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Design And Development of a Robotic Arm for Space Debris Mitigation Using Electrostatic and Gecko-Inspired Gripping Technologies

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Abstract: As space debris poses a growing threat to satellite operations, there is an urgent need for advanced robotic systems capable of effective debris capture in low Earth orbit. This paper presents the development and optimization of a robotic arm equipped with an electrostatic adhesion mechanism, designed specifically for microgravity environments. The primary objective is to engineer a versatile, lightweight robotic arm that can securely capture and hold various types of debris, including non-magnetic and composite materials. Key features include electrostatic adhesive pads for adaptable grip, a telescopic extension arm to increase reach with minimal mechanical complexity, and a retractable storage profile to streamline debris retrieval and handling. Through detailed calculations, we establish the required adhesive force to counter both inertial and gravitational forces acting on debris, ensuring secure capture even during minor satellite manoeuvres. An electrostatic charging system is designed to induce sufficient adhesive force, with calculations for charge requirements and pad dimensions optimized for secure adhesion. This paper details the design, force calculations, and component selection that make the robotic arm efficient, lightweight, and adaptable, contributing to safer, more effective space debris removal.

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1. Introduction

With the exponential growth of satellite launches and the persistence of inactive satellites and fragmented parts, space debris has become a major threat to operational satellites and future space missions. Orbital debris, traveling at high velocities, poses a collision risk to functioning spacecraft and can significantly damage or render them inoperable. To address this growing issue, novel debris capture technologies are essential for mitigating risk and ensuring the longevity of satellite infrastructure. One promising approach leverages electrostatic adhesion, a technique that can attract and securely capture debris in microgravity environments where conventional mechanical gripping methods may prove less effective. This paper explores a conceptual debris capture system designed for a microgravity setting, focusing on calculating and optimizing the adhesive force required to secure debris in orbit. The proposed system uses an electrostatic charging mechanism to attract debris to an adhesive pad on a robotic arm, thereby providing a non-invasive and adaptable solution to space debris collection. The effectiveness of electrostatic adhesion depends largely on two critical factors: the adhesive force required to counteract both inertial and gravitational influences on debris in low Earth orbit, and the electrical charge needed to create a sufficient adhesive force. We calculate the necessary force to counter inertial effects due to satellite movement, estimating the adhesive force needed to prevent debris displacement in response to minor orbital manoeuvres. Additionally, we analyse the gravitational forces acting at an 800 km altitude, where a gravitational acceleration of approximately 7.724 m/s² requires the adhesion system to apply a force that exceeds the gravitational pull on a 0.5 kg debris mass. Using Coulomb's law, we derive the necessary surface charges to

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produce this force and determine the optimal pad area to ensure effective electrostatic adhesion. This study aims to contribute valuable insights to the field of space debris mitigation by refining adhesive force calculations and determining the key parameters for electrostatic-based debris capture. By addressing both inertial and gravitational challenges, this approach offers a scalable solution that could be implemented in future space missions to reduce orbital debris and safeguard active satellites **[1]**.

2. Literature Review

2.1 Analysis of Current Technologies in Space Debris Capture

Space debris removal demands innovative solutions like the Venus flytrap-inspired gripper developed by Zhang et al. (2023). This system integrates bistable origami structures, shape memory alloy springs, and dielectric elastomer actuators (DEA) for rapid and precise debris capture within 300ms. The lightweight design ensures effective locking and adaptability for irregular, high-velocity targets, achieving an 82.14% success rate without damaging debris. Flexible capture mechanisms, including nets and tethers, have limitations in precision and reusability, prompting a shift towards biomimetic designs. Unlike rigid grippers that risk damaging debris or inflating costs, the Venus flytrap approach leverages rapid actuation and bistability to address these challenges. However, issues like system vibrations during high-speed operations remain, with improvements suggested in actuator materials and control strategies **[4]**.

Now, as seen in the paper by Jiang et al. (2017), the integrated gecko-inspired adhesive gripper system demonstrates the ability to manipulate objects up to 370 kg in free-floating environments, with adhesive areas exceeding 100 cm². The gripper utilizes low attachment and detachment forces, which are crucial for avoiding disturbances in space applications. Notably, the system incorporates load-sharing mechanisms and wrist designs that enhance robustness by using multiple smaller units, mitigating the risks associated with surface defects. The adhesive material has been tested in space environments and has reached a technology readiness level (TRL) 6, while the gripper system itself is at TRL 4+ and requires further development for real-world space missions, such as satellite servicing or astronaut assistance.

The paper also discusses ongoing challenges, including lower grasping forces compared to mechanical interlocking systems and the issue of surface contamination from atomic oxygen erosion. Current research is focused on improving the adhesion strength and adaptability of the gripper to different surface conditions. The grippers are made using silicone-based adhesives with flexible and rigid backings, combined with fishing line tendons and pulley systems for load-sharing. Extensive testing in zero-gravity and ISS environments showcases the system’s potential for future space applications **[3]**.

The paper titled "Concept and Design of the Caging-based Debris Gripper for PAF Capturing" by Tanishima et al. (2020) explores an innovative solution for capturing uncooperative space debris during Active Debris Removal (ADR) missions. The authors propose a gripper based on a caging technique, designed to securely capture the Payload Attach Fitting (PAF) on the upper stage of the H-IIA rocket, despite potential position and attitude errors between the ADR spacecraft and the debris. By using form closure, the gripper ensures that the target is held in place without relying on the unpredictable dynamics of contact forces. The gripper's actuation mechanism is based on tendon-driven extension and contraction, allowing it to adapt to varying velocities and provide high-speed operation. This system was designed to meet the challenges of capturing and holding space debris under imperfect conditions, such as relative velocity or angular velocity between the ADR spacecraft and the target. Experimental results validated the gripper's performance, demonstrating that it can successfully capture and hold the PAF. However, the paper acknowledges the need for further development in terms of structural integrity for launch and thermal considerations for on-orbit operations **[2]**.

3. Methodology

The methodology for designing an effective space debris capture mechanism requires a systematic approach to address both the environmental conditions of space and the unique characteristics of the debris. Space debris, ranging from shattered satellites to rocket stages, varies in size, material composition, and location. This particular capture mechanism is tailored for a mission at 700 to 800 km altitude, where a high density of orbital debris is documented, based on analytical studies of debris distribution at these altitudes. This methodology covers the design and operational approach to achieve effective, efficient debris collection while addressing the complexities posed by non-magnetic materials commonly found in space debris, such as aluminium alloys, titanium, and carbon-fiber-reinforced polymers (CFRP).

3.1 Structure and Design Choice

The fundamental structure of the debris capture mechanism comprises three main components: electrostatic adhesive pads on the gripper, an adaptive gripper arm with telescopic extension, and a retractable storage profile. These components are selected to fulfil specific requirements of capturing, securing, and storing debris for subsequent processing.

3.1.1 Electrostatic Adhesive Pads

Electrostatic adhesive pads line each finger of the gripper to generate an electrostatic force that allows the gripper to securely adhere to various materials. Given that space debris often includes both metallic and non-metallic objects, this approach ensures that the gripper can capture a wide range of debris. The adhesive pads are constructed from a lightweight dielectric polymer with a conductive surface, a material choice that balances minimal weight with strong adhesive capabilities. The dielectric polymer offers stable performance in space conditions, providing a steady relative permittivity and effective charge distribution, which are essential for reliable electrostatic adhesion. This design allows for controlled capture without adding significant mass to the mechanism, a critical consideration for space missions were reducing weight directly impacts efficiency and cost.

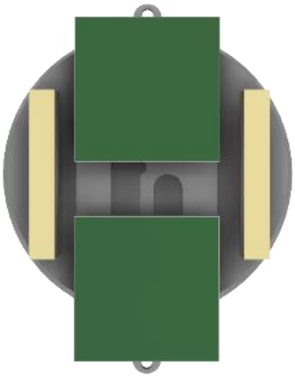

Figure-1 Electrostatic Adhesive Pads

3.1.2 Adaptive Gripper Arm with Telescopic Extension

The gripper arm features adaptive, flexible fingers that require minimal actuators, thus lowering mechanical complexity and energy consumption. To capture debris at various angles, a servo motor is integrated into the gripper. This servo offers ±10° rotational control, allowing for fine adjustments and precise alignment with the debris before capture. A compact high-torque servo was chosen to maintain efficiency without adding excessive weight or power consumption. This design makes the gripper both efficient and versatile, enabling it to adjust to the shape of different debris items without intricate mechanical requirements. The arm also includes a telescopic extension system powered by a rolling screw mechanism, which is paired with a brushless motor capable of extending the arm up to 0.135 meters. This extension capability allows the mechanism to reach and capture debris that is positioned slightly out of its immediate range, making it a valuable feature for accessing debris while minimizing the robot’s own repositioning maneuvers. The telescopic extension adds functionality without significantly increasing power demands, a balance that is essential for prolonged operations in space.

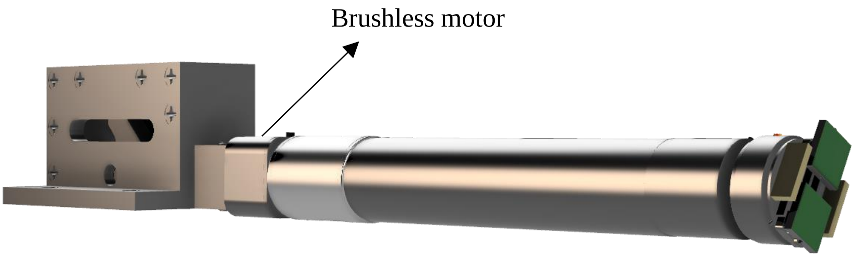

Figure-2 Adaptive Gripper Arm with Telescopic Extension

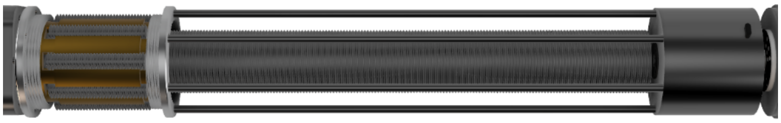

Figure-3 Rolling Screw

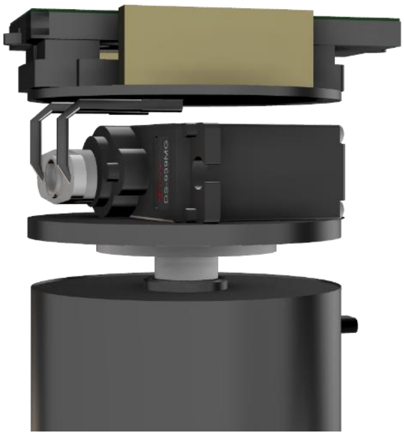

Figure-4 Servo Motor Is Integrated into The Gripper

3.1.3 Retractable Storage Profile

After the debris is captured, it needs to be securely stored until disposal or processing. The mechanism includes a retractable storage profile inspired by retractable landing gear structures, which serves as a compact, secure storage area for debris. This design allows the collected material to be stored safely, reducing the risk of accidental release or re-dispersal into orbit. By providing a designated storage area, the mechanism can manage multiple debris capture events before returning the collected items, adding efficiency and practicality to the overall mission. This profile allows compact storage and safe handling, thus improving the reliability of retrieval operations in space.

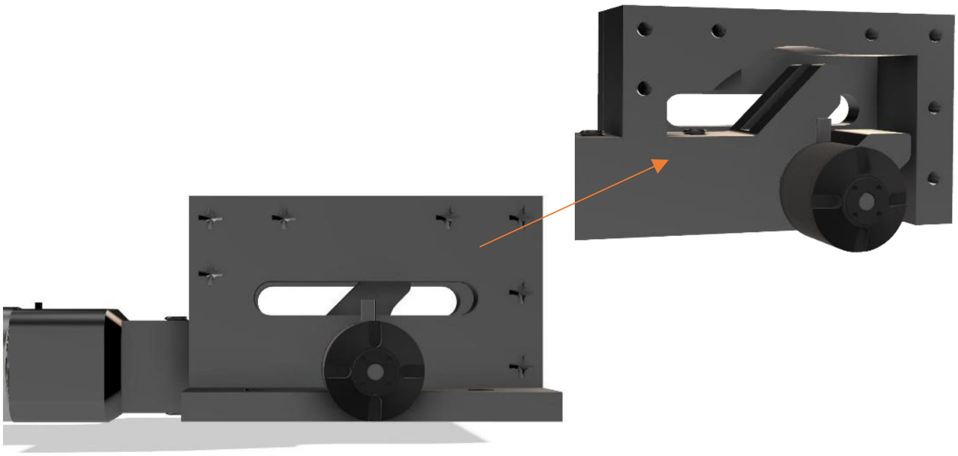

Figure-5 Retractable Landing Gear Structures

3.2 Environmental and Operational Assumptions

Designing for space requires carefully considered assumptions based on realistic conditions. These assumptions simplify the model and allow for a baseline analysis of force and adhesion requirements, aligning the mechanism’s functionality with environmental limitations in space.

3.2.1 Debris Mass and Acceleration

In designing the adhesive force of the gripper, it is assumed that the captured debris will have a maximum mass of 0.5 kg. This standardization simplifies adhesion calculations and ensures that the adhesive pads can manage the gravitational pull experienced in orbit. Additionally, acceleration is considered minimal, approximately 0.1 m/s^2, to simulate gentle movements or minor thrusts applied by the satellite or the debris itself. This low-acceleration environment allows for stable manipulation and capture without excessive adhesion force, as the debris movement relative to the satellite is anticipated to be slow and predictable.

3.2.2 Adhesive Pad Properties

The adhesive pad material, a dielectric polymer, is chosen for its ability to maintain stable relative permittivity and charge distribution in space conditions. Given the absence of atmospheric interference in orbit, electrostatic adhesion becomes a reliable option. The dielectric properties are crucial because they support consistent charge distribution on the surface, allowing the pads to create and maintain an attractive force strong enough to hold debris but not so strong as to cause difficulties in release or repositioning.

3.3 Overcoming Non-Magnetic Debris Challenges

Space debris presents unique challenges because materials like aluminum alloys, titanium, and CFRP are typically non-magnetic, meaning traditional magnetic attraction methods are ineffective. The methodology leverages electrostatic forces and Coulomb force field techniques to achieve the necessary control over non-magnetic debris.

3.3. Electrostatic Force Utilization

In the vacuum of space, electrostatic forces can be highly effective. Space debris naturally accumulates static charges from interactions with solar wind, cosmic rays, and other types of space radiation. This natural charging is advantageous because it allows the capture mechanism to work with pre-charged objects. By equipping the space robot or satellite with surfaces or tools capable of generating a static charge, an opposite charge can be induced on the debris. This induced charge facilitates controlled attraction or repulsion of the debris, making it easier to capture and store. Electrostatic force is especially beneficial for smaller and lighter debris, typically under 10 cm, which can be difficult to capture with traditional mechanical methods. Electrostatic attraction provides a means of manipulating debris of various materials, from non-conductive plastics to conductive metals, as long as these objects carry a charge. This method aligns with the mission requirements for capturing smaller, non-magnetic materials while minimizing the complexity of the capture process.

3.3.2 Coulomb Force Field Application

For even more precise control, the mechanism can employ Coulomb force fields to ionize or induce charges on debris particles. Once charged, these particles can be manipulated through controlled electric or magnetic fields, which allow for highly accurate adjustments to their position relative to the capture mechanism. The mechanism may utilize a plasma or ion beam to impart a positive or negative charge to the debris. This charging enables the robot to use an opposite charge or a controlled electric field to draw the debris towards the gripper or storage area.

This method provides greater control over the movement and orientation of small, lightweight debris, making it ideal for objects that are difficult to capture through physical grippers or magnetic attraction. Charged particle manipulation is versatile and effective for a wide range of debris materials, including aluminum alloys, CFRP, and other non-magnetic materials. By combining electrostatic and Coulomb force techniques, the capture mechanism enhances its ability to manage diverse materials and sizes, extending its functionality to more challenging objects.

3.4 Operational Efficiency and Versatility

The integration of electrostatic forces and Coulomb fields offers an advanced solution for space debris management by allowing the capture mechanism to handle materials of various compositions without relying on traditional magnetic or purely mechanical methods. The mechanism's adaptive design is particularly suited for operating in microgravity and adjusting to the shape, size, and material of different debris objects. This versatility maximizes the capture efficiency for debris between 10 and 80 cm and provides options for managing both larger and smaller items.

This methodology represents a cohesive approach to space debris capture, leveraging innovative principles of electrostatic attraction and charged particle manipulation within a compact, adaptive design. By utilizing lightweight materials, minimal actuators, and energy-efficient extensions, the debris capture mechanism is tailored to operate effectively in the space environment, contributing to sustainable practices in orbital debris management and long-term space mission success.

3.5 Calculation of Required Adhesive Force

The adhesive force necessary for secure debris capture was calculated based on both inertial and gravitational forces, ensuring stability in the microgravity conditions of satellite orbit. Below, we break down the calculations into key components to determine the required adhesive force.

3.5.1 Inertial Force Calculation for Satellite Movement

To counteract inertial effects due to the satellite's movement, an adhesive force must be applied to prevent debris from drifting or dislodging. The calculation below estimates the adhesive force needed to maintain secure contact between the debris and the robot's gripping mechanism during minor movements of the satellite.

Force Requirement (F): The required force to secure the debris against inertial movement is calculated using Newton's second law:

$$F = ma$$

where:

m is the mass of the debris, assumed to be $0.5\ kg$

a is the acceleration due to satellite movement, assumed to be $0.1\ m/s^2$

Substituting in the values:

$$F = 0.5kg \times 0.1\ {}^{m}/_{s^2} = 0.05N$$

Thus, a minimum adhesive force of $0.05N$.

$0.05N$ is required to counteract inertial forces and maintain the debris securely against minor movements of the satellite.

3.5.2 Electrostatic Charging System

To create the adhesive force, an electrostatic charging system transfers charge onto the surface of the debris. This allows the robot's electrostatic gripper to attract and hold the debris. The electrostatic force generated must be sufficient to counter the gravitational force acting on the debris at its orbital altitude.

3.5.3 Gravitational Force at Orbital Altitude

Since the debris is located approximately 800 km above Earth, the gravitational acceleration at this altitude differs from that at sea level.

According to Newton’s law of gravitation, the acceleration can be computed by

$$a = \frac{G\,M}{r^2}$$

where,

Gravitational constant, $G = 6.67 \times 10^{-11}\, Nm^2/kg^2$

Mass of Earth, $M = 5.97 \times 10^{24}\, kg$

Altitude above Earth's surface, $h = 800{,}000\, m$

Radius of Earth, $R = 6.38 \times 10^6\, m.$

$$r = R + h = 6.38 \times 10^6\, m + 800{,}000\, m = 7.18 \times 10^6\, m$$

$$a = \frac{G\,M}{r^2} = (6.67 \times 10^{-11}\, Nm^2/kg^2) * (5.97 \times 10^{24}\, kg) \,/\, (7.18 \times 10^6\, m)^2 \approx 7.7241\, m/s^2$$

At an altitude of 800 km, the gravitational acceleration is approximately $7.724 m/s^2$

Given:

Gravitational acceleration at 800 km altitude: $7.724 m/s^2$

Assumed mass of debris: 0.5 kg

The gravitational force acting on the debris is calculated as follows:

$$F_{\,gravity} = m \times g$$

Substituting the known values:

$$F_{\,gravity} = 0.5kg \times 7.724\, m/s2 = 3.862N$$

This gravitational force of 3.862Nrepresents the minimum adhesive force needed to counter gravitational pull, ensuring the debris remains securely captured.

3.5.4 Electrostatic Force Requirement

To produce an adhesive force strong enough to counter gravitational pull, we calculate the necessary electrostatic force using Coulomb’s law:

$$F = \frac{k * q_1 * q_2}{r^2}$$

Where:

- F is the electrostatic force.
- $k = 8.99 \times 10^{\,9} Nm^2/C^2$ (Coulomb's constant).
- $q1$ is the charge on the debris.
- $q2$ is the charge on the capturing surface (robot gripper).

For example, for debris with a mass of $\mathbf{0.5\ kg}$ (experiencing $\sim 7.724N$ gravitational force), you need an electrostatic force **greater than** $\mathbf{3.8625\ N}$.

Determining the charge required, consider $r = 0.1\ m$ and $F = 7.3N$(given above) And considering both the charges should be equal $q1 = q2$.

$$q = \sqrt{\frac{Fr^2}{k}} = 2.0727\ \mu C$$

$2.0727\ \mu C$ is needed on both the debris and the electrostatic pad to achieve a sufficiently strong adhesive force.

3.5.5 Electrostatic Adhesion Calculations

For reliable adhesion, we estimate the required pad area using an electrostatic force equation adapted for adhesion applications:

$$F = \varepsilon_0 \varepsilon_x E^2 A$$

F : is the force requirement, $0.05\ N$.
$\epsilon 0$: Permittivity of free space ($8.85 \times 10^{-12} F/m$)
ϵr: Relative permittivity of the adhesive material (e.g., 3.4 for polyimide)
E: Electric field strength (in kV/mm, e.g., $1\ kV/mm$)
A: Adhesive pad area in contact with debris

$$A = \frac{F}{(\epsilon 0 * \epsilon r . E^2)}$$

Substituting in the values:

$$A = \frac{0.05}{(8.85 \times 10^{-12} * 3.4.1^2)} \approx 17cm^2 .$$

Each adhesive pad thus requires an area of approximately $17cm^2$. This area ensures sufficient surface contact to achieve the desired adhesive force, balancing both gravitational and inertial requirements.

4. Design and Technical Speciation's

The robotic arm is meticulously designed to execute the challenging task of space debris capture and management within a CubeSat-based cubical structure. This structure enables the compact containment of essential components such as sensors, power systems, and the gripper arm while maintaining robust structural integrity for effective operation in space. The choice of a CubeSat model ensures a modular design that simplifies launch and integration with other spacecraft systems. To support continuous power needs, solar panels are mounted on multiple faces of the cube, maximizing exposure and energy capture regardless of the satellite's orientation.

The robotic arm itself employs a telescoping mechanism designed to retract and extend as needed for debris capture. The retractable arm's main extension mechanism uses a rolling screw driven by a servo motor, allowing precise control and extending up to 0.135 meters from its resting position within the CubeSat housing. The arm's structural components are constructed from lightweight yet durable materials such as aluminum. These materials are essential for maintaining the arm's strength and durability in the harsh space environment while ensuring that the overall weight remains minimal.

To enhance maneuverability and alignment, the robotic arm incorporates multiple joints controlled by servo motors. These motors allow the arm to pivot 90 degrees outward from the cubical housing, positioning it accurately to interact with debris. A servo motor located at the end of the rolling screw provides rotational control for aligning the gripper and electrode plates with the debris. Further, an additional servo-controlled plate enables fine angular adjustments up to 10 degrees, allowing the gripper to make precise contact with debris for a secure grip. This multi-jointed setup is essential for ensuring high accuracy, improving the success rate of debris capture in varied orientations.

The gripper mechanism combines gecko-inspired micro-structured adhesive pads with an electrostatic charging system. The gecko-inspired pads utilize microstructures to enhance surface adhesion, drawing on the natural adhesive mechanisms observed in gecko feet. This micro-structured design is particularly advantageous for adhering to non-conductive surfaces, which are common among certain types of space debris. Complementing this is an electrostatic charging mechanism, wherein electrode plates apply a charge upon contact with the debris. The combination of gecko-inspired adhesion and electrostatic charge provides a powerful, dual-layered grip that effectively secures debris under varying spatial conditions.

The robotic arm integrates an array of sensors to assist with detecting, analyzing, and safely capturing space debris. A lidar sensor is used to scan the surroundings, identifying debris and mapping its spatial dimensions. This volumetric data is essential for planning the robot’s approach and calculating the grip force required. Additionally, an inductive sensor is used to analyze the material composition of the debris, allowing the electrostatic charge to be adjusted to match the material's conductivity and improve adhesion efficiency. Force sensors positioned near the gripper provide feedback on the pressure applied during gripping and release, allowing for safe handling and reducing the risk of damaging the gripper or the debris.

The operational sequence of the robotic arm begins with the detection and approach phase, where the lidar sensor detects and locates the debris. After positioning itself, the robot extends its arm toward the target. Upon contact, the electrostatic charging plates activate, transferring a charge to the debris to enhance the gecko-inspired grip. The arm then retracts, transferring the debris to a storage sac within the CubeSat housing. This sac includes a one-way trap door, allowing the gripper to deposit debris and containing it securely. After each debris capture, the arm resets and prepares to target the next debris piece, repeating the sequence.

5. Results and Discussion

The primary outcome of this research was the development of a detailed CAD model of the robotic gripper mechanism, designed specifically for space debris capture in low Earth orbit. The gripper integrates gecko-inspired micro-structured adhesive pads with an electrostatic adhesion system, ensuring secure handling of non-magnetic and composite materials. The design reflects careful consideration of the unique environmental challenges in microgravity, including the need for lightweight yet durable materials. Key features include flexible gripper fingers, which adapt to various debris shapes, and integrated electrostatic electrodes sized based on calculated adhesive force requirements. The structural components, modelled in lightweight aluminium alloy, achieve a balance between durability and minimal mass. This CAD model serves as a foundational step in validating the feasibility of the proposed debris capture mechanism, aligning with mission objectives for efficient and reliable space debris mitigation.

5.1 Limitations and Challenges

While the system showed robust performance in simulations, certain challenges were noted. For example, the alignment mechanism, though highly precise, requires further refinement to handle high-speed debris effectively. Additionally, the compact CubeSat-based design limits the system's payload capacity, potentially restricting its ability to handle larger debris pieces.

5.2 Future Scope

The proposed robotic arm offers a strong foundation for addressing space debris challenges, with several enhancements that can further improve its functionality. The current storage sac design could be upgraded with an expandable structure featuring a one-way trap door, enabling it to store multiple debris items and support extended missions. Utilizing advanced materials such as shape-memory alloys or self-healing composites could enhance the arm's durability and adaptability in harsh space environments. The gripper mechanism could benefit from more sophisticated gecko-inspired adhesives with improved microstructures to ensure reliable grip across a wider range of debris surfaces, while temperature-resistant coatings could maintain efficiency in extreme thermal conditions. Integrating artificial intelligence and machine learning algorithms would allow the robotic arm to autonomously prioritize and target debris based on parameters like size, material composition, and orbital trajectories, minimizing the need for human intervention. Adding multiple grippers or extendable arms could enable simultaneous debris capture, significantly boosting retrieval rates during missions. Enhanced power management through advanced solar technologies, such as perovskite-based panels, along with optimized energy storage solutions like lightweight batteries or supercapacitors, would support long-duration operations.

Furthermore, the arm could be integrated with larger debris-clearing spacecraft or space tugs for coordinated operations to handle diverse debris sizes and types across various orbital regions. By addressing these advancements, the robotic arm could evolve into a versatile, efficient, and scalable solution for space debris mitigation, ensuring a safer and more sustainable orbital environment.

6. Conclusion

Space debris poses an escalating threat to the sustainability of orbital operations, necessitating innovative and practical solutions for its mitigation. This research presents a highly capable robotic arm design that integrates advanced materials, precise electromechanical systems, and innovative gripping mechanisms inspired by nature. The integration of a retractable arm with electrostatic charging and gecko-inspired adhesive technology ensures reliable debris capture across various surface types and material compositions. By coupling this functionality with a telescoping arm mechanism and precise multi-axis control, the design achieves both versatility and compactness, vital for deployment in space-constrained environments.

The rigorous calculations underpinning the adhesive force requirements, gripper area optimization, and operational power needs ensure that the arm is not only functional but also efficient and reliable under orbital conditions. The incorporation of modular design elements and adaptability to CubeSat dimensions enhances its scalability and integration potential for diverse space missions. Further, the use of lidar, force sensors, and automated control systems facilitates accurate debris detection, material analysis, and operational adjustments, minimizing human intervention while maximizing mission success rates.

In addressing the technical, operational, and environmental challenges of debris mitigation, this robotic arm represents a significant step toward a cleaner and more sustainable orbital space. Its potential for future enhancements, such as multi-debris handling, autonomous operation, and integration with larger space systems, ensures that it can evolve to meet the dynamic demands of space exploration and commercialization. This work not only demonstrates a practical solution for managing space debris but also lays the groundwork for future innovations that will safeguard our access to and use of outer space.

7. References

[1] Pearson, Jerome & Levin, Eugene & Oldson, John & Carroll, Joseph. (2010). ElectroDynamic Debris Eliminator (EDDE): Design, Operation, and Ground Support. 11.

[2] Tanishima, N., Okamoto, H., Iki, K., Watanabe, K., Okumura, T., Kato, H., Hayashi, M., & Hirano, D. (2020). Concept and design of the caging-based debris gripper for PAF capturing. Journal of Space Safety Engineering. **https://doi.org/10.1016/j.jsse.2020.07.011**.

[3] Jiang, H., Hawkes, E. W., Fuller, C., Estrada, M. A., Suresh, S. A., Abcouwer, N., Han, A. K., Wang, S., Ploch, C. J., Parness, A., & Cutkosky, M. R. (2017). A robotic device using gecko-inspired adhesives can grasp and manipulate large objects in microgravity. **https://doi.org/10.1126/scirobotics.aan4545**.

[4] Zhang, Y., Quan, J., Li, P., Song, W., Zhang, G., Li, L. and Zhou, D. (2023), A Flytrap-Inspired Bistable Origami-Based Gripper for Rapid Active Debris Removal. Adv. Intell. Syst., 5: 2200468. **https://doi.org/10.1002/aisy.202200468**.

8. Conflict of Interest

The author declares no competing conflict of interest.

9. Funding

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