Development of MEMS based Electric Propulsion

Berry Sanders, Laurens Van Vliet and Flavia Tata Nardini*
TNO Defense, Security and Safety, Rijswijk, the Netherlands
*flavia.tatanardini@tno.nl

Tor-Arne Grönland[1], Pelle Rangsten[1], Herbert Shea[2] and Muriel Noca[2]
[1]*NanoSpace, Uppsala, Sweden,* [2]*Ecole Polytechnique Fédérale de Lausanne*

Richard Visee[3], Bert Monna[3], John Stark[4]
[3]*SystematIC, Delft, the Netherlands,* [4]*Queen Mary University of London*

and

Alexandra Bulit[5] and Davina Maria Di Cara[5]
[5]*ESTEC, Noordwijk, the Netherlands*

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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 miniaturized, 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 (EP) systems and Micro Electro Mechanical Systems (MEMS). The study identifies a wide variety of mission scenarios, satellites and EP technologies which could benefit from the use of MEMS leading to a selection of one propulsion technology that seems the most promising: the colloid thruster propulsion system. For this technology the requirements are identified and then a preliminary MEMS based EP system design is established. Modularity is very important to enable the same design to be used over and over again 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. Two basic design concepts have been investigated to cover the wide range of applications and missions scenario stated within this study and they are presented in this paper.

1. Introduction

The fundamental challenge of space missions is to achieve the best performance (in terms of accuracy, science data production or commercial return) for the minimum costs (which can be translated to minimum of mass, volume and power) and much of the technology development of ESA is aimed at finding ways to get the same performance for less costs or more performance for the same costs.

In science the trend towards higher accuracy for the same spacecraft mass is obvious and has led to technology development into micro propulsion. On the other hand, small spacecraft are getting more and more capable thus requiring efficient propulsion. Two of the more promising technologies to achieve these goals are electric propulsion and micro system technologies. Electric propulsion is the most efficient propulsion possible and MEMS technologies are very capable in making systems small and efficient.

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) with the consultancy of the Queen Mary University of London (UK) and SystematIC (NL) 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. Outputs of this study are four technical notes and one final report [1], [2], [3], [4] and [11].

2. Determination of most promising MEMS-EP technologies

The goal of this first phase of the study was to evaluate which EP technology is the most promising for MEMS-EP systems by making a trade-off between missions, small satellites (< 500 kg) 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 (shown in Figure 1) of an electrical propulsion system: the Power Control Unit (PCU), the fluid management, the thrust head and the neutralizer.

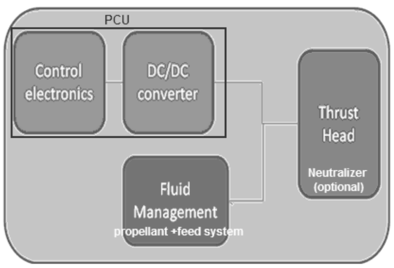

Figure 1 Subsystems of an EP thruster.

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 modelling the PCU mass and volume performances, data of Power Supplies produced by EMCO [11], miniaturized devices with high electrical efficiency have been used. These are not space qualified system but as high grade industrial equipment provide a challenging goal of what might be possible in miniaturization.

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. For 100 kg and 500 kg satellites, conventional EP works perfectly so the miniaturization is not really needed to meet the requirements of today. Figures 2, 3 and 4 show the results obtained for each technology and for each mission considered (attitude control, orbit change and formation flying) for a CubeSat. Similar graphs were produced for each satellite object of this study.

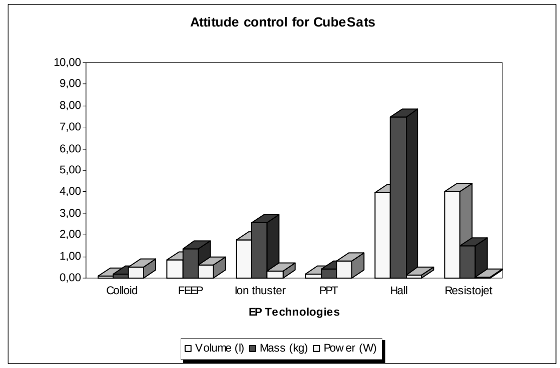

Figure 2 Attitude control for CubeSats.

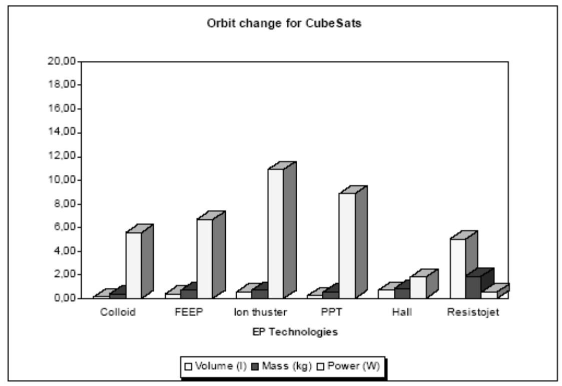

Figure 3 Orbit change for CubeSats.

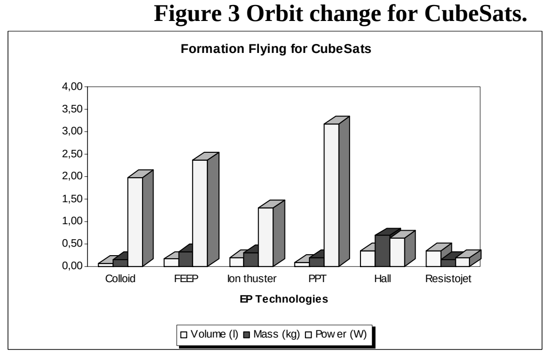

Figure 4 Formation Flying.

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 due to the physics involved. 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 low. The first phase of this study was concluded after the selection of the colloid micropropulsion system technology.

4. Mission analysis and propulsion requirement

The goal of the mission analysis is to define the propulsion system and subsystem requirements based on tangible satellites, missions and propulsion applications. Since the MEMS EP propulsion system had to be defined in the process, the analysis started with a generic approach for defining the mission requirements. The only parameters known at the beginning of the study are performance curves of the colloid micro-fabricated thrusters, performances based on test data but also interpolation and extrapolation of this data. The analysis first gathered information about satellite's typical resources. It then evaluated most plausible attitude control and orbital transfer applications. The final step laid out the performance requirements and characteristics of each identified propulsion applications. The following major requirements were sought to design a propulsion system that would be applicable to most missions: thrust, Isp, minimum impulse bit, total impulse, lifetime, operating points, characteristic currents, voltages, mass, power and volume targets. The mission analysis was performed for a range of pico- to micro-satellites. The average resources, characteristics and mission lifetimes were evaluated for five CubeSats (AAUSat II (DK), BEESat (DE), SwissCube (CH), Delfi-n3Xt (NL) and CanX-2 (CA)), five NanoSats (CanX-4/5 (CA), Brite (CA), SNAP-1 (UK), UNIsat (IT), and the results of an ESA CDF study), and three MicroSats (Myriad (FR), Microscope (FR) and Proba (BE)), [4] to [10].

These evaluations were the basis for the elaboration of satellite models, which were used for all attitude control perturbation sizing and mission analysis. Tables 1 and 2 summarize the relevant data for these satellite models.

Table 1 Satellite models and assumptions ½.

Parameter	CubeSat 1U	CubeSat 3U	NanoSat 8 kg
Mission duration (yrs)	1	1	1
Mass (kg)	**1**	**3**	**8**
Dimensions (cm3)	10 x 10 x 10	10 x 10 x 30	20 x 20 x 20
Aver. power produced (W)	1.5	~ 6*	~ 10*
P_{aver} for prop (Pin_pcu) W	**0.25**	**1.2**	**2**
P_{max} for prop (Pin_pcu) W peak	**4**	**10**	**15**

Table 2 Satellite models and assumptions 2/2.

Parameter	MicroSat 27 kg	MicroSat 64 kg	MicroSat 125 kg
Mission duration (yrs)	2	2	2
Mass (kg)	**27**	**64**	**125**
Dimensions (cm3)	30 x 30 x 30	40 x 40 x 40	50 x 50 x 50
Aver. power produced (W)	~ 20*	~ 65*	~ 90*
P_{aver} for prop (Pin_pcu) W	**4**	**13**	**18**
P_{max} for prop (Pin_pcu) W peak	**24**	**>30**	**>30**

*Assumes MPPTs.

The mission applications included attitude control maneuvers, orbit control and transfer scenarios. The attitude control scenarios considered a bang-bang system to provide precise to very precise attitude control with a conventional bang-bang system. CubeSat and nano-satellites typically achieve pointing accuracies on the order of 1-5 degrees. The purpose of this exercise is to investigate if a MEMS EP bang-bang system could be used for more precise pointing (1 deg to 1 arc-min) but for a part of the mission time. This would enable precise measurements to be done. This feature may be useful when constellations of CubeSats will be launched, and may enable new observation applications for nano-satellites. Another scenario looked at was the wheel unloading for LEO to GEO satellites. And the final scenario was the very low perturbations compensation: this is of most interest to micro-satellites, which goal is to compensate very low levels of perturbations.

The orbit control scenarios included drag compensation, end-of-life de-orbiting (from 1000 to 400 km) and formation flying (40 m/s). The orbital transfer scenarios included a low thrust transfer from LEO-MEO (about 3.8 km/s) and a low thrust transfer from GTO to the Moon (about 4 km/s). Taking into account all the mission scenarios analyzed, a comparison with existing actuators for attitude control, and the satellite power and volume constraints, the propulsion requirements and performance targets for the MEMS EP were established. These requirements were derived for a thruster cluster (assuming a modular approach for the design of the MEMS EP system) via two specific parameters that helped the definition of the propulsion system. These two parameters were Thrust/Power and Thrust/Area. A thrust/power ratio above 0.05 µN/mW and a thrust/area ratio above 0.5 µN/mm^2 per cluster are desirable from a mission performance standpoint. The desirable ISP was above 500 sec and for some applications, above 1500 sec.

The MEMS EP propulsion system was thus designed keeping in mind that it shall combine all three of the above

target performances. It was also recommended that the design of the PCU shall accommodate the selected working points and their estimated performances, as described in Table 3.
The table shows the working point selected for this design but the system can be easily adequated with each range given.

Table 3 MEMS colloid working points.

Isp (sec)	3500	2500	550
Thrust/power (μN/mW)	0.05	0.07	0.3
Thrust/area (μN/mm2)	1.2	2	10
Total system voltage (V)	3300	3300	3300
Extraction voltage (V)	790	900	1400

3. Preliminary design

After establishing the requirements, a phase aiming to achieve a preliminary design started. The main objective and key driver for the preliminary design has been miniaturisation and a high degree of integration between the components. MEMS technology is the enabling technology which offers a quantum leap in terms of miniaturisation of propulsion systems. Another guiding star in the design work has been the idea of a modular propulsion system, where the number of modules can be varied in order to meet as many applications and requirements as possible.
Two basic design concepts are suggested to cover the wide range of applications and missions scenario stated in the requirement specification, where all functions except the electronics and the neutraliser will fit in a MEMS EP thruster module as depicted in Figure 5. The thruster module including housing and 20 g usable propellant will be approximately 60x40x30 mm in size and is designed to have a weight of less than 60 grams.

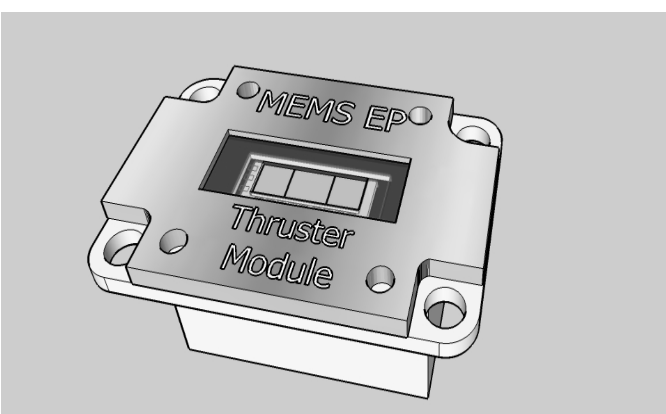

Figure 5 A preliminary design of a miniaturized thruster module, including all main functions except the power supply and control unit.

3.1 Design Logic

Given the wide span of requirements, the objective of this preliminary design work was to find a system design which is the best compromise –and thus best suited to cover the given range of requirements. However, note that the requirements should be looked as target requirements, as guidelines, as any specific mission will have its own set of requirements based on its own set of assumptions, design choices and constraints. Since these results are intimately linked to the assumptions, variations on the values of the requirements can be expected, but the order of magnitude is correct. The logic used to arrive with a preliminary propulsion system design is as follows: 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.

3.2 Colloid Thruster Technology

A colloid thruster uses electrostatic acceleration of charged species for propulsion. The species can be either charged droplets, solvated ions or a mix of them. A typical colloid thruster configuration is illustrated in Figure 6.

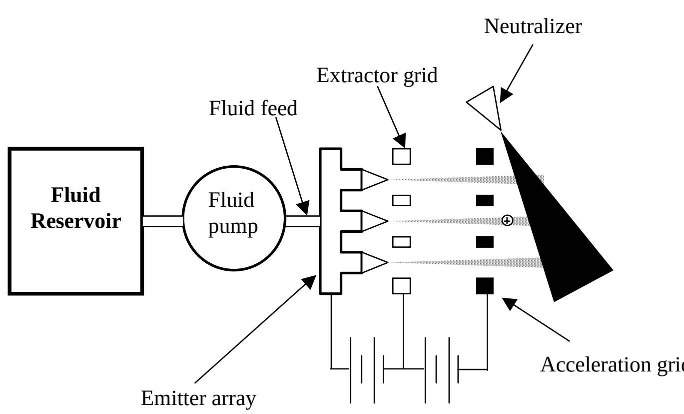

Figure 6 Typical colloid thruster configuration.

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.

3.3 Thruster head and thruster cluster preliminary design

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. Figures 7 and 8 show Scanning Electron Microscope (SEM) images of the thruster head design of EPFL and one single emitter with the shape optimized to minimize liquid spillage.

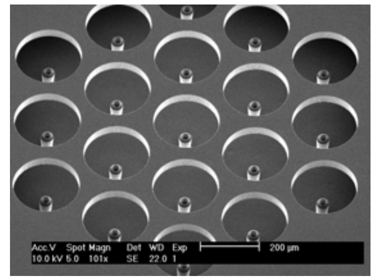

Figure 7 Thruster head design (EPFL), with each capillary centered under one extractor electrode. [12]

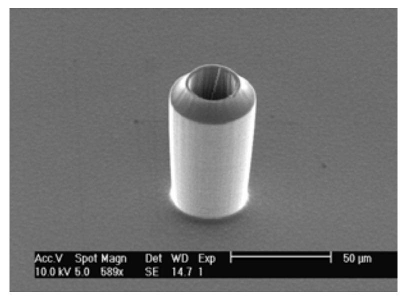

Figure 8 One single emitter, showing shape optimized to minimize liquid spillage. [12]

Figure 9 shows the highly integrated thruster design.

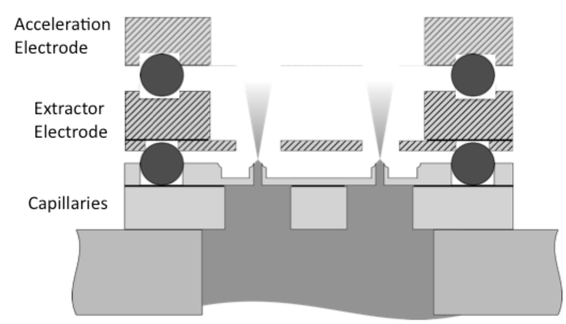

Figure 9 The highly integrated thruster design.

Regarding the propellant two main candidates have been identified: EMI-Im (also referred to as EMI-Tf2N) and EMI-BF4, 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.
Figure 10 shows the two housing parts, the one in PEEK and the upper part in metal.

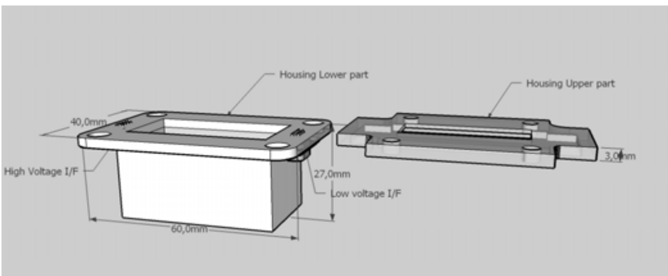

Figure 10 The two housing parts. Lower part (left) made in PEEK and upper part (right) made in metal.

Table 4 shows the explanation of the terms used in the following text.

Table 4 Acronyms explanation

Acronyms	Meaning
CNT	Carbon nanotube
DCIU	Digital Control Interface Unit
LTCC	Low Temperature Co-fired Ceramic
HV	High Voltage
PCU	Power Control Unit
PEEK	Polyether ether ketone
PSU	Power Supply Unit
RTU	Remote Terminal Unit

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.

Figure 11 shows the multilayer hybrid interface chip made in LTCC for mounting and connecting to the thruster cluster.

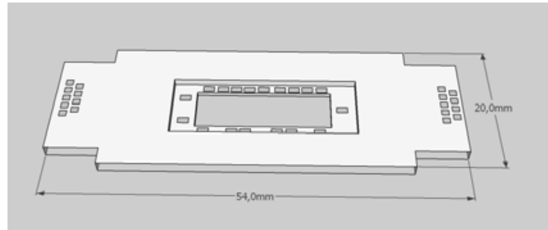

Figure 11 Multilayer hybrid interface chip made in LTCC for mounting and connecting to the thruster cluster.

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 start-up, 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. Figure 12 shows a preliminary design of the neutralizer.

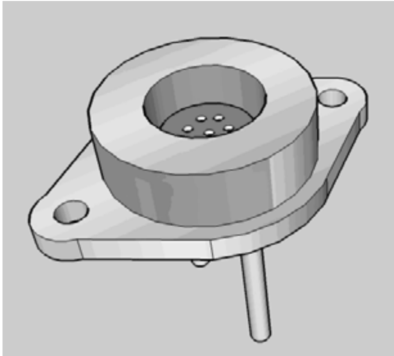

Figure 12 Design of the neutralizer.

3.4 PCU Design

In order to reduce mass of the propulsion system while maintaining thrust capabilities miniaturization and optimization of the power supply unit is important.

Full control of thrust and neutralization saves power and reduces required power budget and fluid mass. In order to reduce mass centralized PSU's will be used. In concept the system is intended to be flexible to extend the number of supply units to facilitate various mission requirements.

The PSCU schematic consists of the DCIU, PCU and PSU part. The extractor voltages and neutralizer voltage are controlled and the emitter voltage is fixed. The individual extractors of up to N thruster clusters are switched to up to M controllable high voltage extractor voltage sources.

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 HV extractor and accelerator supply currents are measured and input to the control loop to accurately control the thrust of the electronic propulsion. An adjustable power supply for the neutralizer is included. The neutralizer current is measured and included in the control loop to counterbalance propulsion ions in a controlled way.

This aspect of flexibility and modularity using M extractor supplies to drive N extractor clusters implies that HV supplies must be switched between extractors at high voltage. A high voltage switch matrix is included to accommodate this.

Part of the control function of the thrust and neutralization is in the analog domain. The actual thrust control is implemented in the digital control as well as the I/O to interface with the spacecraft. Supply regulation of the spacecraft board net to the HV supply is included. 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. Radiation hardness is to be validated.

4. Mission benefits evaluation

After a first iteration on the size of the MEMS EP colloid array (head), the rest of the system elements, such as power processing, tank and feed system, structural elements, neutralizer were designed. The resulting system could be then re-inserted into the mission analysis to evaluate its benefits, i.e., how well the design proposed suited the various mission propulsion applications. This step also allows for a revision of the propulsion requirements for the next iteration of the propulsion system design.

Thanks to its high modularity, the system can be configured to optimize its mass and volume. The following components can be tracked:

1) Number of PSUs,
2) Number of boards: the assumption is that 1 board can fit 1 HVPCU, 1 RTU, 1 switch matrix and one neutralizer. The maximum input power to the board is assumed to be 4 W (to simplify the analysis). In some cases, two boards are needed to accommodate the power available to the propulsion system.
3) Number of cables: this number will incremented as the number of PSU or boards is incremented.
4) Need for an external tank (with associated feed and tubing): some applications will require more propellant that can be found in the current 20 g reservoir in the module. An external tank is then added.

The simplest system configuration applies to the 1U CubeSat (see Figure 14). The High Voltage Power Distribution Unit (HVPDU) provides high voltage to the propellant tank and fluid. PSU provide power to the extractor grids. The switch matrix is used to route the voltages in case of multiple modules. The RTU provides control of the PSU and HVPDU and of the feed system in case of an external tank. It also provides the digital interface with the satellite. The neutralizer power supply provides the neutralizer with appropriate voltage and current. Please note that in the current system design, each PSU independently drives one of extractor grids at a given voltage. This allows running all three emitter arrays at different voltages. However, via the switch matrix, the same PSU can drive another set of grids either independently or simultaneously, as long at the overall power consumption per PSU is respected.

The accelerator lines and neutralizer lines will be between 20-200 V and are considered as low voltage lines. The extractor and reservoir lines are high voltage lines, respectively at '3.3kV-extractor voltage' and at 3.3 kV.

For this simplest configuration, the power, emitter array area and mass breakdown are provided in Tables 4 and 5. This case is highly power limited (input power of 250 mW). It applies to low thrust transfers. It is pointed out that about 200 mW goes into the PCSU, with a total efficiency of 67%. A 4 mm^2 emitter array can use that power and provide 20 µN of thrust. Assuming no external tank, the 20 g of propellant will provide a DV off about 200 m/s to the CubeSat at an Isp of 1100 sec.

Until now a baseline design has been presented.
Here the design is applied to a real mission and the mass breakdown and the configuration are implemented based on the mission.
Figure 13 shows a potential implementation of the MEMS EP cluster with analysis in Table 5.

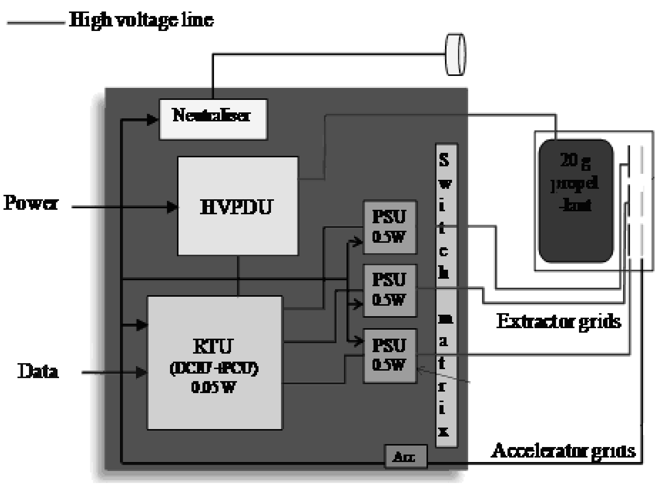

Figure 13 Potential implementation of MEMS EP cluster. CubeSat 1U, 1 module case.

Table 5 Analysis for the CubeSat 1U.

Mission analysis	POWER AND MASS LIMITED		
Average power into IPS	250	mW	
Max power into PCSU	200	mW	
Power into RTU	50	mW	
PCSU efficiency	0.67		
Thruster cluster efficiency	included		
Thruster cluster input power	134	mW	
Microfabricated array size	4	mm2	
Isp for power constraint	1100	s	
Corresponding extraction voltage	1000	V	
Corresponding thrust	20	uN	
Available propellant mass	20	g	
Satellite mass	1000	g	
Achievable DV	218	m/s	

Table 6 shows the corresponding mass breakdown. Comments are provided on the assumptions when necessary. With 30% margin, the system weights about 280 g, which is more than the original allocation, but nonetheless feasible to fly on a CubeSat (SwissCube, launched 23.9.2009 had a mass margin of 180 g at launch).

Table 6 Potential implementation of MEMS EP cluster. CubeSat 1U, 1 module case.

System mass breakdown	QTY	Unit Mass (g)	Total Mass (g)	Comments
Power board			**60.0**	
High Voltage Power Distribution Unit (HVPDU)	1	37.00	37.00	EMCO C, up to 1 W
PSU	1	4.00	4.00	EMCO Q, up to 0.5 W
PSU switch matrix component	1	10.00	10.00	
RTU (acts as DCIU + PCU)	1	4.00	4.00	
Transient Suppression electronics	1	5.00	5.00	Needed?
Thruster module			**46.0**	
Thruster cluster			**16.0**	
Thruster cluster with LTCC + housing, 3x25 uN	1	16.00	16.00	
Thruster cluster with LTCC + housing, 3x100 uN		0.00		
Feed system			**30.0**	
Integrated tank (in module, for 20 g of prop)	1	21.00	21.00	
Feed system fixed	1	9.00	9.00	No tubing nor fitting necessary
Centralised tank (outside module)			**0.0**	
Propellant tank mass, assuming: Mt=0.6321xMp^0.56	0.0	0.00	0.00	
Feed system	1	0.00	0.00	Feed system + tubing and fittings: 20% tank mass
Neutraliser			**25.0**	
Neutraliser	0.02	18.00	10.00	10 g/mA x 1.8 mA/mN, but min is 10 g
Neutraliser power supply	1	15.00	15.00	Prop to power, 50 mW/mA x 1.8 mA/mN
Structure			**33.0**	
Thruster module			**13.00**	
Bottom housing (insulating PEEK)	1	8.00	8.00	
Centralised tank structure	0.04	0.00	0.00	4% propellant mass
Other (screws...)	1	5.00	5.00	
Power board			**20.00**	
PCB	1	20.00	20.00	
Cabling			**16.0**	
PSU to thruster HV cable	0.1	40.00	4.00	40 g/m, # thr mod * 0.05 m * 2 * nbPSU cables
PCSU to fluid reservoir HV cable	0.1	40.00	4.00	40 g/m, # thr mod * 0.05 m * 2 cables
PCSU to acceleration grid LV cable	0.1	10.00	1.00	10 g/m, # thr mod * 0.05 m * 2 cables
PCSU to Neutraliser MV cable	0.1	20.00	2.00	20 g/m, # thr mod * 0.05 m * 2 cables
Other Cabling	1	5.00	5.00	
Thermal			**20.0**	
Thermal control (per board)	1	20.00	20.00	PCSU 67% eff.
MEMS EP system dry			**200**	
Mass contingency (30%)			60	
MEMS EP system dry with contingency			**260**	
Propellants				
Module propellant	1	20		
Centralised tank propellant		0.0		
Non usable propellant	5%	0.0		residuals, fill error, flow rate error, leakage, start/stop
MEMS EP total wet			**280**	with 30% contingency

The current design with 3 x 49 mm^2 (called 3 x 25 μN) can provide 200 μN to 1500 μN depending on the desired Isp/extraction voltage. Characteristics for this case are shown in Table 7.

Table 7 Characteristics of the 3 x 49 mm^2 current configuration of the MEMS EP module.

Isp (sec)	3500	2500	547
Thrust (uN)	~ 200	~ 270	~ 1500
Module input power (mW) (Includes 50% thruster efficiency)	~ 3000	~ 4200	~ 4900
Total system voltage (V)	3300	3300	3300
Extraction voltage (V)	790	900	1400

Superposing now the capabilities provided by the current preliminary design of the MEMS EP system with expectations drawn out of the requirements analysis one clearly sees the width of applications of the proposed MEMS EP technology.

Table 8 Mission applicability of MEMS EP system (left symbol: preliminary requirements, right symbol: results of benefits

Parameter	CubeSat 1U	CubeSat 3U	NanoSat 8 kg	MicroSat 27 kg	MicroSat 64 kg	MicroSat 125 kg
ACS						
Bang-bang system	✓ ⊘	✓ ⊘	✓ ✔	✓ ✔	✓ ✔	✓ ✔
Wheel unloading	✓ ⊘	✓ ⊘	✓ ✔	~	✗	✗
Low perturb. compensation	N/A	N/A	N/A	N/A	✓ ✔	✓ ✔
Orbit control and transfers						
Drag make-up*	✓ ✔	✓ ✔	✓ ✔	✓ ✔	✓ ✔	✓ ✔
FFM*	✓ ✔	✓ ✔	✓ ✔	✓ ✔	✓ ✔	✓ ✔
De-orbiting*	✓ ✔	✓ ✔	✓ ✔	✓ ✔	✓ ✔	✓ ✔
Orbital debris*	✓ ✔	✓ ✔	✓ ✔	✓ ✔	✓ ✔	✓ ✔
LEO ->MEO*	✓ ⊘	✓ ⊘	✓ (✓)	✓ (✓)	~	~
GTO ->Moon*	✓ ⊘	✓ ⊘	✓ (✓)	✓ (✓)	~	~

*Continuous low-thrust scenarios

(✓) Can be done with additional power

For CubeSats the mass requirement of 10% can not be meet. However if the mission could allow a larger propulsion system e.g. 30% of the spacecraft mass, the technology could be also applied in these cases.

The preliminary results of the mission benefits analysis show that the modularity of the current MEMS EP design allows a large variety of application for 1-kg to 125-kg satellites. It also provides a very competitive technology for nano-satellites and small micro-satellites applications, and provides maneuver capability to CubeSats.

5. Conclusions

This study showed the feasibility of a miniaturized and modular MEMS electric propulsion system. From the investigated systems, the colloid technology has the best miniaturization potential by combining a high performance and efficiency with an efficient use of MEMS Technology.

For nano-satellites, a miniaturized Electric Propulsion System is best suited for formation flying, drag compensation and orbital manoeuvres. For microsatellites all propulsion applications can be effectively performed with a miniaturized electric propulsion system.

As output of this study a modular system has been designed consisting of multiple thruster modules and a centralized Power Conditioning Unit. With these basic components the system can be easily adapted for a number of different applications

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.

The complete MEMS EP subsystem schematically inserted into a 10x10x10 cm CubeSat volume is depicted in Figure Y below. Estimated total mass of MEMS EP system is 140 g. Table 9 shows the subsystem component list.

Due to the modularity, the system can be used in a large range of satellites from double and triple cubesats to microsatellites up to 125 kg. For larger satellites, the proposed system does not offer advantages mass and volume over existing electric propulsion systems. However, due to the modular nature, cost might be reduced by economies of scale.

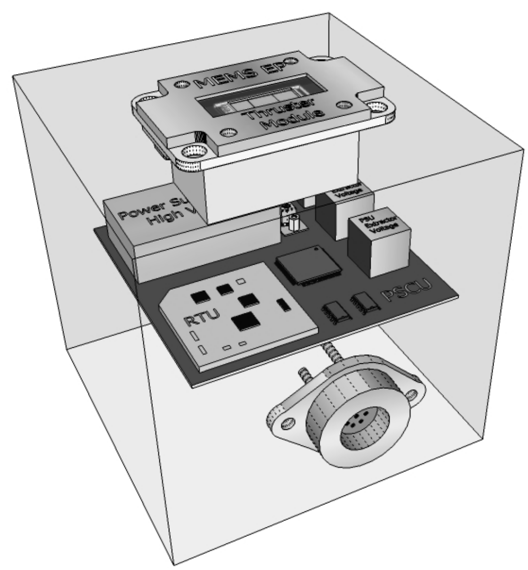

Figure 14 Final design in a CubeSats.

Table 9 MEMS EP Subsystem Component list.

Component	Dimension [mm]	Material
Thruster head	7x21	Silicon and dielectrics
Mechanical and electrical I/F chip	54x20	LTCC
Propellant storage and feed	40x20x21	Porous Si/Si
Neutraliser	38x26x8	Carbon Nano Tube or polycrystalline diamond emitters. Stainless steel housing
Power Supply and Control Unit	80x80x30	ICs, connectors and power supplies on a PCB
Housing	Bottom 60x44x30 Top 60x44x30	Insulating PEEK Al (Ti or SS)
Component	**Manufacturing**	**Mass [g]**
Thruster head	MEMS	3
Mechanical and electrical I/F chip	MCM-C	5
Propellant storage and feed	MEMS	26 (20 prop incl)
Neutraliser	MEMS and conventional for housing	5
Power Supply and Control Unit	Conventional	12 (3xPSU) 37 (1HVPSU) 20
Housing	Conventional Conventional	8 8

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 Engineering Model (EM) and Qualification Model (QM) components or subsystems, developing also an European High Voltage Unit and a new European neutraliser.

6. References

[1] F.Tata Nardini et al., “TN01 MEMS based EP: literature search and trade-off over electrical propulsion technologies”, Issue date 21 April, Rev 25 May, 2009.

[2] M.Noca et al., “TN02MEMS Micro-propulsion requirements, and mission benefits” Issue 3, Rev 1, 23 April 2010.

[3] P. Rangsten et al, “TN03 Subsystem preliminary design report”, Issue 1B, 18 February 2010.

[4] P. Rangsten et al ,“TN04 Subsystem Development Plan”, Issue 1A, 9 February 2010.

[4] C. Müller et al., “Integration of the T3uPS microthruster in the Delfi-n3Xt satellite”, 7th international Symposium of the International Academy of Astronautics (IAA), Berlin, May 4-8, 2009.

[5] Karan Sarda∗, Stuart Eagleson, Eric Caillibot, Cordell Grant, Daniel Kekez, Freddy Pranajaya, Robert E. Zee, “Canadian advanced nanospace experiment 2: Scientific and technological innovation on a three-kilogram satellite, Acta Astronautica 59 (2006) 236 – 24

[6] Nathan G. Orr, Jesse K. Eyer, Benoit P. Larouche, and Robert E. Zee, “Precision Formation Flight: the CanX-4 and CanX-5 Dual Nanosatellite Mission”, Space Flight Laboratory, University of Toronto Institute For Aerospace Studies; 4925 Dufferin Street, Toronto, Ontario, Canada, M3H 5T6.

[7] K.A.Carroll et Al,“Arc-minute Nanosatellite Attitude Control: Enabling Technology for the BRITE Stellar Photometry Mission”,., 18th Annual AIAA/USU Conference on Small Satellites, SSC04-V-2.

[8] F. Santoni et al, “The UNISAT program: Lessons learned and achieved results”, F. Santoni et al., Acta Astronautica 65 (2006) 54 – 60

[9] “Nanosat CDF study”, Presentation February 2009, GSP opportunity studies 09/126.

[10] Kohler (ESA), “An overview of the microsystem-based nanospacecraft NEOMEx strawman theme within the TRP activities 2008-2010” – J Presentation at the 2nd ESA CubeSat workshop.

[11]F.Tata Nardini et al., “Final Report MEMS based EP”, Issue date 23 April, 2010

[12] R. Krpoun and H. Shea, “Integrated out-of-plane nanoelectrospray thruster arrays for spacecraft propulsion”, Journal of Micromechanics and Microengineering, 19, p. 045019, 2009