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The Role of Micro Propulsion in Enabling Autonomous Operations of Nanosatellites

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Abstract: Micro-Electro-Mechanical Systems (MEMS)-based propulsion devices have significant potential for providing high specific power. The application of Micro Power Generation technology to space propulsion systems can enhance orbit and station-keeping capabilities, potentially at lower costs. New-generation spacecraft and satellites are becoming smaller and require micro-propulsion systems for all aspects of their operations. The development of micro-propulsion systems with associated combustors for micro-electricity generation, utilizing liquid fuel, presents major challenges in fuel injection, mixing, combustion, and chemical reactor systems. A micro-spacecraft with high-accuracy station-keeping and attitude control capabilities needs to have low mass and deliver small impulses. Each nanosatellite will weigh a maximum of 10 kg, including the propellant mass. Provisions for orbital manoeuvres, attitude control, multiple sensors, and instruments, along with full autonomy, will result in a highly capable miniaturized satellite. All onboard electronics will endure a total radiation dose of 100 k rads over a two-year mission lifetime. Nanosatellites designed for in-situ measurements will be spin-stabilized and equipped with a complement of particles and fields instruments. Nanosatellites intended for remote measurements will be three-axis stabilized and equipped with imaging and radio wave instruments. Key technologies under development include: advanced, miniaturized chemical propulsion systems; miniaturized sensors; highly integrated, compact electronics; autonomous onboard and ground operations; miniaturized onboard orbit determination methods; onboard RF communications capable of transmitting data to Earth from significant distances; lightweight and efficient solar array panels; lightweight, high-output battery cells; a miniaturized heat transport system; lightweight yet strong composite materials for nano-satellite and deployer-ship structures; and simple, reusable ground systems.

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1. Introduction

TNanosatellites, defined as satellites with a mass typically less than 10 kilograms, have emerged as a transformative innovation in the field of space exploration. These compact, modular platforms are revolutionizing traditional satellite design by offering cost-effective solutions for a variety of applications, including communication, Earth observation, and scientific research. Their small size and ease of deployment have not only reduced the financial and logistical barriers to entry but also opened new avenues for commercial and academic endeavours in space. One of the most promising areas of development in nano-satellite technology

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lies in the advancement of propulsion systems. Micro-Electro-Mechanical Systems (MEMS)-based propulsion devices are being explored for their potential to provide high specific power, enabling enhanced manoeuvrability and station-keeping capabilities. These systems, in conjunction with innovations in micro power generation, offer the promise of improving orbital dynamics and operational efficiency at a reduced cost. This paper reviews key technologies and challenges associated with nano-satellite design and propulsion, emphasizing the role of miniaturized chemical propulsion systems, advanced sensors, and compact electronics. Additionally, it highlights the importance of achieving radiation resistance, autonomous operations, and efficient power generation to support long-duration missions. By leveraging these cutting-edge technologies, nanosatellites are poised to play a critical role in expanding the boundaries of modern space exploration [1-2].

2. Nanosatellite Growing Role in Space Missions

Nanosatellites are rapidly transforming the landscape of space exploration by expanding their applications across scientific, technological, and commercial domains. Their small size, cost-effectiveness, and ability to adapt to modular designs make them ideal candidates for a variety of space missions [1-2].

2.1. Scientific Research

The miniaturization of electronic components has enabled nanosatellites to play a critical role in achieving diverse scientific objectives. For instance, they are increasingly used to study solar and terrestrial phenomena, such as solar irradiance and Earth's radiation budget. By deploying nanosatellites for such missions, researchers can gather valuable data in a cost-effective and time-efficient manner compared to traditional satellite platforms. Their agility and rapid deployment capabilities also make them highly suitable for addressing dynamic scientific challenges, such as monitoring space weather or tracking atmospheric changes.

2.2. Telecommunication and Navigation

Nanosatellites are paving the way for a revolution in telecommunication and navigation systems. When deployed in constellations, these satellites provide enhanced coverage and data transmission capabilities, supporting mobile applications and advanced navigation systems. For example, nano-satellite networks can fill coverage gaps in remote or underserved areas, enabling better internet access and reliable communication services. Furthermore, their potential to augment global positioning systems (GPS) ensures improved accuracy and robustness for various terrestrial and aerial applications.

2.3. Technology Demonstration

Nanosatellites are invaluable as platforms for testing and validating emerging technologies in space. Their compact size and lower development costs allow researchers to experiment with innovative systems that may later be scaled up for larger, more complex missions. From advanced propulsion systems to miniaturized sensors, nanosatellites enable a cost-effective and low-risk approach to introducing cutting-edge technologies into the space environment.

2.4. Quantum Communication

An exciting frontier for nanosatellites is their potential in enabling quantum communication technologies. Equipped with miniaturized photon-pair sources, these satellites can distribute entangled photons to establish secure communication networks. By leveraging quantum principles, nanosatellites could revolutionize cybersecurity in communication systems, providing an unprecedented level of encryption. Additionally, their compact form factor makes them ideal for demonstrating and advancing quantum technologies in space, laying the groundwork for global quantum communication networks.

Through these diverse applications, nanosatellites continue to solidify their role as essential components of modern space missions, offering innovative solutions to some of the most pressing challenges in science, technology, and global communication.

3. Challenges Due to Size and Limited Resources

While nanosatellites offer significant advantages in terms of cost, deployment, and versatility, their compact size and limited resources present several challenges that must be addressed to optimize their performance and ensure mission success [1-2].

3.1. Telecommunication Limitations

One of the primary challenges for nanosatellites is their limited data transmission capabilities. Due to constraints in onboard telecommunication systems, which often operate at low frequencies, these satellites struggle with restricted data rates. This limitation hinders the transmission of large volumes of data, posing challenges for applications that require high-bandwidth communication, such as imaging or high-resolution scientific measurements.

3.2. Power Generation

The small surface area of nanosatellites significantly limits their ability to generate sufficient power through solar arrays. This constraint necessitates the development of advanced, efficient power management systems to ensure that mission-critical operations, such as communication, propulsion, and payload functions, are not compromised. The trade-off between power availability and operational demands remains a key design challenge for nano-satellite missions.

3.3. Attitude Control

Maintaining stable orientation, or attitude, is particularly challenging for nanosatellites due to their small size and limited resources. The process of dampening rotations can be slow, requiring precise and efficient systems such as small reaction wheels or magnetic torquers to manage angular momentum. Additionally, jitter caused by internal movements or external forces can impact the performance of onboard instruments, particularly those used for imaging or communication.

3.4. Space Debris

The increasing deployment of nano-satellite constellations in low Earth orbit (LEO) has raised concerns about their contribution to space debris. Large swarms of nanosatellites increase the risk of collisions, which could exacerbate the long-term problem of orbital debris. Developing strategies for collision avoidance, such as autonomous de-orbiting mechanisms and improved tracking systems, is crucial to mitigate this growing concern.

3.5. Payload Constraints

The limited volume and mass of nanosatellites impose significant restrictions on the payloads they can carry. These constraints challenge designers to develop innovative solutions, such as deployable optics, miniaturized instruments, and multi-functional components, to maximize the scientific and operational returns within the tight confines of a nano-satellite platform.

While nanosatellites hold immense promise and continue to play a growing role in space missions, addressing these challenges is essential for their sustained success. Advancements in miniaturization, power management, communication, and debris mitigation will be pivotal in unlocking the full potential of nano-satellite technology.

4. Types of Micro-propulsion System

The types of micro propulsion systems are broadly divided into two categories based on their primary mechanism of thrust generation, following the classification scheme used for larger propulsion systems. These categories are chemical and electrical propulsion systems, both of which are considered for primary propulsion and attitude control in micro spacecraft. A third category, nuclear propulsion, may be of interest for larger spacecraft but is not yet viable for micro spacecraft **[3-8]**.

4.1. Chemical Micro-propulsion

Chemical propulsion systems generate thrust through the exothermic combustion or decomposition of chemical fuel. Propulsion systems utilizing the force exerted by an inert gas stored under high pressure, which is released through a nozzle, are also classified under this category, even when no chemical reaction occurs. Major chemical propulsion systems include monopropellant, bi-propellant, tripropellant, cold gas, warm gas, solid propellant, and hybrid thrusters. These systems, widely used as primary propulsion in larger spacecraft due to their simplicity and effectiveness, face challenges when miniaturized. The thrust and specific impulse decrease significantly, while the physical size and mass remain prohibitively large. For gas and liquid propellant thrusters, leakage is a critical issue, exacerbated by miniaturization, as reduced propellant storage makes losses more impactful. Additionally, propellant toxicity and other limitations further affect the viability of chemical thrusters for micro-propulsion systems.

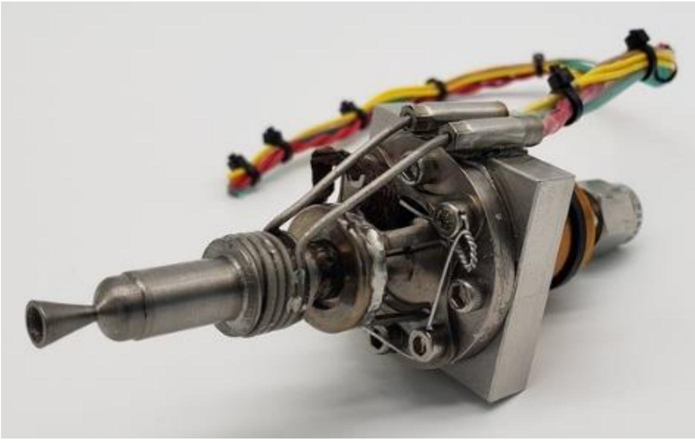

Figure-1 Chemical thruster for Micro-propulsion [Image Courtesy: SatSearch]

4.2. Electrical Micro-propulsion

Numerous concepts for electrical propulsion systems emerged in the 1960s, although many were only tested decades later. These systems often utilize the Lorentz force and plasma physics effects to generate thrust. Hall thrusters and ion thrusters, for example, have been employed as primary propulsion systems for satellites and space probes, providing advantages over chemical systems in terms of specific impulse. For instance, the ion thruster on Deep Space 1 produced 93 mN of thrust with a specific impulse of 3,127 s, compared to a commercially available hydrazine thruster producing 1 N of thrust with a specific impulse of 220 s. However, electrical propulsion systems often resist miniaturization. Some mechanisms, such as ion thrusters, have inherent size limits unless advanced technologies like magnetic confinement are employed. Other systems are too complex, requiring large power-processing units that are difficult to miniaturize, and they may not provide sufficient thrust for their size. Despite these challenges, ongoing research aims to overcome these limitations.

4.2.1. Types of Electrical Micro-propulsion

Efforts to develop electrical micro-propulsion systems include both the miniaturization of established technologies and the invention of new systems.

- ***Miniaturized Existing Technology***

Established technologies currently undergoing miniaturization include ion thrusters, Hall thrusters, and pulsed plasma thrusters.

- ***Ion Thruster***

The ion thruster is one of the earliest conceptual electric propulsion systems to achieve practical application. It has been used in recent space missions, such as NASA’s Deep Space 1 in 1998, and newer, more powerful systems are under development. Computational studies continue to improve system performance and address erosion characteristics. The ion thruster operates by ionizing a neutral gas propellant and accelerating the resulting ions to generate thrust. While the term "ion thruster" can apply broadly to any thruster using plasma for propulsion, it typically refers to gridded ion thrusters. These systems separate the ionization and acceleration processes: ionization occurs in a dedicated chamber, and acceleration happens through a charged grid. Ionization mechanisms include microwave heating, hollow cathode electron emission, and radio-frequency electron acceleration. A neutralization process injects electrons into the ion plume to maintain overall charge balance. Miniaturization introduces challenges, such as the ionization chamber becoming smaller than the mean free path of the ionizing electrons, which suppresses ion production. This issue can be mitigated by applying powerful magnetic fields to confine electrons within the chamber [3].

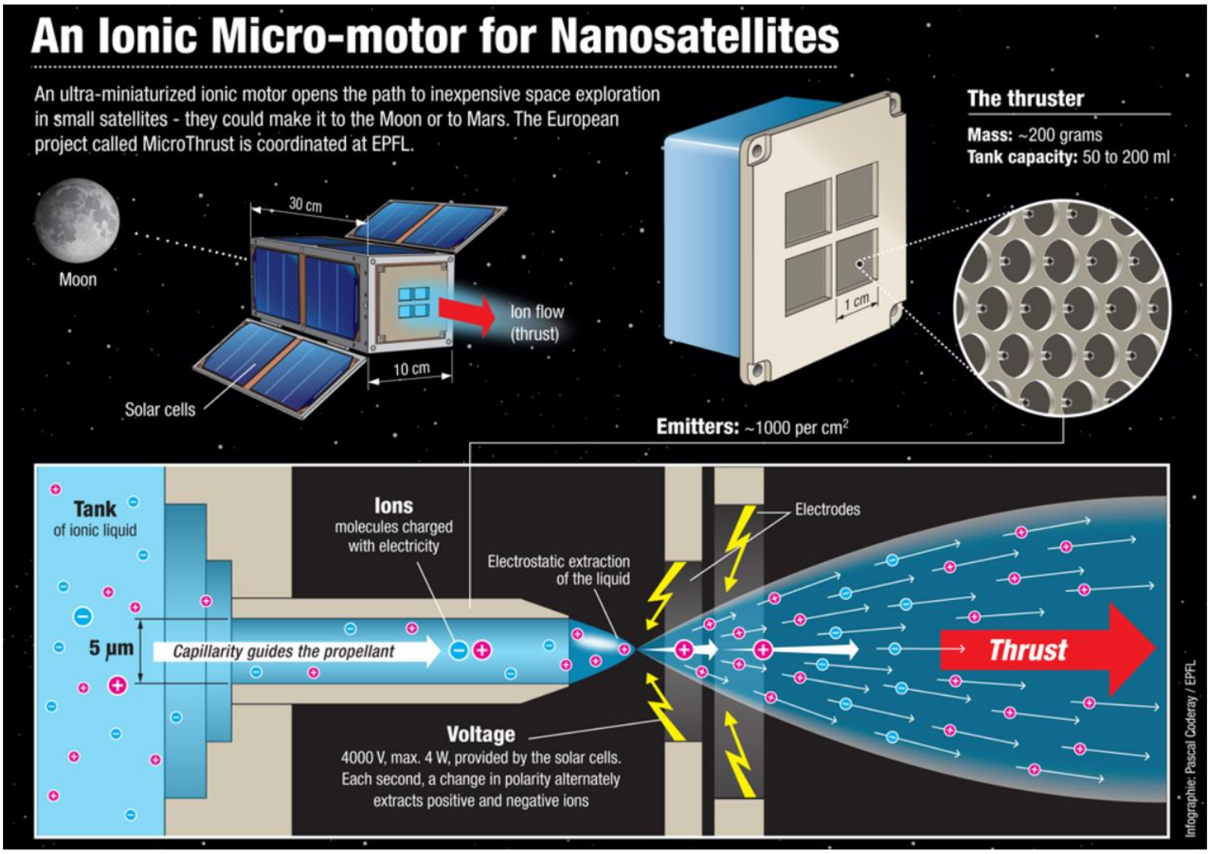

Figure-2 Infographic View of Ionic Micro propulsion System for Nanosatellites [Image Courtesy: EPFL]

- ***New Developments***

Industrial and academic groups are advancing the miniaturization of gridded ion thrusters. One such system, the RIT-X, developed by Astrium Satellites in Germany, employs radio-frequency electron acceleration for ionization, eliminating the need for external magnetic fields. Performance tests indicate a thrust range of 40 µN to 718 µN with power consumption between 10 W and 70 W and a specific impulse of 500 s to 3,500 s. In 2013, the European Space Agency (ESA) tested the RIT-X for its viability on the Laser Interferometer Space Antenna (LISA) mission, a space-based gravitational wave detector. The system demonstrated suitability for fine attitude control and advanced to the qualification phase. A single RIT-X thruster has a mass of 500 g and operates with a mass flow rate of 5 g/s.

5. Micro-propulsion System for Nanosatellites

Micro propulsion systems are a critical component in the advancement of nanosatellites, such as CubeSats, which are small, unmanned satellites designed for a variety of space missions. These systems are engineered to be highly miniaturized, lightweight, and efficient, making them ideal for the limited space and power constraints of nanosatellites. The rapid evolution of miniaturized, automated, and robotic technologies has significantly impacted space technology, enabling the deployment of large constellations of small satellites. These constellations serve as multifunctional platforms for global communication, navigation, data mining, and Earth observation, among other applications. However, the development of efficient and reliable thrust systems remains a significant challenge. Recent efforts have focused on creating various miniaturized space thrusters, including Hall thrusters, ion engines, helicon devices, and vacuum arc thrusters, to meet these demands. One promising development is the Low-Pressure Micro-Resistojet (LPM), which operates under a rarefied gas dynamic regime. This system uses fundamental physical models to estimate thruster performance, making it a suitable option for the strict requirements of nanosatellites. Another innovative approach involves MEMS-fabricated propulsion systems, such as the Free Molecule Micro-Resistojet (FMMR), which has been tested for on-orbit maneuvers using various propellants. Advancements in power systems are also crucial for the operation of these micro propulsion systems. For example, a micro space power system utilizing a micro fuel cell has been developed. This system leverages MEMS fabrication technologies to create a lightweight, corrosion-resistant power source. Similarly, an integrated RF power delivery and plasma micro-thruster system has been designed to save onboard volume for propellant and payloads, ensuring high efficiency for long-term operations in low Earth orbit or deep space. The miniaturized design of micro propulsion systems is essential for the successful deployment and operation of nanosatellites. These systems not only enhance the capabilities of small satellites but also open new possibilities for space exploration and satellite constellations. Ongoing research and development in this field continue to address challenges and improve the performance of these critical components [8].

6. Literature Review

6.1. Micro-propulsion Technologies

The rapid miniaturization of satellite technology has enabled the development of nanosatellites, such as CubeSats, which provide cost-effective and flexible solutions for diverse space missions. However, the limited size and mass of these satellites present significant challenges for propulsion systems, which are critical for precise maneuvering, orbit maintenance, and extended mission durations. Micro propulsion systems have emerged as a promising solution to these challenges, enabling autonomous operations of nanosatellites. This literature review explores advancements in micro propulsion technologies and their impact on the operational capabilities of nanosatellites. Below are few micro-propulsion technologies [9-14]:

RF Power Delivery and Plasma Micro-Thrusters

An integrated RF power delivery and plasma micro-thruster system has been developed to address the power inefficiencies of traditional electric thrusters. This system combines a compact switched-mode DC-RF power inverter with an electro-thermal plasma micro-thruster, which also serves as structural support for CubeSats. By saving onboard volume for propellant and payloads, this innovation enhances mission efficiency. Operational tests in space simulation systems have demonstrated the potential of this technology for long-term applications in low Earth orbit (LEO) and deep space.

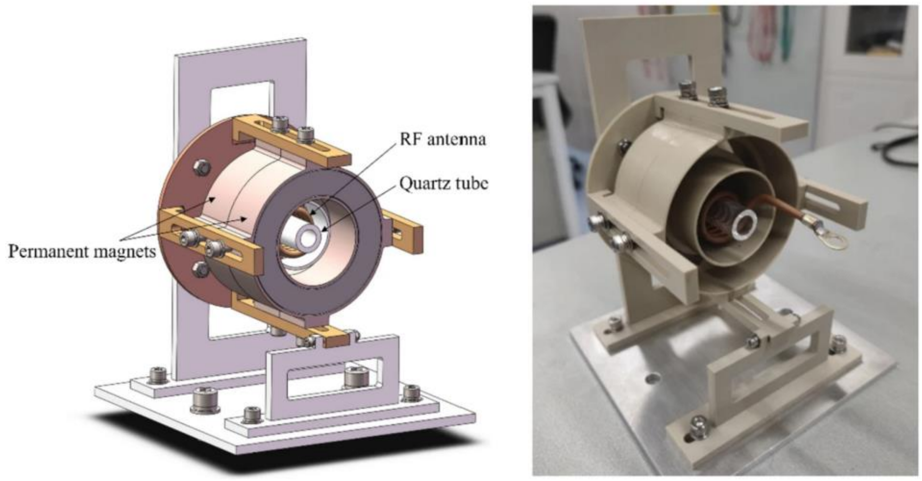

Figure-3 RF Plasma Thrusters [Image Courtesy: Yuzhe Sun.et.al.2024]

Low-Pressure Micro-Resistojet (LPM)

The Low-Pressure Micro-Resistojet (LPM) is a promising propulsion option for nanosatellites, functioning under a rarefied gas dynamic regime. Its performance is predicted using an analytical model based on the Kinetic Theory of Gases and the Maxwell-Boltzmann distribution. Experimental results align closely with numerical simulations, with a maximum deviation of only 3%, highlighting the model's accuracy. A conceptual design using frozen water as a propellant has also been proposed, offering a simple, reliable, and energy-efficient propulsion system with low thrust capabilities suitable for small satellites.

Free Molecule Micro-Resistojet (FMMR)

The Free Molecule Micro-Resistojet (FMMR) is an electrothermal propulsion system specifically designed for on-orbit maneuvers of nanosatellites. Performance testing using torsion force balance techniques has demonstrated its effectiveness in producing the required thrust for attitude control. The experimental outcomes match theoretical predictions, establishing the FMMR as a viable option for enhancing the maneuvering capabilities of nanosatellites.

6.2. Advances in Micro Propulsion Systems

Miniaturized Space Thrusters

Significant advancements have been made in miniaturized thruster technologies, including Hall thrusters, ion engines, helicon devices, and vacuum arc thrusters. These developments aim to overcome the challenges of creating efficient, reliable propulsion systems for small satellites, enabling precise maneuvering and long-term deployment.

3D Printed Micro Thrusters

3D printing technologies using ceramic polymer composites have been leveraged to create micro thrusters. These MEMS-based devices are characterized by their nanomechanical properties, allowing them to produce very small thrust levels. They are particularly suitable for fine-tuning the trajectories of nano and micro-satellites.

Water-Glycol Propulsion Systems

A novel micro propulsion system using water-propylene glycol as a propellant has been developed to achieve milli-Newton thrust levels with specific impulses of approximately 100 seconds. Experimental methods to measure the mass flow rate through micro and nano-channels have been employed, contributing to the design of a water-based cold-gas propulsion system.

Micro propulsion systems play a pivotal role in enabling the autonomous operation of nanosatellites by providing efficient and reliable thrust for precise maneuvering and extended mission lifetimes. Advancements in RF power delivery systems, micro-resistojets, and 3D printed thrusters demonstrate the transformative potential of these technologies. As research continues, micro propulsion systems will solidify their role in shaping the future of space exploration, particularly in advancing nano-satellite capabilities **[9-14]**.

7. The Role of Micro Propulsion in Autonomous Operations

Micro propulsion systems, particularly micro/nanomotors (MNMs), have gained significant attention for their versatility and potential in autonomous operations. These systems are not only vital for space exploration but also find applications in diverse fields such as biomedical engineering, environmental monitoring, and micro air vehicles (MAVs). MNMs leverage various energy sources to achieve autonomous movement, enabling precise control and functionality in complex environments. By facilitating intricate maneuvering and operational autonomy, micro propulsion systems play a critical role in nanosatellites and MAVs, driving innovation across industries and broadening the scope of autonomous technologies **[9-14]**.

7.1. Challenges and Future Prospects

Despite their immense potential, micro propulsion systems face several challenges:

- *Computational Power and Communication*: Limited computational capabilities and data transmission systems hinder the autonomous operation of MAVs and nanosatellites in complex, dynamic environments.
- *Energy Storage Constraints:* Current battery technologies struggle to meet the power demands of autonomous systems over extended durations.
- *Material and Design Limitations:* Advanced materials and innovative designs are needed to enhance durability and efficiency while maintaining compactness.

To overcome these challenges, continuous advancements in propulsion strategies, energy-efficient systems, and material science are essential. Collaborative efforts among researchers, engineers, and material scientists are key to unlocking the full potential of autonomous micro/nanomotors in both terrestrial and extraterrestrial applications.

8. Conclusion

Micro propulsion systems stand at the forefront of innovation, transforming the landscape of satellite technology and space exploration. By addressing the unique challenges of nanosatellites, these cutting-edge systems enable precise maneuvering, extended mission lifetimes, and autonomous operations in the most demanding environments. From RF-powered plasma thrusters to MEMS-based resistojets and 3D-printed micro-thrusters, the advancements in this field are nothing short of revolutionary. These systems are not just miniaturized engines; they are enablers of new possibilities—building vast satellite constellations, powering interplanetary exploration, and even contributing to sustainable and eco-friendly space missions. As we refine their capabilities and push technological boundaries, micro propulsion systems will unlock doors to uncharted territories, turning ambitious space missions into reality. In the vastness of the cosmos, where every gram and watt matter, micro propulsion systems are the tiny, mighty engines driving the future of exploration, ensuring that even the smallest spacecraft can reach the farthest stars.

9. Prospects and Innovations

9.1. Small Spacecraft Electric Propulsion (SSEP)

NASA's Glenn Research Center has pioneered the development of sub-kilowatt Hall-effect thrusters, compact propulsion systems that fit within the palm of a hand. These systems harness the power of the Sun to energize inert gases, producing highly efficient thrust. By miniaturizing these key technologies, Small Spacecraft Electric Propulsion (SSEP) enables spacecraft to perform long-duration missions beyond Earth's orbit, including to the Moon, Mars, and beyond. The ability to downsize these propulsion systems opens the door to more flexible, cost-effective space missions, where smaller spacecraft can carry out complex tasks such as scientific research, planetary exploration, and satellite deployment.

9.2. Challenges and Cosmic Quests

Scaling down propulsion systems while maintaining performance remains one of the greatest challenges in space propulsion technology. The complexity of fitting powerful propulsion systems into small spacecraft, while ensuring efficiency, control, and durability, is akin to fitting the performance of a full-sized car into a toy model. Researchers are actively addressing these challenges, focusing on enhancing the scalability of micro thrusters, improving their control mechanisms, and ensuring their longevity in the harsh conditions of space. These advancements represent significant hurdles but overcoming them will make these miniature propulsion systems a reality for future space exploration.

9.3. Interplanetary Transportation Revolution

The potential of micro propulsion systems goes far beyond traditional space exploration, offering a future where travel between celestial bodies becomes more efficient and affordable. With Small Spacecraft Electric Propulsion (SSEP) technology, spacecraft could easily traverse distances between Earth, the Moon, and Mars, fundamentally changing the way we approach interplanetary missions. These systems act as miniature, highly efficient "transportation hubs" in space, offering a more sustainable alternative to conventional propulsion methods. The compact design and eco-friendly nature of these propulsion systems make them ideal for long-duration missions, enabling frequent and cost-effective travel within our solar system. As these technologies continue to advance, they could usher in a new era of space exploration, allowing for regular missions to distant planets and paving the way for humanity's broader presence in space **[15-19]**.

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11. Conclusion

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