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In-Orbit Manufacturing and Recycling of Solar Power Satellites

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Abstract

This paper examines the challenges involved with the manufacturing, assembly, and recycling of Solar Power Satellites (SPS), proposing innovative methods to address them. SPS systems, designed to capture and wirelessly transmit solar energy to Earth, offer a potential solution for providing continuous clean energy. However, the scale of such systems and the associated challenges in launching, assembling, maintaining, and recycling these massive structures necessitate advanced space manufacturing and recycling techniques.

This work envisions a future fully circular space economy in which SPS can be manufactured in space and their parts repurposed at the end-of-life. Specifically, we propose to investigate the scenario in which the modules of an SPS are manufactured in a construction orbit harvesting material already available in space (debris, defunct satellites, upper stages, but also resources from the Moon) and are transported to their operational orbit for assembly with the rest of the structure. To achieve this, various transfer methods are explored, combining natural dynamics with impulsive manoeuvres. Once at the operational orbit, the modules are attached to the rest of the structure using a swarm of service satellites. In-orbit assembly of a space structure presents numerous dynamic and control challenges, including changes in mass distribution and inertia, varying attitude and stability. These aspects are studied for different SPS concepts, and optimal assembly sequences are proposed to mitigate the dynamic response of the system. At the end of the SPS lifecycle, the same servicing satellites will disassemble the structure and transport the components to a recycling station for re-manufacturing, with the proposed methods being equally applicable during this phase.

This research offers a significant contribution to overcoming challenges related to in-space construction and promotes the sustainable utilisation of space resources, while supporting space-based clean energy generation and generally contributing to the global effort to combat climate change.

Keywords: Solar Power Satellite, In-Orbit Manufacturing, In-Orbit Assembly, In-Orbit Recycling.

1. Introduction

A Solar Power Satellite (SPS), is a system designed to capture solar energy in space and transmit it wirelessly to Earth [1]. The basic concept consists in placing a large satellite equipped with solar panels in Earth orbit to harvest sunlight. The collected solar energy is then converted into electricity and transmitted to the ground using microwave or laser beams. A SPS can collect solar energy continuously, without being affected by atmospheric conditions or the day-night cycle on Earth. This could potentially provide a constant and reliable source of clean energy.

The idea of space-based solar power (SBSP) was first proposed by Dr. Peter Glaser in the late 1960s [1]. The first actual concept was the 1979 NASA-DOE [2], consisting of a single platform with Sun-pointing PV array. This early concept proved to be economically unviable, and the idea was abandoned for a few years. The interest in solar based power was renovated in the 1990s and 2000s, driven by numerous advances in space technology including the in-space assembly and space robotics experience gained during the construction of the International Space Station (ISS). Nevertheless, the concept still faces significant engineering and economic challenges.

To meet Earth's current energy demands, SPS structures require vast collector areas to maximise solar energy harvesting. For instance, the Abacus architecture considers a solar-array platform measuring 3.2 × 3.2 km [3], while the

SPS-Alpha concept is equipped with millions of square meters of reflectors [4].

Traditional spacecraft manufacturing, deployment, and launch methods are inadequate for the development of these structures. The mass and volume of such satellites make it impossible to launch them as single, monolithic units from Earth, due to both the prohibitive launch costs and the volume constraints of launch vehicle fairings [5]. Additionally, ensuring the long-term operation of SPS systems — expected to last several decades — demands regular maintenance and the replacement of faulty components [6], which further complicates their logistics. Furthermore, at the end of their life the components of a SPS should be recycled to prevent the creation of new space debris* [7].

The progress of the SPS concept and other large-scale space structures is closely linked to several key technological advancements. These include the development of in-space assembly techniques, improvements in autonomous collaborative robotics, and innovations in manufacturing processes. Additionally, the ability to source materials from space—whether from Earth orbits, the Moon, asteroids, or other celestial bodies—plays a critical role in reducing dependence on Earth-based resources. Collectively, these advancements are paving the way for more sustainable and efficient methods for constructing large-scale infrastructure in space.

2. Project overview

This project envisions a circular space economy, as illustrated in Figure 1. In this framework, SPS modules are manufactured in a recycling station using material coming from space debris, defunct satellites and even lunar resources. These modules are transported to their operational orbits using natural dynamics and controlled manoeuvres. A swarm of servicing satellites assembles the modules into a functional SPS, addressing all the dynamic and control challenges such as changes in mass distribution, inertia, and maintaining stability during the process. Maintenance is handled by the servicing satellites, which replace degraded components to ensure long-term operation. At the end of their life, the same satellites disassemble the structure, transporting components to the recycling station (that serves also as space warehouse) to be repurposed and recycled.

This paper is organized as follows: the first section introduces the concept of efficient module transportation to and from the recycling station. The second section presents an analysis of the assembly and disassembly dynamics of an SPS. The third section presents an optimal sequence planning of the assembly (and disassembly) processes. In the last part, conclusions and future analysis are discussed.

3. Efficient transport of modules to recycling station

In the context of in-space manufacturing and recycling, it is essential to collect non-active space objects from their orbits and transfer them to a recycling station or space warehouse (e.g., via space tugs). At these facilities, the materials can either be stored for future use or immediately repurposed for the construction of new space systems. To support this process, it is necessary to identify the most populated regions between Earth orbit and cis-lunar space, where material can be found and then transferred to the desired locations. These regions can function as hubs within a larger transport network, all connected to the central recycling station.

The idea proposed in this work is to explore regions in the phase space where natural dynamics plays in favour of orbital transfers. The objective is to map these regions and identify pathways that facilitate in-orbit construction.

By leveraging natural forces, the propellant budget for a Low-Earth Orbit to Geostationary Orbit (LEO-to-GEO) transfer can be significantly reduced, as costly manoeuvres such as inclination changes and periapsis raises can be achieved through third-body perturbation from the Sun [8]. In addition, within the Earth-Moon and Sun-Earth systems, low-energy transfers can be constructed by connecting different dynamical structures, such as invariant manifold structures [9]. Several missions have successfully exploited this strategy, following the intuition of Conley in the late 1960s [10].

This section presents a transport network which connects LEO and Moon Halo orbits with a station located in a Geosynchronous orbit (GSO), the same location of a SPS. Our method combines natural dynamics with controlled orbital manoeuvres to achieve low-cost transfers. Figure 2 shows a conceptual map of the transport network, illustrating key orbits and points of interest that constitute resources of material.

3.1 Low-earth orbit to recycling station

To connect LEO to a station in GSO, the method proposed in the following exploits solar and lunar third-body perturbations to reduce the cost of the manoeuvres required to achieve the final orbit. In particular, we assume that the initial orbit of the object is a circular LEO, with an inclination higher to that of a GEO.

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[*] `https://blogs.esa.int/cleanspace/2022/01/10/recycling-in-space-wannabe-or-reality/`

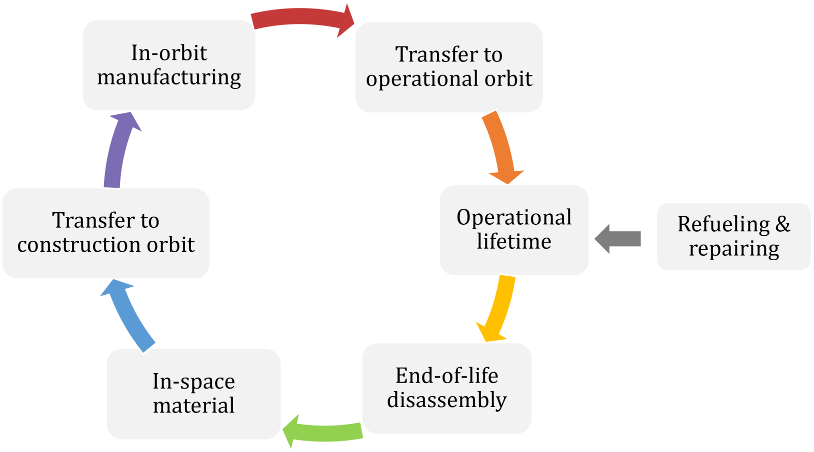

Fig. 1: Fully circular space economy.

Figure 3 shows the transfer strategy. The dynamical model is the perturbed two-body problem, where the accelerations coming from the J2 zonal harmonic of the gravity field of Earth, Sun and Moon gravity are considered. The transfer is divided into three transfer legs and four manoeuvres. The initial manoeuvre increases the apogee of the first transfer orbit. When perturbations are present, the orbital elements can vary. The variation of osculating orbital elements is tracked along the transfer orbit for a maximum of one year. In this case, the perturbations are leveraged so that the change of plane manoeuvre is performed at a point where it requires a lower delta-v, i.e. the osculating inclination is closer to that of the final GSO. Then, a third manoeuvre is performed to match the perigee of the third leg to the radius of the GSO and a final manoeuvre is performed to circularise the orbit.

In order to find the optimal transfer from a given circular LEO to GSO we systematically scan across the initial epoch, radius of apogee, argument of perigee (AOP) and right ascension of ascending node (RAAN) of the first transfer orbit. The assumption is that these elements can be freely chosen.

The systematic scan was performed across different initial conditions and the total manoeuvre costs associated to them was recorded. Table 1 reports these values along with transfer time and gain over direct and bi-elliptic transfer methods [†]. The results show that the proposed strategy outperforms theoretical ones, leading to propellant mass savings, at the expense of a longer transfer time. While this could be a limitation when there is an urgent need for material, it is not an issue if the station functions as a warehouse where material can be stored for future use.

A future analysis will explore similar strategies based on the same rationale, but using low-thrust propulsion in place of impulsive manoeuvres.

3.2 *Lunar region to recycling station*

To connect the lunar region and the GSO recycling station, the method proposed in the following exploits the invariant manifold structures created by the gravitational influences of the Earth, Moon and Sun to reduce propellant consumption.

The dynamical model is a circular restricted three-body problem, considering Earth, the Moon and perturbations from the Sun [9]. Halo orbits about the L_2 Lagrange point are considered, but the analysis can be easily extended to L_1 as well. Choosing these orbits as a starting point gives a good idea of the cost of transferring mass to the GSO from the lunar region. The transfer strategy is depicted in Figure 4.

The process begins by generating multiple trajectories along the unstable manifolds from different points on a southern Halo orbit with a fixed out-of-plane amplitude. These trajectories are propagated for a maximum duration of one year. The cost to leave the Halo orbit is negligible, typically less than 1 m/s. The next step involves identifying the intersection points where these trajectories cross the plane containing the GSO. Once these intersection points

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[†] A direct transfer is a two-burn orbital transfer in which a spacecraft moves directly between two orbits, a bi-elliptic transfer is a three-phase orbital transfer where the spacecraft first transfers to a highly elliptical orbit, performs a second burn at the farthest point, and then circularises at the final orbit.

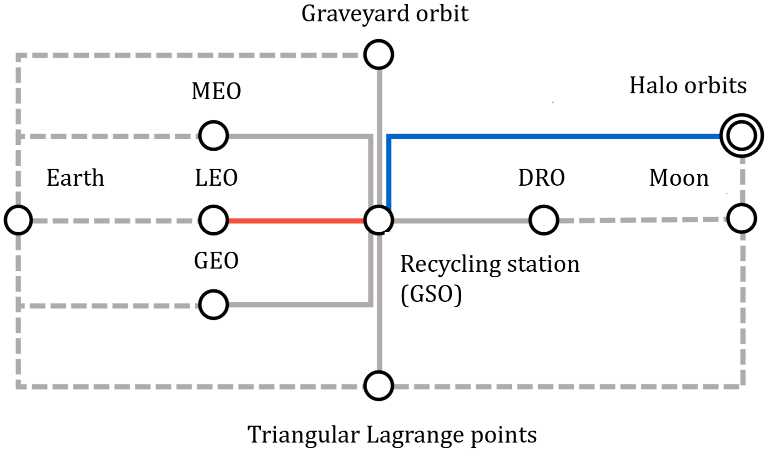

Fig. 2: Conceptual map of the recycling transport network showing all the connections analysed in this paper with coloured solid lines.

i (deg)	Δv (km/s)	ΔT (days)	Revolutions (-)	Gain in Δv over direct (%)	Gain in Δv over bi-elliptic (%)
60	4.16	109.6	4	10.7	3.6
90	4.21	86.2	3	23.6	3.7
120	4.28	85.6	3	31.4	3.3

Table 1: Minimum Δv found with the proposed strategy for different inclination of the initial LEO with the associated total propagation time, number of revolutions and gain over direct and bi-elliptic theoretical transfers. The apogee chosen for the bi-elliptic transfer is the same as the initial apogee for the perturbation-assisted transfer, in this case equal to $700\,000\,\mathrm{km}$.

are identified, a Lambert problem [11] is solved to connect the intersection points to the GSO. The time of flight and the injection point along the GSO are determined by constructing a regular grid of possible values. For each grid point, a solution is computed, and the velocity difference at the intersection point is used to calculate the manoeuvre cost. Finally, at the target point along the GSO, a final manoeuvre is performed to complete the insertion. The optimal coast arc is selected based on the minimum manoeuvre cost. The total transfer cost is the sum of these two manoeuvres.

In order to find the optimal transfers, we systematically scan across the departure date, amplitude of Halo orbit and departure point along the Halo orbit.

The results obtained show that the minimum cost attainable is 1.1 km/s, which is comparable to values found in the literature [12]. This represents a saving of about 35% compared to a direct transfer that includes a change in inclination (to match that of the Moon) at the apogee of the transfer orbit [11].

Future analysis will conduct similar analysis employing low-thrust propulsion.

3.3 Optimal location for recycling station

In the previous section, the assumption was that the recycling station would be located in a GSO. However, this orbit is dangerously close to protected regions, posing potential risks. Therefore, in this section, we utilise the perturbation-assisted methods discussed earlier to identify an optimal location for the recycling station, one that is easily accessible from all the key hubs, while avoiding proximity to protected areas.

For simplicity, the target orbit is assumed to be circular, identified by its RAAN Ω, inclination i and by its radius r. The selection of the orbit starts with an examination of the long-term evolution of the orbital elements to assess the stability of the orbit over time, and whether RAAN and inclination remain bounded and the orbit continues to be approximately circular. Simulations proved that up to a certain altitude, the orbit remains circular and inclination and RAAN stay bounded and describe a closed curve around the

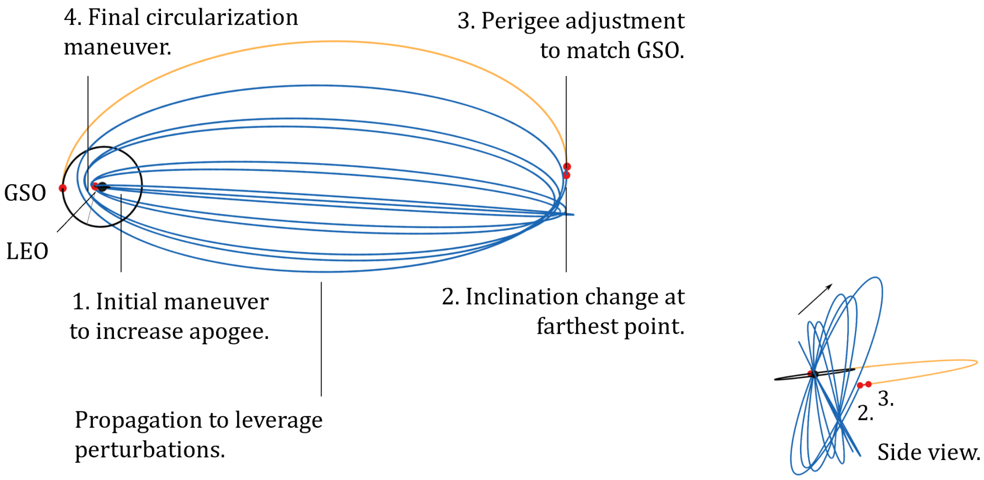

Fig. 3: Illustrative example of a LEO to GSO transfer.

Laplace plane[‡] for up to 50 years. Beyond that, RAAN and inclination no longer follow a closed path and the eccentricity increases. This analysis proves that a circular orbit can be chosen only in the case the altitude is low enough so that the orbital elements remain within specific bounds. The threshold radius for this orbit is $150\,000\,\mathrm{km}$. If a higher altitude is to be chosen, a viable option would be to consider orbits around the Lagrange points of the Earth-Moon system or the Sun-Earth system.

An essential criterion for selecting the optimal orbit for a recycling station, alongside stability and boundedness, is the manoeuvre cost required to reach the orbit from regions of interest. In the current work, perturbation assisted transfers are compared to direct approaches to identify the most cost-effective option.

The rationale used here follows a similar strategy as the transfer in the previous chapter: the effect of the perturbations can aid in achieving the manoeuvres required (like inclination or periapse changes), completely or partially, thus reducing the overall propellant consumption required. A number of transfer orbits with perigees in LEO and GSO are propagated for a maximum time of one year, varying departure date, initial inclination, AOP and RAAN. The data of the apsis points along these transfer orbits are recorded as insertion points of a possible target circular orbit, together with the manoeuvre cost and transfer time. A similar procedure is followed starting from Moon L_2 southern Halo orbits, varying the departure date, departure point and amplitude of the orbit.

For the whole set of data obtained starting from LEO, GSO and Halo orbits, only the orbits that show propellant savings compared to the direct approach are retained. After this, their long-term evolution is studied and only the orbits whose orbital values remain bounded in 50 years are kept.

Figure 5 presents the results of this search, showing the associated manoeuvre costs and transfer times. In this case, savings of up to 15% in propellant mass and 25% in delta-v are achievable, though at the cost of longer transfer times. Good candidate orbits have a radius of approximately $100\,000\,\mathrm{km}$, $20\,\mathrm{deg}$ inclination and RAAN in the range $\pm 40\,\mathrm{deg}$.

4. Assembly and disassembly dynamics

The analysis of the dynamics of an SPS is crucial for maintaining the satellite's proper orientation and functionality in space during nominal operations. At the same time, it is essential to analyse the dynamics of the satellite when faulty components are replaced, during its initial construction, or throughout the dismantling process, so that the dynamics response of the system can be mitigated. In these scenarios, the satellite experiences changes in mass distribution, surface area, inertia, and other key parameters that

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[‡] The classical Laplace plane is the equilibrium solution for the averaged dynamics arising from Earth oblateness and luni-solar gravitational perturbation [13].

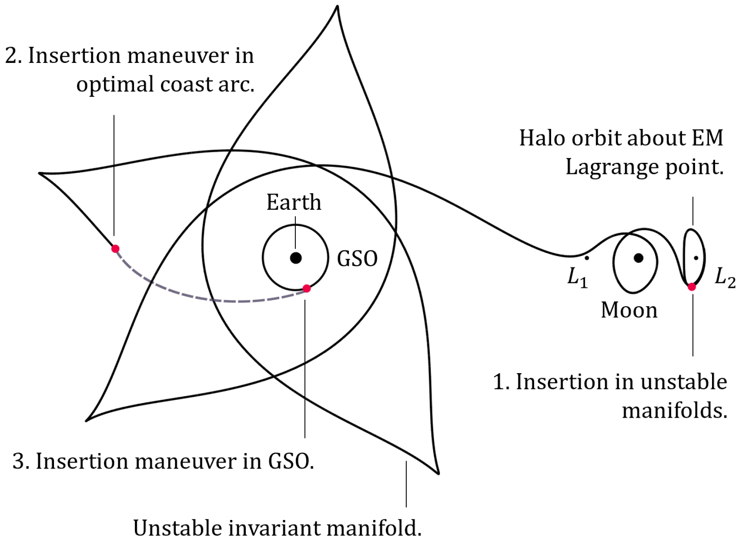

Fig. 4: Illustrative example of a Earth-Moon Halo orbit to GSO transfer.

can affect its dynamics and stability. Furthermore, the interaction with robotic systems during assembly or disassembly further influences the satellite's overall dynamic behaviour.

In this section, a model for analysing the satellite's attitude during both nominal operations and the assembly and disassembly phases is presented. The first step is to define the reference frames employed in the study. In this case, the frames employed are the Earth-Centred Inertial frame [14], the local-vertical local-horizontal frame (LVLH) [§] and the body frame, aligned with the principal axis of the satellite. An example is depicted in Figure 6.

The orbital motion of the satellite is dominated by a perturbed two-body problem, where the perturbing actions of the Sun, the Moon, the solar radiation pressure [14] and the microwave beam [¶] are considered. The rotational motion of the body is described by Euler's equations [16], considering all the torques exerted by the external and perturbative forces about the satellite's centre of mass.

A quaternion formulation is used to represent the orientation of the body [16]. The differential equations governing the orbital and rotational motion of the satellite, together with the equations describing the time evolution of the quaternions describe the orbital and attitude dynamics of the satellite. The solution to these equations is obtained by numerical integration with a single-step Runge-Kutta scheme, employing MATLAB 2024a.

A simplified model is used to characterise the assembly/disassembly process. It is assumed that the elements of the satellite are removed (or added) one by one. When an element is removed (or added) by robots, an impulse is applied to the structure. Conceptually, the process can be viewed as an impulsive separation between two different parts of the satellite. At each step the new mass distribution, inertia tensor and surface area is computed.

The model was applied to the SPS-ALPHA case study [4]. SPS-ALPHA is a highly modular architecture composed by thousands elements connected to form a number of function elements. These are: the solar reflector array, a system of thousands reflectors that intercept the sunlight and act as individually pointing heliostats[**], and the power conversion array, where the the sunlight is ultimately transformed into a microwave beam. Figure 7 shows the satellite and a detailed image of the reflectors.

Simulations were conducted to assess the effects of adding or removing reflectors to the existing satellite structure. The direction of the impulse is random, with magnitude ranging between $1\ \mathrm{mm/s}$ and $1\ \mathrm{m/s}$. The time required to remove or add a reflector was set to either half a day or

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[§] The LVLH frame is centred in the satellite. The x axis is aligned with the radial of the satellite's orbit, the z axis is aligned with the angular momentum vector and the y axis completes the triad

[¶] A non-conservative force, similar in nature to the SRP force, is applied to the satellite in reaction to the discharge of the microwave beam [15].

[**] Heliostats are devices with a mirror that turns to reflect the incoming sunlight toward a predetermined target.

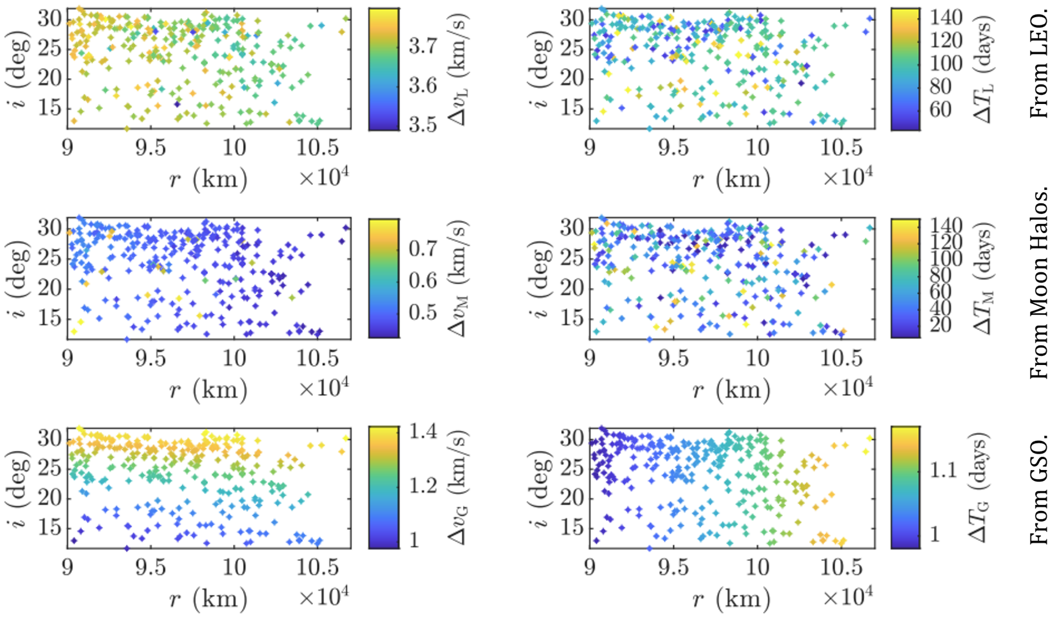

Fig. 5: Candidate orbits for a recycling station with the manoeuvre cost associated and transfer time.

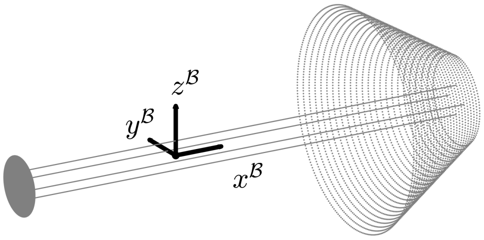

Fig. 6: Satellite body frame.

a full day. For each combination of parameters, a Monte Carlo simulation was performed with 1000 samples.

Figure 8 shows the results of the Monte Carlo simulation. The angles θ_1 and θ_2 are respectively the in-plane (rotation about z axis in Figure 6) and out-of-plane angles (rotation about y axis). The figure shows the distribution of the mean, minimum and maximum angles during the removal of all reflectors in the case of maximum impulse applied, equal to $1\,\mathrm{m/s}$. Even in this limiting case, it can be seen how the attitude angles remain bounded.

A further analysis is needed to analyse the initial assembly of a satellite.

5. Optimal sequence planning

The dynamic behaviour of the modules composing the overall structure during in-orbit assembly is significantly affected by the chosen assembly scheme, especially the sequence in which modules are integrated. Different sequences result in different evolution of the structure and levels of overall disturbance, leading to distinct dynamic responses. Identifying an optimal assembly sequence is essential for ensuring safety and stability, while also minimising the control effort required to maintain the orientation of the satellite throughout the process.

A method for finding an optimal assembly sequence is presented in the following. The case study is a large-diameter flat antenna structure, composed of square sub-panels. The antenna is assembled in GEO. Two robotic arms add the sub-panels two at a time. This will induce small changes in velocity and angular velocity, modeled as impulses on the satellite. The final objective is to minimise attitude response by optimising the assembly sequence of the sub-panels. This optimisation problem is formulated to minimise angular deviations around the x, y, and z axes, with constraints ensuring non-repeatability (no panel is added more than once), realisability (ensuring the robotic arms can perform the task), and continuity (requiring that each new sub-panel is connected to the structure). The optimisation,

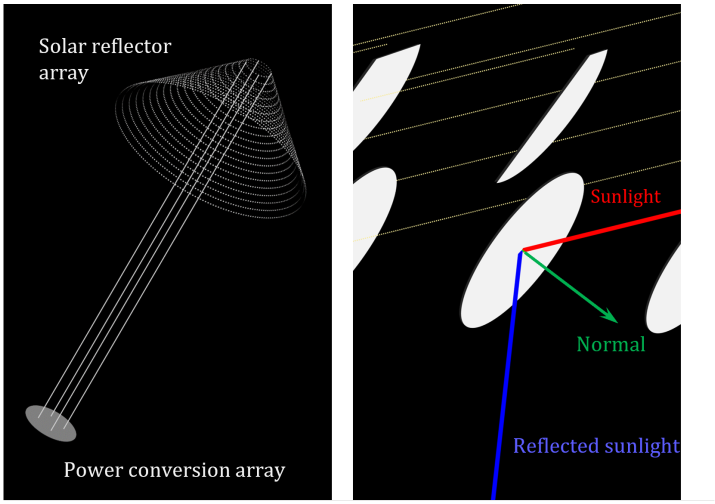

Fig. 7: SPS-ALPHA model and details of the reflector

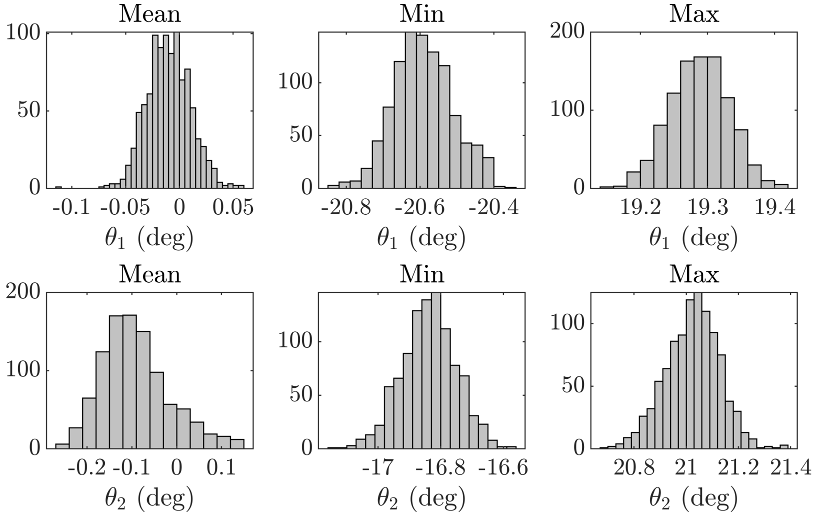

Fig. 8: Results of the Monte Carlo simulation for the in-plane and out-of-plane angles, respectively θ_1 and θ_2.

conducted using a genetic algorithm, aims to add two subpanels at a time in a sequence that keeps the satellite's attitude stable. Analysis revealed that stability is best achieved when the antenna's normal vector aligns with the z-axis of the LVLH frame. Various simulations explored different assembly dates, insertion directions, and impulse magnitudes (1 mm/s and 1 cm/s). Multiple runs of the genetic algorithm provided optimised sequences.

Results showed that when the applied impulse is small and the assembly proceeds symmetrically, starting from the center and moving outwards, attitude angles are bounded and exhibit small amplitudes. It was proven how, conversely, random sequences led to large, uncontrolled evolution of the angles, causing the satellite to tumble. The comparison of attitude evolution for optimised and random sequences, shown in Figure 9, confirmed that a well-planned, symmetrical assembly approach is crucial to maintaining satellite stability during in-orbit construction.

6. Conclusions and future work

This paper presented a comprehensive approach to in-orbit manufacturing, assembly, and recycling of Solar Power Satellites (SPS), aimed at achieving a circular space economy. The key contributions and findings are summarised:

1. *Efficient transport of modules to the recycling station:* the proposed method for transporting modules to and from the recycling station, combining natural dynamics with controlled manoeuvres, was highly effective in reducing the propellant budget for orbital transfers. Simulations for LEO-to-GSO transfers demonstrated propellant savings of up to 31.4% compared to traditional direct transfer methods, and 35% savings for transfers connecting the lunar region to a GSO. This demonstrates the significant benefit of leveraging third-body perturbations from the Sun, Moon, and Earth's gravitational fields, which minimised costly plane changes and periapsis adjustments. A key finding of the study was the identification of optimal orbits for a recycling station that serves as a hub for in-orbit recycling operations. The analysis found that a GSO at approximately $100\,000\,\mathrm{km}$, with an inclination of around $20\,\mathrm{deg}$ and a RAAN within $\pm 40\,\mathrm{deg}$, was ideal for these recycling activities. This orbit offers a balance between accessibility from different material sources (in LEO, GSO, and lunar regions) and long-term stability. Simulations indicated that this orbit provided a 15% saving in propellant mass and a 25% saving in delta-v over direct approaches, making it an efficient option for establishing long-term recycling infrastructure in space.
2. *Assembly and disassembly dynamics:* the dynamic behaviour of large modular structures during their assembly and disassembly in space was analysed. The dynamical model developed considers different sources of perturbation (e.g., SRP, Sun and Moon gravity) for the orbit and attitude of the satellite, as well as the variation of mass, area and inertia during the process. The robot-satellite interaction was modeled in a simplified way, only considering the impulses applied to the satellite. The model was applied onto the assembly and disassembly of the reflectors of SPS-ALPHA. Monte Carlo simulations showed that even under perturbations and with impulses applied from robotic systems (with impulses as high as 1 m/s), the attitude angles remained bounded.
3. *Optimal sequence planning:* the analysis highlighted the importance of optimising the assembly sequence during the initial construction phase of the satellite, particularly when assembling the main functional modules. The optimisation of the assembly sequence using a genetic algorithm provided critical insights. The results indicated that by following an optimised sequence during assembly, the attitude angles could be kept within adequate limits. In contrast, random sequences resulted in uncontrolled tumbling of the satellite, which would require considerable control effort to correct.

Future analysis will conduct a lifecycle sustainability assessment on a ”self-sustaining” SPS system, to better understand the environmental impact and resource efficiency of a circular space economy.

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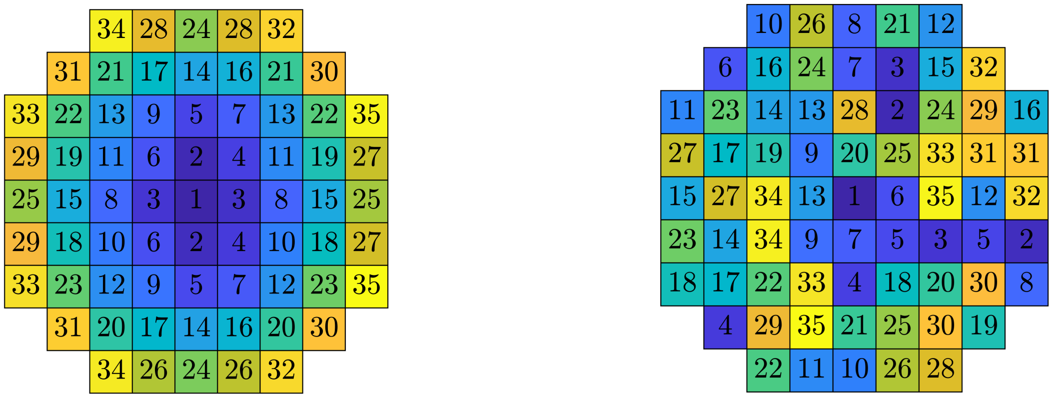
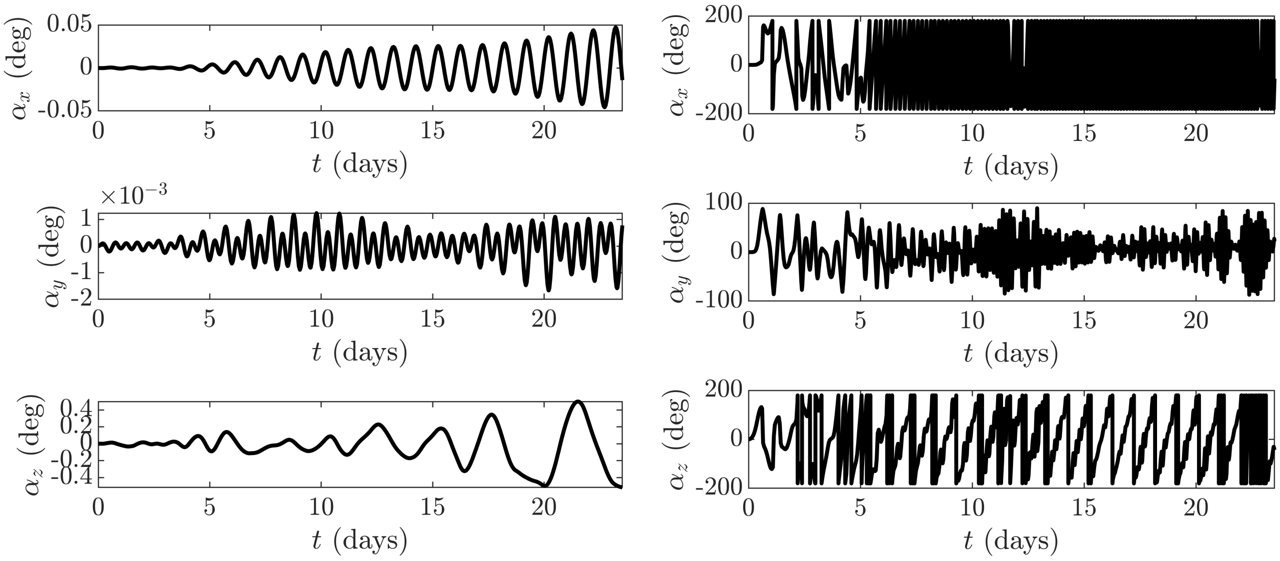


		34	28	24	28	32		
	31	21	17	14	16	21	30	
33	22	13	9	5	7	13	22	35
29	19	11	6	2	4	11	19	27
25	15	8	3	1	3	8	15	25
29	18	10	6	2	4	10	18	27
33	23	12	9	5	7	12	23	35
	31	20	17	14	16	20	30	
		34	26	24	26	32		

(a) Optimal assembly sequence.

		10	26	8	21	12		
	6	16	24	7	3	15	32	
11	23	14	13	28	2	24	29	16
27	17	19	9	20	25	33	31	31
15	27	34	13	1	6	35	12	32
23	14	34	9	7	5	3	5	2
18	17	22	33	4	18	20	30	8
	4	29	35	21	25	30	19	
		22	11	10	26	28		

(b) Random assembly sequence.



(c) Evolution of the attitude angles for an optimal assembly sequence.

(d) Evolution of the attitude angles for a random assembly sequence.

Fig. 9: Evolution of the attitude angles during the assembly process for the corresponding assembly sequences.

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