PROJECT FINAL REPORT

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Final publishable summary report of *MicroThrust*

Executive Summary

In recent years, the interest in small and low cost satellites has increased worldwide. Numerous small and low-cost spacecraft have been launched, often based on the CubeSat format. There is an emerging recognition that nano-satellites (1-10 kg) and micro-satellites (10-100 kg) will play a major scientific role in space exploration. A critical enabling technology that is required to revolutionize planetary space exploration with small satellites is a suitable efficient compact propulsion system. Under the constraints of high delta-V missions, this necessarily leads to an electric propulsion requirement.

The MicroThrust consortium has developed a breadboard of a highly efficient microfabricated electric propulsion system prototype to enable sub-50 kg satellites to perform large orbit changes, thus allowing small satellites to perform exploration missions and mission architectures that were not possible up till now. The MicroThrust propulsion system aims to allow very small (e.g., 10 kg) satellites to move under their own power from Earth orbit to lunar or Mars orbit, thus bringing down the cost of space exploration by orders of magnitude.

Consisting of 5 European partners (EPFL, QMUL, TNO, NanoSpace, SystematIC), each a leader in their respective fields, the MicroThrust consortium was a prime example of industrial and academic collaboration for revolutionary technology development.

The objectives in this 3-year project were to demonstrate experimentally through a breadboard a highly-miniaturized microfabricated electrospray propulsion system to allow high-ISP propulsion for nano-satellites. The driving principle is simplicity and miniaturization, to allow a full thruster to fit easily within a single-unit CubeSat. The system is modular, and scales readily scaling to a wide range of missions, including orbital changes around the Earth, missions to near-Earth objects and the moon, formation flying, and de-orbiting.

We developed in this 3-year project: i) mission analysis of low-thrust trajectories to guide system design, ii) extremely compact 4kV multi-channel power supplies, iii) MEMS thruster chips to emit arrays of molecular ion beams, iv) pumpless microfluidic systems to deliver propellant to the MEMS chips, v) a design of the complete thruster module and vi) a breadboard to validate the key new technologies.

A primary output at the end of the 3-year project was a preliminary design of a miniaturized electrospray thruster module whose mass and volume are 90% smaller than existing electric propulsion system, with a specific impulse of 2700 s. All key technologies (e.g., miniature high-V power supplies, MEMS emitter chips with 127 emitters, capillarity-based propellant management) were demonstrated using a laboratory breadboard. The basic module (including power supply and propellant reservoirs) fit within a less than half a single Cubesat.

The main impact of the MicroThrust consortium is a clear path to develop a miniaturized propulsion system that will enable a new generation of nano-satellites to perform useful science and exploration missions.

1 MicroThrust context and objectives

Context

In recent years, the interest in small and low cost satellites has increased worldwide. Small and low-cost spacecraft have proven to be the initiation for many newcomers in space, be they universities, research establishments, companies or countries without a heritage in space.

Clearly, small spacecraft, and especially nanosatellites (below 10 kg), do have some limitations. One of the major shortcomings is the lack of efficient propulsion allowing them to manoeuvre away from, or even control the orbit into which they are released; this limits their capability to conduct numerous types of scientific space exploration missions. The lack of efficient propulsion also currently precludes missions utilizing a fleet of small satellites to create a synthetic aperture sensor. For these mission types formation flying is a prerequisite, which in turn requires accurate and efficient propulsion on-board all spacecraft in the constellation.

The combination of small and low cost satellites with an efficient propulsion system would offer vast new possibilities to conduct scientific missions both in earth orbit and elsewhere in the solar system. With more players in the space community combined with affordable and capable satellite platforms, the focus can be shifted from **getting there** to **doing science** in space.

The history of space-based scientific enquiry may be described as the nexus of scientific imagination, technological capability and financial resource. The interplay between these is profound. The first is inviolate; humankind has never lacked imagination. The interplay between imagination, technology and resource has till now resulted in complex and costly missions: the history of space science is one essentially of increasing launch mass not only in those missions directed at astronomy, but also in those associated with solar system exploration. The necessary multinational cooperation leads to increased timescales for mission approval and development before ultimately the mission is undertaken.

The counter-element to this trend has been the development of micro and nanosatellite systems, particularly exemplified in the USA by DARPA from a military perspective and in Europe by SSTL (Surrey Satellite Technology Ltd) from a commercial perspective, with complete satellites designed, built and launched in only 2 years. There has been a huge growth in University-based spacecraft in the Europe, Japan, and the USA. These small spacecraft are reaching a high level of maturity: the German BEESAT-1 launched in September 2009 has full three axis control with momentum wheels and the Dutch Delfi N3Xt satellite, launched in 2013, added extendable solar arrays, high data rate and a cold-gas propulsion system. The trend in pico to nano-satellites development is rapidly moving from simple demonstrators toward much more capable satellites, capable of performing real science missions.

However these microsatellite missions are still not driving space exploration in the solar system, nor are they driving scientific formation flying missions in earth orbit. Thus for example there are currently some 24 lunar missions either under development or at the proposal phase; none of these are single-instrument based that would be typified by a true nanosatellite. Contrast this with physical science research based in the laboratory where much may still be achieved with a single instrument; indeed single instrument science is alive and well in the laboratory.

The key building block that is missing in space exploration is the ability, at low cost, to undertake single instrument science at the required location of the measurement. The reason that this is absent is not due to the incapability of the instruments, rather it is the delivery method, i.e., the lack of a suitable propulsion system. Optimally the size of the satellite system should be comparable to the size of the science instrument itself. In the extreme this satellite could be as small as a CubeSat.

In some cases, the instrument performance can be dramatically improved by using a synthetic aperture strategy where a fleet of small satellites in a precise formation forms the equivalent of a very large antenna. For scientific missions like this (such as Darwin) propulsion capability is again a key building block. Typically, the driving requirements on the propulsion system is capability to deliver extremely small and precise impulse bits in order to control the relative position of the spacecraft, and high performance (specific impulse) in order to ensure duration of the mission for a given total mass of the spacecraft. **Today, these kinds of missions cannot be conducted with small and low cost satellite platforms due to the lack of a suitable propulsion system**. Even if such missions were technically feasible with existing propulsion technologies, the size, complexity and cost associated would still make the challenge of **getting there** overshadowing the objective of **doing the science**.

European industries and agencies specializing in small satellites (e.g., CNES, Surrey Space Technologies Ltd) have shown keen interest in the miniaturization of propulsion systems, as current technologies include bulky elements, or do not provide the required high specific impulse needed to reach a large payload/satellite mass ratio. There is without doubt **an emerging recognition that nano-satellites (1-10 kg) and micro-satellites (10-100 kg) have a scientific role in space exploration.** The major impediment is the readiness of current micro-technologies to enable the new missions having new mission architectures. This leads to the conclusion that **a critical enabling technology to revolutionize planetary space exploration is a suitable propulsion system**. Under the constraints of high delta-V (5 km/s) missions, this **necessarily leads to an electric propulsion requirement**. MicroThrust addressed fully this challenge.

Electric propulsion allows very efficient conversion of propellant mass to spacecraft momentum by ejecting particles (typically ions or small charged droplets) at very high velocity, accelerated by an electric field. Of the many different types of electric propulsion systems, the colloid thruster (or electrospray source) is one that can be scaled down to small sizes while maintaining high efficiency. Colloid thrusters rely on a high electric field to extract droplets/ions from a liquid and electrostatically accelerate them away from the spacecraft, providing thrust. From the 1960s to the 1980s, significant progress was made both in the USA and the USSR in this field. Despite its unparalleled fuel efficiency, the low thrust levels associated with this technology resulted in other propulsion techniques being selected. Micromachining (MEMS) technology, which is now a mature technology 30 years after its inception, enables fabrication of large very large number arrays of tiny capillaries densely packed within a small area, and has allowed colloid thrusters to emit not only liquid droplets but pure ion beams, greatly increasing efficiency of the propellant usage. The fundamental limitation (low thrust) of electrospray-based ion engines can now be overcome by microfabricating arrays of thousands miniature emitters on a silicon wafer, thus keeping the high efficiency of colloid thruster while simultaneously scaling thrust by taking advantage of MEMS technology. This is the basic enabling idea behind the MicroThrust approach.

Objectives

The objectives in this 3-year project were to demonstrate through a breadboard a proof of concept of a highly-miniaturized modular propulsion system to allow high-ISP propulsion for nanosatellites. We aimed to develop a thruster with an ISP up to 3000 s (i.e., ions or clusters exiting the thruster with a velocity of 30 km/s) operating at up to 4 kV. The driving principle is simplicity and miniaturization, to allow a full thruster to fit easily within a single-unit CubeSat. The system is modular to allow readily scaling to a wide range of missions, including orbital changes around the Earth, missions to near-Earth objects and the moon, formation flying, and de-orbiting.

In order to develop the full thruster system, we have developed in this 3-year project: i) mission analysis of low-thrust trajectories to several targets (moon, NEO, etc) to guide system design, ii) extremely compact 4kV stable multi-channel power supplies, iii) MEMS thruster chips to emit arrays of molecular ion beams, iv) pumpless microfluidic systems to deliver propellant to the MEMS chips, v) a design of the complete thruster module and vi) a breadboard to validate the key new technologies.

A primary output at the end of the 3-year project was a preliminary **design of a miniaturized electrospray thruster** module whose mass and volume are 90% smaller than existing electric propulsion system, with a specific impulse of 2700 s.

All key technologies (e.g., miniature high-V power supplies, MEMS emitter chips, capillarity-based propellant management) **were demonstrated using a laboratory breadboard**. The key aspects of this micropropulsion system are small size, modularity, and simplicity. The smallest module (including power supply and propellant reservoirs) fit within a less than half a single Cubesat, and is scalable to be used efficiently on spacecraft up to 100 kg.

2 Main S&T results/foregrounds for MicroThrust

The work in MicroThrust is highly interdisciplinary, ranging from the space mission analysis to MEMS microfabrication to high-voltage power supplies. The project was divided into 9 work-packages, reflecting the different tasks and technologies. The consortium was active on several fronts simultaneously: in technology development, system engineering, mission analysis, breadboard testing, and dissemination. The outcome of the three-year project can be summarized as follows:

a) Mission analysis: We performed a mission survey and delivered propulsion system specifications consistent with a feasible implementation of the MEMS technology, including i) a set of exploration destinations (Moon, near-Earth object, Mars, etc.); ii) a set of spacecraft constraints; iii) a propulsion system configuration (module); and iv) a set of feasible thruster performances, or in other words feasible “operating points”. A Mission and System Model was developed that allows system-level trade-offs for different spacecraft and missions.

b) Definition of the baseline thruster module for a) Flight model, and b) Breadboard model. The system engineering was performed to define, following extensive trade-off studies, a baseline thruster module that is scalable, allows pumpless operation, and will thus enable reaching mission goals with the current estimated chip performance figures. The Flight model includes results from the Breadboard testing.

c) MEMS chip microfabrication: different geometries were simulated to optimize the thruster chip design (capillary geometry, means of integrating extraction and acceleration electrodes). Materials compatibility was investigated, and a new high-yield microfabrication process flow was validated. Several generations of MEMS emitter chips were fabricated. Chips have up to 127 emitters, and each emitter has an integrated extraction and acceleration electrode.

d) Characterization of the emitted beam from micromachined electrospray emitters. Two test setups were completed. We successfully emitted ions and droplets from single micromachined capillaries using different ionic liquids, achieving an ISP of 2000 s at less than 1 kV. Beam shape and beam compositions were investigated for several ionic liquids, as was ionic liquid electrochemistry.

e) Miniature HV Power supply: the power supply system was dimensioned, its architecture defined (low and high voltage, including monitoring and switching), and modelling was performed to predict performance of the supply and validate its compliance. All interfaces for integration into the breadboard were defined. Prototypes of both main boards were fabricated and successfully tested in an electrospray setup.

f) Thruster module system design and propellant management. The Breadboard (BB) design was finalized, and all component, included microfluidic chips and compact power supply were fabricated or procured. All fluid handling is done relying solely on capillary forces (no pumps). The Breadboard components were all validated via short loop experiments.

g) Breadboard: the vacuum system and test stand for the breadboard was assembled and tested. A breadboard test plan was defined. The BB itself was successfully fired for 91 and for 127 emitter arrays. The accelerator voltage was shown to focus the beam and increase ISP. Thrust of up to 7 µN with an ISP of over 1000s were shown in full breadboard configuration. A colloid thruster performance mode was thus developed based on experimental results.

h) Field emission neutralizer: a new cold neutralizer was developed based on CNT emitters, and successfully tested. Total mass of emitter and packaging is under 1 g.

i) Dissemination: a professional website aiming at many different audiences was designed and is online. Many presentations were made to the general public, as well as at scientific conferences (IEPC, several best paper awards). MicroThrust was featured in scientific TV programs in Canada, Australia, and Switzerland.

We report the results grouped by Work Package, the structure of which is summarized in Figure 1.

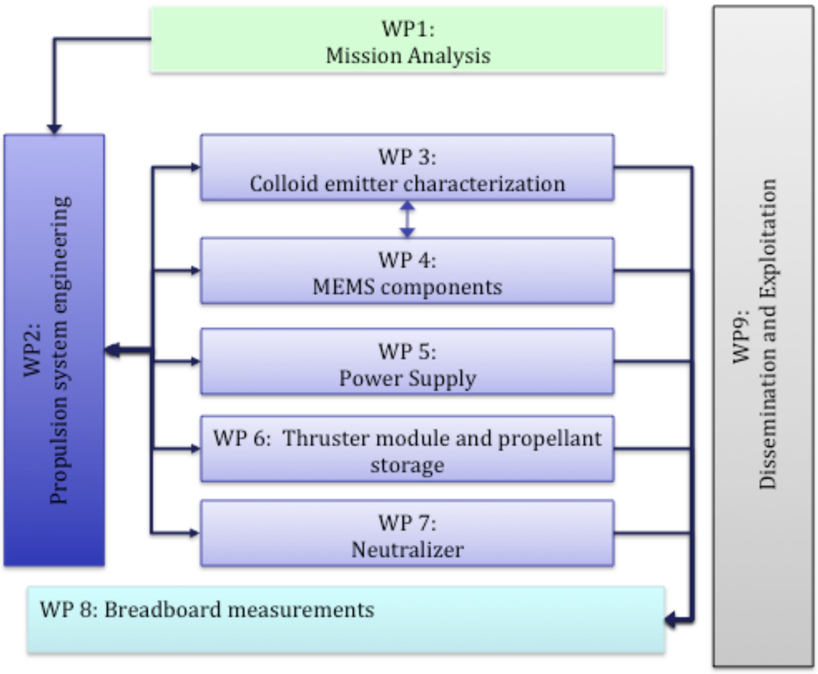


Figure 1: Work Breakdown Structure for MicroThrust

2.1 Summary of WP1 Accomplishments (Mission Analysis)

The objective of Work Package 1 over the 3 years was to guide the breadboard development and steer the overall system design such that a useful propulsion system is achieved. Its main aim was to provide mission and system target performance requirements to ensure applicability for real missions. The end product is thus a set of specifications consistent with a feasible implementation of the MEMS technology. This end product is based on a mission and system analysis, which involves at the highest level a set of exploration destinations, a set of spacecraft constraints, a propulsion system configuration (module) and a set of feasible thruster performances, or in other words feasible "operating points".

Five tasks were established to structure the work over the 3 years:

Task 1.1: Definition of exploration missions and of nano-satellite constraints

A list of the most promising exploration missions was developed, based on flown electric propulsion missions and identified interests from ESA and small satellite mission publications. It was found however that there isn't a wide breadth of exploration missions currently proposed for nano-satellites as their main showstopper is propulsion and power requirements. Our approach has been then to open up the possibilities and propose several destinations as targets of interest. A preliminary set of destinations has been chosen to cover the most likelihood of pertinent scientific data need. This set includes a Mission to the Moon; a Mission to a Near-Earth Object; a Mission to a Lagrange point; and a Mission to Mars.

Similarly, a survey of nano- and micro-satellite, existing and in concept was performed to draw reasonable power, mass and volume resources. Contacts were established (with visits) with two nano-satellite builders, INTA (SP) and OHB (DE) for further design investigations. Again, as these existing small satellites were not designed for exploration missions, extrapolations had to be made based on existing data. Power constraints and mechanical accommodation constraints were analysed and requirements derived.

Task 1.2: Mission Design

A subcontract was issued to a commercial supplier to create a database of low-thrust trajectories to a Near-Earth Asteroid 1996 FG3 in Year 1 and to complete it with trajectories to the Moon in Year 2. During Year-2 review, it was suggested that the NEA destination of 1996 FG3 be changed to the new target of the Marco Polo mission, 2008 EV5. To do so, a simplified low-thrust trajectory tool was elaborated during Year-3, validated with published trajectories. Figure 2 shows examples of the low thrust trajectories used.

The Moon and NEA 2008 EV5 destinations have been used to deduce the MicroThrust mission requirements. It is assumed that L2 and Mars missions will have similar performance requirements.

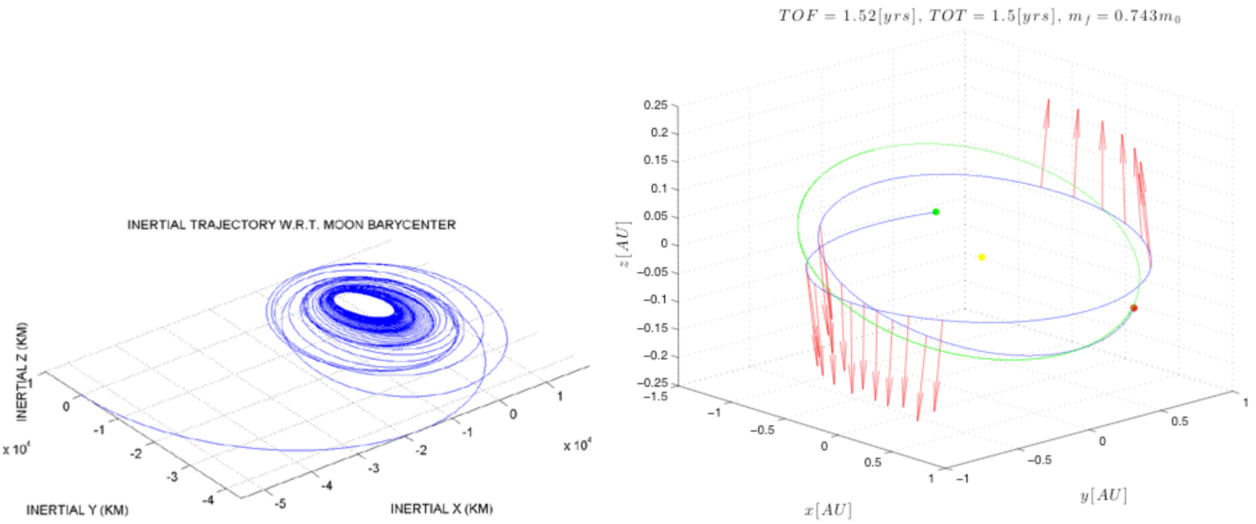


Figure 2: Trajectory to the Moon (left) and to the NEA 2008 EV5 (right)

Task 1.3: MicroThrust Mission and System Model

The MicroThrust Mission and System Model (MMSM) was elaborated to perform the mission analysis and system trade-offs. It includes models of the major propulsion elements (thrusters performance and module, power, tank and feed system), of the spacecraft and its major related subsystems (solar array, thermal). It also includes as a key element a database of trajectories, which will be inquired for particular points. Figure 3 shows the interface GUI of the Matlab implementation.

S/C configuration
Select S/C model Select 30x10x10 S/C
M0 3 [kg]
Height 0.1 [m]
Length 0.1 [m]
Width 0.3 [m]
S/C Power abs 2.5 [W]
Absorbance S/C 0.97 [-]
SA efficency 0.265 [-]
SA area (cells) 0.0585 [m2]
SA mass 0.45 [kg]
SA power @ 1 AU 19.3 [W]
Power for MTPS at 1 AU (with margin) 12.9 [W]
Emittance 0.44 [-]

MTPS Configuration
Propellant Type Select BF4
Select thruster model Select Monomer/Dimer ions (case3)
q/m monomer 868000 [C/kg]
q/m droplets 310000 [C/kg]
Monomer I fraction 0.5 [-]
Current per Emitter (0.1 to 1 uA) 5e-07 [A]
Angular efficency 0.91 [-]
Extractor grid losses 100 [V]
N THC (3,6 or 9) 9 [-]
N TMS 1 [-]
N emitter per THC 325 [-]
Op mode Select
Redundancy factor 1 [-]
Max emitter per THC cfg 1 143
Max emitter per THC cfg 2 418
Max emitter per THC cfg 3 1495
Max emitter per THC cfg 4 7727
cfg max power abs (estimation +/- 20%) 12.3 [W]
Accelerator grid voltage 0 [V]
(emitter-extractor) voltage 700 [V]
Maximum Emitter Voltage 1500 [V]
Minimum Emitter Voltage 1499 [V]

Trajectory Configuration
Select Destination Moon Moon

Power Margin 30 [%]
Mass Margin 30 [%]

MTPS Configuartion Results
Dry Mass (with margin) 0.628 [kg]

TMS mass budget
Dry Mass (with margin) 0.263 [kg]
Height 38 [mm]
Prop mass 0.22 [kg]
MSA 0.124 [kg]
TBA 0.031 [kg]
CFA 0.037 [kg]

PCS budget
Total Mass (with margin) 0.364 [kg]
CPCB 0.096 [kg]
ESA 0.154 [kg]
CPCB 1 [nb]
ESA 3 [nb]
4.4 [W/board]

EPSS mass budget
Total Dry Mass (with margin) 0 [kg]
Prop mass 0 [kg]

Performance
S/C bus mass 1.704 [kg]
Mf/M0 0.93 [-]
Propellant mass 0.219 [kg]
Total time of flight 699 [days]
Burn Time 699 [days]
Burn Time 16776 [h]
Total DV 2.5 [km/s]
Total impulse 213 [N*s]
Initial Isp 3373 [s]
Initial Thrust 212 [uN]
Initial acceleration 0.07061 [mm/s^2]
MTPS power margin EOL 0.6 [W]
MTPS power abs EOL 2.6 [W]
MTPS power avail EOL (with margin) 3.2 [W]

NT mass budget
Total Mass (with margin) 0 [kg]

Figure 3: MMSM GUI interface.

Task 1.4: Thruster Model

Several models of the MTPS thruster performance were elaborated with the partners and integrated in the MMSM. The performance curves were updated over the 3 years, as new data and understanding was emerging. The results of this model are shown in Figure 4.

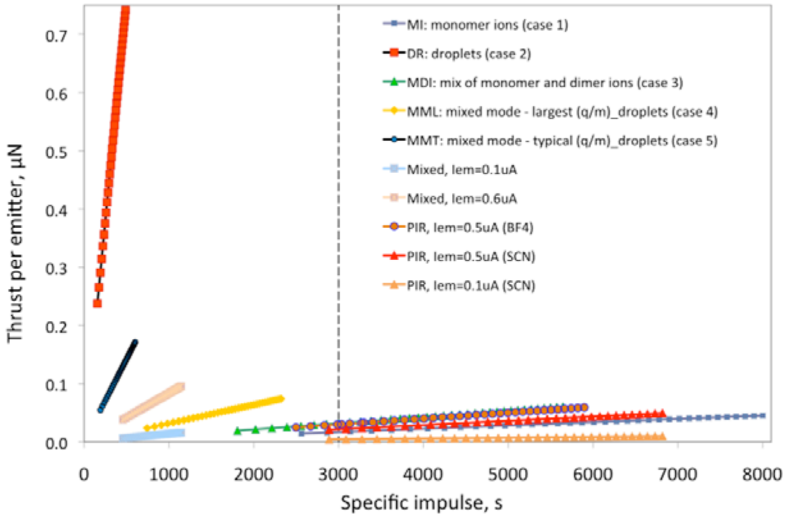


Figure 4: Thrust vs. Isp models for 8 different operating modes.

Task 1.5: Mission Analysis (and propulsion system requirements)

During Year-1, the analysis aimed at defining the high level mission requirements and led to a set of target performance specifications, and electrical, power, mechanical interface constraints. During Year-2 and Year-3, a series of analyses have been performed with the MMSM that allowed **trading-off** different design configurations (see Trade-tree and major results in Figure 5).

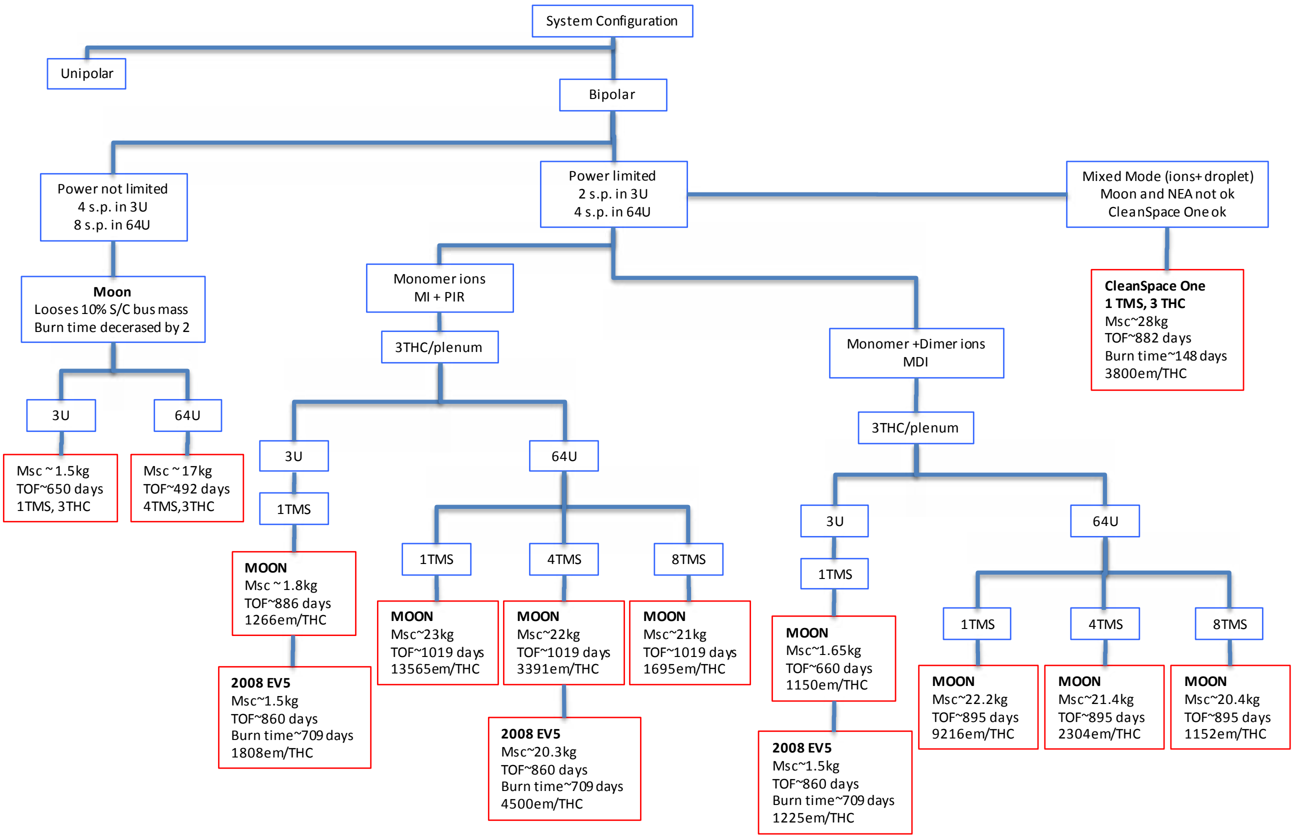


Figure 5: MTPS design options trade tree and major results.

The analyses show that a Moon mission and an NEA (Marco Polo's current target destination) are feasible with the MicroThrust propulsion system. The general trends that should serve as requirements for the continuation of the MicroThrust development are as follow:

1) Interplanetary mission are very demanding in terms of performances: ΔV are high (5 km/s and above), and lifetime requirements are high-end (above 17'000 hours); the emitter should be run in pure ion mode;
2) Number of Thruster Modules: between 1 and 4 fit the missions from 3 kg to 30 kg launch mass; Thruster chips arrays in Configuration 2 or 3 (~ 500 to 2000 emitters/cm^2), with accelerator grid;
3) The best configuration for the propellant tank and feeding system is the integrated version up to propellant mass of about 500 g/thruster module. After that, as per for the high end of spacecraft launch mass, an external propellant system is a better choice.

The MTPS system in its projected monomer and dimer mode of operation is found very suited for nano- to medium micro- satellites (up to 50 kg), as it is modular in nature and as it provides sufficient thrust, even at high Isp, thanks to large emitter arrays (Moon mission in ~3 years at an Isp of ~3400 s and net available spacecraft mass ratio of 0.67, or in 1.4 years at an Isp of 2200 s and net available spacecraft mass ratio of 0.54). Above 50 kg, other configurations of the MTPS may be necessary to increase the thrust/power density.

In the mixed ion and droplets mode, the MTPS is also very suited to lower DV but nonetheless as enabling Earth orbiting missions for again small satellites. An obvious application is orbital debris removal, but the MTPS also opens the door to low mass de-orbiting devices for nano- and micro-satellites.

2.2 Summary of WP2 Accomplishments (Propulsion System Engineering)

MicroThrust aimed to develop a complete propulsion system with several subsystems, each of which is a significant challenge. Hence, a clear definition of the requirements and specifications for these subsystems was indispensable for easy integration. WP2 focused on these tasks with the following major objectives over the project duration:

1. Specify preliminary subsystem key requirements
2. Define the overall propulsion system architecture
3. Specify the interface requirements
4. Specify preliminary test requirements
5. Facilitate system design control and interface control

Based on input from WP1 (Mission Analysis), a set of technical requirements were initially derived for a miniaturized colloid propulsion system for a 3 unit CubeSat. Requirements were specified on mission level (level 0), system level (level 1), subsystem level (level 2) and assembly level (level 3). The system breakdown of the MTPS is shown in Figure 6. The technical requirements were stored in a requirements database, updated several times throughout the project.

After the requirements were specified, a preliminary propulsion system design was made which satisfied the key technical requirements. The design consists of two major subsystems, i.e. the Thruster Module System (TMS) and the Power and Control System (PCS). The MTPS layout is shown in Figure 7. Thrust is generated by 18 integrated thruster chips, covering the face of the TMS.

In parallel to the preliminary propulsion system design, a Microthrust Breadboard (MTBB) has been developed as part of WP 4, WP 5, WP 6 and WP 8. In this work package, an interface control document has been established and maintained to identify and control all relevant interfaces in the MTBB. Other accomplishments of WP2 include the establishment of a numerical requirements analysis tool, a criticality analysis and the definition of a preliminary test plan for the breadboard test campaign.

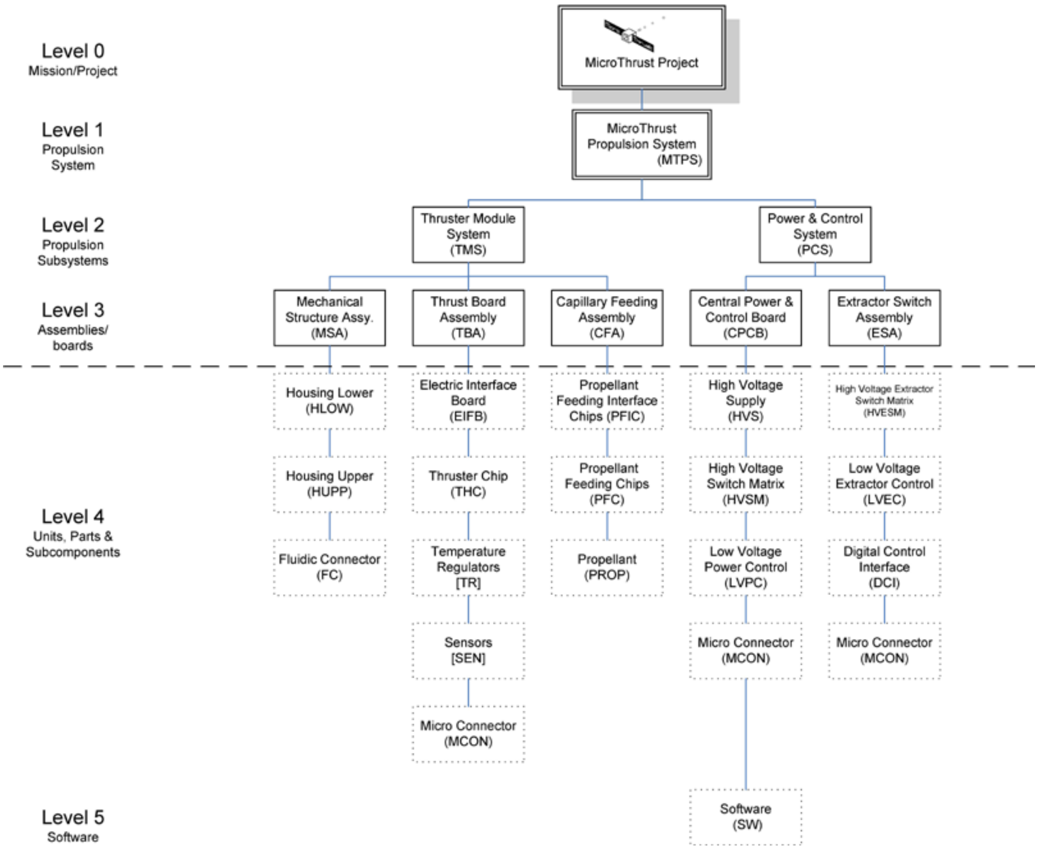


Figure 6: Propulsion system breakdown

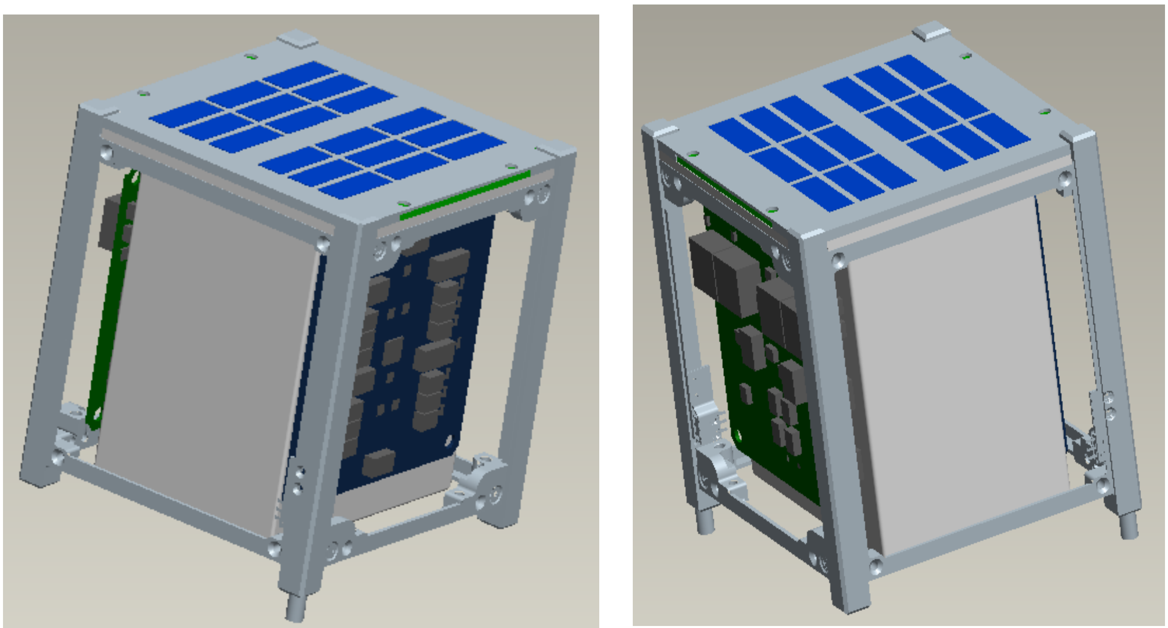


Figure 7: Propulsion system layout; MTS with long propellant tank and PCS boards placed along the sides

2.3 Summary of WP3 Accomplishments (Colloid emitter characterization)

WP3 concerns the “colloid emitter characterization”, with objectives;

- To provide performance data on the test-piece emitters having specified geometric properties, including dependence on hydraulic impedance, with a selected number of potential propellants.
- To develop an empirical performance model for each propellant as to the scaling laws for each propellant in each thrust head arrangement.
- To set up an electrochemical test cell in order to identify materials compatibility between the selected propellants and thruster components as part of the lifetime test programme.
- To identify test chamber requirements in order to undertake thruster breadboard testing in WP8.
- Procure integrate and commission the breadboard test chamber

These objectives were successfully completed, and included:

- Performance data was successfully collected on single emitters (thrust specific impulse), for different possible ionic liquids propellants.
- Single emitters with an accelerator included were tested, with performance improved, including focusing of the plume. This plume focusing with increasing acceleration voltage is illustrated in Figure 8.
- Based on the experimental data a performance model was developed, extending the performance envelope to the flight model.
- An electrochemical cell was designed and tested, and demonstrated that the switching of the polarity did offer a possible method to avoid electrochemical degradation within an electrospray thruster (see Figure 9, demonstrating less discoloration at higher frequencies).
- A test chamber for the Breadboard testing was designed, procured/manufactured, and integrated (Figure 10).

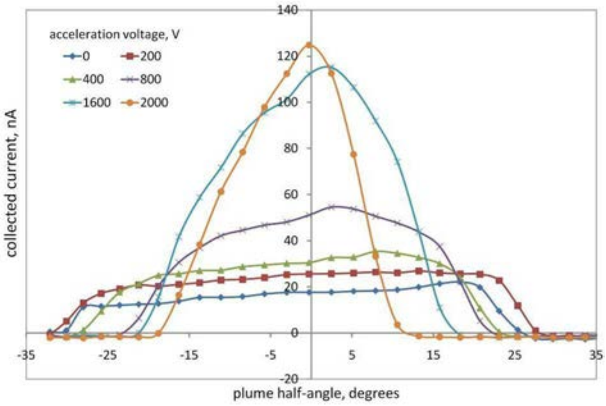


Figure 8. Variation of plume current with position across the plume of the translating Faraday cup.

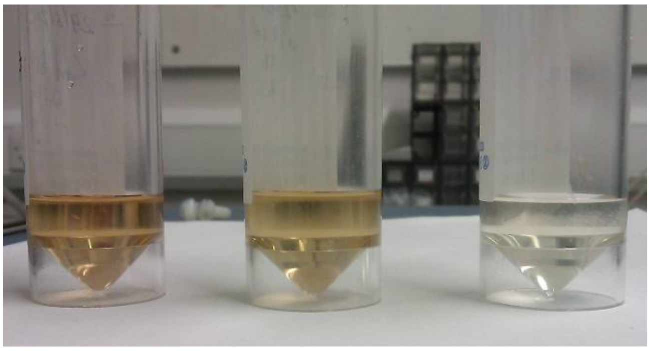


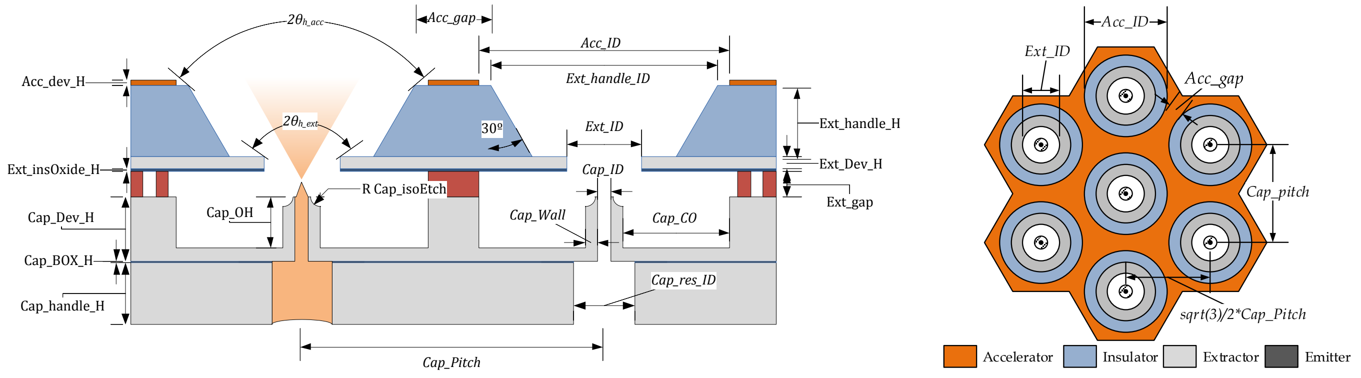
Figure 9. EMI-BF$_4$ discolouration after bipolar electrochemical tests at different frequencies. At (from left to right) 0.1, 1, and 5 Hz respectively.

Figure 10. The breadboard vacuum chamber. Bottom chamber is 400mm diameter, top chamber is 200 mm diameter.

2.4 Summary of WP4 Accomplishments (MEMS Components)

The MEMS thrusters developed and fabricated within this project are some of the world's most advanced electrospray thruster devices. They are the first electrospray thrusters with integrated individual accelerator electrodes, giving them a significant advantage in terms of capabilities (tuneable power consumption, Thrust and I_{sp}) and performance (higher efficiency, beam focusing, Thrust and I_{sp}). Using micro-fabrication, the technology behind semiconductor integrated circuits, it is possible to achieve unmatched tolerances in terms of emitter dimensions, electrode alignment and array density.

The design of the THC (THruster Chip) with integrated accelerator electrodes results from an analysis of manufacturability, performance and reliability. The final design of the chips, shown in Figure 11, allows the fabrication of arrays with emitter densities up to 213 emitters/cm^2. The emitters have nominal inner diameters of 5 µm, sufficiently small to achieve the high fluidic impedance required for ionic mode operation. Their tip is sharpened using an isotropic etch process to reduce the operation voltage and increase liquid containment. The extractor electrodes, spaced 50 µm from the emitters, have inner diameters of 170 µm and the accelerators have diameters of 540 or 765 µm. 250 microns of bulk glass insulate the extractor and accelerator levels, so that upwards of 15 kV of acceleration voltage can safely be applied.

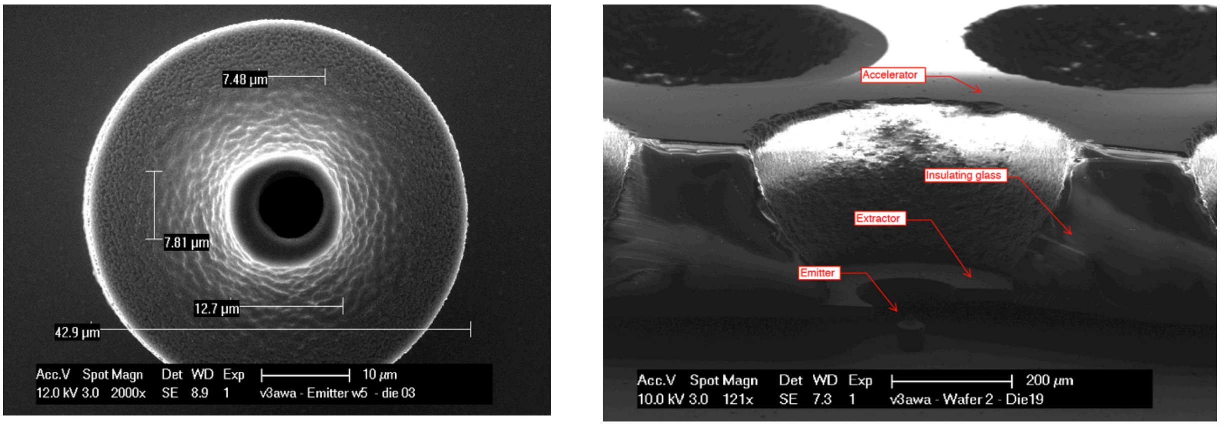


(a) (b)

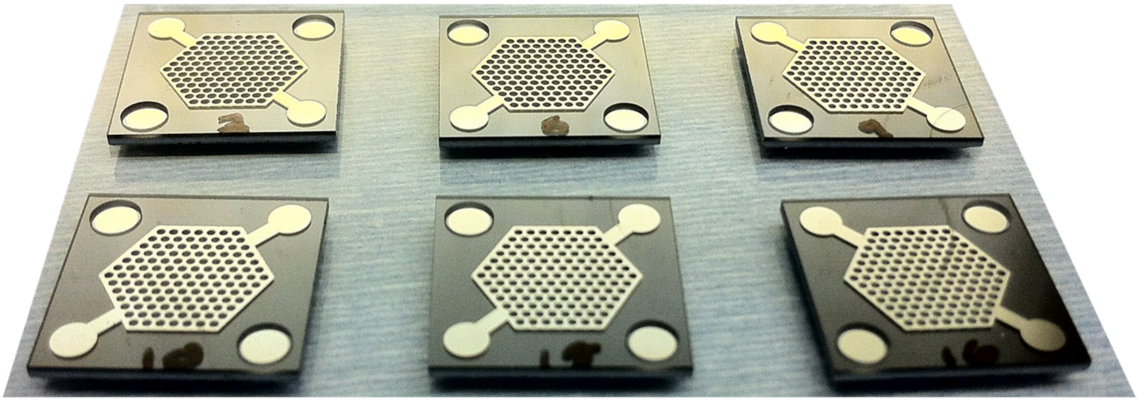
Figure 11: Cross-section (a) and layout (b) of the electrospray thruster array.

Following several years of process development, functioning THC were fabricated according to the design described above. Figure 12 shows Scanning Electron Microscope (SEM) and optical images of chips prior to breadboard integration and testing. An important feature of the fabrication is the wafer-level bonding of the extractor and emitter levels, which allows better than 5 µm alignment of the electrodes on a large scale and excellent electrical insulation.

Additionally, propellant transport in the thruster chips has been extensively studied. We have proposed a model to describe the capillary filling and holding pressures and validated that the emitters were able to contain liquid under shock and vibration. The wetting properties of two candidate ionic liquid propellants, EMI-BF$_4$ and EMI-TF$_2$N, were characterized at different temperatures and pressure for several surfaces.



(a) (b)



(c)

Figure 12. SEM (a-b) and optical (c) images of completed MicroThrust THC.

2.5 Summary of WP5 Accomplishments (Miniaturized Power Supply)

Work package 5 covers the development of the modular miniaturized power supply and control unit that is capable of providing the power requirements defined in the work packages of the consortium partners. The design is intended to be flexible to extend to other voltages and currents. Miniaturization and low power consumption are key parameters.

In the first year engineering efforts in work package 5 were spent on system dimensioning, architecture definition and high-level modelling to predict performance of the supply and validate its compliance before actual hardware is built.

In year two detailed design and fabrication of the power supply and control was planned. In more detail, year 2 activities consisted of:

- Manufacture small HV transformers and inductors, hardware tests to have reproducible results.
- Hardware tests assembled to an actual colloid thruster prototype.
- Refine the models with data of thruster electrical parameters to predict performance before actual hardware is built.
- Detailed design of the electronics, fabrication and test.

SystematIC build a first breadboard with all functional blocks and tested this with an actual thruster chip as a first integration test (September 2012). With this HV control board it was possible to control a thruster chip and have a stable bipolar setup running overnight.

In year 2 the BB model hardware of the PCS was developed which consists of a CPCB board and an ESA board; these boards are depicted in figure 2.

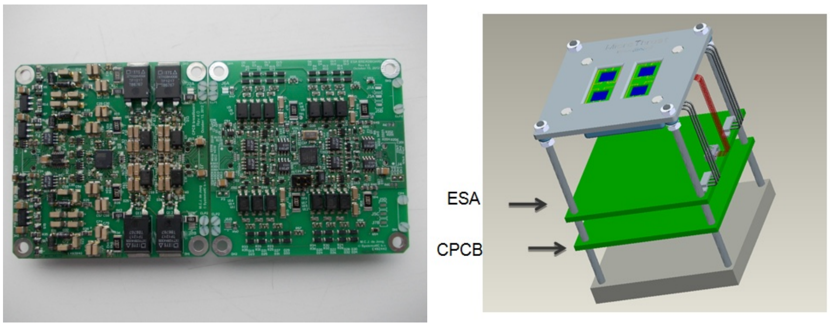


Figure 13: ESA and CPCB PCB (left picture) and BB model with ESA and CPCB (right side), supplying 4 bipolar channels for emitter, extractor and accelerator electrodes.

In year 3 work continued on the integration of the power and control circuit with the thruster module and tests in vacuum as displayed in Figure 14.

Figure 14 : Integration test at QMUL

Integration tests showed functional electronic behaviour and was integrated in the breadboard, showing the ability to operate in bipolar mode with a 127 emitter chip. Figure 15 displays the final board during last step of design. Another SystematIC design team worked on miniaturizing parts of the CPCB and ESA board in an ASIC. This electronic circuit is sent for fabrication during year 3.

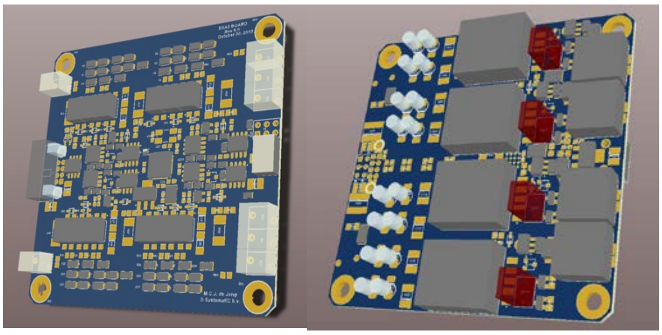
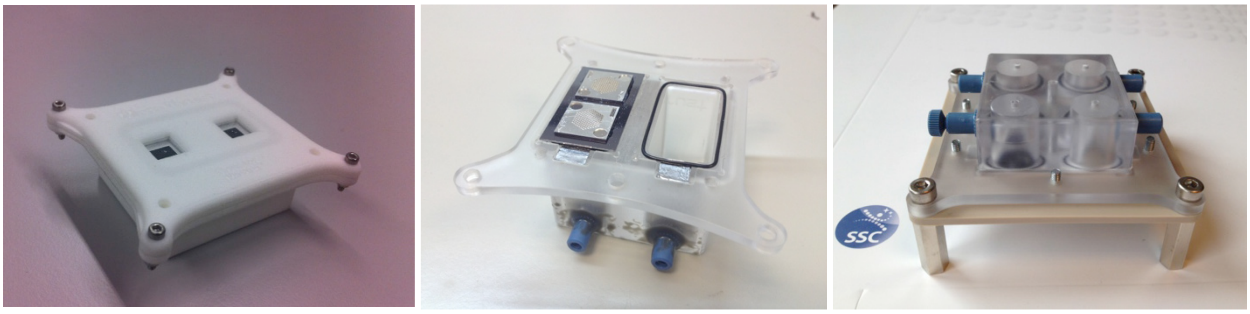


Figure 15: Final ESA and CPCB BB

2.6 Summary of WP6 Accomplishments (Thruster module and propellant storage)

A functional breadboard model of the thruster module (TMS) including propellant feeding and storage (as defined in the MTPS BB Product Tree was finally successfully designed, manufactured, integrated, and delivered for testing.

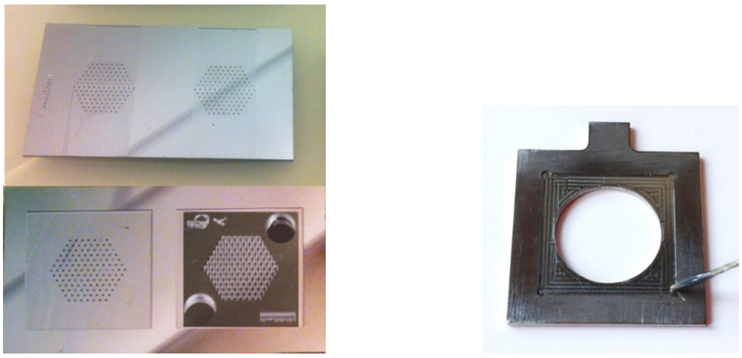
The conceptual design of the breadboard thruster module has evolved during multiple designs and manufacturing iterations and several novel solutions have been conceived along the way. The importance of system thinking and functional interface solutions between all integral parts was early identified and hence a first 3D plastic prototype was manufactured during Y1 (Figure 16a) before the detailed design was agreed during the preliminary design review (PDR) in M18. After the PDR the first version was manufactured (Figure 16b). A second version was manufactured and improved multiple times ending up with a final version one used in the breadboard (Figure 16c).



a) 3D Plastic prototype b) Partial TMS (v1) c) Partial TMS (v2)

Figure 16: Thruster Module System TMS evolution

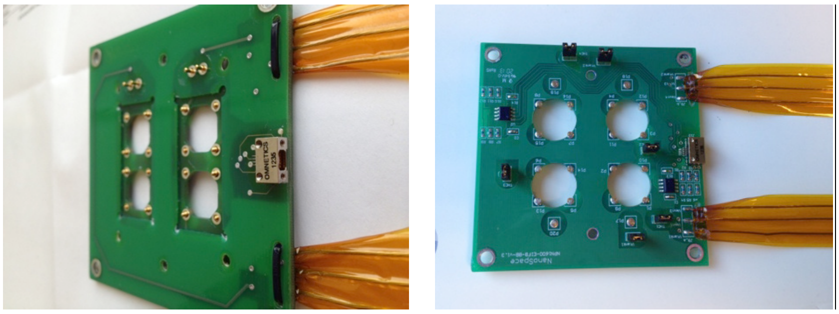
Another important progress is the innovative solution of routing propellant within the thruster module, including MEMS manufacturing of propellant feed interface chips (PFICs) to fit THC deliveries. Experimental short loops validated the feasibility of this capillary feeding principle using “open” structures, including capillary feeding in vertical direction (i.e. not depending of gravity). The capillary feeding function was removed from the second version of PFIC since the TMS was tested in downwards mode. Another iteration was manufactured in metallic material to contact the propellant and supply it with voltage (Figure 17b).



a) PFIC (v1) top and bottom view +THC b) PFIC (v2) on TMS v2

Figure 17: PFIC evolution

The Electrical Interface Board (EIFB) that interfaces from power supply to thruster chips went through several iterations. The first version consisted of one double sided PCB bonded together with a single sided PCB (Figure 18a) to create recesses for fitting the PFIC and sealing the tank by pressing on o-rings. A second version was designed and manufactured using a 2-layer PCB (Figure 18b) with the clamping and sealing of the tank done by incorporating the new HUPP component (see Figure 19).



a) EIFB v1 with recesses for sealing PFIC & o-ring

b) EIFB v2 (no clamping function)

Figure 18: Electrical Interface Board evolution

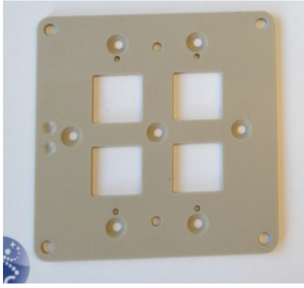


Figure 19: HUPP for clamping

The following picture (Figure 20) shows the TMS integrated on the MTPS Breadboard.

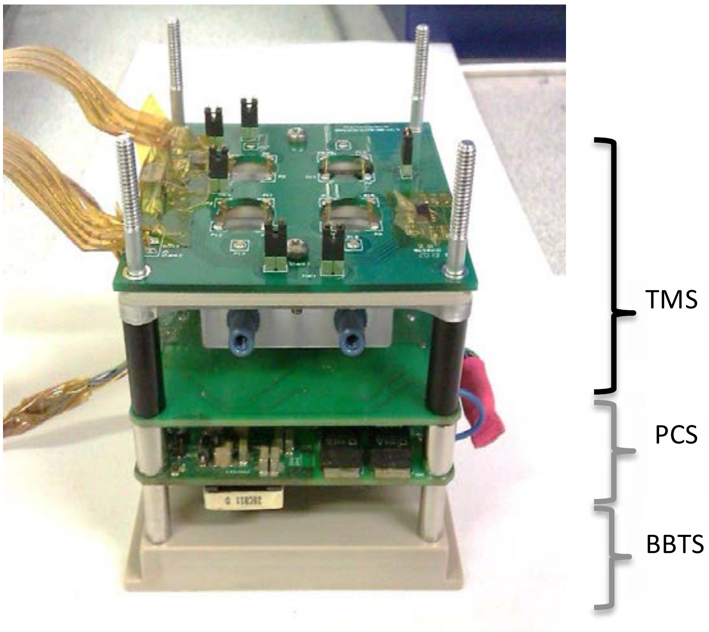


Figure 20: Picture of the MicroThrust BreadBoard System.

2.7 Summary of WP7 Accomplishments (Miniaturized Neutralizer)

The basic function of the neutralizer (electron source to neutralize a positive ion beam) is described in Figure 21.

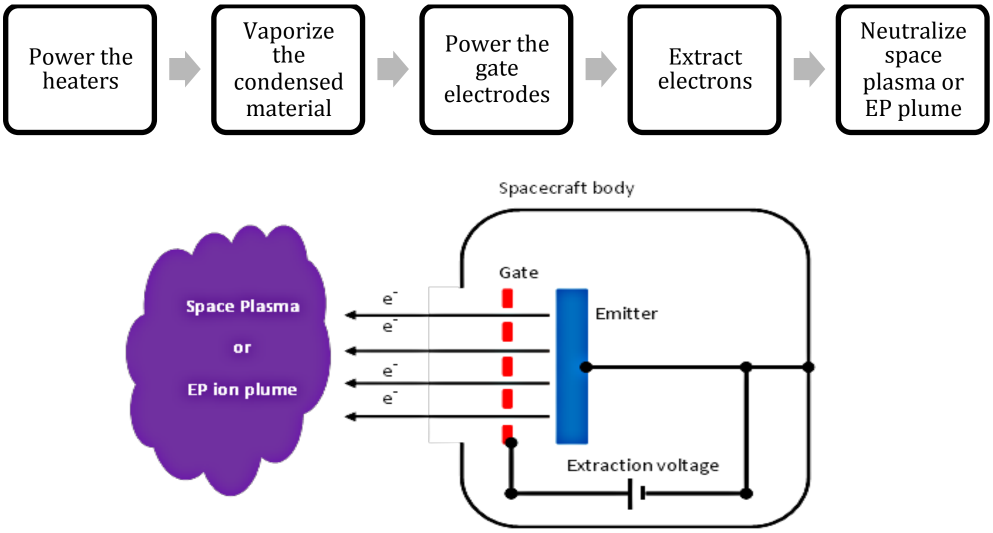


Figure 21. The basic principle of operation of a gated field-emission cathode

One conclusion from a literature study during the first work package was that neutralizer technology based on field emission is of most interest. From the trade-off it was concluded that carbon nanostructures had the greatest potential. CNT emitters have also been tested by RAL, Busek and FEPET. Of all the different CNTs the VACNTs that consist of MWCNTs seemed to be the easiest to synthetize and they had the highest values for current density. The best solution of combination was decided to be vertical aligned multi-walled carbon nanotubes in hexagonal bundles in an hexagonal array due to screening effects, geometrical enhancement factor and synthesis process. Three baseline concepts were designed:

1. A VAMWCNT BB with diode set-up for feasibility testing
2. Tightly bound VAMWCNTs pillars in a gated array as a triode and
3. SOTA version with protection against CEX and electrical breakdown using CLAIR and VECTL.

The objective of that work has been to demonstrate proof-of-concept using a miniaturised VAMWCNT-based neutralizer.

The housing of the neutralizer serves both as an electrical interface and protects the CNTs mechanically. The neutralizer breadboard is mounted in a TO-39 capsule (Figure 22), which also fulfils the mass and dimension requirements. The total mass of the neutralizer and housing (TO-39) is less than 1 gram. To validate the current emission of the neutralizer breadboard without an integrated extractor, it was tested in a diode set-up. The set-up consists of an ultra-high vacuum (UHV) chamber with a base pressure of < 10^{-6} mbar, source-measuring unit as well as electrical connections to the anode and grounding of the substrate. A picture of the experimental set-up, measurement of the emission current and a Fowler-Nordheim plot is shown in Figure 23.

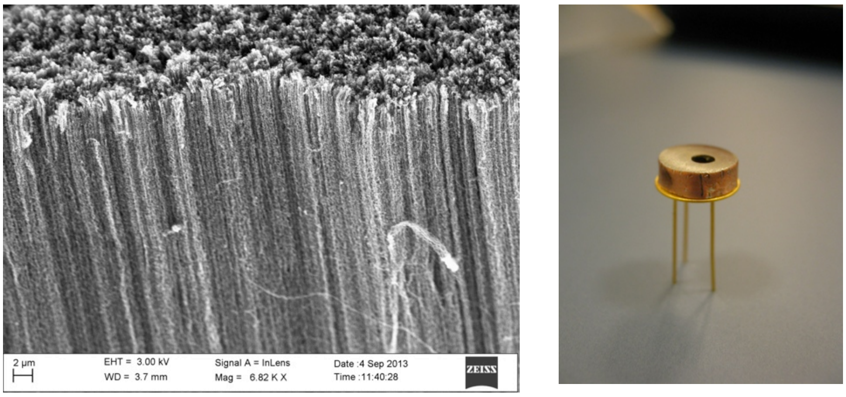


Figure 22. Breadboard a) SEM image of VAMWCNTs b) neutralizer breadboard

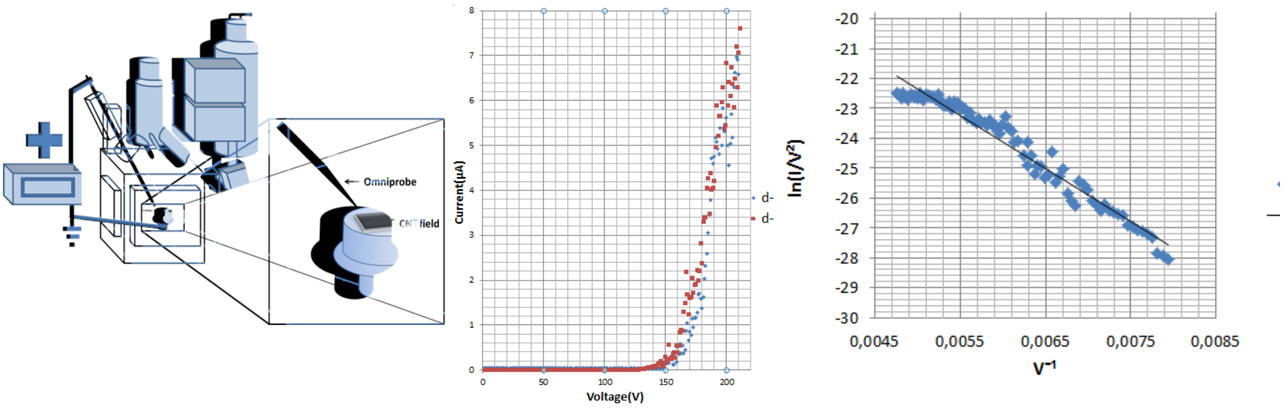


Figure 23. Conceptual design of the set-up, emission current and Fowler-Nordheim plot with a linear fit to demonstrate field emission.

Analytical and laboratory studies validated the predictions regarding field emission from a VAMWCNT breadboard. Compared to the requirements, the emission current was within range and the extraction voltage reached target values. In addition, the size and mass of the miniaturized breadboard model are well below requirements.

2.8 Summary of WP8 Accomplishments (Breadboard Testing)

WP8 concerns the “Breadboard Model Testing”, with objectives:

- Assemble breadboard model components into QMUL test stand
- Improve understanding of colloid system physical processes
- Obtain detailed performance data on breadboard model
- Develop colloid thruster performance model

The main (primary) objective was to assemble, test, and obtain detailed performance data on the breadboard model, in a specially commissioned thruster chamber. This has been successfully accomplished, with the breadboard model illustrated in Figure 24, along with an electrospray thruster array as tested in the BB model. This BB model includes;

- A lower and upper housing to contain the propellant and interface with the thruster chip. The housing has four separate propellant chambers, allowing for the spraying of four thruster chips simultaneously.
- An electrical interface board (EIFB) PCB making the high and low voltage electrical connections.
- ‘Interface’ chips, onto which the thruster arrays (as illustrated in Figure 24) are glued. At a later stage of thruster development this will be replaced by a Propellant Feeding Interface Chip with propellant feeding channels, forming a part of an overall propellant wicking system for the electrospray thruster system.

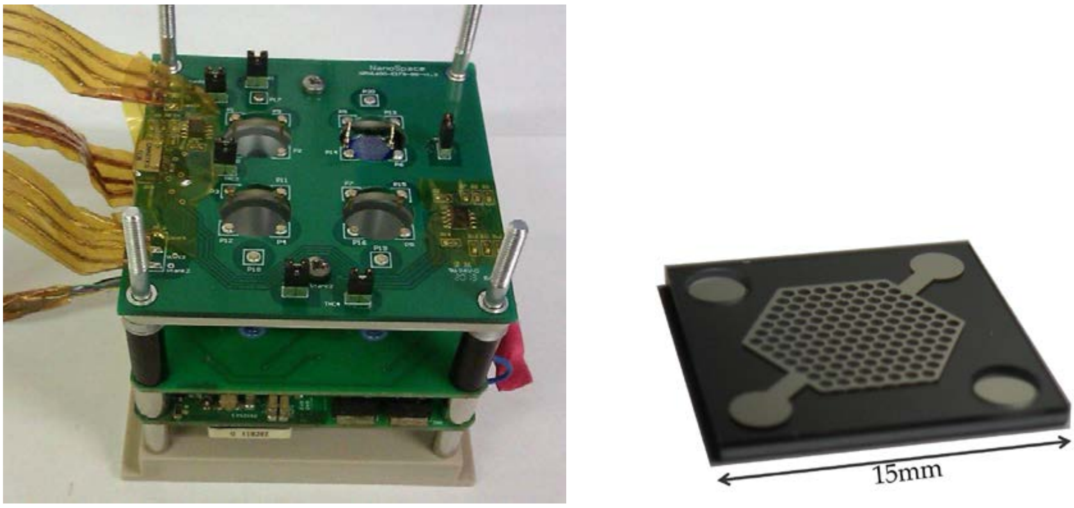


Figure 24. left) Full BB (incl. power supply) with one MEMS chip installed. Right) Single electrospray thruster array chip.

The accomplishments of the breadboard testing include;

- The successful firing of the BB model thruster, including 91 or 127 emitter arrays. Representative current-voltage data from these successful firings is illustrated in Figure 25.
- The demonstration that applying a varying acceleration voltage to the thruster arrays does not affect emission process, as demonstrated by the data in Figure 25 falling on the same line, and that the acceleration process acts to increase the specific impulse and thrust, whilst decreasing the plume half angle (Figure 26).
- The BB model, using the baseline propellant is operating in a mixed ion-droplet mode, resulting in a specific impulse for the array of between 350 and 1000s dependent on the magnitude of the acceleration voltage applied.
- The BB model was successfully operated in bipolar mode, up to a frequency of 10Hz.
- The BB model was operated continuously for a period of five hours, demonstrating little indication of electrochemical degradation.
- A colloid thruster performance model was developed, based on experimental results, demonstrating what performance would be possible for a full electrospray thruster flight model.
- The Power and Control System (PCS) has been successfully tested using a single emitter, a 19 emitter array, and the full BB model using a 127 emitter array.

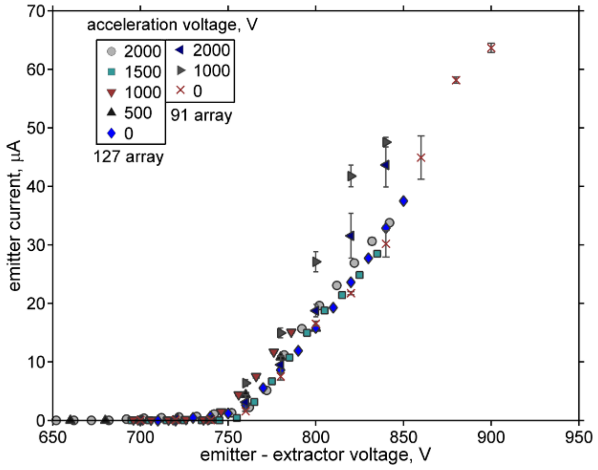


Figure 25. Variation of emitter current with voltage difference between emitter and extractor, at different acceleration voltages, showing the accelerator does not influence emission current

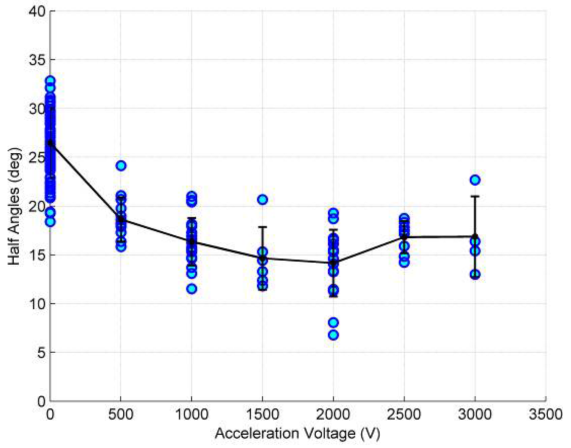


Figure 26. Plume half-angles for different acceleration voltages (at fixed emitter-extractor voltage), showing focusing effect of accelerator electrode.

Key lessons for further short-term development based on BB testing results

Based on the data on the BB, we have identified aspects that require further development to increase TRL and performance. A global view of development steps is summarized in Figure 29.

- Lifetime of the MEMS thruster chips is currently hours (up to 48 hours continuous operation observed). A detailed study of failure modes and an associated redesign of the chips is needed, for instance incorporating additional porous layers for better fluid containment.
- Operation in pure ion mode was not observed (mixed mode of 95% ions and 5% droplet was achieved for the BB chips). Two paths related to tuning hydraulic impedance and capillary pressure

have been confidently identified to achieving pure ion mode and hence higher ISP and can be readily implemented in a chip redesign.

- Stability of miniaturized power supply can be improved by modifying the feedback mechanism. The power supply size can be significantly reduced by using an ASIC rather than discrete components. An investigation of radiation tolerance will be needed.
- Direct Thrust measurement is required to validate the thrust determined from beam current and charge/mass characterization. This requires a minor redesign of the breadboard for compatibility with thrust benches.
- The above steps will allow increasing TRL of the thruster to 5 and allow an accurate estimate of lifetime.

3 Potential impact and the main dissemination activities and exploitation of results of *MicroThrust*

3.1 Potential impact

MicroThrust is a critical enabling technology to revolutionize planetary space exploration by enabling small satellites to have highly efficient on-board propulsion, allowing for high Delta-V missions, and thus play a major scientific role in robotic space exploration. This new technology thus enables the scientists to focus on acquiring the data they need, with less concern on getting the spacecraft to the orbit required to perform the mission. Mission cost is drastically reduced, since 10 kg class spacecraft can be used for real scientific missions. The missions serve to increase our knowledge of our universe, but also to solve immediate problems, such as removing space debris that pose a risk of destroying existing spacecraft.

The expected impacts of *MicroThrust* are a) new missions using very small spacecraft for space exploration, on a much faster time frame than previously possible, b) miniaturized thruster with unique performance and modular structure, c) space compatible compact high voltage power supplies, d) important Earth-bound applications in arrays of printing and ion sources.

Expected Impact 1: Using the performance data from our breadboard of a miniaturized colloid thruster propulsion system whose mass and volume are 90% smaller than existing electric propulsion system, with a specific impulse of 2700 s and a power/mass ratio of 0.05 µN/mW, and a specific thrust of 0.2 $\mu N/mm^2$, it is possible for **space agencies, majors space companies, and universities to design exploration mission scenarios that are either much lower cost than possible with more conventional thrusters, or simply not feasible with conventional thrusters. Having a modular and low mass electric propulsion system frees up more spacecraft mass for the payload, or reduces mission cost by reducing overall mass**.
For universities, space scientists, and astronomers, the performance data allows the definition of innovative and currently unrealizable mission scenarios based on nano-satellites. A clear example of this is the Dutch OLFAR initiative, to place a network of radio-astronomy satellites on the far side of the moon. Using the technology developed in MicroThrust, it will be possible to have 3 to 10 kg satellites navigate under their own power from Low Earth orbit (which is relatively cheap to reach with a piggy-back launch) to lunar orbit (normally prohibitively expensive). One cannot overstate the importance of enabling small spacecraft to reach lunar orbits (or Lagrange points) from LEO, as the launch costs are different by an order of magnitude. We expect that an entire new class of science and exploration mission will become possible because the mission cost will no longer be dominated by the prohibitive launch cost and lack of suitable launchers for such orbits.

Expected Impact 2: **detailed and validated design of a miniaturized colloid thruster allowing commercialization of a low-mass high-ISP thruster for small satellites.**
The main users of the detailed design of the thruster will be the companies that will commercialize this technology. These include system integrators who would offer the MicroThrust system as a complete unit, and the component manufacturers who would supply the parts to the integrator. A European space

company could be the integrator of the thrusters, with a European MEMS foundry supplying the MEMS thrust head parts, Nanospace providing the fluid handling, and SystematIC delivering the power supply.
It is expected that the MicroThrust activity will lead to the commercialization of a compact modular thruster, with all key elements made in Europe, providing an ITAR-free high specific impulse thruster of interest well beyond Europe.

Expected Impact 3: **Miniaturized space compatible HV regulated power supply.** The 4 kV multi-channel power supply developed for the MicroThrust breadboard is an order of magnitude smaller than any existing commercial products with similar performance specifications. This power supply would be essential not only for the MicroThrust propulsion systems, but also for other electric propulsion systems for small spacecraft (e.g., pulsed plasma, mini ion-engine, FEEP, neutralizers) in view of its greatly reduced mass and compact size. Other potential users will be found in the fields of power supplies for photo multiplier, plasma and electrostatic applications.

Expected Impact 4: **Application to direct writing (additive manufacturing) of functional materials**

Whilst the main purpose of MicroThrust is to facilitate the exploration of the solar system, there are many applications of electrospray research in terrestrial applications, from micro-combustors to drug discovery that can benefit from the development done in MicroThrust. One area of developing industrial importance is the use of electrospray to provide the direct writing of functional materials. Over the past decade there has been increasing interest in the direct writing of functional materials. Direct writing is referred to here in the context of placing materials into a two or three-dimensional structure without the use of photo-lithographic techniques thereby producing an additive rather than subtractive manufacturing process. As a result the technology is an exemplar of green manufacturing.

There are however significant difficulties associated with the use of conventional inkjet, that has led the way in direct writing technology. These are principally due to the very limited window of fluid properties, particularly those of the fluid viscosity and conductivity of precursor materials. These limitations are not shared by electrospray technology, as it can deposit materials over three orders of magnitude in viscosity and conductivity.

The approaches required for the space propulsion system, namely a large, dense array of emitters combined with miniaturized high voltage control and voltage switching of the electrodes relative to the emitters, are ideally suited to the design and manufacture of a high performance versatile printheads. A major achievement in the Microthrust programme was the development of Si processing methods and the control of these methods to form what would be in the printhead world print channels rather than ion sources. The 2D arrays of capillaries provide the opportunity to obtain very densely packed channels in a printhead exceeding that achievable in conventional inkjet printers, allowing parallel microprinting of a broad range of materials.

3.2 Main Dissemination activities

The MicroThrust Consortium consists of leading partners from industry, universities and research institutes, which promoted awareness of the project's accomplishments by disseminating the research results as widely as possible, starting from the beginning of the project.

The main goal of the dissemination activities was to create impact in Europe and beyond with the results of this project by actively pursuing dissemination goals in three areas: scientific, economic and societal. An interactive website was set up and updated during the project. The website addressed different audiences, and even allowed visitors to design their own propulsion system. Furthermore, a LinkedIn group was set up and maintained to update interested people on the progress of the project.

To reach the scientific and technical communities, we presented not less than 13 conference papers at Space and MEMS conferences (we received several best paper awards), and gave talks at several universities, including MIT and Yale. We published 2 papers in peer-reviewed journal, with several more in preparation. ESA and key European industry were directly informed of the project outcome.

MicroThrust was featured in scientific TV programs in Canada, Australia, and Switzerland.

Besides numerous papers and conference attendance, the dissemination included outreach activities including numerous presentations at universities and high-schools for the general public, as well as YouTube videos (over 30'000 views), newspaper articles, and articles in several magazines (GEO, etc). A model of the MicroThrust propulsion system was created which is now at the Space: a human adventure exhibition in Utrecht, the Netherlands.

Figure 27: Dissemination in action: Left,:B. Sanders presenting MicroThrust at the public observatory in Rijswijk, NL. Right: the MicroThrust model on public display at the Space: A human adventure

3.3 Main exploitation activities

Two missions have already shown particularly interest in the MicroThrust technology. The first is the Dutch OLFAR mission, which aims at creating an interferometer considering of a swarm of small satellites to listen to radiowaves from the early universe. By circling the Moon, the swarm can be shielded from all radio interference coming from the Earth. This mission needs MicroThrust ion propulsion to fly to the moon and to maintain the constellation. The second mission is Cleanspace-1, a mission that flies to space debris in Earth orbit and removes it from orbit. The Microthrust system will deliver a large delta V capability to allow flying to different targets after a piggy back launch.

Exploitation already performed

During MicroThrust a number of exploitation activities have been carried out
These are:

- Discussion with potential missions: the use of MicroThrust technology was extensively discussed with The OLFAR mission and with the CleanSpaceOne team.
- Talks with industry: several major European space and aerospace companies were briefed on the possibilities of the technology.
- Development plan was established, paving a path forward, identifying key areas that require further development, and giving a roadmap (see Figure 29)
- 3 application studies were completed:
  - E-Moth, mission to the Moon
  - CubeSat mission for the demonstration of a Colloid Electrospray Thruster System (CETS)
  - CleanSpace One debris removal mission

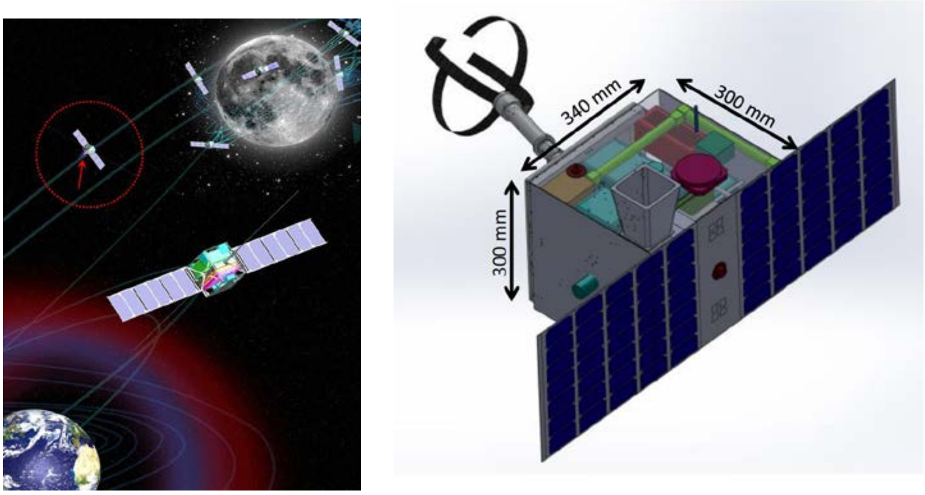


Figure 28: E-Moth (left) and CleanSpace One possible configurations (right)

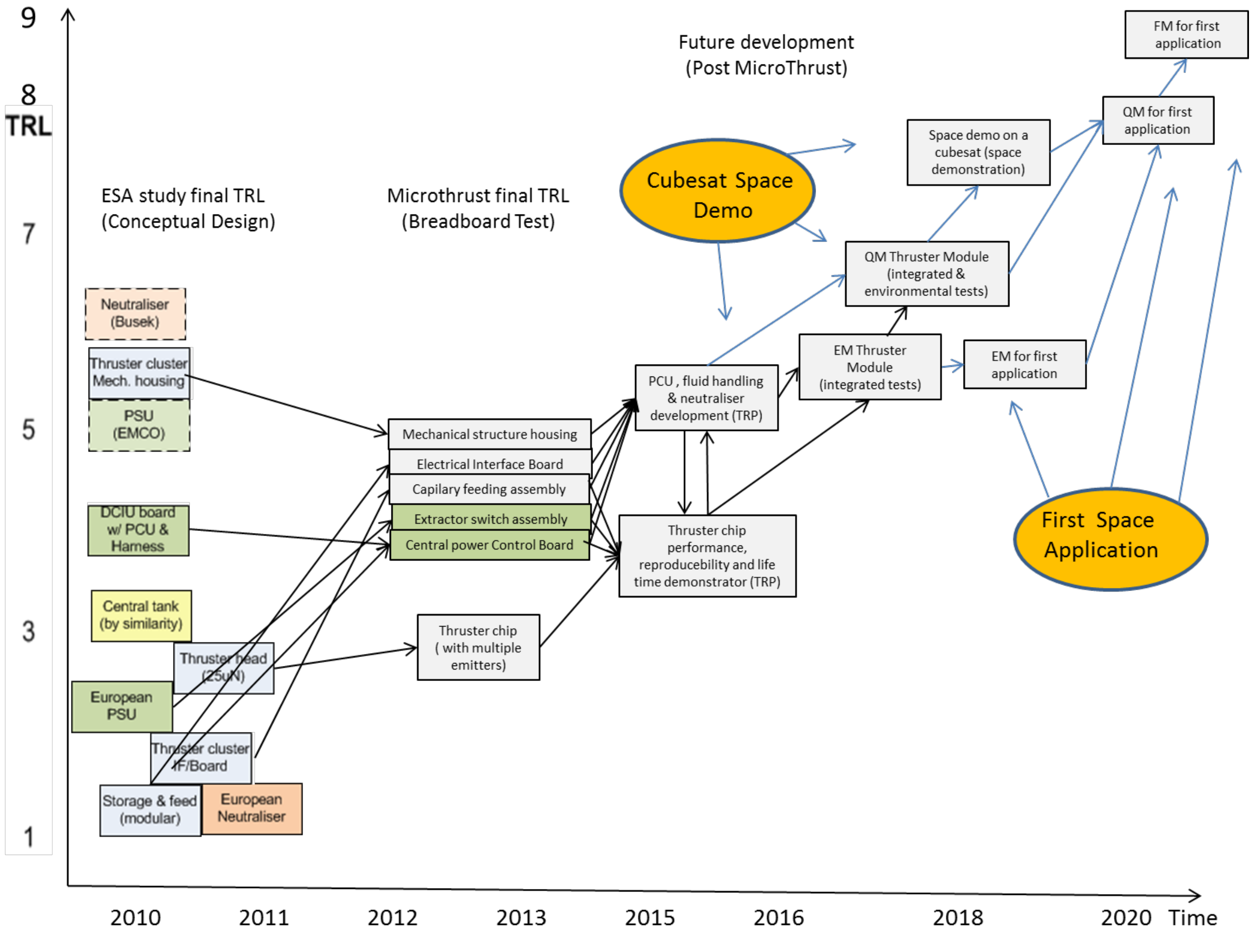


Figure 29: The development plan for MicroThrust

Future exploitation

With most of the sub-systems achieving TRL 3 to 4 at the conclusion of the MicroThrust project, the preparation for the exploitation phase of the technology has started. The exploitation has two main directions: space and non-space.

Exploitation in the space domain

During MicroThrust, the team has had many discussions with companies, academia and agencies on the potential applications of MicroThrust. During these talks, the expected applications, set out in the MicroThrust proposal were confirmed. They fall into three groups:

- Small Scientific Spacecraft (like OLFAR and its predecessor E-Moth, ESA E-type missions)
- Space debris removal spacecraft (like CleanSpaceOne)
- Space tug, orbital propulsion module, which can bring a satellite from a piggyback launch to an operational orbit beyond the capabilities of present propulsion systems.

From the first two groups, there is real interest in the technology and firm contacts have been made. For example, the OLFAR [application study 1] mission has declared that the MicroThrust technology is enabling for their mission. CleanSpaceOne [applications study 3] can work with conventional propulsion, but the MicroThrust technology will make is vastly more efficient as it will allow CleanSpaceOne to fly to space debris from many different initial orbits. This means that CleanSpaceOne type spacecraft can be launched piggy back with any launcher into an initial release orbit and then fly to a target by its own.

Both applications rely on institutional funding and the MicroThrust system for these applications should be funded as part of the development of the whole satellite system.

The Space Tug is slightly further in the future. The large amount of plans for very small launchers (like, among others, the LauncherOne initiative of Virgin Galactic and the space launcher proposal of XCOR for their Lynx) shows that others also see this market. A small satellite can be put into a dedicated orbit by a very small launcher, but it is also possible to use an Orbital Propulsion Module to perform the change of orbit after launch into a piggy back orbit. This will increase flexibility and reduce costs. A first analysis shows that an OPM based on MicroThrust technology can be more cost efficient than a dedicated launch with a micro launcher.

The MicroThrust exploitation for space applications goes beyond direct use of the technology in space propulsion systems, but can have a broader application in the space market. Examples are:

- The testing and evaluation techniques and experience built up in MicroThrust can be used for testing other electric propulsion systems. An example is the ToF technique to characterize the ion beam
- Control of the ionic liquid by capillary forces can also be applied to other ionic liquid space applications
- System engineering and mission analysis tools developed can be used for a broad range of missions

Exploitation in non-space domain

During MicroThrust several technologies and components have been identified that could be used outside space, as presented in the potential impact section above. Some of these are:

- Efficient miniaturized high voltage technology could be used in many applications, for example medical x-ray, piezocontrollers, ion pumps, electrophoresis, igniters,
- The colloid fluid handling and extraction technology could be used in 3D printers and other micro droplet distribution systems
- The micro capillary and fluid handling MEMS production techniques could be used for other Lab-on-a-chip applications.
- Test and evaluation techniques developed within MicroThrust could be used for testing other ion sources.

3.4 MicroThrust project public website

The public website is www.microthrust.eu

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