Towards Sustainable Space Exploration: Assessing Hall Thrusters for CubeSat Missions

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This study investigates Hall thrusters' applicability in CubeSats, assessing their maneuverability and efficiency under low-power constraints. CubeSats, known for cost-effectiveness, may benefit from propulsion systems, and this work studies the possible usefulness of Hall thrusters, known for their efficiency and high thrust-to-power ratio. Our analysis includes cataloguing CubeSat thrusters, developing an energy-based simulation for station-keeping and collision avoidance, and benchmarking different propulsion technologies. To date, only three Hall thrusters have flown in CubeSat missions and this research attempts to identify the potential strengths of these thrusters. Our findings underscore Hall thrusters' effectiveness in low Earth orbit collision avoidance, aligning with space debris regulatory standards.

Hall thrusters offer a distinct advantage over ion thrusters in terms of their thrust capabilities. Despite having similar levels of efficiency, Hall thrusters typically exhibit a thrust-to-power ratio that exceeds that of gridded ion thrusters by more than threefold. This trait positions Hall thrusters as particularly beneficial for missions requiring drag compensation and precise maneuverability [1]. For assessing orbital capabilities, an energy based simulator was coded and uses orbital energy, the drag equation and forces work to assess athmospheric decay and orbital corrections introduced by a thruster. [2]. The atmospheric model used is based on a scale height depending on Solar and Geomagnetic conditions and were set as the predicted for a cubesat launched after 2030. A validation exercise regarding the orbital decay was performed using DRAMA software, indicating satisfactory results [3]. In this study, we focus on two critical orbital maneuvers for CubeSats: station-keeping and collision avoidance. Station-keeping involves maintaining a specified orbital altitude to counteract decay due to atmospheric drag. Collision avoidance refers to the capability of maneuvering quickly in space, and requirement of rising 100 meters is set. Four different altitudes: 200, 250, 300, and 400 km. These altitudes were chosen because of the higher values of atmospheric density in those regions. To perform a thruster comparison, each maneuver is assigned two performance metrics related to time and energy consumed. In station-keeping, the time added to the orbit and the ratio of energy consumed to the time added to the orbit are utilized. In collision avoidance, the time of the maneuver and energy consumption are defined. After calculating the performance metrics for the thrusters, they are normalized to a scale between 0 and 1. The thrusters selected for the analysis are retrieved from [4] and have flown in Cubesats. Thrusters until 70 W and 1U volume were considered, from a range of solutions both chemical and electrical. The Hall thruster inputted in the database (ExoMG nano S [60W, including system losses]) have some features that distinguish them from other electric propulsion types. The thrust (2.5 mN) and thrust-to-power ratios are the highest. System efficiency levels are also high. On the other hand, it presents low specific impulse (I_{sp} of 800 s) and fuel mass (0.11 kg). The platform considered is a 12U cubesat, with a baseline mass of 15 kg, surface area of 0.08 m^2 and CD (drag coefficient) of 2.2. Results for the two maneuvers are present in the following table.

Table 1 Hall thruster retrieved performance.

	Station-keeping			Collision Avoidance		
Alt. [km]	Time added [months]	Time Score	Energy Score	Time [minutes]	Time Score	Energy Score
200	0.2	1	0	19.7	0	0
250	0.7	0.11	0.74	8.1	0.95	0.94
300	2.5	0.05	0.83	6.9	0.99	0.94
400	24	0.05	0.83	6.5	0.94	0.83

Within the realm of electric propulsion, the Hall thruster displays the best scores, due to their high Thrust-to-Power ratio (T/P). Additionally, within a 12U system, Hall thrusters operate effectively at lower altitudes due to the higher trust, which allows them to combat atmospheric effects. Regarding the energy scores, for both station-keeping and collision avoidance, the Hall thruster presents the best energy scores among electric propulsion. This can be explained due to their high T/P and thrust that allow to perform maneuvers quickly and thus spend less overall energy on the maneuver. The top scores in this category are attributed to chemical propulsion. However, comparing them directly may not be entirely fair, as the energy output of chemical propulsion systems is derived from the chemical energy stored in fuels, oxidizers, and pressure chambers. Therefore, the chosen Hall thruster seems to be designed for evasive maneuvers without much consideration for longevity at the altitudes considered, due to its limited low I_{sp} and fuel capacity. It's unclear whether this latter issue stems from the technology being constrained by volume, having more weight than other options, or if it's simply an issue of challenging resizing for fitting into a 1U form factor. Results indicate minimal mission time extension below 300 km, yet the thruster maintains collision avoidance capabilities, unlike other electric propulsion options. The comparative analysis also highlights promising alternatives like the FEEP technology, which offers significantly extended orbital lifetimes. However, despite scoring lower in station-keeping due to factors such as low I_{sp} and fuel mass, the thruster allowed for a threefold increase in orbital lifetime beyond 400 km (without propulsion, at 400 km, a 12U would decay in one year) indicating satisfactory overall performance. New regulations restricting the orbital lifetime of spacecraft in low Earth orbit (LEO) to five years are being discussed, making collision avoidance requirements more important than longevity ones, so, the capabilities of Hall thrusters indicate a good solution to be employed in a CubeSat in LEO.

In summary, our study validates Hall thrusters choice for CubeSat propulsion, offering significant advantages in thrust-to-power ratio, maneuverability, and compliance with space debris mitigation requirements. These attributes not only enhance CubeSat mission effectiveness but also pave the way for safer, more sustainable low Earth orbit operations. Our research contributes valuable insights into propulsion technology selection, underscoring the potential of Hall thrusters to revolutionize small satellite missions in the emerging era of space traffic management and debris regulation.

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