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A Review of MEMS Micropropulsion Technologies for CubeSats and PocketQubes

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Abstract: CubeSats have been extensively used in the past decade as scientific tools, technology demonstrators and for education. Recently, PocketQubes have emerged as an interesting and even smaller alternative to CubeSats. However, both satellite types often lack some key capabilities, such as micropropulsion, in order to further extend the range of applications of these small satellites. This paper reviews the current development status of micropropulsion systems fabricated with MEMS (micro electro-mechanical systems) and silicon technology intended to be used in CubeSat or PocketQube missions and compares different technologies with respect to performance parameters such as thrust, specific impulse, and power as well as in terms of operational complexity. More than 30 different devices are analyzed and divided into 7 main categories according to the working principle. A specific outcome of the research is the identification of the current status of MEMS technologies for micropropulsion including key opportunities and challenges.

Keywords: micropropulsion; MEMS; CubeSat; PocketQube;

1 Introduction

Micropropulsion systems are important to improve small satellites' capabilities since some missions require station keeping, de-orbiting, formation flying, and orbit transfer. Miniaturization and integration are basic characteristics that these devices need in order to provide thrust in the levels of micronewtons up to a few millinewtons with stringent constraints of mass, volume, and power [1]. These propulsion systems are part of a general trend in space research towards miniaturization therefore they can be extended to other classes of spacecraft. For artificial satellites, the mass is usually used to define the level of miniaturization. The categories of miniaturized satellites used in this publication are nano-satellites with masses ranging from 1 to 10 kg, and pico-satellites from 0.1 to 1 kg.

The popularity of nano- and pico-satellites has increased in the last decades as these spacecraft have allowed a transition from technology demonstrators and educational tools to industrial scale with some companies starting to make business with those satellites especially for Earth observation [2],[3], [4]. In this context, two standards have become more and more attractive: CubeSats and PocketQubes [5]. In these standards, a satellite is composed of one or more modular units, which, in the case of a CubeSat, is a cube of $10\times10\times10$ cm denoted 1U CubeSat. Therefore, a 3U CubeSat is a satellite composed by three of these modules with a form factor of $30\times10\times10$ cm [6]. For a PocketQube, a unit is a cube of $5\times5\times5$ cm.

Developing standard subsystems for those satellites is a clear niche for scientists and companies. However, there is still a significant gap between current technology and the theoretical limits [6]. One of the subsystems which have gained increasing attention is micropropulsion. Several researchers have been working on different concepts to meet the maneuvering requirements. This paper reviews the current status of development of micropropulsion systems that are suitable for

CubeSats and PocketQubes. Similar efforts have been made in the past, for example [7], [8] but none specifically analyzing devices designed for those kinds of satellites.

This paper reviews the recent development on the micropropulsion systems that can be manufactured using MEMS (micro electro-mechanical systems) technologies since it is key towards miniaturization, although other promising alternatives are also available, such as solar sail systems [9–11] . Only a few CubeSats have been launched to demonstrate the use of this technology [12]. Most of the micropropulsion systems analyzed here are under development and only cold-gas systems (among MEMS devices) have already flown in CubeSats, for example [6], [13–15] and there is sufficient flight heritage and information. For most of the concepts, there is still a long way towards a design of a system that is suitable for launching. Several reviews have been published in the last decade regarding propulsion systems for small spacecraft including CubeSats but with limited analysis on MEMS technologies and their applications to pico-satellites (such as PocketQubes) [8], [16–22].

Requirements for the propulsion system in CubeSats and PocketQubes concern mainly mechanical and electrical constraints as the development of this system is still in an early stage with few successfully in-flight operated devices. The CanX-2 [15] was the first CubeSat to use a propulsion system in space, specifically a cold-gas thruster, and it could achieve a maximum thrust of $35\ \mathrm{mN}$ and average specific impulse of $46.7\ \mathrm{s}$ intended to be used in formation flying missions. The minimum impulse bit was ranging from $0.07\ \mathrm{mNs}$ to $0.15\ \mathrm{mNs}$. In that case, the velocity increment requirement, termed as Δv, was set to $2\ \mathrm{m/s}$ because of mass and size constraints. In [23] it is suggested an estimation of the required velocity increment of $12.4\ \mathrm{m/s}$ for a formation flying mission. This would require a thruster with a specific impulse around $90\ \mathrm{s}$ for a 3U CubeSat.

The remainder of the paper is organized as follows: in section 2, the devices based on MEMS technology are presented. Section 3 compares and discusses the different types of micropropulsion systems with a focus on performance parameters such as thrust, specific impulse and power, and the conclusions are drawn in section 4.

2 MEMS micropropulsion

2.1 Resistojets

The working principle of this type of micropropulsion is based on heating the gaseous propellant with a resistance and then accelerating and expelling it to space. Some devices use propellants stored in liquid or solid phase, therefore phase-change accompanies the heating of the gas. The phase-change is done by heating a resistance in contact with a part or all the propellant that is kept in certain conditions of pressure and temperature to allow the specific process (sublimation or vaporization) to occur.

Considering the type of phase-change within the devices we can identify two main types of micro-resistojets which also differ regarding the governing flow regime: vaporizing liquid micro-thruster – VLM and low-pressure micro-resistojet – LPM (also known as Free Molecule Micro-Resistojet). The VLM accelerates the vaporized gas by means of adiabatic expansion in a convergent-divergent nozzle. In this case the flow can be modeled in the continuum flow range (Knudsen number $\mathrm{Kn} \leq 0.1$) although some authors [24] suggest that a statistical method such as DSMC (Direct Simulation Monte-Carlo) is better than the usual approach using Navier-Stokes equations for the flow in the nozzle exit because the Knudsen number in that region is high. Thus, for simulations, a combination of methods is apparently the most suitable approach to help and guide the design. The LPM works in a very low range of pressure and high Knudsen number ($0.1 < \mathrm{Kn} \leq 10$) in which the flow has to be modeled in the transitional flow regime. Usually, these devices use nitrogen as the propellant to evaluate the performance of the nozzle and water to prove the concept in terms of vaporization or even as the actual propellant [25].

2.1.1 Vaporizing Liquid Micro-thruster – VLM

This is one the most frequently found micro-resistojet generally manufactured using MEMS technologies in silicon or ceramic wafers. It consists of an inlet channel through which the propellant is fed, a chamber where the propellant is vaporized by a heating element, and a convergent-divergent nozzle to accelerate the gasses to supersonic velocities. Most of the work concerning this device has been focused on the numerical analysis of flow in micro-nozzles and in the design of the chamber that contains the heating element [26], [27]. However, the boiling process in the chamber is a complex and important factor to be analyzed in order to optimize the design of the chamber thus improving performance [28–30].

The geometry and material of the heating element are one of the key features towards performance improvement since this is where most of the energy is converted and is usually a low-efficiency process [26], [27], [31], [32]. Most of the devices are tested with water due to its safety of handling and ease of acquiring but it can also be used as the actual propellant as it can be stored as a liquid with the conditions of temperature and pressure considered for CubeSats and PocketQubes [33]. The main drawback of water as a propellant is its high heat of vaporization that represents high power consumption to operate the thruster, however water has the best Δv (change in velocity) per volume of propellant and specific impulse when compared to other substances that are suitable for CubeSats and PocketQubes [33].

There are two different designs that arise from differences in the manufacturing process chosen (Figure 1). The etching process can be tuned together with the type of wafer to create cavities with walls inclined around 54.7° which are used to create the nozzle perpendicular (out-of-plane) to the plane of the wafer [32], [34–36]. This might simplify the manufacturing but it reduces the freedom of the design and perhaps degrading performance. Another option is to use a more elaborated etching step that uses the Bosch process in order to create out-of-plane nozzles with more complex shapes [37].

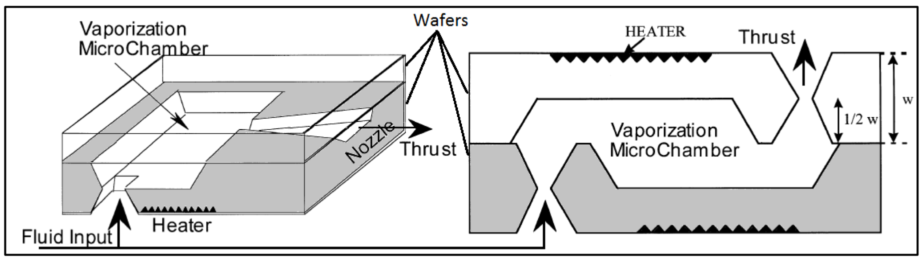

Figure 1 – Comparison between two different designs (figure adapted from [32]): in-plane thrust design (left) and out-of-plane thrust design (right).

In the in-plane design, the shape of the nozzle (and the chamber) is etched on the surface of the wafer to create a pseudo-two-dimensional feature [32], [38–40]. The freedom in the design in this case, in contrast to the out-of-plane design, is a little bit better while the simplicity in the manufacturing may be lost depending on the types of features one wants to fabricate.

Concerning the material used for fabrication and the process itself, silicon is the main choice but low temperature co-fired ceramic (LTCC) is an interesting choice for being simpler to manufacture and cheaper [41], [42].

Current devices are able to deliver thrust in the range from around $1\ \mu\text{N}$ to around $7\ \text{mN}$ while consuming from 1 to $10\ \text{W}$ which might be high depending on the type mission in consideration.

2.1.2 Low-Pressure Micro-Resistojet – LPM

The low-pressure micro-resistojet, also known as Free Molecule Micro Resistojet (FMMR), works in the transitional flow regime due to the low pressure, i.e. $0.1 < \mathrm{Kn} \leq 10$. Therefore, statistical methods based on the gas kinetic theory have to be used to model and simulate the operation of this microthruster [43], [44]. The devices, see Figure 2, are usually composed of an inlet section, a plenum where the gas is injected with low pressure typically below $1000\ \mathrm{Pa}$, and a heater chip with slots or microchannels through which the gas is accelerated to space. The heater chip, usually fabricated with MEMS manufacturing, contains a resistance to increase the temperature of the channels thus the energy of the particles in contact with the walls. Therefore, the geometry of the channels is a very important point to consider in the design in order to enhance the efficiency of the heat transfer to the gas and the overall efficiency of the thruster [45], [46]. The type of resistance and the manufacturing approach is also important to ensure an optimal conversion of electrical to thermal energy.

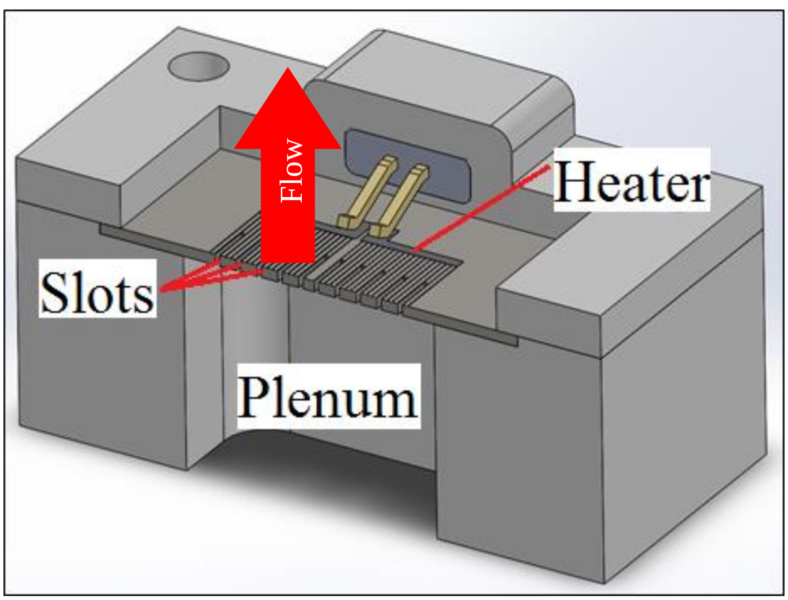

Figure 2 – Cross section of a LPM indicating the parts of the thruster; the flow goes in the direction indicated by the red arrow.

Although this propulsion concept has been investigated numerically and experimentally it still needs to overcome some issues in the design such as propellant choice and storage. The level of pressure needed in the plenum, in particular, poses a challenge for the design of the valve and the tank for example.

In general, these devices are simulated or tested with inert gasses, such as helium or nitrogen, or water but other propellants might be also considered [25], [43], [47], [48].

An interesting advantage of this type of micropropulsion system is the scalability of the design which can be extended or shrunk by changing the number of channels in the heater chip. Each channel provides a certain amount of thrust so that the total thrust can be adjusted in the design for the particular mission by choosing the correct number of channels for the desired levels of thrust.

2.2 Cold-gas micro-thrusters – CG

This type of micropropulsion system uses a pressurized gas as the propellant stored either in liquid, gaseous, or solid phase. The gas passes through a nozzle and it is accelerated to high velocities producing thrust. In general, the leakage levels of cold gas systems is the main challenge to overcome since the contamination with microscopic particles poses a threat to the sealing of valves, for example, which has to be taken into account when designing the system and estimating its performance. Depending on how long the satellite is stored waiting for launch (which in the case of CubeSats might be very long) leaks might consume much of its propellant if not treated with caution. The leak rate in the system presented in [49], for example, is below 10^{-5} ssc/s which is acceptable for that system.

These systems are at an advanced level of development for CubeSats as they are simple to build and operate. Some of them, e.g. the one shown in Figure 3, have already integrated control circuits to interface with the satellite bus and all fitting in 1U or less [49–53]. Integrated sensors and control valves might be the next milestone for these engines.

Some differences arise in the propellant storing scheme that can be stored in the gaseous phase, liquid phase, or solid phase. The latter usually ignites a propellant pellet to generate a certain amount of gas in the plenum or tank; just as with solid propellant engines, the control and efficiency of the ignition are crucial for the performance of the thruster. Inert gasses are a common choice due to safety concerns but other options, such as butane or other gasses with low boiling points, might be interesting since efficiency might improve when using liquid propellant.

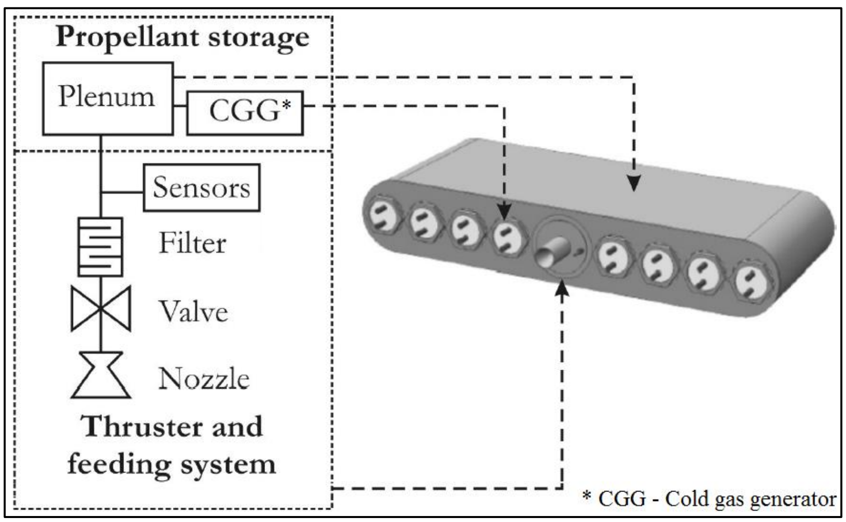

Figure 3 – Example of cold-gas thruster (adapted from [51]) designed for the Delfi-N3xt mission.

2.3 Solid propellant – SP

Solid propellant micro-thrusters consist of a chamber containing a small amount of propellant, an igniter (usually a heater), and a nozzle to accelerate the gasses after combustion (Figure 4). These devices are among the most compact ones since there is no need of a feeding system or a pressurized container. Also, a good advantage brought by the compactness is the possibility to put many engines in a single chip as in [54], [55–57], [58] and [59], [60], for example.

The main concerns in the development are in the design of the igniter and the chamber to assure an optimal combustion of the propellant in order to avoid the exhaust of unburned propellant grains [61–63]. The disadvantages of these devices are the lack of control after ignition and that they are not able to restart. For repetitive ignitions, several stages would have to be used which increases the system complexity.

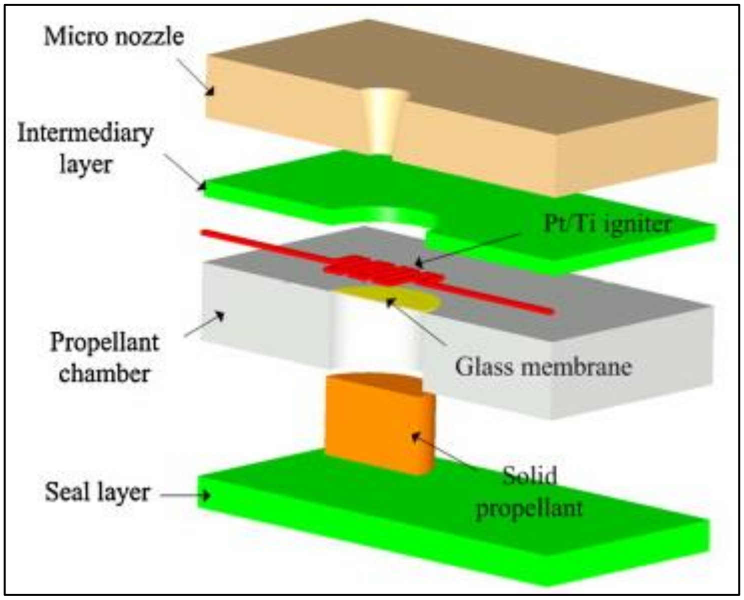

Figure 4 – Example of a solid propellant micro-thruster (adapted from [60]).

The efficiency of the combustion might be limited by the placement of the igniter which can be either on top or on the bottom of the propellant grain [55], [64–66]. The placement of the propellant grain might be also a challenge depending on the size of the igniter and amount of propellant since they can be on the micrometer scale. These facts are determinant since the efficiency of this type of micropropulsion system can be as low as 10% [54] and the repeatability in terms of thrust is degraded by these circumstances and is very important for precision applications [67], [68].

2.4 Liquid propellant – LP

This category comprises the MEMS micro-propulsion systems which uses some liquid as a propellant that when catalyzed decomposes into hot gasses. The gasses are then accelerated through a nozzle to generate thrust. Common propellant choices for these systems are hydrazine and hydrogen peroxide which, when properly catalyzed, decompose generating hot gasses. However, other alternatives are also interesting, for example using bipropellant concepts such as in [69]. The devices are composed of an inlet section, a catalyst chamber, and a nozzle as seen in Figure 5.

Hydrazine thrusters have been developed and used as primary propulsion and attitude control for large spacecraft due to the medium level performance regarding specific impulse. However, due to its high toxicity and flammability, it needs special procedures and equipment to handle it on ground which represents an increase in the overall development cost for CubeSats and PocketQubes [70].

Hydrogen peroxide is an interesting alternative since it does not need the level of precaution in handling it [71], [72]. One of its disadvantages is that organic materials are very likely to serve as a catalyst for its decomposition, therefore it might slowly decompose in the propellant tank due to minimum contact to undesired substances present in the storage. In the case of CubeSats that might be stored for long periods waiting for launch, a significant amount of propellant might be lost due to this fact.

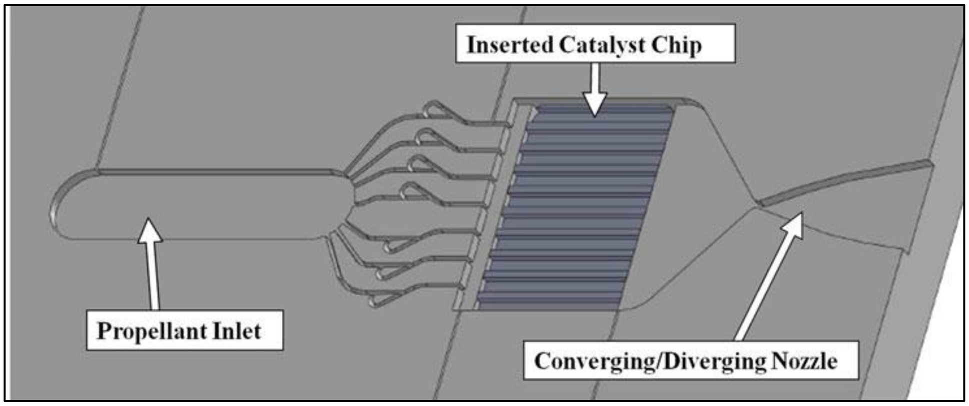

Figure 5 – Example of liquid propellant thruster [73].

2.5 Electrospray thrusters – ES

Electrospray thrusters are devices that produce thrust by emitting a spray of particles created by what is called a Taylor cone [74]. This effect occurs when an electric potential is applied to an ionic liquid in a capillary; once a threshold voltage is applied the liquid at the tip of the capillary sharpens and forms a cone emitting particles that can be either single ions, droplets or both. A schematic is shown in Figure 6.

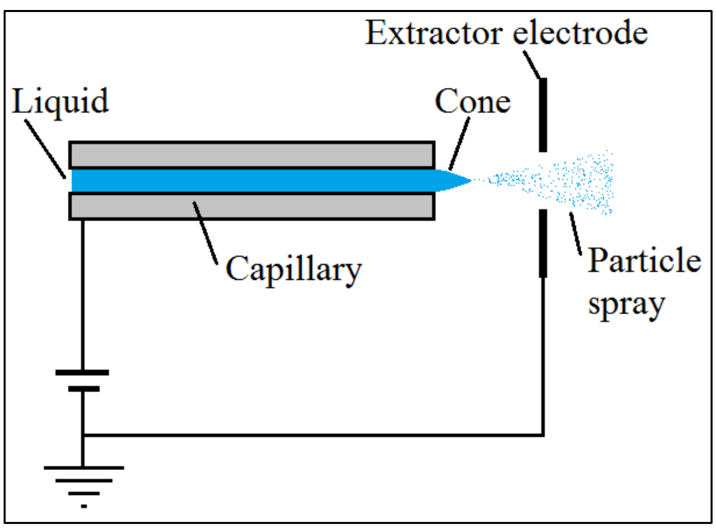

Figure 6 – Schematic of an electrospray thruster.

Each emitter depending on the design and type of propellant generates a thrust in terms of nano- to micro-Newtons [75], [76]. The number of emitters can be chosen depending on the type of satellite and mission and it usually is in the order of thousands of emitters per thruster in order to achieve reasonable thrust levels to perform maneuvers [77–80]. The propellant can be either an ionic liquid or mixture or a liquid metal and the emitters can be incremented with an accelerator grid after the extractor to further increase the exit velocity of the particles [81], [82].

The levels of thrust and specific impulse of these devices are aligned with the needs of PocketQubes and CubeSats and the modularity of the design and possibility of linearly changing the thrust by choosing the right number of emitters makes them an interesting choice for a propulsion system.

3 Analysis and discussion

In this paper, the performance of the micropropulsion systems is analyzed in terms of thrust, specific impulse, and power consumption. The first two are important performance parameters to be chosen depending on the type of mission and the size of the spacecraft. Only the thrust may have a maximum boundary, which, in the case of very small spacecraft, can be set by the maximum disturbances the attitude control system can handle, to assure a safe operation of the spacecraft. The power consumption is particularly important for small satellites, since CubeSats and PocketQubes have strict limitations on available power. Therefore, it is especially important for electric propulsion, e.g. resistojets or electrospray thrusters, and in other cases, such as liquid propellant thrusters, serves the only purpose of powering the control electronics which is needed for any system. Considering that each CubeSat unit typically produces about 2 W of power in low Earth orbits [83], then a 3U CubeSat would generate up to 6 W on average. A PocketQube has an area four times smaller than that of a CubeSat, then the power generated by 1U PocketQube can be considered up to 0.5 W, and a 3U PocketQube would generate up to 1.5 W on average. The average power of a spacecraft is, however, a different thing to the power required by the propulsion system, because the thruster might not work continuously. However, this is also strictly connected to the thrust level: for low thrust systems, the thruster would need to be operated for a very long time in order to provide the same total impulse, which can be considered the same order of magnitude of the actual orbital time of the spacecraft; for systems where the thrust level is higher one can operate the thruster for a much shorter time, meaning that the required power is close, or higher, than the average power produced by the spacecraft. In this analysis we suggest some boundaries for these parameters in order to help the reader in selecting a propulsion system for their mission.

In the following, we elaborate on a case of a 3U CubeSat to derive the maximum thrust suggested for a safe operation of the spacecraft. Considering a 3U CubeSat with an attitude control system using reaction wheels that can provide up to 0.2 mNm of torque [84], [85] and a misalignment of the center of mass of the spacecraft of around 2 cm [86], we can derive the maximum disturbance torque that the thruster can generate while being counteracted by the attitude control. This represents a thrust of about 10 mN which can be considered a maximum for safe operation of the spacecraft. As the mass of a PocketQube is eight times smaller than that of an equivalent CubeSat, the maximum thrust for that category can be divided by the same factor resulting in a maximum thrust of around 1.25 mN. These values are shown in Figure 7 to Figure 9 suggesting maximum boundaries for 3U satellites. It is noted that these boundaries might be larger in case of more advanced systems for power and stability control.

We present in Figure 7~12 an analysis of the average values of the mentioned parameters (thrust, specific impulse and power) collected from existing literature to provide an assessment of the current placement of each type of MEMS micropropulsion system. In the figures, the centers of the ellipses represent the average values for the parameters while the eccentricity of the ellipses represent their standard deviation. The actual values of the parameters analyzed are presented in Table 4 along with other important aspects to consider, such as pressure and temperature. The average and standard deviation values are presented in Table 1.

In terms of thrust the solid-propellant thrusters are those with the highest values that might be interesting for missions of space debris removal or where fast orbital maneuvers are needed, but the lack of control in the operations renders them less interesting for applications requiring precision maneuvers for example. In this case, systems using liquid propellant are more suitable since the propellant flow can be controlled with valves. This comes, however, with a downside as the complexity of the system would increase in contrast to solid-propellant engines.

Table 1: Average values of thrust, specific impulse and power of MEMS from existing literature. The standard deviation is given in brackets.

	F [N]	I_{sp} [s]	P [W]
VLM	9.58E-4 (1.79E-3)	5.28E+1 (4.62E+1)	3.62E+0 (3.34E+0)
LPM	9.45E-4 (8.51E-4)	7.08E+1 (2.72E+1)	2.36E+0 (2.78E+0)
CG	6.08E-4 (8.00E-4)	5.77E+1 (1.04E+1)	2.18E+0 (2.02E-1)
LP	5.07E-1 (1.13E+0)	1.18E+2 (1.06E+2)	-
SP	9.99E-1 (1.63E+0)	5.93E+1 (3.87E+1)	5.77E-1 (6.75E-1)
ES	5.45E-5 (3.96E-5)	2.97E+3 (1.72E+3)	8.34E-1 (8.51E-1)

In terms of specific impulse, the electrospray thrusters perform very well due to the high velocity the propellant particles are expelled. The thrust produced by these engines, however, is relatively low which makes them an attractive option for propulsion systems dedicated to, for example, attitude control or for long duration operation in case of orbit transfers.

As seen in Figure 8 and Figure 9, the power used by solid-propellant thrusters is low since they only require it for ignition of the propellant grain. Other devices, such as resistojets, need continuous power to ensure that the propellant is fully vaporized which requires higher energy consumption. Note that the power usually presented in references does not take into account the electronic circuits necessary to operate the engines. The reason is that most of them are in an early stage of development and the electronics are not designed for the flight model.

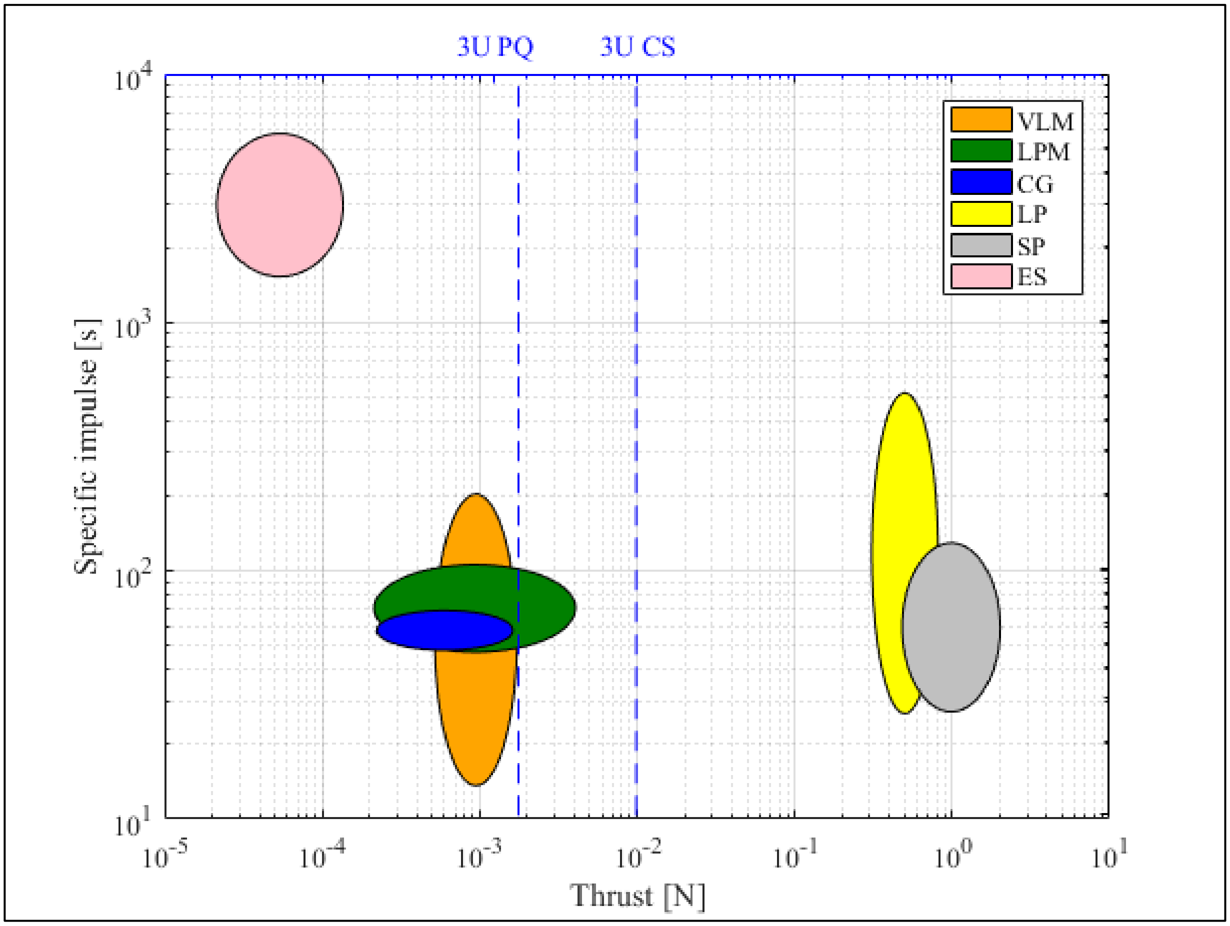

Figure 7 – Comparison of specific impulse and thrust of the different types of micropropulsion systems. The centers of the ellipses are the average values and the minor and major axes are proportional to the standard deviation. The dashed lines represent the maximum (suggested) thrust for 3 units PocketQubes (PQ) and CubeSats (CS).

Figure 7 shows a clear division in three sectors: high thrust, high specific impulse, and low thrust and specific impulse. This provides helpful insights into selecting the proper propulsion system for a specific mission. It also shows that there are regions not covered but could be achieved by doing, for example, some design optimization or using hybrid technology that combines the characteristics of two or more types. Table 2 presents the suggested applications of thrusters in the regions identified. This is however just a rough classification, with the exact applicability of specific propulsion systems depending on the specific mission and spacecraft characteristics.

Table 2: Suggested applications for the different regions on Figure 7.

Thrust	Specific impulse	Suggested application
High	Low	space debris removal, fast orbital transfer/maneuvers (when spacecraft stability is not an issue)
Low	High	precise pointing, slow orbital transfer/maneuvers
Low	Low	attitude control, small orbit corrections (max. ΔV in the order of a few m/s)

As mentioned, the power is a special constraint for the classes of satellites analyzed here (also for other classes) and, as Figure 8 and Figure 9 illustrate, there are no significant gaps in the range of power. However, the top values as indicated with the dashed lines are high for the limits of 3U CubeSats and PocketQubes.

Figure 7 clearly shows two different trends for chemical propulsion, and for electrical propulsion. Furthermore, the area covered by resistojets (orange and green ellipses) can fit within both trends, thus showing the hybrid nature of this concept where the propellant is heated electrically, but accelerated thermodynamically in a nozzle. In Figure 8, looking at the centers of the ellipses (the averages) a relationship between power and thrust for all electric propulsion concepts is evident. This is expected, since in electric propulsion the thrust is power-driven. It can also be observed that chemical propulsion is not part of this trend. Finally, in Figure 9, a close relationship between power and specific impulse for all the concepts considered. Again, this is to be expected, since specific impulse is a measure of the energy delivered by the system.

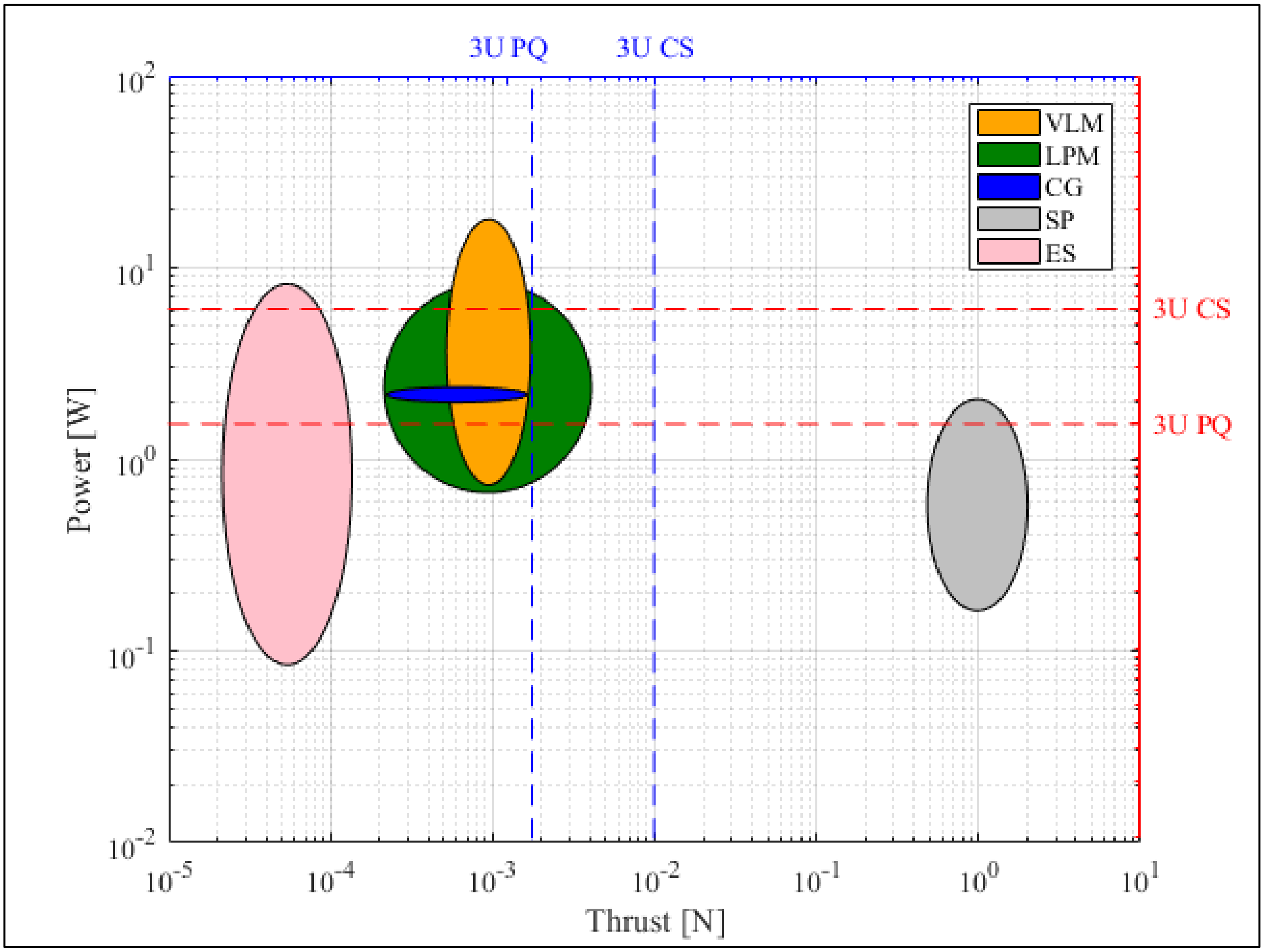

Figure 8 – Comparison of power and thrust of the different types of micropropulsion systems. The centers of the ellipses are the average values and the minor and major axes are proportional to the standard deviation. The devices using liquid propellant usually use electric power only for control electronics, so they are not present in the graph. The dashed lines represent the maximum (suggested) thrust for 3 units PocketQubes (PQ) and CubeSats (CS).

Looking at the boundaries suggested, if the boundary line falls in the middle of an ellipse, that type of propulsion is probably feasible since there might be a way of scaling it down to the desired power level levels of power or thrust. If the entire ellipse lies higher than the maximum level, then we can conclude that the current technology does not allow the use of that type of propulsion in that type of satellite. Thus, it can be concluded that in terms of power, most of the devices fit into the maximum for 3U CubeSats but if we increase this threshold, then we can consider all of the types for a possible propulsion system. For a 3U PocketQube, however, the situation is more difficult since the limitation in the power affects all types analyzed. In terms of thrust, solid and liquid propellant engines generate more thrust than the suggested maximum. This problem can be overcome with a more advanced attitude control system to compensate for disturbances or by reducing uncertainties in the position of the center of mass.

One important aspect when comparing or selecting a micropropulsion system is the complexity of the system in terms of integration and operation characteristics. The former regards additional constraints to the design, such as fluidic fittings and connections, and the latter relates to, e.g., scheduling constraints in the communication link that have to be considered in the actuation of the thrusters, since control of the input parameters might not be realizable with CubeSats and PocketQubes due to data link limitations for example. An automatic controller may be considered to avoid this issue but will require more effort in the development. Here, to characterize complexity, we select four parameters characterizing each system: the minimum number of additional components that are needed in the system on top of the actual thruster and control electronics; the number of control parameters for the system; and the start-up and shut-down times which are respectively the times needed to achieve steady state full thrust and to completely shut down the engine, i.e. achieve zero thrust, from the moment when the command is sent. These last two parameters are important if one wants to perform precise maneuvers that need a specific total impulse, then the time needed to achieve steady state and to shut the engine down have to be taken into account in the calculations.

The number of components and the number of control parameters are given quantitative values from 1 to 3 and the start-up and shut-down times are given qualitative values from low to high corresponding to short and long times respectively. The complexity is then calculated as the average of these parameters (taking the numbers 1 to 3 for the qualitative values) and if the result is from 0 to 1 we consider low complexity, from 1 to 2 medium, and from 2 to 3 high. Table 3 lists the 4 parameters for each type of system and provides the resulting complexity.

As we can see, the complexity increases with number of components and parameters. But on the other hand, a more controllable operation of the thruster may be achieved therefore increasing the performance and optimal use of propellant.

Table 3: Assessment of operational complexity of the types of MEMS micropropulsion.

Type	Complexity	Minimum number of components	Number of control parameters	Start-up time	Shut-down time	Comment
VLM	High	3 (heater, valve, tank)	2 (power, flow rate)	high	high	Liquid left in the path from the valve to the thruster gives high shut down time.
LPM	Medium	2 (valve, tank)	1 (flow rate)	low	medium	Number of control parameters and components increase if applying temperature to the gas or using liquid propellant.
CG	Medium	2 (valve, tank)	1 (flow rate)	low	medium	Number of control parameters and components increase in warm gas mode.
LP	Medium	2 (valve, tank)	1 (flow rate)	medium	high	May require power to accelerate the start up. Same issue with liquid and shut down time as for VLM.
SP	Low	1 (igniter)	1 (power)	medium	-	Shut down is not controllable.
ES	Medium	2 (tank, energy storage)	1 (power)	low	low	Number of control parameters increases if using an accelerator grid

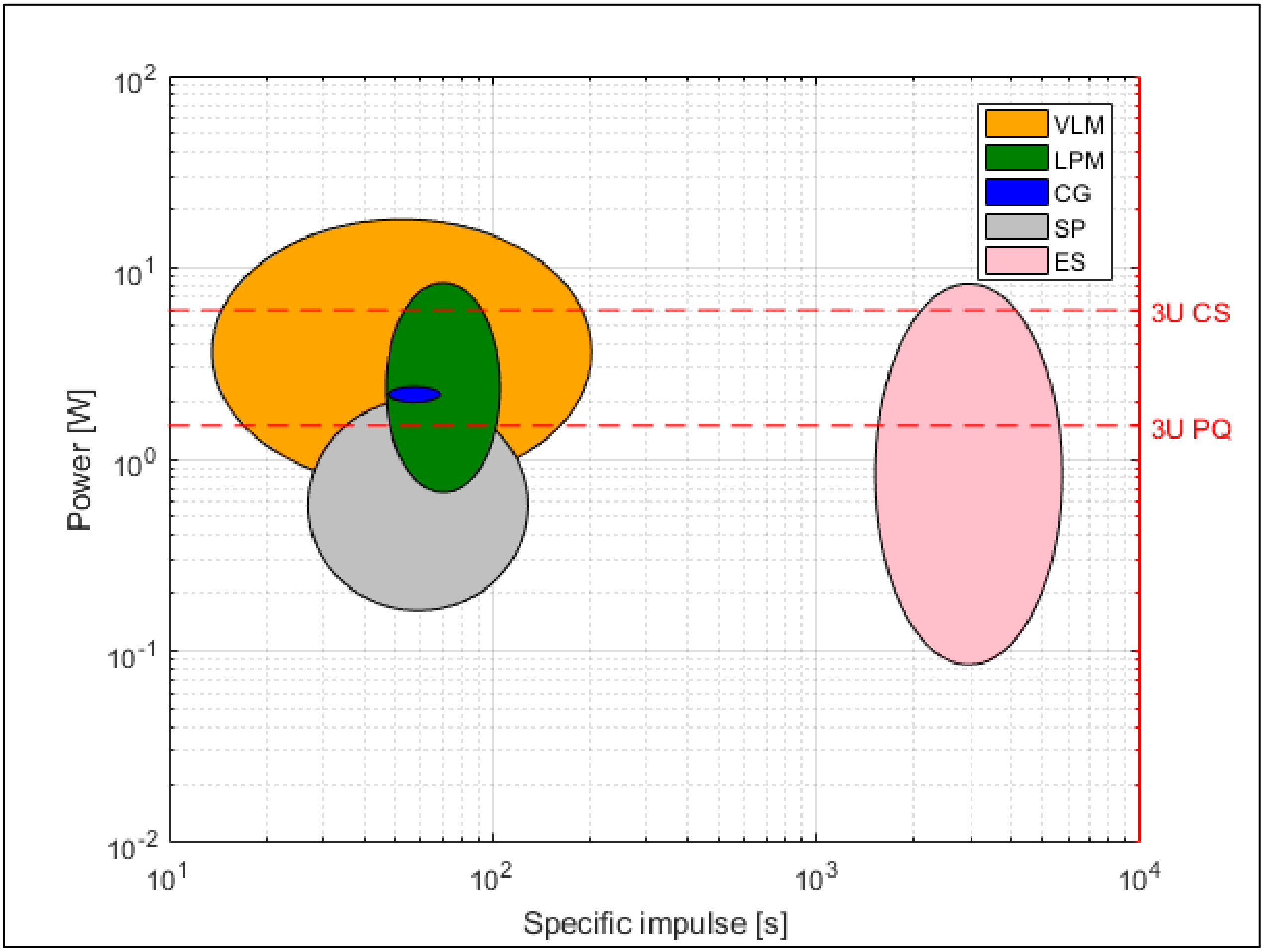

Figure 9 – Comparison of power and specific impulse of the different types of micropropulsion systems. The centers of the ellipses are the average values and the minor and major axes are proportional to the standard deviation. The devices using liquid propellant usually use electric power only for control electronics, so they are not present in the graph. The dashed lines represent the maximum (suggested) thrust for 3 units PocketQubes (PQ) and CubeSats (CS).

Table 4: Data for comparison extracted from the references in the first column.

Ref.	Type	P_{min} [W]	P_{max} [W]	F_{min} [N]	F_{max} [N]	Isp_{min} [s]	Isp_{max} [s]	p_{min} [Pa]	p_{max} [Pa]	T_{min} [K]	T_{max} [K]
[49]	CG	n/a	n/a	0.00E+00	2.00E-03	4.50E+01	4.50E+01	0.00E+00	5.00E+05	n/a	n/a
[50]	CG	2.35E+00	2.35E+00	0.00E+00	1.00E-03	6.80E+01	6.80E+01	2.00E+05	5.00E+05	n/a	n/a
[52]	CG	2.00E+00	2.00E+00	0.00E+00	6.50E-04	6.00E+01	6.00E+01	2.00E+05	5.00E+05	n/a	n/a
[78]	ES	5.53E-01	2.50E+00	3.12E-05	9.98E-05	4.74E+02	5.93E+03	n/a	n/a	n/a	n/a
[77]	ES	6.50E-01	4.00E-01	2.00E-05	3.00E-05	3.00E+03	3.00E+03	n/a	n/a	n/a	n/a
[75]	ES	1.00E-01	8.00E-01	5.00E-06	5.00E-05	1.50E+03	3.26E+03	n/a	n/a	n/a	n/a
[80]	ES	n/a	n/a	1.00E-04	1.00E-04	2.00E+03	4.60E+03	n/a	n/a	n/a	n/a
[69]	LP	n/a	n/a	0.00E+00	1.00E+00	0.00E+00	1.50E+02	0.00E+00	1.20E+06	n/a	n/a
[87]	LP	n/a	n/a	2.00E-04	1.97E-03	2.92E+00	1.34E+01	n/a	n/a	n/a	n/a
[47]	LPM	1.16E+00	1.16E+00	1.70E-03	1.70E-03	5.60E+01	5.60E+01	n/a	n/a	n/a	n/a
[43]	LPM	n/a	n/a	1.00E-04	1.00E-03	4.00E+01	8.00E+01	5.00E+01	2.00E+02	3.00E+02	5.73E+02
[88]	LPM	8.00E-01	5.60E+00	1.00E-03	1.60E-03	7.00E+01	7.00E+01	4.90E+01	4.90E+01	5.74E+02	1.17E+03
[89]	LPM	1.46E+00	9.68E+00	2.80E-04	2.72E-03	6.37E+01	1.11E+02	5.00E+01	3.00E+02	3.00E+02	9.00E+02
[90]	LPM	1.00E+00	3.40E+00	1.00E-04	1.70E-03	4.00E+01	1.40E+02	3.50E+01	1.20E+02	3.00E+02	5.00E+02
[25]	LPM	0.00E+00	2.50E+00	1.29E-04	1.29E-04	7.92E+01	7.92E+01	n/a	n/a	3.00E+02	5.80E+02
[48]	LPM	0.00E+00	1.60E+00	0.00E+00	1.07E-03	5.20E+01	5.40E+01	2.55E+02	9.00E+02	2.74E+02	5.44E+02
[64]	SP	1.60E+00	1.60E+00	4.00E-03	1.00E-02	1.00E+02	1.00E+02	n/a	n/a	n/a	n/a
[59]	SP	3.40E-01	3.40E-03	3.62E+00	3.62E+00	6.23E+01	6.23E+01	n/a	n/a	n/a	n/a
[55]	SP	0.00E+00	7.50E-01	4.00E-02	5.10E-02	n/a	n/a	n/a	n/a	1.53E+03	1.53E+03
[67]	SP	1.60E-01	1.60E-01	5.00E-02	6.00E-01	2.68E+00	2.83E+01	n/a	n/a	n/a	n/a
[28]	VLM	n/a	n/a	2.00E-03	6.50E-03	1.10E+02	1.10E+02	1.00E+05	2.60E+05	4.54E+02	5.74E+02
[41]	VLM	0.00E+00	5.00E+00	2.50E-04	6.34E-04	3.10E+01	3.10E+01	n/a	n/a	3.24E+02	6.83E+02
[30]	VLM	n/a	n/a	1.00E-03	6.00E-03	3.07E+01	3.07E+01	1.00E+05	2.00E+05	4.23E+02	5.73E+02
[42]	VLM	7.10E+00	9.20E+00	3.36E-05	6.77E-05	3.42E+00	6.90E+00	1.04E+05	1.04E+05	4.00E+02	4.22E+02
[38]	VLM	1.60E+00	3.60E+00	1.50E-04	1.01E-03	5.00E+01	1.05E+02	1.00E+05	1.00E+05	3.74E+02	4.74E+02
[72]	VLM	2.00E+00	2.20E+00	3.00E-04	1.08E-03	8.00E+01	1.80E+02	n/a	n/a	4.23E+02	4.23E+02
[35]	VLM	1.00E+00	2.40E+00	5.00E-06	1.60E-04	2.04E+01	2.04E+01	n/a	n/a	3.75E+02	3.76E+02
[34]	VLM	1.00E+00	2.40E+00	5.00E-06	1.20E-04	1.75E+01	1.75E+01	n/a	n/a	n/a	n/a
[39]	VLM	n/a	n/a	2.00E-05	9.60E-04	6.53E+01	6.53E+01	0.00E+00	6.00E+05	2.74E+02	6.24E+02
[32]	VLM	7.80E+00	1.08E+01	3.10E-04	4.60E-04	8.85E+01	8.85E+01	n/a	n/a	n/a	n/a
[36]	VLM	9.00E-01	9.70E-01	7.10E-07	2.86E-06	1.91E+00	7.68E+00	n/a	n/a	n/a	n/a

3.1 Future developments

Although there has been a significant effort in developing micropropulsion systems, there are still challenges to be addressed. For highly miniaturized satellites, the devices may be so small that interfacing them to other larger components of the system becomes more and more difficult. In some cases, the electronics might be integrated into the fabrication process, which is one of the advantages of using MEMS, to incorporate sensors and control circuits into the “smart thrusters”. This integration can also be extended to, for example, valves or pumps [91], [92] that can be manufactured in wafers with similar processes leading to a complete “propulsion on a chip” system which is very interesting for extremely miniaturized satellites.

The integration of the components of a propulsion system is one of the main challenges since traditionally these parts come separately (e.g. valves, tanks, etc.). However, with the advance of MEMS technology, more integrated devices can be accommodated in very small spacecraft. This requires a good and reliable interface between mechanical, electrical, and fluidic parts. The integration of the system and interfaces between the macro and micro systems, and components, such as microvalves to control the mass flow rate, the electronic circuits, and the propellant management, are some of the engineering challenges that can be facilitated with the use of MEMS.

Regarding the manufacturing processes, new technologies and materials such as membranes, thin metal layers, or composites will allow for designing and building ultra-light components, for example tanks, that currently consume most of the dry mass budget. With the development of additive manufacturing methods, the emerging 3D printing technology is an interesting option that might facilitate the integration and interfacing of mechanical, electrical, and fluidic parts [93–95]. Other conventional manufacturing approaches also allow the development of advanced systems that may be compatible with CubeSat standards [96–113]. Also, innovative propellants, especially green ones, might open the path to new concepts of thrusters or new ways of using them.

Concerning operation of thrusters, there are challenges related to disturbances generated by the thruster in combination with a possibly movable center of mass. This might require a more sophisticated system with micro-gimballed nozzles or arrays of micro-thrusters in order to allow thrust direction control. The use of MEMS pumps for avoiding pressurization of the propellant may also be considered an option to facilitate the operation by having a more controlled pressure system and reducing the total mass of the system in exchange of complexity and power consumption.

4 Conclusions

This paper presented and analyzed the status of development of micropropulsion systems that are candidates for CubeSat and PocketQube missions. We have analyzed more than thirty devices regarding performance aspects and assessed them in face of limitations imposed by the types of satellites.

We have introduced a simple way of comparing the operational complexity of the systems in order to help the reader in choosing a propulsion system for the mission but the comparison also shows where interesting operational characteristics can be found on each type of device and where new methods could be developed.

As we discussed in the previous section, there is room for improvements in general for all the types of propulsion systems assessed here. In some cases, there is no definite design of the system but only analyzes on the propulsive performance. The use of MEMS fabrication technologies is a great advantage in the sense that this is a very active research field and its processes are well developed so that some of the possible challenges in the miniaturization of propulsion systems have already been addressed with other perspectives in other fields. Also, it is very interesting especially for the fabrication of very small structures and channels. However, other components of the system, such as propellant tanks and electronic circuits, have to be made using conventional manufacturing techniques. Also, other fabrication methods have to be analyzed considering costs of fabrication since MEMS can be highly expensive in a small-scale production which is the case for nano- and pico-satellites. In addition, other unconventional approaches of propellantless propulsion (solar sail is the main option) or the ejection of solid particles can be interesting alternatives and have to be further investigated.

We have shown that the systems analyzed can be grouped and separated according to the performance parameters evaluated and also the operational complexities can be used to define which approach is better for certain missions.

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