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Challenges and Innovations in Electric Propulsion Systems for Space Transportation: A Comprehensive Review

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Abstract: As the demand for sustainable propulsion solutions grows in response to climate change and stringent environmental regulations, electric propulsion has emerged as a transformative technology across aerospace and maritime sectors. This paper comprehensively analyses advanced electric propulsion systems, including ion thrusters, Hall-effect thrusters, magnetoplasmadynamic (MPD) thrusters, and electrospray thrusters, highlighting their capabilities and limitations. Key challenges such as power management, energy storage integration, thermal control, and system scalability are examined in detail. Additionally, recent innovations, including atmosphere-breathing electric propulsion, optimized power management strategies, and hybrid-electric architectures, are explored to assess their potential to enhance efficiency and operational reliability. The study further evaluates the application of electric propulsion in deep-space exploration, satellite manoeuvring, and next-generation aviation and maritime transport. As technological advancements continue to address existing limitations, electric propulsion is poised to play a critical role in shaping the future of sustainable and high-performance propulsion systems.

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1. Introduction

There are increasing concerns about the impacts of climate change, highlighted by the latest report from the IPCC, which urges a swift reduction of greenhouse gas emissions (GHG) across all sectors of society. The International Energy Agency (IEA) states that the transport sector contributes 24% of direct CO2 emissions from fuel combustion, although the rise in emissions did slow somewhat during the COVID-19 pandemic.[1] A viable solution to this problem is the use of electric propulsion. As the space industry contributes significantly to carbon emissions, adopting electric propulsion could benefit the environment and reduce costs associated with high-rated fuels. Several advanced electric propulsion systems, such as ion thrusters, Hall-effect thrusters, Magnetoplasmadynamic (MPD) Thrusters and Colloid and Electrospray Thrusters have been developed, offering innovative solutions for efficient and sustainable space exploration.[2] There are many challenges emerging like the Integration of Battery Energy Storage Systems (BESS) with existing ship propulsion systems[3] energy losses, power quality issues[4], Environmental Regulation: due to stringent international environmental regulations, which necessitate the development of integrated electric propulsion systems to reduce greenhouse gas emissions[5], Difficulties in Thruster Calibration[6], systems face challenges in scaling to high power levels needed for ambitious space missions[7] there are many such challenges discussed in this review further. As new challenges emerged, innovative approaches were developed to address them effectively through methods such as Blending atomic gases (e.g., argon) with molecular propellants (e.g., oxygen, nitrogen) to improve thrust, specific impulse, and thermal efficiency by leveraging their combined chemical properties[7], Parallel Hybrid Architecture[8], Adoption of ducted fans to improve thrust efficiency, reduce noise, and enhance safety[9], Atmosphere-Breathing Electric Propulsion[10], Optimized Power Management Algorithms11 such types of innovations are further described in the paper. This paper takes a closer look at the different types of electric propulsion systems and the challenges they face when used in space. These challenges cover a wide range of technical areas. For instance, designing the mechanical structure of satellites is a complex task, as it must adapt

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to the harsh conditions of space. Choosing the right propulsion engine for a specific mission is another key focus, where factors like thrust efficiency and reliability come into play. Weight is always a concern, pushing for innovations in lightweight materials and smarter structural designs to make missions more practical. Battery technology is another hurdle, with a growing need to extend battery life for longer missions. Managing heat is equally important since electric propulsion systems produce a lot of it, which needs to be handled efficiently to keep everything running smoothly. Finally, the paper explores how advanced systems and cutting-edge technologies are being developed to make propulsion more efficient and ensure mission success. These improvements are all steps toward tackling the challenges of using electric propulsion in space.

2. Challenges

In ion thrusters, the space charge effect limits the amount of charge that can be accelerated at once, reducing the thrust density, which is difficult for miniaturisation.[12-13] The intense erosion of electrodes and channel walls from high-energy plasma fluxes reduces the service life of thrusters.[14-16] Reliability in miniaturized versions of ion thrusters is still a challenge.[12][13]Erosion occurs as plasma ion bombardment ejects atoms from ceramic walls (e.g., boron nitride-silica), causing material loss and weakening.[17–20] High-temperature storage using NaS adds design complexity and recycling challenges due to toxicity. Lithium-ion and flow batteries need to be lower-cost and have higher energy density.[21] Deposited energy, low-pressure breakdowns, and Ion thruster breakdowns with grid arc discharge can cause damage as a result, monitoring is necessary.[22] Arc discharge ignition, plasma plume formation, ion energy control, and magnetic/electric field interactions, Scaling down is difficult due to power losses and reduced efficiency and degradation of the indignosticter electrode film are physical challenges.[15][23].Battery Energy density is low, thermal instabilities, charging time is higher, integration of superconductor materials[18][24–26] Wake and grid resolution are difficult to analyse in CFD for eVTOL.2727. Batteries with energy output matching aviation fuel often exceed aircraft weight limits due to low energy density. Turboelectric and hybrid systems lose efficiency during conversion and distribution.[28][29] High-power solar array and propulsion modelling improvements are necessary.30SmallSats lack sufficient delta-v for beyond earth orbit, voltage ranges, modelling plasma currents, voltage potential and expensive xenon propellant are restricting electric propulsion.[15][19][31–33]Thrust vs efficiency trade-off as chemical propulsion has high thrust and low specific impulse and high unlike electric propulsion.3431,3533In aircraft using air-breathing electric propulsion air chemistry model validation, less thruster efficiency and high-power requirement by thrusters need improvement.[36][37] regarding electrical vehicle technology using electric propulsion has problems like Power management and control algorithm, integration and packaging of EPS components leading to less system-level use as it has less efficiency and performance.[26][38]. CubeSat needs high delta-v values but thrusters are inappropriate for limited volume and power.[18][39] Combining or separating chemical and electric propulsion systems introduces design complexity, resource demands, and challenges in using efficient, eco-friendly green propellants.[40][41] Traditional propulsion systems require high fuel consumption for orbit maintenance, while simultaneous air intake and propulsion reduce reliability and efficiency.[42]Electric propulsion faces challenges including high radiation exposure during orbit raising, increased risk of anomalies, thruster erosion, and limited maneuverability in geostationary orbit.[13][43] Modelling the individual rotor blades of the EDFs (Electric Ducted Fans)would be computationally expensive and time-consuming. [44]Electric propulsion faces challenges like insufficient battery technology, complex power management, high cooling needs, and shifting emissions to power generation.[26][45] Chemical Electric propulsion faces challenges in energy density, high demand, efficiency losses, control complexity, and environmental dependence.[29][46] CubeSat often face challenges regarding energy and power constraints, volume and mass limitations, and propellant storage issues.[13][26][47–50] Thrust limitations, power constraints, discharge instability, plasma-wall interaction, reliability are general electric propulsion topics that need improvement.[19][50] Designing a system to handle varying thermal loads, losses due to heat generation, power distribution and balancing heat loads, and limited battery temperature range are thermal management challenges.[26][48][49][51] Energy transfer losses and integration complexity are challenges for hybrid systems.[25] In case of UAVs armature reaction in motors, thermal effects, electrical losses and battery performance needs improvement due to magnetic flux interference and voltage drop during operations due to internal resistance.[49][52] Aviation contributes 2% of global CO2 emissions and 3% of greenhouse gases, with emissions projected to grow significantly by 2050,energy storage limitations considering battery technology, electric drive weight more and has less reliability for long range also propulsion efficiency reduces with electric or hybrid electric aircraft propulsion system.[26][29][48][53] Propellent exhaustion for long deep space exploration leading to limited mission lifetime.[32] For hydrogen fuel cells, Hydrogen's low volumetric energy density complicates storage in a compact and lightweight form, it also faces durability and high cost issues.[54] FEEP(Field Emission Electric Propulsion) has low thrust levels so not beneficiary for advanced missions, high thrust levels in turn reduce mass efficiency, it also has complex power processing units, emission instability and scaling issues.[53][55] Conventional propulsion system increase mission duration leading to radiations, power and mass balancing, payload limitations are considerable in electric and chemical propulsion.[50] Electric propulsion faces challenges in technology scaling, power supply limitations, and adoption due to unproven systems and diverse, complex options.[14] Challenges in integrating BESS into ship propulsion include system compatibility, energy demands, battery limitations, high costs, regulatory compliance, and operational safety in marine environments.[56][57] Challenges include energy losses from power converter stages, power quality issues affecting propulsion reliability, and increased cavitation with fixed-pitch propellers, reducing system performance and longevity.[58] Lack of comprehensive design guidelines for pure electric propulsion ships.[57] Environmental challenges of high emission of Nox and Sox,CO2,high lifecycle cost with maintenance of COGES(Combined Gas Turbine Electric and Steam) compared to Diesel Electric Systems(DE) and integrating them is complex.[53][59] Complexity and uncertainty of Digital twin model.[60] Conventional electric, higher ionization energy reduces efficiency, and scaling to high power is challenging.[15] Electric and hybrid designs need sophisticated integration and precise energy management, as they lack mature standards.[29][61] Increasing power density, efficient thermal management, EMI, component reliability, and integrating advanced powertrains are significant challenges for electric aircraft design.[61][62] The small commuter aircraft market has declined due to high costs, poor infrastructure, and insufficient technological innovation.[63] Cathode wear, contamination, current oscillations, and erosion rates limit all stability and lifetime for interplanetary missions.[20] Electric propulsion's low thrust and suboptimal optimization methods result in longer maneuvers compared to chemical propulsion.[64–66] RF systems experience power inefficiencies, plasma thrusters need precise impedance matching, and current designs limit CubeSat volume utilization.[23] Electric propulsion (EP) units struggle at low altitudes due to limited thrust and high drag.[67] Electric propulsion needs frequent orbital adjustments due to low thrust, straining precision and efficiency tools.[68] Optimizing electric propulsion systems requires balancing thrust-to-weight trade-offs, as shorter activation times increase thruster mass, while efficiency and specific impulse (Isp) critically influence performance, often driving toward a minimum thrust design.[69] Dual thruster systems increase development risks and complicate satellite integration due to added weight and size.16 Electric propulsion systems, result in a significantly longer time for transfer orbit, existence of a radiation belt reduces power for propulsion.[70] The complex architectures of electric propulsion systems, like Hall thrusters, make testing and qualification resource-intensive, consuming up to 55% of lifecycle costs.[71] Limited performance due to low thrust-to-weight ratios, complexity, bulkiness, and high power requirements of pulsed propulsion systems, makes them less suitable for small satellite missions.[72] Existing electric propulsion systems, like M-70 and SPT-100 thrusters, struggled with inefficiency and rising operational demands, driving the need for advanced systems with better thrust, efficiency, and reduced mass.[73] Mode switching, and plasma throttling, limit efficiency and versatility.[74] Efficient fuel use is vital for low-thrust electric propulsion for satellites to sustain satellite orbits.[75] Early Electric Cyclotron Resonance Thrusters (ECRT) faced low efficiency, high background pressure, and limited thrust data, reducing their competitiveness.[76] Small satellites face limited propulsion options, high fuel consumption, and trade-offs between specific impulse and thrust-to-power ratios.[77] Orbital debris, power limits, low thrust, and complex designs challenge the effectiveness of electric propulsion systems.[78] Electric propulsion reduces propellant mass but requires heavier actuators and continuous thrust, complicating system balance and mission planning.[66] Traditional chemical propulsion requires frequent station-keeping, reducing orbit accuracy and increasing fuel consumption.[79] Limited launch capacity, long insertion times, and thermal challenges hinder efficient satellite deployment with electric propulsion.[80] Magnetic field interactions and measurement challenges complicate precise ion flow control in low-power electric propulsion systems.[81] Most CubeSats lack propulsion, restricting orbital maneuvers and effective deorbiting.[82] Electric propulsion faces challenges in efficiency, lifetime, heat management, and insufficient thrust for complex maneuvers.[83] All-electric satellites face low fuel efficiency, angular momentum management issues, and complex control algorithms, limiting their operational longevity and real-time practicality.[84] Small low Earth orbit satellites face challenges from solar disturbances, weight constraints of propulsion systems, and difficulty maintaining position with low thrust.[85] Chemical propulsion's low efficiency, challenges in precise orbit maintenance, and high power demands of electric propulsion systems hinder optimal satellite performance.[86] The PPU must efficiently handle a wide voltage range while ensuring over 99% reliability to support critical space operations.[87] Electric Aircraft design faces challenges in power density, thermal management, Electromagnetic Interference control, component reliability, and integrating advanced electric propulsion systems.[61] Ion thrusters face challenges in high power demand, compact design for SLATS, and adapting PPCU for a 50 V electrical bus.[88] EMI testing for electric thrusters is limited by unrecognized RVC standards, high power demands of SACs, and the need for vacuum environments.[89] The growing use of Hall thrusters in satellites has significantly increased xenon demand, straining its limited availability.[90] Electric propulsion systems face mass and payload limitations, outdated performance, and safety hazards from toxic chemical propellants.[91] The surge in small satellite launches drives the need for efficient propulsion systems, while challenges in cost, power, and thrust controllability persist, compounded by hollow cathode limitations.[92] Electric propulsion satellites in GEO face radiation exposure that degrades solar cells, with modeling challenges due to dynamic proton flux variations complicating risk assessment.[93] Traditional electric propulsion systems face efficiency issues, uneven current distribution in RF plasma thrusters, and challenges with magnetic field variability affecting thruster stability.[94] The solar electric propulsion (SEP) system faced challenges with excessive propellant consumption, extended thruster operation durations, and longer flight times compared to solar-sail trajectories, affecting mission efficiency.[95] Electric propulsion systems face low torque challenges, complex orbital transfers, and computational difficulties in optimizing for precise maneuvers and fuel efficiency.[96] CubeSats face challenges with bulky propulsion systems, limited thrust and precision, spacecraft charging risks, and restricted propellant activation times[97].

3. Innovations

Ion Propulsion: Ionizes a propellant (e.g., xenon) and accelerates ions with electric fields for efficient, long-duration thrust (e.g., NASA's Dawn).[12][34][98] Uses an electrostatic field to accelerate positively charged ions, generating thrust and Neutralized by electron injection to prevent spacecraft charging.[14] Electric propulsion systems, such as the Safran PPS5000 and PPS1350, improve thrust-to-weight ratio, reduce fuel consumption, and achieve higher specific impulse by using electrical energy to accelerate ions, enabling longer lifetimes and lower fuel mass.[99] Boeing's 702SP satellite uses electric propulsion, including arcjet technology, achieving over 500 seconds of specific impulse by electrically heating propellant, with reduced thrust.[65]control Scheme for North/South Station Keeping (NSSK) a novel control method that by placing the electric thruster at the end of a manipulator, the system can actively adjust its position and orientation.[84] This flexibility allows for precise control over the thrust direction, facilitating effective angular momentum unloading without the need for additional thrusters on the satellite's body.[84] Integrated Electric Propulsion (IEP) efficiently transfers satellites from GTO to GEO, with thrusters optimized for specific impulses of 1000, 1500, and 2100 seconds, integrated with the thermal control system. High thrust-to-power options reduce insertion times to under 100 days.[80] The Power Processing Control Unit (PPCU) efficiently supplies electrical power to the ion thruster while minimizing volume and weight, integrating multiple power supplies and a controller. It includes eight power supplies, with beam and accelerator converters operating at high and negative voltages for effective ion acceleration.[88] SiC-based converters use lighter, more efficient Silicon Carbide (SiC) electronics, reducing weight and maintaining EMI levels.[61] Multiphase motors with asymmetric windings optimize efficiency under varying MEA conditions, lowering propulsion energy consumption.[61] Injection methods enable low-thrust propulsion to transfer spacecraft from any orbit to GEO through continuous thrust application for effective maneuvers.[66]

Hall-Effect Thrusters: Use magnetic fields to ionize and accelerate ions, commonly for satellite orbit-raising and station-keeping.[12] HETs use a magnetic field to ionize xenon and accelerate ions via an electric field, achieving high specific impulse (up to 3000 s) for orbit maintenance.[14][65][86] it provides higher total thrust output with similar power consumption. [34] Xenon gas is ionized via electric discharge, and ions are accelerated through a magnetic field to generate thrust. Exotrail’s tools analyze low-thrust propulsion impacts, optimizing mission planning by quantifying fuel mass and duration differences.[77] Advanced boron-based coatings and self-healing materials enhance erosion resistance in electrodes and discharge channels, extending thruster lifespan.[100] Metamaterials improve performance and reduce degradation.[101] Cathode less Hall Effect thrusters use low work function materials for passive plume neutralization.[18] Magnetic shielding, alternative thruster designs, and advanced materials like diamond and nanocomposites reduce wall erosion and enhance durability.[13][17][31]Electrodeless plasma thrusters, like RF and helicon types, use magnetic nozzles to transport high-density plasma, reducing erosion and extending lifespan.[16] Developed a simulation using GT-SUITE to model and validate the hybrid propulsion system's performance.[53]

Pulsed Plasma Thrusters: Discharge energy to vaporize solid propellant, expelling plasma for thrust.[12] A compact rectangular breech-fed PPT that can use a self-inductor for coupling, simplifying the design can discharge a capacitor to create a plasma puff for thrust, with the self-inductor enabling efficient energy transfer, the system can use a 35 mF, 2.5 kV oil-filled capacitor to store and release energy, providing efficient ionization of the propellant and generating thrust across a range of discharge energies.[72] Gives a high thrust-to-power ratio.[31]

Pulsed Vacuum Arc Thrusters (VATs) generate highly ionized plasma efficiently at low power, making them ideal for small spacecraft. The use of small cathodes increases the thrust-to-mass ratio while reducing weight and overheating risks. Additionally, magnetic fields enhance thruster lifespan by ensuring uniform cathode erosion and improving plasma collimation, leading to higher ionization and increased thrust.**[39]** PPTs generate thrust by sparking between high-voltage electrodes to ionize solid propellant, achieving a high specific impulse (800-1200s) for small maneuvers.**[86]** Pulsed Inductive Thrusters (PIT) use an inductive coil to ionize and accelerate plasma, allowing chemically reactive gases and monopropellant byproducts for improved performance.**[91]** A tongue-flared design in pulsed plasma thrusters improves plasma flow and thrust efficiency by ensuring uniform current distribution. The side-fed design enhances spacecraft integration, simplifies assembly, and improves plasma control for better performance.**[94]** A novel design that uses radio-frequency (RF) power to generate plasma without a cathode, reducing system complexity and weight.**[36]** Plasma breakdowns can be controlled by improving beam focus and reducing ion density.**[22]** Researchers developed the STG-ET high-vacuum plume test facility, using a gridded ion thruster (RIT10/37) and Helmholtz coils to study ion beam deflection under varying magnetic fields.**[81]** GIEs generate and accelerate positive ions using grids, achieving high specific impulses (up to 9620 seconds) for deep space missions, such as NASA's Deep Space 1 and JAXA's Hayabusa.**[86]**

Electrothermal Propulsion: Heats and expels propellant using electricity, ideal for small spacecraft maneuvers.**[12]** Arcjets and resistojets provide higher specific impulse than chemical rockets.**[31]** Electrothermal thrusters, such as the helicon plasma thruster (HPT), the electron cyclotron resonance thruster (ECRT), and the variable specific impulse magnetoplasma rocket (VASIMIR), are suitable for station-keeping maneuvers in Earth's orbit **[34]**.

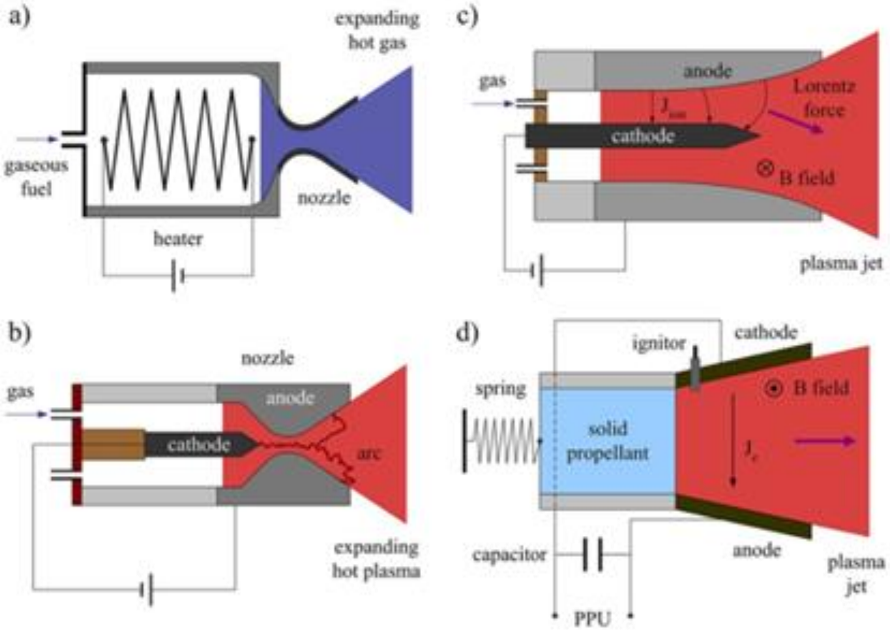


Figure-1 is a schematic of electrothermal and electromagnetic thrusters, including (a) resistojets, (b)arcjet thrusters, (c) self-field MPD thrusters, and (d) ablative pulsed plasma thrusters.[19]

Field Emission Electric Propulsion: Uses electric fields to accelerate ions from a solid surface, efficient for small satellites.**[12]** Also, it provides precise thrust and high specific impulse, a lighter propulsion system. **[31][85]** FEEP generates thrust below 1 mN by emitting ions from a field emission source, enabling precise satellite positioning and continuous orbit adjustments.**[85]** The indium-FEEP Thruster uses a needle-type emitter, where a high voltage pulls indium ions from a liquid metal reservoir, creating thrust.**[102]** Incorporates multiple capillaries to control indium flow and ensure uniform emission characteristics.**[102]** Operates with high efficiency at low thrust levels and achieves peak thrusts up to 1 mN.**[102]** For geostationary station -Electric propulsion systems, such as the BPT-4000 and SPT-100, reduce fuel consumption with higher specific impulse.**[79]** Thrusters on robotic arms improve maneuverability, and the Fuel-Optimal Model Predictive Controller (FOMPC) optimizes fuel use while maintaining station-keeping.**[79]**

SOLAR: Solar fuels convert solar energy into storable fuels like hydrogen with near 100% efficiency, ideal for remote use.[21] Cryogenic Energy Storage (CES) uses liquefied gases for high-density energy storage, benefiting hybrid systems and transport.[21] The study models high-power solar arrays like Boeing FAST and IBIS, analyzing performance and radiation degradation in LEO-to-GEO transfers.[30] It incorporates electric propulsion trends for Hall-effect thrusters, ion engines, and VASIMR.[30] Additionally, it optimizes low-thrust trajectories using meta-modelling and response surface equations while modeling GEO transfers with HYTOP, considering solar degradation and orbital perturbations.[30] SEP systems use photovoltaic cells to power electric thrusters, making them ideal for inner solar system missions due to their power decreasing with distance from the Sun.[34] Solar-sail technology, harnessing solar radiation for propulsion, offers a superior alternative to SEP, enabling longer missions without requiring significant propellant. [95] The orbital model simulates a satellite with deployable solar panels in circular orbits, calculating power input and drag based on panel inclination throughout the year.[37] It introduces the concept of equivalent specific impulse, linking thrust requirements to solar panel performance, enhancing propulsion efficiency analysis.[37]

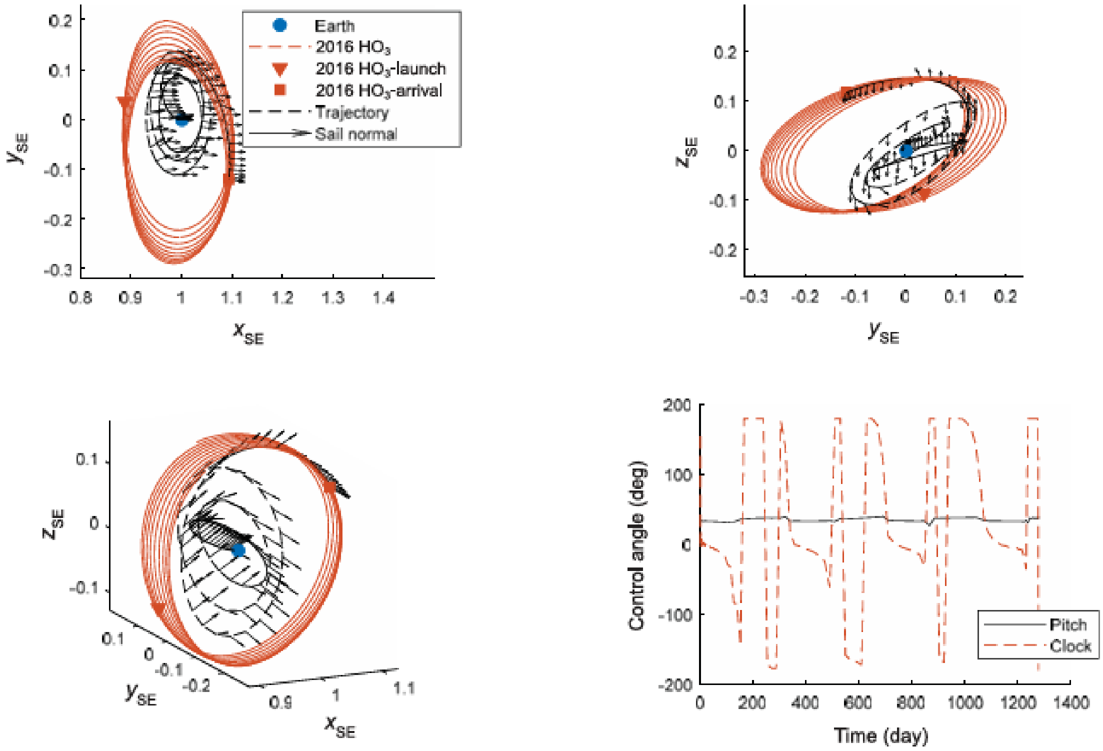


Figure-2 Solar-sailcase—optimized trajectory and controls for ideal sail model.[95]

Thermal: Advanced battery chemistries and thermal management systems aims to enhance battery performance and safety, potentially reducing charging times and improving lifecycle management[24] Thermal cycling and heating prevent grid short circuits.[22] Employ HTS materials for high-power, lightweight motors with improved cooling[28] The HC1 cathode enables efficient thrust generation in the HT100 Hall thruster by supplying discharge current while optimizing thermal management and propellant flow.[92] Advanced cooling designs, including water-cooled housings and predictive thermal management, enhance thermal performance, enable higher power density, reduce energy consumption, and extend component lifespan in MEA applications.[61] The IEP uses thrusters with optimized specific impulses and an integrated power processor for efficient heat dissipation and power management.[80] The TinyPR CubeSat thruster employs RF-generated plasma to achieve higher exhaust velocities than traditional cold gas thrusters, enhancing propulsion performance.[23] Switched Mode DC-RF Power Inverter: This design achieves up to 90% efficiency by minimizing thermal losses. [23] A LaB6 insert capable of high electron emission at temperatures exceeding 1,400°C for long-term stability.[20]

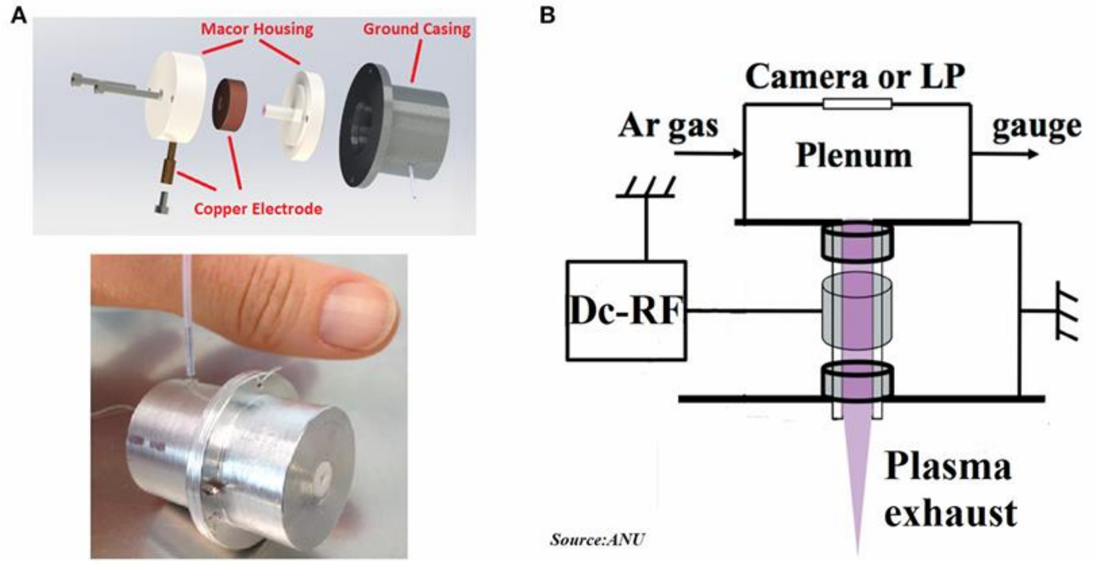


Figure-3 | The micro electro-thermal plasma thruster TinyPR developed at ANU. (A) Assembly view of the TinyPR, the smallest Pocket Rocket series electro-thermal micro thruster developed at ANU. (B) Schematics of the TinyPR [23]

SUPERCONDUCTOR: Utilizing HTS (High-Temperature Superconducting) coils to increase power density and efficiency.**[48]** Advanced cooling techniques, such as the reverse Brayton cycle cryocooler, to enable the practical use of superconductors in aircraft propulsion systems.**[101]**

Battery: Batteries with higher energy densities. For instance, achieving a BED of over 500 Wh/kg is crucial for making all-electric urban air vehicles (UAVs) viable**[24]** develop high-energy-density batteries like lithium-sulfur, solid-state, and lithium-air.**[26][28]** Integration of multiple energy sources (e.g., battery and fuel cell) on a common DC bus regulated by EMSs **[46]**.Used in battery thermal management for heat absorption during transient operations.**[51]** Battery model to estimate battery performance considering internal resistance and load.**[52]** Battery Management Systems (BMS) optimize performance, integrate with EMS for load balancing, while improved battery technologies enhance energy density, efficiency, and safety with fire suppression systems.**[56]** Battery Energy Storage System (BESS): BESS as the sole power source for the electric propulsion ship, which allows for efficient energy storage and usage.**[57]** Improvements in battery modeling based on state-of-charge (SOC) and energy density.**[27]** State-of-the-art lithium-ion batteries with higher energy densities (300 Wh/kg) for better weight-to-performance ratios.**[27]** Hybrid powertrains, using series or parallel configurations, combine battery and fuel energy, with a parameterized energy hybridization factor controlling energy distribution, resulting in improved mission flexibility and smaller batteries for long-range missions.**[29]**

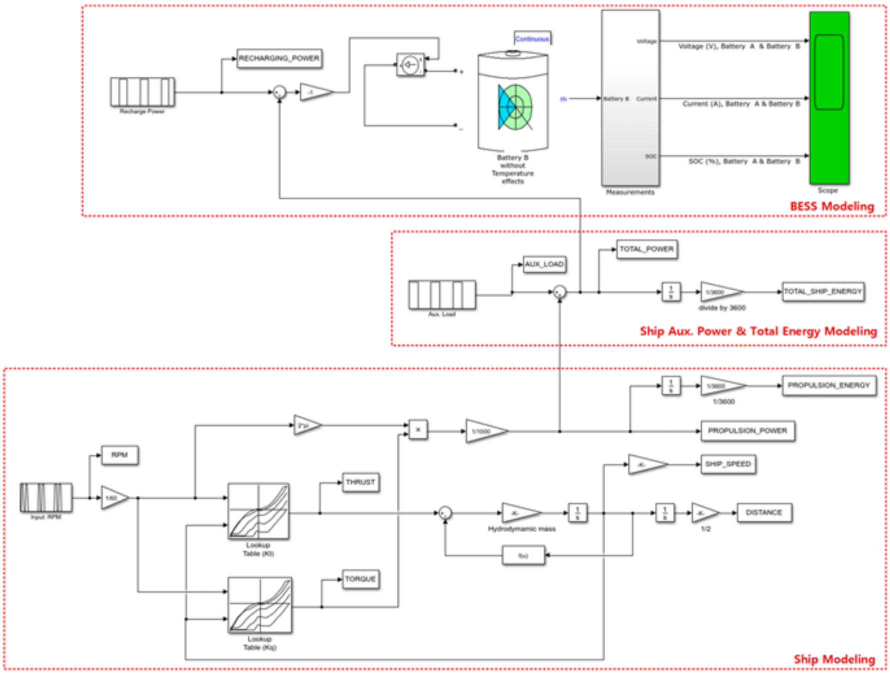


Figure-4 Simulation for BESS capacity design [57]

Hydrogen:

PEMFCs operate at low temperatures (30°C to 110°C) and exhibit high efficiency (40–60%), making them suitable for aviation applications.

Mechanism: Hydrogen is split into protons and electrons at the anode. Protons pass through the membrane, while electrons generate current before combining with oxygen to form water at the cathode (hydrogen).

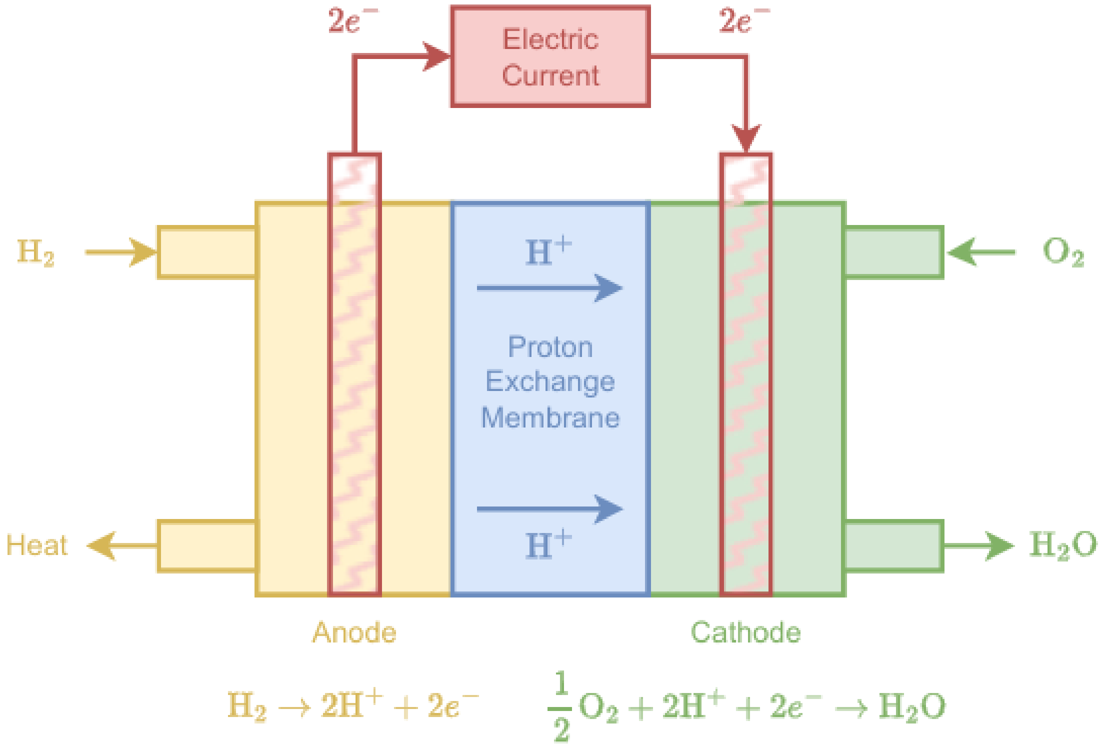


Figure-5 PEMFC representation. [54]

NUCLEAR:

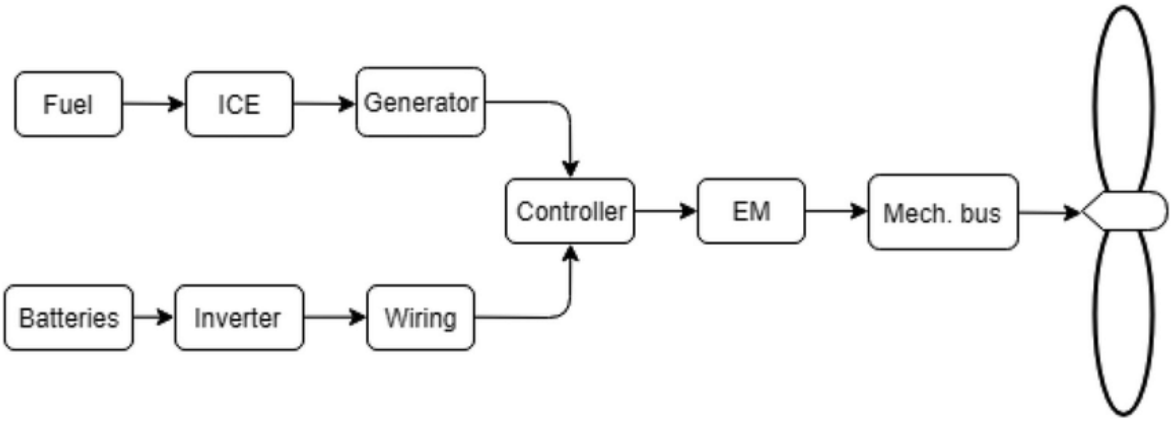
Nuclear reactor or a radioisotope thermoelectric generator (RTG) and are best suited for missions to the outer planets or beyond, where the power requirements are higher **[34]** Advanced solar arrays and nuclear systems for extended missions. **[32]** The system uses a nuclear reactor to generate heat, converting it into electricity to power ion thrusters for high specific impulse and thrust efficiency, including six subsystems: reactor, shield, power conversion, heat rejection, power management, and electric propulsion. **[50]**

CATHOD:

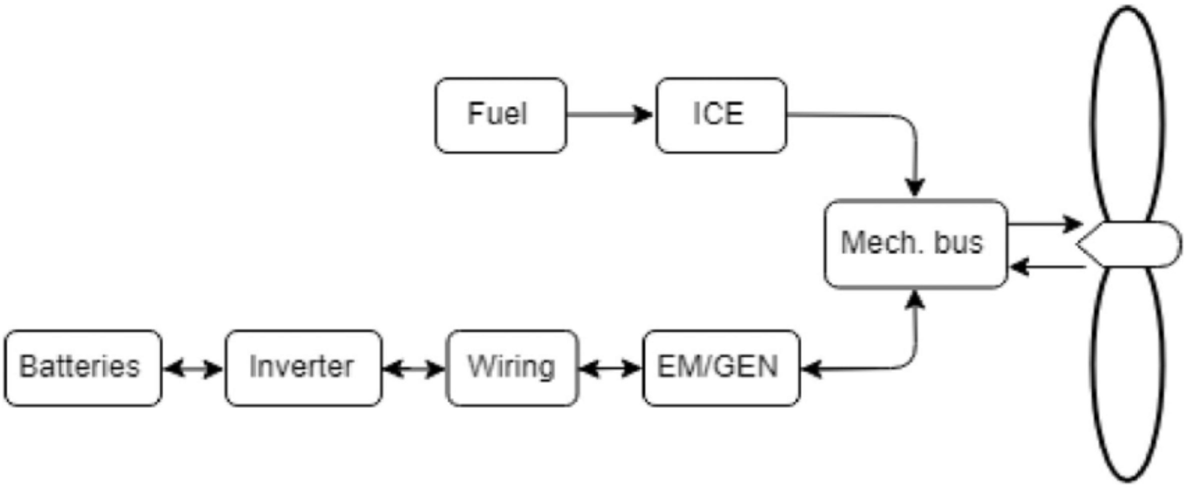
Small cathodes in pulsed VATs enhance thrust-to-mass ratios by reducing system weight and minimizing the need for heavy insulators and anodes, which can cause overheating.**[83]** The GM can serve as a design tool for VLEO missions, contributing to the development of cathode-less ABEP(Atmosphere-Breathing Electric Propulsion) technologies.**[36]** Creation of low-current, self-sustaining thermionic cathodes optimized for low-power Hall thrusters. Use of innovative materials and designs to reduce startup power consumption.18A LaB6 insert capable of high electron emission at temperatures exceeding 1,400°C for long-term stability.**[20]** The HC1 cathode achieves stable operation below 1 A through optimized geometry and materials, enhancing electron emission and ionization.**[92]**

HYBRID:

Development of Li–air and Li–S batteries, with higher energy density and potential specific energy improvements.**[48]**



a) Series Hybrid Outline

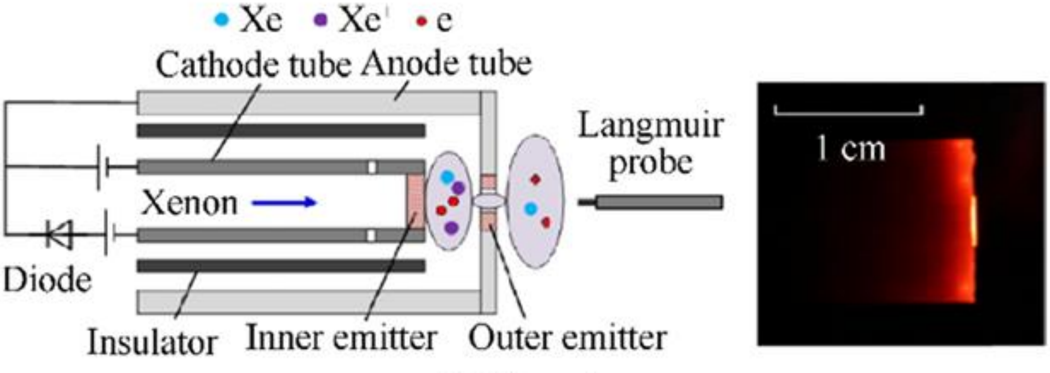


b) Parallel Hybrid Outline

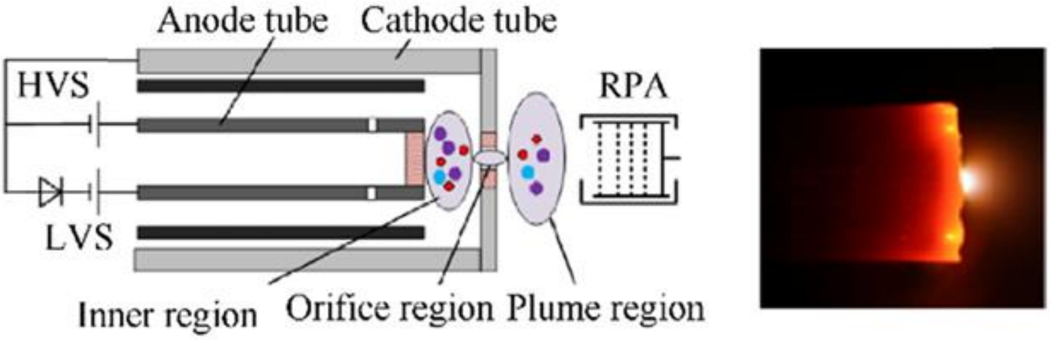
Figure-6 a) Series Hybrid Outline and b) Parallel Hybrid Outline [25]

DUAL:

In this configuration, the chemical and electric propulsion systems are separate but operate alongside each other in the spacecraft. An example is a system with a green monopropellant chemical thruster and an electric RF ion thruster, each with their own dedicated propellant.[40] A bi-directional plasma ejection system enables thrust control, switching between acceleration, deceleration, and debris removal by adjusting the magnetic field and gas flow.[16] The Dual-Emitter Hollow Cathode (DEHC) features two emitters for operation in neutralizer (N-mode) and thruster (T-mode), enhancing flexibility and efficiency.[74] In N-mode, it neutralizes charge in electric propulsion, while in T-mode, it accelerates ions via electrostatic forces and gas expansion.[74] Its design enables plasma throttling by increasing electron pressure, improving thrust generation.[74]



(a) N-mode



(b) T-mode

Figure-7 Schematic diagrams of Dual-Emitter Hollow Cathode (DEHC). [74]

Small Satellite:

The compact PPU integrates the Thruster Switching Unit for active selection and failure isolation, and the Filter Unit for stability.[31] Redundant control modules ensure continuous operation, while high-efficiency DC/DC converters achieve over 93% power conversion efficiency. [31]

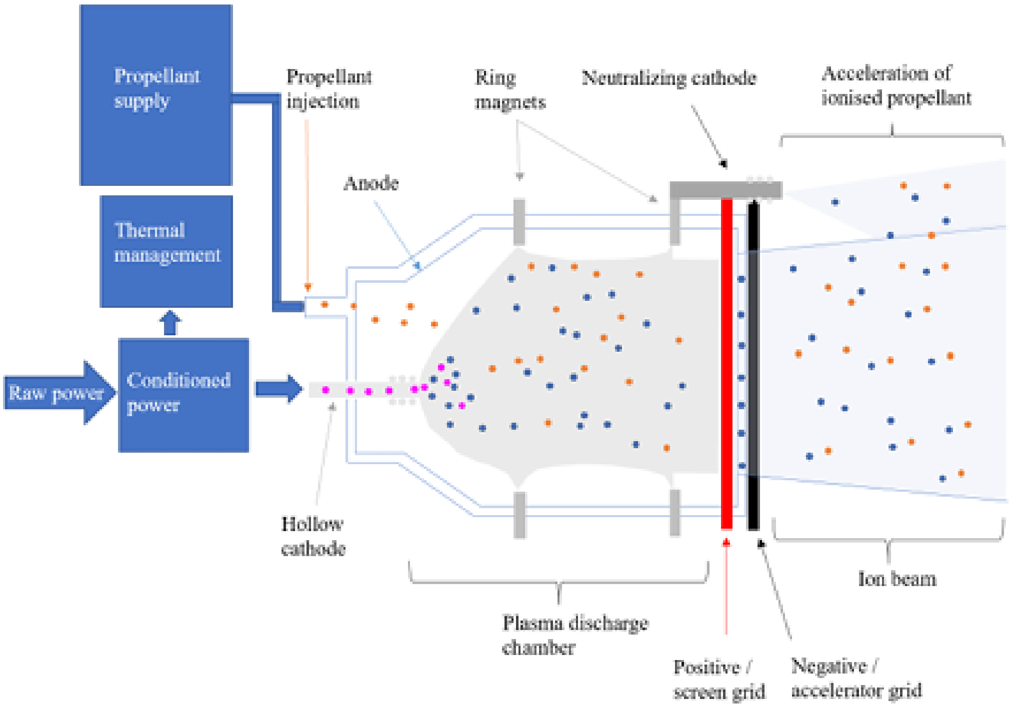


Figure-8 A two grid Gridded Ion Thruster (GIT) as a simplified schematic diagram [31]

Propellant: TPA and TEA offer high efficiency and specific impulses with lower toxicity than xenon, while condensable propellants like bismuth and iodine provide compact storage.[90] TPA and TEA ionize efficiently, improving thrust, and condensable propellants are easily vaporized for propulsion.[90]

Green propellant: Propellants like nitrous oxide, hydrogen peroxide, and ionic liquids, which are more environmentally friendly alternatives to traditional hydrazine.[40] The use of green monopropellants and PIT technology reduces the risks associated with traditional chemical propulsion, making space missions safer and more sustainable.[91] green monopropellants, such as AF-M315E and LMP-103S, reduces toxicity and volatility.

4. Application

Potential use of cryogenic systems, such as liquid hydrogen and high-temperature superconductors, for hybrid-electric propulsion in aircraft and airships.[101] IEP enhances capture fraction, market competitiveness, and power management, enabling efficient satellite launches and operations.[80] Interplanetary Mission, Constellation Maintenance, Sustainable Deorbiting, Scientific Missions[31] Electric propulsion cuts launch costs, increases payload capacity, opens new space insurance opportunities, and advances space weather forecasting for satellite operations.[43]The rotor disk method models EDFs for faster simulations, BLI improves lift and reduces drag, tandem wings distribute thrust efficiently, and tilt-wing mechanisms enable both horizontal flight and STOL capabilities.[44] Hybrid-electric aircraft improve efficiency and reduce emissions, UAVs benefit from electric propulsion, cryogenic systems enhance energy density, thermal management addresses cooling needs, and airport infrastructure must adapt for new aircraft types.[45] Solar Electric Propulsion suits inner solar system, Nuclear Electric Propulsion is for outer planets, ion and Hall Effect Thruster enable deep space and interplanetary travel, electrostatic and electrothermal thrusters offer high efficiency, electromagnetic thrusters excel in thrust, and propellant-less thrusters use ambient radiation and plasma.[34] ECRA(Electron cyclotron resonance thruster) used for CubeSat. [47] and magnetic nozzles for deep space.[47] Green propellant is used for satellite operations, deep space missions, air breathing electric propulsion, and hybrid propulsion.[13] Advanced thermal management technologies, including additive manufacturing, PCMs, cryogenic and thermoelectric cooling, nanofluids, and advanced motor cooling, enhance efficiency, reduce weight, and optimize hybrid-electric propulsion and high-energy systems.[51] Parallel hybrid systems and distributed propulsion enhance efficiency, reduce energy losses, and enable lighter, more fuel-efficient, and eco-friendly aircraft designs.[25] Advanced modeling techniques, including armature reaction, thermal effects, propeller-motor interaction, and battery voltages for large multicopter UAVs.[52] Advanced propulsion systems, including fuel cells, hybrids, and laser-charged technologies, enable UAVs to achieve extended flight durations, improved efficiency, diverse operational roles, and high-altitude, long-duration missions.[49] Advanced propulsion enables hybrid-electric transport, urban air mobility, lower emissions and noise, and gradual integration into existing airframes.[48] Gridded ion thruster enable deep-space exploration, long-duration missions, small satellite constellations, Mars and lunar transport, and sustainable satellite operations.[32] Hybrid systems combining PEMFCs and batteries in UAVs enhance endurance and efficiency, reduce emissions, and support energy-efficient aviation, with scalable testing paving the way for large-scale applications.[54] Satellite formation flying, orbital corrections, and advanced space missions benefit from precise thrust control and simplified systems, enhancing capabilities for missions like LISA, SMART-2, and GOCE while reducing PPU size and complexity.[102] NEP systems enable faster exploration, interstellar missions, and sample returns with higher payloads and efficiency, outperforming chemical and solar propulsion.[50] Electric and hybrid vessels with BESS systems reduce emissions and improve efficiency across marine applications.[56] In-Situ Resource Utilization (ISRU) enables cost-effective, flexible space missions by utilizing local propellants like CO2 and oxygen for long-duration missions, reducing dependence on Earth resources and expensive xenon [15]. Advancements in motor, battery, and power electronics enhance efficiency, reduce emissions, and support energy systems in automotive, aerospace, and consumer electronics.[26] Urban air mobility through eVTOL development, and hybrid-electric aircraft, through optimized designs, and accurate performance testing have advanced.[29] All-electric satellites with Hall thrusters boost payload capacity and enable precise station-keeping.[20] Planetary constellations of small satellites enable cost-effective science missions for Mars, Venus, including atmospheric studies and planetary exploration.[33] Argon use instead of xenon.[16] Design for Qualification to develop high-power (20 kW) Hall thrusters for deep-space missions while minimizing T&Q risks and costs.[71] The IonJet propulsion system enhances small satellite missions with cost-effective solutions, high thrust-to-power ratios, and longer operational lifetimes.[103] Pulsed plasma thruster suited for small satellites due to its lightweight, low power consumption, and compact design.[72] KM-60 integrated in national satellites.[73] Dual emitter hollow cathode used in plasma thrusters.[74] Space orbital debris removal using Hall thrusters [78][81] Continuous Control System allow for a control algorithm that commands the thrusters at small intervals.[85] EMC testing for electric thrusters in the converted RVC ensures safe space operation by evaluating electromagnetic compatibility and pre-compliance, with initial tests on a pulsed plasma thruster [89] The HC1 cathode is enhancing electric propulsion systems for nano and microsatellites [92].

5. Conclusion

Electric propulsion systems have revolutionized space transportation, offering efficient, sustainable, and high-performance alternatives to conventional chemical propulsion. Despite significant advancements in ion thrusters, Hall-effect thrusters, and hybrid-electric propulsion, several challenges persist, including power management, energy storage, thermal control, and scalability for deep-space missions. Innovations such as atmosphere-breathing electric propulsion, optimized power management algorithms, and the integration of superconductors and advanced battery technologies show promise in overcoming these limitations. Furthermore, the increasing adoption of electric propulsion in interplanetary missions, satellite station-keeping, and hybrid-electric aviation underscores its growing importance in modern aerospace applications. As research continues to address technical constraints and improve efficiency, electric propulsion is poised to play a pivotal role in the future of sustainable space exploration and advanced aerospace systems.

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7. References

[1] Levchenko I, Baranov O, Pedrini D, et al. Diversity of Physical Processes: Challenges and Opportunities for Space Electric Propulsion. Applied Sciences (Switzerland). 2022;12(21). doi:10.3390/app122111143

[2] Turchi PJ. An electric propulsion memoir. Journal of Electric Propulsion. 2022;1(1). doi:10.1007/s44205-022-00004-z

[3] Kolodziejski M, Michalska-Pozoga I. Battery Energy Storage Systems in Ships' Hybrid/Electric Propulsion Systems. Energies (Basel). 2023;16(3). doi:10.3390/en16031122

[4] Nuchturee C, Li T, Xia H. Energy efficiency of integrated electric propulsion for ships – A review. Renewable and Sustainable Energy Reviews. 2020;134. doi:10.1016/j.rser.2020.110145

[5] Kim YR, Kim JM, Jung JJ, Kim SY, Choi JH, Lee HG. Comprehensive design of dc shipboard power systems for pure electric propulsion ship based on battery energy storage system. Energies (Basel). 2021;14(17). doi:10.3390/en14175264

[6] Wu X, Dong Y. Hierarchical Model Updating Method for Vector Electric-Propulsion Satellites. Applied Sciences (Switzerland). 2023;13(8). doi:10.3390/app13084980

[7] Chadwick AR, Dally B, Herdrich G, Kim M. High-power inductive electric propulsion operation with alternative propellants. Aeronautical Journal. 2020;124(1272):151-169. doi:10.1017/aer.2019.141

[8] Frosina E, Caputo C, Marinaro G, Senatore A, Pascarella C, Di Lorenzo G. Modelling of a Hybrid-Electric Light Aircraft. In: Energy Procedia. Vol 126. Elsevier Ltd; 2017:1155-1162. doi:10.1016/j.egypro.2017.08.315

[9] Zhang J, Liu Y, Zheng Y. Overall eVTOL aircraft design for urban air mobility. Green Energy and Intelligent Transportation. 2024;3(2). doi:10.1016/j.geits.2024.100150

[10] Souhair N, Magarotto M, Andriulli R, Ponti F. Prediction of the Propulsive Performance of an Atmosphere-Breathing Electric Propulsion System on Cathode-Less Plasma Thruster. Aerospace. 2023;10(2). doi:10.3390/aerospace10020100

[11] Kuśmierek A, Galiński C, Stalewski W. Review of the hybrid gas - electric aircraft propulsion systems versus alternative systems. Progress in Aerospace Sciences. 2023;141. doi:10.1016/j.paerosci.2023.100925

[12] Levchenko I, Xu S, Mazouffre S, et al. Perspectives, frontiers, and new horizons for plasma-based space electric propulsion. Phys Plasmas. 2020;27(2). doi:10.1063/1.5109141

[13] Dale E, Jorns B, Gallimore A. Future directions for electric propulsion research. Aerospace. 2020;7(9). doi:10.3390/AEROSPACE7090120

[14] Turchi PJ. An electric propulsion memoir. Journal of Electric Propulsion. 2022;1(1). doi:10.1007/s44205-022-00004-z

[15] Chadwick AR, Dally B, Herdrich G, Kim M. High-power inductive electric propulsion operation with alternative propellants. Aeronautical Journal. 2020;124(1272):151-169. doi:10.1017/aer.2019.141

[16] Takahashi K, Charles C, Boswell RW, Ando A. Demonstrating a new technology for space debris removal using a bi-directional plasma thruster. Sci Rep. 2018;8(1). doi:10.1038/s41598-018-32697-4

[17] Brown NP, Walker MLR. Review of plasma-induced hall thruster erosion. Applied Sciences (Switzerland). 2020;10(11). doi:10.3390/app10113775

[18] Potrivitu GC, Sun Y, bin Rohaizat MWA, et al. A review of low-power electric propulsion research at the space propulsion centre Singapore. Aerospace. 2020;7(6). doi:10.3390/AEROSPACE7060067

[19] Mazouffre S. Electric propulsion for satellites and spacecraft: Established technologies and novel approaches. Plasma Sources Sci Technol. 2016;25(3). doi:10.1088/0963-0252/25/3/033002

[20] FUNAKI I, CHO S, SANO T, et al. 1,000-hours Demonstration of a 6-kW-class Hall Thruster for All-Electric Propulsion Satellite. TRANSACTIONS OF THE JAPAN SOCIETY FOR AERONAUTICAL AND SPACE SCIENCES, AEROSPACE TECHNOLOGY JAPAN. 2019;17(5):589-595. doi:10.2322/tastj.17.589

[21] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: A critical review. Progress in Natural Science. 2009;19(3):291-312. doi:10.1016/j.pnsc.2008.07.014

[22] Peng Z, Li Z, Song F, Zhang Y, Xi H, Liu F. Ion Electric Propulsion System Electric Breakdown Problems: Causes, Impacts and Protection Strategies. IEEE Access. 2023;11:97340-97352. doi:10.1109/ACCESS.2023.3312719

[23] Liang W, Charles C, Raymond L, et al. An integrated RF power delivery and plasma micro-thruster system for nano-satellites. Front Phys. 2018;6(OCT). doi:10.3389/fphy.2018.00115

[24] Rendón MA, Sánchez R CD, Gallo M J, Anzai AH. Aircraft Hybrid-Electric Propulsion: Development Trends, Challenges and Opportunities. Journal of Control, Automation and Electrical Systems. 2021;32(5):1244-1268. doi:10.1007/s40313-021-00740-x

[25] Bravo GM, Praliyev N, Veress Á. Performance analysis of hybrid electric and distributed propulsion system applied on a light aircraft. Energy. 2021;214. doi:10.1016/j.energy.2020.118823

[26] Sarlioglu B, Member S, Morris CT, Han D, Li S. Benchmarking of Electric and Hybrid Vehicle Electric Machines, Power Electronics, and Batteries.; 2012.

[27] Zhang J, Liu Y, Zheng Y. Overall eVTOL aircraft design for urban air mobility. Green Energy and Intelligent Transportation. 2024;3(2). doi:10.1016/j.geits.2024.100150

[28] Adu-Gyamfi BA, Good C. Electric aviation: A review of concepts and enabling technologies. Transportation Engineering. 2022;9. doi:10.1016/j.treng.2022.100134

[29] Hu J, Booker J. Preliminary Sizing of Electric-Propulsion Powertrains for Concept Aircraft Designs. Designs (Basel). 2022;6(5). doi:10.3390/designs6050094

[30] Martinelli SK, Penn JP, Judnick D, Rossi O, Ranieri C, Feistel A. Electric propulsion tug modeling improvements and application to the NASA/DARPA manned geosynchronous servicing study. In: AIAA SPACE Conference and Exposition 2012. ; 2012. doi:10.2514/6.2012-5103

[31] O'reilly D, Herdrich G, Kavanagh DF. Electric propulsion methods for small satellites: A review. Aerospace. 2021;8(1):1-30. doi:10.3390/aerospace8010022

[32] Levchenko I, Goebel DM, Bazaka K. Electric propulsion of spacecraft. Phys Today. 2022;75(9):38-44. doi:10.1063/PT.3.5081

[33] Girija AP, Saikia SJ, Longuski JM. Aerocapture: Enabling Small Spacecraft Direct Access to Low-Circular Orbits for Planetary Constellations. Aerospace. 2023;10(3). doi:10.3390/aerospace10030271

[34] Casanova-Álvarez M, Navarro-Medina F, Tommasini D. Feasibility study of a Solar Electric Propulsion mission to Mars. Acta Astronaut. 2024;216:129-142. doi:10.1016/j.actaastro.2024.01.001

[35] Ramakrishnan S. LIQUID PROPULSION SYSTEMS IN ISRO-EVOLUTION AND PERSPECTIVE.

[36] Souhair N, Magarotto M, Andriulli R, Ponti F. Prediction of the Propulsive Performance of an Atmosphere-Breathing Electric Propulsion System on Cathode-Less Plasma Thruster. Aerospace. 2023;10(2). doi:10.3390/aerospace10020100

[37] Barato F. Optimal use of electric propulsion for drag compensation in very low earth orbit on satellites with deployable solar panels. Acta Astronaut. 2023;213:1-19. doi:10.1016/j.actaastro.2023.08.038

[38] Kumar L, Jain S. Electric propulsion system for electric vehicular technology: A review. Renewable and Sustainable Energy Reviews. 2014;29:924-940. doi:10.1016/j.rser.2013.09.014

[39] Kühn-Kauffeldt M, Kühn M, Mallon M, Saur W, Fuchs F. Vacuum Arc Plasma Coating for Polymer Surface Protection— A Plasma Enhanced In-Orbit Additive Manufacturing Concept. Plasma. 2022;5(4):470-481. doi:10.3390/plasma5040035

[40] Nosseir AES, Cervone A, Pasini A. Review of state-of-the-art green monopropellants: For propulsion systems analysts and designers. Aerospace. 2021;8(1):1-21. doi:10.3390/aerospace8010020

[41] Jeyaraj AK, Liscouët-Hanke S. A Safety-Focused System Architecting Framework for the Conceptual Design of Aircraft Systems. Aerospace. 2022;9(12). doi:10.3390/aerospace9120791

[42] Zuo X, Xu M, Huang M, Li M, Peng N. Maintenance Strategy for Elliptical Orbit Satellite with Air-Breathing Electric Propulsion. IEEE Trans Aerosp Electron Syst. 2023;59(5):6863-6877. doi:10.1109/TAES.2023.3282611

[43] Horne RB, Pitchford D. Space Weather Concerns for All-Electric Propulsion Satellites. Space Weather. 2015;13(8):430-433. doi:10.1002/2015SW001198

[44] ZHANG X, ZHANG W, LI W, ZHANG X, LEI T. Experimental research on aero-propulsion coupling characteristics of a distributed electric propulsion aircraft. Chinese Journal of Aeronautics. 2023;36(2):201-212. doi:10.1016/j.cja.2022.07.024

[45] Kuśmierek A, Galiński C, Stalewski W. Review of the hybrid gas - electric aircraft propulsion systems versus alternative systems. Progress in Aerospace Sciences. 2023;141. doi:10.1016/j.paerosci.2023.100925

[46] Yang S, Xu B, Li X. Optimization of Geostationary Orbit Transfers via Combined Chemical–Electric Propulsion. Aerospace. 2022;9(4). doi:10.3390/aerospace9040200

[47] Wijnen M, Aguera-Lopez N, Correyero-Plaza S, Perez-Grande D. CubeSat Lunar Positioning System Enabled by Novel On-Board Electric Propulsion. IEEE Transactions on Plasma Science. 2018;46(2):319-329. doi:10.1109/TPS.2017.2779756

[48] Wheeler P, Sirimanna TS, Bozhko S, Haran KS. Electric/Hybrid-Electric Aircraft Propulsion Systems. Proceedings of the IEEE. 2021;109(6):1115-1127. doi:10.1109/JPROC.2021.3073291

[49] Joshi D, Deb D, Muyeen SM. Comprehensive Review on Electric Propulsion System of Unmanned Aerial Vehicles. Front Energy Res. 2022;10. doi:10.3389/fenrg.2022.752012

[50] Miao X, Zhang H, Wang Q, Xia Y, Sun W. Optimum design of nuclear electric propulsion spacecraft for deep space exploration. Energy Reports. 2022;8:9629-9641. doi:10.1016/j.egyr.2022.07.146

[51] Asli M, König P, Sharma D, et al. Thermal management challenges in hybrid-electric propulsion aircraft. Progress in Aerospace Sciences. 2024;144. doi:10.1016/j.paerosci.2023.100967

[52] Jeong J, Shi H, Lee K, Kang B. Improvement of electric propulsion system model for performance analysis of large-size multicopter uavs. Applied Sciences (Switzerland). 2020;10(22):1-30. doi:10.3390/app10228080

[53] Frosina E, Caputo C, Marinaro G, Senatore A, Pascarella C, Di Lorenzo G. Modelling of a Hybrid-Electric Light Aircraft. In: Energy Procedia. Vol 126. Elsevier Ltd; 2017:1155-1162. doi:10.1016/j.egypro.2017.08.315

[54] Farinha J, Silva LM, Matlock J, Afonso F, Suleman A. Hydrogen fuel cell integration and testing in a hybrid-electric propulsion rig. Int J Hydrogen Energy. 2023;48(97):38473-38483. doi:10.1016/j.ijhydene.2023.06.090

[55] Tajmar M, Genovese A, Buldrini N, Steiger W. At the Edge of Revolution. Published online 2002:9-12.

[56] Kolodziejski M, Michalska-Pozoga I. Battery Energy Storage Systems in Ships' Hybrid/Electric Propulsion Systems. Energies (Basel). 2023;16(3). doi:10.3390/en16031122

[57] Kim YR, Kim JM, Jung JJ, Kim SY, Choi JH, Lee HG. Comprehensive design of dc shipboard power systems for pure electric propulsion ship based on battery energy storage system. Energies (Basel). 2021;14(17). doi:10.3390/en14175264

[58] Nuchturee C, Li T, Xia H. Energy efficiency of integrated electric propulsion for ships – A review. Renewable and Sustainable Energy Reviews. 2020;134. doi:10.1016/j.rser.2020.110145

[59] Ammar NR, Seddiek IS. Evaluation of the environmental and economic impacts of electric propulsion systems onboard ships: case study passenger vessel. doi:10.1007/s11356-021-13271-4/Published

[60] Wu X, Dong Y. Hierarchical Model Updating Method for Vector Electric-Propulsion Satellites. Applied Sciences (Switzerland). 2023;13(8). doi:10.3390/app13084980

[61] Cecati C, Song S, Buticchi G. Special Issue on More Electric Aircraft. IEEE Transactions on Transportation Electrification. 2020;6(4):1382-1385. doi:10.1109/TTE.2020.3026761

[62] Gesell H, Wolters F, Plohr M. System analysis of turbo-electric and hybrid-electric propulsion systems on a regional aircraft. Aeronautical Journal. 2019;123(1268):1602-1617. doi:10.1017/aer.2019.61

[63] Grimme W, Paul A, Maertens S, Van Wensveen J. The prospects of hybrid-electric regional air transport - An assessment of travel time benefits of domestic short-haul flights in Germany with 19-seater aircraft. In: Transportation Research Procedia. Vol 51. Elsevier B.V.; 2020:199-207. doi:10.1016/j.trpro.2020.11.022

[64] Di Pasquale G, Sanjurjo-Rivo M, Pérez Grande D. A multi-objective variable-specific impulse maneuvers optimization methodology. Advances in Space Research. 2024;73(1):20-30. doi:10.1016/j.asr.2023.10.019

[65] Feuerborn SA, Neary DA, Perkins JM. Finding a way: Boeing's "all electric propulsion satellite." In: 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference. Vol 1 PartF. American Institute of Aeronautics and Astronautics Inc.; 2013. doi:10.2514/6.2013-4126

[66] Asai T, Yamada K, Jikuya I. Fuel-Efficient. Vol 12.; 2014.

[67] Volotsuev V V., Salmin V V., Safronov SL, et al. Application of Electric Propulsion for Low Earth Orbit Station Keeping. In: Procedia Engineering. Vol 185. Elsevier Ltd; 2017:254-260. doi:10.1016/j.proeng.2017.03.338

[68] Li L, Zhang J, Zhao S, Qi R, Li Y. Autonomous onboard estimation of mean orbital elements for geostationary electric-propulsion satellites. Aerosp Sci Technol. 2019;94. doi:10.1016/j.ast.2019.105369

[69] Barato F. Comparison between Different Re-Entry Technologies for Debris Mitigation in LEO. Applied Sciences (Switzerland). 2022;12(19). doi:10.3390/app12199961

[70] Mughal AH, Chadalavada P, Munir A, Dutta A, Qureshi MA. Design of deep neural networks for transfer time prediction of spacecraft electric orbit-raising. Intelligent Systems with Applications. 2022;15. doi:10.1016/j.iswa.2022.200092

[71] Borgue O, Paissoni C, Panarotto M, Isaksson O, Andreussi T, Viola N. Design for test and qualification through activity-based modelling in product architecture design. Journal of Engineering Design. 2021;32(11):646-670. doi:10.1080/09544828.2021.1950656

[72] Rezaeiha A, Anbarloui M, Farshchi M. Design, Development and Operation of a Laboratory Pulsed Plasma Thruster for the First Time in West Asia*. Vol 9.; 2011.

[73] Vorontsov V V., Kostin AN, Lovtsov AS, et al. Development of KM-60 Based Orbit Control Propulsion Subsystem for Geostationary Satellite. In: Procedia Engineering. Vol 185. Elsevier Ltd; 2017:319-325. doi:10.1016/j.proeng.2017.03.310

[74] NING Z, LIU C, ZHU X, WANG Y, AN B, YU D. Diagnostic and modelling investigation on the ion acceleration and plasma throttling effects in a dual-emitter hollow cathode micro-thruster. Chinese Journal of Aeronautics. 2021;34(12):85-98. doi:10.1016/j.cja.2021.02.007

[75] Burroni T, Thangavel K, Servidia P, Sabatini R. Distributed satellite system autonomous orbital control with recursive filtering. Aerosp Sci Technol. 2024;145. doi:10.1016/j.ast.2023.108859

[76] Désangles V, Packan D, Jarrige J, et al. ECRA thruster advances: 30W and 200W prototypes latest performances. Journal of Electric Propulsion. 2023;2(1). doi:10.1007/s44205-023-00046-x

[77] Lascombes P, Henri D. Electric propulsion for small satellites orbit control and deorbiting: The example of a hall effect thruster. In: 15th International Conference on Space Operations, 2018. American Institute of Aeronautics and Astronautics Inc, AIAA; 2018. doi:10.2514/6.2018-2729

[78] Golubek A V., Dron MM, Petrenko OM. ESTIMATION OF THE POSSIBILITY OF USING ELECTRIC PROPULSION SYSTEMS FOR LARGE-SIZED ORBITAL DEBRIS POST-MISSION DISPOSAL. Space Science and Technology. 2023;29(3):34-46. doi:10.15407/knit2023.03.034

[79] Li C, Xu B, Zhou W, Peng Q. Geostationary Station-Keeping of Electric-Propulsion Satellite Equipped with Robotic Arms. Aerospace. 2022;9(4). doi:10.3390/aerospace9040182

[80] Byers DC, Dankanich JW. Geosynchronous-earth-orbit communication satellite deliveries with integrated electric propulsion. J Propuls Power. 2008;24(6):1369-1375. doi:10.2514/1.35322

[81] Neumann A, Mühlich NS. Ground-Based Experiment for Electric Propulsion Thruster Plume—Magnetic Field Interaction. Aerospace. 2023;10(2). doi:10.3390/aerospace10020117

[82] Morales JE, Kim J, Richardson RR. Gyroless Spin-Stabilization Controller and Deorbiting Algorithm for CubeSats. International Journal of Aeronautical and Space Sciences. 2021;22(2):445-455. doi:10.1007/s42405-020-00311-5

[83] Kolbeck J, Anders A, Beilis II, Keidar M. Micro-propulsion based on vacuum arcs. J Appl Phys. 2019;125(22). doi:10.1063/1.5081096

[84] Ye L, Liu C, Zhu W, Yin H, Liu F, Baoyin H. North/South Station Keeping of the GEO Satellites in Asymmetric Configuration by Electric Propulsion with Manipulator. Mathematics. 2022;10(13). doi:10.3390/math10132340

[85] Elbayoumi G AM. ORBIT MAINTENANCE FOR SMALL SATELLITES USING ELECTRIC PROPULSION.

[86] Dudeck M, Doveil F, Arcis N, Zurbach S. Plasma propulsion for geostationary satellites for telecommunication and interplanetary missions. In: IOP Conference Series: Materials Science and Engineering. Vol 29. ; 2012. doi:10.1088/1757-899X/29/1/012010

[87] Savvas S, Malamas D, Manoudis A, et al. POWER PROCESSING UNIT FOR MICRO SATELLITE ELECTRIC PROPULSION SYSTEM.

[88] Nagano H, Kajiwara K, Osuga H, Ozaki T, Nakagawa T. Topics Research and Development of a New Power Processing Control Unit of Ion Engine System for the Super Low Altitude Test Satellite. Vol 8.; 2010.

[89] Kiefer F, Holste K, Klar PJ, Rover Y, Probst U, Volkmar C. Reverberation chamber for electromagnetic compatibility testing of electric thrusters. Journal of Electric Propulsion. 2023;2(1). doi:10.1007/s44205-023-00038-x

[90] Tirila VG, Demairé A, Ryan CN. Review of alternative propellants in Hall thrusters. Acta Astronaut. 2023;212:284-306. doi:10.1016/j.actaastro.2023.07.047

[91] Rovey JL, Lyne CT, Mundahl AJ, et al. Review of multimode space propulsion. Progress in Aerospace Sciences. 2020;118. doi:10.1016/j.paerosci.2020.100627

[92] Pedrini D, Ducci C, Cesari U, Misuri T, Andrenucci M. SITAEL HC1 low-current hollow cathode. Aerospace. 2020;7(7). doi:10.3390/AEROSPACE7070096

[93] Lozinski AR, Horne RB, Glauert SA, Del Zanna G, Heynderickx D, Evans HDR. Solar Cell Degradation Due to Proton Belt Enhancements During Electric Orbit Raising to GEO. Space Weather. 2019;17(7):1059-1072. doi:10.1029/2019SW002213

[94] Lee HC, Ng ZH, Lau YT, Chin OH, Goh BT, Lim CH. Study of a side-fed, tongue-flared configured pulsed plasma thruster. In: AIP Conference Proceedings. Vol 2319. American Institute of Physics Inc.; 2021. doi:10.1063/5.0037141

[95] Heiligers J, Fernandez JM, Stohlman OR, Wilkie WK. Trajectory design for a solar-sail mission to asteroid 2016 HO3. Astrodynamics. 2019;3(3):231-246. doi:10.1007/s42064-019-0061-1

[96] Salmin V V., Petrukhina K V., Kvetkin AA. Transfer of a Satellite from High Elliptical to Geostationary Orbit with the Help of Electric Propulsion. In: Procedia Engineering. Vol 185. Elsevier Ltd; 2017:352-358. doi:10.1016/j.proeng.2017.03.315

[97] Kramer A, Bangert P, Schilling K. UWE-4: First electric propulsion on a 1U cubesat-in-orbit experiments and characterization. Aerospace. 2020;7(7). doi:10.3390/AEROSPACE7070098

[98] Petrescu RV, Aversa R, Akash B, et al. Modern Propulsions for Aerospace-A Review. Journal of Aircraft and Spacecraft Technology. 2017;1(1):1-8. doi:10.3844/jastsp.2017.1.8

[99] Benamar K. EaglEye a mission for RSO catalogue construction & satellite inspection in the geostationary orbit. Advances in Space Research. 2022;70(4):1004-1012. doi:10.1016/j.asr.2022.06.015

[100] Levchenko I, Baranov O, Pedrini D, et al. Diversity of Physical Processes: Challenges and Opportunities for Space Electric Propulsion. Applied Sciences (Switzerland). 2022;12(21). doi:10.3390/app122111143

[101] Levchenko I, Baranov O, Pedrini D, et al. Diversity of Physical Processes: Challenges and Opportunities for Space Electric Propulsion. Applied Sciences (Switzerland). 2022;12(21). doi:10.3390/app122111143

[102] Tajmar M, Genovese A, Buldrini N, Steiger W. At the Edge of Revolution. Published online 2002:9-12.

[103] Scholze F, Pietag F, Adirim H, et al. Development and test of a cost-efficient gridded ion thruster propulsion system for small satellites – IonJet. Journal of Electric Propulsion. 2022;1(1). doi:10.1007/s44205-022-00028-5

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