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Advancing Ion Thruster Technology for Efficient and Sustained Spacecraft Acceleration: A Review

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ABSTRACT

Ion thrusters are the most advanced of all electric propulsion systems. They provide the capability of extended thrust operations in the vacuum of space that can change the velocity of the spacecraft. It is no longer an open question if ion propulsion is a usable systems technology. The question now is what needs to be done to make ion thrusters more practical to utilize. The technology also needs to be more applicable to science and cargo missions and more scaled to fit future small deep-space missions. It was their goal to address these questions in the context of ion thrusters. This review uses early texts, NASA technical reports, wall test results, and in-flight demonstration results to evaluate the current state of technology. It also identifies what design levers most contribute to sustained propulsion. According to those texts, changes to power architecture, lifetime engineering, propellant and feed systems, and control at the spacecraft level are where most of the progress has occurred. The flight testing of the ion propulsion systems on Deep Space 1 and Dawn, along with the NEXT test, showed the capability of ion engines and how they provide extended endurance. The review also points to this ion propulsion research and the trade-offs associated with thermal and material constraints on space systems. The review strongly suggests that the future of ion propulsion research will be in the trade-offs associated with erosion resistance, autonomy, storage, and efficiency.

Keywords—*ion thrusters, electric propulsion, sustained acceleration, spacecraft propulsion, grid erosion, xenon, iodine, power processing units, deep-space missions*

I. INTRODUCTION

There are multiple competing requirements that space missions beyond the Earth's orbit have to face. These requirements are the controllability, the lifespan, the mass discipline and the propulsion system's efficiency. It is not possible to get around using chemical propulsion systems for eliminating the gravity well of the Earth and for short-duration, high-thrust manoeuvres [1], [2].. However, the short velocity change that needs to be achieved requires many low-thrust maneuvers, and these systems have the disadvantage of low specific impulse and are not appropriate for these maneuvers. Electric propulsion can be used to overcome this drawback, as the propulsion system can separate the energy source and the propellant, and can achieve velocities that far exceed the velocities achieved by chemical propulsion systems. Of the various systems of electric propulsion, the gridded ion engines are most useful for cases when a trade-off can be made between energy efficiency and time and a spacecraft can be provided a continuous thrust for a long period of time[1]-[3]..

A trade-off is what the ion thruster systems are. The thrust provided is not large, however, when they are used for a long period of time they can change the velocity of the spacecraft by a very large amount of energy that would not be possible with a chemical propulsion system. Advanced ion propulsion systems are already beyond the research and development stages and have been used for a long time for purposes such as changing the orbit of the spacecraft and for other purposes during the missions where they provided free thrust for a long time [3]-[6]. . They have been used for missions with a high scientific value as well. Engineering issues are not limited to designing a system, that provides a stream of ions to the gridded thrusters. The major issues are to maintain a high durability and stability of the entire propulsion system within the limitations of the electrical energy the spacecraft provides, the thermal restrictions of the spacecraft, the system's mass, and the materials used to construct the system [2], [5], [6].

This distinction is critical for the discussion of ‘sustained acceleration.’ In terms of ion propulsion, large, launch-like acceleration is ruled out, but sustained acceleration is low-thrust propulsion that is reliable for long duration which can allow for mission-level delta-v in an economically sound manner. The system is then a propulsion feed system, a discharge chamber, a hollow cathode, ion optics, a neutralizer, and the ship’s power system and power processing electronics, to perform that system function as a tightly integrated system, and that integrated system supports the mission [1], [3], [8]. This is the case, for example, in the majority of the critical advances in the field occurring at the subsystem-interface level and the component level of the subsystem.

This interpretation can be analyzed through historical examples. For the first interplanetary mission that validated ion propulsion as a primary propulsion method, Deep Space 1 also validated the use of ion propulsion in addition to other methods. More than that, the mission demonstrated a scientifically complex technology mission that orbited (2) distinct bodies in the solar system, [10], [11]. Further technology was added to the system based on field endurance testing that extended the mission duration to 50,000 hours of continuous ion propulsion and defined a new baseline for ion thruster endurance, [12], [13]. Along with the NEXT mission length and endurance testing, propellant and propulsion systems that utilized alternative chemistry of propellants, one of which was based on iodine, expanded the design of compact spacecraft with other systems that did not use high pressure xenon and that did not support a system of high pressure xenon. [3], [14], [15].

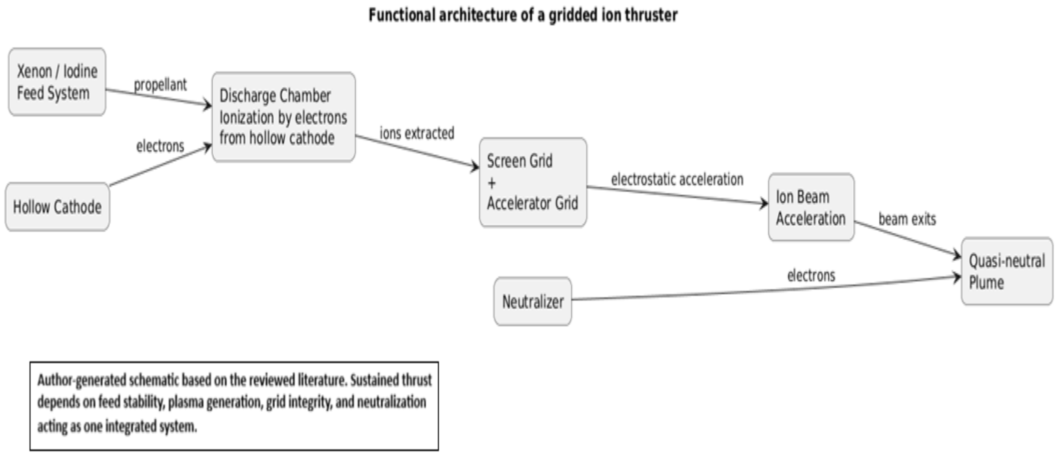
In this context, this document revises and develops the original student draft to create a review article formatted to suit publication purposes. This document strives to provide a more precise technical format and synthesis, and to standardize IEEE-style citations. The primary focus will address the question: What are the prospects and challenges of improving the efficiency of propulsion systems using ion thruster technology, to enable continual acceleration, and to overcome the voids of spaces? This question will be addressed by providing a review of the basic operational parameters of ion thrusters, and of the relevant literature. The review will describe the method of evidence synthesis. The key constraints and possible design pathways will be discussed and concluded with the design of the future deep space missions.

II. LITERATURE REVIEW

A. Operating Principle and Performance Metrics Gridded ion thrusters take in electrical power and create directed energy through acceleration of ions in a beam. When propellant is used, it is first neutral and injected into the discharge chamber. Cathodes emit electrons and collide and create a plasma with the neutral propellant. A beam of electrons is created, and a grid is used to charge and direct the ion beam. To discharge the ion beam and preserve the spacecraft charge, a neutralizer is used to emit electrons [1], [3]. This process, while simple in theory, is difficult to implement. There are lots of design trade-offs and each design stage has varying requirements in terms of integration, lifetime and efficiency [1], [2].

Ion thrusters are evaluated through linked metrics rather than through one value in the literature. Specific impulse is one of the metrics and is related to propellant efficiency. Thrust is the level of force, while thrust-to-power ratio indicates the electrical energy input converted into useful momentum. This is also the case for Total efficiency. Total efficiency consists of propellant and beam utilization as well as electrical efficiency, which is useful in comparing mission profiles and systems of varied sizes [1], [2], [6]. The review articles further clarify that for sustained acceleration, there needs to be gravel thrust, high specific impulse, and there needs to be a balance in beam quality and thrust efficiency. This should be the case for an extended period of time as well [2], [3], [5].

Many people believe that increasing beam voltage makes an ion thruster “better”. However, raising beam voltage leads to a higher exhaust velocity, which may improve specific impulse, but also increases erosion risk, power requirements, and integration complexity with the spacecraft. More recent design trends reflect that the guiding framework of spacecraft design is optimising a propulsion system to power systems, expected duty cycles, delta-v, and the spacecraft's thermal and structural capacity [1], [2]. The interactions between the spacecraft subsystems in need of thermal, structural, and power integration synthesize the performance of an ion thruster for sustained operational missions in a vacuum, as indicated in figure 1.



Functional architecture of a gridded ion thruster

Author-generated schematic based on the reviewed literature. Sustained thrust depends on feed stability, plasma generation, grid integrity, and neutralization acting as one integrated system.

Fig. 1. Author-generated schematic of a gridded ion thruster, showing where propellant feed stability, plasma generation, ion extraction, and neutralization interact to determine sustained propulsion performance.

B. Propellant Choice, Feed Systems, and Power Processing

Xenon is the preferred propellant because of its properties of high atomic mass, chemical inertness, low ionization energy and ease of storage. This makes Xenon the preferred ion source because of low cost and high capacity and the source can move quickly or for long durations in missions [1], [2]. Propellant selection is linked with feed system design. Achieving stable low mass flow is critical for predictable discharge behavior in ion source systems and for repeatable throttling. Xenon feeds in Snyder et al studies showed that stable engine operation is achieved for the throttle range and further integrates the engine while minimizing the harness system [8]. This is particularly important for sustained thrust papers, because seemingly engineering subsystems such as valves, PR controllers, and controllers often determine the ability of a thruster to transit between various operating states over long missions.

Power processing serves the same role. Propulsion systems and ion sources for a subset of propulsion systems (like ion propulsion) rely entirely on electrical power for the operation of ion sources. Therefore, the performance of these propulsion systems is limited to the available power in the spacecraft in a given mission. Propulsion capacity especially needs improved solar systems, high Power Processing Units for propulsion systems, and heat removal systems with controlled waste [2], [5], [6]. Propulsion scaling is essentially a spacecraft system challenge as much as a thruster design problem.

The shift toward smaller satellites and deep-space CubeSats has increased the demands for xenon alternatives, and iodine has presented an appealing complement with the advantages of dense solid storage, and the avoidance of the mass and volumetric disadvantages associated with metallic or gas tanks. Holste et al. highlight the potential of alternative propellants as a frontier in technology for ion-thruster research, within the context of small satellite and commercial satellite technology. [3]. Test flights of iodine-based systems for electric propulsion have validated the direction of the solutions, and the potential of these technologies. There are, however, serious design challenges with respect to thermal management, materials compatibility, and control systems [14], [15].

C. Lifetime-Limiting Mechanisms and Materials

Ion beam hardware damage defines ion thruster lifetime. Major processes related to hardware damage include beam-cathode contact, charge exchange ions, and plasma encroachment, cathode graze, grid contact erosion, and damage from the continuous cycling of cathode losses/examples. These challenges push performance to unintended limits and cause a shift from acceptable to unacceptable device functioning [1], [3]. This chapter outlines damage to ion thruster hardware attributed to combined effects of plasma erosion and charge exchange ions. This chapter further advocates the crucial aspect of the materials science of ion propulsion.

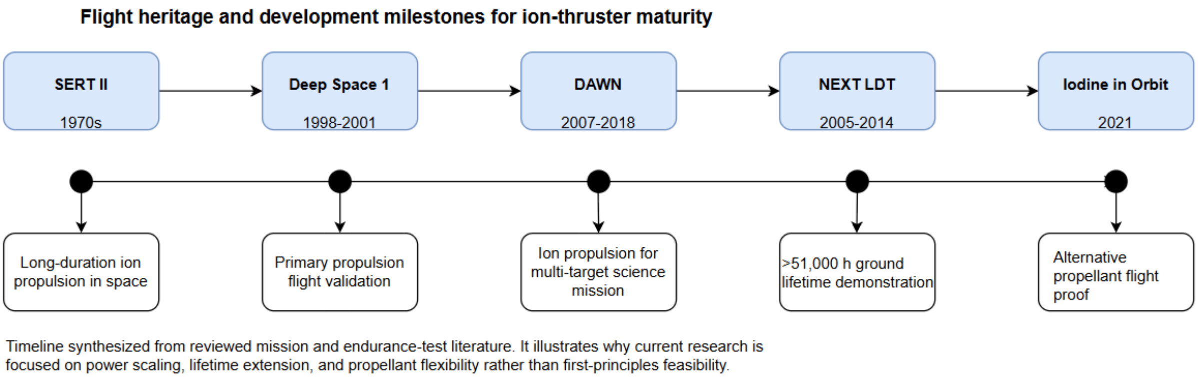
Williams et al. provided widely employed xenon sputter yield data for materials relating to ion-thruster construction, namely molybdenum, titanium, and carbon-based materials [9]. These assessments are relevant as longevity predictive assessments are reliant on the researchers' understanding of ion energy and impact angle resulted in the modifications of surface recession and redeposition. When these data are combined, and in the presence of beam-transport, erosion gaps are defined and successive design and modification alternatives are predicted to be the most significant in increasing longevity [1], [9].

Design, tolerance, and cathode material integration have shown substantial gains with long-lasting endurance tests. The NEXT program exemplifies industry advancement in this field. As an example, Herman showed that NEXT's long-duration test exceeded 50,000 hours processing over 900 kg of xenon with virtually no loss in performance [12]. The inspections performed positively. The findings showed it had major useful lifespan retainments, and several wear mechanisms, observed in earlier iterations, had been significantly lessened [13]. The considerations for future designs were rather apparent. It is not solely the use of withstand materials, but the careful collaboration and improvements in grid geometry, gap control, discharge behavior, and wear mechanisms predictive of degradation.

D. Flight Heritage and Mission Evidence

The argument for the maturity of ion thrusters is strongly supported by flight history. For Deep Space 1, it was validated that the NSTAR ion propulsion system operated in the interplanetary space, and for the first time, propriety of the primary propulsion system was established using a real, not speculative, technology ion propulsion system, rather than relegating it to the kind of propulsion system that is peripheral to the primary propulsion system [10]. Ion propulsion was the mechanism that enabled the transfer, orchestration, and operations of the spacecraft in the proximal space of Vesta and, subsequently, Ceres [11]. The majority of the referenced literature presents the unique logic of ion propulsion. The logic states that for long, continuous thrust arcs as opposed to short, simultaneous thrust as was the case in other propulsion systems, thrust was deemed as acceptable. As a result, missions using the aforementioned logic are often cited as examples of ion propulsion [1], [3], [5].

The literature is clear that both ground and mission evidence complement one another. Ground evidence allows for the acquisition of pertinent lifetime and wear data, which is difficult if not impossible to accomplish during the flight mission. Deep Space 1, Dawn, and NEXT are essentially a sequence of first validation, operational maturity, and lifetime qualification within the span of ion thrust propulsion systems [10]-[13]. As shown in Figure 2, the synthesis of the aforementioned historical narrative illustrates why the focus of the current research is in scaling, endurance, and propellant flexibility rather than the basic feasibility.


Flight heritage and development milestones for ion-thruster maturity

Timeline synthesized from reviewed mission and endurance-test literature. It illustrates why current research is focused on power scaling, lifetime extension, and propellant flexibility rather than first-principles feasibility.

Fig. 2. Author-generated timeline showing how ion propulsion progressed from early in-space validation to mission-enabling operation, record-setting endurance testing, and alternative-propellant demonstrations.

Table 1: Selected Literature And Its Design Implications For Sustained Ion-Thruster Acceleration

Ref.	Primary Focus	Representative Evidence	Design Implication
[8]	Xenon feed system simplification	Reduced complexity while maintaining stable operation over the throttle range.	Feed architecture is a first-order reliability variable, not a peripheral subsystem.
[9]	Sputter yields for key materials	Measured how xenon ion energy and incidence angle affect erosion of common materials.	Lifetime modeling must be anchored to material-response data.
[10]	Deep Space 1 flight validation	First interplanetary validation of an ion propulsion system as primary propulsion.	Operational feasibility is proven for long-duration deep-space use.
[11]	Dawn mission system implementation	Ion propulsion enabled transfer and orbital operations at multiple targets.	Mission architecture can be built around persistent low thrust.
[12]	NEXT long-duration endurance	>50,000 h operation and >900 kg xenon throughput with steady performance.	Lifetime margins can be expanded through integrated design improvements.
[13]	Post-test ion optics inspection	Confirmed reduced wear and substantial remaining life in critical optics components.	Geometry control and wear management are essential scaling levers.
[14]	Iodine in-orbit demonstration	Showed that iodine-based EP can function in space and support practical propulsion.	Alternative propellants are credible where storage volume is constrained.
[15]	Improved iodine thruster control	Demonstrated the importance of control architecture and radiation robustness after flight.	Propulsion maturity increasingly depends on electronics and autonomy, not only plasma physics.

E. Emerging Research Directions

The developing field of ion-thrusters nowadays is described as expansive and integrative, not merely embryonic [3]-[7], [16], with several repeating patterns. The first of which, is fuel alternatives being tested and considered for reasons beyond performance, such as: supply-chain, cost, storage-density, and mission-packaging. The second trend involves small, compact, and modular designs of RF ion thrusters, which may scale better with smaller thrusters than conventional designs [3], [7]. The third emerging trend is the increased application of model-based design and diagnostics. This is driven by the understanding of test-facility effects and the necessity of interpreting the effects of plume measurements, erosion, and lifetime extrapolations to predict in-space behavior [3], [5], [6].

Another trend within the field focuses on systems integration rather than component optimization. The intersection of commercial electric propulsion and the integration of repeatable, controllable, and autonomous robust systems, optimized for manufacturing and fault tolerance has been a game changer for systems sustaining new types of in-space transport that favor controlled or sustained acceleration [3], [16]. A dominant game-changer in this market centralizes systems, where sustained acceleration and sustained integration of optimal electric propulsion are critical to success. Although ion lifters are more systems engineering in nature, they are also scientifically multifaceted in propulsion.

III. REVIEW METHOD

This paper demonstrates a unique perspective on a topic rather than an original dataset. Selected sources included foundational references on ion propulsion and design, NASA documents on missions and endurance, and other recently published review articles on trends and limitations in design and alternative propellants [1]-[7], [10]-[15]. The source selection focused on constructing a unifying evidence base that cut across the basic functional design, subsystems and components, lifetime and mission endurance, thereby the review was not bounded by framing an empirical statistical meta analysis.

The review outlined the literature in sections and performed a four-step analysis. First, the literature was divided into: operating principles, propulsion systems, feed systems, mechanisms of erosion and lifetime trade offs, and endurance. Second, the most frequently stated design restrictions. Third, the literature was assessed across different scales (component vs. mission) to characterize subsystem and system-level challenges. Fourth, an integrated roadmap that extended beyond systems of ‘fuel propulsion’ to advanced spacecraft propulsion was developed.

This approach fits the current topic because the development of ion thrusters relates to many engineering fields. An attractive propulsion concept from the plasma-physics standpoint may be limited by issues such as the mass of the power-processing unit, thermal management of the spacecraft, the wear of the components, or the complexity of operations. Thus, an effective review paper should do more than compile findings from different, unrelated studies. It must explain the relationships among the findings, how they cross the boundaries of the various engineering systems, and what these relationships may suggest for future systems. The following observations and discussions are based on this cross-scale synthesis.

IV. OBSERVATIONS AND DISCUSSION

A. What the Literature Consistently Shows

The literature consistently confirms three key findings. First, gridded ion thrusters and other variants are no longer experimental. They are well-established systems with significant scientific grounding and flight heritage [1]-[3], [10], [11]. Second, the barrier to more extensive use is not found in the efficiency of the system. Rather, the barrier lies in the system’s ability to ensure efficiency, controllability, and the health of the components within the power and thermal constraints of a spacecraft [2], [5], [6]. Third, the literature consistently shows that improvements in endurance come from miniature, interconnected systems changes in the cathode, feed systems, optical systems, and technique rather than a single bold move in beam voltage and/or propulsion flow change [8], [9], [12], [13].

These findings compel a rethinking of how the central research question should be framed. In the quest to “increase propulsion efficiency” and “sustain acceleration,” the more appropriate goal to aim for isn’t maximizing specific impulse, but rather, mission-effective long duty cycle performance. This entails the provision of sustained thrust, a favorable thrust-to-power ratio, low erosion, repeatability and control of stopping, and a manageable system contamination, all within a spacecraft that is constructed to continuously provide and dissipate the needed electrical power. It can be said that from the perspective of a case study, perspective sustained acceleration should be considered far more than any single propulsion performance parameter.

B. Major Constraints to Sustained Acceleration

The first constraint concerns power availability. The primary benefit of ion thrusters is using electricity to propel the fuel more rapidly, but its downside is that it limits the performance of the thruster. Increasing thrust while maintaining a high degree of specific impulse requires an increase in beam current that is proportional to an increase in electrical power. This poses a challenge to spacecraft designers that power all solar array systems or use alternative power sources to mitigate the issue of higher propulsion unit mass and increased thermal load. Surveying reviews of future electric propulsion systems consistently cite the power architecture as the number one factor that enables the next leap in performance.

The second constraint concerns system lifetime. An endurance program conducted by NEXT has shown that very long operating times of ion engines are possible, but it has also shown how slow the rate of erosion is of ion optics and the cathodes. In high repeat missions, ion engine cathodes are at risk of erosion. This raises the necessity that lifetime and erosion modeling, as well as a post-test inspection, are not secondary validation system processes, but are in fact integral design system processes. The third constraint concerns system complexability. There are multiple functional systems that are integrated to one system. They are feed systems, mechanisms, thermal paths, and control subsystems that are gimbal and attitude. These complex systems can all become risk of failures in the systems. Finally, the fourth constraint concerns on-system packing. Xenon is very effective as an ion fuel, but it provides high penalties on the economy of spacecraft constrained volume and in spacecraft, switches are now being increased.

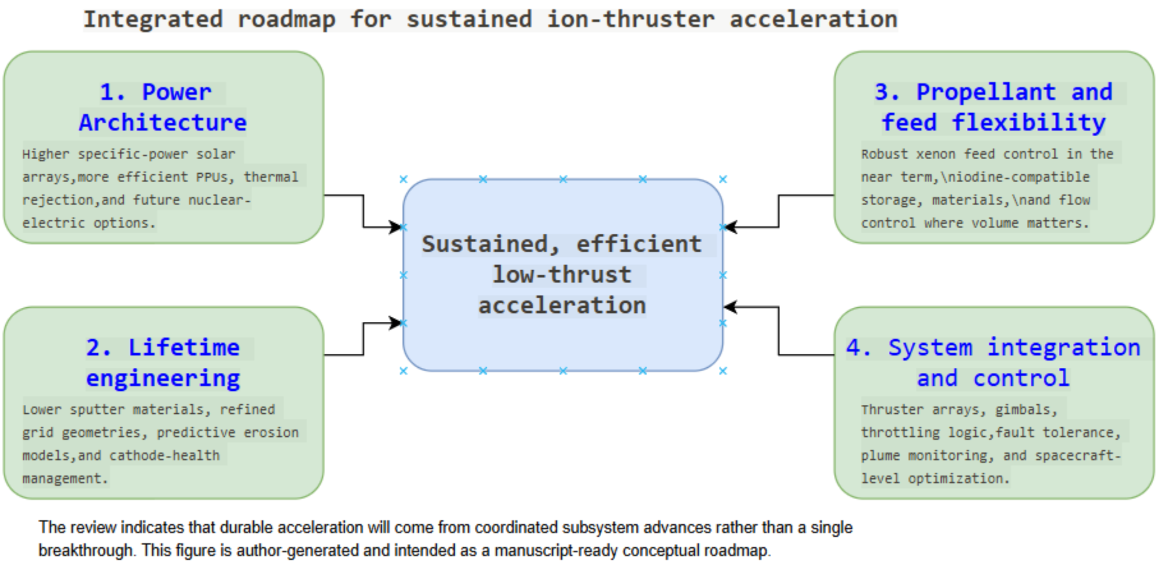
Table 2: Major Bottlenecks And The Most Promising Responses Identified In The Review

Bottleneck	Why It Matters for Sustained Acceleration	Most Promising Response
Power scaling	Higher thrust without losing efficiency requires more electrical input and more thermal rejection.	Specific-power solar arrays, efficient PPUs, and power-aware throttle strategies.
Grid erosion	Cumulative wear can end a mission long before theoretical performance limits are reached.	Low-sputter materials, optimized ion optics, and predictive erosion models.
Cathode endurance	Poor electron emission stability degrades ionization and plume neutralization.	Improved cathode materials, health monitoring, and robust start-stop control logic.
Feed complexity	Flow instability or excessive component count reduces reliability over long campaigns.	Simplified feed architectures with stable low-mass-flow control.
Propellant packaging	High-pressure xenon storage is challenging for mass- and volume-limited spacecraft.	Iodine-compatible materials, thermal conditioning, and flexible storage geometry.
Spacecraft integration	Propulsion, power, guidance, and thermal subsystems must operate as one coordinated system.	Model-based integration, modular arrays, gimbals, fault tolerance, and autonomy.

C. A Review-Based Roadmap for Next-Generation Ion Thrusters

The literature shows there are four design levers that can be used to organize future development. The first design lever shows changes in power architecture. Ion thrusters achieve only low power and thrust (with respective margins) that are unacceptable for most mission profiles. The second lever describes lifecycle engineering. The design and selection of materials, geometry, and optics must be taken in equal measure at the beginning of development. The third lever describes the flexibility of feed and propellant. Higher power missions often use xenon systems, but with thrust to weight ratios often required in domains such as military and space operations, space missions with significant volume and footprint restrictions increasingly will be addressed by iodine and iodine-like propellant systems. The fourth lever describes flexibility of integration. Autonomous systems that are strongly integrated with attitude and thermal subsystems of the space vehicle create propulsion related issues in themselves, linked to the functional and software tool and design electronics of the system [3], [5], [6], [15], [16].

This perspective of case systems helps to understand the value of review papers in mature fields, and why this is the case. The highest value insights are usually derived from the integration of works that, in the first instance, exist in distinct technical fields, such as plasma physics, and the evaluation of materials, and the testing and evaluation of space operations and systems design.



The review indicates that durable acceleration will come from coordinated subsystem advances rather than a single breakthrough. This figure is author-generated and intended as a manuscript-ready conceptual roadmap.

Fig. 3. Author-generated roadmap showing the four subsystem domains that most directly govern whether ion thrusters can deliver efficient and durable sustained acceleration in future missions.

D. Implications for Future Missions

The evidence suggests a hybrid design for future missions. Ion propulsion will not be a substitute for chemical propulsion when high thrust is required. However, for missions where delta-v, economy of propellant, and mission control demand long periods of low thrust, ion propulsion will dominate. Missions of deep-space science, cislunar logistics, transfer of logistics to and from cislunar space agencies, orbit raising and lowering, and multi-targeted missions, will all benefit from ion propulsion [2], [5], [10], and [11].

The same evidence suggests the meaning of “modern circuitry” should be expanded. Integration is often viewed simply in the context of mechanical and electrical interface. However, it also encompasses budgeting of propulsion system systems, interaction of plumes, design of mission autonomy and fault recovery, as well as design of mission operational systems. While the propulsion system might perform well in a vacuum, be easy to throttle, and be theremally well supported, a system that is highly constrained, as in the case of spacecraft that utilize the system, is unlikely to sustain the required acceleration in a mission context. Reliable ion propulsion is a combination of design and plasma system architecture and optimization. This is perhaps the most valid observation that is to be drawn from the flight, endurance, and review literatures in the collection.

V. CONCLUSION

The review demonstrates that ion thruster tech has advanced. Today, it has the capability of operational flight heritage record-setting endurance. Ion propulsion can assist prolonged complex interplanetary operations, as evidenced by the operations of Deep Space 1 and Dawn. The NEXT program showed what can be accomplished by engineering novel ion optics and cathodes with dynamic thruster parameters [10]-[13]. Thus, there is no debate that ion thrusters provide the most operationally efficient propulsion for missions that require low-thrust operation over extended periods of time.

The review presents that the greatest system-imposed constraints result from either current or potential ion thrusters. These include power, erosion and wear of components, reliability of the feed system, integration constraints, and the packaging of the propulsion system. Several newer propulsion systems, such as iodine propellants, improved high efficiency control electronics, and power systems, and model-based life prediction [3]-[6], [14], [15], provide design imposition constraints. The primary goal for the provision of sustained acceleration is integrated and system-wide coordination of power, propulsion systems, and space vehicle autonomy. Isolated improvements for thruster components will not provide the necessary design imposition constraints.

Ion thrusters can be regarded as systems that provide precision propulsion over extended periods of time, which becomes increasingly valuable as spacecraft become more autonomous, power-rich, and optimized for extended periods of time in transit. Ion thrusters will become infrastructure-mass-propulsion-mission dominant as spacecraft systems of high autonomy, high power, and efficient long cruise phases for extended time transit continue to be developed. Ion thrusters will also become the dominant efficient systems propelling the mission. The systems of endurance, controllability, and economical use of propellants will encourage sustained investments in ion thruster propulsion for long-haul, deep-space missions and exploration.

REFERENCES

[1] D. M. Goebel and I. Katz, Fundamentals of Electric Propulsion: Ion and Hall Thrusters. Hoboken, NJ, USA: Wiley, 2008.

[2] S. Mazouffre, "Electric propulsion for satellites and spacecraft: Established technologies and novel approaches," Plasma Sources Sci. Technol., vol. 25, no. 3, Art. no. 033002, 2016, doi: 10.1088/0963-0252/25/3/033002.

[3] K. Holste et al., "Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer," Rev. Sci. Instrum., vol. 91, no. 6, Art. no. 061101, 2020, doi: 10.1063/5.0010134.

[4] I. Levchenko et al., "Recent progress and perspectives of space electric propulsion systems based on smart nanomaterials," Nat. Commun., vol. 9, Art. no. 879, 2018, doi: 10.1038/s41467-017-02269-7.

[5] I. Levchenko et al., "Perspectives, frontiers, and new horizons for plasma-based space electric propulsion," Phys. Plasmas, vol. 27, no. 2, Art. no. 020601, 2020, doi: 10.1063/1.5109141.

[6] E. Dale, B. Jorns, and A. Gallimore, "Future directions for electric propulsion research," Aerospace, vol. 7, no. 9, Art. no. 120, 2020, doi: 10.3390/aerospace7090120.

[7] D. O'Reilly, G. Herdrich, and D. F. Kavanagh, "Electric propulsion methods for small satellites: A review," Aerospace, vol. 8, no. 1, Art. no. 22, 2021, doi: 10.3390/aerospace8010022.

[8] J. S. Snyder, T. M. Randolph, R. R. Hofer, and D. M. Goebel, "Simplified ion thruster xenon feed system for NASA science missions," in Proc. Int. Electric Propulsion Conf., Ann Arbor, MI, USA, 2009, Paper IEPC-2009-064.

[9] J. D. Williams, M. M. Gardner, M. L. Johnson, and P. J. Wilbur, Xenon Sputter Yield Measurements for Ion Thruster Materials, NASA/CR-2003-212306, 2003.

[10] J. Polk, R. Kakuda, J. Anderson, J. Brophy, V. Rawlin, J. Sovey, and J. Hamley, "In-flight performance of the NSTAR ion propulsion system on the Deep Space One mission," Jet Propulsion Lab., Pasadena, CA, USA, NASA NTRS 20060041025, 2000.

[11] J. R. Brophy, M. G. Marcucci, G. B. Ganapathi, C. E. Garner, M. D. Henry, B. Nakazono, and D. Noon, "The ion propulsion system for Dawn," Jet Propulsion Lab., Pasadena, CA, USA, NASA NTRS 20060029232, 2003.

[12] D. A. Herman et al., "Status of NASA's Evolutionary Xenon Thruster (NEXT) Long-Duration Test as of 50,000 h and 900 kg throughput," Glenn Research Center, Cleveland, OH, USA, NASA NTRS 20150004419, 2015.

[13] G. C. Soulas and R. Shastry, "Post-test inspection of NASA's Evolutionary Xenon Thruster long duration test hardware: Ion optics," NASA NTRS 20210009717, 2021.

[14] D. Rafalskyi et al., "In-orbit demonstration of an iodine electric propulsion system," Nature, vol. 599, pp. 411-415, 2021.

[15] A. Bore, P. Proynov, and D. Rafalskyi, "Improved control architecture and strategy for iodine ion thruster following in-orbit demonstration and system-level radiation testing," J. Electr. Propuls., vol. 2, Art. no. 7, 2023, doi: 10.1007/s44205-023-00041-2.