International Journal of Basic and Applied Sciences, 14 (SI-1) (2025) 409-413

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/ddqmsv22
Research paper

Space Exploration Vehicles: Innovations in Propulsion and Autonomous Navigation

Debarghya Biswas [1] *, Dhablia Dharmesh Kirit [2], Dr. Komal Khatter [3]

[1] Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India
[2] Research Scholar, Department of CS & IT, Kalinga University, Raipur, India
[3] Associate Professor, New Delhi Institute of Management, New Delhi, India
**Corresponding author E-mail: ku.debarghyabiswas@kalingauniversity.ac.in*

Received: May 2, 2025, Accepted: May 29, 2025, Published: October 31, 2025

Abstract

Future deep space missions use technology that combines propulsion system advancements with autonomous navigation. Chemical propulsion systems can't handle excessive fuel consumption and tasks that go beyond the short term. Ion propulsion and nuclear propulsion deliver better specific impulse and fuel efficiency for near-fast interplanetary flight. The ion propulsion on NASA's Dawn spacecraft extends mission duration while using less fuel than conventional systems, but nuclear power generates enough power to explore interplanetary space. Modern automated navigation is a critical system to minimize human intervention when operating spacecraft over long distances. Extended missions have trouble keeping real-time Earth communication links due to mission distance, which introduces signal delay problems. When spacecraft integrate inertial navigation with star trackers and artificial intelligence, their computers can do real-time tasks like trajectory changes and mission changes, and space obstacle avoidance.

Keywords: *Deep Space Propulsion; Ion and Nuclear Propulsion; Autonomous Navigation; Artificial Intelligence in Spaceflight; Inertial Navigation Systems; Interplanetary Missions.*

1. Introduction

The advancement of space exploration vehicles is a priority for scientists who want to make missions more efficient and sustainable with minimal human intervention [1]. The fundamental problem with chemical-powered fleet launches is still the fuel consumption and limited operational range [13] [2]. Directed propulsion systems using fuel and oxidizer combustion perform better against planetary gravity by generating immediate propulsion acceleration [4]. Chemical-propelled spacecraft consume a lot of fuel, which makes them less efficient and their range less efficient, effectively ruling out deep space missions. Ion and nuclear propulsion is the emerging solution to current propulsion system constraints in space flight [3]. Ion propulsion is more fuel efficient because it ionizes and accelerates xenon, which expands the range of spacecraft and consumes less fuel [10]. Ion and nuclear propulsion technologies prove most effective during missions longer than basic orbit flights because they help extend fuel reserves [6]. Integration of thermal and electric nuclear propulsion systems returns maximum fuel efficiency through the direct use of nuclear reactor energy output [14]. Propulsion based on nuclear thermal concepts utilizes reactor heat to create thrust by heating propellants, while nuclear electric systems generate thrust with electricity-driven ion thrusters [8]. These space technologies enable faster space transit combined with enhanced mission durations, which fulfill the requirements of interplanetary exploration. Autonomous guide systems have revolutionized the way we operate space vehicles [18]. Since the implementation of artificial intelligence (AI) and machine learning together with sensor networks, spacecraft navigation systems have isolated human operators during flight while ensuring higher mission safety and operational efficiency with better precision and adjustable capabilities for extended missions [15].

2. Innovation in Propulsion Systems

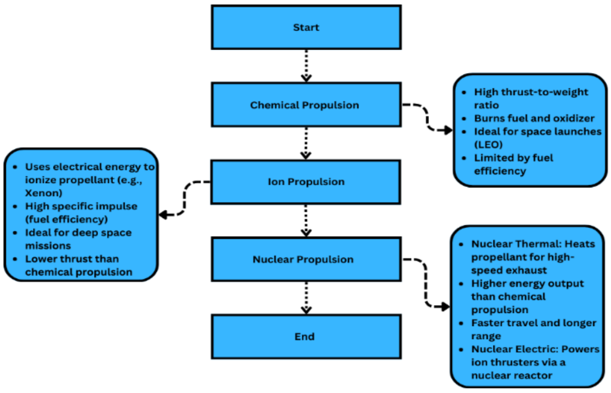

Fig. 1: Flowchart Representation of the Innovations in Propulsion Systems.

A flowchart that is used to illustrate the innovations in propulsion systems is provided in Figure 1. It graphically shows the flow of processes of each of the three propulsion technologies mentioned: chemical propulsion, ion propulsion, and nuclear propulsion. The diagram indicates the order of functions in both systems, starting with the fuel combustion or ionization to the generation of thrust, with the major processes being propellant consumption, fuel consumption, and the period in the mission. This flow chart is also required when comparing the working attributes of both types of propulsion, especially the fuel efficiency and scalability of both ion and nuclear propulsion systems, which are highly needed during deep-space missions. This figure can be used to explain the ideas presented in the text and give a clearer vision of how each of the technologies can be used to increase the mission times and spend the minimum amount of fuel.

2.1. Chemical propulsion

Chemical propulsion stands as the dominant space vehicle launch method because it delivers unmatched thrust-to-weight capabilities needed to escape Earth's gravitational pull [7]. Moving into space requires the rapid development of propulsion due to chemical reactions between fuel and oxidizer substances. The main operational limitation of chemical propulsion systems stems from their high fuel requirements, which reduces the effective range along efficiency during extended missions [5]. Chemical rockets function best for spacecraft launches together with LEO travel, but prove insufficient for deep space research due to demanding requirements for better propulsion technologies [16].

2.2. Ion propulsion

The NASA Dawn spacecraft demonstrates the high-flying capabilities of ion propulsion technology, which exceeds chemical propulsion efficiency during deep space missions [9]. Each system achieves thrust by converting electric power into ionized propellants (such as xenon) that electric fields move to generate propulsion thrust force. Normal operation of this system generates a propulsion efficiency that significantly overshadows chemical propulsion while permitting vehicles to achieve greater distances using lesser amounts of propellants. The fuel-efficient character of ion propulsion technology makes it ideal for missions requiring extended working time in space while reducing global fuel consumption. However, ion propulsion systems create less thrust yet are more efficient than chemical propulsors [17].

2.3. Nuclear propulsion

Nuclear propulsion systems using nuclear thermal and electric methods enhance spacecraft capabilities for planetary missions [11]. When a propellant undergoes nuclear thermal heating, it releases exhaust gases with high velocity to generate thrust. Nuclear propulsion is superior to chemical propulsion, which allows faster and longer missions [12].

Different nuclear propulsion systems have been developed, such as nuclear thermal and nuclear electric propulsion. Specific impulse values of 800 to 900 seconds are very large in comparison with chemical propulsion in nuclear thermal propulsion. These are systems that use nuclear reactors to warm up a propellant, which is usually hydrogen, to produce propulsion. Contrarily, nuclear electric propulsion employs a nuclear reactor to produce electricity, which drives ion thrusters. They are highly specific, with impulses many higher (usually more than 1,500 seconds) and lower thrust. There are several types of reactors, solid-core, gas-core: each of them has its own advantages in regard to its ability to transfer heat and its operating temperature limits. Nuclear propulsion can also be scaled, especially in long-range interplanetary missions, where the propulsion is fuel-efficient and prolonged interplanetary missions compared to ion propulsion systems that have to maintain an electric power supply. The selection between ion and nuclear propulsion is dependent on the mission profile; ion propulsion is best suited to missions that need a lot of fuel efficiency over long periods, whereas nuclear propulsion is better suited when there is a need to travel long distances within a short time.

Recent developments in nuclear propulsion, specifically with DARPA, DRACO (Demonstration Rocket for Agile Cislunar Operations) program, provide good news on what the future space missions hold. The DRACO program is concerned with developing nuclear thermal propulsion systems with which it can greatly decrease cislunar space missions and deep space exploration missions. Among the main outputs of this project can be identified the optimization of reactor designs, which make them more fuel-efficient and able to maximize the thermal performance of the reactor. This is the direct opposite of traditional ion propulsion systems, which, despite being very efficient, cannot compete with the thrust of nuclear thermal systems. Nuclear propulsion technologies are, however, making progress but still need breakthroughs in terms of minimizing reactors and their long-term sustainability to be used on mass space missions.

2.4. Interdependence of propulsion and autonomous navigation

Space exploration vehicles have an inherent connection between their propulsion system and autonomous navigation technologies, and the development of one has a direct impact on the abilities of the other. Ion and nuclear propulsion are fuel-efficient propulsion systems and will go a long way in minimizing the complexity of navigation of spacecraft by extending their missions and consumption of fuel. The spacecrafts that use these advanced propulsion engines can have a greater mission time, and it is more apt to save the fuel they use, as more efficient navigation software can change the trajectory with minimal use of fuel. Moreover, the higher thrust/weight ratio of nuclear propulsion systems helps the spacecrafts to tackle more challenging problems of navigation, such as real-time correction of the trajectories and avoiding space obstacles without impacting the fuel expenditure of the mission. Thus, as the propulsion systems become better, the autonomous navigation system can become more versatile, hence the capability of spacecrafts to travel to interstellar distances without fuel wastage. This has been extremely crucial to missions whose purpose is to survey distant astronomical bodies which are distant such as Mars or Jupiter moons, and missions that require precision in their navigation and prolonged missions.

3. Autonomous Navigation for Space Exploration Vehicles

3.1. The need for autonomous navigation

Spacecrafts undertaking missions of Earth orbit crossing require long durations of flight, which goes beyond the distance covered by ground control relay, posing a difficulty in simultaneous communication. Autonomous navigation is required in remote space operations to enable spacecrafts to make independent decisions of the trajectory and mission concerning routes and maintain continuous contact with Earth controllers. The use of these technologies allows the spacecrafts to operate independently when communication links are lost, hence achieving success in the mission besides the safety parameters. An autonomous navigation system is an essential need of deep space exploration since it requires no constant mission control supervision to deliver an efficient, self-sufficient exploration.

3.2. Key technologies for autonomous navigation

The functions of the spacecrafts that use the autonomous navigation systems rely on the different modern technological approaches that allow precise self-directed paths. Gyroscopes and acceleration data provide spacecraft thermal motion data, which are used to provide real-time position and velocity updates to the Inertial Navigation System (INS). The accuracy of orientation determination requires the use of star trackers that make use of the photographing of stars in distant locations to determine the directions of the platform. Machine learning and artificial intelligence aid spacecrafts to analyze sensor data and make autonomous choices depending on the alterations in the environment. The joint capabilities of these technologies improve navigation of spacecraft in a severe environment of space.

Autonomous space navigation is one of the spheres where AI algorithms are very important in sensor data interpretation and decision-making. Machine learning and reinforcement learning enable spaceships to adapt to the environment and optimize their path in real time. The proper orientation and movement control is made possible because of sensor integration, e.g., integration of star trackers, gyroscopes, and accelerometers. The sensor fusion methods are also used to increase the accuracy of the AI-based systems, not to mention the removal of errors. In particular, the AI models are capable of dynamically optimizing the route of flights to avoid contaminants and compute the most efficient routes, and dampen drift during the effect of exogenous forces such as the pressure of solar radiation. In comparing the autonomous navigation with the ion propulsion systems, one would notice that nuclear propulsion is stronger and more complex to provide the direction is necessary direction with a high degree of accuracy at longer distances, as compared to when using the ion propulsion systems that have longer mission ranges and lower acceleration.

On the same point, the latest work of NASA in AI-controlled autonomous space exploration missions (e.g., the 2024 AI Navigation for Deep Space Missions project) demonstrates that the autonomy of spacecraft is becoming more enhanced using machine learning algorithms and sensor fusion. With these AI systems, spacecrafts can make autopilot choices regarding the change of missions, collision avoidance, and optimum trajectory without involving human interaction. When examining these works critically, it is possible to note that the AI gains in the field of autonomous navigation are as large as it is, yet the system is weak regarding the conditions of the space, such as high radiation zones or areas of cosmic rays, which can damage the sensors and processing units.

4. Prospects for space exploration vehicles

4.1. Advanced propulsion systems

The space exploration of the Domino-space is dependent on the establishment of propulsion systems that embrace friendly technologies in the environment, which are sustainable. The science community believes that fusion propulsion systems will be a game-changer to generate boundless energy in space during long-duration missions. The fusion propulsion will allow us to eliminate the chemical and nuclear propulsion engines with the application of atomic nucleus fusion to obtain spacecraft velocities that are close to significant portions of the speed of light. Studies done on this technology have high potential to reduce spaceflight time to the celestial locations and allow humans to venture into the vast regions of the heavens.

Even though it is not yet well developed, fusion propulsion can revolutionize the movement of spacecraft by making them travel at speeds that are considerably small portions of the speed of light. But latest studies in fusion propulsion are on paper, and most of the studies in this area have been on achieving sustainable fusion reactions and enhancement of reactor designs. To give an example, the recent research, including that of the National Ignition Facility (NIF) and ITER, has shown that fusion technology has made advancements, yet it is still far off as far as space propulsion is concerned.

It should be mentioned that although fusion propulsion could greatly shorten mission times, particularly on the long-range interstellar missions, there are still serious problems to solve, including scaling of the fusion reactor and the creation of compact and dependable spacecraft systems. In this regard, fusion propulsion is yet to see a breakthrough in the world of both fusion reactors and material science before it becomes viable for space exploration.

4.2. Autonomous navigation and AI

The solution to space travel is the current artificial intelligence technology capable of controlling autonomous space navigation. It is possible to have AI robotic systems analyze long-term real-time sensor data and make automated evaluations when Earth is out of communication. AI-driven autonomous navigation systems have enormous prospects of improving mission efficiency and space exploration within deep space. However, the ability of AI devices to survive in extreme conditions in space has been pointed out as one of the key gaps in the literature. The radiation, the space rays, and the higher temperatures are becoming a threat to the long-term functionality of AI equipment and can cause the malfunction or collapse of the system. Scientists are working on radiation-hardened circuit designs and AI algorithm optimization to make sure that autonomous systems work safely throughout their lives.AI that is based on real-time data processing and sensor fusion will need powerful hardware that will not compromise performance to withstand such harsh conditions. Solutions to these problems will be essential to missions such as NASA Artemis and ESA ExoMars, where autonomous navigation and decision-making systems are important to achieve successful mission results in conditions where communication with Earth can be limited or delayed.

5. Conclusion

Space exploration will advance because of modern propulsion systems working with autonomous navigation systems. We need safe outposts in faraway destinations that require these to minimize crew dependency for long interplanetary missions. New peripheral development using ion tech and nuclear tech will allow for faster space discovery with less fuel. These capabilities will span multiple orbits with less fuel, that is why they're so important for interplanetary destinations and solar system bodies. Future ships will be automated by AI to navigate and make decisions about space and planetary changes without human supervision from Earth. Spaceflight will get safer and more efficient with these devices for every mission phase and duration, including communication blackouts. Existing propulsion tech merges with AI to allow humans to explore distant orbital destinations as part of Mars mission planning. These will be the baseline for long-term space exploration because they'll enable the tasks and planetary settlement activities that will allow human communities to expand into interstellar space.

References

[1] Chatzitheodoridis, E., de Vera, J. P., Kereszturi, A., Mason, N., Possnig, C., Puumala, M., ... & Vago, J. L. (2025). Perspectives for Crewed Missions to Mars: Exploration from Orbit and/or Short Stay. In *Mars and the Earthlings: A Realistic View on Mars Exploration and Settlement* (pp. 117-197). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-66881-4_6.

[2] Asadolahi, J., Kimiayee, S. A., & Parast, T. A. (2016). The Effect of Transactional Analysis Group Therapy on the Decrease of Aggression in Couples with Addict Husbands. *International Academic Journal of Innovative Research, 3*(1), 11–17.

[3] Borders, K. V., & Petro, E. M. (2025). Exploration of Regenerative Cooling for High-Power Electric Adiabatic Thrusters. In AIAA SCITECH 2025 Forum (p. 0910). https://doi.org/10.2514/6.2025-0910.

[4] Malbašić, V., Milošević, Dimšo, & Miodrag, Č. (2019). Management Model for Discontinuous System on Surface Mines. *Archives for Technical Sciences, 1*(20), 23–34. https://doi.org/10.7251/afts.2019.1120.001S.

[5] Lane, T. G., & Revankar, S. T. (2025). Advances in technology, design, and deployment of microreactors-a review. Progress in Nuclear Energy, 178, 105520. https://doi.org/10.1016/j.pnucene.2024.105520.

[6] Çetinkaya, S. (2020). The effects of sous-vide cooking method on rainbow trout by adding natural antioxidant effective sage: basic quality criteria. *Natural and Engineering Sciences, 5*(3), 167-183. https://doi.org/10.28978/nesciences.832987.

[7] Thomas, L., Houts, M., Wang, D., Hollingsworth, K., Frederick, R. A., & Cassibry, J. T. (2025). The Centrifugal Nuclear Thermal Rocket: Foundations, Challenges, and Progress. *In AIAA SCITECH 2025 Forum* (p. 0377). https://doi.org/10.2514/6.2025-0377.

[8] Taleb, A. A., & Odeh, A. O. A. (2024). Effective Routing of Mobile Sink in Wireless Sensor Networks Using Steiner Trees. *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications, 15*(2): 135-151. https://doi.org/10.58346/JOWUA.2024.I2.010.

[9] Genta, G. (2025). Propulsion for Interplanetary Journeys. In Journey to The Planets: The Technology to Build a Spacefaring Civilization (pp. 51-111). *Cham: Springer Nature Switzerland.* https://doi.org/10.1007/978-3-031-57696-6_3.

[10] Ruudsari, M. Q. (2016). Intertextual Relationship between Altalbyn Mrsadalbad and Garlic Treatise Kashf al-Mahjub. *International Academic Journal of Innovative Research, 3*(2), 9–19.

[11] Bheemavarapu, R. (2024). Comparison of Propulsion Options for Interplanetary Missions. *Acceleron Aerospace Journal, 3*(5), 573-584. https://doi.org/10.61359/11.2106-2459.

[12] Corfield, R. (2024). Nuclear spacecraft: from dream to reality. *Physics World, 37*(3). https://doi.org/10.1088/2058-7058/37/03/30.

[13] Sharma, N., & Sharma, S. (2025). Advanced Battery Cooling Systems for Enhanced Efficiency and Longevity. *Optimized Energy Management Strategies for Electric Vehicles,* 63-86. https://doi.org/10.4018/979-8-3693-6844-2.ch003.

[14] Saeed, R. M., Novotny, V., Sweeney, K., Worsham, E. K., Reyes Molina, E. A., Root, S. J., ... & Knighton, T. (2025). Thermal Integration of Advanced Nuclear Reactors with a Reference Refinery, Methanol Synthesis, and a Wood Pulp Plant (No. INL/RPT-24-76435-Rev001). *Idaho National Laboratory (INL), Idaho Falls, ID (United States).*

[15] Silva, J. C. F., de Godoy Machado, K. L., de Souza Silva, A. F., Dias, R., Bodnar, V. R., Vieira, W. O., ... & Costa, L. C. (2025). Challenges and Opportunities for New Frontiers and Technologies to Guarantee Food Production: A Broad Systematic Perspective. https://doi.org/10.20944/preprints202501.1140.v1.

[16] Zhu, Y., Chen, M., Wang, S., Hu, Y., Liu, Y., Yin, C., & Quek, T. Q. (2025). Passive Inter-Satellite Localization Accuracy Optimization in Low Earth Orbit Satellite Networks. *IEEE Transactions on Wireless Communications.* https://doi.org/10.1109/TWC.2025.3525852.

[17] Paek, S. W. (2025). Sustainability Considerations of Nuclear Power and Nuclear Propulsion in Space. *Routledge Handbook of Space Policy,* 359-368. https://doi.org/10.4324/9781003342380-29.

[18] Jaiswal, H., & Pradhan, S. (2023). The Economic Significance of Ecosystem Services in Urban Areas for Developing Nations. *Aquatic Ecosystems and Environmental Frontiers, 1*(1), 1-5.

[19] Rahim, R. (2025). Bridging the gender gap in aerospace innovation: A global study of women's roles, barriers, and future directions in space technology. Journal of Women, Innovation, and Technological Empowerment, 1(1), 12–18.

[20] Vishnupriya, T. (2025). Real-time infrared thermographic characterization of functionally graded materials under thermomechanical loads in high-temperature combustion chambers. Advances in Mechanical Engineering and Applications, 1(1), 32–40.

[21] Sathish Kumar, T. M. (2025). Comparative analysis of Hatha Yoga and aerobic exercise on cardiovascular health in middle-aged adults. Journal of Yoga, Sports, and Health Sciences, 1(1), 9–16.

[22] Usun, S., & Ait Fares, S. (2025). Energy-efficient building design using bio-inspired materials and machine learning optimization. Journal of Smart Infrastructure and Environmental Sustainability, 2(1), 21–30.

[23] Rahman, F., & Prabhakar, C. P. (2025). From synapses to systems: A comprehensive review of neuroplasticity across the human lifespan. Advances in Cognitive and Neural Studies, 1(1), 28–38.

[24] Patel, P., & Dusi, P. (2025). Optimization models for sustainable energy management: A multidisciplinary approach. Bridge: Journal of Multidisciplinary Explorations, 1(1), 1–10.

[25] Chandrakumar, R., & Sikalu, T. C. (2025). Policy frameworks and innovation roadmaps for accelerating renewable energy transition in emerging economies. National Journal of Renewable Energy Systems and Innovation, 1(4), 10–16.

[26] Shaik, S., & Luedke, R. G. (2025). AI-driven predictive control for renewable-integrated smart grids: Toward enhanced stability and efficiency. National Journal of Intelligent Power Systems and Technology, 1(2), 44–51.

[27] Mori, T., & Geweely, N. (2023). Precision Agriculture 4.0: Integrating IoT and Artificial Intelligence for Data-Driven Crop Monitoring and Sustainable Farming Systems. National Journal of Smart Agriculture and Rural Innovation, 1(1), 49-56.
[28] Hugh, Q., & Soria, F. (2025). Internet of Energy (IoE): A scalable architecture for smart grid applications. National Journal of Intelligent Power Systems and Technology, 1(4), 25–33.
[29] Fu, W., & Zhang, Y. (2025). The role of embedded systems in the development of smart cities: A review. SCCTS Journal of Embedded Systems Design and Applications, 2(2), 65–71.
[30] Nabende, P., & Zengeni, T. G. (2025). Advanced HVDC transmission solutions for reliable and scalable offshore wind power integration into modern grids. National Journal of Electrical Electronics and Automation Technologies, 1(3), 1–9.
[31] Sarvas, M., Bondarenko, Y., Ukraynets, L., Sorokovyi, P., & Zhygalo, I. (2025). Automated Compliance Systems in International Trade: The Role of AI and VLSI Systems in Streamlining Customs Procedures. Journal of VLSI Circuits and Systems, 7(1), 46-55. https://doi.org/10.31838/jvcs/07.01.07.
[32] Mahajan, S., Gupta, S., Deepak, S., Jebaselvi, A., Patra, B., & Dwivedi, A. D. (2025). Next Generation Wireless Sensor Networks for Smart Healthcare Applications. National Journal of Antennas and Propagation, 7(2), 59-66. https://doi.org/10.31838/NJAP/07.02.11.
[1] Maximilian A. Müller, Charlotte Keller, J.C. Zimmermann, G. Maria Fischer, & Sebastian Martin Weber. (2024). Smart Cities with IoT Security Framework: From Vulnerability to Protection. International Journal of Communication and Computer Technologies, 12(2), 66–80.