# Space Debris Cleanup in Cost-Effective Way

By

Jayram Deshpande[1] and Mahantesh Hiremath[2]

[1]Founder/CEO
[2] Senior Vice President
Aadi Space Inc.
San Jose, California, USA
Aadi Space R&D Private Limited, Pune, Maharashtra, India

## 1. Introduction

Ladies and gentlemen, esteemed colleagues, I stand before you today as the Founder and CEO of Aadi Space Inc. (www.aadispace.com), based in San Jose, California and an office in Pune (Maharashtra, India), a company dedicated to addressing the challenge of On-Orbit Services, Space Sustainability and Space Debris Mitigation in a most cost-effective way. This will allow life extension and reuse of Space assets, safe and effective debris mitigation and make the Space economy truly circular.

The dream of a thriving space economy hinges on a critical but often overlooked issue: space debris. Low Earth Orbit (LEO), a prime location for constellations and future space stations, is becoming increasingly congested with defunct satellites, rocket parts, and fragments from collisions. This debris poses a significant threat to operational spacecraft, requiring expensive maneuvers to avoid catastrophic impacts. The Kessler Syndrome, a scenario where collisions create a cascading effect of debris generation, looms large if we fail to address this problem. The space debris is feared to have formed a cloud.

Current methods of space debris removal, such as grappling arms and specialized capture vehicles, are in their nascent stages and face significant challenges. They are often complex, expensive to launch, and limited in their ability to target a wide range of debris sizes. This high cost hinders large-scale cleanup efforts, leaving the space environment increasingly perilous.

This paper proposes a novel and cost-effective approach to debris removal: leveraging the potential of cheaper Orbital Transfer Vehicles (OTVs) that Aadi Space plans to develop. OTVs are spacecraft designed to maneuver payloads between different orbits. By equipping these vehicles with specialized capture mechanisms or utilizing their propulsion capabilities for controlled de-orbiting of debris, we can significantly increase the efficiency and affordability of cleanup efforts.

The benefits of such a strategy are manifold. A cleaner LEO environment translates directly to a more sustainable space economy. Reduced collision risks will lead to less frequent satellite replacements, minimizing launch costs and the associated environmental impact. Additionally, with less debris obstructing observation, scientific and Earth observation missions will become more effective.

Furthermore, a robust debris removal infrastructure will pave the way for the expansion of on-orbit servicing (OOS). OOS allows for the repair, refueling, and upgrading of satellites in space, extending their lifespans and maximizing their return on investment. A reliable OOS infrastructure in turn necessitates a clean and safe operational environment, creating a mutually beneficial cycle for both OOS and debris removal technologies.

This paper will explore the technical feasibility of utilizing cheaper OTVs for space debris removal. We will discuss the design considerations for capture mechanisms and de-orbiting strategies, considering the size, mass, and orbital parameters of different debris objects. Cost analyses will be conducted to demonstrate the economic viability of this approach compared to current methods. Finally, the paper will explore the long-term impact of an affordable debris removal strategy on the sustainability and growth of the space economy.

By implementing this cost-effective solution, we can usher in a new era of space exploration and utilization. A clean and safe space environment will not only ensure the continued success of existing missions but also open doors for groundbreaking innovations, fostering a thriving and sustainable space economy for generations to come.

## 2. Understanding Space Debris in LEO: A Looming Threat

Low Earth Orbit (LEO), the region roughly between 160 km and 2000 km above Earth's surface, is becoming increasingly crowded. This growing congestion brings with it a serious threat: space debris. Understanding the sources and types of debris, the risks they pose, and mitigation strategies is crucial for ensuring the sustainability of space activities.

### 2.1 Sources and Types of Space Debris

LEO is littered with millions of pieces of human-made junk, ranging from defunct satellites and rocket bodies to paint chips and shrapnel from collisions. These objects travel at tremendous speeds, creating a hazard for operational spacecraft. Let's explore the main culprits:

Fragmentation Events and Debris Clouds: These dramatic events, such as anti-satellite missile tests or accidental collisions, can shatter spacecrafts and rockets into thousands of pieces. These fragments form high-density clouds that significantly increase the collision risk for other objects.

Derelict Satellites and Rocket Bodies: Once their missions are complete, defunct satellites and upper stages of rockets remain in orbit. These "space junk" objects pose a threat due to their size and uncontrolled trajectories.

End-of-Life Considerations for Spacecraft: Even responsible planning for spacecraft disposal can contribute to debris. Satellites designed to burn up in Earth's atmosphere upon mission end may not completely deorbit, leaving small fragments behind.

These various sources contribute to a diverse population of space debris. The most numerous are small objects (less than 1 cm) that are difficult to track but can still damage spacecraft.  Larger objects (greater than 10 cm), though less frequent, pose a significant threat of catastrophic collisions.

### 2.2 Impact of Space Debris on Spacecraft Operations

The high speeds of space debris make even tiny objects incredibly dangerous.  A collision with a piece of debris as small as marble could critically damage or even destroy a satellite.  The consequences of such an event are far-reaching:

Collision Risks and Cascading Effects:  A collision with debris can trigger a domino effect.  The resulting fragments can collide with other objects, creating a chain reaction that exponentially increases the debris population.  This scenario, known as Kessler Syndrome, could render LEO unusable for future missions.

Disruptions to Critical Infrastructure:  Many aspects of modern life rely on satellites in LEO, including GPS navigation, communication networks, and weather forecasting.  Damage or destruction of these satellites by debris could have severe economic and social impacts.

These risks highlight the need for proactive debris mitigation strategies.

### 2.3 Debris Mitigation Strategies for Space Agencies

Space agencies around the world are working to address the growing problem of space debris.  Here are some key strategies being implemented:

#### 2.3.1 Post-Mission Disposal:
Encouraging spacecraft operators to deorbit their satellites at the end of their missions is crucial.  This can involve maneuvers to lower the orbit and allow atmospheric drag to take effect.

#### 2.3.2 Passivation of Upper Stages:
Rockets often release their upper stages into orbit after deployment.  Passivating these stages by depleting their fuel tanks minimizes the risk of future explosions that could create debris clouds.

#### 2.3.3 Collision Avoidance Techniques:
Spacecraft can be equipped with systems that detect and avoid debris.  These systems allow for maneuvers that steer the spacecraft clear of potential collisions.

#### 2.3.4 Active Debris Removal (ADR):
This ambitious approach involves developing technologies to capture and deorbit existing debris.  While still in its early stages, ADR has the potential to significantly reduce the overall debris population.

International cooperation is essential for effective debris mitigation.  By working together, space agencies can establish best practices, share data on debris tracking, and develop new technologies to ensure a sustainable future for space exploration and utilization of the LEO region.

Space debris in LEO poses a serious threat to the future of space activities. Understanding the sources and types of debris, the risks they pose, and the mitigation strategies being developed is crucial for addressing this challenge. Through continued international collaboration and technological advancements, we can ensure that LEO remains a safe and accessible environment for generations to come.

## 3. Current Methods for Space Debris Cleanup

The ever-growing presence of space debris poses a significant threat to operational spacecraft and future space exploration. With millions of pieces of debris whizzing around Earth at orbital velocities, even a tiny object can inflict catastrophic damage upon collision. To address this growing concern, space agencies and private companies are exploring various methods for space debris cleanup, with a focus on Active Debris Removal (ADR) missions, debris tracking, and international collaboration.

### 3.1 Active Debris Removal (ADR) Missions

ADR missions represent the most direct approach to space debris cleanup. These missions involve dedicated spacecraft equipped with capture mechanisms to grapple and deorbit defunct satellites or large debris pieces. The capture mechanisms can vary depending on the target object's size and shape. Some potential techniques include:

**3.1.1 Robotic Arms**: These extendable arms can physically grab onto a debris object.

**3.1.2 Docking Mechanisms**: These employ standardized interfaces to establish a secure connection with the target.

**3.1.3 Nets or Tethers**: These deployable nets or tethers can ensnare debris for controlled deorbiting.

Once captured, the debris is then deorbited through a controlled re-entry into Earth's atmosphere. The friction caused by the atmosphere burns up the object, effectively removing it from orbit. Deorbiting techniques can involve onboard propulsion systems for maneuvering the debris or utilizing natural atmospheric drag over an extended period. Alternatively, canisters with multiple tethering modules can be integrated on to existing satellite bus as an effective debris mitigation technique.

### 3.2 Capture Mechanisms and Deorbiting Techniques

The choice of capture mechanism and deorbiting technique depends on several factors, including:

**3.2.1 Debris Size and Shape**: Larger objects might necessitate robotic arms, while nets or tethers could be suitable for smaller, less defined debris.

3.2.2 Debris Material Composition: Certain materials might require specific capture techniques to avoid damage or fragmentation.

3.2.3 Operational Cost: Propulsion-based deorbiting can be expensive, while atmospheric drag relies on a longer timeframe.

### 3.3 Challenges and Limitations of Current ADR Technologies

Despite their potential, current ADR technologies face several challenges:

3.3.1 Technological Complexity: Developing and deploying robust capture mechanisms and reliable deorbiting systems requires significant technological advancements.

3.3.2 Cost: ADR missions are expensive due to the complexity of spacecraft design, launch costs, and potential risks involved.

3.3.3 Debris Diversity: The vast volume of debris in orbit exhibits a wide variety in size, shape, and material composition, requiring adaptable capture mechanisms.

3.3.4 Legal and Regulatory Issues: International regulations and agreements regarding debris ownership, liability, and mission conduct need to be established.

### 3.4 Debris Tracking and Monitoring Systems

Effective debris cleanup relies heavily on robust tracking and monitoring systems. These systems utilize ground-based radars and optical telescopes to detect, characterize, and track debris objects in orbit. This data is crucial for:

3.4.1 Mapping debris population: Identifying the number, size, and distribution of debris objects in various orbital regions.

3.4.2 Collision Risk Assessment: Predicting potential collisions between operational spacecraft and debris objects.

3.4.3 Targeting ADR Missions: Determining suitable debris targets for capture and deorbiting based on size, location, and collision risk.

### 3.5 Importance of Space Situational Awareness (SSA)

Space Situational Awareness (SSA) encompasses the knowledge and understanding of the near-Earth space environment, including the location and behavior of natural objects like asteroids and human-made objects like satellites and debris. Robust SSA capabilities are vital for:

### 3.5.1 Maintaining the safety of operational spacecraft: Identifying potential collision threats and enabling maneuvers to avoid them.

### 3.5.2 Optimizing ADR missions: Prioritizing targets for capture based on their risk potential.

### 3.5.3 Supporting future space exploration: Ensuring the long-term sustainability of space activities by addressing the debris issue.

## 3.6 International Collaboration for Debris Monitoring

The issue of space debris cleanup transcends national borders. International collaboration is crucial for establishing effective debris monitoring systems and coordinating ADR missions. This can be achieved through:

### 3.6.1 Sharing of tracking data: Collaborating on data gathered from radars and telescopes worldwide for a comprehensive picture of the debris environment.

### 3.6.2 Developing common standards: Establishing uniform protocols and communication channels for debris tracking and risk assessment.

### 3.6.3 Joint ADR missions: Partnering on missions to tackle large or high-risk debris objects, leveraging expertise and resources from multiple nations.

Addressing the growing threat of space debris requires a multi-pronged approach. Active Debris Removal missions offer a direct method for debris removal, but they face technological and economic challenges. Robust debris tracking and monitoring systems are essential for effective cleanup efforts. International collaboration on space debris management is critical for ensuring the long-term sustainability of space activities. By combining innovative technologies with international cooperation, we can safeguard the future of space exploration and ensure a clean and debris-free near-Earth environment.

# 4. Cheaper Orbital Transfer Vehicles: A Game Changer for Space Debris Removal?

The growing space economy faces a critical threat: orbital debris. Disused satellites, rocket parts, and fragments from collisions clutter Earth's orbit, posing a risk to operational spacecraft. Orbital Transfer Vehicles (OTVs), traditionally used to deliver satellites to their final positions, hold immense potential for addressing this issue – especially if their costs can be significantly reduced.

## 4.1 Advantages of Cost-Effective OTVs

Reduced Launch Costs and Mission Flexibility: Cheaper OTVs would make debris removal missions more financially viable. This would incentivize companies to invest in dedicated OTVs for debris clearing, or even allow for the development of smaller, more targeted OTVs designed for specific debris objects. This flexibility could lead to a more efficient and cost-effective approach to debris mitigation.

Reusable OTVs and Economic Sustainability: Reusable OTVs would be a game-changer. The high cost of launching a new OTV for each debris removal mission is a major hurdle. Reusable OTVs could significantly lower operational costs, making debris removal a more sustainable economic activity in the long run.

## 4.2 Challenges and Considerations for OTV Implementation

While cost-effective OTVs offer a promising solution, there are significant challenges to overcome:

Technological Advancements for Debris Grappling and Retrieval: Effectively capturing debris objects in space requires specialized grappling mechanisms. Current technology may not be sufficient for the wide variety of debris shapes and sizes. Advancements in grappling technology, including the ability to adapt to different debris characteristics, are crucial for successful debris removal missions.

Developing OTV Docking Procedures for Non-Cooperative Debris: Most operational satellites are designed for docking and servicing. Debris objects, however, are often non-cooperative, lacking designated docking ports or standardized interfaces. OTVs will need to be equipped with the ability to grapple with and potentially even secure onto irregular or damaged objects. This will require innovative solutions for debris capture and maneuvering.

Cheaper OTVs have the potential to revolutionize space debris removal. By reducing mission costs and enabling the development of reusable vehicles, they can create a more sustainable economic model for tackling this growing problem. However, significant technological advancements are needed in debris grappling and non-cooperative object handling. Overcoming these challenges will pave the way for a cleaner and safer space environment, fostering the continued growth of the space economy.

## 4.3 Aadi Space Solution to OOS using OTVs.

Aadi Space Inc. is positioning itself to be the premier solution provider for OOS and Debris Mitigation by its own set of multi-taking OTVs at a fraction of today's prices. Figure 1 depicts the type services that will be available from Aadi OTVS.

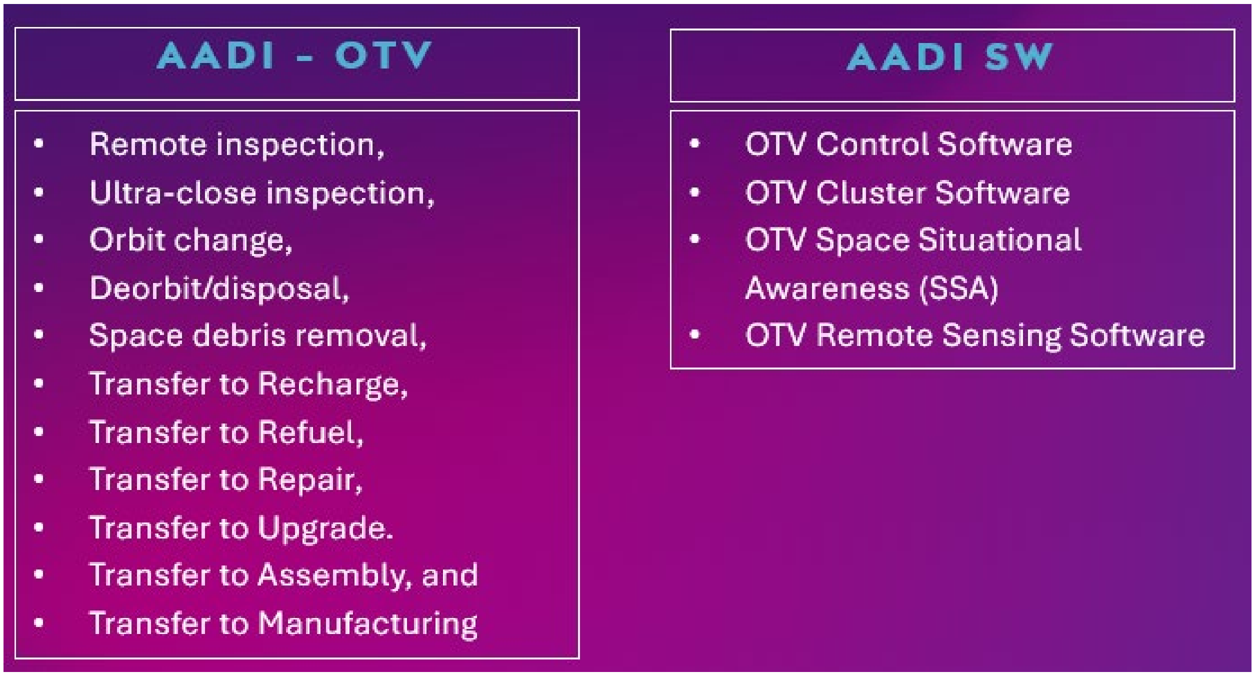


*Figure 1: Aadi Space OTVs and Their Utility*

## 5. Resulting Impact on Sustainability of Space Activities

As discussed earlier, the growing problem of space debris poses a significant threat to the future of space exploration and economic activity. Discarded rocket stages, defunct satellites, and collision fragments create a high-speed hazard for operational spacecraft. This debris can damage or destroy critical infrastructure, leading to costly disruptions in communication, navigation, and Earth observation services. Mitigating this threat requires innovative solutions, and cost-effective Orbital Transfer Vehicles (OTVs) offer a promising approach.

### 5.1 Economic Benefits of a Clean Space Environment

A clean space environment offers a plethora of economic benefits. Here's how:

**5.1.1 Reduced Launch Costs**: Debris avoidance maneuvers for operational spacecraft consume valuable fuel, increasing launch costs. Removing debris eliminates the need for such maneuvers, leading to significant cost savings for future launches.

**5.1.2 Improved Satellite Lifetime**: Debris collisions can shorten the lifespan of operational satellites. By mitigating debris risk, OTVs can extend satellite life, maximizing return on investment for operators.

**5.1.3 Unveiling New Orbital Opportunities**: With a reduced debris threat, previously unusable orbits become accessible. This opens doors for constellations with optimal coverage, scientific missions in cleaner environments, and exploration of untouched regions.

### 5.1.4 Stimulating the Space Economy

Debris removal creates a new market for specialized services. This fosters innovation, attracts private investment, and generates jobs within the burgeoning space industry.

A recent report estimates that the economic impact of uncontrolled debris growth could be substantial. Conversely, a clean space environment can unlock economic potential worth billions of dollars in the coming decades.

## 5.2 Reduced Risks for Satellite Constellations and Deep Space Missions

The proliferation of satellite constellations, particularly mega-constellations with thousands of satellites, exacerbates the debris problem. Collisions within constellations can create a domino effect, generating even more debris and jeopardizing the entire network. OTVs can play a crucial role in mitigating this risk by:

### 5.2.1 Deorbiting Non-functional Satellites

OTVs can capture defunct satellites and safely deorbit them, preventing them from becoming future debris sources.

### 5.2.2 Performing Collision Avoidance Maneuvers

OTVs can be used to maneuver operational satellites out of the path of potential collisions with debris, safeguarding critical infrastructure.

Deep space exploration also faces challenges due to debris. Asteroids and other celestial bodies can harbor debris hazards. OTVs can be equipped with sensors and targeting systems to identify and deflect such threats before they endanger spacecraft venturing beyond Earth's orbit.

## 5.3 Potential for New Space Debris Removal Services

The development of cost-effective OTVs opens doors for a new era of space debris removal services. Here's how this could work:

### 5.3.1 Public-Private Partnerships

Governments can collaborate with private space companies to develop and operate OTV fleets dedicated to debris removal. This model would leverage private sector expertise while ensuring a broader focus on long-term space sustainability.

### 5.3.2 Incentive Programs

Governments could create incentive programs to encourage private companies to develop and operate OTV-based debris removal services. These incentives could include tax breaks, subsidies, or guaranteed contracts for debris removal missions.

5.3.3 Standardization and Reusability: Standardization of OTV interfaces and components can reduce development costs and enable reusability. This allows for a more efficient and cost-effective approach to debris removal operations.

These initiatives can foster a vibrant space debris removal industry, providing solutions for both public and private entities.

### 5.4 Environmental Considerations and Long-Term Benefits

Debris removal activities must be conducted with environmental considerations in mind. OTVs should be designed to be refueled in space or utilize sustainable propellants to minimize the environmental footprint of their operations. Additionally, strategies should be developed to ensure safe and controlled re-entry of captured debris into Earth's atmosphere.

The long-term benefits of a clean space environment are undeniable. By removing existing debris and implementing stricter regulations for future launches, we can ensure a sustainable space environment for generations to come. This will allow us to:

5.4.1 Continue Exploring Space: A clean space environment paves the way for continued exploration of the cosmos, fostering scientific discovery and technological advancement.

5.4.2 Secure Critical Infrastructure: With reduced debris risk, we can ensure the continued functioning of critical infrastructure like communication, navigation, and weather monitoring satellites, upon which our daily lives increasingly depend.

5.4.3 Inspire Future Generations: A clean space environment inspires future generations to pursue careers in space exploration and fosters a sense of global responsibility towards our shared celestial neighborhood.

The development of cost-effective OTVs is a crucial step towards achieving this vision. Space debris is a growing threat to the sustainability of space activities. Cost-effective OTVs offer a promising solution by enabling the capture and removal of debris, thereby reducing risks for operational spacecraft, and unlocking new opportunities for space exploration. By investing in OTV technology, fostering international collaboration, and implementing responsible practices, we can secure a clean and

## 6. Building a Thriving Space Economy with Affordable On-Orbit Services

Aadi Space is proposing the use of cost-effective OTVs as a key driver for a robust space economy and the development of on-orbit servicing capabilities.

## 6.1 Economic Benefits of a Clean Space Environment:

### 6.1.1 Increased Investment and Insurance Availability: A space free of debris reduces risks for new ventures, encouraging investment and making space insurance more accessible. This fosters a more dynamic space industry.

### 6.1.2 Growth of On-Orbit Servicing Industry: OTVs enable regular maintenance and repair of existing satellites, creating a new service sector with significant commercial potential.

### 6.1.3 Life Extension for Existing Satellites: By servicing existing satellites, operators can extend their operational lifespan, maximizing their return on investment and delaying expensive replacements.

### 6.1.4 Debris Removal as a Core Service for On-Orbit Operations: OTVs can be used to remove debris from orbit, a critical service that ensures the long-term sustainability of space activities. This debris removal can become a core revenue stream for companies offering on-orbit servicing.

## 6.2 The Future of Space Exploration and Resource Utilization:

The success of this strategy extends beyond near-Earth space. Cost-effective OTVs will be crucial for:

### 6.2.1 Deep Space Exploration: OTVs can be used for refueling and maintenance of spacecraft venturing beyond Earth's orbit, enabling longer-duration missions and deeper exploration.

### 6.2.2 In-Space Resource Utilization (ISRU): OTVs can support the development of ISRU, where resources like water ice on the Moon or asteroids are extracted and utilized for further space exploration.

By facilitating a clean and accessible space environment, cost-effective OTVs pave the way for a vibrant space economy, enabling not only on-orbit servicing but also future space exploration and resource utilization endeavors.

6.3 Aadi Space - Overarching Solution Provider

Given the range of issues discussed along with Space debris management that need attention to sustain the Space economy, Aadi Space plans to be a premier solution provider (Figure 2) to many of the immediate needs.

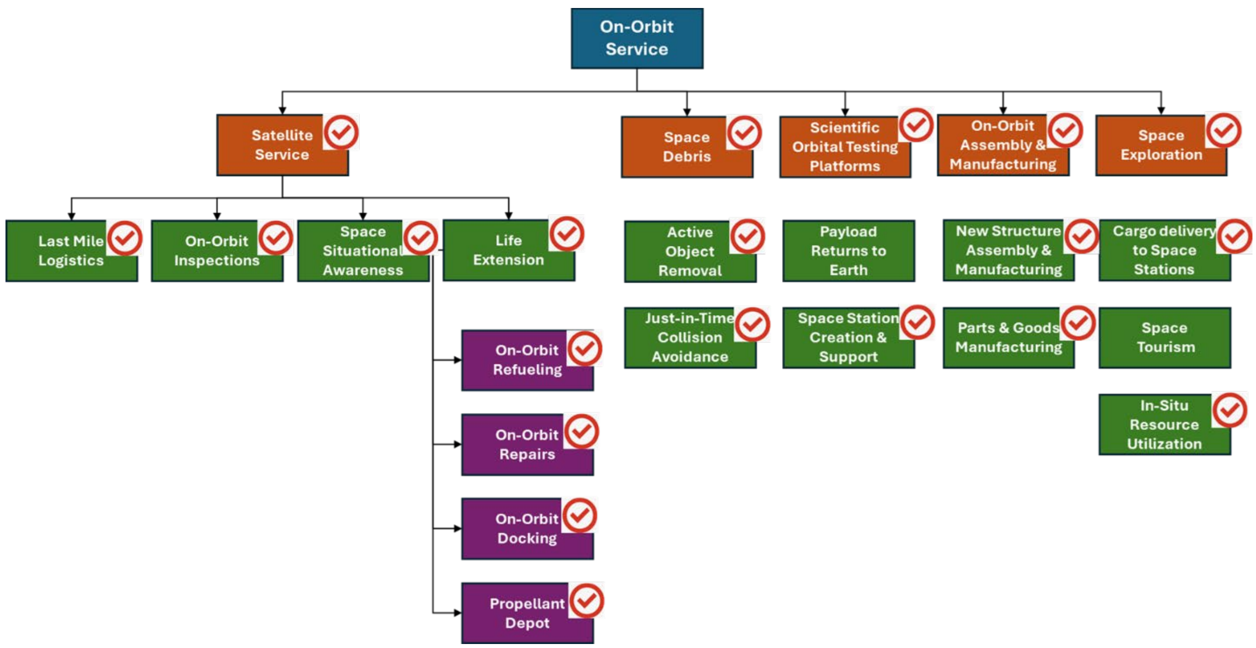


*Figure 2: Range of Aadi Space Solutions (Checkmarks indicate Aadi Support)*

## 7. Conclusion: A Cleaner Future Through Cost-Effective Debris Removal

This paper has highlighted the critical issue of space debris in Low Earth Orbit (LEO) and its growing threat to the burgeoning space economy. Current debris removal methods, while technically feasible, are often prohibitively expensive. However, the development of cheaper Orbital Transfer Vehicles (OTVs) offers a game-changing opportunity.

By deploying a fleet of cost-effective OTVs, we can significantly expedite debris removal efforts in LEO. This will not only mitigate the risk of collisions with operational spacecraft but also create a more sustainable space environment. A cleaner LEO will pave the way for the expansion of the space economy, enabling the deployment of larger constellations and fostering the growth of on-orbit servicing – a market projected to be worth billions in the coming decades.

The economic benefits of a proactive debris removal strategy extend beyond traditional spacefaring nations. By reducing the risks associated with space debris, we can encourage greater participation from developing nations, fostering international collaboration and scientific progress. This collaborative effort will not only ensure the long-term sustainability of space exploration but also unlock its vast potential for scientific discovery and economic growth.

Investing in cost-effective OTV technologies is not just about cleaning up a past mess; it's about securing a future where space is accessible, sustainable, and beneficial to all. By addressing the debris challenge head-on, we can unlock the true potential of the space economy and embark on a new era of exploration and innovation for the betterment of humanity.

## 8. Recommendation of A Three-Pronged Approach to Tackling Space Debris

Space debris poses a growing threat to satellites and future space exploration. To address this challenge in a cost-effective manner, advancements in three key areas are crucial: Orbital Transfer Vehicle (OTV) technology for debris capture and retrieval, economic models for debris removal missions, and standardized regulations for on-orbit servicing.

**8.1 Smarter Capture with Advanced OTVs**: Current methods for grabbing debris are limited. The next generation of OTVs needs to be more adept. Research and development should focus on versatile robotic arms, improved grappling mechanisms, and advanced sensors for precise debris characterization and manipulation. These advancements will enable OTVs to handle a wider range of debris sizes and materials, leading to more efficient capture and retrieval missions. Aadi Space will be at the forefront leading this effort.

**8.2 Economic Models for Sustainable Cleanup**: Debris removal missions are expensive. Developing robust economic models is essential for prioritizing targets and optimizing mission planning. These models should consider factors like debris size, potential collision risk, and ease of capture. Additionally, exploring public-private partnerships and creating debris removal incentives can attract investment and make debris removal financially viable.

**8.3 Standardization for Safe and Efficient On-Orbit Servicing**: As on-orbit servicing becomes more prevalent, clear regulations and standardized practices are needed to ensure safety and prevent additional debris creation. Standardization should cover areas like debris categorization, docking protocols for debris capture by OTVs, and post-mission debris disposal procedures. This will streamline operations, minimize risks, and foster collaboration between space agencies and private companies.

By focusing on these three areas – advanced OTV technology, economic models, and standardized regulations – we at Aadi Space believe that we can develop a more cost-effective and sustainable approach to space debris cleanup. This will ensure a cleaner and safer space environment for future generations of space exploration.

## 9. References


1. *Understanding the Orbital Transfer Vehicle Trade Space*, Hugh McManus, and Todd Schuman, AIAA Space-2003, Long Beach, CA.
2. *Small Orbit Transfer Vehicle (OTV) for On-Orbit Satellite Servicing and Resupply*, John T. Collins, Hans F. Meissinger, and Robert Bell, 15th Annual/USU Conference on Small Satellites, 2001.
3. *Orbital Transfer Vehicle Concept Definition and System Analysis Study,* Glen Dickman and J. Keeley, NAS8-36108, 1987.