Advanced MEMS components in closed-loop micro propulsion applications

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ABSTRACT

This paper presents recent advances in the development of two MEMS (Micro Electro Mechanical Systems) components suitable for small satellite propulsion applications. First a cold gas MEMS thruster with proportional and closed-loop thrust control and secondly a Xenon flow control module for precision control of extremely low flow rates to Ion engines. The development of these products is ongoing but recent achievements have demonstrated that besides miniaturization also unique performance and functionality can be achieved. The components are described in terms of design, manufacturing, and test results. The flow control module can regulate flows in the range of 5-50 µg/s with a resolution better than 0.2 µg/s. By using the same closed-loop control in a MEMS-based thruster configuration, the combination of milli-Newton thrust range, sub micro-Newton resolutions, and fast response time can be achieved. In our view, using MEMS technology and integrating the flow control valve, mass flow sensor and chamber/nozzle on a single chip is the best –if not the only- way to realize a closed-loop control thruster that can meet new tough small satellite propulsion requirements.

INTRODUCTION

MEMS

Micro Electro Mechanical Systems (MEMS) technology will in many space applications add value simply through reduced mass, volume and required power of components and subsystems. Introducing MEMS technology offers a mass reduction from several hundred grams per component using conventional technology to tens of grams for a MEMS sensor packaged as a stand-alone sensor. Given the opportunity to integrate the MEMS component in any other mechanical housing, the additional weight is in the order of grams only. The inherently low mass, volume and power consumption does add value to the system in terms of reduced costs, but does also in many cases allow increased redundancy, performance and functionality.

Closed-Loop Control in MicroPropulsion Applications

The two MEMS components presented here provide completely new functionality and unique performance for micro propulsion systems in small spacecraft applications. Today, most thrusters and fluid control components are operated in ON/OFF mode and in a control system where the feed-back signal comes from sensors (such as accelerometers or star trackers) on-board the spacecraft. The novel MEMS devices presented here do enable both continuous/proportional and closed-loop flow control. In the application of a thruster (cold gas or chemical) this enables continuous throttling capability with a real time measurement of the delivered thrust. In case of a Xenon feed system this allows the Ion thruster to always operate at maximum specific impulse regardless of the commanded thrust. Such functionality does enable advanced missions such as precise formation flying, drag free flight. Furthermore, the miniaturization that comes along with the MEMS technology does also in general open up for propulsion on-board CubeSats. This functionality is possible thanks to the MEMS technology which allows an extremely small and highly integrated valve, mass flow sensor, and control electronics.

Regardless whether the main objective is to reduce size and cost or to enable precision formation flying, the concept of MEMS-based micro propulsion needs to be demonstrated in space before this new technology will be accepted on a broader base. First after this has been achieved, MEMS components and systems will be more widely used in space applications [1-4].

CUBESAT PROPULSION MODULE DESIGN

Micropropulsion is one of the space applications where MEMS can play a significant role. This is especially true for the CubeSat community that up to now have had essentially no alternative to equip their satellites with propulsion capability. Our strategy to overcome this problem has been to develop a single MEMS chip containing flow control valve, flow sensor and chamber/nozzle.

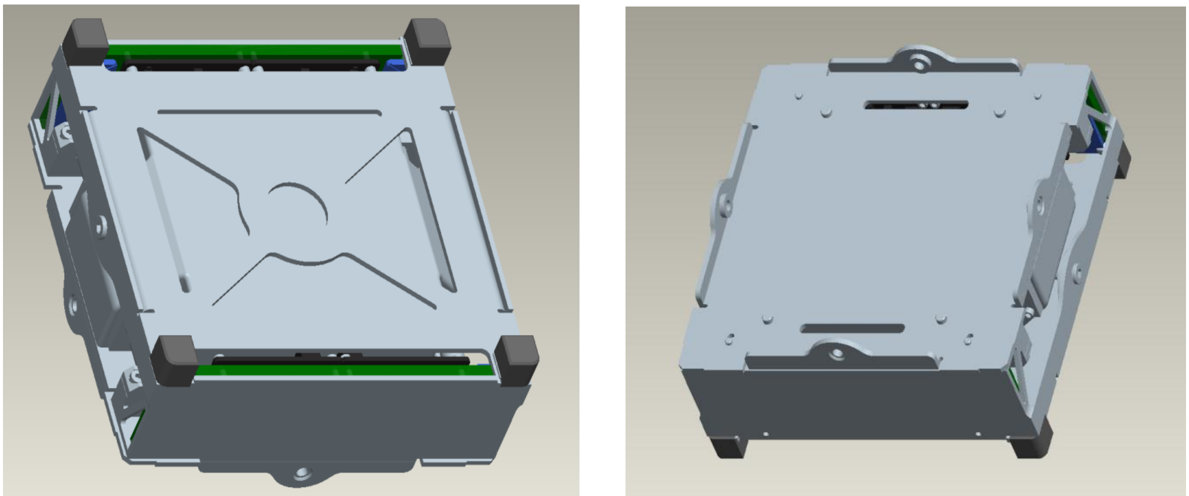

Figure 1: CAD-drawings of the MEMS-based propulsion module for CubeSats with closed-loop thrust control

Four of these chips are then integrated in a 10x10x3cm module together with propellant tank, fill/drain valve and four isolation valves (one per thruster). The required electronics to read the mass flow sensors of the four thrusters are also included in the CubeSat propulsion module. This makes the propulsion module complete and self-contained with the exception of an interface electronics card that is needed to interface the power- and databus of the spacecraft.

In summary the specifications of the CubeSat propulsion module is as follows:

- Four 1mN thrusters with closed-loop thrust control
- Thrust resolution: 10µN
- Propellant: Butane
- Total impulse: 40 Ns
- Size: 10x10x3cm
- Weight: 250g (dry)
- Propellant capacity: 50g (butane)
- Operating pressure: 2-5 bar
- Power consumption: 2 W (average, operating)
- Mechanical interface: CubeSat payload I/F
- Electrical interface: 52 pins analog (0-12V) and digital (SPI)

Figure 1 shows the CubeSat propulsion module described in this paper.

For a 1 kg CubeSat this module can generate a delta-V of 40 m/s which is sufficient for a significant formation flying operation or a small orbit change. If more delta-V is required the size of the propellant tank can be increased accordingly.

CLOSED-LOOP THRUST CONTROL

The unique functionality of the propulsion module is the closed-loop thrust control. This is achieved by implementing a mass flow sensor in the MEMS thruster which enables a measurement of delivered mass flow (and hence thrust) in real time. The real time thrust data is used in the control loop for the proportional thruster valve. This concept has been successfully developed and tested and highly improves the functionality of the thruster.

As an example, thrust resolution better than 0.1 µN has been demonstrated, and with this technology precise formation flying, docking and drag free flight is feasible also for nanosatellites.

Thruster Design

In summary our proposed thruster design consists of the following components:

- MEMS Inlet filter (optional).
- ON/OFF valve. Normally-closed solenoid valve for pulse mode operation.
- MEMS proportional flow control valve.
- MEMS mass flow sensor.
- MEMS chamber/nozzle.
- Heaters and temperature sensors.
- Front-end electronics to read mass flow sensor signal.

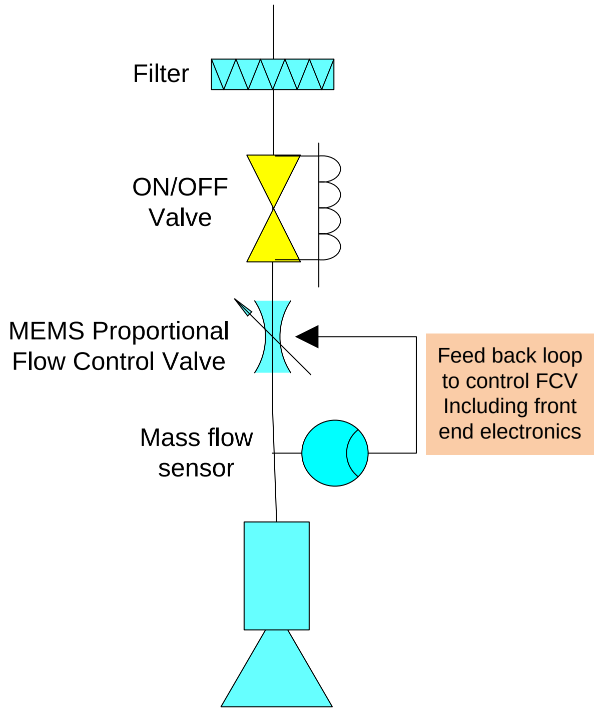

Figure 2: Schematic view of the closed-loop thruster concept.

The most interesting component is the thruster chip where the mass flow sensor, the proportional flow control valve and the chamber/nozzle are integrated in the same chip. With the front-end electronics, this enables the closed-loop thrust control functionality.

Test results

The following subsections present a few key results from tests performed using NanoSpace's existing hardware and control algorithms. Neither the hardware nor the algorithms have been optimized at this point. Still these results show that a closed loop MEMS thruster is capable of controlling the thrust both precisely and with extremely high resolution.

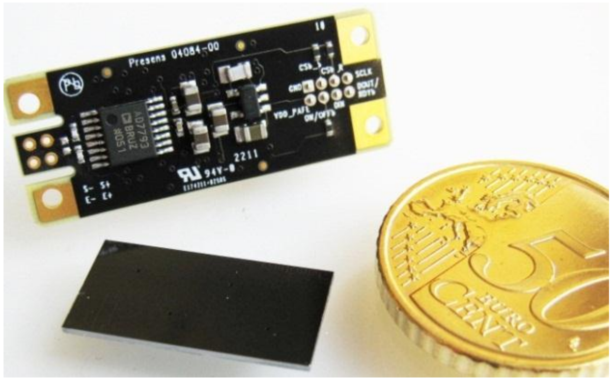

Figure 3: The key components of the microthruster: Valve, chamber/nozzle and sensor integrated in a single chip together with the front-end electronics card. The chip size is approximately 10x20x1 mm.

Thrust range

This section presents a few key results from tests performed with the closed-loop MEMS thrusters. First a result using the ON/OFF valve in order to create pulse modulated impulse bits as shown in Figure 4. This capability is not at all unique but is often required by the GNC system of the satellites. This result does also show maximum thrust level (in this case 650 µN), response time and repeatability. In this case only the ON/OFF valve is used and the proportional MEMS valve is fully open.

Step response & Thrust resolution

Figure 5 below shows a test result using the proportional MEMS valve in closed-loop control where commanded and delivered thrust are compared. This result shows how the control loop and the delivered thrust responds to 5 µN step changes in the lower end of the thrust regime where precise thrust control is normally most needed.

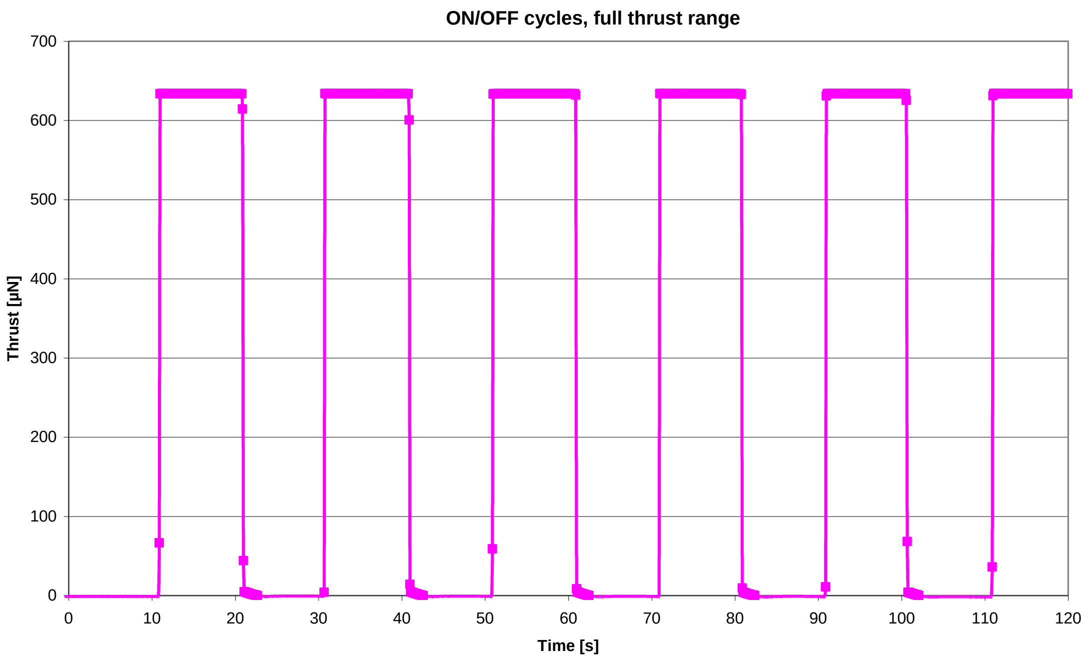

Figure 4: Test result of a thruster operating in ON/OFF mode (open loop, using solenoid valve only) to show thrust range. Thrust is calculated from the measured flow rate and assuming an Isp of 60 sec.

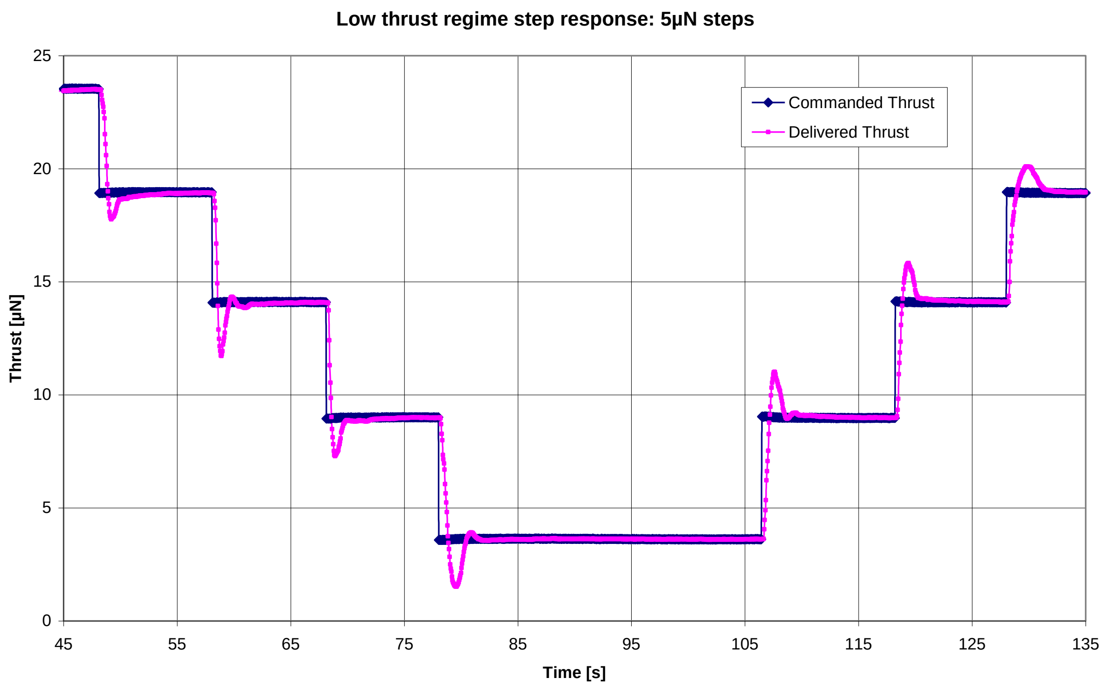

Figure 5: Test result of a MEMS thruster valve operating in closed loop control mode using the integrated mass flow sensor to respond to the commanded steps of 5 µN. Thrust is calculated from the measured flow rate and assuming an Isp of 60 sec.

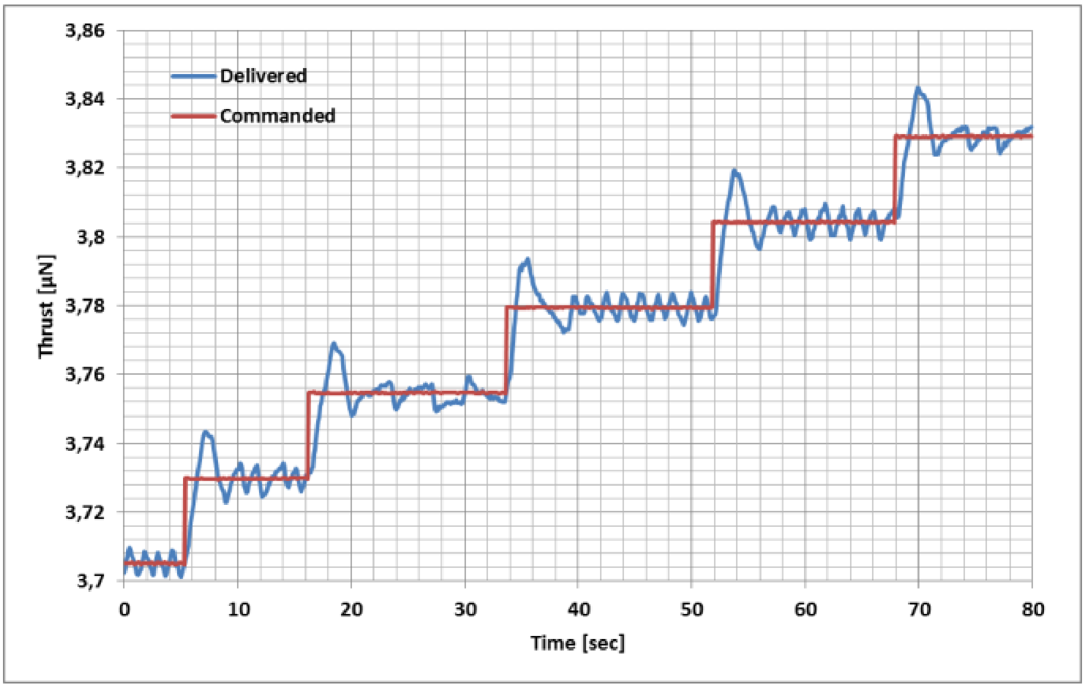

Figure 6: Test result of a low flow MEMS thruster valve operating in closed loop control mode using the integrated mass flow sensor to respond to the commanded steps of 0.025 µN (25 nN) Thrust is calculated from the measured flow rate and assuming an Isp of 60 sec.

Response time and latency

Another important parameter of the closed loop thrust control system is the intrinsic latency. The graph below shows the control current in the proportional MEMS valve heater and the resulting response. From this we can determine that the intrinsic valve latency is in the order of 50 ms.

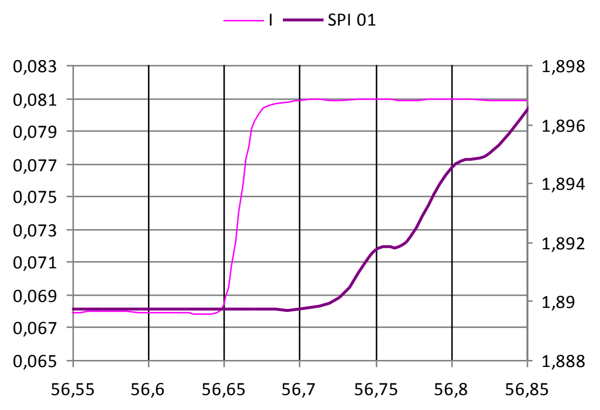

Figure 7: Graph showing the intrinsic valve latency, which is in the order of 50 ms.

At a thruster level, which also includes several other delays and latencies, the response time is currently about 500 ms. Figure 8: shows a typical test result from such a test at a very low flow rate which is the most challenging case.

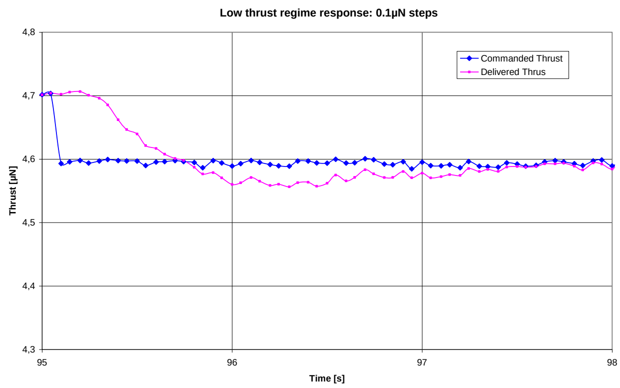

Figure 8: Test result of a MEMS thruster valve operating in closed loop control mode using the integrated MEMS valve to respond to the commanded steps of 0.1 µN. Thrust is calculated from the measured flow rate and assuming an Isp of 60 sec.

Drift and hysteresis

Continues operation of the MEMS thruster valve does of course generate an average temperature change over time. In an open loop configuration this shows up as a temperature drift, or in other words a drift in resulting thrust to the same applied control voltage. This effect is easily overcome in a closed loop configuration through observation of the thruster flow rate and adaption of the valve input. The drift in operating point must however be reduced by the temperature bias control in order to maintain a coherent temperature stack. The temperature drift should not be confused with hysteresis, which if not by design, is an unwanted effect. The MEMS microthruster does <u>not</u> suffer from any hysteresis. The figure below demonstrates the MEMS thruster valve response to a uniform input signal. The sample has been running for a long time in order to reach steady state, but still a small drift is noticeable due to a complete lack of temperature bias control.

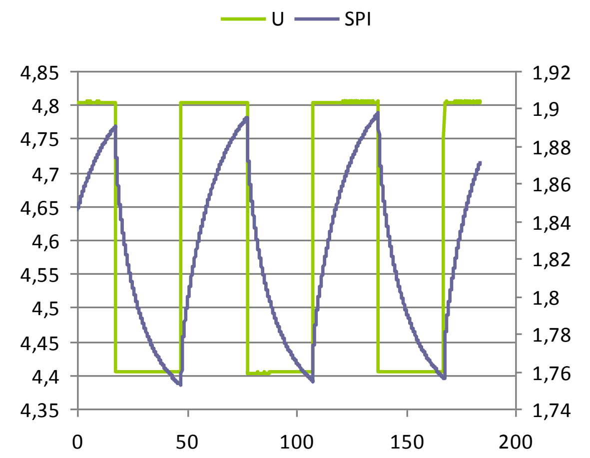

Figure 9: Mass flow sensor response to a uniform pulse train as input signal.

Concluding remarks on test results

The test results above demonstrate the unique performance and functionality in terms of thrust range, step response, and thrust resolution by using integrated MEMS components and closed-loop control. By optimizing the algorithms and customize the design further the thrust range could be scaled up to 100 mN, still with a thrust resolution of 0.1%, and response times below 200 ms.

XENON FLOW CONTROL SYSTEM

The Xenon Flow Control Module (XeFCM) presented in this paper is intended to be part of a complete Xenon feed system as depicted in Figure 10.

Note that at system level the strategy is to have a single pressure regulator module (PRM) which would be close to the tank and multiple XeFCMs, which would reside close to the Ion thrusters. Also a neutralizer and other valves, sensors and filters would be needed but are for reasons of simplicity not necessarily depicted in Figure 10.

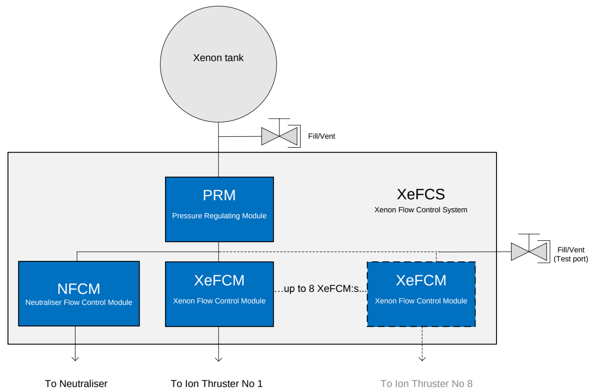

Figure 10: Block diagram of the Xenon Flow control System

This paper will describe the Flow control module only. Details of the Pressure regulator module can be found in [5].

XeFCM design

The Xenon Flow Control Module comprises several components shown in Figure 11**:**

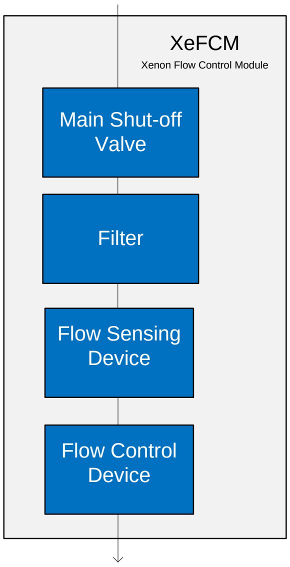

Figure 11: Block diagram of the Flow Control Module.

The primary Main shut of valve is a COTS, normally-closed, solenoid valve. This valve provides perfect seal when the specific XeFCM branch is not used. Upon activation of the branch the valve is opened and the regulation is performed by the downstream components of the XeFCM.

The downstream components of the XeFCM are all MEMS-based. The main component of the XeFCM is the proportional thermally actuated MEMS valve. The functional MEMS valve is equipped with multiple sensors. Both pressure and temperature are measured within the valve chip. The mass flow through the device is measured with a mass flow sensing device, manufactured using MEMS technology.

The module is a cylinder with 43 mm in diameter. The height of the cylinder is 17 mm, as shown in Figure 12.

Mechanical interface is formed by 1/8" weldable studs on the inlet and outlet. Electrical interface is formed by 10 flying leads. The installation length, i.e. weld stud to weld stud is approximately 37 mm. The mass of the module, manufactured in stainless steel, is approximately 60 grams. The voltage input requirement for the pressure and mass flow sensing device is at least 7 volt, and the output pressure and temperature measurement are digital, using the SPI bus. Fluidic input is gaseous Xenon at 2 bars (MEOP). The proportional valve requires an analogue voltage between 3-5 V, and consumes around 0.5 W power.

Figure 12: The manufactured housing and flow control valve.

Manufacture

The Flow Control MEMS chip comprises sensors and a proportional normally open valve with an integrated mass flow sensor. The small and complex MEMS chip is manufactured by fusion bonding of four silicon wafers. One valve measures 20x7 mm, and has a thickness around 1.2mm.

A close-up of the MEMS valve is shown in Figure 13. The backside of the valve is shown, with the electrical contact pads to the valve clearly visible.

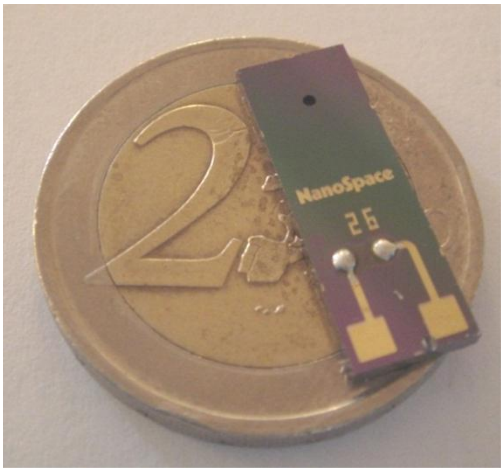

Figure 13: One manufactured chip on a €2 coin for reference.

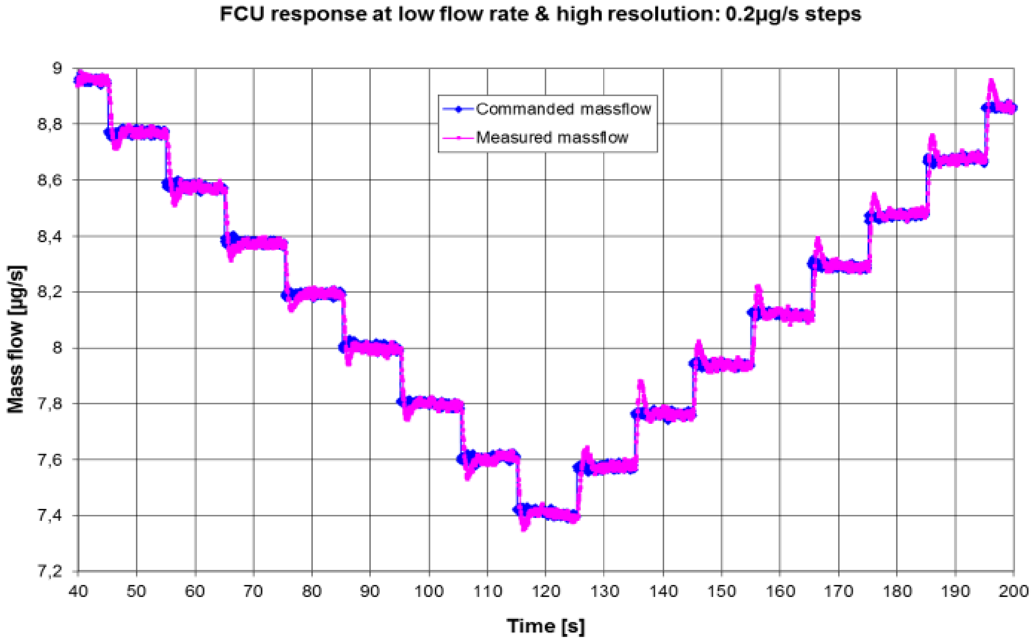

Figure 14: Test result showing a the XeFCM capability to deliver low flow rates with high precision. Flow resolution is well below the targeted 0,2 µg/s in this case.

Results

The XeFCM has been calibrated versus an external mass flow sensor (Bronkhorst) and tested extensively throughout in the flow range between 5 and 50 µg/s which is the specified range for the Astrium micro-Newton RIT Ion thruster. In the same way as for the thruster application, the challenge in this case is to deliver a precise flow rate in the lower end of the regime. A test result showing commanded steps of 0,2 µg/s and the response in delivered flow is shown in Figure 14.

MICROTHRUSTER HERITAGE

The CubeSat propulsion module is a new design but has a heritage from the MEMS thrusters that were on board the PRISMA satellites that where launched 2010 [6].

All essential MEMS design features in the CubeSat propulsion module thrusters have heritage from the PRISMA development. This includes the proportional flow control valve, chamber/nozzle, filter and heaters. However, there are some differences which make the proposed thrusters less mature than the ones used on PRISMA. The most obvious difference is the closed-loop control which essentially is the mass flow sensor and the associated electronics. A brief description of the PRISMA microthruster design is included in order to show the heritage of the MEMS thruster technology.

Heritage: The PRISMA microthrusters

NanoSpace has developed, built and tested the MEMS microthruster technology on board the PRISMA satellites. On PRISMA the eight milli-Newton thrusters were located in two thruster pods with four thrusters each. The propellant was Nitrogen. Each thruster was individually controllable and had open loop proportional thrust control. The dimension of the thruster pod is 44 mm in diameter and 68 mm in height. The total weight of the MEMS thrusters pod is 115 g.

Figure 15: PRISMA thruster module that accommodates four proportional milli-Newton MEMS thrusters.

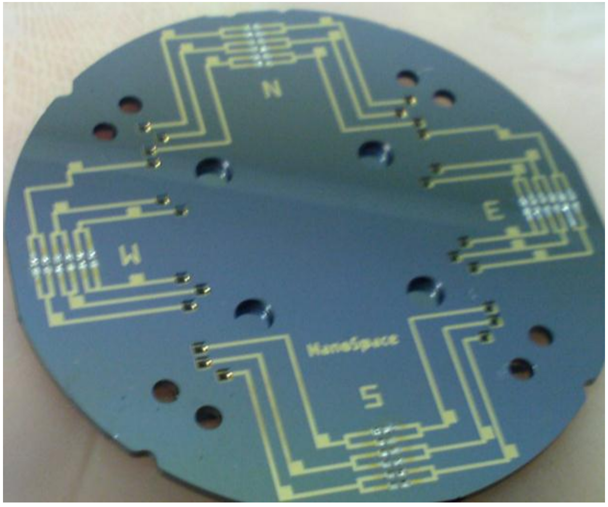

Figure 16: PRISMA thruster MEMS chip with four proportional thrusters with thrust axis in the equatorial plane with 90 degree separation. Total mass of the open-loop PRISMA thruster chip is <4 grams.

The mechanical design of the thruster pod assembly consists of a spherical housing, acting as a pressurized plenum. It is conventionally fabricated fine-mechanical aluminum housing. Each thruster pod assembly comprises a MEMS thruster chip, mechanical and electrical interface components between the MEMS chip and the pod and to the rest of the spacecraft. The pod is designed for a maximum expected operating pressure (MEOP) of 6 bars of non-corrosive gases. The thruster pod assembly interfaces a conventional gas storage and feed system with a screwed fitting to the feed system tubing.

After the PRISMA flight a second generation of the microthruster module was developed under an ESA contract. This version had the mass flow sensor and the front end electronics included into the thruster pod and the number of thrusters was two (in opposite directions) instead of four. A summary of the design requirements for the micropropulsion thruster is given in Table 1.

Table 1: Design requirement for the micropropulsion thruster.

Micropropulsion Thruster Specification		
Thrust	10 µN - 1 mN	Each thruster
Isp	50 - 100 sec	higher with heated N2
Power	<3 W/thruster	Average
Feed pressure	4 bar	Nominal
MEOP	6 bar	
Proof/Burst	9/12 bar	
Temperatures	0 to 50°C	Operating
	-10 to 60°C	Non-operating
Mass	115 g	
Dimension	44 mm 51 mm	Diameter Height

DISCUSSION

Three extremely challenging requirements for several scientific missions and drag free flight missions are the low thrust level, the fine thrust resolution and the short response time. In particular the combination of low thrust (and thus flow rates) together with short response time is a challenging combination. The physics behind this becomes clear when reviewing the schematics of the closed-loop thruster in Figure 17 and considering the given example. From a fluid control perspective, the regulated system consists of a flow restrictor (the MEMS flow control valve), an internal gas volume (the sum of feed lines and thrust chamber volumes) and another flow restrictor (the nozzle throat).

Understanding the physics, an example:

Assume that the MEMS valve is closed. This implies (in vacuum) zero pressure and zero mass flow through the nozzle. Now assume that the valve immediately opens to allow a flow rate of 5µg/s (which corresponds to 2 µN). Also assume that the nozzle throat is sized such that this flow rate corresponds to 0.1 bar pressure in the chamber (which corresponds to thruster dimensioned for ~100 µN at full thrust). Now, to reach this new steady state condition, the total volume between the valve and the nozzle throat must be "filled up" with gas from zero to 0.1 bar. Assume that the total volume of feed lines and thrust chamber is 10 mm3. A first order estimate of the response time of such a system is 230 ms. Response time increases linearly with volume. This is an optimistic estimate neglecting a number of effects such as valve opening response, reduced flow rate as the pressure increases, delays in the control loop, etc. that in reality will slow down the response time significantly. However, this example illustrates how crucial it is to minimize the internal volumes in a regulated system with low flow rates.

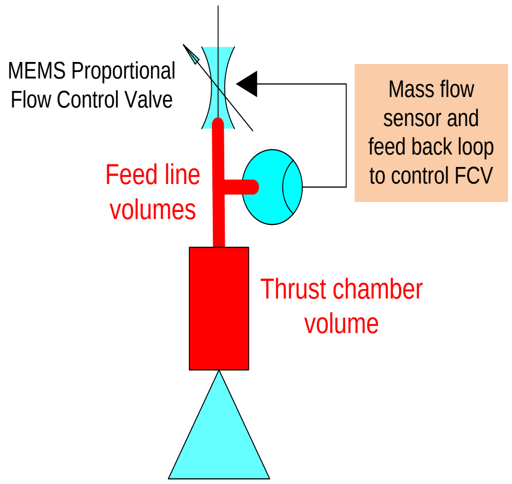

Figure 17 Schematic view of a closed loop micro thruster with internal volumes

A remaining issue is to address variations in temperatures. All experiments have been performed in room temperature. Variations in temperature will clearly affect the flow rate. This is a known issue, why the valve chip is equipped with temperature sensors. At this time no temperature correlation experiments have been performed.

CONCLUDING REMARKS

The presented components are two examples of how size and mass can be decreased, and still allow advanced functionality that can enable new space missions. The main achievement of this custom designed micropropulsion system for CubeSats is that several critical components such as the flow control valve, mass flow sensor and chamber/nozzle have been integrated on the same chip. It is our belief that many of the future small satellite missions will be able to conduct more advanced missions given the propulsion capability and thus deliver better science or more added value for commercial applications in the future.

In particular the combination of low thrust (and thus flow rates) together with short response time is a challenging combination.

In our view, using MEMS technology and integrating the flow control valve, mass flow sensor and chamber/nozzle on a single chip is the best –if not the only- way to realise a closed loop control thruster that can meet new tough small satellite propulsion requirements.

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