravitational maneuver in the Earth's action sphere and entering a trajectory with an aphelion of 3.6 AU and zero inclination; then due to the use of light pressure, a circular orbit is formed with a semi-major axis of 2.9 AU; (3) at the last long stage of research, the SSSC is oriented perpendicular to the direction of the light flux and moves along a twisting spiral. At the same time, the spacecraft will fly over and study many objects of the asteroid belt. In this paper, a complete ballistic calculation of this mission is carried out for a degrading solar sail with a non-ideally reflective surface [1]. In addition, during the mission, mathematical models of the SSSC movement and degradation of its surface will be refined.

References

[1] Rozhkov, Miroslav A., Olga L. Starinova, and Irina V. Chernyakina, Influence of optical parameters on a solar sail motion, Advances in Space Research **67** (2021) 2757-2766.

Advances in Preliminary Solar Sail Trajectory Design

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A solar sail is a specific type of continuous, low-thrust propulsion, i.e. one where the spacecraft is pushed by a relatively low acceleration, applied for extended amounts of time, changing the orbital parameters slowly. The design of an orbital transfer, with given initial and final conditions, is a boundary-value problem subject to path constraints which encode the variational orbital equations as dynamics and any other constraint on the thrust. This process is computationally expensive and often requires a first-guess solution to be initiated.

This presentation will show some recent research and results on techniques for fast, preliminary design of solar sail trajectories. These techniques are intended to be used either (1) as a first guess, to start a more accurate (but more computationally expensive) optimization process, or (2) to provide the mission designer a quick assessment of feasibility and time of flight of a solar sail trajectory, for the purpose of mission design, especially when hundreds or thousands of options are considered.

One method [1] is based on artificial neural networks (ANNs). An ANN mimics the structure and learning process of the human brain. "Layers" of neurons, interconnected to each other through inputs and outputs, are simulated with activation functions, and the outermost layers are fed and provide inputs and outputs of the overall network. The weights of the connections are optimized by "training" the network with known inputs and outputs. A trained network aims to estimate the outputs for given inputs, even if not included in the training; this is called "generalization" property. ANNs have been successfully used in a variety of applications, and primarily pattern recognition. We propose to use ANNs to estimate the time of flight (output) of a solar sail transfer between two orbits of given parameters (inputs of the network). We train the ANN on a sub-set of known transfers between near-Earth asteroids. The results then show that ANNs can estimate the duration of other, new solar-sail transfers with good accuracy in a modest computational time.

Another method [2] is based on inverse, or shape-based, trajectory design. With this method, a geometrical curve for the trajectory, connecting a departure and target orbit or state, is established analytically by means of tuning the shape parameters. Then, the control is retrieved by "inverting" the differential equations of motion. Shape-based trajectory design has extensively been used with low-thrust propulsion; in that case, however, the direction of the thrust is unconstrained. Previous research on shape-based solar-sail trajectory design focused on planar transfers. We introduce novel shaping functions to describe the 3D time evolution of the spacecraft state vector. The shape optimization problem is solved using a genetic algorithm, in which a set of shape coefficients and the initial and final spacecraft position are computed, while enforcing suitable constraints on the magnitude and direction of the solar radiation acceleration vector. Numerical simulations of transfers to potentially hazardous asteroids show that this method provides good estimates of solar sail trajectories.

References

[1] Viavattene, G. and Ceriotti, M., "Artificial Neural Networks for Multiple Nea Rendezvous Missions with Continuous Thrust," *Journal of Spacecraft and Rockets*, 59 (2022) 574-586.

[2] Caruso, A., Quarta, A. A., Mengali, G. and Ceriotti, M., "Shape-Based Approach for Solar Sail Trajectory Optimization," *Aerospace Science and Technology*, 107 (2020) 106363.

Controllability of Solar Sails

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Solar sails belong to control-affine systems with constraints of conical nature on the control set, because of their ability of creating thrust (solar radiation pressure force) only in the directions delimited by a half-space defined by the direction of the Sun. Moreover, when considering a non-ideal sail, those directions are contained in a convex cone of revolution with axis aligned to the solar vector. Due to this constraint, classical approach based on the rank of Lie algebra is not suitable to study controllability of solar sails. In this talk, we proposed a novel necessary condition for local controllability of solar sails in orbit about a celestial body [1]. This condition inspects whether a non-ideal sail is capable of generating an arbitrary variation of its current orbital elements, i.e., decrease or increase any function of the Keplerian integrals of motion.

After recalling the theoretical formulation of the necessary condition, we propose an efficient methodology to verify the aforementioned condition numerically. The methodology is based on finding forbidden maneuvers to perform with the sail, what represents an obstruction to the necessary condition. Numerical methods that we use rely on squared functional systems of bivariate trigonometric polynomials, which allow us to verify the obstruction by solving a convex optimization problem. This methodology is then extensively used to determine minimum requirements on the refelctivity of the sail allowing local controllability for any orbital configuration [2]. Our results are conservative and independent of the gravitation constant as well as two out of five Keplerian orbital elements, and may be used for preliminary mission analysis purposes. Finally, we generalize the proposed methodology to tackle station-keeping applications around an arbitrary periodic orbit (e.g., Halo, Lyapunov) [3].

References

[1] J.-B. Caillau, L. Dell'Elce, A. Herasimenka, J.-B. Pomet. On the controllability of nonlinear systems with a periodic drift. SIAM Journal on Control and Optimization, submitted.

[2] A. Herasimenka, L. Dell'Elce, J.-B. Caillau, J.-B. Pomet. Controllability Properties of Solar Sails. J. Guidance, Control, and Dynamics, 2023, in press.

[3] A. Herasimenka, L. Dell'Elce, A. Farres. Controllability of satellites on periodic orbits with cone-constraints on the thrust direction. Space Flight Mechanics Meeting, Janvier 2023, Austin, Texas, US.

Blended Locally-Optimal Control Laws for Space Debris Removal in LEO Using a Solar Sail

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As the number of space debris in low Earth orbits keeps increasing, new strategies for active removal must be conceived to prevent the overcrowding of this orbital region. A promising approach, which has been investigated in the literature, relies on a chaser satellite that can rendezvous with one or multiple debris objects to collect and de-orbit them. This spacecraft must be equipped with a propulsion system capable of delivering a relatively high Delta-V, as these objects can often be spread over large regions around the Earth, especially at different altitudes and inclinations.

In this regard, the use of propellantless propulsion systems, such as solar sails, might enhance the effectiveness of this removal strategy, and could allow a larger orbital element space to be explored, while also extending the mission duration at the same time.

To this aim, this work addresses the problem of finding near-optimal transfers for an ideal solar sail in low Earth orbit to collect and remove space debris. The proposed strategy consists of reaching the orbit of a target debris, collecting it, and bringing it down to a lower altitude where the aerodynamic forces can eventually lead to its natural decay and burn. The disposal orbit must be carefully chosen in order to allow the sail to increase its altitude again with the aim of targeting a new object. The dynamical model used in this study considers the effect of solar radiation pressure (including eclipses), aerodynamic forces and Earth oblateness.

Locally-optimal control laws are used to deal with the complexity of the dynamical model, while still providing a reasonable approximation to minimum-time transfers for a preliminary mission design. The instantaneous time derivatives of each orbital element are expressed through Gauss' form of Lagrange planetary equations, and then properly blended to control one or more orbital parameters at the same time. The optimal control problem is then solved by means of a numerical approach to find the sail attitude that maximizes (or minimizes) a cost function instantaneously. The latter coincides with the time derivative of a single orbital parameter, or consists of a suitable combination of two or more derivatives. A formulation based on modified equinoctial elements is then used to propagate the optimal solution avoiding singularities, until the osculating orbital parameters of the sail match those of the target debris.

The proposed transfer strategy is intended to lay the foundations for a scenario where the sail will repeatedly perform this transfer and dispose of multiple debris objects within a single mission, thus making the best use of a single spacecraft and launch.

Solar-sail Steering Laws to Calibrate the Accelerations from Solar Radiation Pressure, Planetary Radiation Pressure, and Aerodynamic Drag

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Solar sailing is a propulsion method which takes advantage of solar radiation pressure (SRP) as main source of thrust. However, around Earth, other sources also affect the solar-sail dynamics, including planetary radiation pressure (PRP) and atmospheric drag. In literature, the accelerations from SRP, PRP, and atmospheric drag are modeled using different theoretical and idealistic models, most of which assume the sail to be a thin, flat surface with known optical properties. These models therefore do not account for secondary effects, like the sail billowing, presence of wrinkles, degradation, and uncertainties in the sail's optical properties. Furthermore, the models make use of simplifying assumptions to describe the near-Earth dynamical environment, particularly with respect to the atmospheric density and the intensity of the solar and planetary radiation. As a consequence, sailcraft in orbit experience accelerations different from the theoretically predicted ones. In order to quantify these discrepancies between the real and modeled solar-sail dynamics, we develop a set of calibration steering laws in this paper. These steering laws allow to characterize the acceleration envelope of the sail, that is, they allow to quantify the solar-sail acceleration at every sail orientation and identify the contributions due to different sources of acceleration; in particular solar radiation pressure, planetary radiation pressure, and aerodynamic drag. This paper provides a first definition and preliminary assessment of a range of calibration steering laws. The analyses presented make use of NASA's upcoming ACS3 mission as baseline scenario and account for different possible orientations of its orbit as well as operational constraints (e.g., limiting the solar sail's maximum attitude rate of change). The results highlight the benefits and drawbacks of each steering law and the impact that they have on the orbital elements, with particular focus on the orbital altitude.

A Solar Sail Shape Modeling Approach for Attitude Control Design and Analysis

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Solar sails operating in the space environment experience deformations in sail shape that result in relatively large disturbance torques which dictate the required performance of the spacecraft attitude control and momentum management systems. These deformations are driven by thermal loads on the booms (due to uneven solar heating), manufacturing and assembly tolerances, and variations in membrane tension. The Solar Cruiser spacecraft utilizes a four-quadrant sail design with four 30-meter length booms and four triangular sail membranes, creating a square sail structure of >1600 m2. Medium-fidelity mesh models were developed based on a characteristic deformed shape. A series of parametric studies were conducted using this shape paradigm to determine worst-case deformed sail shapes which produce bounding disturbance torques. A large database of shapes was produced, and the forces and moments induced by each individual shape were calculated using a Rios-Reyes reduced order generalized sail model [1]. Two were selected as reference worst-case shapes for the Solar Cruiser mission: one which produced the highest pitch/yaw root-sum-squared (RSS) torque, and one which produced the highest roll torque. The results showed that the worst-case shapes at high solar incidence angles induce significantly higher (2-10x) disturbance torques than an ideal, flat-plate sail. Even with considerable safety margins, assuming an ideal sail is unlikely to sufficiently bound the disturbances, which is critical when designing the attitude control system and sizing actuators. Accurate sail shape modeling methodologies should therefore be employed on future solar sail missions.

References

[1] L. Rios-Reyes and D. J. Scheeres, “Generalized Model for Solar Sails,” Journal of Spacecraft and Rockets, Vol. 42, Jan. 2005, pp. 182–185, 10.2514/1.9054.

A Comparison of Diffractive Films for Solar Sailing

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Radiation pressure on a non-absorbing body is attributed to optical scattering, e.g., reflection, refraction, or diffraction. To achieve the optimized spiral orbit maneuvers a sun-facing solar sail that uniformly scatters light perpendicular to the sunline is desirable. Here we discuss diffraction techniques that provide a path toward achieving this goal, including grating, meta-material, geometric phase, and faceted reflective films. In common to each of these systems is a non-uniform spectral response, i.e., the transverse momentum transfer efficiency (TMTE) varies with wavelength across the solar spectrum. This variation has two fundamental causes: the grating equation (which relates diffraction angles to the wavelength of light); and the diffraction efficiency (which accounts for the power contained in the orders). Optimizing a thin diffractive film to achieve a large spectrally averaged diffraction angle is a non-trivial task. In principle the design must account for internal and external reflections owing to boundary conditions, polarization and material dispersion, as well as both refraction and diffraction. Although a scattering angle approaching 90° may be achieved across the solar spectrum by using a low dispersion dielectric prism, it is unfeasible for radiation pressure owing to the enormous mass. Lessening the mass by using a series of small prisms is more sensible, but mass remains a disadvantage unless the prism base can be reduced to the micrometer scale [1]. Based on diffraction theory alone, the value of TMTE can be shown to exceed that provided by an ideal sail at the optimum angle of 35°. Unless anti-reflection surfaces are used, however, the value of TMTE decreases by roughly a factor of three. This decrease is largely attributed to light scattered from the front surface in an opposing direction compared to the scattered transmitted light. An uncoated prism grating is therefore not feasible; but neither is a coated prism, owing to the added mass penalty from a broadband anti-reflective coating. Using an open source finite difference time domain (FDTM) software package called MEEP we compared optimized meta-surface films with optimized prism gratings. Although both structures provided roughly the same value of TMTE (~20%), the meta-surface provided ~50% greater acceleration owing to its decreased mass. More sophisticated grating designs are required to achieve larger values of TMTE. One promising candidate is a hybrid structure comprised of a prism grating with selectively reflective facets, for which FDTD models predict values of TMTE exceeding 40%. Another makes use of geometric phase gratings whereby liquid crystal materials provide exceptionally high values of the first order diffraction efficiency.

References

[1] G.A. Swartzlander, Jr., Theory of radiation pressure on a diffractive solar sail, J. Opt. Soc. Am. B **39**, (2022) 2556-2563.

Advanced Approaches to Solar Sailing

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Solar sailing offers new opportunities for space exploration with non-Keplerian orbits and high delta-V missions. Without limitations of rocket equation, solar sails can place spacecraft onto obits beyond the reach of chemical and electrical rockets. Future solar sail missions would require novel materials that are lightweight and that can get close to the sun, as novel control approaches to steer large area sails. Here we will overview our work on extreme solar sailing, we will show that solar sails are well fitted for missions in the inner solar corona and imaging the poles, as we well as for a fast transit interstellar probe mission. We will discuss the limitations of present day sail materials and highlight our work on novel sail materials capable of getting close to the sun. In addition, we will survey our work on sail controls, we will show that metamaterials and metasurfaces can provide a new degree of freedom for controlling radiation pressure forces. We will finally give a brief outlook on the future solar sail missions and show that solar sails prove a unique possibility for breakthrough space exploration, offering low cost, fast and scalable exploration of the solar system and beyond.

Trajectory Design for a Solar Sail Mercury Impactor

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Our study analyzes the advantages of solar sailing for a Mercury impact mission. The mission goal is to create the largest and deepest crater possible in the polar regions of the planet, where there is evidence for the presence of ice [1,2]. A near-vertical impact in this region requires a high-inclination trajectory, which cannot be achieved with conventional chemical or electric propulsion systems due to the large DV required. The impact would produce an ejecta plume whose composition could be analyzed with the instruments onboard the BepiColombo spacecraft, a joint ESA/JAXA mission, if it could be achieved to reach Mercury while BepiColombo is still operational. Two mission design alternatives are analyzed for the interplanetary transfer to Mercury. In the first scenario, either the reusable or the expendable version of the Falcon Heavy launcher inserts the spacecraft on a ballistic trajectory that is aimed directly at the planet for impact. This scenario can be improved with an (almost) unpowered Venus flyby, which allows to reduce the escape energy for the Earth departure, thereby increasing the maximum launch (and thus impact) mass. Our analysis shows that such a mission is feasible, but its drawback is that a near-vertical impact can only be achieved at moderately low latitudes but not in the polar regions. In the second scenario, we investigate the feasibility of such a mission using a solar sail. Unfortunately, the solar-sail option is hardly feasible within the lifetime of BepiColombo, which has its Mercury insertion in December 2025 and its nominal end of mission in May 2027 with a probable 1-year extension. Given the still low technological maturity of high-performance solar sail hardware, we do not believe it is realistic to expect a suitable solar sail to be built and flown to Mercury in the short time available. However, the results of our study show that solar sails would significantly improve the performance of such a mission, i.e., create larger and deeper craters for the same impactor mass. Because solar sails are particularly effective close to the Sun, they allow the spacecraft's inclination to be changed very effectively at small heliocentric distances, achieving perpendicular or even retrograde impact trajectories with respect to the planet's orbital plane. Perpendicular impact trajectories allow near-vertical impacts at high latitudes, while retrograde impact trajectories allow near-vertical impacts at lower latitudes, but with impact velocities greater than 100 km/s. The low-thrust transfer of the solar sail is optimized using a combination of genetic algorithms and shooting methods. The

results are validated against the results of InTrance ("Intelligent Trajectory optimization using neurocontroller evolution"), which uses evolutionary neurocontrol to find near-global time-optimal solar sail trajectories [3].

References

[1] N. L. Chabot, C. M. Ernst, J. K. Harmon, et al, Craters hosting radar-bright deposits in Mercury’s north polar region: Areas of persistent shadow determined from MESSENGER images, Journal of Geophysical Research: Planets, **118** (1) 26–36, 2013.

[2] N. L. Chabot, E. E. Shread, and J. K. Harmon, Investigating Mercury’s south polar deposits: Arecibo radar observations and high-resolution determination of illumination conditions, Journal of Geophysical Research: Planets, **123** (2) 666–681, 2018.

[3] B. Dachwald, Optimization of interplanetary solar sailcraft trajectories using evolutionary neurocontrol, Journal of Guidance, Control, and Dynamics, **27** (1) 66–72, 2004.

Bridging the Gaps between the CubeSat Trend, Sailcraft-specific Requirements, Complex Deployment Tasks, and Interplanetary Space

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The recent loss of a significant but also typical fraction of the CubeSats on the Artemis I launch was a wake-up call for the 'small-space' community as well as for their funding agencies. It highlighted the apparent incompatibility of ambitious science, technology and interplanetary missions with the corner factors of the 'Iron Triangle of Management' within the current trend towards CubeSats. Presented as variations of 'Cost', 'Scope', and 'Time' in textbooks, often with 'Quality' placed in the vague space between, these translate into CubeSat project practice as 'oh it's small so it must be cheap', 'then go buy COTS modules and focus on your part', and 'be done with it in x years' (x barely large enough to justify plural and definitely ≤ 3), respectively. The simplified model ignores that this Triangle is really an Iron Tetraeder which forces a fourth point upon 'Management' that it is unwilling to accept, willing to postpone, and not intending to win: Risk. Risk demands clear decisions, continuous commitment, and lasting responsibility. These thus morph quickly into processes and procedures which are standardized, proven, and well developed – for large spacecraft, with their employeepower and cost. There are two obvious ways out: leave cubesats to universities and training

courses where losses don’t really hurt (and for which they were invented) or leave them, too, to the large systems integrators and their ways (for which they write specific positions into their proposals to space agency ITTs). But there is another way: accept the risk that you are on an ambitious science and technology interplanetary mission and deal with it. This footpath into the wilderness hardly tread comes with all the rewards of the frontier. The GOSSAMER-1 solar sail deployment demonstrator’s team found ways to make 5 CubeSats (well hidden within the complicated mechanisms for their tasks) work *at the same time* to deploy a membrane in a uniquely controlled way. The concurrently developed asteroid nanolander MASCOT (9.64 kg, ≈17 U) was optimized into an envelope pre-determined to the mm and gram with custom-made units designed with ‘now-term’ technology and immediately available parts, and for re-use. MASCOT2 was to open the gate towards resources *inside* asteroids. Now they are needed by the greatest solar sail challenge ahead, a planetary sunshade to take the painful extremes out of the time we need to fix climate change on Earth.

Global Trajectory Optimization for Solar-Sail Propelled Mercury Rendezvous and Impact Missions

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The innermost planet in the solar system, with its enigmatic craters, and its hostile environment, defined by an atypical magnetic field, dynamic gravitational forces, and rapid thermal cycling, has long captivated the attention of planetary scientists. But the exploration of Mercury is particularly challenging. Because of its close proximity to the Sun, the high eccentricity and inclination of its orbit, and the resulting high DV-requirements, it requires complex and sophisticated trajectory designs with multiple flybys. Previous missions such as MESSENGER and BepiColombo required intricate trajectory designs with multiple flybys to satisfy the demanding DV-requirements of the mission, resulting in longer flight times and high propellant consumptions. As a propellantless alternative propulsion system, driven only by the free and inexhaustible solar radiation pressure, a solar sail with a moderate performance can deliver similar or even larger payloads to Mercury than MESSENGER and BepiColombo, while also potentially achieving the same or even shorter flight times. Another advantage of solar sails is that they allow more flexible trajectories that do not depend on the exact timing of flybys and a perfectly functioning propulsion system. Therefore, solar sails prevail to be a better and more cost-effective means for the exploration of the inner solar system. This study highlights their potential to provide a better performance for Mercury missions compared to conventional propulsion systems, such as the chemical system used by MESSENGER and the electric ion thrusters used by BepiColombo. However, designing an optimal solar-sail trajectory for a minimum flight time is a complex optimization problem due to the continuous and relatively low thrust of the spacecraft. Traditional direct and indirect optimization methods require a fairly good initial guess for the solution, leading to a high computational effort to obtain good solutions. To overcome this problem, we have optimized the trajectories using a smart, nature-inspired trajectory optimization method to determine the optimal spacecraft steering angles, evolutionary neurocontrol. This approach combines an evolutionary algorithm and an artificial neural network, allowing for a more extensive search within the vast search space, which typically leads to not only good but near-global optimal solutions. In this study, trajectories are proposed for two types of Mercury mission scenarios, rendezvous missions and polar impactor missions. In the rendezvous mission scenario, the sailcraft is steered from

Earth to Mercury with the lowest characteristic acceleration to achieve the same flight time as MESSENGER / BepiColombo. In the polar impactor scenario, we analyze the required performance of a solar sail for this type of mission as a function of impact mass, impact velocity, and flight time. This analysis allows for a better understanding of the benefits and limitations of using solar-sail propulsion for future Mercury missions.

Cyclic Interplanetary Motion of a Cargo Solar Sail

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Future of mankind lies in a Mars colonization and exploiting resources floating in our Solar system. Solar sails can become a key technology to provide that future with constant flow of materials to Earth and from it. We propose applying a solar sail to ensure cyclic heliocentric motion of a cargo spacecraft between Earth and inner planets. The work investigates following ballistic aspects of the suggested transport system: cyclic motion dynamics and numerical simulation that considers eccentricity and non-coplanarity of orbits, non-ideally reflective surface of the sail and optical parameters degradation; heliocentric trajectory optimization by minimum time criterion. As a prototype spacecraft for the simulation, we use a design from work [1] that can carry 1905 kg of payload with 0.25 mm/s^2 acceleration. Applying Pontryagin's maximum principle we define Hamiltonian and solve the boundary value problem with consideration of non-ideal reflection and degradation. The simulation is carried out for 4 loops of cyclic motion Earth-Mars-Earth and Earth-Mercury-Earth to demonstrate a possibility of the suggested transport system. Results show that the degradation causes an increase of flight time for each loop up to 11 years for Mars and 9 years for Mercury. Despite that the system can be efficient with deployment of several cargo spacecrafts with solar sail to maintain a flow of material with shorter periods.

References

[1] G.W. Hughes, M. Macdonald, C.R. McInnes, A. Atzei, P. Falkner, Sample return from mercury and other terrestrial planets using solar sail propulsion, Journal of Spacecraft and Rockets, **43** (2006) 828–835.

Solar Sail Torque Model Characterization for the Near Earth Asteroid Scout Mission

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Near Earth Asteroid Scout (NEA Scout) was a mission to test solar sail propulsion for orbital transfer from cislunar space to flyby and image an asteroid. One of the goals of the mission was to characterize the solar torque on the sail to ensure successful attitude control for the orbit transfer and imaging of the asteroid. The simulation used to develop the flight attitude control software [1] uses the generalized model for solar sails [2], a tensor equation of the forces and torques on sails of arbitrary shape. Rios-Reyes and Scheeres developed a general process [3] to update the torque tensor coefficients using estimates of sail torque over a range of directions to the sun. Their process was adapted and implemented for the specific case of NEA Scout using spacecraft telemetry collected during sail characterization maneuvers in combination with simulation models and parameters. The NEA Scout maneuvers were limited to the operating range of the mission and constraints of the control hardware and allowed safe testing of each attitude before proceeding to the next. The NEA Scout reaction wheel speeds are used to measure accumulated momentum, while the Active Mass Translator (AMT) position is used to subtract out the torque from the center of mass crossed with the sail force and isolate the torque from only the sail shape. The process was tested by running attitude control simulations of the characterization maneuvers, generating simulated telemetry, estimating the solar torques, then using a least squares estimate of the solar torque coefficients. These estimated coefficients were tested by evaluating the solar torques under the same conditions as the simulated telemetry and comparing them to the true simulated torques. Solar force model updates can be performed separately by observing the effect of the sail on the trajectory, and the torque model can be refined using those solar force updates. This process met the needs of the NEA Scout mission and can be adapted to characterize the solar torque for other missions with different sails.

References

[1] Juan Orphee, Ben Diedrich, Brandon Stiltner, Chris Becker, and Andrew Heaton, Solar Sail Attitude Control System for the NASA Near Earth Asteroid Scout Mission, International Symposium on Solar Sailing 2017, Kyoto, Japan.
[2] L. Rios-Reyes and D. J. Scheeres, Generalized Model for Solar Sails, Journal of Spacecraft and Rockets **42** (2005) 182-185.
[3] L. Rios-Reyes and D. J. Scheeres, Solar-Sail Navigation: Estimation of Force, Moments, and Optical Parameters, J. Guidance, Control, and Dynamics **30** (2007) 660-668.

Highly Efficient Membrane-Based Photovoltaic Array for Solar Sailing Missions

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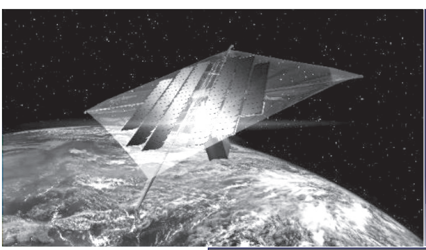
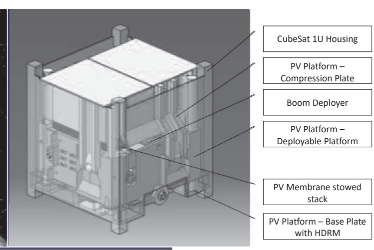
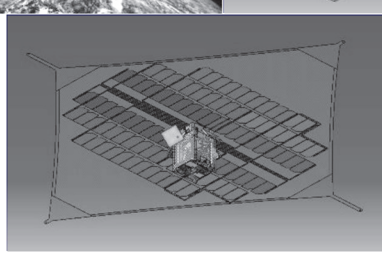
Besides large reflecting membrane areas as means of propulsion solar sailing missions also need power supply. In order to avoid additional structures like rigid solar arrays photovoltaic array studies based on membranes like Lisa-T (NASA MSFC) [1] or GoSolAr (DLR) [2] were conducted. Both adapted traditional solar array materials and their supporting deployment mechanisms to utilize thin-film solar cells, lightweight polyimides, and compact mechanical mechanisms. However, the efficiency of the thin-film solar cells is decisively lower compared to standard triple-junction GaAs cells, which leads to less area for necessary for propulsion.







In the project DEAR (Deployable 100W PV Array for SmallSats), funded under ESA contract 4000133890/21/NL/MM/ra in the ARTES 4.0 programme, a deployable 100W solar array is developed that can be stowed in and deployed out of a 1U CubeSat volume. DEAR is a joint project between DLR, Astronika, AZUR SPACE Power and ESA. In this paper an overview of the DEAR 100W solar array concept is given. It offers highly efficient power generation and thereby using only a limited amount of available area due to highly efficient PV cells. Compared to precursor studies a technology is developed that allows a safe stowage and deployment of a membrane with standard GaAs PV cells which are mechanically delicate parts.

The DEAR concept is composed of a deployable photovoltaic platform which contains a boom deployer and the deployable and stowed solar array blanket. The PV platform will be deployed out the of the 1U cube upon HDRM release and will lift the boom deployer and the membrane out this volume. With this the PV membrane and booms can be deployed. The PV membrane is composed of a thin film with least possible thickness to realize a highest mass related power output. This technology can be introduced in deployable reflecting membranes for solar sailing offering high power output for solar sailing missions.

References

[1] John A. Carr et. al., The Lightweight Integrated Solar Array and Antenna: 3rd Generation Advancements, and Beyond.

[2] Spröwitz, T.; Banik, U.; Grundmann, et al., CEAS Space Journal, **2019**, *Concept for a Gossamer solar power array using thin-film photovoltaics*. Springer, ISSN 1868 -2502.

Solar Sail Attitude Control Using Shape Modulation: The Cable-Actuated Bio-inspired Lightweight Elastic Solar Sail Concept

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Through the use of solar radiation pressure (SRP)-based propulsion, solar sails offer unique mission capabilities, including orbits outside of the ecliptic plane [1] and interstellar travel [2]. Solar sail technology has advanced in recent years, and it is now possible to fabricate and deploy sails with areas of 10-100 m^2 (e.g., LightSail 2 [3] and NEA Scout [4]), with the likelihood that substantially larger sails will be considered in the coming years and decades (e.g., Solar Polar Imager [1]). An unsolved challenge in the design of solar sails is ensuring its attitude and momentum can be controlled accurately and reliably using technology that scales up to the size of these large, next generation solar sails [5].

This work presents the Cable-Actuated Bio-inspired Lightweight Elastic Solar Sail (CABLESSail) concept that will enable robust, precise, and scalable attitude control of solar sails. This concept leverages lightweight cable-driven actuation [6] to achieve large, controllable elastic bending and torsional deformations in the booms of a solar sail that mimic the motion of an elephant's trunk or a starfish's arms. These large cable-driven boom deformations, which are actuated using winches located near the solar sail's center of mass, modulate the shape of the entire sail to create an imbalance of SRP to induce control torques in all three solar sail axes. This actuation method scales well with an increase in solar sail size, as cables can transmit forces over kilometers in length from a lightweight and small stowed volume.

We will highlight early work on the CABLESSail concept, focusing on 1) an initial conceptual design with preliminary analysis of the actuation requirements, magnitude of attitude control torques generated, and feasibility of integration with existing deployable boom designs; 2) initial dynamic simulation development efforts to capture CABLESSail's structural dynamics and provide an environment in which to test the concept; 3) early prototyping results demonstrating the real-world feasibility of the proposed actuation mechanisms; and 4) plans for the control and estimation algorithms to be used to reliably actuate the cable-actuated mechanisms.

References

[1] D. Thomas, K. Kobayashi, B. Mike, Q. Bean, P. Capizzo, K. Clements, L. Fabisinski, J. Garcia, S. Steve, Solar polar imager concept, *ASCEND* (2020) 4060.
[2] S. Gong and M. Macdonald, Review on solar sail technology, Astrodynamics **3** (2019) 93–125.
[3] D.A. Spencer, B. Betts, J.M. Bellardo, A. Diaz, B. Plante, and J.R. Mansell, The LightSail 2 solar sailing technology demonstration, Advances in Space Research **67** (2021) 2878–2889.
[4] T.R. Lockett, J. Castillo-Rogez, L. Johnson, J. Matus, J. Lightholder, A. Marinan, and A. Few, Near-earth asteroid scout flight mission, IEEE Aerospace and Electronic Systems Magazine, **35** (2020) 20–29
[5] D.A. Spencer, L. Johnson, A.C. Long, Solar sailing technology challenges, Aerospace Science and Technology **93** (2019) 105276.
[6] R.J. Caverly and J.R. Forbes, Dynamic Modeling and Noncollocated Control of a Flexible Planar Cable-Driven Manipulator, IEEE Transactions on Robotics **30** (2014) 1386-1397.

Planetary Sunshades for Solar Radiation Management: A Noninvasive, Feasible, and Affordable Climate Emergency Insurance Option

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Efforts to reduce greenhouse gas (i.e., CO_2 and other) emissions, as well as those foreseen for the coming decades, will likely be insufficient to prevent widespread damage to the environment, society, economy, and life. Complementary methods to control the Earth's temperature through geoengineering should be considered in concert with all established greenhouse forcing reduction. A planetary sunshade based on solar sail technology could be one complementary asset to actively counteract climate change.

Preliminary analyses using state-of-the-art climate models, natural analogues, and physical understanding, have shown that a planetary sunshade orbiting around a solar radiation pressure (SRP) Displaced (Sun-Earth) Lagrange 1 point (SEDL1) could reduce enough incident solar radiation to limit the Earth's average, annual, global temperature increase. This strategy could be temporarily deployed (multi-decadal to century-long timescales) to allow greenhouse forcing reduction efforts sufficient time to take effect. Models indicate that solar reduction, while an imperfect offset to the effects of greenhouse gases, would substantially reduce risks in terms of average climate (temperature, precipitation, sea ice extent, etc.) and extreme events (like heat waves, floods, and droughts). Modifying the latitude of solar reduction can result in a greater reduction of side effects, although geoengineering is not finely tunable.

Relevant technologies needed to emplace a planetary sunshade, solar sails, have advanced rapidly in recent years, indicating that implementation of this approach is likely technically feasible in the mid-term (within 25 years with significant effort) instead of the far-term. Demonstration missions can be built in the near-term (within 10 years) to show the feasibility.

Solar sails offer not only an occulting aperture for solar flux reduction but are also capable of prolonged station keeping at SEDL1 for the long mission lifetimes that would be necessary to support such an ambitious goal. Also, by definition, a solar sail-based sunshade does not directly tamper with Earth's ecological systems; it can be turned off quickly, e.g., in the case of a major climate-cooling volcanic eruption; and the side effects of launching space hardware are understood and can be significantly optimized. If catastrophic climate change becomes unavoidable, the costs of building a planetary sunshade may be significantly less than the costs of inaction. It would be prudent to carry out research in conjunction with continuous ethical assessments of such technologies, including the possibility of there being a moral hazard and how to respond to it. The development of the key technologies and flight operations of solar sailing is already well under way, and it is imperative that world leaders have as much information as possible about this approach as critical decision points draw rapidly near. This paper will describe the concept, possible implementation approaches, and an assessment of the readiness of a planetary sunshade.

References

[1] A. Jehl, E. Scott, and R. Centers. A planetary sunshade built from space resources. ASCEND 2020. 2020. 4077.

[2] C. R. McInnes, V. Bothmer, B. Dachwald, et al., Gossamer Roadmap Technology Reference Study for a Sub-L 1 Space Weather Mission. Advances in Solar Sailing (2014): 227-242.

A New Model for the Planetary Radiation Pressure Acceleration for Optical Solar Sails

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Solar sailing is a propellantless propulsion method that exploits solar radiation pressure to generate thrust. In recent years, several solar sails have been successfully launched to demonstrate this technology's potential for both Earth-bound and interplanetary missions. In addition, several other missions are planned for the near future, including NASA's ACS3 and Gamma's Gama Beta missions to be launched in 2023 and 2024, respectively. The majority of sailcraft have flown (or will fly) in close proximity of the Earth, where planetary radiation pressure can reach significant levels of intensity, even comparable to that of solar radiation pressure. As a consequence, planetary radiation pressure cannot automatically be neglected in near-Earth solar-sail mission design studies. Nevertheless, the effect of planetary radiation pressure on the solar-sail dynamics has been investigated only to a very limited, first-order extent, and every study considered an "ideal" sail model, that is, the sail was assumed to be perfectly reflecting. While employing the ideal sail model is useful for preliminary orbital analyses of solar-sail missions, its limited fidelity prevents more in-depth research into the near-Earth solar-sail dynamics, orbit control, and trajectory optimization. In light of this, this paper provides a new planetary radiation pressure acceleration model particular for optical solar sails. This model is an extension of the "spherical" planetary radiation pressure acceleration model for ideal solar sails devised by Carzana in Reference [1]. In the current paper, the underlying assumptions and full derivation of the newly devised optical model are presented. Then, the accuracy of the optical model compared to the ideal model is analyzed and discussed. Finally, the effect of planetary radiation pressure on the maneuvering capabilities of solar sails in low-Earth orbit is investigated, using NASA's ACS3 mission as real-case, reference scenario.

References

[1] L. Carzana, P. Visser, J. Heiligers, A New Model for the Planetary Radiation Pressure Acceleration for Solar Sails, in 2022 AAS/AIAA Astrodynamics Specialist Conference [AAS 22-715] (2022).

Factoring Force Uncertainty into Solar Sail Mission Planning

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In the early 2000s, NASA's In-Space Propulsion (ISP) program at the Marshall Space Flight Center (MSFC) conducted significant development of solar sail technology, resulting in the fabrication and vacuum deployment testing of two different 20-meter size sail configurations. In addition to this system development, ISP supported two different efforts to develop solar sail simulation software packages to model sailcraft characteristics and performance to allow better solar sail mission planning. This author leveraged one of these packages to complete a PhD dissertation [1] focused on identifying and estimating factors that may detract from the expected performance of a "perfect" solar sail. Major dissertation results were summarized in a presentation at the 2010 ISSS conference [2].

This paper (and ISSS 2023 presentation) will summarize these "realistic" solar sail performance factors, and demonstrate how these should be incorporated into future solar sail mission planning. Recommendations on operations to characterize the actual performance of a solar sail propulsion system, either for a demonstration or operational mission, will also be described. In addition, recommendations for pursuing potentially more palatable initial solar sail missions are also provided.

References

[1] Campbell, Bruce A, An Analysis of Thrust of a Realistic Solar Sail with Focus on a Flight Validation Mission in a Geocentric Orbit, ProQuest Dissertations Publishing, 2010. (http://gateway.proquest.com/openurl?url_ver=Z39.88-2004&res_dat=xri:pqdiss&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&rft_dat=xri:pqdiss:3407845)

[2] Campbell, Bruce A, Description of a Realistic Solar Sail and Comparison to an Ideal Sail, (Presentation, 2010 ISSS, Brooklyn, NY).

Space Environmental Damage Assessment on Sail/Deorbit Materials in Low Earth Orbit

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NASA researchers are developing structural systems for future small spacecraft solar sailing projects, such as the Advanced Composite Solar Sail (ACS3) mission [1]. ACS3 will demonstrate a solar sail using different materials in a 1000-km-altitude low Earth orbit (LEO) in late 2023. For the ACS3 mission, several candidate metallized thin film polymer membrane materials and composite laminate materials were evaluated for the solar sail. Simulated space environment tests for many of these materials have been performed using ultraviolet (UV), electron, and proton radiation in ground-based laboratories [2,3]. However, there has been limited information on the lifetime and durability of these materials under the combined effects present in a space environment. During the period of 2019 to 2021, space environmental effects on these materials were evaluated on the International Space Station (ISS) as part of the two Materials International Space Station Experiment (MISSE) 10 and 14 projects. For this experiment, ACS3 solar sail membrane materials and composite boom laminate samples were exposed to the space environment outside of the ISS (vacuum, UV, atomic oxygen, solar particle events, etc.). Duration times on MISSE 10 and 14 were 1.2 year and 0.4 year, respectively. The samples were returned to Earth for post-flight analysis. Pre- and post-flight material properties including morphological, optical, and thermal properties, were evaluated to assess the effects of space environmental exposure on the samples. Results from these tests will be presented in this paper. Although the space environment of the ISS is different from that in deep-space, the current results should be applicable to designing solar sails or deorbiting drag sails for future Earth-centered space missions.

References

[1] W. K. Wilkie, et al., Overview of the NASA Advanced Composite Solar Sail System (ACS3) Technology Demonstration Project, AIAA Scitech Forum, AIAA 2021-1260, Virtual, January 2021.
[2] J. H. Kang, et al., Simulated Space Environment Effects on a Candidate Solar Sail Material, NASA/TP-2017-219644.
[3] M. Sznajder, et al., Solar Sail Propulsion Limitations due to Hydrogen Blistering, Advances in Space Research, 67 (2021), 2655.

Solar Sail Propulsion Limitations Due to Hydrogen Blistering: Progression of Reflectance Decrease

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Context: Solar sails are an advancing technology for transportation in interplanetary space. The sail membranes generally are metallized thin films. During their lifetime the functional surfaces are exposed to various types of radiation, among them the low energy solar wind (SW) protons.

In Sznajder et al. 2020 [1], it was investigated what influence the recombination processes of SW protons with metal electrons has on the thermo-optical properties of the sail membrane. The results indicated a harsh degradation after only few days of exposure to the interplanetary solar wind environment depending on the surface temperature.

Aims: In view of the drastic degradation observed due to proton irradiation, it is the aim of this work to understand the development of the specular reflectance over the accumulated fluence. Furthermore, this data is mapped to certain mission scenarios, so that an understanding of the process with its change of specular reflectance over mission time is gained.

Methods: Reflectance and temperature over fluence data has been further evaluated to gain knowledge on the processes during irradiation. Therefore, time-lapse pictures of the radiation tests were analysed. In particular, the brightness of pixels and its change from picture to picture were evaluated. This data was combined with spectrometric measurements taken before and after the test such that a progression over time or fluence, respectively, could be derived.

Results: Improved evaluation of previously presented experiments are given. The progression of the specular reflectance over fluence and mission time is derived. The analyses allow a more accurate assessment of the performance of solar sails in dependence of the mission fluence for future missions.

References

[1] Sznajder, M.; Seefeldt, P.; Spröwitz, T.; Renger, T.; Kang, J. H.; Bryant, R.; Wilkie, W. (2020): Solar sail propulsion limitations due to hydrogen blistering. In: *Advances in Space Research*.

A Reduced-Order Model for the Dynamics of a Flexible Solar Sail

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Solar sail (or solarcraft) is a spacecraft with a large reflective surface that is propelled by sunlight reflecting off of the surface. Since the force generated per unit area of the surface (solar radiation pressure) is extremely small, the surface must be sufficiently large to generate the amount of force needed to propel the solarcraft. Also, to reach high accelerations, the solarcraft must have small structural mass. Hence, having a large structure with low structural mass, and low stiffness as a result, simply indicates that solarcraft tends to be very flexible and that its dynamics for the rigid body and the elastic motions are highly coupled. The motions are also coupled through the solar radiation pressure and the gravitational forces. Hence, our objective in this paper is the derivation of a comprehensive mathematical model of a flexible solarcraft, which accounts for effects of rigid body and elastic motions, as well as their interactions.

We model a square solar sail as a flexible multibody system subject to solar radiation pressure and gravitational forces where the bodies are a reflective sail film, four booms that support it, four control vanes and a hub housing the payload. The equations of motion are derived by means of Lagrange's equations of motion in quasi-coordinates, which require the knowledge of only kinetic and potential energies, and virtual work of external forces. The resulting system of equations are a set of six ODEs for the rigid body translations and rotations, and a PDE for the elastic motion of the flexible body. The PDE is discretized by the finite elements method (FEM) and replaced by a set of ODEs governing the nodal displacements. The whole system of equations then becomes a set of nonlinear ODEs of relatively high dimension. The system is cast in a first-order (or state-space) form, since it is the preferred form of many numerical solution, stability analysis, and control design methods.

The problem with the nonlinearity is obviated by employing a perturbation solution, which divides the dynamics of the solarcraft into a *zero-order system* for the nominal dynamics and a *first-order system* for the perturbation about nominal dynamics. The zero-order system is used to compute an open-loop control input for a desired maneuver. The first-order system, on the other hand, is used for assessing stability about the desired maneuver and for designing feedback control if improvements in stability is needed. The problem with the high-dimensionality is obviated by a model reduction method that transfers the original system to a reduced-order system that retains the major dynamical characteristics of the system. To that end, the elastic nodal displacements are expressed in terms of a desired number of free vibration modes of the unconstrained (free-free) solarcraft. The numerical results are given in terms of open-loop controls for circular orbits around the Sun, stability analysis about these orbits, and simulation of the response of the solarcraft to some control vane angles using the nonlinear reduced-order model.

Adaptive Terminal Sliding Mode Control for Asteroid Hovering by Solar Sailing: Application to 433 Eros

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Asteroid exploration not only helps to reveal the origin of solar system, but it also assists significantly with space resource exploitation and planetary defense. Since transfers to asteroids usually require high delta-v budgets, solar sailing is an ideal option as it is capable of providing theoretically-unlimited delta-v. Extensive research has investigated the use of solar sails for asteroid rendezvous missions [1-3], while little effort has been made on the operations of a solar sail in close proximity of an asteroid [4, 5]. In order to maximize the scientific return of the mission, asteroid close-proximity operations will be essential, including hovering. Hovering is the station-keeping of the sail-craft above the asteroid, which can be used for high-resolution imaging [6], landing [7], deployment of landers such as MASCOT [8] and gravity field mapping amongst others. Apart from spacecraft with three-axis impulse or continuous thrusters, the literature mainly discusses asteroid hovering using solar sails with an adjustable lightness number [9, 10]. Such hovering is accurate in position but is limited within certain regions, and it also significantly increases the cost and system complexity. This paper aims at achieving asteroid-hovering with a simple solar sail without reflectivity control devices (RCDs), and hence with lower complexity and cost.

There are three major challenges in the control of solar sail asteroid hovering. Firstly, differently from spacecraft with three-axis thrust, a conventional sail-craft only has two controllable attitude angles for orbit control, resulting in an acceleration vector that is constrained in both direction and magnitude. Thus, it is challenging or impossible to track orbits in three dimensions; this is indeed typical of an underactuated system. No doubt a variable lightness number can be implemented so that a third control variable makes the control complete; however, a two-input control may still be needed as backup given the reliability of RCDs. Secondly, the input sail attitude angles affect its dynamics via trigonometric terms, in other words, the control is not linear but non-affine. An additional complexity is that the gravity field of an asteroid cannot be precisely known prior to a mission, adding uncertainty and disturbances to the control problem.

The solution proposed in this paper is an adaptive terminal sliding mode control law. By converting the dynamics from Cartesian to cylindrical coordinates, the desired displaced orbit radius and hovering height are tracked regardless of polar angle, which transforms the underactuated system into a fully-actuated one. By differentiating the dynamics, the first-order derivatives of the sail attitude angles appear in linear form and are therefore chosen as the control input so that the non-affine issue can be solved. Moreover, an estimation law is designed to update the upper bound of disturbances, making the control robust to the complex gravity field of an asteroid. The case of hovering on a displaced orbit above 433 Eros is simulated. The results successfully demonstrate that it is feasible to achieve an asteroid-hovering mission using a solar sail with only two controllable attitude angles.

References

[1] Zeng, X., S. Gong, and J. Li, *Fast solar sail rendezvous mission to near Earth asteroids.* Acta Astronautica, 2014. **105**(1): p. 40-56.

[2] Dachwald, B., W. Seboldt, and L. Richter, *Multiple rendezvous and sample return missions to near-Earth objects using solar sailcraft.* Acta Astronautica, 2006. **59**(8-11): p. 768-776.

[3] Peloni, A. and M. Ceriotti, *Solar-Sail Trajectory Design for a Multiple Near-Earth-Asteroid Rendezvous Mission.* Journal of Guidance, Control, and Dynamics 2016. **39(12)**.

[4] Moore, I. and M. Ceriotti, *Solar sails for perturbation relief: Application to asteroids.* Advances in Space Research, 2021. **67**(9): p. 3027-3044.

[5] Morrow, E., D.J. Scheeres, and D. Lubin, *Solar Sail Orbit Operations at Asteroids.* Journal of Spacecraft and Rockets, 2001. **38**(2): p. 279-286.

[6] Guelman, M.M., *Closed-loop control for global coverage and equatorial hovering about an asteroid.* Acta Astronautica, 2017. **137**: p. 353-361.

[7] Yang, H., X. Bai, and H. Baoyin, *Finite-time control for asteroid hovering and landing via terminal sliding-mode guidance.* Acta Astronautica, 2017. **132**: p. 78-89.

[8] Moore, I., M. Ceriotti, and C.R. McInnes, *Station-keeping for a solar sail during lander/probe deployment using feedback control.* Acta Astronautica, 2022. **201**: p. 182-197.

[9] Zeng, X., et al., *Solar Sail Body-Fixed Hovering over Elongated Asteroids.* Journal of Guidance, Control, and Dynamics, 2016. **39**(6): p. 1223-1231.

[10] D'Ambrosio, A., C. Circi, and X. Zeng, *Solar-photon sail hovering orbits about single and binary asteroids.* Advances in Space Research, 2019. **63**(11): p. 3691-3705.

Development of Gram-Scale Flight Computers for Free-Flying Light Sail Demonstration in LEO

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Cornell University's Alpha CubeSat mission seeks to demonstrate the deployment of a free-flying light sail in LEO [1]. The novel sail architecture, 57.5cm x 57.5cm in area and 175μm thick, carries four gram-scale spacecraft known as "ChipSats." The sail deploys via a nitinol wire cross frame, fully separating from the CubeSat, and expands from its origami Miura fold stowage configuration. Without the CubeSat's avionics, the ChipSats mounted to the four corners of the light sail are the sole source of sail telemetry. Current-generation ChipSats for the Alpha mission collect data on the sail's orbital position and attitude kinematics, while future generations of these probes shall steer the sail through modulation of the retroreflective sail material. Each ChipSat weighs on the order of three grams and is a single flexible thin circuit board spanning an area less than 6cm^2. All the components for power, data acquisition and processing, and radio communications fit on this singular spacecraft-on-a-chip form factor.

The presented work highlights the design motivations for and the hardware development of the ChipSat that will fly on the Alpha light sail. The main hurdle that this generation of femtosatellites seeks to overcome is end-to-end communications with a distributed network of low-cost ground stations. This objective was shared with the KickSat missions, during which larger dish antennas instead proved essential to detect the low-power ChipSat signals. Due to the low altitude of the CubeSat's orbit (400km), the sail, once deployed, shall deorbit extremely quickly. Multiple passes over primary ground stations are not guaranteed, making a globally distributed ground network more critical for the Alpha mission profile.

Taking advantage of recent advances in low-power radio communications, the Alpha ChipSat employs Semtech's LoRa protocol. LoRa (short for "long range") is based on spread spectrum modulation up to 500kHz in bandwidth and transmits at an output power of up to 100mW on current hardware implementations. A growing number a nanosatellites with LoRa communications have now launched and in parallel thousands of LoRa ground stations have sprouted around the world, organized through a network known as TinyGS. The developing infrastructure is well-suited to gather telemetry from the Alpha sail.

The Alpha mission will be the first to launch with LoRa implemented on the ChipSat form factor. This work presents the key milestones behind the design, prototyping, and testing of this current-generation ChipSat, with particular attention to RF communication. Major events in the development cycle include antenna selection, optimization, and tuning, as well as sail integration and range-testing via high altitude balloon (HAB) launches. Results from both lab and field testing are discussed. The Alpha mission aims to launch via the NASA CubeSat launch initiative in early 2024.

References

[1] Umansky-Castro et al. "Design of the Alpha CubeSat: Technology Demonstration of a ChipSat-Equipped Retroreflective Light Sail," AIAA SciTech 2021 Forum, January 2021.

Constellation Around Small Bodies Using Spinning Solar Sails Under Simultaneous Orbit-Attitude-Structure Control

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Orbital motion of solar sails is controlled by steering the orientation of the sail relative to the sun. Because solar radiation pressure (SRP) not only gives thrust for orbit control but also disturbs attitude motion, coupled orbit-attitude control takes a significant role in solar sailing. To date, various methods for solar sail attitude control have been proposed. Many of them manipulate the center-of-mass and/or center-of-pressure locations, using internal actuators, to control the SRP disturbance. Such methods are usually specific to solar sails deployed and supported by booms. Spinning solar sails are another type of solar sails in which the sails are deployed using centrifugal force without booms. They can keep sun-pointing attitude automatically because of gyroscopic inertia, but maintaining a specific sun-relative attitude for constant acceleration is difficult. Some methods are needed to control the motion of spinning solar sails.

To solve this issue, Takao et al. [1] proposed an active shape control method for spinning solar sails for application to coupled orbit-attitude control. In this method, the sail membrane is vibrated in synchronization with the spin, resulting in a three-dimensional waveform (i.e., deformation) that stands still in the inertial space. Active deformation of the solar sail allows for simultaneous control of thrust and torque caused by SRP. It was demonstrated that an interplanetary flight was possible using internal actuation only.

In this study, we propose a new application of spinning solar sails under active shape control. In the Hayabusa2 mission, which successfully completed sample return from the asteroid Ryugu in 2020, deployable payloads such as artificial markers and surface landers played an important role in exploring the asteroid. The present study proposes a new deployable payload that has an autonomous flying ability using a solar sail. Similarly to the orbiting experiment of deployable payloads in the Hayabusa2 mission [2], multiple solar sails are inserted in a periodic orbit around the small body. Each solar sail changes its orbit, forming a constellation around the small body. The solar sails have planar antennas that allow for orbit determination through communication among other individuals and the mother spacecraft. The constellation in low-altitude orbits makes it possible to perform high-resolution global mapping. Intercommunication can support the guidance, control, and navigation of the mother spacecraft to perform critical operations such as descent, landing, and sampling.

References

[1] Y. Takao, O. Mori, J. Kawaguchi, Optimal Interplanetary Trajectories for Spinning Solar Sails Under Sail-Shape Control, Journal of Guidance, Control, and Dynamics, **42.11** (2019) 2541–2549.

[2] Y. Oki, K. Yoshikawa, Y. Takei, H. Takeuchi, H. Ikeda, S. Kikuchi, N. Ogawa, T. Saiki, Y. Tsuda, M. Yamada, T. Kouyama, S. Kameda, Orbiting Experiment of Artificial Objects Deployed from Hayabusa2, Hayabusa2 Asteroid Sample Return Mission, Chap. 16 (2022) 313–340.

Uncertainty Quantification for Solar Sails in the Near-Earth Environment

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Solar sailing is a propellantless propulsion method taking advantage of solar radiation pressure to generate thrust. In the last decade, an increasing number of solar sails have been launched, especially in close proximity to the Earth, where the dynamical environment is highly perturbed and nonlinear. In the literature, these solar-sail dynamics have been studied using different dynamical models, varying in complexity and fidelity, but all deterministic in nature. As a consequence, these models cannot be used to analyze how uncertainties in the system dynamics affect the motion of solar sails. Some of these uncertainties are related to environmental factors, such as the uncertainties in the solar and planetary radiation fluxes and the Earth's atmospheric properties. In addition, uncertainties in the solar-sail state, attitude, and optical and aerodynamic properties can also be present. These uncertainties can strongly affect the solar-sail performance and, therefore, they should be taken into account for mission design purposes. Nevertheless, a very limited amount of research has been conducted in the literature to quantify the effect of these uncertainties, particularly for solar sails in Earth-bound orbits. This paper aims to bridge this gap of knowledge by presenting effective methods to propagate these uncertainties. In particular, the uncertainties in the solar-sail optical coefficients, deformation, injection state, and attitude control are considered, To propagate the uncertainties in the optical coefficient, sail deformation, and injection state, the Gauss von Mises distribution-based uncertainty propagation method by Horwood and Poore is employed [1]. This technique achieves uncertainty realism at a fraction of the computational cost of Monte Carlo simulations and for much longer propagation times than other sigma-point methods. The propagation of the sailcraft state with uncertainty on the solar-sail attitude control is performed by integrating the stochastic differential equations of the dynamics and modeling the deviation of the control angles from their nominal profiles as a random Ornstein-Uhlenbeck process [2]. This novel approach has never been used before and can simulate a noisy control profile similar to those found in past sailcraft missions. The methodology adopted in this paper allows one to quantify the impact of uncertainties on the final state of the sailcraft, identify possible coupling effects, and provide novel insights into their effect on the Earth-bound solar-sail dynamics.

References

[1] Joshua T. Horwood and Aubrey B. Poore. Gauss von Mises distribution for improved uncertainty realism in space situational awareness. In: SIAM-ASA Journal on Uncertainty Quantification 2.1 (2014), pp. 276–304. ISSN: 21662525. DOI: 10.1137/130917296.

[2] G. E. Uhlenbeck and L. S. Ornstein. On the Theory of the Brownian Motion". Phys. Rev. 36, 823, 1930.

The ADEO Space Sail Products

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Over the last 10 years, several space sail technologies have been industrialized based on previous developments from ESA and DLR research projects together with HPS GmbH [1, 2, 3, 4]. The result is the ADEO product family [6] consisting of three different space sails, varying in size and application. An overview of the different sails is provided and their performance is described.

The aim of the ADEO products is to provide commercially available sails for different customer needs. Therefore, the products are available in different sizes, Nano (N), Medium (M) and Large (L). While the smaller ADEO-N and ADEO-M sails are primarily designed to provide a drag sail for de-orbitation, the larger sail utilizes technology originally developed for solar sails and therefore also covers this application.

Different technologies are used for the different sizes and applications. While the smaller sails use metal tapes and Storable Tubular Extendable Members (STEMs), the larger sail uses Carbon Reinforced Fiber Polymer (CFRP) booms. The sails also differ in the stowing and deployment techniques used, as well as the hold down and release mechanisms. Ongoing developments for the sail membrane focusing on non-reflective atomic oxygen robust materials and designs for drag sails. In the first designs and for solar sails aluminized polyimides are used.

Already available on the commercial market, ADEO sails are fully qualified, lightweight, small and cost-effective drag augmentation subsystems. With ESA's Zero Debris Approach, as well as the European Commission's Green Deal and Space Traffic Management, new requirements are emerging for all spacecraft to be deorbited within 5 years, with increasing reliability of up to 99% [7, 8]. The scalable technology used specifically for ADEO-L also allows for more ambitious future missions in the field of solar sailing.

References

[1] P. Seefeldt, P. Spiez, T. Spröwitz, et al., Gossamer-1: Mission Concept and Technology for a Controlled Deployment of Gossamer Spacecraft, Advances in Space Research 59.1 (2017): 434-456
[2] M. Leipold, C.E. Garner, R. Freeland, et al. ODISSEE, A proposal for demonstration of a solar sail in earth orbit, Acta Astronautica 1999 45/4, 557-566
[3] D. Agnolon, Study overview of a solar sail demonstrator: GEOSAIL, DLR/ESA, 2008.

[4] T. Sinn, P. Seefeldt, et al., Design, Analysis and Testing of the ADEO Passive De-Orbit Subsystem Demonstrator, European Conference on Spacecraft Structures Materials and Environmental Testing, 2016
[5] M. Leipold, M. Eiden, C.E. Garner, et al., Solar sail technology development and demonstration, Acta Astronautica 52/2, 317-326, 2003
[6] D. Stelzl, E.K. Pfeiffer, H.G. Hemme, et al., ADEO - The European Commercial Passive De-Orbit Subsystem Family Enabling Space Debris Mitigation: CEAS Space Journal 2021, volume 13 (issue 4), 591-598
[7] NN, IAA Position Paper Space Debris Mitigation, ESA SP-1301, ESA, ISBN 92-9092-445-4, 2004
[8] Space Debris Mitigation Policy for Agency Projects (ESA/ADMIN/IPOL(2014)2)

A New Tethered Sail Architecture: the Solar Kite

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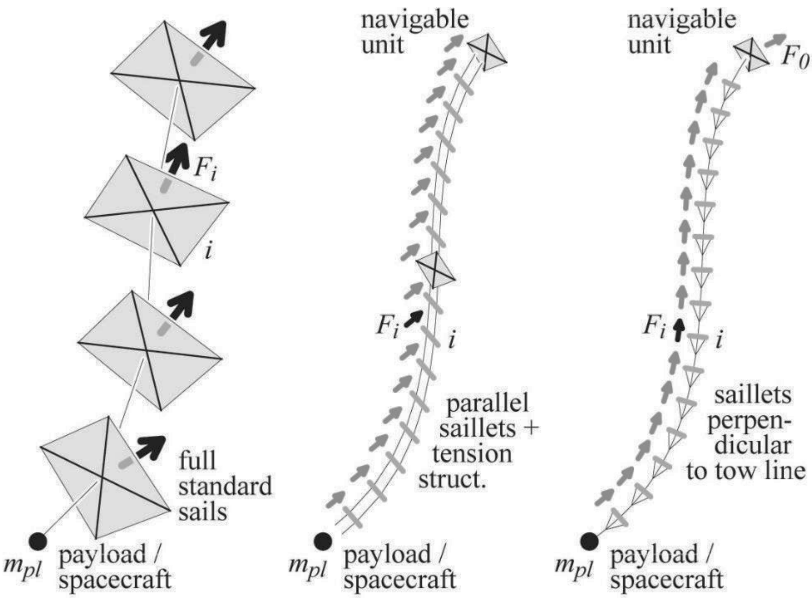
The *solar kite* photonic sail is proposed for interplanetary cargo with the compelling simplicity, modularity, and low-risk development path of the *space tow* but without critical control and navigational issues. Namely, minimalist passive film panels are hung with filament harnesses from a *tow line* such that they remain locally perpendicular to the latter – except for the first panel which can navigate, turning the leading end in a new direction. Such a re-orientation of the far end then automatically initiates the progressive and self-propelled re-alignment of the whole, modifying the global thrust vector as desired. The residual dynamics need not be eliminated because it is stable and it does not adversely affect cargo missions. The design is fit for both light or heavy payloads, without the mass overheads of classic sail designs and without the bottlenecks of the earlier tethered sail concepts: the *space liner* [1] and the *space tow* [2-4].



(a) Space liner (Lukyanov, 1982); (b) Space tow (Greschik, 2006);
(c) Solar kite (here proposed).
Fig. 1. Tethered solar sail concepts.

Practicable engineering solutions are outlined for the system as well as its elements: the saillets, their suspension, the lead sail, and the means of its navigation. Characteristic acceleration (thrust efficiency) is shown to potentially approach the (practically unattainable) “net film sail” ideal. A tow line with 2D redundancy provides configuration stability and safety against cable severance.

References

[1] A. V. Lukyanov, *Spase sail liner*, Acta Astronautica **9** (1982) 359-364.
[2] G. Greschik, *Solar sail scalability and a “truly scalable” architecture: the space tow*, J of Spacecraft and Rockets **44** (2007) 831-839,
[3] G. Greschik, *Some structural, mission performance, and navigational features of the space tow*, ISSS’07 – The 1st Intl. Symposium on Solar Sailing, Herrsching at Lake Ammersee, Germany, June 27-29, 2007.
[4] G. Greschik, *Pitch slew simulation for a tow of 25 m square sails*, AIAA 2008-2207.

Design and Analysis of a Quasi-Rhombic Pyramid Drag Sail for Passive Attitude Control and De-Orbit of OirthirSAT

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The proliferation of space debris poses an undeniable threat to the continuation of human activity in space, with even millimetre-sized pieces of debris being capable of severely impairing the function of satellites. This monumental rise in space debris objects is predicted to continue accelerating and is being fueled by the relatively recent advent of so-called nanosatellites [1]. Traditional satellites are generally equipped with bespoke hardware (such as propulsion systems) that facilitate the timely de-orbit of the platform at the end of its useful mission life. For nanosatellite missions, where the minimisation of cost and complexity is of utmost concern, such systems are not always feasible. This is particularly true for researchers, student teams, and SMEs, which heavily rely on the accessibility of nanosatellite technology. Consequently, there is a need for low-cost alternative technology that can be easily integrated to support the sustainability of nanosatellite missions. Such technology would help to ensure that nanosatellite missions are compliant with clean space standards while reducing the development burden on small teams. Due to the recent abundance of missions of this scale, the overall impact on the sustainability of the space environment would be significant.

This paper presents the detailed mechanical design of a novel quasi-rhombic pyramid (QRP) drag sail for use on 3U CubeSats alongside relevant analysis to assess its performance. The mission overview of the student-led OirthirSAT programme is discussed as a de-orbit demonstrator case. OirthirSAT is a 3U Earth observation mission which has secured £600,000 of UK Space Agency funding to provide rapidly streamlined data on the UK's ever-changing coastline using efficient onboard processing routines [2]. As a secondary payload, the drag sail will facilitate the timely de-orbit of OirthirSAT, while also providing valuable flight heritage for this emerging space sustainability technology. A design suitable for use on 3U CubeSat structures is presented that is also able to provide some level of passive aerodynamic stability, thus ensuring maximum drag augmentation and a stable de-orbit trajectory during the disposal phase. A comparison to existing methods for de-orbiting nanosatellites is presented before the design of the drag sail is detailed. The extensive requirements of a real-world nanosatellite mission, such as OirthirSAT, provide both tangible and practical justification for decisions made throughout the design process.

References

[1] National Science and Technology Council, 2021. "National Orbital Debris Research and Development Plan", p.2.

[2] F. Muir, J. Gibbs, N. Chari, G. Titas, "Mapping Coastal Dynamism from Space: A Small Satellite Application for the Onboard Automatic Extraction of Coastal Boundaries", *73rd International Astronautical Congress, Paris, France*, 18-22 September, 2022.

Optimal Deep-Space Heliocentric Transfers with an Electric Sail and an Electric Thruster

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In its originally proposed configuration, an electric solar wind sail (E-sail) consists of a grid of charged tethers kept at a high positive voltage that interact with the solar wind ions to generate a propulsive acceleration [1]. However, due to the difficulty of deploying a huge tether structure in deep space, recent works suggest that near-term E-sail missions should involve small satellites with a limited number of spinning tethers that generate thrust [2]. Accordingly, the resulting magnitude of the propulsive acceleration is small, and a recent E-sail thrust model suggests that the thrust vector is constrained within a cone with half-angle lesser than 20 degrees centered along the radial direction [3].

A possible strategy to overcome the aforementioned issues consists in equipping the spacecraft with a small number of charged tethers and a high-specific impulse electric thruster. This strategy resembles the hybrid sail concept, in which a solar sail and an electric thruster are combined. Hybrid sails have been deeply investigated, ultimately leading to the design of a *solar power sail* to propel JAXA's OKEANOS mission (eventually not financed) towards a Jupiter Trojan asteroid. Like the hybrid sail concept, the combination of an E-sail and an electric thruster could significantly increase their effectiveness.

This work focuses on deep-space heliocentric transfers performed by a small spacecraft equipped with an electric sail composed of a limited number of tethers and an electric thruster. The power available for the electric thruster is assumed to be provided by solar panels only, and, as such, to scale with the inverse square heliocentric distance. A recent and accurate model [3] is used to describe the E-sail thrust contribution as a function of the tether spin plane attitude and the Sun-spacecraft distance. Orbital transfers are analyzed within an optimal framework, in which a suitable performance index (such as the flight time, the propellant consumption, or a combination of both) is minimized. The solution of the optimal control problem makes use of an indirect multiple shooting method and is based on the Pontragyn's maximum principle. In the general case, the control variables are the E-sail spin plane attitude, the direction of the thrust generated by the electric engine, and the amount of available power supplied to the thruster. Different test-case numerical simulations are performed, also considering cases in which the E-sail passively maintains a Sun-facing attitude. The typical transfer times are compared with those obtained with an E-sail alone, to quantify the advantage of the combination with an electric thruster.

References

[1] P. Janhunen, Electric sail for spacecraft propulsion, Journal of Propulsion and Power **20** (2004) 763–764.

[2] A. Slavinskis, P. Janhunen, P. Toivanen, K. Muinonen, A. Penttilä, M. Granvik, T. Kohout, M. Gritsevich, M. Pajusalu, I. Sunter, H. Ehrpais, J. Dalbins, Nanospacecraft fleet for multi-asteroid touring with electric solar wind sails, 39th IEEE Aerospace Conference, Big Sky (MT), USA, 2018, **3 – 10 March.**

[3] M. Huo, G. Mengali, A.A. Quarta, Electric sail thrust model from a geometrical perspective, Journal of Guidance, Control, and Dynamics **41** (2018), 734–740.

[4] G. Mengali, A.A. Quarta, Tradeoff performance of hybrid low-thrust propulsion system, Journal of Spacecraft and Rockets **44** (2007), 1263–1270.

Notes