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Assessment of the Challenges Facing the Propulsion Subsystem of Satellites

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Abstract: This research work was aimed at studying some challenges facing the propulsion subsystem of satellites. The work employed the use of the explanatory and review research methods. The work highlights some of the common challenges facing the propulsion subsystem of satellites based on the knowledge and understanding of the authors as well as based on the works done in the research areas by other authors, accessed from reputable databases. The analysis revealed that some of the challenges of the propulsion subsystem of satellites are vibration loads during launch, testing complexity, leakage problems, propellant sloshing and management in microgravity, and thruster degradation and erosion. From the results, it was concluded that the propulsion subsystem of satellites, irrespective of the types of satellite, is faced with several challenges, which can lead to poor efficiency of satellites or even total failure.

Keywords: Leakage Problem, Propellant Sloshing, Propulsion, Thermal Management fuel, Satellite, Space.

1.0 Introduction

A satellite propulsion subsystem is defined as the subsystem of a satellite that is responsible for generating and controlling thrust used for launch support, orbital transfer, station keeping, and attitude control operations of a satellite. The satellite market currently faces several new trends that will significantly change today's product portfolio. Thus, besides upcoming mega-constellations and the maturation of electric propulsion, several other factors, like clean space, require a redefinition of propulsion concepts (Ulrich, 2015). According to Larson and Wertz (2005), in the broadest sense, space propulsion systems do three things, which are to lift the launch vehicle and its payload from the launch pad and place the payload into low-Earth orbit; transfer payloads from low-Earth orbits into higher orbits for mission operations or into trajectories for planetary encounters; and provide thrust for attitude control and orbit corrections. As reported by José (2011), the use of electric propulsion will enable the use of cheaper launchers or extend the life of current telecommunication spacecraft. Also, in view of the increasing mass and mission duration for the new GEO platforms, the requirements on the total impulse to be provided by the electric propulsion system are constantly increasing.

Irrespective of the roles, satellite propulsion subsystems can be classified into chemical propulsion subsystems, electric propulsion subsystems, cold gas propulsion subsystems, plasma propulsion, nuclear propulsion subsystems, hybrid propulsion subsystems, and solar sail subsystems. A chemical propulsion subsystem is the type that generates thrust through the combustion of chemical propellants such as fuel and oxidizer. They are commonly used for launch vehicles, orbital transfer, and rapid maneuvers (Sutton & Biblarz, 2017). An electric propulsion subsystem is the type of propulsion subsystem that uses electrical energy to accelerate charged particles or plasma in order to generate thrust. This type produces lower thrust compared to chemical propulsion but is highly fuel-efficient and suitable for long-duration missions and station keeping (Goebel & Katz, 2008). A cold gas propulsion subsystem is the type that stores compressed gas and releases it through a nozzle to create thrust without combustion. They are simple, lightweight, and reliable because they contain few moving parts. It produces low thrust and is mainly used in small satellites and attitude control systems (Fortescue, Swinerd, & Stark, 2011). The plasma propulsion subsystem is the type that generates thrust by ionizing gas into plasma and accelerating it using electric or magnetic fields. They are suitable for deep-space missions because of their high efficiency and long operational life (Jahn & Choueiri, 2003). A nuclear propulsion subsystem is the type that uses energy produced from nuclear reactions to heat a propellant or generate electricity for propulsion (Borowski, 1998). The solar sail propulsion subsystem is the type that uses large reflective sails to capture momentum from sunlight and generate movement in space. They do not require conventional fuel, making them suitable for extremely long-duration missions. (McInnes, 1999). A hybrid propulsion subsystem is the type that combines two or more propulsion technologies within a single spacecraft. For example, a satellite may use chemical propulsion for high-thrust maneuvers and electric propulsion for station-keeping. (Brown, 2002).

2.0 Research methodology

The materials used for this study were secondary sources, which included online materials, library resources, and video materials. These sources were carefully studied, and their findings were stated in support of the explanations as regards the challenges of satellites' propulsion subsystems. In addition, this study adopted the explanatory research method. The explanatory research method enabled the authors to clearly explain why and how the identified issues constitute challenges to the propulsion subsystem of satellites. The method also assisted the authors in discussing these challenges in detail, thereby enhancing clarity and promoting better understanding among readers.

3.0 Analysis of the challenges facing the propulsion subsystem of a satellite

The role of the propulsion subsystem of a satellite is the same whether the satellite is in geostationary orbit, low earth orbit, or medium earth orbit. It is also the same whether the satellite is for earth observation, communication, navigation, etc. Below are some challenges of the propulsion subsystem of satellites.

1. Thruster Degradation and Erosion

Thruster degradation and erosion is defined as the gradual wear, damage, and loss of material within a satellite’s thruster caused by repeated firing, high temperatures, and combustion processes, which reduce propulsion efficiency and performance over a given time. Satellite propulsion systems are responsible for orbital correction, station-keeping, attitude control, and end-of-life deorbiting operations. Over time, the continuous operation of these thrusters leads to gradual wear and deterioration of internal components. This can reduce the overall efficiency and reliability of the satellite. For example, in electric propulsion systems such as ion thrusters and Hall-effect thrusters, high-energy ions are accelerated at extremely high velocities to generate thrust. During this process, these ions repeatedly collide with internal surfaces such as discharge chambers, grids, and channel walls. The repeated bombardment slowly erodes the material surfaces, causing thinning, cracking, and gradual structural damage. As erosion increases, the geometry of the thruster changes, which alters the flow of ions and affects thrust performance. This condition leads to thrust instability, reduced specific impulse, and lower propulsion efficiency after some time. According to Lepore et al. (2023), repeated firing of thrusters exposes propulsion components to extreme heat, pressure, and high-energy particles, which gradually wear out internal surfaces such as nozzles and combustion chambers. The work went further to explain that in electric propulsion systems, ion bombardment continuously erodes thruster walls, while in chemical propulsion systems, repeated combustion processes weaken materials through thermal stress and oxidation. The work concluded that advanced heat-resistant materials, protective coatings, and improved cooling systems are important for reducing erosion and improving propulsion durability.

2. Propellant Sloshing and Management in Microgravity

Propellant sloshing and management in microgravity can be defined as the uncontrolled movement and unstable behavior of liquid fuel inside spacecraft tanks in zero-gravity conditions, which makes it difficult to maintain a steady and reliable fuel supply to the thrusters. Unlike on Earth, where gravity keeps fuel settled at the bottom of a tank, propellants in orbit float freely and move unpredictably within the container. During satellite maneuvers or attitude adjustments, liquid propellant inside the tank begins to move and oscillate, a phenomenon known as sloshing. These uncontrolled fluid motions create shifting mass distributions inside the spacecraft. And as the fuel moves, the satellite's center of mass also changes slightly, resulting in disturbances in attitude stability and control. In some cases, excessive sloshing can introduce unwanted vibrations and rotational movements that interfere with accurate pointing systems, especially in communication and Earth observation satellites where precision is very important.

In the work by Lu et al. (2025), it was explained that liquid fuel behaves differently in space because gravity is absent, such that instead of settling at the bottom of storage tanks, propellants float freely and move unpredictably during satellite maneuvers. The authors observed that fuel movement changes the spacecraft's center of mass and affects attitude stability. Similarly, Eko et al. (2024), in their work "Energy Dissipation and Efficiency Challenges of Cryogenic Sloshing in Aerospace Propellant Tanks: A Systematic Review," explained that sloshing creates unwanted forces and vibrations that reduce spacecraft control accuracy and increase fuel consumption.

3. Contamination and Clogging

Contamination and clogging can be defined as the accumulation of chemical residues, small particles, or degraded fuel products within propulsion components such as pipes, valves, and nozzles, restricting propellant flow and affecting thrust performance. Satellite propulsion systems rely on the smooth and controlled movement of propellants through valves, pipes, injectors, and thruster nozzles in order to generate accurate thrust. But the presence of very small particles, chemical residues, or degraded fuel products within the propulsion lines can obstruct these components and interfere with normal operation. During spacecraft manufacturing and assembly, microscopic dust particles, metallic fragments, or residues from lubricants and sealing materials may accidentally remain within the propulsion components. In addition, prolonged storage of propellants can sometimes lead to chemical decomposition, producing unwanted solid particles or deposits, and all these can lead to clogging.

This is because, as these particles circulate through the propulsion system, they may become trapped inside narrow passages such as injector openings, control valves, or nozzle throats. Once blockage begins to develop, the propellant flow rate becomes unstable, and thrust generation may no longer remain consistent. Partial clogging can reduce propulsion efficiency and affect maneuver accuracy, while severe clogging may completely prevent the thruster from firing. According to Lepore et al. (2023), small particles, combustion residues, and degraded fuel products can accumulate within valves, pipelines, and thruster nozzles. These contaminants restrict propellant flow and reduce propulsion efficiency. It highlights that clogging may lead to unstable thrust generation and inaccurate satellite maneuvering.

4. Thermal Management

Thermal management is defined as the process of controlling and maintaining safe operating temperatures within a satellite propulsion subsystem to prevent overheating, fuel freezing, material damage, and performance instability caused by extreme space temperatures. Propulsion systems generate a large amount of heat during operation while also being exposed to severe temperature variations in orbit. A satellite may experience intense solar radiation on one side and extreme cold on the opposite side at the same time. Ordinarily, during thruster operation, combustion processes and plasma generation produce very high temperatures within propulsion chambers, nozzles, and surrounding structures. Apart from internally generated heat, satellites are also exposed to the extreme thermal environment of space. When a satellite faces direct sunlight, temperatures can rise rapidly, while movement into Earth's shadow can cause sudden cooling. These repeated heating and cooling cycles create thermal expansion and contraction within propulsion components, which over time may lead to cracking, material fatigue, seal damage, and structural weakening. As stated by Lu et al. (2025), the propulsion subsystem generates significant heat during operation while simultaneously being exposed to severe temperature changes in space, and this excessive heat may weaken propulsion materials and reduce thruster efficiency, while extremely low temperatures may cause fuel freezing and restricted fuel flow. Also, Eko et al. (2024) added that thermal instability affects propellant pressure and fuel behavior inside storage tanks.

5. Leakage Problem

A leakage problem can be defined as the unintended escape of propellant or pressurized gas from the propulsion subsystem due to cracks, weak seals, material fatigue, or structural damage, which can reduce thrust capability and shorten mission lifespan. Satellite propulsion systems rely on sealed tanks, valves, and pipelines to safely store and transport propellants needed for orbital control and maneuvering. But leaks may occur due to manufacturing defects, weak seals, material fatigue, or damage caused during launch vibrations and harsh space conditions. Once leakage begins, propellant gradually escapes into space, reducing the amount of fuel available for satellite operations, which is a big challenge. In addition, reduced fuel levels may prevent the satellite from maintaining its proper position, which can disrupt communication, navigation, or observation services. Leakage can also lower the pressure needed to deliver fuel to the thrusters, resulting in unstable thrust or complete propulsion failure. As stated by Lepore et al. (2023), leaks may occur due to material fatigue, poor sealing, vibration stress, or structural cracks caused during launch and operation. The study reported further that propellant leakage reduces fuel availability for orbital maneuvers and decreases tank pressure needed for stable thrust generation. Similarly, Eko et al. (2024) noted that pressure instability and poor propellant management inside propulsion tanks can increase the risk of leakage, especially in cryogenic propulsion systems. The authors explained that thermal expansion and contraction caused by extreme temperature variations may weaken tank structures and fuel connections over time. This condition may lead to gradual fuel leakage and unstable propulsion performance during long-duration missions.

6. Testing Complexity

Testing complexity can be defined as the difficulty and high cost involved in accurately evaluating satellite propulsion systems on Earth because space conditions such as microgravity, vacuum, and long-term thermal cycling cannot be perfectly reproduced during ground testing. Before launch, propulsion systems must be tested to ensure that thrusters, valves, and fuel systems operate correctly. Engineers use vacuum chambers and thermal testing facilities to imitate some space conditions such as low pressure and extreme temperatures. However, these facilities are very expensive and still cannot fully reproduce the actual conditions of orbit due to some limitations like gravity. On Earth, gravity pulls liquid fuel downward, while in space, propellants float freely in microgravity. This difference makes it difficult to accurately test fuel movement and sloshing behavior before launch.

According to Lu et al. (2025), engineers use vacuum chambers and thermal testing facilities to simulate some characteristics of space, but these systems cannot fully reproduce microgravity and long-term orbital conditions. The work explained that fuel behavior in Earth's gravity differs significantly from fuel behavior in space, which makes it difficult to accurately predict sloshing, thermal effects, and propulsion performance before launch. In the same way, Eko et al. (2024) also noted that long-term exposure to radiation and thermal cycling cannot easily be replicated during laboratory testing. As a result, some propulsion problems only become visible after satellites are launched into orbit.

7. Vibration Loads During Launch

Vibration loads during launch can be defined as the mechanical stresses, shocks, and intense vibrations experienced by a satellite propulsion subsystem during launch, which may result in misalignment, component damage, or reduced thrust accuracy. The propulsion subsystem contains sensitive components such as thrusters, fuel tanks, pipelines, valves, and mounting structures. During launch, powerful vibrations travel through the spacecraft structure and may cause loosening, misalignment, or physical damage to these components. If the thrusters shift slightly from their original position, it will affect the satellite's ability to maintain proper orientation and orbital control. Vibration loads can also result in the weakening of joints, damage seals, and create tiny cracks within fuel lines and tanks. According to Lepore et al. (2023), strong launch vibrations and shock forces can damage propulsion components such as fuel tanks, pipelines, valves, and thrusters. It was also reported that vibrations may loosen structural connections, weaken seals, or misalign thrusters, affecting thrust vector accuracy and satellite stability after launch**.** In the same way, Lu et al. (2025) explained that launch vibrations also influence fluid behavior inside propulsion tanks and that strong mechanical oscillations during launch may increase propellant movement and internal pressure fluctuations within fuel tanks. These disturbances can affect propulsion subsystem stability and create additional stress on structural components.

4.0 Conclusion

This research work, titled "Assessing the challenges facing a satellite's propulsion subsystem," was done using a mixed combination of explanatory and review research methods. The work highlights some of the common challenges facing the propulsion subsystem of satellites based on the knowledge and understanding of the authors as well as based on the works done in the research areas by other authors, accessed from reputable databases. The analysis revealed that some of the challenges of the propulsion subsystem of satellites are vibration loads during launch, testing complexity, leakage problems, thermal management, propellant sloshing and management in microgravity, and thruster degradation and erosion. From the results, it was concluded that the propulsion subsystem of satellites, irrespective of the types of satellites, is faced with several challenges, which can lead to poor efficiency of satellites or even total failure.

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