Review on Semi-Autonomous Robots for Satellite Maintenance and Refueling

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Abstract - *As the number of satellites in Earth's orbit continues to grow, the need for efficient satellite servicing solutions becomes increasingly pressing. Currently, about 9,900 satellites are in orbit, with over 3,300 of these being inactive, posing a threat as space debris. Traditional methods for satellite maintenance and refueling are complex, expensive, and risky. The development of semi-autonomous robots, powered by advancements in artificial intelligence and robotics, presents a more efficient alternative. These robots can perform complex maintenance and refueling tasks with minimal human intervention, reducing costs and risks associated with satellite servicing. This paper investigates the design, technological advancements, and operational strategies behind these robots, and how they can mitigate space debris while enhancing the sustainability of satellite operations.*

Key Words: Maintenance, Satellites, Refuelling, Robots.

INTRODUCTION

Today about 9,900 satellites are orbiting around earth. That's more than twice as many as just 3 years ago. Another 3300 are inactive satellites, aimlessly orbiting space junks and about tens of satellites retire every year due to lack of propellant. As the global reliance on satellite technology expands, ensuring its longevity and functionality is paramount for extending the operational lifetimes of this mission. Traditional methods for satellite servicing often included risk of costly and complex space missions. This constraint necessitates the innovative approach to address the challenges of satellite maintenance and in-orbit refueling. One significant problem exacerbating the need for efficient satellite servicing is the proliferation of space debris. Thousands of satellites are orbiting around the earth playing a key component in the global communication network and the funds involved in making this spacecraft can exceed billions of dollars. However, a minor breakdown or running out of fuel can lead these expensive spacecraft to become a useless junk of iron. Broken satellite is not only useless but can pose a potential danger to other satellites if it turns into space debris heightening the risk of collision. This debris can be a substantial risk for operational satellites and space missions. This also increases the likelihood of collision due to this debris, which can lead to further fragmentation and a cascading effect known as Kessler syndrome. Consequently, developing effective strategies for in-orbit satellite maintenance and refueling is not only crucial for extending mission lifetimes but also for mitigating the hazards posed by space debris.

Semi-autonomous robots offer a promising solution to these challenges. By leveraging advancements in robotics, artificial intelligence, and autonomous systems, these robots can perform complex maintenance and refueling tasks with minimal human intervention. This approach not only reduces the risks and costs associated with traditional methods but also enhances the capability to service satellites in a more timely and efficient manner. [13,14]

In this review paper, we will investigate the development of semi-autonomous robots for in-orbit satellite maintenance and refueling. We will explore the technological advancements, design considerations, and operational strategies that underpin the functionality of these robotic systems. Additionally, we will discuss the implications of this technology for addressing the problem of space debris, highlighting the potential of semi-autonomous robots to contribute to a more sustainable and resilient space environment.

1. Background and Historical Overview

1.1. Evolution of In-Orbit Servicing Technologies

The evolution of in-orbit satellite servicing methods marks a significant milestone in advancement of space missions. Earlier satellite missions such as the Hubble telescope, set the foundation for current practice. NASA launched the Hubble telescope in 1990. Unlike other NASA telescopes, Hubble was designed to be serviced regularly by astronauts. Unfortunately, Hubble later encountered technical issues, which necessitated the on-orbit services(oos). The first servicing mission in 1993 corrected this flaw, restoring the telescope's functionality and ensuring its continued contribution to astronomy. This demonstrated the feasibility and importance of in-orbit servicing.

Additional servicing missions were held in 1997, 1999, 2002 to replace ageing instruments with advanced scientific instruments. This mission highlighted the importance of in-orbit servicing for extending the operational life and enhancing the performance of space-based observatories.

The Space Shuttle Columbia disaster in 2003, led to safety concerns and the temporary cancellation of final servicing mission SM-4. However, in 2006, NASA approved the mission as the attention shifted to robotic servicing options, which dominated the public discussion on Hubble’s future. However, the mission was approved soon after and this was the start to in-orbit robotic servicing missions.

The study of Hubble space telescope servicing missions showed the transitioning from early manual efforts to significant advancements towards automated and semi-autonomous systems. Automated systems, such as robotic arms used on the International Space Station (ISS) and satellites like DARPA's Orbital Express, demonstrated the potential for robotic systems to perform complex tasks in space. Orbital Express, a mission in 2007, showcased the ability of a robotic spacecraft to refuel and replace components on another satellite autonomously, marking a pivotal moment in the transition towards more sophisticated servicing technologies. This shift from manual to automated and semi-autonomous systems has been driven by the need for cost-effective, efficient, and safer methods for maintaining and extending the life of space assets. [11]

1.2. The Concept of Semi-Autonomous Robotics in Space

Semi-autonomous robotics in space represent a hybrid approach, combining the strengths of both autonomous and human-controlled systems. A semi-autonomous robot is designed to perform tasks independently but under the supervision and potential intervention of human operators. This is distinct from fully autonomous robots, which operate entirely without human intervention, and from teleoperated robots, which require continuous human control.

The importance of human-in-the-loop control in semi-autonomous systems cannot be overstated. This approach leverages human intuition and decision-making capabilities for complex or unforeseen situations, while the robotic system handles routine or hazardous tasks autonomously. This balance enhances the flexibility and reliability of space missions, allowing for real-time adjustments and interventions as necessary. Human operators can oversee multiple robots, intervening only when critical decisions or problem-solving is required, thus optimizing efficiency and safety in space operations.

In summary, the progression from early manual servicing missions to sophisticated semi-autonomous robotic systems highlights the ongoing innovation in satellite maintenance and refueling. This evolution is crucial for addressing the increasing demand for satellite longevity and mitigating the challenges posed by space debris, ensuring the sustainable and effective use of space resources. [12]

2. Key Technological Components

In-Orbit Servicing (IOS) refers to extending the life or functionalities of spacecraft that are already in orbit. This can be done by performing maintenance, adjusting a spacecraft’s orbit, changing the direction it is facing, providing more fuel, or even changing or upgrading the instruments onboard. [15]

Satellite maintenance and refueling are critical for extending the operational life of satellites and reducing space debris. Here are the key technological components involved in these processes:

2.1 Robotic Systems for Refuelling

Robotic systems play a crucial role in the refueling of satellites. These systems can autonomously capture and service satellites in orbit. The technology has matured significantly over the past decade, allowing for the development of dedicated refueling satellites that can be launched from Earth or from larger spacecraft or space stations. This capability is essential for performing maintenance tasks without requiring human intervention in space. [9]

In a typical refueling mission, a servicer will approach a satellite before performing a rendezvous maneuver followed by the capture of the satellite. After the capture a rigid connection between servicer and satellite will be established. In all these operations robotic components or subsystems, e.g. a robot arm. [16]

2.2. Maintenance Methods

Various maintenance methods are being explored to ensure satellites remain operational. These include on-orbit repairs and upgrades, which can involve replacing components or performing software updates. The goal is to address premature failures and extend the useful life of satellites, which typically ranges from 5 to 15 years. Innovative startups are actively working on these maintenance solutions, highlighting the growing importance of sustainability in space operations.

2.3. Collision Avoidance Technologies

With the increasing number of satellites in orbit, collision avoidance technologies are vital. These systems help prevent satellite collisions, which can create hazardous space debris. For instance, the International Space Station (ISS) has had to perform maneuvers to avoid debris from satellite collisions, underscoring the need for effective tracking and avoidance systems. [10]

2.4. Ground Support Equipment

Ground support equipment is also essential for satellite maintenance and refueling operations. This includes the infrastructure needed to launch refueling missions and support robotic operations in space. The integration of ground systems with orbital technologies ensures that refueling and maintenance can be conducted efficiently.

3. Applications in Satellite Maintenance

Space robotics is considered one of the most promising approaches for on-orbit servicing (OOS) missions such as docking, berthing, refueling, repairing, upgrading, transporting, rescuing, and orbital debris removal. [6]

ESA has conducted extensive work on IOS, as part of this research, ESA Preparation invited industry partners to outline their vision of Europe's first IOS mission. Astroscale, ClearSpace, D-Orbit and Telespazio were given funding to mature their ideas, and their results were presented in preparation for the 2022 ESA Council at Ministerial level.

D. GÓMEZ et al (2019) presented manned missions performing maintenance in geostationary orbit around 2030, their conclusion was that it would be possible to perform services for up to four different satellites in orbit in one single mission spanning over around 20 days. A servicing spacecraft would dock to the satellite to be serviced, and perform upgrading and refueling. Astronauts would install upgrades, perform eventual repairs and if needed help with the refueling, while ground controlled robotic arms perform the refueling. Another different type of service that could be considered is the assembly of a telecommunication satellite or a space telescope in orbit, which would be beneficial because it does not take into account size limitations, since the components can be launched into orbit in separate launches. [7]

3.1. Spacecraft Refueling Service

There are currently companies, such as Orbit Fab, which are developing alternatives to eliminate the single-use spacecraft paradigm with in-space refueling. Spacecraft are still limited to the amount of fuel they launch with, which limits flexibility and poses long-term risks to the space environment.

Orbit Fab is building the in-space propellant supply chain that will enable future missions to pursue entirely new options during operations. Orbit Fab has developed enabling technologies that make in-space refueling possible, two of these are the Rapidly Attachable Fluid Transfer Interface (RAFTI) and the Grappling and Resupply Interface for Products (GRIP). Orbit Fab will use these two technologies on its fuel shuttles and fuel depots to deliver refueling services to spacecraft. Fuel shuttles are designed to deliver to a customer spacecraft whereas the fuel depot is intended to store deliverable fuel and pressurant. [8]

refueling spacecraft offers significant advantages, particularly in optimizing the mass budget essential for mission success. Traditional spacecraft often carry substantial amounts of pressurant and fuel, which consume a large portion of this budget. By minimizing or eliminating the need for these at launch, more mass can be allocated to data-generating hardware, enhancing the overall value of the mission.

4. Challenges in Developing Semi-Autonomous Robots for Space

Semi-autonomous robots for satellite maintenance and refueling in orbit face numerous technical, environmental, operational, and safety-related challenges. These robots are designed to assist with tasks like repairs, refueling, debris removal, and assembly in space, which can significantly extend the lifespan and functionality of satellites. However, their deployment and operation in space are not without difficulties. Here are the main challenges:

4.1. Harsh Space Environment

- Microgravity: Operating in microgravity means that standard terrestrial robotics principles don't always apply. The lack of gravity affects how robots move and manipulate objects, requiring specialized algorithms for motion control and stability.
- Radiation: High levels of radiation in space can degrade electronic components and software systems, leading to potential malfunctions or reduced performance of sensors, cameras, and processors.
- Thermal Extremes: Temperatures in space can vary dramatically between sunlit and shadowed areas, affecting the robot's materials and components. Thermal expansion and contraction can lead to mechanical failures or changes in operational tolerances.

Example: International Space Station (ISS): The ISS has dealt with microgravity, radiation, and thermal extremes. Its robotic arm, Canadarm2, has required specialized design and maintenance to operate effectively.

Mars rovers (Spirit, Opportunity, Curiosity, Perseverance): These rovers have faced extreme temperatures, radiation, and dust storms on Mars. Their designs and operations have been adapted to withstand these harsh conditions.

Hubble Space Telescope: The Hubble has faced various environmental challenges, including thermal extremes and radiation. Servicing missions have been necessary to maintain its operation.

Solar Orbiter: This mission is designed to study the Sun. It faces extreme temperatures and radiation near the Sun, requiring specialized shielding and cooling systems.

4.2. Communication Delays and Latency

- Space robots rely on commands from Earth, but communication signals can take several seconds to minutes to travel between Earth and the robot, depending on the satellite's orbit. This delay makes real-time control impractical and necessitates a degree of autonomy in decision-making.
- Robots must be capable of handling unforeseen situations without immediate human intervention, which requires advanced AI and machine learning algorithms to enable situational awareness and problem-solving skills.

Example: The Mars rovers (Spirit, Opportunity, Curiosity, Perseverance) faced significant communication delays due to the vast distance between Earth and Mars. These delays required the rovers to operate with a high degree of autonomy, making decisions and performing tasks based on their own sensor data and onboard software.

NASA's Robotic Refuelling Mission (RRM) was a NASA mission on the International Space Station (ISS) to test different methods of refueling satellites in space that required precise control and coordination between ground-based operators and the robotic arm. This was important for developing technology to allow satellites to stay in orbit longer. The mission highlighted the challenges of teleoperation due to communication delays. Even minor delays can lead to errors in delicate operations like refueling, highlighting the importance of autonomy for space robots.

4.3. Precision in Maneuvering and Tool Handling

- Orbital servicing tasks, such as satellite refueling, require extreme precision in docking, attachment, and manipulation of highly sensitive components. Even small errors can result in mission failure or catastrophic damage.
- The robot's actuators, grippers, and sensors must work with high accuracy, which is difficult to achieve in a microgravity environment, particularly when dealing with fluid dynamics in zero gravity during refueling tasks.

Example: The DARPA's (The Defense Advanced Research Projects Agency is a research and development agency of the United States Department of Defense) Robotic Servicing of Geosynchronous Satellites (RSGS) program seeks to develop robotic capabilities for precise satellite repairs and refueling in the challenging geosynchronous orbit. The DARPA robotic mechanic is anticipated to start making on-orbit service calls in space in 2025.

The program faces the ongoing challenge of maintaining precision in the unpredictable orbital environment along with challenges like Microgravity that cause objects to move unpredictably and fluid dynamics that can be difficult to control. High Sensor accuracy must be maintained to ensure precise positioning and control during delicate operations. Specialized tools may be required for specific tasks, such as refueling or repairing different types of satellites. In some cases, human operators may need to provide guidance or assistance to the robot, for precision and coordination.

4.4. Autonomy and Decision-Making Challenges

- Semi Autonomous robots must make decisions independently, including identifying correct target components, avoiding collisions, and executing repairs or refueling. Developing reliable AI systems that can adapt to the dynamic space environment is complex and requires rigorous testing.

- Decision-making algorithms must balance autonomy with the ability to take commands from human operators, ensuring the robot can function effectively without oversight while maintaining operator control when needed.

Example: The NASA OSAM-1 mission aimed to refuel the Landsat 7 satellite in space. This would have been a groundbreaking achievement, demonstrating the potential to extend the life of satellites. However, the mission faced significant challenges due to the satellites' original design, which did not anticipate refueling. The satellites currently in space were not designed to be serviced, there are significant challenges to doing so successfully. This shows how hard it is to repair old satellites in space. It's important to design new satellites with refueling in mind.[4]

4.5. Limited Power Supply

- Robots in space are often powered by solar panels, but power availability can be inconsistent due to orbital paths that may temporarily block sunlight. Energy management becomes critical, especially during high-power operations like refueling or handling heavy tools.

- Efficient power distribution and storage systems are needed to ensure continuous operation, which adds complexity to the robot's design. The robot must expend significant energy to maneuver itself to the target satellite and maintain a stable position during refueling operations. This can quickly deplete the robot's battery if not managed carefully.

Example: Lunar Gateway (NASA's Artemis Program): To establish a permanent lunar presence, the Lunar Gateway will require advanced robotic systems for various tasks, including servicing spacecraft and constructing lunar infrastructure. Efficient power management will be crucial for these robots to operate effectively in the harsh lunar environment. The lunar rovers planned for Artemis missions will also need reliable power systems to support their exploration activities and potential interactions with orbiting satellites.

4.6. Safety and Risk Management

- There is a significant risk of damaging the target satellite, the servicing robot, or even creating space debris that could threaten other space assets. Collision avoidance, safe approach algorithms, and emergency shutdown protocols are essential to minimize risks. Docking maneuvers are highly complex in space due to the need for precise alignment and speed control. A miscalculation in these parameters could result in high-velocity impacts or failure to dock.

- Any mistakes, such as a fuel leak during refueling, can have catastrophic consequences, not only for the mission but also for the broader space environment.

Example: Orbital Express by DARPA was a demonstration program that involved two satellites: the Transport Robotic Operations (ASTRO) servicing satellite and the Next-generation Satellite (NEXTSat) client satellite, aimed at validating autonomous satellite servicing. During one of the mission's tests, an unplanned separation occurred between ASTRO and NEXTSat due to a software anomaly. This incident forced ground control to intervene to prevent a potential collision, which highlighted the risk associated with autonomous operations.

One of the major risks involved autonomous docking maneuvers, which required ASTRO to approach and dock with NEXTSat without human intervention. If ASTRO had collided with NEXTSat or failed in its docking attempts, it could have created significant space debris, posing a long-term hazard to other satellites in the vicinity.[1]

4.7. Integration and Compatibility

- Not all satellites are designed for servicing, creating challenges in docking and interfacing with existing components. The development of standardized interfaces for refueling ports, repair access points, and attachment fixtures is ongoing but not yet widespread.

- Compatibility between the servicing robot and various satellite designs is crucial for mission success, and retrofitting older satellites poses additional difficulties.

Example: The MEV (Mission Extension Vehicle) by Northrop Grumman, designed to dock with satellites extends their operational life and provides propulsion and attitude control services. MEV-1 successfully docked with Intelsat 901 in 2020, and MEV-2 followed with Intelsat 10-02 in 2021.

Non-Servicing Design of Target Satellites: The targeted satellites, such as Intelsat 901 and Intelsat 10-02, were not originally designed with servicing in mind. They lacked standardized refueling ports, docking mechanisms, or attachment fixtures that are conducive to robotic servicing. This created significant challenges in the autonomous docking process, as the MEV had to rely on specialized capture mechanisms to attach to the satellite's existing hardware, which was never intended for such operations.

Compatibility Issues: MEV had to adapt its docking procedures to the specific designs of the satellites, using a custom-developed capture tool that interfaces with the satellite's apogee engine nozzle—a non-standard and unconventional approach. This compatibility issue highlights the difficulties of retrofitting older satellites with servicing capabilities, which often require bespoke solutions for each target.

Standardization Challenges: The MEV program underscores the broader industry challenge of developing standardized interfaces for satellite servicing. The absence of uniform docking fixtures and refueling ports across satellites means each mission must account for unique satellite configurations, increasing the complexity and risk of servicing operations.[4]

4.8. Complex Mission Planning and Execution

- Planning orbital servicing missions involves complex calculations, including orbital mechanics, satellite orientation, and operational windows. Errors in mission planning can lead to failed maneuvers or missed docking opportunities.

- Execution needs precise timing and coordination between ground control and the autonomous functions of the robot.

Example: The Orbital Express mission, a joint venture between DARPA and NASA, aimed to demonstrate the feasibility of autonomous satellite servicing faced significant challenges in mission planning, which underscored the importance of precision in maneuvering and timing.

The primary difficulties were the need for precise maneuvering of the servicing satellite to approach and dock with the target satellite. Accurate navigation and control systems were necessary to ensure that the two satellites were aligned correctly and at the appropriate speed as any deviations could result in a collision or missed docking.

The timing of the mission was important as the servicing satellite had to arrive at the target satellite's location at the exact moment when the target was available for servicing which required careful coordination and precision to save fuel and time.

The planning process had to account for the dynamic nature of the space environment as orbital decay, atmospheric drag, and solar radiation could affect the trajectories of both satellites, making it difficult to predict their exact positions at any given time.

The Orbital Express mission, despite advanced tools, faced risks and uncertainties. Its success demonstrated the feasibility of autonomous satellite servicing but highlighted the challenges for routine operations.

4.9. Debris Avoidance and Navigation

Space debris poses a significant risk to semi-autonomous robots due to high relative velocities.

- Key Challenges:
  - Debris Detection: Identifying small debris with traditional sensors is difficult.
  - Path Planning: Efficiently planning trajectories around debris while minimizing fuel consumption and mission duration.
  - Collision Avoidance: Quickly reacting to unexpected debris encounters and adjusting the robot's trajectory.
- Solution:
  - Advanced Sensors: Equip robots with radar, lidar, and optical cameras for comprehensive debris detection and tracking.
  - Machine Learning: Utilize machine learning to analyze sensor data and identify potential debris threats.
  - Real-Time Path Planning: Develop algorithms that can rapidly adapt to changing debris environments and plan trajectories that minimize the risk of collision.
  - Autonomous Maneuvers: Enable robots to perform autonomous maneuvers like rapid course corrections and evasive actions to avoid debris.

Example: ESA's Clear Space One is to remove large debris from orbit. Advanced debris detection, path planning, and collision avoidance are essential for the robotic arm to navigate through the debris-filled environment and capture the target object. Clean Space One will utilize cutting-edge technologies like lidar, vision systems, and machine learning for debris detection and avoidance. It will also employ precise maneuvering capabilities to avoid collisions.[4]

The RemoveDEBRIS mission aimed to remove space debris using different techniques. It had a main spacecraft and two smaller ones. It tested using nets, harpoons, cameras, and a large sail to capture and deorbit space debris. Most of the tests were successful, but the final test with the sail failed. [4]

4.10. Software Reliability and Robustness

- Challenge: The software that controls space robots must be extremely reliable and capable of functioning in the unpredictable conditions of space. Bugs, glitches, or unexpected software behaviors can lead to mission failures. Ensuring the software can handle unexpected situations, recover from faults, and remain stable over long periods without human intervention is critical.

- Solution: Extensive software testing, validation, and redundancy are required. The systems must be designed with fail-safes, self-diagnosis capabilities, and fault-tolerant architectures to handle unforeseen scenarios or software errors without compromising the mission.

Example: The Space Infrastructure Dexterous Robot (SPIDER) program by NASA has extensive software reliability testing to ensure that the robot can autonomously assemble and repair satellites. Using robots to build and assemble new structural components from scratch would be an important step towards a type of space-based construction that had been impossible to date.

4.11. End-of-Life Disposal and Sustainability

- Challenge: After completing their missions, semi autonomous robots themselves become potential sources of space debris if not properly disposed of. Effective end-of-life planning is essential to prevent these robots from becoming hazards to other spacecraft.

- Solution: Robots should be equipped with deorbiting systems or other disposal mechanisms, such as controlled reentry or parking in graveyard orbits. Additionally, developing reusable robot platforms could minimize waste and enhance sustainability.

Example: The Mission Extension Pods (MEPs) by Northrop Grumman are designed to not only service satellites but also to have deorbit capabilities to safely remove themselves from orbit, emphasizing the importance of responsible end-of-life management in satellite servicing missions.

4.12. Mechanical Wear and Tear

- Challenge: Prolonged exposure to the harsh conditions of space, such as extreme temperatures, radiation, and micrometeoroid impacts, can lead to the degradation of mechanical components in semi autonomous robots. Joints, gears, and other moving parts are especially susceptible to wear and tear, potentially compromising the robot's operational capabilities over time.

- Solution: Developing durable materials, advanced lubricants suited for vacuum conditions, regular maintenance routines, self-repair and reconfiguration technologies, and inculcating the concept of Modularity can help mitigate mechanical wear and tear and further enhance the robot's robustness, adaptability ensure long-term operational success in the harsh space environment.

Modularity and reconfigurability: Breaking down the robot into smaller interchangeable modular components allows for easier repairs and adaptability. Robots can replace damaged parts and reconfigure themselves to continue functioning, also enabling them to adapt to different mission requirements.

Self-repair capabilities: Robots can autonomously replace failed modules, enhancing their self-maintenance capabilities. The use of spare modules and reconfiguration in the event of a local module failure further supports the concept of self-repair.

Self-reconfigurable systems offer the potential for semiautonomous robots to autonomously change their configuration or shape without external input.

Example: Several missions, including NASA's Commercial Resupply Service for the ISS, ESA's RemoveDEBRIS mission, and DARPA's RSGS, have demonstrated on-orbit reconfiguration operations. Projects like iBOSS specifically focused on modularity and reconfigurability for space systems.[5]

5. Ongoing Missions

5.1. Orbital Express: An Early Vision for Autonomous Satellite Servicing

Launched by DARPA in 2007, the Orbital Express mission was an ambitious project designed to push the boundaries of satellite servicing and set the stage for future on-orbit maintenance and refueling operations. The mission consisted of two spacecraft: ASTRO, the servicing satellite, and NextSat, the client satellite. Together, they were tasked with demonstrating a range of autonomous servicing capabilities, including docking, refueling, and the replacement of components.

ASTRO and NextSat were equipped to perform fully autonomous docking maneuvers, a feat that involved precise navigation and control to safely connect the two spacecraft in space. Once docked, ASTRO could transfer fuel to NextSat, demonstrating the possibility of in-orbit refueling, which is crucial for extending the operational life of satellites. Additionally, the mission showcased the ability to swap out modular components on NextSat, such as batteries and computers, providing a proof of concept for future missions that could upgrade or repair satellites on the fly. This autonomous capability reduced the reliance on launching entirely new satellites to replace those that are simply in need of maintenance or minor upgrades.

The technology behind Orbital Express was advanced for its time and laid the groundwork for many of the satellite servicing technologies used today. The mission employed a combination of sophisticated sensors, guidance systems, and robotic arms to perform its autonomous tasks. ASTRO was equipped with advanced vision-based navigation, using cameras and LIDAR to identify and approach the docking target precisely. The robotic arm on ASTRO was crucial for handling and replacing satellite components. The mission also showcased a sophisticated fluid transfer system for refueling, which required meticulous engineering to manage fluids in the microgravity environment of space. These technological innovations not only proved that satellite servicing was feasible but also paved the way for modern servicing missions, such as NASA's OSAM-1 and Northrop Grumman's MEV series, making Orbital Express a true trailblazer in the field of autonomous satellite maintenance. [17][18]

5.2. Northrop Grumman's Mission Extension Vehicle (MEV-1 and MEV-2)

Northrop Grumman's Mission Extension Vehicles, MEV-1 and MEV-2, offer a cost-effective and sustainable solution to extend the operational life of geostationary satellites. These vehicles dock with aging satellites that are low on fuel, taking over critical functions like station-keeping and attitude control, which can extend a satellite's life by up to five years or more. By reducing the need to launch replacement satellites, the MEVs not only save costs but also help mitigate space debris, contributing to more sustainable space operations. The historical milestones of MEV-1 docking with Intelsat 901 in 2020 and MEV-2 docking with Intelsat 10-02 in 2021 marked the first commercial in-orbit servicing missions, setting a new standard in satellite maintenance and pioneering the future of space servicing capabilities.

The capabilities of MEV-1 and MEV-2 are designed to provide comprehensive support to satellites in orbit. They are equipped with a sophisticated docking mechanism that allows them to attach securely to the satellite's apogee motor, effectively taking over control of its orbit and attitude. This enables the MEVs to manage all propulsion needs, including station-keeping, repositioning, and de-orbiting, ensuring that satellite services continue without interruption. What makes MEVs truly versatile is their ability to undock and move to another satellite after completing one life-extension mission, allowing them to serve multiple satellites over their operational lifetime. This reusability and adaptability make the MEVs a game-changer in the satellite servicing industry.

The technology powering MEV-1 and MEV-2 is at the forefront of space engineering. They utilize autonomous navigation systems equipped with a combination of optical, LIDAR, and RF sensors, enabling precise rendezvous and docking, the use of electric propulsion, specifically Hall-effect thrusters, provides efficient propulsion for the long-duration station-keeping and orbit transfer maneuvers required for servicing. The robust docking system is designed to interface with the standard apogee kick motor nozzle, a common feature on many geostationary satellites, allowing the MEVs to service a wide range of satellites without the need for modifications.[19]

5.3. NASA's Restore-L

NASA's Restore-L mission, now part of the broader OSAM-1 (On-orbit Servicing, Assembly, and Manufacturing 1) program, marks a significant leap in the way we manage and maintain space assets. At its core, the mission aims to extend the operational life of satellites by performing tasks such as refueling, repairing, and upgrading directly in orbit. This approach not only helps save costs by reducing the need to replace aging satellites but also mitigates the growing issue of space debris, making our space operations more sustainable. OSAM-1 is setting the stage for a future where long-term space missions, including those to the Moon and Mars, can be supported by a robust in-orbit infrastructure.

Equipped with highly dexterous robotic arms and a suite of specialized tools, the mission can autonomously rendezvous and dock with a target satellite, such as Landsat 7. Once docked, the robotic arms can perform complex tasks ranging from basic repairs to more sophisticated upgrades, like swapping out outdated components or installing new systems. This level of on-orbit servicing, combined with the mission's ability to refuel satellites, means that we can keep these valuable space assets operational far beyond their original lifespans, adapting them to new needs as technologies and requirements evolve.

To achieve these groundbreaking feats, OSAM-1 leverages cutting-edge technology. Its autonomous navigation and control systems, advanced sensors like cameras and LIDAR, enable the spacecraft to maneuver with incredible precision. The mission's fluid transfer system, designed to handle and transfer propellant in microgravity, underscores its capability to refuel satellites, a critical task for extending their missions. The use of modular tool storage and management allows OSAM-1 to carry a variety of tools, ensuring it's prepared for a wide range of servicing scenarios. Together, these technologies make OSAM-1 a pioneer in transforming how we think about space operations, moving us closer to a future where our satellites and spacecraft are not just launched, used, and abandoned, but cared for and continually optimized in orbit.[20]

5.4. DARPA Robotic Servicing of Geosynchronous Satellites (RSGS)

DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) program is a pioneering initiative designed to transform the way we maintain and manage satellites in geostationary orbit. This program aims to develop a robotic servicing spacecraft capable of performing a wide range of tasks, including repairs, inspections, refueling, and even upgrades directly in space. By offering these advanced in-orbit services, RSGS addresses a critical need in satellite operations: extending the life and functionality of satellites without the high costs and complexities of launching new ones. This not only helps save resources but also supports more sustainable space operations by reducing the frequency of satellite replacements.

Equipped with dexterous robotic arms, the vehicle can carry out precise operations such as replacing damaged components, handling intricate repairs, and installing new hardware, all while in orbit. Its autonomous navigation and docking systems are designed to approach and dock with satellites safely, utilizing a combination of sensors like cameras, LIDAR, and RF-based systems to ensure precision. Additionally, the spacecraft is outfitted with high-resolution cameras and diagnostic tools that allow it to inspect and assess the condition of satellites, providing invaluable data for operators. One of the standout features of RSGS is its ability to refuel satellites, which can significantly extend their operational life, along with performing orbit adjustments to optimize satellite performance or avoid potential collisions.

The significance of RSGS lies in its potential to revolutionize the economics and logistics of geostationary satellite operations. By enabling in-orbit servicing, RSGS reduces the need for costly and frequent satellite replacements, making satellite operations more cost-effective and resilient. The program employs cutting-edge technology, including robotic arms equipped with versatile tools for various servicing tasks, and advanced AI-driven systems for autonomous decision-making during complex operations. The navigation systems integrate data from multiple sensors to achieve precise docking in the challenging environment of space, and the refueling system is specifically designed to manage fluid transfers in microgravity. Together, these technologies make RSGS a game-changer in the field of satellite servicing, setting new standards for future space missions by emphasizing the adaptability, sustainability, and long-term resilience of our space assets.[21]

5.5. Phoenix (DARPA): An Innovative Approach to Satellite Servicing

The Phoenix program, initiated by DARPA in the early 2010s, was a visionary project aimed at transforming the way we think about satellite servicing by focusing on repurposing and salvaging parts from non-functional satellites in geostationary orbit. Instead of simply maintaining or refueling satellites, Phoenix took a more radical approach: it sought to "harvest" usable components, like antennas and other valuable parts, from decommissioned satellites and integrate them into new, functional spacecraft. The goal was to create a modular servicing system where defunct satellite pieces could be reused, thus significantly cutting costs and reducing the need for launching new satellites. This innovative strategy aligned with the broader goals of sustainability and efficient resource use in space, presenting a forward-thinking vision of how space operations could evolve.

Phoenix was designed with several advanced capabilities that set it apart from other satellite servicing missions. A key element was the development of a robotic arm capable of carefully disassembling old satellites and extracting components that could still be useful. These harvested parts would then be reassembled or combined with "satlets," small modular satellite units designed to integrate with these reclaimed components. The mission explored the use of cutting-edge robotics, autonomous rendezvous, and docking technologies, as well as innovative robotic manipulators that could perform precise operations in the harsh environment of space. The "servicer" spacecraft was envisioned to autonomously carry out complex tasks like cutting, grasping, and reassembling satellite components, showcasing a new level of ingenuity in space servicing. This approach not only aimed to make space operations more sustainable but also demonstrated a creative use of existing assets, pushing the boundaries of what satellite servicing could achieve.

Significance and Differences from RSGS:

While Phoenix and RSGS share a common goal of enhancing satellite servicing capabilities, their approaches and scopes differ significantly. Phoenix was unique in its focus on repurposing existing space assets, essentially treating old satellites as "space junk yards" from which valuable parts could be reclaimed. This contrasts with RSGS, which primarily aims at directly servicing operational satellites by performing repairs, refueling, and upgrades without dismantling them. Phoenix was more experimental and forward-thinking in its concept of reusability and modularity, pushing the boundaries of what satellite servicing could entail by not just maintaining but also creatively reusing space assets.

However, Phoenix faced significant technical and logistical challenges, and its ambitious goals were ultimately not realized as fully as planned. The project highlighted the complexities of working with aging and varied satellite designs and underscored the difficulties of autonomous robotic disassembly in the harsh environment of space. Despite these hurdles, Phoenix's innovative approach to satellite servicing set the stage for future missions that continue to explore modularity and reusability in space operations, making it a significant, though distinct, milestone compared to DARPA's RSGS program.[22]

5.6. ESA’s e.Deorbit Mission: Pioneering Space Debris Removal and Servicing

ESA’s e.Deorbit mission is a groundbreaking initiative aimed at addressing the growing problem of space debris, particularly in the heavily trafficked low Earth orbit. Launched as part of ESA's Clean Space initiative, e.Deorbit is primarily focused on demonstrating the capability to capture and remove large defunct satellites or debris using advanced robotic technologies. The mission represents a crucial step toward ensuring the long-term sustainability of space operations by actively reducing the risk of collisions that can generate even more debris

The capabilities of e.Deorbit are centered around its use of semi-autonomous robotic arms designed to grapple and control large objects in space. The spacecraft is equipped with advanced robotics capable of capturing and stabilizing defunct satellites or debris using precise manipulation. This involves complex operations like approaching the target, safely grabbing it, and then guiding it to a designated disposal orbit or reentry trajectory, where it can safely burn up in the Earth’s atmosphere. The robotic arms are designed with multiple degrees of freedom, allowing for flexibility and precision in capturing objects that may be tumbling or rotating. This capability not only demonstrates the removal of hazardous debris but also showcases the potential for robotic systems to service or reposition functional satellites in the future.

The technology used in e.Deorbit is at the cutting edge of space robotics and autonomous systems. The mission relies on a combination of high-precision sensors, including LIDAR, cameras, and radar, to detect, track, and approach target debris accurately. These sensors feed data into the spacecraft's autonomous navigation and control systems, enabling it to perform complex maneuvers without requiring constant input from ground operators. The robotic arms are equipped with specialized end-effectors designed to grasp a variety of satellite components, ensuring versatility in dealing with different types of debris. Additionally, the mission employs sophisticated algorithms for collision avoidance and motion control, making it capable of adapting to the unpredictable dynamics of space debris. By integrating these advanced technologies, e.Deorbit not only addresses the immediate challenge of space debris but also lays the groundwork for future missions that could expand into broader roles of satellite servicing and on-orbit maintenance, helping to keep our space environment safe and sustainable for generations to come.[23]

6. Successful development of space robots for on-orbit assembly and maintenance

6.1 Space robots in the International Space Station

Currently there are three robots in the ISS, the Canada’s Mobile Servicing System (MSS), that helps to give maintenance to the ISS; the European Robotic Arm (ERA) and the Japanese Experiment Module Remote Manipulator System (JEMRMS).

As mentioned before, the Robotic refueling Mission (RRM) is carried out by NASA to provide a constant refueling service of the spacecraft. These are just some examples of effective robots used in the ISS to provide maintenance and refueling services. [24]

6.2 The Skyworker Robot

Skyworker is one of the first mobile manipulators designed for orbital assembly, inspection, and maintenance, developed by Carnegie Mellon University in the 1990s. It autonomously transports payloads of various sizes using a continuous gait, optimized for power efficiency. The robot's "hand-over-hand" walking motion allows it to move efficiently on space structures, enabling it to perform tasks without impacting the design of the structure. Skyworker showcases key technologies for future robotic advancements in space, highlighting the benefits of attached mobile robots for orbital missions. [24]

6.3 The JAXA four-legged robot

JAXA has been researching the Space Solar Power System (SSPS) and developed a four-legged robot for on-orbit assembly and maintenance. This robot is designed to move gently across lightweight structures, capturing and connecting vibrating parts during assembly. Ground experiments show the feasibility of using multiple robots for tasks like assembling large, flexible structures. The four-legged robot demonstrates high precision and speed, making it suitable for constructing and maintaining complex space systems, ensuring stability and effectiveness in fragile environments. [24]

6.4 The FREND robot

The FREND mission, conducted by the Naval Research Laboratory, focuses on servicing satellites in orbit without pre-designed grappling interfaces. It aims to develop technology that enables robots to autonomously grapple non-cooperative targets, a major challenge in space servicing. FREND is a seven-degree-of-freedom robot equipped with machine vision and advanced control algorithms. It has successfully demonstrated satellite servicing capabilities in simulated orbital conditions and is undergoing further development to prepare for full spaceflight readiness. [24]

7. The future of autonomous robots for satellite maintenance in deep space missions

Autonomy is the characteristic of all spacecraft that doesn't require a ground operations team to operate. This autonomy has become increasingly important because of its application in long distance missions, to planets like Mars, the asteroid belt, or further away. [25]

Traditional deep space navigation relies on ground-based tracking, but autonomous methods, such as crosslink radiometric navigation (which uses inter-satellite communication), are gaining attention for reducing reliance on ground support. Navigation methods are categorized into onboard and offboard systems, where onboard methods rely on satellite autonomy, and offboard methods depend on ground-based support. [25]

One type of spacecraft that is important are the satellites, specifically small satellites, like the mini, micro, nano, pico, and femto satellites, which are increasingly being used for deep space exploration due to advances in miniaturization and overall mission success.

Some examples of notable past missions include PROCYON (2014), Hayabusa-2 (2018), and MarCO (2018).

However, despite these missions, there is still a long wait to go so we can have robots refueling and giving maintenance to satellites in deep space, like the satellite "Deep Space-1" or the satellite of the mission "Dawn" to go to the asteroids Ceres and Vesta. If we could have an autonomous robot that could go that far in space, maybe we could have longer missions, and in that case the Dawn mission wouldn't have ended because of lack of fuel.

CONCLUSIONS

The future of satellite maintenance and refueling relies heavily on advancements in robotic technology, innovative maintenance methods, collision avoidance systems, and robust ground support infrastructure. These components work together to enhance the sustainability and longevity of satellite operations in space.

It can be concluded that refueling capabilities can lead to cost savings, enhanced mission flexibility, and improved safety, making them a valuable consideration for modern space missions.

Hence, some key technologies the autonomous robots must have to be able to give an efficient refueling and maintenance service to satellites in space are: high degrees of freedom and robust interfaces for complex tasks, robots must avoid collisions and optimize movement paths considering external factors, advanced vision systems to recognize non-cooperative spacecraft, and long-duration power sources for sustained operation in space.

REFERENCE

[1] Jiang, Z., Cao, X., Huang, X., Li, H., & Ceccarelli, M. (2022). Progress and development trend of space intelligent robot technology. *Space Science & Technology*, *2022*. https://doi.org/10.34133/2022/9832053

[2] Anders, C., Roy, C. (2014): On orbit Spacecraft Servicing: An element in the evolution of space robotics applications. NASA Technical Reports Server.

[3] Tatsch A., Fitz-Coy N. (2006). Gladun S. On-orbit servicing: A brief survey. . NIST Special Publication. https://doi.org/10.6028/nist.sp.1062

[4] Opromolla, R., Grishko, D., Auburn, J., Bevilacqua, R., Buinhas, L., Cassady, J., Jäger, M., Jankovic, M., Rodriguez, J., Perino, M. A., & Bastida-Virgili, B. (2024b). Future In-Orbit servicing operations in the space traffic management context (section 1.1). *Acta Astronautica*, *220*, 469–477. https://doi.org/10.1016/j.actaastro.2024.05.007

[4] Opromolla, R., Grishko, D., Auburn, J., Bevilacqua, R., Buinhas, L., Cassady, J., Jäger, M., Jankovic, M., Rodriguez, J., Perino, M. A., & Bastida-Virgili, B. (2024b). Future In-Orbit servicing operations in the space traffic management context (section 2.12). *Acta Astronautica*, *220*, 469–477. https://doi.org/10.1016/j.actaastro.2024.05.007

[4] Opromolla, R., Grishko, D., Auburn, J., Bevilacqua, R., Buinhas, L., Cassady, J., Jäger, M., Jankovic, M., Rodriguez, J., Perino, M. A., & Bastida-Virgili, B. (2024b). Future In-Orbit servicing operations in the space traffic management context (section 2.2.2). *Acta Astronautica*, *220*, 469–477. https://doi.org/10.1016/j.actaastro.2024.05.007

[5] Zhang, Z., Li, X., Li, Y., Hu, G., Wang, X., Zhang, G., & Tao, H. (2023). Modularity, reconfigurability, and autonomy for the future in spacecraft: A review (section 2). *Chinese Journal of Aeronautics*, *36*(7), 282–315. https://doi.org/10.1016/j.cja.2023.04.019

[6] Flores-Abad, A., Ma, O., Pham, K., & Ulrich, S. (2014). A review of space robotics technologies for on-orbit servicing. *Progress in Aerospace Sciences*, *68*, 1–26. https://doi.org/10.1016/j.paerosci.2014.03.002

[7] Alexandrova, S., PhD. (2022). Future trends of commercial In-Orbit Satellite Servicing, Active Debris Removal and End-Of Life services. *Journal of Physics Conference Series*, *2255*(1), 012014. https://doi.org/10.1088/1742-6596/2255/1/012014

[8] Burkhardt, Z., O'Leary, A., Spessert, E., & Faber, D. (2023). Operational flexibility and asset retasking enabled by In-Space refueling. *ResearchGate*. https://www.researchgate.net/publication/368781143_Operational_Flexibility_and_Asset_Retasking_Enabled_by_In-Space_Refueling

[9] Das, H., Florini, P. (1993). Integrated tools for teleoperated satellite repair. Automation in Construction, 2 (1), 81-89. https://doi.org/10.1016/0926-5805(93)90037-X

[10] Gryniewski, L., Crymble, D., & Individual. (2007, March 9). *US20080237400A1 - Satellite refuelling system and method - Google Patents*. https://patents.google.com/patent/US20080237400A1/en.

[11] Smith, M. (2012). Hubble Space Telescope Servicing Missions. *NASA Goddard Space Flight Center*.

[12] Reilly, E. (2008). Orbital Express: A New Paradigm for Satellite Servicing. *Aerospace America*, 46(4), 26-30.

[13] Koryanov, V., Toporkov, A., & Pozdnyakov, A. (2021). The concept of a long-term service station to increase the life duration of some satellites or to remove space debris. *Journal of Space Safety Engineering*, *8*(1), 23–28. https://doi.org/10.1016/j.jsse.2021.02.002

[14] Sellmaier, F., Boge, T., Spurmann, J., Gully, S., Rupp, T., & Huber, F. (2010). On-Orbit Servicing Missions: Challenges and solutions for spacecraft operations. *SpaceOps 2010 Conference*. https://doi.org/10.2514/6.2010-2159

[15] Hatty, I. (2022). Viability of On-Orbit servicing spacecraft to prolong the operational life of satellites. *Journal of Space Safety Engineering*, *9*(2), 263–268. https://doi.org/10.1016/j.jsse.2022.02.011

[16] Bi, Z., Luo, C., Miao, Z., Zhang, B., & Zhang, C. W. (2020b). Automatic robotic recharging systems – development and challenges. *Industrial Robot the International Journal of Robotics Research and Application*, *48*(1), 95–109. https://doi.org/10.1108/ir-05-2020-0109

[17] Luu, M. A., & Hastings, D. E. (2022). On-Orbit servicing system architectures for proliferated Low-Earth-Orbit constellations. *Journal of Spacecraft and Rockets*, *59*(6), 1946–1965. https://doi.org/10.2514/1.a35393

[18] Thangavel, K., Sabatini, R., Gardi, A., Ranasinghe, K., Hilton, S., Servidia, P., & Spiller, D. (2024). Artificial intelligence for trusted autonomous satellite operations. *Progress in Aerospace Sciences*, *144*, 100960. https://doi.org/10.1016/j.paerosci.2023.100960

[19] George, S., Ash, A., Bessell, T., Frith, J., Scott, L., Skuljan, J., Furfaro, R., & Reddy, V. (2020). PHANTOM ECHOES: A Five-Eyes SDA experiment to examine GEO rendezvous and proximity operations. In *AMOS 2020 Conference* (16-18 September 2020, Virtual)

20] NASA. (2024, January 11). *Robotic Refueling Mission3-NASA*. https://www.nasa.gov/nexis/robotic-refueling-mission-3/

[21] Froehlich, A. (2020). *On-Orbit Servicing: next generation of space activities*. Springer.

[22] Ogilvie, A., Allport, J., Hannah, M., & Lymer, J. (2008). Autonomous robotic operations for on-orbit satellite servicing. In *Sensors and Systems for Space Applications II* (Vol. 6958, p. 695809). SPIE. https://doi.org/10.1117/12.784081

23. Bonnal, C., Ruault, J., & Desjean, M. (2013). Active debris removal: Recent progress and current trends. *Acta Astronautica*, *85*, 51–60. https://doi.org/10.1016/j.actaastro.2012.11.009

[24] Wang, Y., Li, D., Wang, Y., Tang, Z., Wang, N. (2016). Beijing Institute of Spacecraft System Engineering. https://robotics.estec.esa.int/ SAIRAS/isairas2016/Session4a/S-4a-2-WangYouyu.pdf

[25] Turan, E., Speretta, S., Gill, E. (2022). Autonomous navigation for deep space small satellites: Scientific and technological advances. Acta Astronautica, 193, 56-74. https://doi.org/10.1016/j.actaastro.2021.12.030.