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Electrical propulsion systems for satellites: a review of current technologies and future prospects

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Abstract

Electrical propulsion systems have revolutionized satellite technology by offering greater efficiency, longer mission durations, and increased maneuverability compared to traditional chemical propulsion systems. This review explores current technologies and future prospects in the field of electrical propulsion systems for satellites. The discussion begins with an overview of existing technologies, including ion propulsion systems, Hall effect thrusters, and pulsed plasma thrusters. Each technology's principles of operation, advantages, limitations, and notable applications are examined. The review delves into the future prospects of electrical propulsion systems, exploring advanced concepts such as magnetoplasmadynamic thrusters, variable specific impulse magnetoplasma rockets, and electrospray propulsion systems. Additionally, miniaturization and efficiency improvements, as well as sustainable and green propulsion alternatives, are discussed. Challenges and opportunities facing the field are addressed, including technical hurdles like power generation and management, thruster lifespan, and regulatory and economic considerations such as policy frameworks and market dynamics. In conclusion, the review underscores the critical role of continued research and development in electrical propulsion systems for satellites. As the demand for more capable and sustainable satellite missions grows, advancements in propulsion technology will be essential in meeting these evolving needs and pushing the boundaries of space exploration.

Keywords: Electrical Propulsion Systems; Satellites; Current Technologies; Future Prospects

1. Introduction

Satellites play a crucial role in modern society, facilitating communication, navigation, weather forecasting, Earth observation, and scientific research (Venkatesan et al., 2013). However, the effectiveness and longevity of satellite missions heavily rely on propulsion systems for orbit maintenance, attitude control, and orbital maneuvers. Traditional chemical propulsion systems have been the mainstay for satellite propulsion, but they have limitations such as limited fuel capacity, high mass, and low efficiency (Sonko et al., 2024). Electrical propulsion systems offer a compelling alternative to chemical propulsion, providing several key advantages. Firstly, they utilize electric power from onboard solar panels, enabling efficient and sustainable propulsion without the need for bulky and finite chemical propellants (Sonko et al., 2024). This characteristic significantly extends satellite mission lifetimes, as electrical propulsion systems can operate for extended periods, enabling longer missions and enhanced maneuverability. Secondly, electrical propulsion systems offer higher specific impulse (ISP) compared to chemical propulsion, resulting in higher velocities and lower propellant consumption for the same delta-v requirements (Nardini et al., 2020). This efficiency advantage translates to reduced launch mass and cost, making electrical propulsion systems particularly attractive for small

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satellite missions and interplanetary exploration (Etukudoh et al., 2024). Furthermore, electrical propulsion systems exhibit smoother and more precise thrust control, enabling precise orbit adjustments and station-keeping maneuvers critical for applications such as satellite constellation deployment and formation flying. Current electrical propulsion technologies encompass various approaches, including ion propulsion systems, Hall effect thrusters, and pulsed plasma thrusters. Ion propulsion systems, such as the xenon-based ion thrusters, utilize electrostatic or electromagnetic acceleration of ions to generate thrust (Hamdan et al., 2024). While highly efficient and capable of delivering low thrust over extended durations, ion thrusters have limitations related to their low thrust levels and long acceleration times, which can restrict their use for rapid orbit changes or large spacecraft maneuvers. Hall effect thrusters operate by accelerating plasma using a magnetic field, offering higher thrust compared to ion thrusters while maintaining reasonable efficiency (Atadoga et al., 2024). However, they still face limitations related to erosion of the discharge channel and potential efficiency degradation over time. Pulsed plasma thrusters generate thrust by ejecting plasma through a series of discrete pulses, offering high thrust-to-weight ratios but at the cost of lower efficiency and shorter operational lifespans due to electrode erosion (Abatan et al., 2024). While these technologies have significantly advanced satellite propulsion capabilities, they still face challenges such as limited thrust levels, mass constraints, and operational lifespans, highlighting the need for ongoing research and development.

Exploring future prospects in electrical propulsion systems is essential for addressing the limitations of current technologies and unlocking new capabilities for satellite missions (Sahoo et al., 2020). Advanced propulsion concepts, such as magnetoplasmadynamic thrusters and variable specific impulse magnetoplasma rockets, offer the potential for higher thrust levels, faster acceleration, and improved efficiency compared to existing technologies. Miniaturization and efficiency improvements will further enhance the performance of electrical propulsion systems, enabling their integration into smaller satellites and reducing mission costs. Additionally, research into sustainable and green propulsion alternatives, such as solar-electric propulsion and propellant alternatives, will contribute to reducing the environmental impact of satellite missions and ensuring long-term sustainability in space exploration (Obaigbena et al., 2024). By exploring these future prospects and investing in research and development, the satellite industry can continue to push the boundaries of space exploration, enabling new missions and applications that benefit humanity and advance our understanding of the universe.

2. Current technologies

Ion Propulsion Systems; Ion propulsion systems operate based on the principle of electrostatic or electromagnetic acceleration of ions to generate thrust (Holste et al., 2020). These systems typically utilize a propellant, commonly xenon gas, which is ionized within a discharge chamber. The ions are then accelerated by an electric field and expelled through a nozzle to produce thrust. The acceleration process results in a high exhaust velocity, leading to high specific impulse (ISP) values compared to chemical propulsion systems (Umoga et al., 2024). Ion propulsion systems can achieve specific impulses several times greater than traditional chemical propulsion, resulting in lower propellant consumption and longer mission durations. Ion thrusters can operate continuously for extended durations, enabling gradual velocity changes and precise orbit adjustments. The high ISP of ion propulsion systems allows for smaller propellant tanks, reducing spacecraft mass and launch costs. Ion thrusters typically produce low thrust, making them unsuitable for rapid orbit changes or large spacecraft maneuvers (Atadoga et al., 2024). Due to their low thrust, ion thrusters require extended acceleration times to achieve significant velocity changes, limiting their utility for time-sensitive missions. Ion propulsion systems are more complex and costly to develop and operate compared to chemical propulsion systems, requiring sophisticated power management and thruster control systems. NASA's Dawn spacecraft; dawn utilized xenon ion propulsion for its mission to study the asteroids Vesta and Ceres, enabling efficient trajectory adjustments and extended mission durations. ESA's SMART-1 mission, SMART-1 employed a Hall effect thruster for propulsion, demonstrating the feasibility of ion propulsion for deep space missions.

Hall Effect Thrusters, Hall effect thrusters operate by accelerating plasma using a magnetic field. These thrusters typically consist of a cathode that emits electrons, an anode, and a magnetic field source (Sodiya et al., 2024). When a voltage is applied between the cathode and anode, electrons are emitted and form a plasma. The magnetic field then traps the electrons, creating a Hall current, which accelerates ions out of the thruster, generating thrust (Boeuf, 2017). Hall effect thrusters are commonly used for station-keeping and orbit maintenance in geostationary satellites and deep space missions. These thrusters offer higher thrust levels compared to ion propulsion systems while maintaining reasonable efficiency and specific impulse values. Hall effect thrusters are particularly suitable for missions requiring moderate thrust levels and precise maneuverability, such as satellite constellation deployment and orbital transfers.

Hall effect thrusters offer higher thrust levels compared to ion thrusters, making them more suitable for rapid orbit changes and large spacecraft maneuvers (Olajiga et al., 2024). However, ion propulsion systems typically achieve higher specific impulse values and lower propellant consumption, making them preferable for missions with long-duration propulsion requirements and limited propellant mass.

Pulsed Plasma Thrusters, Pulsed plasma thrusters generate thrust by ejecting plasma through a series of discrete pulses (Zhang et al., 2019). These thrusters typically consist of a capacitor bank that stores electrical energy, a discharge chamber containing a propellant (such as a noble gas), and electrodes. When the capacitor bank is discharged, it generates a high-voltage pulse that ionizes the propellant and accelerates it out of the thruster, producing thrust. High thrust-to-weight ratio: Pulsed plasma thrusters can achieve high thrust levels relative to their mass, making them suitable for small satellite missions and attitude control applications. Simple design: Pulsed plasma thrusters have relatively simple designs compared to other electric propulsion systems, making them easier to develop and integrate into spacecraft. Pulsed plasma thrusters typically have lower specific impulse values compared to ion propulsion systems and Hall effect thrusters, resulting in higher propellant consumption for the same delta-v requirements (Ani et al., 2024). The repetitive pulsing action of these thrusters can lead to electrode erosion and degradation over time, limiting their operational lifespan and reliability. Pulsed plasma thrusters are commonly used for attitude control and small orbit adjustments in CubeSats and other small satellite missions. Ongoing research is focused on improving the efficiency and reliability of pulsed plasma thrusters, as well as exploring novel propellant options and electrode materials to extend their operational lifespans and broaden their applicability in space missions.

3. Future prospects

Magnetoplasmadynamic Thrusters (MPDT), MPDTs utilize electromagnetic forces to accelerate plasma, offering potentially higher thrust levels and specific impulse values compared to existing electric propulsion systems (Omole et al., 2024). These thrusters operate by passing a current through a plasma, creating a magnetic field that interacts with the plasma to produce thrust. MPDTs have the potential to enable faster interplanetary travel and more efficient orbit transfers, opening up new possibilities for deep space exploration missions.

Variable Specific Impulse Magnetoplasma Rockets (VASIMR), VASIMR engines operate by heating and ionizing a propellant gas to form a plasma, which is then accelerated and expelled through a magnetic nozzle (Chavers, 2003). One of the key advantages of VASIMR engines is their ability to vary the specific impulse by adjusting the power input, allowing for efficient propulsion across a wide range of mission profiles. VASIMR engines have the potential to revolutionize long-duration space missions, offering high efficiency and versatility for crewed missions to Mars, asteroid mining operations, and beyond.

Electrospray propulsion systems operate by emitting charged droplets of propellant through an electric field, resulting in thrust generation. These systems offer the potential for extremely precise thrust control and high efficiency, making them suitable for small satellite missions requiring precise maneuverability and orbit adjustments (Adeleke et al., 2024). Electrospray propulsion systems are particularly promising for CubeSats and other small spacecraft, offering a compact and lightweight propulsion solution with minimal power requirements.

Advances in miniaturization technologies are enabling the development of compact and lightweight propulsion systems tailored for nano- and microsatellites (Okoli et al., 2024). Miniature thrusters, such as cold gas, micro-resistojet, and micro-electrothermal systems, are being developed to provide propulsion capabilities for small satellites without sacrificing payload capacity or mission flexibility. These propulsion technologies will enable a new generation of small satellite missions, including formation flying, constellation deployment, and high-resolution Earth observation (Olu-lawal et al., 2024). Ongoing research is focused on improving the efficiency and performance of electric propulsion systems through innovations in thruster design, power management, and propellant utilization. Advances in ion optics, electrode materials, and plasma confinement techniques are enhancing thruster efficiency and extending operational lifespans. Optimization of power management systems, including solar array technology and energy storage solutions, is increasing the overall efficiency and reliability of electric propulsion systems (Babatunde et al., 2024). Efforts are underway to seamlessly integrate propulsion systems with satellite platforms, enabling autonomous and on-demand maneuverability for spacecraft. Propulsion systems are being designed to be modular and scalable, allowing for easy integration with a wide range of satellite configurations and mission profiles (Iwuanyanwu et al., 2024). Integration of propulsion systems with advanced attitude control and navigation systems will enable precise orbit control and station-keeping, enhancing the capabilities of future satellite missions.

Sustainable and Green Propulsion, Research is ongoing into alternative propellants that offer reduced environmental impact and increased sustainability compared to traditional xenon gas. Green propellants, such as hydroxylammonium nitrate (HAN) and ammonia, are being investigated for their potential to provide high-performance propulsion with lower toxicity and greenhouse gas emissions (Remissa et al., 2023). Utilization of propellant alternatives will reduce the environmental footprint of satellite propulsion operations and contribute to sustainable space exploration efforts.

Solar-electric propulsion (SEP) systems, which utilize solar power to generate electrical energy for propulsion, are being advanced to improve efficiency and performance (Nwokediegwu et al., 2024). Advances in solar panel technology, such as high-efficiency photovoltaic cells and lightweight deployable arrays, are increasing the power output of SEP systems and extending mission capabilities. Integration of SEP systems with energy storage technologies, such as batteries and supercapacitors, will enable continuous propulsion during periods of limited solar exposure, further enhancing mission flexibility and autonomy. As space exploration activities continue to increase, there is growing recognition of the need to minimize the environmental impact of satellite propulsion operations (Odulaja et al., 2023). Efforts are underway to develop propulsion systems and technologies that minimize the generation of space debris and mitigate the risk of collisions in orbit. Environmental impact assessments are being conducted to evaluate the potential ecological consequences of propulsion system operations, guiding the development of sustainable and responsible space exploration practices (Etukudoh et al., 2024).

4. Challenges and opportunities

4.1. Technical Challenges

Electrical propulsion systems require efficient power generation and management solutions to supply the necessary energy for thruster operation (Ibekwe et al., 2024). Challenges arise in designing solar arrays or other power sources that can provide consistent and reliable power levels throughout a satellite's mission, especially during periods of eclipses or other environmental factors. Efficient power management systems are needed to distribute power to propulsion systems while ensuring other onboard systems receive adequate power, optimizing overall satellite performance (Adekuajo et al., 2023). Ensuring the long-term reliability and operational lifespan of propulsion thrusters is crucial for mission success. Thruster components, such as electrodes and ion optics, can degrade over time due to erosion, sputtering, or other factors, leading to reduced performance or failure. Developing materials and manufacturing processes that can withstand the harsh space environment and prolonged operation is essential for improving thruster reliability and longevity (Levchenko et al., 2018). Integrating propulsion systems with satellite platforms presents technical challenges related to spacecraft design, structural considerations, and thermal management. Propulsion systems must be compatible with satellite structures and interfaces, ensuring proper alignment, attachment, and integration without compromising spacecraft performance. Thermal control is critical to prevent overheating of propulsion components and maintain optimal operating conditions, requiring careful design and integration of thermal management systems.

4.2. Regulatory and Economic Factors

Regulatory frameworks govern the use of propulsion systems in space, including licensing requirements, safety standards, and international agreements. Policy considerations include space debris mitigation measures, frequency coordination for propulsion operations, and adherence to spectrum allocation regulations (Oyewole et al., 2023). Collaboration between government agencies, industry stakeholders, and international organizations is necessary to develop coherent and enforceable policies that promote safe and responsible use of propulsion technologies in space. Cost considerations play a significant role in the development and deployment of propulsion systems for satellites (Farayola et al., 2023). Achieving cost-effectiveness involves optimizing manufacturing processes, minimizing material and component costs, and streamlining assembly and integration procedures (Hassan et al., 2024). Commercial viability depends on factors such as market demand, competition, and the ability to offer differentiated or value-added propulsion solutions that meet customer needs. The satellite propulsion market is dynamic, with evolving trends driven by technological advancements, market demand, and competitive dynamics (Apeh et al., 2023). Market trends include increasing demand for small satellite propulsion solutions, growing interest in electric propulsion for geostationary and deep space missions, and emerging applications such as satellite servicing and in-space transportation. Competition among propulsion system manufacturers and service providers is intensifying, driving innovation, cost reductions, and the development of new business models to capture market share and sustain growth (Nair and Paulose, 2014). Addressing these challenges and opportunities requires collaboration across disciplines, including engineering, policy, economics, and international relations (Okoro et al., 2023). By overcoming technical hurdles, navigating regulatory landscapes, and adapting to market dynamics, the satellite propulsion industry can continue to advance the state-of-the-art and unlock new opportunities for space exploration and commercial applications (Oladeinde et al., 2023).

5. Conclusion

In this review, we have explored the current state and future prospects of electrical propulsion systems for satellite applications. We discussed the principles of operation, advantages, and limitations of existing technologies such as ion propulsion systems, Hall effect thrusters, and pulsed plasma thrusters. Additionally, we examined emerging advanced propulsion concepts, including magnetoplasmadynamic thrusters, variable specific impulse magnetoplasma rockets, and electrospray propulsion systems. Furthermore, we explored the potential for miniaturization and efficiency improvements in nanoSat propulsion technologies, as well as advancements in sustainable and green propulsion alternatives. We highlighted the technical challenges facing the industry, including power generation and management, thruster lifespan, reliability, and integration with satellite systems. Additionally, we addressed regulatory and economic factors, such as policy considerations, cost-effectiveness, and market trends.

Looking ahead, it is essential to prioritize research and development efforts aimed at addressing the technical challenges identified in this review. This includes advancements in power generation and management systems to ensure reliable and efficient operation of electrical propulsion systems. Additionally, efforts should focus on improving thruster lifespan, reliability, and integration with satellite platforms to enable seamless and robust propulsion capabilities. Furthermore, policymakers and industry stakeholders must collaborate to develop coherent regulatory frameworks that promote safe and responsible use of propulsion technologies in space. This involves addressing issues such as space debris mitigation, frequency coordination, and spectrum allocation to ensure the sustainability of space activities. From an economic perspective, there is a need to continue driving cost reductions and improving commercial viability through innovation, efficiency improvements, and market differentiation. This includes leveraging emerging market trends, such as the increasing demand for small satellite propulsion solutions and the growing interest in electric propulsion for geostationary and deep space missions. The importance of continued research and development in electrical propulsion systems for satellite applications cannot be overstated. These propulsion systems offer significant advantages in terms of efficiency, maneuverability, and mission longevity compared to traditional chemical propulsion systems. As the demand for satellite missions continues to grow, propelled by advancements in communication, Earth observation, and scientific research, the need for efficient and sustainable propulsion technologies becomes increasingly critical.

Investment in research and development is essential to unlock the full potential of electrical propulsion systems, enabling new capabilities for space exploration, satellite servicing, in-space transportation, and beyond. By addressing technical challenges, navigating regulatory landscapes, and adapting to market dynamics, the satellite propulsion industry can continue to innovate and drive the next generation of space missions and applications.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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