Robotic Strategies for Orbital Sustainability: A Comparative Analysis of Capture Techniques, Guidance Systems, and Servicing Integration

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***Abstract*—This research addresses the increasing challenge of space debris, including defunct satellites, spacecraft fragments, and tiny, high-velocity particles that threaten operational satellites and other orbital assets. The accumulation of such debris poses a significant risk, potentially triggering a cascade of collisions known as Kessler syndrome, which could render the orbital environment increasingly hazardous. Traditional, centralized management approaches have proven insufficient, prompting some researchers to advocate for engaging the private sector to foster more innovative solutions. In this study, we compare advanced robotic technologies for capturing and managing space debris, evaluate various guidance systems, and examine integrated servicing solutions, all aimed at enhancing orbital sustainability in a cost-effective manner.**

I. Introduction

Since the launch of the first artificial satellite, Sputnik 1, in 1957, Earth's orbit has become increasingly crowded with a diverse array of human-made objects. Over the decades, as satellites and spacecraft have fulfilled their missions and subsequently become defunct, these objects, ranging from entire satellites and spent rocket stages to fragments generated by explosions and collisions, have accumulated to form what is now commonly known as space debris. This growing cloud of debris poses serious risks to operational satellites, spacecrafts, and other valuable assets in orbit.

Scientists and researchers Donald J. Kessler and Burton G. Cour-Palais introduced the concept that later became known as Kessler Syndrome [1]. It represents a scenario in which collisions between debris objects generate further fragments, leading to an exponential increase in the amount of debris. Such a cascade could eventually render certain orbital regions so hazardous that future satellite operations and space missions would be severely compromised. Some researchers emphasize that addressing the debris issue is not solely an engineering problem but also a matter of global policy and cooperative management [2]. This perspective argues that space, much like Earth's shared environmental resources, must be managed as a global issue. It calls for the development of international guidelines and cooperative strategies that combine preventive measures—such as designing satellites with end-of-life deorbiting capabilities, ones with active debris removal techniques, some including the use of robotic systems to capture and deorbit space debris. Not only does debris threaten current space operations through increased collision risks and potential loss of critical infrastructure, but it also poses a threat to the future accessibility of space if left unmitigated. Consequently, both engineering innovations and international collaboration are essential to develop cost-effective, scalable solutions that can sustainably manage and eventually reduce the proliferation of space debris.

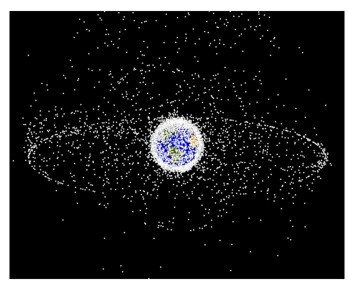

Fig. 1. Simulation of the Kessler effect

II. Comparative Review of Robotic Capture Methods

Initial research into space debris mitigation explored the use of harpoon systems as a straightforward means to secure fast-moving, non-cooperative targets. Harpoons are deployed rapidly using spring or pyrotechnic mechanisms, making them attractive due to their simplicity, low mass, and ability to engage debris in a single, decisive action [3]. However, while harpoons can capture debris quickly, they may impart excessive forces that risk damaging the target and provide limited post-capture control [3].

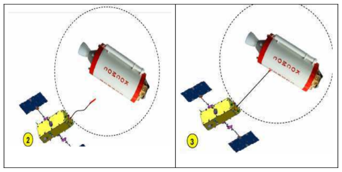

Fig. 2. Harpoon technique

In response to these challenges, subsequent studies have investigated robotic arms as an alternative capture mechanism. There has been lots of research which instead focuses on the use of lightweight robotic arms that offer enhanced precision and controlled manipulation [3]–[6]. These systems allow for multi-point contact, thereby reducing the risk of damaging delicate or irregularly shaped debris. The flexibility of robotic arms also opens up possibilities for on-orbit servicing tasks beyond mere capture. Despite these advantages, the complexity of their mechanical systems and the requirement for precise coordination during rendezvous maneuvers introduce challenges in terms of energy consumption and operational reliability. More recently, laser-based approaches have emerged

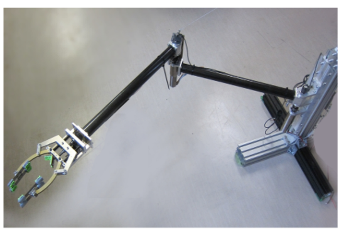

Fig. 3. Robotic arm

as another promising method. Lasers can be used to alter the trajectory of debris through ablation—vaporizing a small portion of the target surface to produce a reaction force that nudges the object into a safer orbit [7]. This contactless method avoids some of the mechanical risks associated with harpoons and robotic arms. However, laser systems demand high energy input and precise targeting capabilities to ensure efficiency without inadvertently damaging nearby functional satellites. Additional capture concepts, such as net systems and electrodynamic tethers, have also been explored [8]. Nets provide a middle ground by passively enveloping debris, thus reducing the risk of impact shock while still allowing for subsequent manipulation, whereas electrodynamic tethers can utilize ambient magnetic fields to gradually alter debris orbits. These methods, though promising, remain in various stages of conceptual and experimental development. In summary, each robotic capture method offers distinct strengths and weaknesses. Harpoons provide rapid engagement, but pose risk of damage; robotic arms afford greater control and versatility, but introduce mechanical and coordination complexities; laser systems offer a non-contact solution with high precision demands, but only for small objects. The optimal strategy for orbital debris capture highly depends on specific mission requirements and debris characteristics, suggesting that a hybrid approach combining elements of these technologies might be the most effective solution for sustaining the orbital environment.

III. Autonomous Guidance and Control Systems

Advanced computational techniques, including adaptive control, deep reinforcement learning, and trajectory optimization, play a crucial role in enabling autonomous guidance and control systems for space debris removal. One approach focuses on decentralized adaptive control, where multiple robotic manipulators collaborate to maneuver debris without prior knowledge of its physical properties [9]. This method ensures real-time adaptability by allowing each robot to estimate object parameters independently, improving functionality in uncertain environments. Another technique employs deep reinforcement learning to refine the capture phase of debris retrieval [10]. By integrating sensor data, it enables the robotic system to learn optimal grasping strategies without predefined models, making it more resilient to noisy or random sensory input. Similarly, DRL-based trajectory planning can help robotic manipulators efficiently avoid obstacles in dynamic environments [10]. Using algorithms like the deep deterministic policy gradient, robots can autonomously learn collision-free paths while maintaining task efficiency [11]. These studies highlight how AI-driven approaches, including adaptive control and DRL, are essential for developing autonomous robotic systems capable of safely and efficiently capturing and disposing of orbital debris.

IV. Cost-Effective Strategies for Debris Removal

From an economic standpoint, the financial risks posed by space debris, such as damage to operational satellites and the loss of revenue from collisions, often outweigh the cost of removal missions. The analysis suggests that investing in early debris removal can prevent exponentially rising expenses in future cleanup operations [12]. This perspective reinforces the importance of developing cost-efficient removal methods while ensuring long-term financial sustainability. A NASA study using the LEGEND model suggests that removing even a small number of debris objects per year (5 to 20) can significantly lower long-term debris proliferation [12], [13]. The study emphasizes that targeting large, high-risk objects yields the most substantial impact. Another cost-effective approach involves the use of electromagnetic launch systems to clear debris. A supposed ground-based railgun system could launch small, high-speed projectiles to deorbit debris, significantly reducing removal costs compared to traditional spacecraft missions. This method, estimated to cost around 160,000 USD per debris object, presents a scalable, low-cost alternative that eliminates the need for direct space-based intervention [14].

V. Integration of Orbital Maintenance and Servicing

Another way to reduce space debris is by servicing satellites before they reach the end of their operational life, preventing them from becoming inactive, uncontrollable debris. On-orbit servicing encompasses a variety of techniques, from autonomous robotic repairs to astronaut-assisted maintenance, each aimed at extending satellite functionality and reducing the need for premature decommissioning. One approach involves autonomous robotic systems that can capture and stabilize tumbling or drifting satellites for servicing. Vision-guided control methods enable these robots to identify, approach, and manipulate spacecraft using real-time feedback. A proposed framework integrates optimal control strategies with an eye-to-hand visual servoing method, ensuring precise capture even in scenarios where the target satellite is moving unpredictably. This method minimizes capture time and also allows for fault detection and recovery, making it a highly adaptable solution for autonomous satellite servicing [15]. Another method relies on robotic manipulator systems, which can be mounted on servicing satellites to conduct various maintenance tasks. Two configurations have been proposed, each designed to handle refueling, repairing, inspecting, and upgrading satellites. By deploying servicing satellites equipped with these robotic arms, operators can prolong the operational lifespan of critical infrastructure while avoiding the high costs of premature replacements [16]. For more complex repairs, astronaut-assisted servicing missions are an alternative solution. A proposed mission plan involves deploying a servicing spacecraft that docks with multiple satellites over a 20-day period, allowing astronauts to perform essential maintenance, hardware upgrades, and refueling. While astronauts conduct hands-on repairs, robotic arms assist with fuel transfer and other precision tasks. Additionally, plans, accordingly, include extravehicular activities where astronauts manually capture and dock satellites if automated docking attempts fail [17]. By integrating these various servicing techniques, space agencies and commercial operators can significantly reduce the rate at which satellites become debris. Whether through autonomous robotic intervention, servicing spacecraft with manipulators, or astronaut-led maintenance missions, on-orbit servicing represents a crucial strategy in the effort to create a more sustainable space environment [15]–[17].

VI. Comparative Study Analysis and Discussion

In recent years, several missions have been initiated to address the growing concern of space debris and to demonstrate on-orbit servicing capabilities [18]–[20]. A comparative analysis of these missions provides insights into the current state and future directions of space sustainability efforts.

A. ELSA-d Mission by Astroscale

The ELSA-d mission aimed to showcase technologies essential for capturing and removing defunct satellites from orbit. Launched in 2021, ELSA-d consisted of two spacecraft: a servicer equipped with a magnetic capture mechanism and a client satellite simulating a piece of debris. The mission successfully demonstrated key rendezvous and proximity operations (RPO) technologies, including magnetic capture, paving the way for future debris removal missions [18].

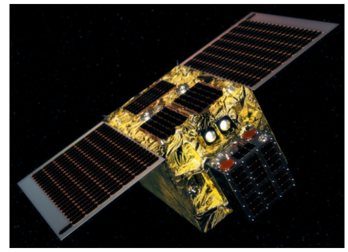

Fig. 4. ELSA-d: Chaser

B. OSAM-1 Mission by NASA

The OSAM-1 mission seeks to deploy technologies for refueling, relocating, and assembling satellites in orbit. The mission plans to rendezvous with the Landsat 7 satellite to demonstrate on-orbit refueling and repositioning. Additionally, OSAM-1 intends to assemble a communications antenna using a robotic arm. However, the mission has encountered substantial cost increases and schedule delays since its inception in 2015, with the latest assessments indicating a projected launch readiness date in March 2028 [19].

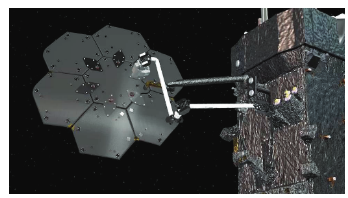

Fig. 5. Artist's rendering of NASA's OSAM-1 SPIDER Demonstration

C. Comparison

While each mission addresses space debris and on-orbit servicing, they differ in scope and approach. The ELSA-d mission focused on demonstrating fundamental debris capture technologies, achieving significant milestones in magnetic capture and RPO [18]. In contrast, the OSAM-1 encompasses a broader range of objectives, including refueling, repositioning, and in-orbit assembly, but faces challenges related to budget and schedule adherence [19]. The UK ADR mission emphasizes developing operational capabilities for removing uncooperative debris, with a strong focus on collaboration between industry and government to advance space sustainability [20]. These missions collectively contribute to space debris mitigation and on-orbit servicing, highlighting both technological advancements and the complexities inherent in executing such compound endeavors.

VII. Conclusion

In conclusion, addressing the challenge of space debris requires a multifaceted approach that combines advanced robotic technologies, autonomous control systems, and cost-effective removal strategies. The findings underscore the economic and operational benefits of early intervention, emphasizing that proactive debris management is not only a necessity but also a financially viable investment. Furthermore, global cooperation and policy development will play a pivotal role in fostering sustainable space operations, with private sector involvement driving further innovation. By integrating technological advancements with collaborative efforts, the long-term stability and safety of Earth's orbital environment can be secured for future space exploration.

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