Advancing Space Sustainability: On-Orbit Repair and Recycling Through Additive Manufacturing and Automated Systems

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ABSTRACT:

Managing space debris and defunct satellites in Earth's orbit poses a critical challenge necessitating innovative solutions for sustainable space operations. This study investigates an advanced approach integrating additive manufacturing, specifically 3D printing using recycled materials sourced from space debris and materials from pioneering resupply logistics, with autonomous swarm robotics for on-orbit interventions. Leveraging advanced materials such as graphene for superior mechanical properties, additive manufacturing enables rapid production of bespoke components onboard nano-satellite swarms.

Targets are identified through advanced sensor networks or ground-based tracking systems, activating distributed swarms of nano-satellites equipped with bio-inspired robotics for precise repair operations. Autonomous machine learning algorithms analyze real-time data to optimize repair strategies and adapt to dynamic space environments, enhancing operational efficiency and resilience against single-point failures.

In scenarios where satellites are irreparable, innovative in-situ resource utilization (ISRU) technologies facilitate the extraction of materials from space debris for on-orbit 3D printing. This sustainable approach reduces dependence on Earth-based resources and minimizes space debris accumulation. Furthermore, blockchain technology secures the spacecraft supply chain, ensuring the traceability and authenticity of components throughout the phases of construction and maintenance.

By integrating these advanced technologies, this research advances the frontier of on-orbit repair and recycling, setting new standards for sustainable space exploration. It promotes efficiency, environmental stewardship, and operational autonomy in Earth's orbit, thereby laying the groundwork for future missions to operate autonomously and sustainably in space.

Keywords: - Space Debris Management; Additive Manufacturing; Swarm Robotics; In-Situ Resource Utilization (Isru); Autonomous Space Operations

1. Introduction

The vast expanse of space surrounding Earth, once thought of as infinite and untouchable, is now facing a pressing challenge: the proliferation of space debris and defunct satellites. This accumulation of man-made ob- jects poses significant risks to operational satellites and spacecraft, threatening not only their functionality but also the safety of future missions. As the number of ob- jects in orbit continues to escalate, the need for innovative solutions in on-orbit repair and recycling becomes increasingly urgent.

Space exploration has entered a new era marked by a growing emphasis on sustainability and efficiency. Central to this paradigm shift is the development of on-orbit infrastructure systems aimed at enabling sustainable space exploration endeavors. Of particular interest are robotic on-orbit servicing (OOS) infrastructures, which offer the potential to provide repair services for malfunctioning satellites in orbit, thus revolutionizing traditional spacecraft maintenance practices [1–5].

Concurrently, in-space additive manufacturing (ISAM) and material recycling have emerged as promising al- alternatives to conventional spacecraft maintenance approaches, which often rely on the cumbersome logistics of carrying numerous spare parts onboard.

The integration of these technologies stands poised to profoundly impact future satellite missions and their de-
sign. Advances in robotics and autonomy have paved the way for fully robotic OOS operations, minimizing the need for human intervention and thereby reducing costs and mitigating risks associated with crewed missions.
While early OOS endeavors, such as the repair of the Hubble Telescope by space shuttle crews, demonstrated the feasibility of on-orbit servicing, the high costs and inherent risks associated with human involvement underscored the need for autonomous robotic solutions [6–8].
Recent developments have seen the conceptualization of permanent OOS infrastructures, comprising a moth-

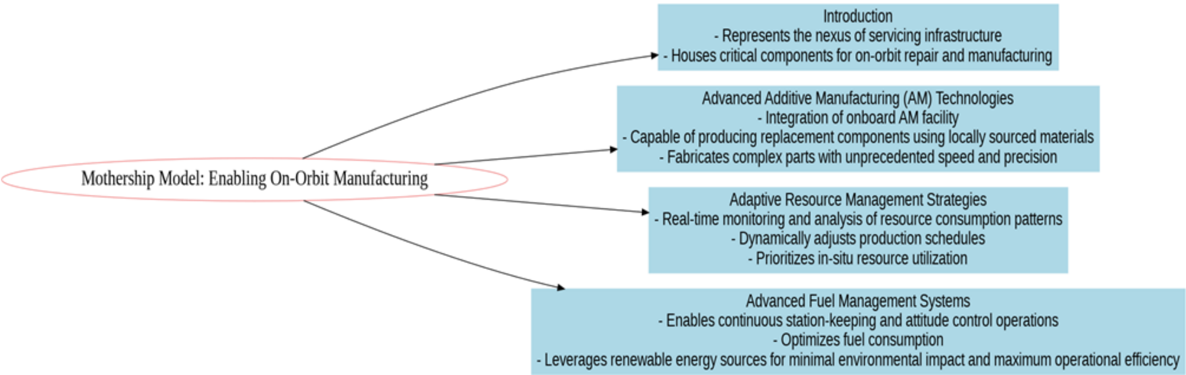

Fig. 1: Mothership Model

ership (see Fig.1) and servicer, capable of providing re-responsive servicing to satellites distributed across orbit
[5]. Moreover, modularized satellite concepts, exemplified by DARPA's Satlet project, offer the potential for easy component replacement and scavenging, thus promoting sustainability and cost-effectiveness [9]. Concurrently, ISAM has emerged as a transformative technology with far-reaching implications for mission logistics reduction. Initiatives such as NASA's "The Road to Realizing In-space Manufacturing" have underscored the potential of ISAM to revolutionize space manufacturing by enabling on-demand fabrication of replacement components [10]. Successful demonstrations, such as Made In Space's 3-D printing experiments aboard the International Space Station (ISS), have showcased the viability of ISAM for producing plastic and composite components in microgravity environments [11].
Looking ahead, ISAM holds the promise of extending its capabilities to include metal and electronics fabrication, further enhancing its utility for deep-space missions [12, 13]. NASA's ongoing development of electron beam freeform fabrication (EBF) for metal deposition and initiatives like the University of Texas at El Paso's multi3D printer underscore the expanding horizons of ISAM technology [14, 15]. These advancements herald a future where in-space manufacturing of complex components is not only feasible but also sustainable.
In parallel, efforts to develop in-space manufacturing (ISM) systems capable of fabricating and assembling large structures on orbit are underway. Projects like Archinaut and SpiderFab explore the potential of AM technology and robotic assembly to construct custom space structures, ranging from small satellites to large geostationary platforms [16, 17]. Such endeavors hold promise for streamlining spacecraft assembly processes and reducing reliance on Earth-based manufacturing. Critical to the appeal of AM technology for space appli- cations is its inherent ability to recycle materials, thereby reducing dependency on Earth-bound resources. Initia- tives like NASA's Positrusion project aim to establish sustainable ISM ecosystems by demonstrating the recy- cling of plastic 3-D printer materials aboard the ISS [18]. By closing the material loop and enabling the reuse of spaceborne resources, these initiatives contribute to the realization of self-sustaining space exploration endeavors.
The convergence of OOS, ISAM, and material recycling technologies presents a compelling opportunity to enhance the sustainability and efficiency of space missions. However, realizing this vision necessitates a comprehensive framework for evaluating the impact of these technologies on OOS infrastructure performance. This paper proposes an integrated simulation model to ad- dress this need, focusing on the servicing of modularized geostationary satellites as a case study. By considering factors such as satellite component failures, module re- placement, AM/scavenging processes, and resupply logistics, the simulation model offers insights into the effectiveness of various ISAM technologies in improving OOS infrastructure performance.

In conclusion, the integrated simulation model pre- presented herein represents a crucial step toward the de- sign and evaluation of OOS infrastructures augmented by emerging ISAM and recycling technologies. By elucidating the potential benefits and challenges associated with these technologies, this research aims to inform future endeavors in space exploration and technology development [19].

2. On-Orbit Servicing: Enhancing Space Sustainability

The integration of on-orbit servicing (OOS) capabilities with advanced additive manufacturing (AM) and automated systems represents a transformative approach to enhancing space sustainability. This section explores the pivotal role of OOS in revolutionizing satellite design, operation, and maintenance while highlighting novel per- perspectives and advancements in the field.

2.1. Evolution of On-Orbit Servicing

On-orbit servicing has evolved from a concept to a strategic imperative in the realm of space exploration and satellite operations. Early studies by Saleh et al. (2002) and Long et al. (2007) underscored the flexibility and value proposition offered by OOS, emphasizing its potential to extend satellite lifespan, mitigate mission risks, and en- hance mission adaptability [1, 2]. Subsequent research efforts, such as those by Yao et al. (2013) and Verstraete et al. (2016), focused on system assessment, optimization, and trajectory planning, laying the groundwork for advanced OOS architectures [3, 4].

2.2. Advancements in On-Orbit Servicing Infras- tructure

Recent years have witnessed significant advancements in OOS infrastructure, driven by collaborative initiatives and technological breakthroughs. Studies by Sarton du Jonchay and Ho (2016) and Barnhart et al. (2013) have quantified the responsiveness of OOS infrastructure and provided insights into mission planning and execution [5, 6]. Furthermore, the emergence of projects such as DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) and JAXA's Manipulator Flight Demonstration signify a paradigm shift towards autonomous and versa- tile OOS capabilities [6, 8].

2.3. Integration of Additive Manufacturing and Automated Systems

The convergence of On-Orbit Servicing (OOS) with Additive Manufacturing (AM) and automated systems presents novel opportunities for space sustainability and mission resilience. Studies by Saleh et al. (2007) and Clinton (2014) have highlighted the customer-centric perspective and the roadmap for realizing in-space manufacturing, respectively, underscoring the transformative potential of AM in space applications [20, 21]. More- over, advancements in 3D printing technology, as demonstrated by Johnston et al. (2014) and Owens et al. (2015), offer unprecedented capabilities for on-demand fabrication of replacement components and structures [13, 22].

Blockchain technology secures the spacecraft supply chain, ensuring traceability and authenticity of compo- nents throughout the phases of construction and mainte- nance.

2.4. Towards a Sustainable In-Space Ecosystem

The realization of a sustainable in-space ecosystem re- quires a holistic approach encompassing efficient resource utilization, waste minimization, and resilience to external dependencies. Studies by Hafley et al. (2007) and Espalin et al. (2014) have explored innovative manufacturing techniques and multifunctional structures, herald- ing a new era of space infrastructure design and operation [12, 14]. Furthermore, ongoing projects such as NASA's In-Space Manufacturing and Archinaut demonstrate the feasibility and scalability of in-space fabrication and assembly capabilities [7, 8].

Innovative in-situ resource utilization (ISRU) technolo- gies facilitate the extraction of materials from space de- bris for on-orbit 3D printing. This sustainable approach reduces dependence on Earth-based resources and mini- mizes space debris accumulation.

3. Novel Servicing Infracture Model

As humanity's presence in space expands, so too does the need for innovative solutions to ensure the sustain- ability and efficiency of space missions. In this section, we introduce a novel servicing infrastructure model tai- lored to meet the evolving demands of space exploration. Our approach integrates cutting-edge technologies and novel concepts to revolutionize on-orbit repair and recycling, paving the way for a more sustainable and resilient space ecosystem.

3.1. Introduction to the Novel Servicing Infrastructure Model

Our novel servicing infrastructure model reimagines traditional approaches to on-orbit servicing by leverag- ing advanced automation, additive manufacturing (AM), and adaptive resource management strategies. At its core, the model comprises five interconnected elements: the launch vehicle, autonomous servicing drones, a central servicing hub, modularized satellites, and an onboard AM facility. Unlike conventional paradigms, our model emphasizes adaptability, scalability, and autonomy, enabling seamless servicing operations in the harsh environment of space.

Figure 2 provides an overview of the conceptual frame- work of our servicing infrastructure model, highlighting the dynamic interactions between its

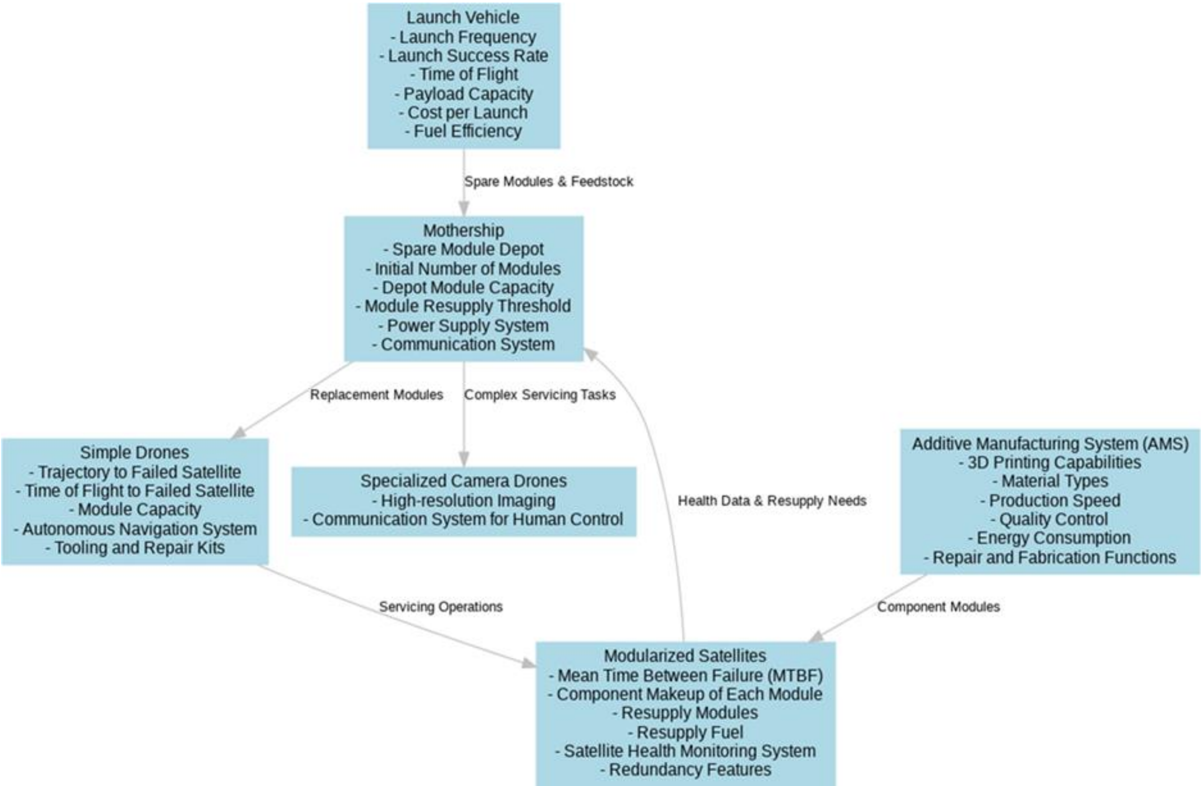

Fig. 3: Overview of baseline infrastructure model and key considerations.

constituent ele- ments and their roles in enabling sustainable space mis- sions.

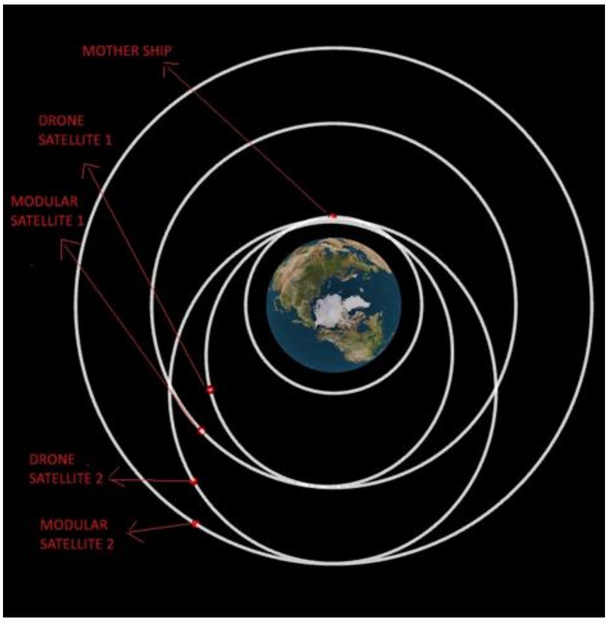

Fig. 2: Servicing architecture diagram

3.2. Autonomous Servicing Drones and Central Servicing Hub

Central to our novel servicing infrastructure is the de- ployment of autonomous servicing drones equipped with advanced robotic capabilities. These drones serve as agile and versatile agents, capable of autonomously navigating the space environment and performing a wide range of servicing tasks, from module replacement to debris re- moval.

The central servicing hub, stationed in a geostationary orbit, serves as the command center for servicing oper- ations. Equipped with state-of-the-art communication and control systems, the hub orchestrates the activities of the servicing drones, coordinates resource allocation, and facilitates real-time decision-making based on mission priorities and environmental conditions.

3.3. Modularized Satellites and Onboard AM Facility

Modularized satellites form the backbone of our ser- vicing infrastructure, designed to accommodate inter- changeable modules for easy repair and upgrades. Each satellite is equipped with standardized interfaces and self- diagnostic systems to facilitate seamless integration with the servicing drones and minimize downtime in the event of component failures.

The onboard AM facility represents a paradigm shift in space manufacturing, enabling on-demand fabrication of replacement components using locally sourced mate- rials. Utilizing advanced additive manufacturing tech- niques, such as in-situ resource utilization (ISRU) and regolith processing, the facility is capable of producing high-quality parts with minimal waste and energy con- sumption.

3.4. Adaptive Resource Management and Re-supply Logistics

A key feature of our novel servicing infrastructure is its adaptive resource management system, which optimizes resource utilization and minimizes reliance on external resupply missions. By leveraging predictive analytics, machine learning algorithms, and real-time sensor data, the system dynamically allocates resources, such as spare
parts and feedstock materials, to maximize operational efficiency and mission success.

Furthermore, our infrastructure incorporates advanced resupply logistics capabilities, including autonomous rendezvous and docking procedures, to streamline the re- plenishment of critical resources. By reducing the re- liance on Earth-based supply chains, we enhance the sus- tainability and resilience of space missions, ensuring continued exploration and scientific discovery. A schematic
describing the key parameters and interaction between the baseline infrastructure models is shown in fig 6.

4. Novel Launch Vehicle and Mothership Models

In our pursuit of advancing space sustainability, we introduce groundbreaking models for the launch vehicle and mothership, integral components of our innovative servicing infrastructure. Through the integration of cutting-edge technologies, including advanced automa- tion, predictive analytics, and adaptive resource

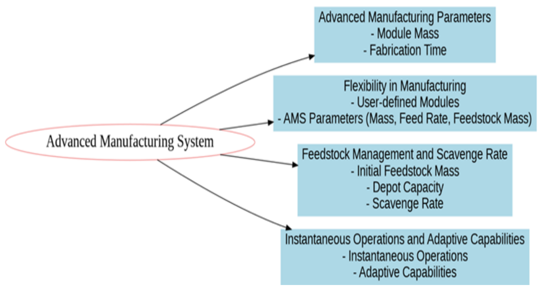

Fig. 4: Advanced Manufacturing System (AMS)

management, our models redefine traditional paradigms of on-orbit servicing, laying the foundation for a more resilient and efficient space ecosystem.

4.1. Launch Vehicle Model: Pioneering Resup- ply Logistics

The launch vehicle model serves as the linchpin of our servicing infrastructure, orchestrating the replenishment of critical resources aboard the mothership [5]. Our model introduces a revolutionary approach to resupply logistics, leveraging real-time data analytics and predictive modeling to anticipate and respond to the dynamic demands of space missions.

Central to our launch vehicle model is the utilization of machine learning algorithms to forecast resource require- ments based on historical trends and mission parameters [5]. By analyzing data on component reliability, mission duration, and consumption rates, our model can accu- rately predict the need for spare modules and feedstock, ensuring that the mothership is adequately provisioned for the duration of its mission.

Moreover, our launch vehicle model incorporates mod- ular design principles to maximize payload capacity and minimize launch costs [23]. By standardizing mod- ule sizes and optimizing packing configurations, we can achieve greater efficiency in resource delivery, reducing the overall cost of space missions while enhancing oper- ational flexibility.

To mitigate the risks associated with launch failures, our model employs probabilistic risk assessment techniques to evaluate the reliability of specific launch vehicles [5]. By quantifying the probability of mission success and failure, we can optimize resource allocation and con- tingency planning, ensuring continuity of operations in the event of unforeseen challenges.

Furthermore, our launch vehicle model emphasizes sustainability by integrating in-situ resource utilization (ISRU) techniques, such as regolith processing and material recycling [23]. By minimizing reliance on

Earthbound resources and maximizing the utilization of local materials, we can reduce the environmental impact of space missions and pave the way for self-sustaining exploration ventures.

4.2. Mothership Model: Enabling On-Orbit Manufacturing

The mothership (see Fig.1) represents the nexus of our servicing infrastructure, housing critical components for on-orbit repair and manufacturing [5]. Our model intro- duces a paradigm shift in space manufacturing capabil- ities, leveraging advanced additive manufacturing (AM) technologies and adaptive resource management strate- gies to enhance operational efficiency and sustainability.

At the heart of our mothership model is the integration of an onboard AM facility, capable of producing replace- ment components using locally sourced materials [12]. By harnessing the power of additive manufacturing, we can fabricate complex parts with unprecedented speed and precision, reducing lead times and minimizing de- pendency on external supply chains.

In addition to AM capabilities, our mothership model incorporates adaptive resource management strategies to optimize resource allocation and minimize waste [5]. Through real-time monitoring and analysis of resource consumption patterns, we can dynamically adjust pro- duction schedules and prioritize in-situ resource utiliza- tion, ensuring optimal utilization of onboard resources throughout the mothership's lifecycle.

Furthermore, our model integrates advanced fuel man- agement systems to enable continuous station-keeping and attitude control operations [5]. By optimizing fuel consumption and leveraging renewable energy sources, such as solar power and regenerative fuel cells, we can minimize the environmental impact of space missions and maximize operational efficiency.

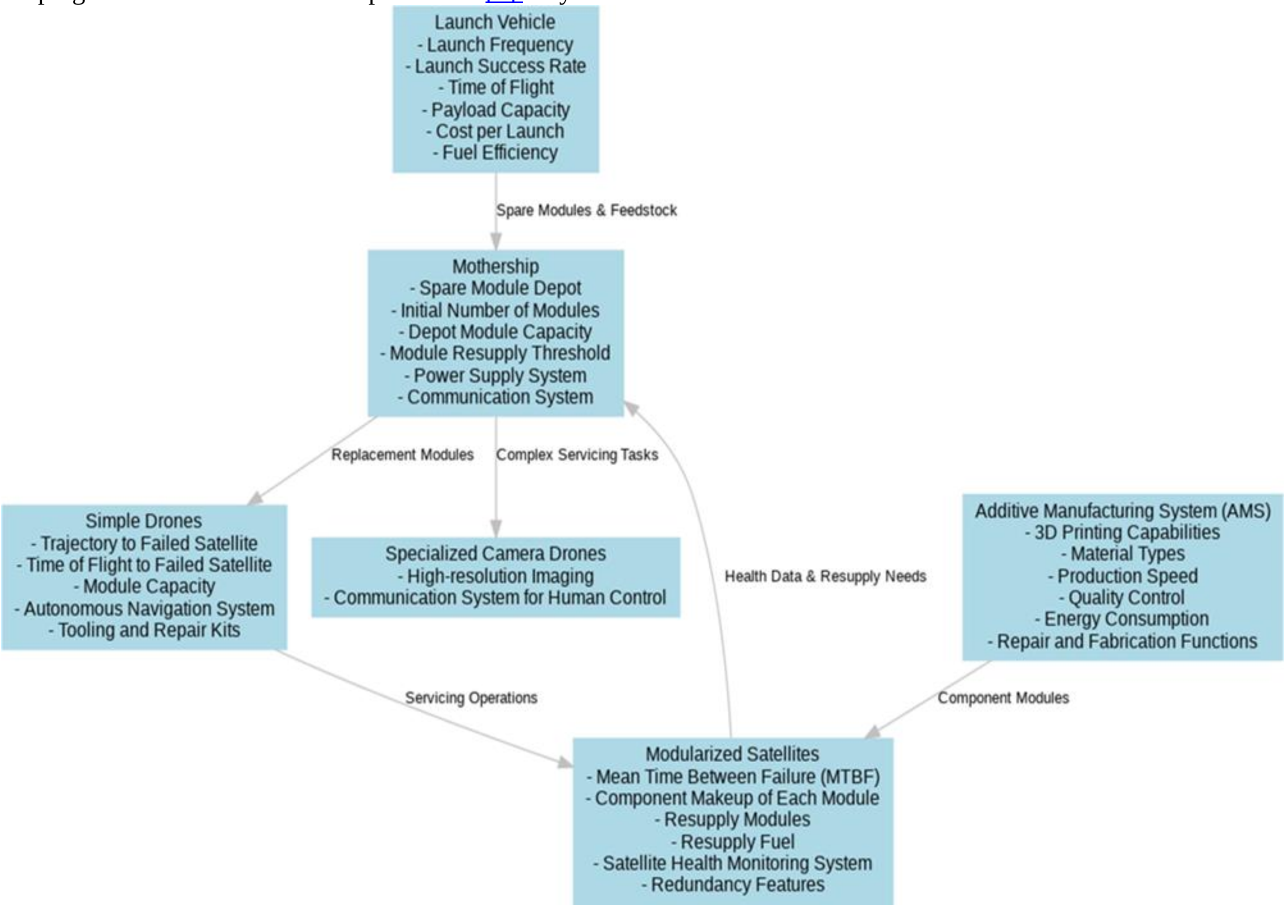

Fig. 5: Launch Vehicle Model

4.3. Advanced Manufacturing System (AMS) Model

.In our proposed infrastructure (as in Fig4), the Ad- vanced Manufacturing System (AMS) plays a pivotal role in enabling on-orbit servicing capabilities. Unlike tra- ditional models where the AMS is not considered, our framework integrates the AMS as a central component of the Autonomous Modular Satellite (AMS) infrastruc- ture.

- Advanced Manufacturing Parameters: The AMS's design and functionality are determined by several critical parameters, including its mass for specific technologies and the time required to fabricate each module. While manufacturing time can vary based on factors such as material properties and printer specifications, we implement a simplified first-order manufacturing time model. This model accounts for module size, specified manufacturing system's volumetric feed rate, and total module volume to estimate the manufacturing time accurately.
- Flexibility in Manufacturing: Our model offers flexibility by allowing users to define which
- modules can be manufactured on orbit. Users specify the corresponding AMS parameters, including manufacturing system mass, feed rate, and feedstock mass for each module. This approach simplifies the AMS's role, assuming it
- can manufacture en- tire modules autonomously using only feedstock. The time required to
- manufacture a part depends on many factors, such as geometric complexity and precision. However, a simplified first-order manu- facturing time model can be implemented based on the module size [13].
- Feedstock Management and Scavenge Rate: The initial feedstock mass and depot

capacity are crucial for AMS operations. By ensuring that the total mothership mass remains constant, we establish initial feedstock quantities. Moreover, our model incorporates a scavenge rate parameter, defining the percentage of feedstock material that can be re- cycled from a failed module. A high scavenge rate promotes a closed-loop recycling process, reducing dependence on Earth-based feedstock resupply [19].

- Instantaneous Operations and Adaptive Capabilities: In our framework, AMS operations are assumed to be instantaneous, including feedstock retrieval and module placement. This assumption streamlines manufacturing processes, ensuring minimal downtime between module replacements. Additionally, our model can adapt to changing mission requirements and environmental conditions, enhancing the AMS's resilience and autonomy.

4.4. Responsive Robotic-Servicer Model

The robotic servicer is a cornerstone of both the baseline Out-of-Service (OOS) and AMS OOS infrastructures. Its trajectory planning and execution are critical for timely satellite servicing. In our novel approach, the servicer

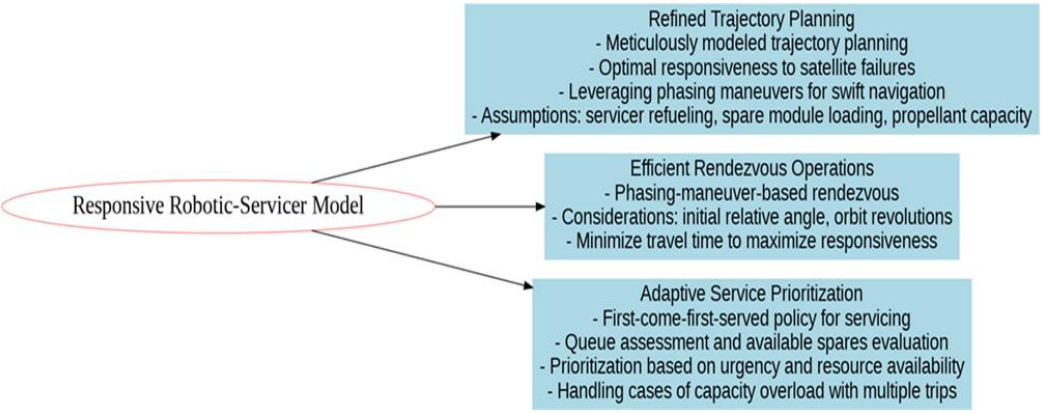

Fig. 6: Responsive Robotic-Servicer Model

operates in conjunction with the AMS-equipped mother- ship to enhance responsiveness and efficiency.

- Refined Trajectory Planning: The servicer's trajectory planning is meticulously modeled to en- sure optimal responsiveness to satellite failures. By leveraging phasing maneuvers, the servicer can swiftly navigate to the target satellite's location. Assumptions regarding servicer refueling, instantaneous spare module loading, and ample propellant capacity facilitate uninterrupted servicing operations.
- Efficient Rendezvous Operations: Phasing-maneuver based rendezvous enable efficient satellite replacement operations. Travel time calculations consider parameters such as initial relative angle and complete orbit revolutions for both the servicer and target satellite. Our analysis prioritizes minimizing travel time to maximize responsiveness while considering mission-specific constraints.
- Adaptive Service Prioritization: The servicer adopts a first-come-first-served policy for servicing multiple satellite failures. It assesses the queue of failures and available spares, prioritizing missions based on urgency and resource availability. In cases where demand exceeds the servicer's capacity, multiple trips are made to address all failures effectively.

Our unique approach to AMS integration and responsive servicer modeling enhances the efficiency and effectiveness of on-orbit servicing infrastructures. By combining advanced manufacturing capabilities with optimized trajectory planning, our framework promises to revolutionize satellite maintenance in space. The AM OOS infrastructure schematic illustrating the flow of commodities as well as the sizing parameters of each model is shown in Fig. 4.

5. Key Analysis Metrics

In our study, we introduce key analysis metrics to evaluate the effectiveness and efficiency of the proposed infrastructure. These metrics provide insights into the performance and benefits of our novel approach to on-orbit servicing.

5.1. Total Resupply Launch Mass:

This metric quantifies the total mass of modules and feedstock resupplied to the mothership over the simulation period. It encompasses both the physical modules and the required feedstock to sup- port on-orbit manufacturing and servicing operations. By comparing resupply launch masses be- tween different scenarios, we assess the impact of our approach on reducing reliance on Earth-based resupply missions.

5.2. Average Modular Satellite Waiting Time Before Service:

The waiting time experienced by modular satellites before servicing completion is a crucial indicator of operational efficiency. It is calculated as the sum of the time in the queue before the servicer departs, the travel time for the servicer to reach the tar- get satellite, and the time taken to complete the replacement operation. This metric offers insights into the responsiveness of the servicing infrastructure and its ability to mitigate satellite downtime.

By analyzing these key metrics, we aim to demonstrate the advantages of our proposed Autonomous Modular Satellite (AMS) infrastructure over traditional baseline models. These metrics provide a comprehensive evalua- tion of the system's performance, highlighting its poten- tial to revolutionize on-orbit servicing capabilities.

6. Servicer's Trajectory and Rendezvous Operations to a Satellite

In satellite servicing missions, precise trajectory planning and execution of rendezvous operations are critical for mission success. This section examines the trajectory dynamics and essential equations governing the operations of a servicer transitioning from a low Earth orbit (LEO) to a medium Earth orbit (MEO), servicing
a modular satellite, and returning to the mothership [13, 20, 21].
The servicer initially docks with the mothership in LEO, characterized by orbital parameters $a_{LEO} = 1.05 \times R_E$ and $i_{LEO} = 51.64◦$ [20]. This orbit is strategically chosen for its efficiency in launch accessibility and incli- nation, reducing fuel consumption and launch costs com- pared to higher inclination orbits. Modularized satellites are placed in various orbits around Earth, necessitating a Hohmann transfer orbit model for the servicer to reach a specific satellite in MEO [13].
Several assumptions underpin this trajectory planning: the servicer is refueled before each mothership departure, spare module loading is instantaneous, and the servicer's propellant capacity exceeds operational requirements [21]. This ensures that propellant limitations do not constrain the servicer's ability to wait for satellite servicing opportunities [14].

Consider a scenario where a modular satellite in MEO, with orbital parameters $a_{MEO} = 4.17 \times R_E$ and $i_{MEO} = 55^{\circ}$, requires servicing. A drone satellite (servicer) initially docked with the mothership in LEO, with parameters a_{LEO} and i_{LEO}, undocks with necessary replacement payloads and embarks on a Hohmann transfer orbit towards the modular satellite. After successful rendezvous, the servicer performs the required operations and returns to the mothership [22].
The trajectory planning (Fig.7) involves sequential steps starting with computing the orbital velocities in LEO and MEO using basic orbital mechanics equations:

$$v_{LEO} = \sqrt{\frac{\mu}{a_{LEO}}} \qquad v_{MEO} = \sqrt{\frac{\mu}{a_{MEO}}} \tag{1}$$

where μ = 398600 km3 /s 2 is the gravitational parameter of Earth. Next, the semi-major axis of the Hohmann transfer orbit, essential for determining the transfer trajectory, is calculated as:

$$a_t = \frac{2a_{LEO}+a_{MEO}}{2} \tag{2}$$

The velocities at perigee and apogee of the transfer orbit are then derived to understand the speed variations during the trajectory:

$$v_p = \sqrt{\mu\left(\frac{2}{a_{LEO}} - \frac{1}{a_t}\right)} \qquad v_a = \sqrt{\mu\left(\frac{2}{a_{MEO}} - \frac{1}{a_t}\right)} \tag{3}$$

Delta-v requirements are crucial for maneuver planing, computed as:

$$\Delta v_1 = v_p - v_{LEO} \qquad \Delta v_2 = v_{MEO} - v_a \tag{5}$$

In scenarios requiring inclination changes between LEO and MEO, additional delta-v is calculated using the two-impulse approximation:

$$\Delta v_i = 2v_t \sin\left(\frac{\Delta i}{2}\right) \tag{6}$$

where $\Delta i = |i_{MEO} - i_{LEO}|$ and v_t is the orbital velocity at the intersection of the two orbits.
The total delta-v required for the entire transfer operation is the sum of individual delta-v components:

$$\Delta v_{\text{total}} = \Delta v_1 + \Delta v_2 + \Delta v_i \tag{7}$$

Careful analysis of these trajectory dynamics and delta-v requirements ensures optimal resource utilization and mission success in satellite servicing missions [14, 22].

6.1. CLCULATIONS

Orbital Velocities:

Orbital velocity in LEO:

$$v_{LEO} = \sqrt{\frac{\mu}{a_{LEO}}} = \sqrt{\frac{398600}{1.05 \times 6371}} \approx 7.77\text{km/s}$$

Orbital velocity in MEO:

$$v_{MEO} = \sqrt{\frac{\mu}{a_{MEO}}} = \sqrt{\frac{398600}{4.17 \times 6371}} \approx 3.86\text{km/s}$$

Transfer Orbit Semi-Major Axis:

$$a_t = \frac{2a_{LEO} + a_{MEO}}{2} = \frac{2 \times 1.05 \times 6371 + 4.17 \times 6371}{2} \approx 2.61 \times 6371\text{km}$$

Velocities at Perigee and Apogee:

Perigee velocity:

$$v_p = \sqrt{\mu\left(\frac{2}{a_{\text{LEO}}} - \frac{1}{a_t}\right)} \approx \sqrt{398600\left(\frac{2}{1.05 \times 6371} - \frac{1}{2.61 \times 6371}\right)} \approx 10.85\text{km/s}$$

Apogee velocity:

$$v_a = \sqrt{\mu\left(\frac{2}{a_{\text{MEO}}} - \frac{1}{a_t}\right)} \approx \sqrt{398600\left(\frac{2}{4.17 \times 6371} - \frac{1}{2.61 \times 6371}\right)} \approx 5.54\text{km/s}$$

Delta-v Calculation:

Delta-v for transfer from LEO to transfer orbit:

$$\Delta v_1 = v_p - v_{LEO} \approx 10.85 - 7.77 = 3.08\text{km/s}$$

Delta-v for transfer from transfer orbit to MEO:

$$\Delta v_2 = v_{MEO} - v_a \approx 3.86 - 5.54 = -1.68\text{km/s}$$

Inclination Change (if Necessary):

Inclination change delta-v:

$$\Delta v_i = 2v_t \sin\left(\frac{\Delta i}{2}\right)$$

where

$$\Delta i = |i_{MEO} - i_{LEO}| = |55^\circ - 51.64^\circ| = 3.36^\circ$$

Total Delta-v for Transfer:

Total delta-v:

$$\Delta v_{\text{total}} = \Delta v_1 + \Delta v_2 + \Delta v_i$$

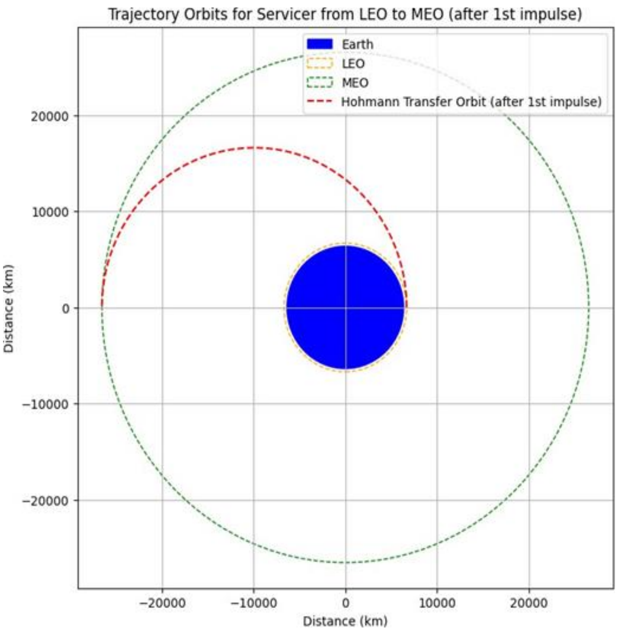

Fig. 7: Drone Satellite Trajectory Diagram

7. Advanced Trajectory Dynamics and Optimization Techniques.

The success of satellite servicing missions hinges on precise trajectory planning and optimization of rendezvous maneuvers. This section explores advanced mathematical models and optimization techniques used to enhance the efficiency and effectiveness of service operations in transitioning between orbits and performing satellite servicing tasks.

7.1. Trajectory Optimization Techniques

7.1.1. Optimal Transfer Orbits

One of the fundamental aspects of satellite servicing is the optimization of transfer orbits between different orbital regimes. Traditional methods like Hohmann transfers provide a baseline for trajectory planning but may not always be optimal in terms of time or fuel efficiency, especially when considering multi-step missions or complex orbital dynamics. Recent advancements have introduced more sophisticated optimization algorithms such as genetic algorithms, particle swarm optimization (PSO), and differential evolution (DE) to find trajectories that minimize fuel consumption or mission duration while meeting operational constraints [24, 25]. These methods iteratively refine trajectory parameters such as thrust profiles, phasing orbits, and gravity assists to achieve superior performance compared to classical methods.

7.1.2. Multi-impulse Maneuver Planning

In missions involving multiple rendezvous or complex orbital adjustments, traditional single-impulse maneuvers may be insufficient. Multi-impulse planning techniques are employed to strategically distribute propulsion events throughout the mission timeline, leveraging gravitational assists and low-thrust maneuvers to achieve desired orbital changes [26, 27]. These techniques are crucial for missions requiring precise station-keeping or inclination adjustments over extended periods.

7.2. Perturbation and Uncertainty Management

7.2.1. Orbital Perturbations and Sensitivity Analysis

Satellite orbits are subject to various perturbations including gravitational effects of the Earth, solar radiation pressure, and atmospheric drag. Understanding and mitigating these perturbations are essential for maintaining long-term orbital stability and operational efficiency [28]. Advanced models incorporating perturbation theory, such as Jacobi perturbations and secular effects, provide insights into orbit evolution and enable proactive mission planning to counteract detrimental effects. Sensitivity analysis techniques quantify the impact of uncertain parameters on mission outcomes, such as variations in atmospheric density or solar activity. These analyses guide robust mission planning by identifying critical parameters and designing contingencies to mitigate their influence on trajectory dynamics [29, 30].

7.3. Autonomous Navigation and Control

7.3.1. Autonomous Rendezvous and Docking (AR&D)

Autonomous navigation capabilities are pivotal for satellite servicing missions, enabling real-time decision-making and adaptive control in dynamic orbital environ- ments. AR&D systems integrate sensor data with predic- tive algorithms to autonomously guide servicers through precise rendezvous maneuvers and docking procedures with target satellites [31, 32]. Advanced sensor technologies, including lidar and optical imaging systems, provide critical situational awareness for navigation and proximity operations.

7.3.2. Model Predictive Control (MPC)

Model predictive control techniques optimize trajectory adjustments and station-keeping maneuvers in real- time, considering dynamic constraints and uncertainties. By predicting future states and iteratively optimizing control inputs, MPC enhances the accuracy and responsiveness of orbital maneuvers, crucial for maintaining operational safety and efficiency in satellite servicing scenarios [33, 34].

In conclusion, the evolution of satellite servicing missions is driven by advancements in trajectory optimization, autonomous navigation, and experimental validation. By integrating advanced mathematical models with practical demonstrations, researchers continue to push the boundaries of mission capability and operational efficiency in the dynamic realm of space exploration.

8. OOS Model assumption summary.

Our study relies on several assumptions to develop both the baseline and Autonomous Modular Satellite (AMS) on-orbit servicing (OOS) infrastructures. These assumptions provide the foundation for our analysis and may impact the outcomes presented in the subsequent case study. However, the flexibility of our model allows for easy updates and adjustments as new information becomes available. Below is a summary of the major assumptions implemented in our model:

1. **Servicer Design and Propellant Capacity:** We consider the servicer design at a high level, focusing primarily on its dry mass and specific im- pulse to calculate the required propellant for completing phasing maneuvers. The servicer's propel- lant capacity is not explicitly modeled as a limiting factor in module service waiting time, although the required propellant mass for each mission is calculated.
2. **Manufacturing Precision and Technology Evolution:** Our model assumes that the manufacturing processes within the AMS have evolved over time, obtaining the necessary precision to manufacture quality parts comparable to those produced on Earth. This assumption enables us to evaluate future technologies such as modularized satellites and In-Situ Additive Manufacturing (ISAM), even though current capabilities may not meet the re- quired precision levels.
3. **Impact of AM/Recycling Technologies on Modularized Satellites:** We focus on assessing the impact of future AM/recycling technologies for modularized satellites. Modularized satellites are considered as one of the most feasible options for implementing AM/recycling into an

autonomous satellite servicing infrastructure. Each individual module is assumed to be manufacturable using one material, and the impact of ISAM is evaluated based on its ability to recycle material rather than solely man- ufacturing modules.

These assumptions serve as the basis for our analysis and allow us to explore the potential benefits of AMS infrastructure compared to traditional baseline models. While these assumptions simplify certain aspects of the OOS infrastructure, they enable a comprehensive evalu- ation of the proposed approach's viability and effective- ness.

9. Case Studies and Experimental Validation

9.1. In-Orbit Servicing Demonstrations

Recent advancements in satellite servicing have been validated through in-orbit demonstrations and exper- imental missions. Case studies such as the DARPA Phoenix program and ESA's Remove DEBRIS mission highlight the successful deployment of robotic services and technologies for debris removal and satellite maintenance tasks [35, 36]. These missions provide empirical data and operational insights, validating theoretical models and advancing the technological readiness of satellite ser- vicing capabilities. For instance, the Phoenix program demonstrated the feasibility of assembling and refurbish- ing spacecraft components in orbit using robotic arms, significantly reducing costs and risks associated with traditional servicing methods [35]. Similarly, the Re- move DEBRIS mission showcased innovative debris capture technologies, such as net and harpoon systems, offering practical solutions to the growing problem of space debris [36].
The MEV-1 (Mission Extension Vehicle) by Northrop Grumman further exemplifies successful in-orbit servic- ing. Launched in 2019, MEV-1 docked with the Intel- sat 901 satellite, extending its operational life by several years through a direct transfer of propulsion and attitude control capabilities [37]. Such missions not only validate the technical feasibility of on-orbit servicing but also highlight the economic benefits of extending the lifespan of existing space assets, thereby optimizing the return on investment in space infrastructure [37].

10. Future Directions in Satellite Servicing Technologies

10.1. Enhanced Propulsion Systems

The development of advanced propulsion systems is a key area of research for improving the efficiency and capability of satellite servicing missions. Electric propul- sion, particularly Hall effect thrusters and ion engines, offers significant advantages in terms of specific impulse and fuel efficiency over traditional chemical propulsion systems. These systems enable prolonged operational periods and more flexible maneuvering capabilities, which are essential for complex servicing tasks [38, 39].
Recent innovations in propulsion technology have fo- cused on the miniaturization of thrusters for small satel- lite applications and the development of high-power electric propulsion systems for large-scale missions. The integration of advanced materials and manufacturing tech- niques, such as 3D printing, has further enhanced the performance and reliability of these systems, making them more viable for a wide range of satellite servicing applications [40, 41]. For example, the development of iodine- propellant ion thrusters offers a cost-effective and effi- cient alternative to traditional xenon-based systems, significantly reducing mission costs [40].

10.2. Robotic Systems and Artificial Intelligence

Robotic systems play a crucial role in satellite servicing missions, enabling precise manipulation and repair tasks that are beyond the capabilities of human operators. The development of advanced robotic technologies, including dexterous manipulators, autonomous inspection systems, and in-orbit assembly capabilities, has significantly expanded the scope of satellite servicing missions [42, 43]. The Robotic Refueling Mission (RRM) by NASA has demonstrated the feasibility of using robotic systems to refuel and repair satellites in orbit, showcasing significant advancements in robotic autonomy and precision.
Artificial intelligence (AI) and machine learning (ML) algorithms are increasingly being integrated into robotic systems to enhance their autonomy and decision-making capabilities. These technologies enable robots to adapt to dynamic environments, recognize and diagnose faults, and execute complex servicing tasks with minimal human intervention. The application of AI and ML in satellite servicing is expected to drive significant advancements in mission efficiency and effectiveness [44, 45]. For in- stance, AI-driven algorithms for autonomous navigation and docking can significantly reduce the time and fuel required for rendezvous operations [44].

10.3. Collaborative Satellite Constellations

The concept of collaborative satellite constellations in- volves the deployment of multiple satellites working in tandem to perform servicing tasks. This approach lever- ages the strengths of individual satellites, such as spe- cialized sensors or propulsion systems, to achieve more complex objectives than a single satellite could accom- plish alone.

Collaborative constellations can enhance mission resilience, flexibility, and efficiency, making them an attractive option for future satellite servicing missions [46, 47].

One prominent example is the concept of fractionated spacecraft, where different modules or satellites within a constellation share resources and capabilities, allowing for greater adaptability and resilience in mission opera- tions [48]. Such constellations can dynamically reconfig- ure themselves in response to mission requirements or failures, significantly enhancing operational robustness and reducing mission risk [48].

10.4. On-orbit manufacturing and Assembly

On-orbit manufacturing and assembly technologies have the potential to revolutionize satellite servicing by enabling the construction and repair of satellites directly in space. These technologies include additive manufac- turing, in-space welding, and automated assembly sys- tems, which can be used to build and maintain large structures, such as space stations or satellite arrays, without the constraints of terrestrial launch limitations [49, 50].

The International Space Station (ISS) has served as a testbed for on-orbit manufacturing technologies, such as the 3D printing of tools and components, demonstrat- ing the feasibility and benefits of in-space manufacturing [49]. These advancements can significantly reduce the need for spare parts to be launched from Earth, lower- ing mission costs and increasing the flexibility of space operations [49].

10.5. Advanced Materials and Structural Designs

The use of advanced materials and innovative struc- tural designs is critical for enhancing the performance and durability of satellite servicing systems. Materials such as carbon composites, shape memory alloys, and self-healing polymers offer significant advantages in terms of strength, weight, and resilience to the harsh conditions of space [51, 52].

Innovative structural designs, such as modular and re- configurable architectures, enable satellites to be easily upgraded or repaired in orbit, extending their opera- tional lifetimes and reducing the need for frequent re- placements. Research in this area is focused on develop- ing materials and designs that can withstand the extreme temperatures, radiation, and mechanical stresses encoun- tered in space, while also providing the flexibility needed for diverse servicing tasks [53, 54]. For example, the use of shape memory alloys in deployable structures can significantly reduce the complexity and weight of satellite components, enhancing their reliability and performance [53].

11. Conclusion

In conclusion, the future of satellite servicing missions is being shaped by advancements in propulsion systems, robotic technologies, collaborative constellations, on-orbit manufacturing, and advanced materials. These developments are driving significant improvements in mission efficiency, capability, and resilience, enabling a new era of space operations that can support the growing demands of commercial, scientific, and defense applica- tions. Continued research and innovation in these areas will be essential for overcoming the challenges of space exploration and ensuring the sustainable and efficient use of orbital resources.

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