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Design of Robotic Arm for Active Space Debris Tracking and Analysis

Neha K M[*]

ORCID: 0009-0005-1704-4899

Akash C N[†]

ORCID: 0009-0002-2547-4408

Sonal Sanjay Vernekar[‡]

ORCID: 0009-0002-9395-7356

Punith Babu C[§]

ORCID: 0009-0000-2941-5064

MVJ College of Engineering, Bangalore, Karnataka, India

Abstract: Space debris, or orbital debris, presents substantial challenges to space exploration due to collision risks and threats to spacecraft. This project addresses these challenges by introducing an advanced tracking framework utilizing cutting-edge technologies to enhance data precision for predicting and managing space debris trajectories. The framework includes a predictive model guiding the deployment of a flexible webbed robotic arm, strategically positioned to mitigate collision risks and optimize efficiency in debris collection. The robotic arm, designed using Catia V5, features a flexible length mechanism and a web structure made of highly flexible polymer, enabling it to navigate complex orbital spaces and delicately capture space debris. Structural analysis using Ansys ensures the arm's resilience in collisions and informs optimal design refinements for enhanced performance and durability. Integration of GMAT, ORDEM, and DAS with MATLAB facilitates dynamic and accurate mapping, providing a robust system for monitoring space debris and enabling informed decision-making for debris mitigation efforts. This comprehensive approach contributes to the advancement of space debris management and space exploration safety.

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1. Introduction

Space debris, comprising defunct satellites, spent rocket stages, and other fragments, poses a critical threat to space operations and exploration due to collision risks and impacts on satellite functionality. As of 2019, there were over 128 million debris pieces smaller than 1 cm and thousands larger than 10 cm in Earth's orbit [1], with the United States Space Surveillance Network reporting over 25,000 artificial objects in orbit by November 2022 [2]. The exponential growth of space debris not only heightens collision risks but also undermines the sustainability of space activities and exploration [3]. Current efforts to mitigate this threat involve tracking, debris removal technologies, and regulatory frameworks for effective management. However, existing debris tracking systems are limited, necessitating the development of an autonomous robotic arm capable of actively collecting and tracking space debris. This study aims to address this challenge by introducing a novel framework employing

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[*] UG Research Scholar, MVJ College of Engineering, Bangalore, India. **Corresponding Author: nehakmath24@gmail.com**
[†] UG Research Scholar, MVJ College of Engineering, Bangalore, India. **Contact: cnakash2001@gmail.com**
[‡] UG Research Scholar, MVJ College of Engineering, Bangalore, India. **Contact: sonalvernekar432@gmail.com**
[§] UG Research Scholar, MVJ College of Engineering, Bangalore, India. **Contact: punithbabuc@gmail.com**
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advanced technologies for precise tracking and decommissioning of space debris. The primary objective is to simulate satellite launches and space junk capture using a webbed robotic arm, thereby contributing to enhanced space debris management and sustainable space operations. Achieving these objectives requires overcoming technological hurdles to design a precise, adaptable, and autonomous robotic system suitable for the dynamic space environment, highlighting the importance of international collaboration and regulatory frameworks for its successful development and deployment.

2. Scientific Methods and Materials

Design and Construction of the Robotic Arm: The robotic arm was designed using Solid Edge software, facilitating detailed modeling and optimization of its structure. Featuring four degrees of freedom (4-DOF), the arm incorporates a claw mechanism with adjustable length for enhanced functionality. The design process ensured flexibility in movement and adaptability through the adjustable claw.

Materials for Robotic Arm: After conducting an extensive literature survey, Aluminium 7050 alloy was determined to be the optimal material for the robotic arm construction. This alloy, part of the 7000 series, exhibits high strength, excellent corrosion resistance, and favorable machinability, essential for robotic arm applications. The alloy contains zinc, chromium, and copper as major alloying elements, contributing to its strength and durability.

Materials for Web of Robotic Arm: The web of the robotic arm is composed of Vectran fiber, a high-performance synthetic fiber known for its exceptional strength, durability, and resistance to environmental conditions. Vectran fiber is spun from a liquid polymer precursor through a complex manufacturing process, resulting in properties such as:

- Density: 1.40 g/cm^3
- Tensile strength: 3.4 GPa
- Tensile modulus: 70 GPa
- Elongation at break: 4%
- Moisture regain: <0.1%
- Rupture work: 40 mN/tex

Flexibility and Control Mechanisms: The flexibility of the robotic arm is achieved through sophisticated tendon routing mechanisms, meticulously monitored by actuators. This control system enables precise manipulation and adaptability crucial for navigating through space debris fields and capturing objects of varying sizes and shapes.

Gripper Mechanism: At the business end of the robotic arm, the gripper operates on the principle of a worm gear mechanism, ensuring secure and reliable grasping of debris items. This design allows for efficient collection and containment within the webbed structure.

Data Analysis of Space Debris: Analysis of space debris was conducted using Ordem and GMAT software tools. Various analyses, including average flux versus size, butterfly graph, and velocity distribution, were performed to enhance understanding of space debris dynamics, aiding in collision risk assessment and trajectory planning for space missions.

Criteria for Debris Selection: Debris selection criteria involved comparing debris velocities and inclinations against orbital time graphs, facilitating comprehensive analysis using GMAT software. Selected debris underwent thorough evaluation to identify potential collision risks and develop space debris management strategies, ensuring efficient monitoring and mitigation in orbital environments.

3. Results

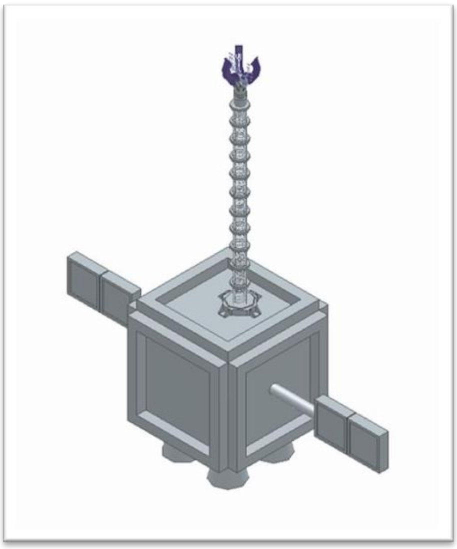
The results of our study and subsequent discussions offer insights into our findings. Through thorough discussion, we interpret the implications of these results within the context of our research objectives, drawing connections to existing literature and theories. Additionally, we address limitations, potential biases, and avenues for further investigation. Overall, this chapter serves as a critical component of our research, illuminating key findings and advancing our understanding of the subject matter.

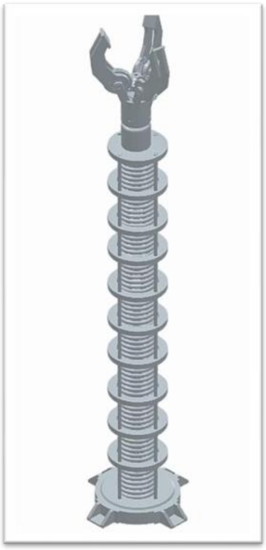
3.1. Design of Robotic Arm

3.1.1. Design Results

- ***Innovative Integration:*** Combining a webbed gripper with a continuum robotic arm boasting variable length and flexibility represents a groundbreaking approach in robotics.
- ***Enhanced Manipulation:*** The integrated system showcases superior dexterity, adeptly grasping diverse objects and navigating through complex environments.
- ***Optimized Performance:*** Experimental results demonstrate efficient handling of objects of varying sizes and shapes, highlighting the system's optimized performance.
- ***Versatile Applications:*** The system's adaptability renders it suitable for a wide array of applications across industries, from manufacturing to extraterrestrial exploration.
- ***Efficiency and Reliability:*** Rigorous testing confirms the system's reliability and efficiency, ensuring consistent performance in designated tasks.
- ***Future Challenges:*** Calibration precision and control optimization pose ongoing challenges, warranting further research for improved accuracy and responsiveness.
- ***Impact and Contribution:*** This innovative design has the potential to revolutionize robotics, offering solutions to complex challenges and advancing automation and human-machine interactions.

Limited availability of materials and technology has restricted the implementation of the webbed arm design in the gripper reframe. Given the limited resources, we have prioritized other essential functionalities or aspects of the gripper reframe design over the implementation of the webbed arm, opting for a simpler, more feasible solution.





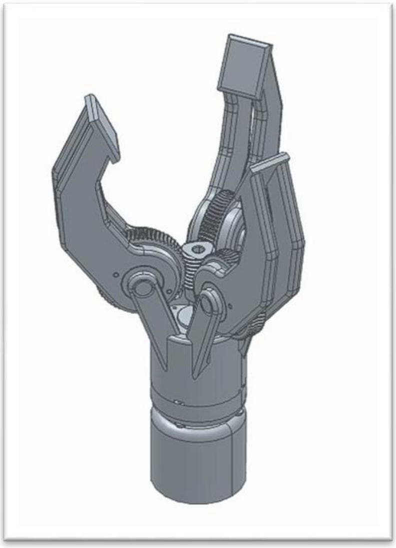


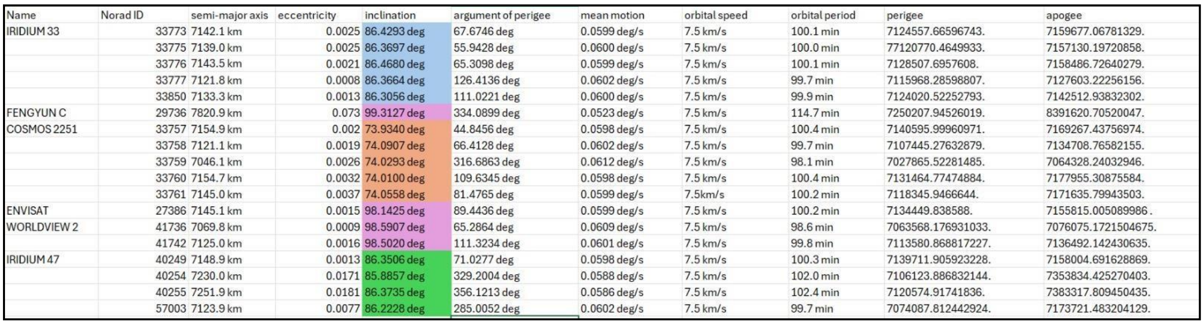
Figure-1 (Left) Robotic Arm Affixed to a Satellite; Figure-2 (Center) Flexible Robotic Arm; Figure-3 (Right) Gripper

3.2. Debris Selection and Analysis

3.2.1 Criteria for Debris Selection

- Debris selection criteria involve comparing debris velocities and inclinations against orbital time graphs.
- Orbital time graphs serve as a reference for analyzing debris behavior and trajectory characteristics.
- Selected debris undergo comprehensive analysis, including data collection and tracking using GMAT software.
- GMAT software facilitates precise tracking and analysis of debris trajectories over time.
- Evaluation of debris characteristics enables the identification of potential collision risks and space debris management strategies.
- The process ensures efficient monitoring and mitigation of space debris threats in orbital environments.

Table-1 List of Selected Debris and Their Data



Name	Norad ID	semi-major axis	eccentricity	inclination	argument of perigee	mean motion	orbital speed	orbital period	perigee	apogee
IRIDIUM 33	33773	7142.1 km	0.0025	86.4293 deg	67.6746 deg	0.0599 deg/s	7.5 km/s	100.1 min	7124557.66596743.	7159677.06781329.
	33775	7139.0 km	0.0025	86.3697 deg	55.9428 deg	0.0600 deg/s	7.5 km/s	100.0 min	77120770.4649933.	7157130.19720858.
	33776	7143.5 km	0.0021	86.4680 deg	65.3098 deg	0.0599 deg/s	7.5 km/s	100.1 min	7128507.6957608.	7158486.72640279.
	33777	7121.8 km	0.0008	86.3664 deg	126.4136 deg	0.0602 deg/s	7.5 km/s	99.7 min	7115968.28598807.	7127603.22256156.
	33850	7133.3 km	0.0013	86.3056 deg	111.0221 deg	0.0600 deg/s	7.5 km/s	99.9 min	7124020.52252793.	7142512.93832302.
FENGYUN C	29736	7820.9 km	0.073	99.3127 deg	334.0899 deg	0.0523 deg/s	7.5 km/s	114.7 min	7250207.94526019.	8391620.70520047.
COSMOS 2251	33757	7154.9 km	0.002	73.9340 deg	44.8456 deg	0.0598 deg/s	7.5 km/s	100.4 min	7140595.99960971.	7169267.43756974.
	33758	7121.1 km	0.0019	74.0907 deg	66.4128 deg	0.0602 deg/s	7.5 km/s	99.7 min	7107445.27632879.	7134708.76582155.
	33759	7046.1 km	0.0026	74.0293 deg	316.6863 deg	0.0612 deg/s	7.5 km/s	98.1 min	7027865.52281485.	7064328.24032946.
	33760	7154.7 km	0.0032	74.0100 deg	109.6345 deg	0.0598 deg/s	7.5 km/s	100.4 min	7131464.77474884.	7177955.30875584.
	33761	7145.0 km	0.0037	74.0558 deg	81.4765 deg	0.0599 deg/s	7.5km/s	100.2 min	7118345.9466644.	7171635.79943503.
ENVISAT	27386	7145.1 km	0.0015	98.1425 deg	89.4436 deg	0.0599 deg/s	7.5 km/s	100.2 min	7134449.838588.	7155815.005089986 .
WORLDVIEW 2	41736	7069.8 km	0.0009	98.5907 deg	65.2864 deg	0.0609 deg/s	7.5 km/s	98.6 min	7063568.176931033.	7076075.1721504675.
	41742	7125.0 km	0.0016	98.5020 deg	111.3234 deg	0.0601 deg/s	7.5 km/s	99.8 min	7113580.868817227.	7136492.142430635.
IRIDIUM 47	40249	7148.9 km	0.0013	86.3506 deg	71.0277 deg	0.0598 deg/s	7.5 km/s	100.3 min	7139711.905923228.	7158004.691628869.
	40254	7230.0 km	0.0171	85.8857 deg	329.2004 deg	0.0588 deg/s	7.5 km/s	102.0 min	7106123.886832144.	7353834.425270403.
	40255	7251.9 km	0.0181	86.3735 deg	356.1213 deg	0.0586 deg/s	7.5 km/s	102.4 min	7120574.91741836.	7383317.809450435.
	57003	7123.9 km	0.0077	86.2228 deg	285.0052 deg	0.0602 deg/s	7.5 km/s	99.7 min	7074087.812442924.	7173721.483204129.

3.2.2 Space Debris Analysis

Average Flux vs. Size Graph:

This graph depicts the Average Flux vs. Size along a spacecraft orbit, showcasing cumulative particle flux data. It serves as a standard metric for assessing the debris environment, utilized in ORDEM and ESA's MASTER series. The graph includes differentiation between flux values and their corresponding one-sigma uncertainties, both minimum and maximum. The plotted data provides insights into the distribution of particles encountered by satellites during orbit. Such visualizations are crucial for understanding and mitigating risks posed by space debris.

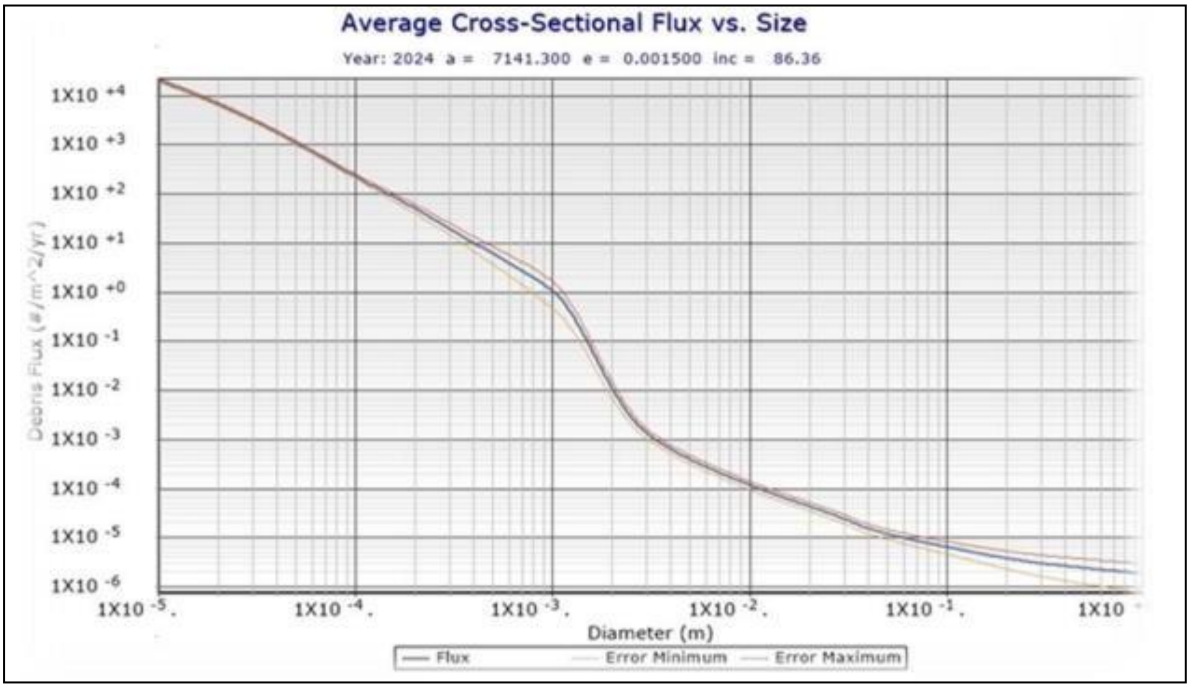


Figure-4 Average Flux vs. Size graph of Iridium-33 deb

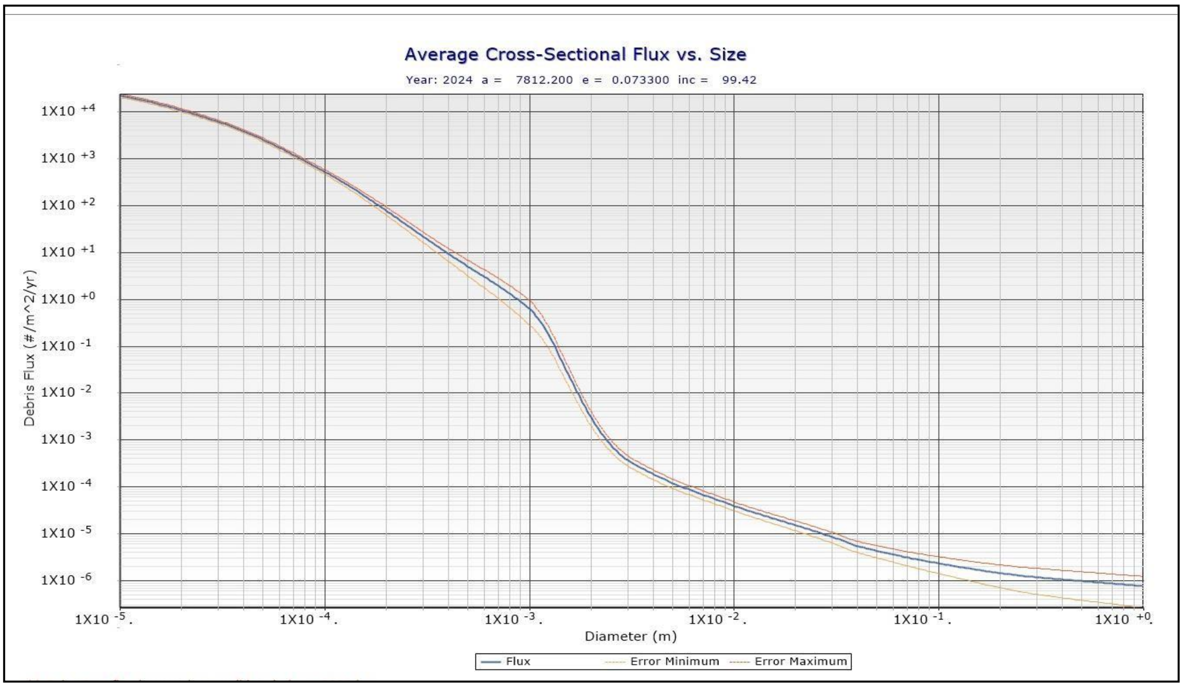


Figure-5 Average Flux vs. Size graph of Fengyun C deb

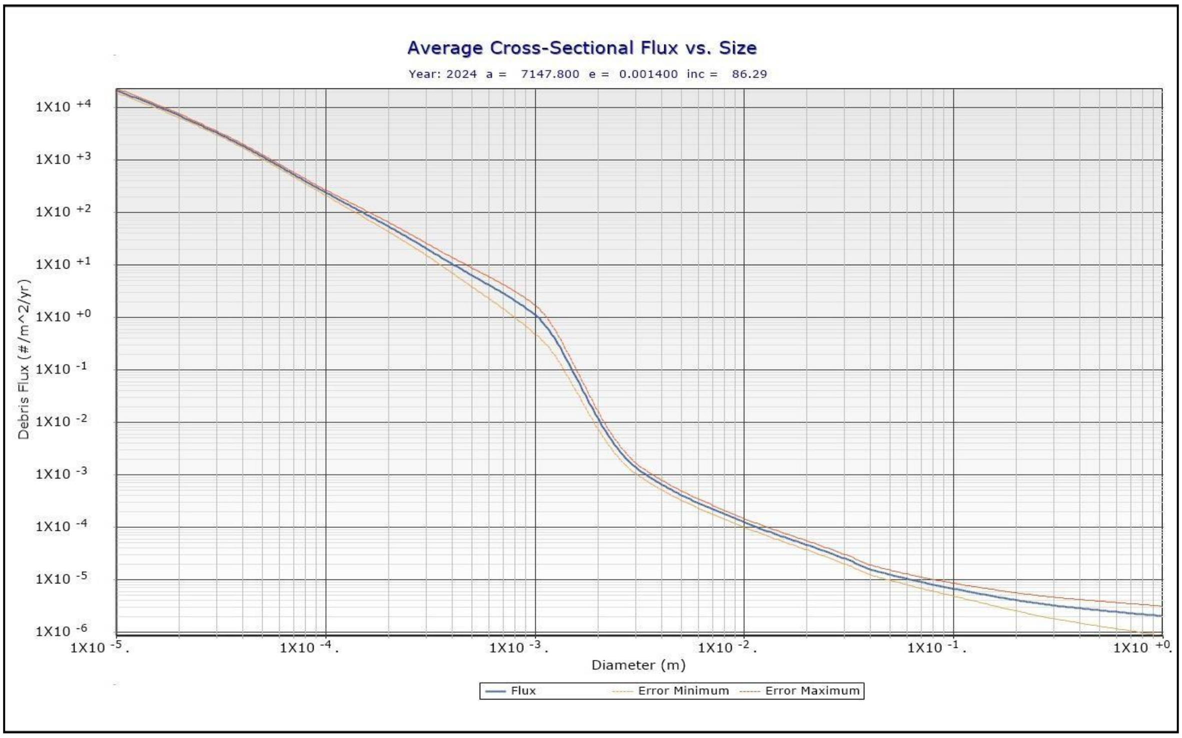


Figure-6 Average Flux vs. Size graph of Irridum-47 deb

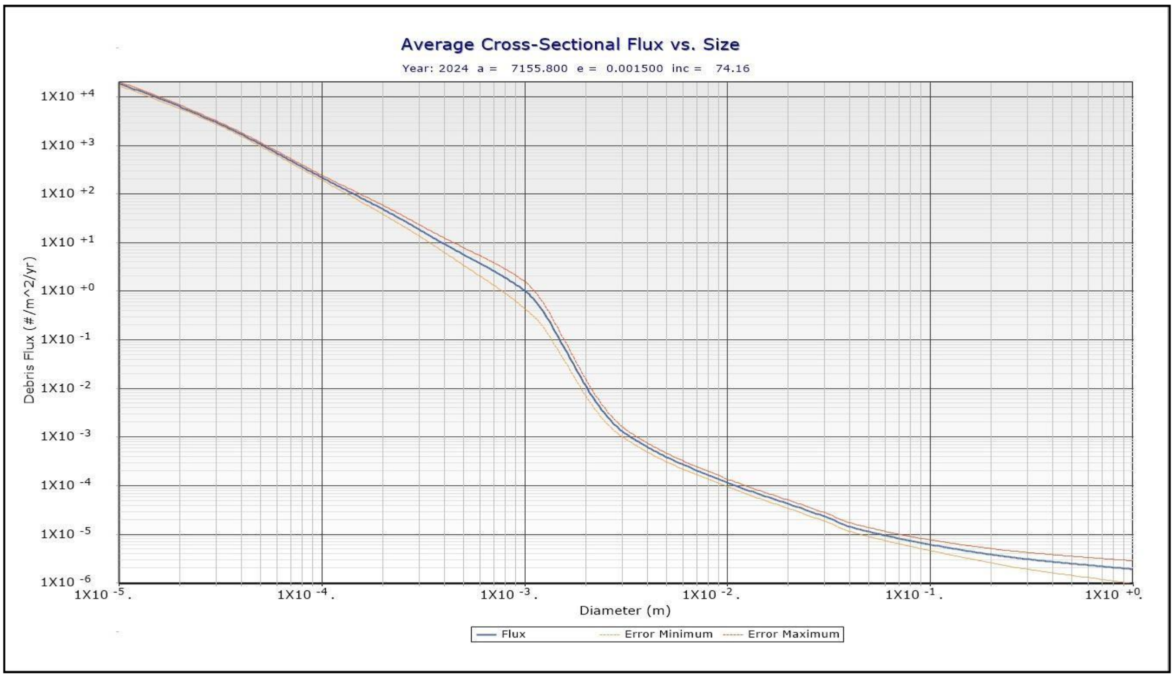


Figure-7 Average Flux vs. Size graph of Cosmos 2251 deb

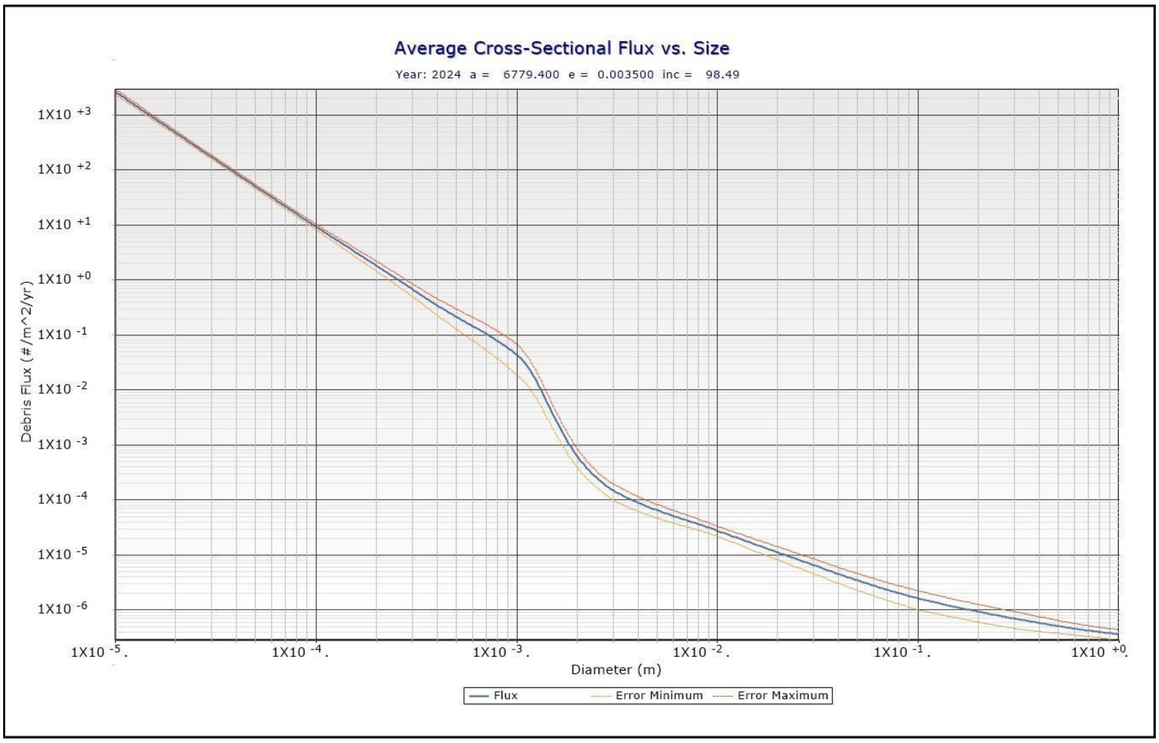


Figure-8 Average Flux vs. Size graph of Worldview 2 deb

Butterfly Graph

This figure represents average directional fluxes on the spacecraft from all directions, in three dimensions. These fluxes are summed and then collapsed to the 2-D spacecraft plane defined by the velocity and angular momentum vectors.

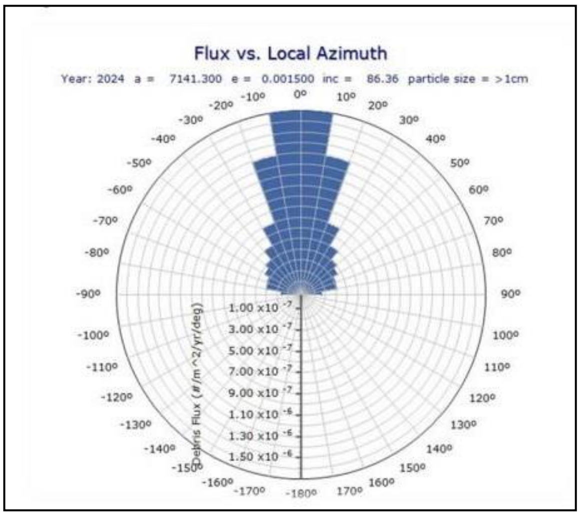


Figure-9 Butterfly graph of Iridium-33 deb

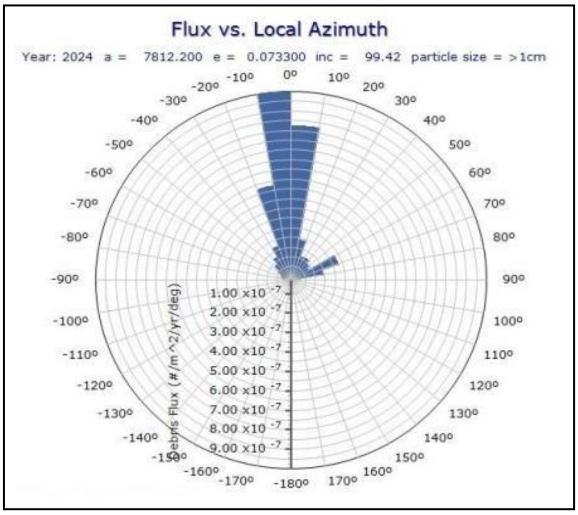


Figure-10 Butterfly graph of Fengyun C deb

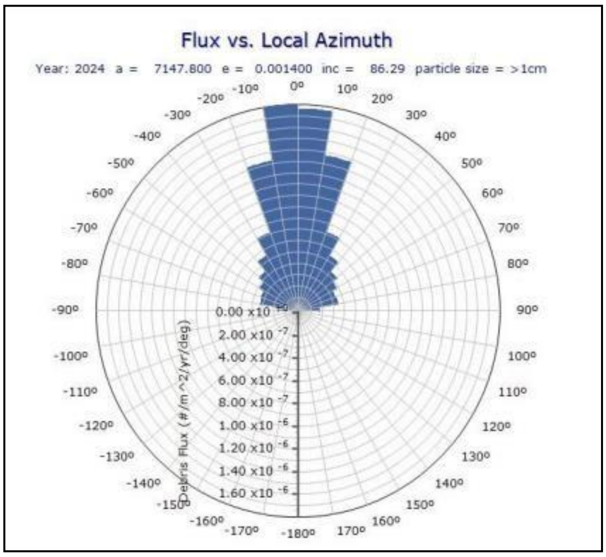


Figure-11 Butterfly graph of Irridum-47 deb

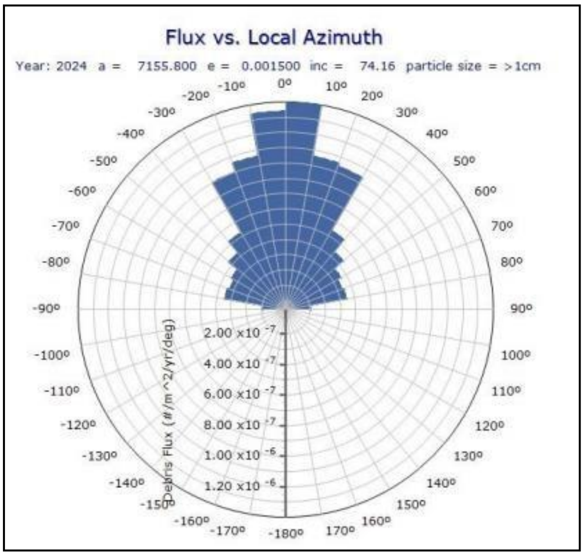


Figure-12 Butterfly graph of Cosmos 2251 deb

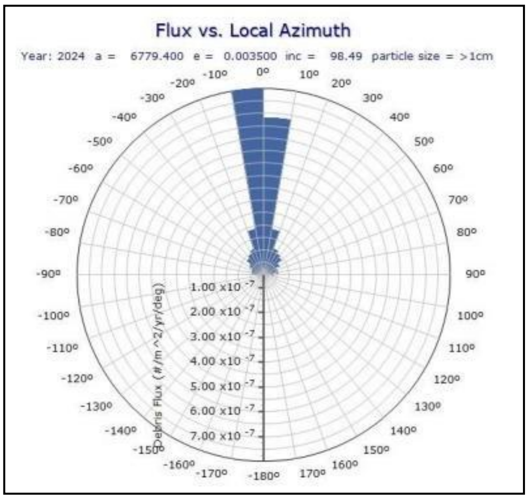


Figure-13 Butterfly graph of Worldview 2 deb

Velocity Distribution Graph

The velocity distribution graph from ORDEM provides a visual representation of the distribution of velocities exhibited by space debris in orbit. By plotting velocity values along the x-axis and the corresponding frequency or occurrence along the y-axis, the graph illustrates the range and prevalence of different velocities within the debris population. This analysis offers valuable insights into the dynamics of space debris movement, helping to understand the relative speeds of objects and their potential collision risks with operational satellites and spacecraft.

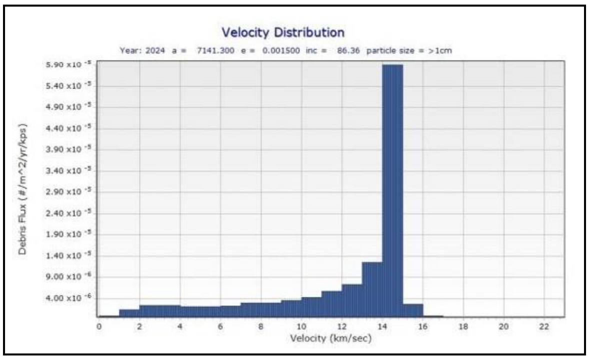


Figure-14 Velocity distribution of Iridium-33 deb

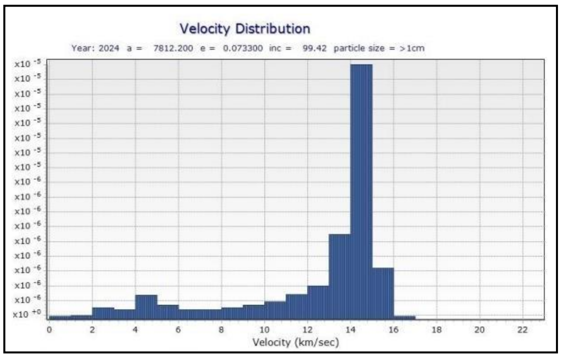


Figure-15 Velocity distribution of Fengyun C deb

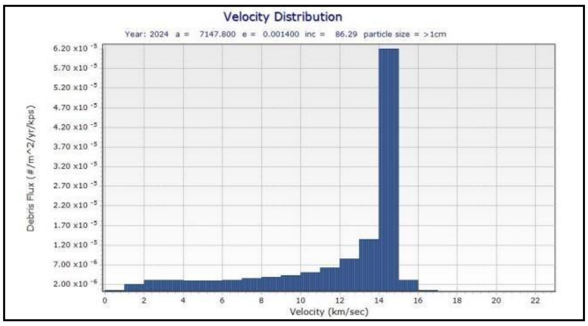


Figure-16 Velocity distribution of Irridum-47 deb

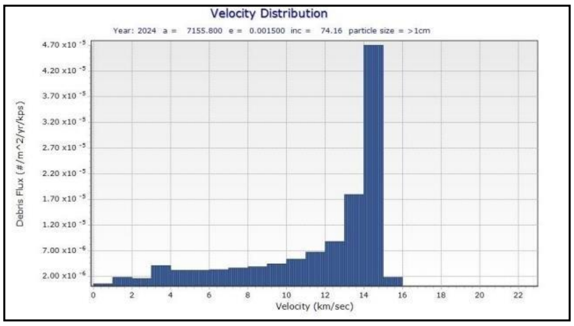


Figure-17 Velocity distribution of Cosmos 2251 deb.

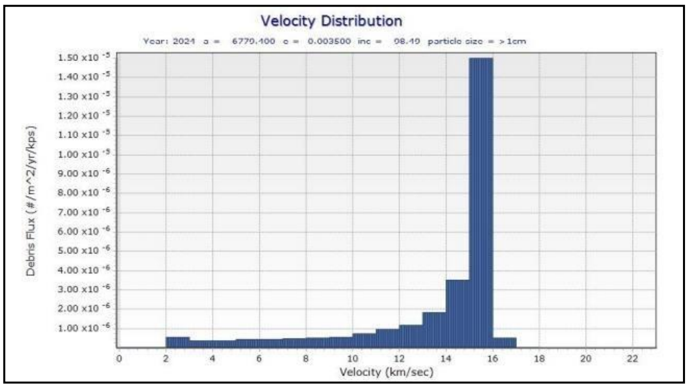


Figure-18 Velocity distribution of Worldview 2 deb.

4. Conclusion

In this exhaustive review paper, an in-depth examination of the burgeoning field of telemetry data anomaly In conclusion, the objectives of achieving successful tracking and decommissioning of space debris data, as well as simulating the launching of satellites and capturing space junk using a webbed robotic arm, have been met. Through diligent research and development, we have established a framework for efficient space debris management. The integration of advanced tracking technologies and the innovative use of a webbed robotic arm demonstrate our commitment to addressing the pressing challenges of space debris mitigation. Looking ahead, these advancements pave the way for future applications, such as enhanced debris removal missions, autonomous space infrastructure maintenance, and sustainable space exploration endeavors. This project not only contributes to the advancement of space exploration but also lays the groundwork for future initiatives aimed at ensuring the sustainability of space activities.

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6. Team Biography

The team behind the innovative project "Design of Robotic Arm for Active Space Debris Tracking and Analysis" comprises a group of dynamic engineers and space enthusiasts dedicated to advancing the field of space technology. Led by seasoned professionals with diverse backgrounds in robotics, aerospace engineering, and systems analysis, the team is driven by a shared passion for exploring the frontiers of space exploration. Neha K M, the project's founder, brings visionary leadership and expertise in aerospace engineering to the table, while Akash C N contributes technical prowess and creative ingenuity. Sonal Sanjay Vernekar, with a keen eye for detail and dedication to excellence, enhances the team's capabilities, and Punith Babu C's skills in engineering and problem-solving round out the quartet. Together, this dynamic team combines their skills, knowledge, and enthusiasm to tackle the pressing issue of space debris management. With a commitment to innovation and collaboration, they are poised to make meaningful contributions to the advancement of space technology and exploration. This project was presented at National Space Science Symposium 2024 held at Goa University.

7. Acknowledgement

We extend our heartfelt gratitude to all whose support and contributions have been instrumental in realizing this project's success.

8. Conflict of Interest

The author declare no competing conflict of interest.

9. Funding

No funding was received to support this study.