Development of MEMS based Electric Propulsion
Executive summary

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Abstract
In recent years, there has been a large increase in the number of small satellites being designed, built and launched. Due to resource constraints, these spacecraft have not generally included any propulsion capability, and this has severely limited mission capabilities and lifetime. To enhance their performances, next generation of small spacecraft will require extremely miniaturised, highly integrated propulsion systems capable to meet stringent mass, volume and power constraints. Two of the most promising technologies to achieve these goals are electric propulsion systems and micro system technologies: electric propulsion is the most mass efficient propulsion that exists and MEMS technologies enable high levels of integration and multifunctionality (combining mechanical, fluidic and electrical functions on one chip), leading to more compact and robust systems. A MEMS based electric propulsion system, combining advantages from both technologies, is likely to respond to future needs.

In this frame, the ESA-funded study on 'MEMS-based Electric Propulsion' was carried out by a consortium consisting of TNO (NL), NanoSpace (S), the Ecole Polytechnique Fédérale de Lausanne (CH) and the Queen Mary University of London (UK) with the primary aim of investigating new electric propulsion system concept based on MEMS. The study identified a wide variety of mission scenarios which could benefit from the use of MEMS EP systems and then looks for radically new propulsion subsystem concepts, novel materials and manufacturing techniques.

The study started in March 2009 and was completed in March 2010.

Task 1: determination of most promising MEMS-EP technologies for small satellites

The first task (WP 200) was conducted in March and April 2009. TNO was the main responsible for this part of the study. This task goal was to evaluate which EP technology is the most promising for MEMS-EP systems by making a trade-off between missions, satellites and EP technologies.

The task starts with a broad investigation of the existing MEMS-based EP; in this inventory not only each technology was presented with its peculiar characteristics and performances, but also an analysis of the mass budget of each subsystem of the technology was performed, in order to find information about the impact of these subsystems to the entire thruster and to understand the physical constraints in the downscaling process. This analysis lead to a development of scaling laws for the design of an advanced concept of miniaturized and micromachined Electric Propulsion technologies. The down-scaling laws were developed based on statistical relations for each subsystem of an electrical propulsion system: the PCU, the fluid management, the thrust head and the neutralizer. This approach helps to understand the trend of the downscaling process from conventional systems or subsystems to some smaller one. In this way it is possible to individuate the effects in term of performance, power consumption, masses and volume of components when the aim is to miniature or reduce a conventional EP technology.

For modeling the PSU mass and volume performances, data of Power Supplies produced by EMCO, miniaturized devices with high electrical efficiency have been used.

A first trade-off was performed ranking in a table the technologies/satellites/mission combinations and the main conclusions are that colloid (electrospray) thruster have the highest down-scaling capability, the FEEP follows the trend of Colloid but it needs more power, mass and volume and higher level of Voltage, the Hall Effect Thruster and the Ion have the lower down-scaling capability, while for 100 kg and 500 kg satellites, conventional EP works perfectly so the miniaturization is not really needed.

Therefore a second trade-off has been carried out: in this one, the weighting factor for each criterion is based on a technology evaluation approach. In the selection of an EP in the development of decided mission, criteria as TRL level of the technology, lifetime and contamination are really important for the success of the mission; here the aim was to evaluate which technology can be object of a new propulsion system and to have a view of the potential of this technology in a development road, so flexibility and capabilities are more important criteria.
From this trade-off it becomes clear that according to these criteria the colloid technology scores the highest. It is a very scalable technology with good mass, power and volume performance and MEMS technology can be applied to all its components.
The other technologies (FEEP, Ion, PPT and Hall) score lower. Hall and Ion are very mature technologies, but have very limited downscaling potential. FEEP technology is similar to Colloid, but is less easy to scale and has the problem of higher voltages and contamination. PPT is interesting, but the technology is difficult to be designed in MEMS technology and the efficiently is very low.
Task 1 was concluded after the selection of the colloid micropropulsion system technology.

Colloid thruster technology is and electrostatic propulsion technology, where the charged ions or droplets are produced by electrospray atomization, whereby a conductive fluid (now generally ionic liquids with conductivities ~1 S/m) housed in a fluid reservoir is fed though emitter capillary into an electric field (~10^8V/m) generated by an electrical potential difference between the emitter and an extraction grid. The fluid, under the influence of the electric field, forms into a structure known as a Taylor cone which then breaks up to form a charged spray (with charge to mass ratios ~1-100kC/kg). The charged spray is then accelerated in a static electric field generated by an electric potential difference between the extraction grid and an acceleration grid. This charged spray is then emitted from the spacecraft to produce the required thrust. A neutraliser is also required to neutralize the spacecraft due to the emitted charged spray.

Task 2: requirements evaluation of the colloid's subsystem based on different mission scenarios

The second task was to derive the requirements evaluation of the colloid's subsystem based on different mission scenarios. This work was performed by EPFL in collaboration with QMUL and other parties. This task was performed in May and June 2009.
At this point of the study, the most probable mission scenarios were investigated and the mission requirements evaluated, independently of the technologies selected during the previous task. The mission (or scenarios) requirements provided target and guidelines for the development of the MEMS EP propulsion subsystem.
The requirements evaluation include performance requirements (total thrust, total impulse, impulse bit, lifetime, total propellant mass), accommodation constraints (mass, dimensions, beam divergence), interface requirements (bus voltages, currents), environmental temperatures and other operational requirements. These requirements served as input to the preliminary system design. An additional iteration has been performed once the preliminary design of the MEMS propulsion system was completed.
The trade-off performed concluded that a modular MEMS micro-propulsion was of interest to pico, nano and potentially micro-satellites so these satellites were taken into account during this task, combined with the following missions: combined functions of wheel unloading and de-orbiting; fast de-orbiting of pico- and nano satellites; formation flying and drag compensation capability; orbital transfers of at least 500 m/s to pico- and nano-satellites.

So the requirements on the propulsion subsystem has been established for a wide range of satellites (1-125 kg) and a variety of mission demanding between 1 and 8 thrusters and a dV budget ranging from 40 – 4000 m/s.

The more important driver during this analysis was correlated to the potential for modularity of the MEMS EP. It was thus of interest to develop a MEMS EP Module that will fit almost all applications, and provide as many modules as needed for a specific requirement. These modules can then be combined in what has been defined during this study as a “cluster of thrusters”. The requirements set are thus based on a possible implementation for the MEMS EP module. As the MEMS EP propulsion system be easily adaptable to various interfaces (plug and play interface), the interface requirements try to address a wide range of satellite buses. A thruster module should be flexible enough to respond to low thrust demand and high thrust demand

The main results in term of requirements show that a thrust/area ratio above 0.5 $\mu N/mm^2$ is desirable from a mission performance standpoint and it is also desirable to have a MEMS EP system with an Isp above 500 sec and for some applications, above 1500 sec.

It was evaluated that the design of the PCU shall accommodate a 3300 V operating curves, with highest Isp at 3500 sec and lowest at around 500 sec. The target working point is at 2500 sec.

The requirement specification defined also two versions of the thruster heads: the 25 µN and the 100 µN version.

Given the wide span of requirements set in the second task, the objective of the preliminary design work was to find a system design that is the best compromise –and thus best suited to cover the given range of requirements.

Task 3: preliminary design of the MEMS-EP subsystem

Task 3 was lead by NanoSpace in collaboration with all other consortium members. The objective of the task was to establish and justify a complete MEMS based EP subsystem design. This design work has been built on established requirements at both subsystem and component level, and the major design guideline was to minimize mass, volume and power consumption of the subsystem.

Firstly, a short overview and background of the selected concept was performed to define the main functional units and components in a typical colloid thruster propulsion system; then the requirements are analyzed and the most critical design drivers are identified.

Thereafter, a survey is done to identify the most suitable components available on the market. Here it is important to note that apart from existing components, the survey has allowed to look at less mature, but feasible technologies, or even more immature concepts, that will evolve to future components that could be foreseen in the propulsion system.

Thereafter, integration and interface aspects are discussed since this is known a priori to be a critical system design driver to all MEMS based system builds.

Finally, and with the results from the above mentioned work at hand, the actual preliminary system design has been worked out, allowing not only existing components but allowing extrapolation into the future by considering also relevant technologies and concepts that could evolve into viable components in the system design.

Two basic design concepts have been investigated to cover the wide range of applications and mission scenarios stated within this study, The components, thruster cluster, feed system and propellant storage, in the colloid-based micropropulsion subsystem have been design to be integrated into one single module called MEMS thruster module. A separate design configuration has been developed for the electronics.

Here some of the design choices and baselines are presented.

In order to systematically sort out the best possible configuration for the different subsystem of a colloid, a mass breakdown for the different components has been established. From this mass breakdown some main conclusions have been carried out: the centralized PSU is more mass and volume efficient than distributed PCUs in single stacks; for small amount of propellant it appears as the efficient strategy to have distributed tanks, one integrated tank for each thruster cluster while for large amounts of propellants (above 1500 g) it appears more attractive to have a centralized tank.
To really benefit from the fact that all fluid flow can be regulated by capillary and electrostatic forces and to stress the ambition to miniaturize the design a capillary propellant feed principle is chosen as baseline. Based on the selected feed system principle and conclusions from the mass breakdown analysis only two system configurations among the entire possible identified are left as optional. Due to modularity reasons the distributed tank is kept in the standardized thruster module as a reservoir, from which capillary feed can still be used from in the centralized tank alternative. Hence, the selected baseline design investigated is a thruster module consisting of all functions/building blocks integrated into a single stack, but with a separate centralized PSCU.

In order to keep the mass and volume within the allowable limits the thruster cluster has been designed to be integrated on wafer level in a single mechanical housing.
Each thruster cluster has individually addressable thruster heads in order to achieve the required thrust range modulation improving also redundancy and reliability in a mass and volume efficient manner. A new and innovative mixture of the capillary and porous emitter type is chosen as baseline.
The emitters should be configured in a planar array, preferably in a circular to achieve a well defined thrust axis. Given the two versions of the thruster heads, two different thruster cluster configurations have been considered in the system designs hereafter: the 3x25µN thruster heads in a single housing and the 3x100µN thruster heads in a single housing.

The 3x25µN thruster cluster covers the range below 100 µN and hence to there is no need for larger clusters than using three thruster heads. Larger thrust range will be covered by multiple thruster clusters or by using the 100µN thruster heads. The thruster head have high integration level and due to the dimensions will be manufactured using MEMS processes. Due to a higher risk with wafer level packaging a chip level system is preferable if accurate alignment can be reached.
Regarding the propellant two main candidates have been identified: EMI-Im (also referred to as EMI-Tf_2N) and EMI-BF_4 , both shown in the ground as good candidate propellants for colloid thrusters, and capable of being used in ionic mode.
For the propellant storage selection, from a miniaturization point of view and with regards to integration aspects the silicon is chosen as baseline, with the modification of using multiple wafers to admit larger volumes and to enable integrated filling and interface structures in the design. For the special case where a centralized propellant storage is needed and for large dV manoeuvres a more conventional propellant storage, i.e a tank, can be used, but then the capillary feeding principle are foreseen to be replaced by pressure fed and the interface chip complemented with a valve.
The porous propellant storage material and the propellant need also an outer housing. This housing will be the mechanical interface to the rest of the thruster system but since the propellant will have the same high potential as the emitter during operation an insulating material better be chosen to avoid unnecessary short circuiting.
To provide the mechanical and electrical interfaces to the thruster head chips, two more components are needed; a holding structure for mechanical and electrical I/F for the thruster chips

and the housing for protecting the propellant storage and feed component and for mounting on the S/C.

A multilayer hybrid interface component made in LTCC is suggested to solve the mechanical and electrical interface to the thruster chips. A mounting structure for all components is also needed in order to I/F the S/C. The housing also accommodates high voltage electrical feed troughs and connectors.

In order to reduce mass of the propulsion system while maintaining thrust capabilities miniaturization and optimization of the power supply unit is important. The architecture is constructed in a way to allow extension of the number of supplies in the propulsion system. Changing the actual control ranges allows use of the concept in different missions. The system state diagram of supply startup, regulation and fault handling is programmed in the digital control. Redundancy is included on the architectural level.

The PSU, PCU and DCIU are built with available discrete components, several of which need to be qualified for space. The environmental vacuum is expected not to affect performance, while radiation hardness is to be validated.

Regarding the neutraliser, no existing neutraliser meets the target requirements at the moment and further development is needed. The US version supplied by BUSEK can maybe meet the power-to-current ratio for very small thrusts but then needs to allocate high voltage from a PSU.

Based on the experience within the team a novel tentative miniaturized neutraliser design is suggested, based on earlier work made at Uppsala University, where different field emitting structures to be used as cold cathodes in a miniature x-ray source were investigated.

The reasons for improved field emission capabilities with CNTs are partly due to material properties, but mostly due to the field enhancing geometry of the individual nanotubes. In fact polycrystalline diamond films shows even more superior field emitting performances in comparison to CNT. Diamond has the best thermal conductivity of all materials and actually has a negative electron affinity, which is excellent for field emitting applications. Since the competence and experience exist within the team on diamond-based field emitter, a first neutraliser design to demonstrate the feasibility is suggested below. By combining MEMS manufacturing in silicon, a mould for a polycrystalline diamond tip can be manufactured.

Including these components and subsystems, a preliminary colloid system has been designed.

The size of the thruster module is 60x40x30 mm. The weight is roughly estimated to less than 60 grams including 20 g usable propellant. Total estimated target mass for a complete MEMS EP system including one thruster module, a centralized PSCU and a neutraliser will be about 140 grams in total.

Fig1: MEMS propulsion module with integrated 20g propellant supply.

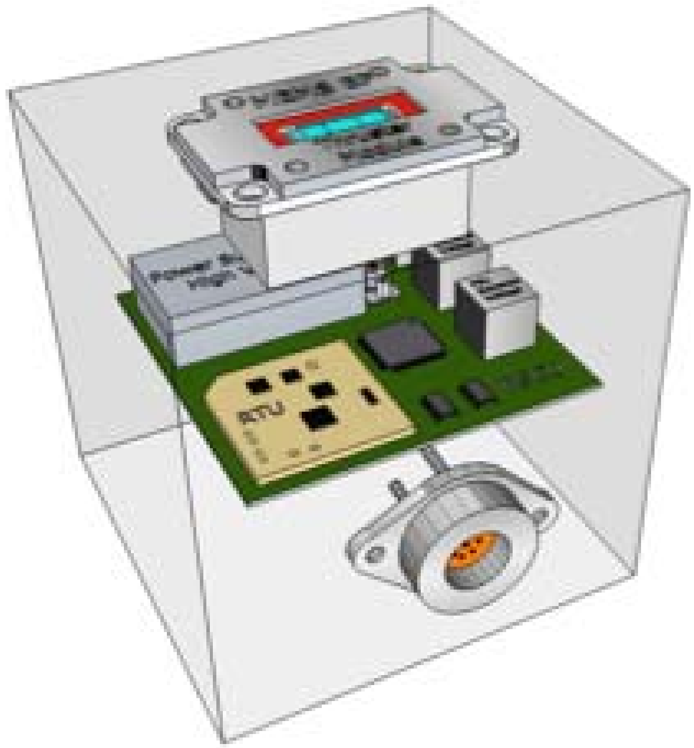

Fig2: Illustration of the MEMS-EP complete system (including all power supplies and neutralizer) in a 10x10x10 cm^3 volume, showing how it could readily fir in a cubesat.

After the completion of the preliminary design, a development plan has been established, detailing how the maturity level of the MEMS based EP system shall be raised towards the first potential space flight (TRL-7)), or a formal on-ground qualification program.

The road map mainly focus on the estimated cost and estimated time schedule to develop EM and QM components or subsystems, developing also an European High Voltage Unit and a new European neutraliser.

Conclusions

This study has identified colloid thruster as the most promising candidate for a MEMS-based electric propulsion system, and requirements based on a variety of missions for satellites up to 100 kg were derived. This input was used to develop a conceptual design of a modular MEMS EP system which his very compact and modular. The essential requirement on the resulting MEMS based EP subsystem concept has been extreme miniaturization and high efficiency, while also considering how miniaturization can increase redundancy and reliability.

Modularity is very important to enable the same design to be re-used and critical subsystem units, such as the high voltage power and control electronics, have also to be developed for the integration in the modular concepts. Table 1 summarizes the delta-V, ISP, mass and power for a MEMS-EP system based on the conceptual design in this study for a range of small satellites and applications, showing that the MEMS-EP concept developed in this study can enable a wide range of missions for small spacecraft.

	CubeSat 1U	CubeSat 3U	NanoSat 8 kg		MicroSat 27 kg		MicroSat 64 kg
			Continuous thrust	ACS	Continuous thrust	ACS	Continuous thrust
Number of MEMS EP modules	1	1	1	8	1	8	4
MEMS EP system total input power (W)	0.25	1.2	2	15	4	24	13
Emitters area per module (mm2)	4	22	36-49	64	70-95	110	60 - 80
Thrust (uN)	20	135	220 - 80	400	430 - 150	675	1500 - 500
Isp (sec)	1100	1000	1000-3000	1000	1000-3000	1000	1000 - 3000
System dry mass (g), with 30% conting.	~ 280	~ 290	~ 810	~ 1480	~ 2600	~ 2700	~ 6400
Propellant mass integrated (g)	20	20	20	160	20	160	80
Propellant mass external tank (g)	0	0	120	0	1000	80	1700
DV capability (m/s)	~ 200	60+	175 - 500	8 x 25	380 - 1100	8 x 10	280 - 2000

Table 1: key MEMS-EP system parameters for different small spacecraft missions.