Acceleron Aerospace Journal || AAJ.11.2106-2474
Volume 3, Issue 7, pp (758-763)
Research Paper
E-ISSN- 2583-9942 || DOI: 10.61359/11.2106-2474

Optimization of Interstellar Travel through Design Approaches with Gimballing Ion Thrusters

Fawzan Mohamed Kareem Navaz*

Department of Aerospace Engineering, Amity University, Dubai Academic City, Dubai, United Arab Emirates

Abstract: Interstellar travel, constrained by current propulsion technologies, suffers from limitations in efficiency and maneuverability essential for vast interstellar distances. This paper presents a rigorous investigation into optimizing interstellar travel through advanced design methodologies, with a primary focus on the deployment of gimbaled ion thrusters to enhance maneuverability and trajectory correction. The research meticulously examines two-axis thrust vectoring, propulsion system efficiencies, fuel transfer mechanisms, and energy management strategies, aiming to significantly improve propulsion and control system performance. A detailed comparative analysis of gimbaled thrust versus traditional thrust systems evaluates the impact on fuel efficiency and overall spacecraft performance. By integrating aerospace engineering and materials science principles, this study advances the discourse on interstellar travel. The findings and recommendations from this research aim to drive the development of cutting- edge spacecraft propulsion systems, facilitating more efficient and adaptable exploration beyond the solar system.

Table of Contents

1. Introduction

The prospect of travelling in space to other star systems has driven humans to live many things, but propulsion is the major hitch. This research deals with gimballing thrusters which make spacecraft more maneuverable and provide a proper control in any trajectory by merely modifying the direction of thrust. Such high precision for future long duration missions where minor course correction could mean a lot. The primary aim of this study is to improve the design of gimballing thrusters for better spacecraft efficiency and fuel economy towards sustainable deep space travel. In solving several propulsion challenges, the novel way brings a step forward in the expedition for interstellar exploration toward the unknown mysteries of the cosmos and across the vast interstellar medium. Traveling through space between stars, interstellar space travel is one of those dreams that humankind aspires for. The most substantial obstacle would be propulsion. The research deals with gimballing thrust, which makes the spacecraft maneuvers better and controls the change of trajectory by merely changing the thrust direction. As for the longer duration missions, long-course corrections are very important. This study intends to optimize the design of gimballing thruster for better spacecraft efficiency as well as fuel economy towards sustainable deep-space journeys. Here are some propulsion bottlenecks that have been addressed by the top revolution in that step toward the expedition for interstellar exploration into the unknown mysteries of the cosmos and across the vast interstellar medium.

2. Problem Statement

As interplanetary travel advances, the need for efficient propulsion systems grows. This research explores gimballing ion thrusters to enhance maneuverability, fuel efficiency, and trajectory control during long missions. By focusing on thrust vectoring, energy management, and propulsion efficiency, it provides a framework for

*Department of Aerospace Engineering, Amity University, Dubai Academic City, Dubai, United Arab Emirates. **Corresponding Author: fawzanmohamed10@gmail.com.**
** Received: 20-December-2024 || Revised: 28-December-2024 || Accepted: 29-December-2024 || Published Online: 30-December-2024.

future studies. Gimballing thrusters address challenges like gravitational assists and orbital corrections, offering adaptable solutions for interstellar travel. Integrating aerospace engineering, materials science, and astrodynamics, this study lays the groundwork for more efficient spacecraft propulsion, advancing humanity's exploration of the universe.

3. Current Propulsion Technologies

Efficient propulsion systems are pivotal in advancing humanity's space exploration efforts, enabling longer missions and expanding our reach into the cosmos. By 2024, propulsion technologies have diversified, including chemical, electric, plasma, and nuclear systems, each tailored to meet specific mission requirements and advancing the exploration frontier.

Chemical Propulsion:

Chemical propulsion remains fundamental due to its high thrust-to-weight ratio and simplicity. Combustion in a high- pressure chamber produces exhaust velocities of 1800 – 4300 m/s, operating under extreme temperatures that necessitate advanced cooling (NASA, 2024). Propellants include liquid, solid, gaseous, and hybrids, offering varying benefits like throttling, stability, or combined strengths (Wong et al., 2023; Smith et al., 2022).

Electric Propulsion:

Electric systems, including ion and Hall-effect thrusters, minimize propellant use while achieving high exhaust velocities, reducing launch mass and costs. Ideal for interplanetary missions, these systems have demonstrated potential in missions like *Cassini* and *New Horizons*, with nuclear-electric propulsion emerging as a solution for constant low-thrust deep-space travel (JPL, 2024; ESA, 2023).

Hybrid Systems:

Hybrid propulsion integrates methods like chemical systems for initial thrust and electric systems for deep-space maneuvers, optimizing performance for varying mission phases (Brown et al., 2023). Advancements in propulsion technologies are not only enabling current missions but also paving the way for interstellar exploration, bringing humanity closer to unraveling the mysteries of the universe.

4. Gimballing Spacecraft Thruster

4.1 Thrusting Mechanism

Thrust is a fundamental aspect of propulsion systems, acting at the center of mass of a vehicle to enable movement. Generated by the ejection of high-velocity exhaust gases, thrust follows Newton's third law: every action has an equal and opposite reaction (NASA, 2024).

Chemical Propulsion:

Liquid rocket engines, such as SpaceX's Merlin, produce thrust through controlled combustion of fuel and oxidizers. These engines deliver high thrust but have a moderate specific impulse of about 282 seconds, limiting fuel efficiency (Wong et al., 2023).

Electric Propulsion:

Electric systems, like NASA's NEXT ion engine, achieve specific impulses exceeding 3,000 seconds by accelerating ions via electromagnetic fields, providing excellent fuel efficiency. However, their low thrust limits applicability for missions requiring rapid acceleration (ESA, 2023). Mission objectives often dictate the choice of propulsion system. Hybrid solutions combining chemical and electric systems optimize performance across diverse operational requirements.

4.2 Gimballing Mechanism

A gimballing mechanism is vital in spacecraft propulsion systems, offering precise control over thrust direction during maneuvering and stabilization. By using pivoted supports (gimbals), this technology allows for the rotation of rocket engines along multiple axes, facilitating trajectory adjustments or stability maintenance during flight. Historically, gimballing was pivotal in the Apollo missions, where the Saturn V rocket utilized gimballing for pitch and yaw control, ensuring accurate flight paths despite external factors like wind shear (NASA, 1973). More recently, SpaceX's Merlin engines have advanced gimballing technology, supporting precise ascent, descent, and reusability for cost-effective space operations (SpaceX, 2023). Gimballing also plays a crucial role in spacecraft attitude control systems, maintaining orientation for tasks such as communication, observation, and scientific measurement, even in the challenging conditions of space (Smith & Lee, 2022). This versatility underscores the importance of gimballing mechanisms in modern space exploration.

5. Design and Efficiency Optimization of the Gimballing Ion Thruster

5.1. Design of the Thruster

The gimballing ion thruster incorporates a gimbal mechanism that enables two-axis articulation of the thrust vector, providing precise control over spacecraft orientation and trajectory. This design utilizes electrostatic acceleration of xenon ions, achieving a high specific impulse (>3000 s) and low propellant consumption, ideal for deep-space missions. The gimbal system employs stepper motors and low-friction bearings for smooth motion, with integrated feedback sensors ensuring accurate vector alignment. This innovation reduces reliance on traditional attitude control systems, optimizing spacecraft mass and complexity while enhancing mission flexibility.

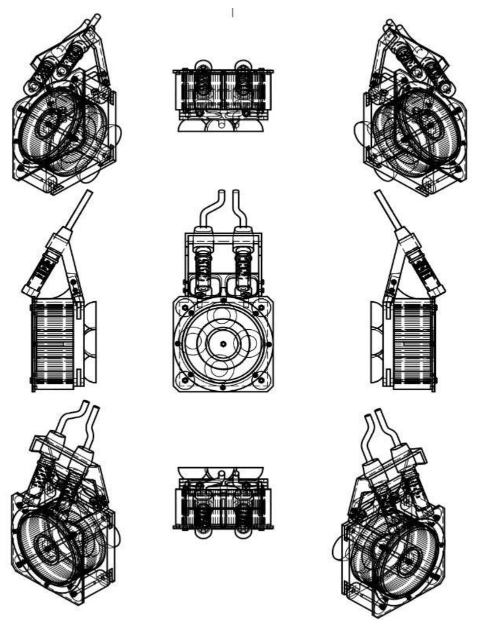

Figure-1 2D drawing of Gimballing Ion Thruster

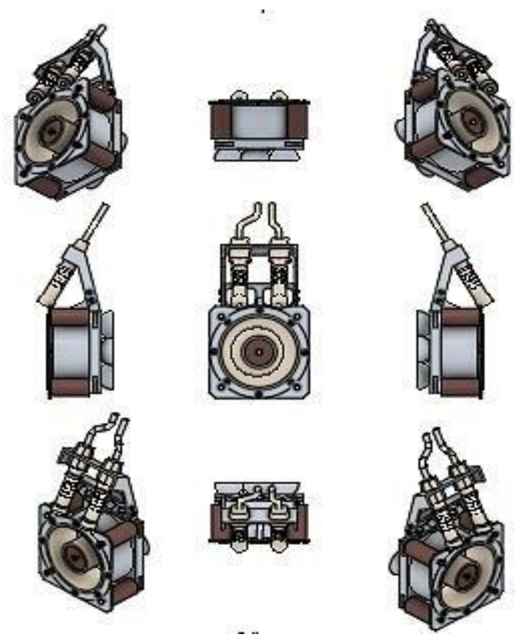

Figure-2 Rendered Images of Gimballing Ion Thruster

Figure 1 presents the detailed 2D orthographic projections of the gimballing ion thruster, providing front, side, top, and isometric views. These projections outline the structural configuration and dimensions of the thruster, including the gimbal mechanism and ion acceleration components. The technical drawings serve to illustrate the spatial arrangement of critical subsystems, enabling a precise understanding of the mechanical layout for fabrication and assembly.

Figure 2 displays rendered 3D images of the gimballing ion thruster from multiple perspectives. These renders offer a realistic visualization of the system, highlighting the gimbal articulation mechanism, ion acceleration chamber, and overall geometry. The 3D representations complement the 2D drawings by providing a clear perspective on the integrated design, aiding in the visualization of the thruster's functional architecture and its capacity for thrust vectoring

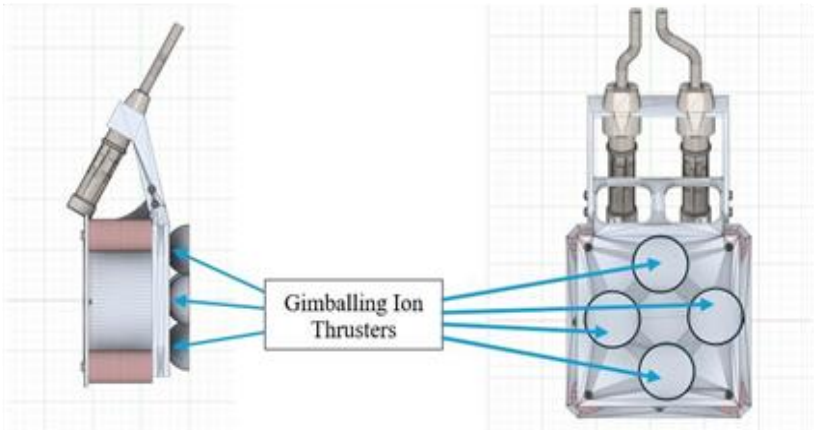

Figure-3 Configuration of Gimballing Ion Thrusters with Side and Top Views

Figure 3 showcases the configuration of gimballing ion thrusters, highlighting their structural design and clustered arrangement. The side view illustrates the thruster's gimbal mechanism, which enables thrust vectoring by allowing articulation around two axes. The top view displays a quad-thruster configuration, where four gimballing ion thrusters are symmetrically arranged to provide precise control over thrust direction. This layout enhances spacecraft maneuverability, enabling fine attitude adjustments and trajectory corrections without additional attitude control systems. The clustered design ensures redundancy and improved efficiency, making it ideal for long-duration.

The gimbals are solid hemispheres instead of hollow hemispheres, this does increase the weight a little but due to the miniature size of the thruster the weight from such small size is negligible. Also shock absorbers are kept inside these solid hemispheres that can absorb any vibrations that may be caused due to the mechanical parts. These shock absorbers stabilize the thrusters so that the payload doesn’t go astray in case of a vibrating mechanical part of the thruster.

5.2. Efficiency Optimization of the Thruster

This gimballing ion thrusters work by automatically controlling the gimbals using push pull rods. There will be 4 push pull rods per gimbal that allows the gimbals to rotate freely for 2 degrees of freedom which means the gimballing ion thruster can rotate along 2 axes. This can vector the thrust generated efficiently so that the propellant used to thrust using traditional methods can be used less which means more areas of exploration using the same amount of propeller.

The properties of Deep Space 1 Mission are taken for calculation purposes. During the testing phase of the mission data were recorded. Thrust changes a spacecraft's velocity through the application of force as described by Newton's Second Law of Motion (F = ma), where the force generated by the propulsion system causes acceleration proportional to the spacecraft's mass. In the vacuum of space, where there is no resistance, even a small but continuous thrust produces a cumulative velocity change over time. This principle is demonstrated by the ion propulsion system on NASA’s Deep Space 1 (DS1), which generated a gentle thrust that increased the spacecraft's speed by less than 15 miles per hour each day. Despite the small daily increments, the consistent application of thrust over 2.5 months resulted in a significant velocity change of over 1500 miles per hour, consuming only 11.5 kg of xenon propellant. This highlights the effectiveness of ion propulsion for long-duration missions, as it allows for precise and fuel-efficient velocity adjustments critical for interplanetary travel.

Table-1 Performance comparison of Traditional and Gimballing Ion Thrusters at 45^o gimbal angle.

Parameters	Traditional Ion Thruster	Gimballing Ion Thruster (Gimbal angle = 45^o)
Distance Travelled (miles)	1500	**1500**
Fuel Used (kg)	$6.38 \text{ x } 10^{-3}$	**$4.511\ x\ 10^{-3}$**
Time Taken (hours: minutes: seconds)	**1:00:00**	**0:42.30**

Table 1 compares the performance of a traditional ion thruster with a gimballing ion thruster operating at a gimbal angle of 45^o. Both thrusters traveled the same distance of 1500 miles, but the efficiency and time differ significantly. The traditional ion thruster used 6.38×10^{-3} kg of fuel and took 1 hour to cover the distance. In contrast, the gimballing ion thruster consumed less fuel (4.511×10^{-3} kg) and achieved the same distance in a reduced time of 42:30 minutes. This highlights the improved fuel efficiency and time optimization of the gimballing ion thruster configuration, likely due to its ability to adjust thrust direction dynamically, minimizing energy loss and enhancing overall performance.

The comparison between the Traditional Ion Thruster and the Gimballing Ion Thruster operating at a gimbal angle of 45^o demonstrates a 29.29% improvement in fuel efficiency. While both thrusters traveled the same distance of 1500 miles, the Gimballing Ion Thruster consumed 4.511×10^{-3} kg of fuel, significantly less than the 6.38×10^{-3} kg used by the Traditional Ion Thruster. This increased efficiency can be attributed to the dynamic thrust adjustment enabled by the gimballing mechanism, which optimizes the thrust direction, reduces energy losses, and enhances overall propulsion performance. Such improvements are critical for long-duration space missions where fuel conservation is essential

6. Conclusion

This study highlights the significant advantages of gimballing ion thrusters over traditional ion thrusters, demonstrating a 29.29% improvement in fuel efficiency. Reduced fuel consumption results in a lower launch mass, enabling cost savings, enhanced spacecraft maneuverability, and faster mission timelines, which collectively extend observation periods and improve scientific outcomes. By emphasizing the importance of advanced propulsion systems, including thrust vectoring, trajectory adjustments, and energy management, this study provides a strong foundation for future research into efficient propulsion methods. While flow models were not utilized, the findings underscore the potential of gimballing thrusters to address challenges such as gravitational assistance, orbital corrections, and course changes, representing a substantial advancement in interstellar travel capabilities. Integrating aerospace engineering, materials science, and astrodynamics, this research offers vital insights for developing adaptive and efficient spacecraft propulsion systems, paving the way for sustainable and effective exploration beyond our solar system.

7. Biography of the Author

Fawzan Mohamed Kareem Navaz is a fourth-year Aerospace Engineering student at Amity University, Dubai, with a strong academic background in space science, physics, and engineering mechanics. He has developed expertise in areas such as propulsion systems, astrodynamics, and space exploration technologies, with a particular focus on ion propulsion systems and spacecraft maneuverability. Fawzan has presented research at international conferences, including the 74th International Astronautical Congress 2023, and has won numerous awards, such as the Best Outstanding Research at the Space Conference Week 2024 hosted by UAE Space Agency, National Award in The International Astronomy and Astrophysics Competition 2023. He is passionate about advancing space exploration technologies and aims to contribute to sustainable interstellar travel through innovative propulsion systems. Currently, Fawzan is also involved in projects related to satellite imagery, space habitats, and Martian mineralogical studies, continuing his commitment to advancing the field of aerospace engineering and space research.

8. Acknowledgement

I extend my heartfelt thanks to everyone who supported me through my phase of this research. Special thanks to the Almighty, my family and my professors who guided me throughout.

9. References

[1] Anz-Meador, P., & Carman, C. (2023). History of on-orbit satellite fragmentations (NASA Technical Paper No. TP-20220019160). NASA.

[2] Billik, B. (1962). Survey of current literature on satellite lifetimes. ARS Journal, 32(11), 1641–1650. **https://doi.org/10.2514/8.6304**

[3] Celestrak. (n.d.). Space data for the last 5 years. Retrieved 2024, from https://celestrak.org/SpaceData/SW-Last5Years.txt

[4] De Lafontaine, J., & Garg, S. C. (1982). A review of satellite lifetime and orbit decay prediction. Proceedings of the Indian Academy of Sciences - Section C: Engineering Sciences, 5, 197–258. **https://doi.org/10.1007/BF02839302**

[5] Dolado-Perez, J., & Pardini, C. (2014). OPERA: A tool for lifetime prediction based on orbit determination from TLE data. Proceedings of the 24th International Symposium on Space Flight Dynamics.

[6] Inter-Agency Space Debris Coordination Committee (IADC). (2021, June 10). IADC Space Debris Mitigation Guidelines. Retrieved from **https://www.iadc-online.org**

[7] Liou, J.-C., & Johnson, N. L. (2006). Risks in space from orbiting debris. Science, 311(5759), 340–341. **https://doi.org/10.1126/science.1121337**

[8] Mukherjee, B., & Bhatia, A. (2021). Post mission disposal of Cartosat-2: Compliance with IADC guidelines. 8th European Conference on Space Debris, 135.

[9] Park, S.-H., & Hwang, D.-S. (2018). Orbit, orbital lifetime, and reentry survivability estimation for orbiting objects. Advances in Space Research, 62(11), 3012–3032. **https://doi.org/10.1016/j.asr.2018.08.010**

[10] Petersen, N. (1956). Lifetimes of satellites in near-circular and elliptic orbits. Journal of Jet Propulsion, 26(5), 341–351. **https://doi.org/10.2514/8.7003**

[11] Woodburn, J., & Coppola, V. (2005). A numerical study of orbit lifetime. Proceedings of the AAS/AIAA Astrodynamics Specialists Conference, 2005–297.

10. References

The author declares no competing conflict of interest.

11. Funding

No funding was issued for this research.