Pushing the Limits of In-Situ-Resource-Utilisation for In-Orbit Activities: Solar for Ice to Thrust - S4I2T

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***Abstract*— The increasing number of satellite launches, the rise of In-Orbit Servicing (IOS), and the necessity for Active Debris Removal (ADR) services require long-term, reliable, affordable, and scalable solutions for in-space mobility. Utilizing solar energy and space resources offers the potential to create a renewable and self-sustaining mobility infrastructure, providing significant benefits for European satellite owners and enhancing the strategic autonomy of the European Union. Consequently, it is crucial to identify and develop innovative Solar Electric Propulsion (SEP) systems that can effectively use advances in Solar Energy Harvesting (SEH) to reduce propellant and spacecraft mass, enhance in-space mobility, and thus lower costs. At the same time, these propulsion systems must be environmentally friendly and overcome the challenges associated with using in-space solar energy harvesting for innovative propulsion.**

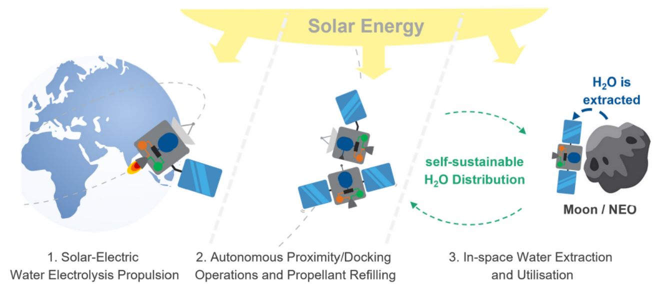

Fig. 1. S4I2T-Vision of self-staining mobility enabled by solar energy harvesting and water as propellant

I. Introduction

S4I2T aims to develop an innovative solar electric water propulsion system that is cost-effective, eco-friendly, and superior to traditional solutions. To maximize launch mass savings and extend satellite lifespans, we plan to use water as a propellant, enabling autonomous spacecraft docking and refueling. This approach seeks to enhance the economic and environmental sustainability of spacecraft operations and facilitate in-orbit servicing, robotics, and in-space manufacturing. Additionally, we intend to integrate this with In-Situ Resource Utilization (ISRU) technology for extracting water from the regolith of various solar system bodies, laying the groundwork for a self-sustaining circular economy in space and unlocking new economic opportunities.

To achieve versatile and sustainable in-space mobility solutions, two fundamental components are necessary: an energy source and a reaction mass (i.e., propellant). The principal challenge in employing solar-harvested energy for propulsion lies in the astute selection of an appropriate propellant. We contend that water is the ideal propellant candidate, and thus, it is central to the three technological elements we aim to investigate and develop in our proposed project.

- **Solar-Electric Water Electrolysis Propulsion:** Utilizing water as a propellant offers environmentally friendly, cost-effective advantages, ensuring European autonomy. In our proposed innovative Water Electrolysis Propulsion (WEP) system, it has the potential to surpass even the most advanced chemical propulsion systems currently available for in-space applications. Within the WEP system, an electrolyzer functions during flight to decompose water into gaseous oxygen and hydrogen, which are then utilized in a thruster to propel the spacecraft. The integration of water, hydrogen (H_2), and oxygen (O_2) as propellants facilitates the establishment of a unified propellant supply system capable of servicing hot-gas, cold-gas, and electrical thrusters, catering to diverse propulsion requirements across missions and spacecraft scales. Furthermore, this system can effectively leverage both thermal and electrical energy harvested from solar sources, either locally on the spacecraft itself or through distribution via a SEH network.
- **Autonomous Proximity/Docking Operations and Propellant Refilling:** Water presents a straightforward solution for spacecraft refueling in orbit, as it involves the transfer of a single non-reactive liquid, simplifying the establishment of a reliable fluid connection compared to high-pressure gases like Xenon or Krypton. Refueling satellites in space offers the opportunity to decrease launch masses and extend satellite lifespans, thereby enhancing the economic or scientific utility of the satellite. When combined with our proposed autonomous proximity and docking technology, this approach facilitates dependable and large-scale IOS and ADR services, and on-orbit spacecraft assembly.
- **In-Space Water Extraction and Utilisation:** Moreover, water stands out as one of the most readily accessible and abundant substances on other celestial bodies within the solar system, such as the Moon or Near-Earth Objects (NEOs), achievable through thermal extraction methods at relatively low temperatures. The corresponding technology for extracting water stands to benefit significantly from advancements in solar energy harvesting. When integrated with WEP and docking and

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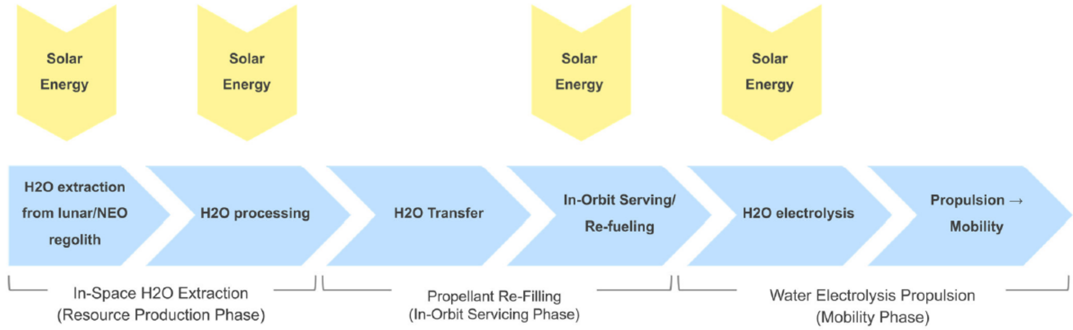

Fig. 2. S4I2T chain of processes relying on solar energy

refilling operations, this presents the potential for a fully self-sustainable space mobility framework. Water extracted from the icy regolith can be utilized to replenish satellites, subsequently serving the propulsion needs of the WEP system.

S4I2T seeks to elevate these three foundational technologies to lay the groundwork for a self-sufficient space mobility infrastructure. To achieve this goal, the project endeavors to outline a feasible pathway for implementing an economically and technologically sound architecture. Additionally, it aims to validate the necessary critical technologies through laboratory testing. The objectives established for S4I2T and aligned with this pathway are outlined as follows:

- **Providing a comprehensive idea, a plan for execution, and a strategy for commercialization of a sustainable space mobility infrastructure independent of Earth:** This objective seeks to guarantee the pertinence of the research and development efforts while maximizing their impact, extending beyond the Pathfinder Challenge. The goal is to ensure the availability of innovative green water propulsion systems in the European market by the end of the decade. Trade-off studies will delineate technological choices and pathways for economically feasible implementation of the proposed infrastructure, thereby unlocking new economic opportunities while ensuring scalability and growth potential, particularly in conjunction with solar energy harvesting.
- **Laboratory validation of the inaugural environmentally friendly, storable propulsion system surpassing traditional systems:** Research, development, and demonstration of a WEP system will be undertaken, aiming to markedly surpass conventional and alternative green chemical propulsion systems in specific impulse, thereby significantly enhancing in-space mobility. This advancement, powered by solar-harvested energy, addresses a major obstacle in transitioning to environmentally friendly and cost-effective propellants.
- **Validation of autonomous docking and propellant refilling procedures using hardware-in-the-loop (HIL) testing:** The crucial ability to autonomously dock and refill spacecraft using water propulsion will be showcased in a laboratory environment that emulates zero gravity [1]–[3]. This demonstration will validate the viability and straightforwardness of water-based space mobility, thereby mitigating risks associated with commercial initiatives for IOS and in-space robotics.
- **Showcasing the first-ever global demonstration of an end-to-end In-Situ Resource Utilization (ISRU) technology chain under realistic conditions:** The entire process, starting from the extraction of water from an icy regolith simulant to generating thrust using a WEP system, will be demonstrated in a unified test setup within a vacuum chamber. This demonstration will involve extracting water from the regolith simulant and directing it straight to the electrolyzer of the WEP system, resulting in thrust production from the water extracted. By thoroughly examining the effects of the extraction process on water purity and its subsequent impact on electrolysis, we aim to enable the practical utilization of space-mined resources.

II. Conclusions

The scientific and technological outcomes of S4I2T will take tangible strides toward facilitating in-orbit servicing, extending spacecraft lifespan, implementing fuel cost reductions, adopting competitive on-orbit assembly and manufacturing (OSAM) methods, and more. Consequently, these developed technologies fulfill the fundamental requirements of space-based energy harvesting, as autonomous docking is imperative for assembling large structures for SEH, thus establishing a self-sufficient mobility solution to sustain such structures.

Acknowledgment

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