# SYSTEM ANALYSIS AND DEVELOPMENT OF A COOL GAS GENERATOR BASED MICROPROPULSION SYSTEM

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## Abstract

To date there is a growing interest in the use of micro and nano spacecraft within government and industry. Because micro and nanosatellites reduce the cost of access to space, their use is more and more widespread, especially for in-space technology demonstration missions. Also, these spacecrafts can be used for a vast number of missions that could involve inspections of other spacecraft like the International Space Station (ISS) or formation flying in order to establish a satellite array used for communications or creating a deep space telescope. For these missions, micro satellites need a propulsion system that can provide ΔV for orbit transfer, orbit change and/or attitude control.

In order to investigate the possibilities for propulsion on very small spacecraft by using space qualified conventional components, a scaling exercise was performed to give insight in how the mass and volume of the propulsion system components will change relative to the spacecraft mass when the satellite is scaled down from a mass of 300kg to a mass of 10kg and 1kg. This scaling exercise was based on a cold gas propulsion system because of the fact that this type of propulsion system is most applicable for micro satellites. The exercise shows clearly that the main focus of scaling propulsion systems must not only be aimed at miniaturising the thruster but also at integration and miniaturisation of the feed and storage system of the propellant.

With this focus in mind, TNO, TU Delft and UTwente are exploring technologies that contribute to enabling compact storage of propellants and small, low mass highly integrated feeding and thruster systems making use of Micro Systems Technology. This research is performed as part of MicroNed, a Dutch national research programme, and more specifically within the research cluster MISAT. This research has led to the design of a cool gas generator based micro propulsion system, the $T^3$µPS (the **T**NO, **T**U Delft, U**T**wente Micro Propulsion System).

$T^3$µPS uses solid propellant cool gas generators. The propellant is initially stored in solid form before being released as pure Nitrogen. Several cool gas generators can be used successively to refill the plenum when necessary. The system is unpressurized at launch and operates at low pressure (a few bars) in orbit, making it possible to have a flexible low volume, low mass and low risk design. A printed circuit board carries the electrical interface and is also the mechanical interface with the structure of the spacecraft. Thus $T^3$µPS is a plug-and-play device that can easily be integrated in any CubeSat.

TNO has manufactured the first engineering model of the $T^3$µPS system. A pressure sensor and a valve, commercial off-the-shelf components, have been integrated in that engineering model to perform the first functional tests. With the manufacturing, the assembly and testing of $T^3$µPS, it has been demonstrated that a new kind of micro propulsion system based on cool gas generators is particularly suitable for micro satellites.

## Nomenclature

| | |
|---|---|
| CGG | Cool Gas Generator |
| COTS | Commercial Of The Shelf |
| GTMS | Glass-To-Metal Seal |
| I/F | Interface |
| MST | Micro Systems Technology |
| PCB | Printed Circuit Board |
| T$^3\mu$PS | **T**NO, **T**U Delft, U**T**wente Micro Propulsion System |
| TNO | Netherlands Organisation for Applied Scientific Research |
| TU Delft | Delft University of Technology |
| UTwente | University of Twente |

## 1. Introduction

As many other engineering fields, space technologies follow a trend to miniaturisation. This is true for spacecraft and subsystems. Because each kilogram adds tens of thousands of euros to the total costs, microsatellites offer access to space at a more affordable cost. This is particularly interesting for space technology demonstration missions where the risk is always high and can be a factor of hesitation to make the final step towards in-space demonstration. By reducing the financial risk, miniaturisation of satellites allows an easier access to space.

Standardisation is another way to reduce cost. At the beginning of the twenty-first century, California Polytechnic State University San Luis Obispo and Stanford University's Space Systems Development Lab proposed the CubeSat standard[1] for microsatellites. CubeSat microsatellites are composed of one to three modules, 10 by 10 by 10 centimetres and one kilogram each. Several universities worldwide use this standard to develop their own satellite. Module structure and subsystems are available commercial off-the-shelf and serve as basic elements for the integration of payloads and other subsystems.

With the increase of more and more advanced payloads, attitude control systems are under development to ensure a proper stabilization of the satellite, which allows technology demonstration in nominal conditions. Due to the low power that is available and due to the constraints on volume and on mass, few micropropulsion projects have come to an advanced stage. Yet propulsion capabilities would considerably extend the range of applications of microsatellites. Indeed, with propulsion systems, it would for example become possible to fly several microsatellites in a formation and apply corrections regularly to maintain the relative positions of spacecrafts.

With this focus in mind, TNO, TU Delft and UTwente are exploring technologies that contribute to enabling compact storage of propellants and small, low mass highly integrated feeding and thruster systems making use of Micro Systems Technology (MST). This research is performed as part of MicroNed, a Dutch national research programme, and more specifically the research cluster MISAT[2,3]. Aim of the research in this cluster is to design and build prototype sensors, actuators, and payloads based on Micro Systems Technology adaptable to and suitable for a variety of new space missions. This research has led to the design of a cool gas generator based micropropulsion system, the T$^3\mu$PS (the **T**NO, **T**U Delft, U**T**wente Micro Propulsion System).

The first engineering model of T$^3\mu$PS has been manufactured and assembled. The result of the first tests performed on the integrated system will be presented in this paper. Also our vision for the future for our T$^3\mu$PS will be addressed.

## 2. Scaling of a satellite

Nowadays conventional propulsion systems like cold gas, mono propellant, bi-propellant and electric propulsion systems are scaled down for small satellites but these systems will reach a certain limit when satellites on micro scale are being considered.

In order to investigate these limits, by using conventional production techniques, a scaling exercise was performed to give insight in how the mass and volume of the propulsion system components will change relative to the spacecraft mass when the satellite is scaled down. This scaling exercise was based on a cold gas propulsion system because of the fact that these types of propulsion systems are valued for their low system complexity and their small impulse bit.

First a 300 kg baseline satellite with a standard cold gas propulsion system using nitrogen stored under high pressure was selected and adapted to be applicable for the exercise (UoSat-12[4]). Using commercially of the shelf (COTS) components for the same system architecture as the baseline satellite, the satellite was scaled down to a 10 kg satellite and to a 1 kg satellite. For components that are not commercially available in the range of the specific requirements a basic scaling of the COTS component, which corresponds most with the required properties, was performed. For deviations of the COTS components that were simply unacceptable, a basic scaling with respect to the original component mass of the baseline satellite and basic mechanical constraints was made to estimate a probable component mass.

For the baseline satellite it can be concluded that the three propulsion system components that have the largest impact on the wet mass percentage are the nitrogen storage tank, the pipe work/brackětry and the nitrogen, as can been seen in Figure 1. Together they represent almost 66% of the total propulsion system wet mass.

Scaling the baseline satellite to a 10kg satellite result in a decrease of the percentage pipe work/bracketry, accumulators and the nitrogen, and an increase of the percentage thrusters and pressure transducers.

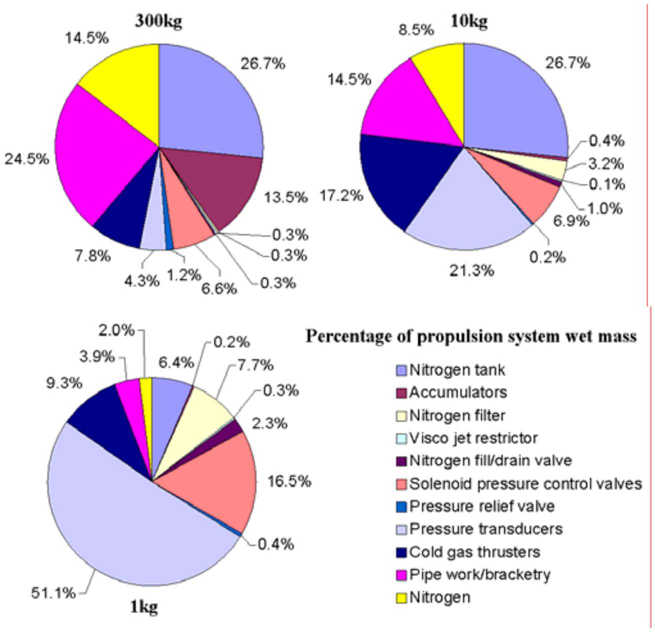

**Figure 1 – Distribution in components in percentages of propulsion system wet mass**

Again scaling but know to a 1kg satellite shows that more than 50% of the propulsion system wet mass are pressure transducers and almost 17% is for the solenoid pressure control valves. Now, the nitrogen tank, the pipework/bracketry, and the nitrogen are together only 12.3% of the systems wet mass.

The overall conclusion from the scaling exercise is that when cold gas propulsion systems (based on the UoSat-12 system architecture) for small satellites with masses ranging from 10 kg to 1kg and even smaller, the emphasis of the disadvantageous impact of conventional propulsion system technology lays on the huge dry mass and volume percentages increase of the propulsion feed system components of the propulsion system. In order to be able to use small (micro) satellites for specific missions, non-conventional techniques should be considered to reduce propulsion system component mass, especially propulsion feed system components, and to integrate the complete propulsion system to reduce propulsion system volume.

Bear in mind that for this exercise only COTS space qualified components space were used or scaled. Also, the possibility of using conventional technologies to produce new small propulsion system components was not taken into account. It was clear that most of the available components were not developed for satellites with masses of 10 kg and smaller. For example the lightest available space qualified COTS pressure transducer has a mass of 100 grams, and also the smallest solenoid control bang-bang valve is 64 grams.
This exercise does not show that the conventional techniques can be concluded to be the limiting factor, but does show that the available COTS space qualified components limit scaling down of the satellite.

New techniques could establish a potential weight and volume reduction, and other benefits could be achieved by using techniques like Microsystems Technology (MST), and Cool Gas Generator (CGG) techniques for the propulsion system for micro satellites.
MST is the integration of multiple components in many domains such as electrical, mechanical, chemical, thermal, and/or optical on a common silicon substrate through microfabrication technology.
A cool gas generator consists of a solid block of material inside a casing. The gas is chemically stored inside the solid material. A small igniter starts the decomposition of this block into the required gas and a slack that remains in the gas generator. Due to the unique design no external cooling is needed for the gas, this giving a high storage efficiency. The gas is released at ambient temperature.
Using these technologies, the propulsion system mass can be decreased significantly, as shown in Figure 2. Due to the fact that the propellant storage for the 1kg non-conventional satellite now also functions as the structure (thus including pipe work/bracketry) of the propulsion system, the mass increases compared to the 1kg conventional satellite. Thereby, the propellant is now stored under low pressure.

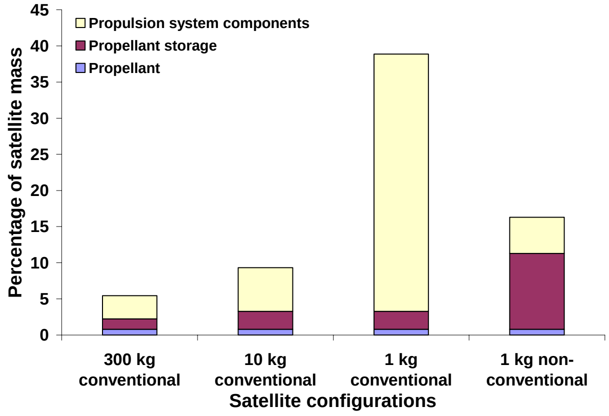

**Figure 2 – Propulsion system mass percentages of total satellite mass**

## 3. Concept for the micropropulsion system

The next step has led to the design of a cool gas generator based micro propulsion system, the T$^3$µPS (the **T**NO, **T**U Delft, U**T**wente Micro Propulsion System). The design concepts for the preliminary design of the propulsion system are given in Figure 3[5].

Cool gas generators allow an efficient storage of the propellant in a solid form. When activated, a gas generator releases nitrogen in a plenum that is connected to an integrated thruster. When the pressure in the plenum becomes too low the next gas generator can be activated to refill the plenum. The system is unpressurized at launch and operates at low pressure (a few bars) in space, which allows designing a low volume, low mass storage system, without pressure regulation. Furthermore a gas generator is inert until it is activated. All these advantages are of high interest for micro and nanosatellite applications where low risk, safety and simple systems are of high importance.

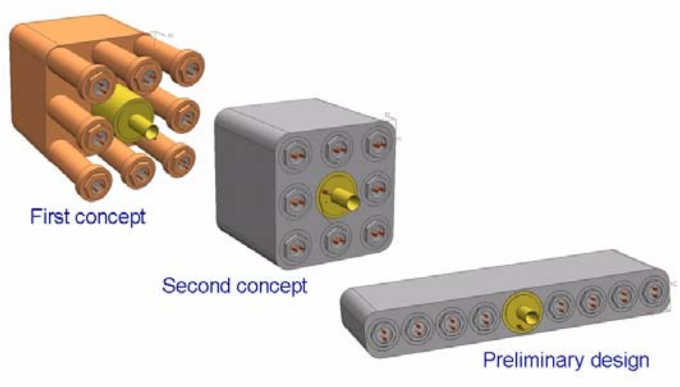

**Figure 3 - Design concepts for micropropulsion system[5]**

## 4. Requirements for the T$^3$µPS

No specific microsatellite mission was defined for the MISAT satellite. The CubeSat standard has been used as reference to design a modular micropropulsion system that could be easily integrated in a CubeSat as a plug-and-play module. Based at the CubeSat standard a system requirements document is compiled[6].

The main requirements for the system are listed in Table 1 below.

**Table 1 – Main requirements**

| Characteristic | Requirement |
|---|---|
| Mass | <100 g |
| Volume of the system | <100 cm$^3$ |
| Total impulse | >0.5 Ns |
| Total power | <10W during two minutes |
| Modularity | Plug-and-play |
| Mechanical interface | Printed Circuit Board (94x94 mm$^2$) |

Requirements on mass and volume were defined as 10% of the respective values for a CubeSat module. A Printed Circuit Board (PCB) is used as mechanical interface. Indeed, CubeSats, like the Dutch Delfi C3[7], usually consists of a stack of PCBs. Using the same kind of interface allows an easy integration of the micropropulsion system in any CubeSat.

Besides the given requirements, the CubeSat standard prescribes that the satellites must not contain any pyrotechnics or pressurized systems. In addition, it is not possible to have access to the satellite between delivery to the launch agency and launch.

## 5. Design of the engineering model

The design of the engineering model[8] of T$^3$µPS is illustrated in Figure 4. It consists of:

- Plenum
- Plate
- One or more (up to 16) gas generators
- Pressure transducer
- Nozzle assembly
- On/off valve
- Printed Circuit Board that holds the electronics and a microcontroller

The plenum (empty) has an inner volume of about 40 cm$^3$. It is closed by a plate. This plate includes nine holes to insert seven gas generators and a pressure transducer and to connect the feeding subsystem which includes a valve whose outlet is connected to a nozzle.

**Figure 4 - Design of T$^3$µPS**

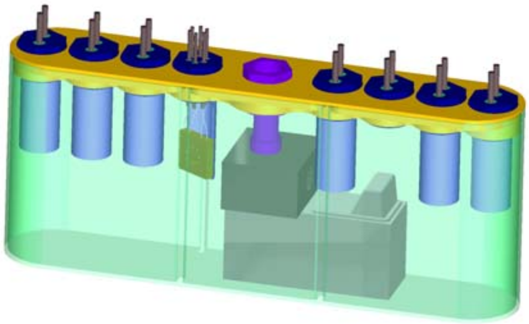

**Figure 5 – View of the inside of the system**

Each gas generator consists of a cap making the interface with the plate and providing electrical feedthrough, and a tube. The ignition device is connected to the electrical feedthrough, while a charge and filters are placed inside the tube before it is screwed in the cap.

The pressure transducer (Kulite LE-30-125[9]) is connected to an electrical feedthrough featuring six pins. Four are used for the pressure transducer; two are available to connect the valve.

The assembly formed by the aforementioned elements is fixed on a PCB that holds the electrical interface and serves as mechanical interface with the structure of the spacecraft.

The electrical interface connects the micropropulsion system with the bus of the spacecraft. It carries out several functions: the conversion to the appropriate voltages for the various subsystems, the handling of the pressure data, the ignition of the gas generators and the actuation of the valve. The main component is a microcontroller compatible with the CAN2.0B protocol but other protocols would be possible. For safety reasons, two commands are required to either start ignition of a gas generator or to actuate the valve.

The complete system is presented in the block-diagram of Figure 6.

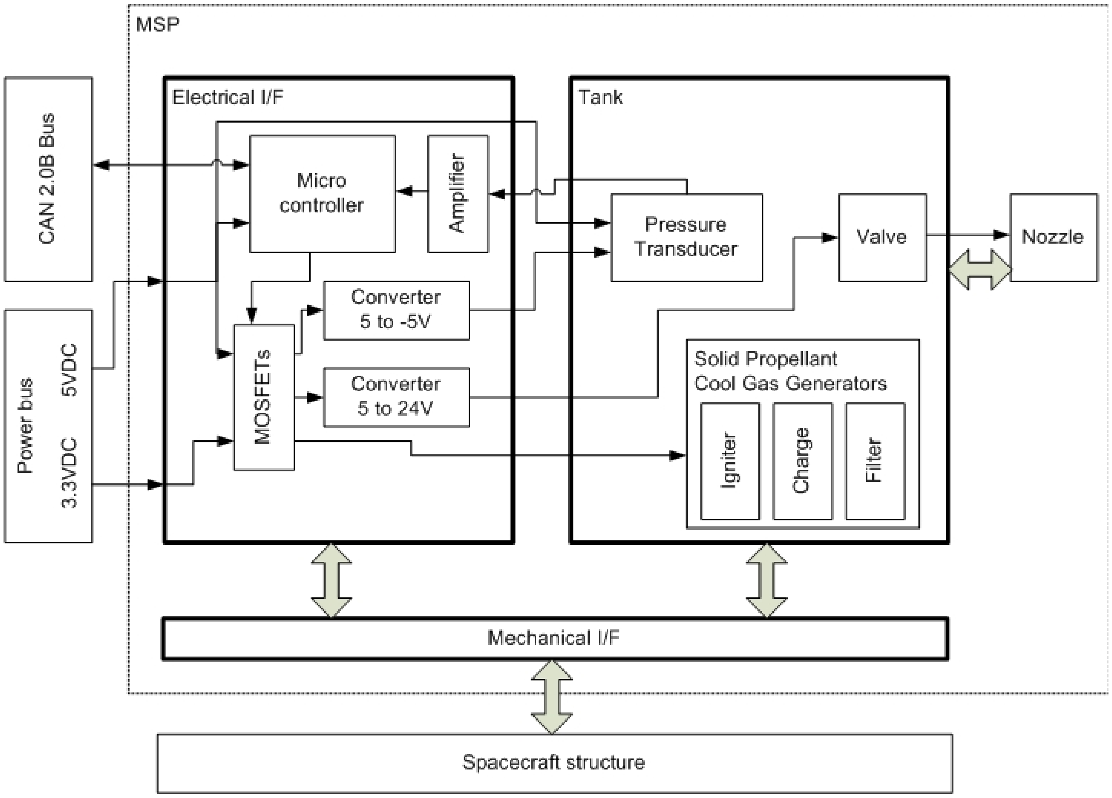

**Figure 6 - Block-diagram of $T^3\mu PS$**

## 6. Manufacturing and assembly

The first engineering model has been manufactured in the second quarter of 2007. Plenum, plate, gas generator casing and the additional elements to connect the valve, the nozzle and the pressure transducer were manufactured in $TiAl_6V_4$ by the workshop of TNO. This material has the advantage of a large yield stress value and a low density, which is particularly interesting to design light-weight elements.

The Glass to Metal Seal (GTMS) of the electrical feedthroughs for the gas generators and the pressure transducer assembly were made by Louwers BV. Those GTMS electrically insulate the pins (in titanium grade 2 for the gas generators and grade 1 for the pressure transducer assembly) from the casing while providing a leaktight seal.

The printed circuit board (PCB) was created by PLTc BV and components were assembled at TNO. It includes a six pins header for In-System Programming of the microcontroller, which allows uploading software on the microcontroller without removing it from the circuit. It also includes a four pins header to connect the electrical interface to a computer through the serial port, which is easier to use for first tests than the more complex CAN interface.

Originally, it was planned to mount the valve inside the plenum, but in the final design the valve was placed outside the plenum to perform the first tests on the integrated system. This solution also offered the possibility to replace the valve if required.

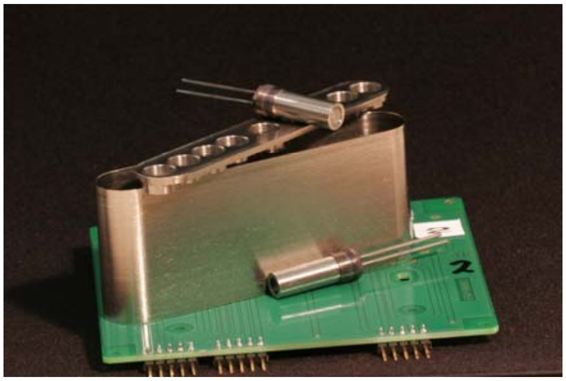

**Figure 7 – Plenum, plate, gas generators and electrical interface before assembly**

The plate was welded on the plenum to form the tank. O-rings were inserted in grooves in the plate in order to ensure the leak tightness of the system.

## 7. Specifications

The main specifications of the configuration of $T^3\mu PS$ used for the first series of tests on the integrated system are presented in Table 2. The mass breakdown is given in Table 3.

**Table 2 – Specifications of the engineering model**

| | |
|---|---|
| Mass | 128 g |
| Box dimensions | 94 x 94 x 18 mm |
| • Plenum | 84 x 34 x 16 mm |
| • PCB | 94 x 94 mm |
| Number of gas generators | Up to 6 |
| Amount of nitrogen produced per GG | 0.15 g |
| Valve – model | Clippard E210A |
| Valve – response time | 10 ms |
| Pressure sensor – model | Kulite LE-30-125 |
| Pressure sensor – range | 0-7 bar |
| Communication | Serial port |

**Table 3 – Mass breakdown of the engineering model**

| | |
|---|---|
| Plenum | 19.6 g |
| Plate | 9.1 g |
| Gas generator (complete) | 7 x 2.0 g |
| Valve assembly (outside) | 31.7 g |
| Pressure sensor assembly | 2.9 g |
| Nozzle assembly | 9.6 g |
| Electrical interface | 40.9 g |
| **TOTAL** | **128 g** |

Each gas generator can release 0.15 grams of nitrogen. A typical flight configuration could have 7 gas generators as the configuration shown in Figure 4. Depending on the mission, additional gas generators could be added on the other side of the tank if required. Thus, up to 16 gas generators could be installed, providing 2.4 grams of nitrogen, without major modification of the design and with a very limited mass increase. Considering a typical specific velocity of nitrogen cold gas thruster (680 $m.s^{-1}$) and a one-kilogram satellite, such a mass of propellant could provide a total velocity increment of about 1.6 $m.s^{-1}$.

## 8. Tests of the integrated system

The first series of tests was performed on the integrated system at the end of May 2007 after subsystems (electrical interface, valve and pressure transducer) had successfully been tested individually.

### *8.1 Setup*

The test setup used for the tests on the integrated system is shown in Figure 8. The tank is shown in Figure 9. Gas generators can be inserted at positions 1 to 4, C and 7. Position 5 is for the pressure transducer assembly, position 6 is for the safety valve assembly and position 8 is for the nominal valve.

The test setup features the tank with one or more gas generators and the pressure transducer assembly. The valve and the nozzle were connected to one of the external orifices (right side) of the tank in order to keep an easy access to gas generators on the left side. For safety reasons, a ball valve and a relief valve were also connected to the tank. The tank was locked in a cage to prevent any displacement.

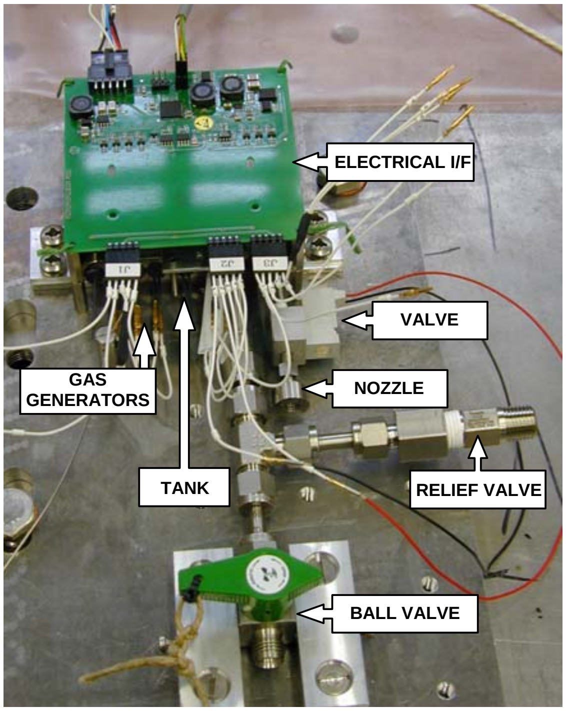

**Figure 8 – Test setup**

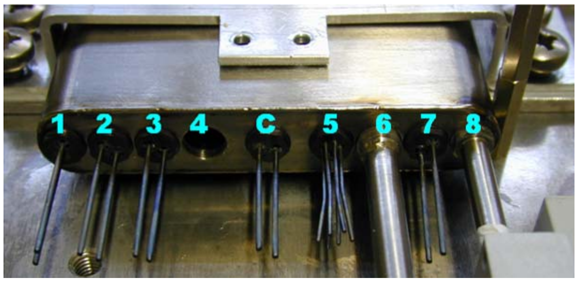

**Figure 9 – Plenum with integrated gasgenerators during testing at TNO test facilities**

The electrical interface was placed above the tank and connected to the gas generator(s), the valve and the pressure transducer. Two different power sources were used; one (5VDC and current limited to 3A) connected to the microcontroller, the valve and the pressure circuits; one (3.3VDC-5VDC) connected to the ignition circuit and controlled from the data acquisition room. The interface was also connected to the serial port of a remote computer, which allowed communicating with the micro-controller.

A thermocouple was connected to the plate, close to the gas generators, and connected to the data acquisition system. The temperature data brings important information, especially when an ignition attempt fails. Indeed, it helps determining whether the failure can be attributed to a problem with the ignition device (no temperature increase for example).
Matlab® scripts were written to create an automatic procedure to send the appropriate commands to the microcontroller for ignition, pressure data monitoring and valve actuation. Pressure data were both displayed on the screen and collected in a file, allowing post-processing.

### *8.2 Test series*

Several tests were performed to verify that the requirements are met by the integrated system.

For the first test, the gas generator was directly connected to its power source. The objective was to test ignition of the gas generators integrated into the micropropulsion system, to determine more accurately the power requirement. Gas generator development tests had already been performed but with a different setup. Consequently, this test was the first one taking place with the actual design of the micropropulsion system.

Then, gas generators were also connected to the electrical interface. Ignition was attempted for various voltages and configuration of the ignition device (resistance). It was decided to fix the voltage (3.3VDC, 4VDC or 5VDC) rather than the current to simulate the conditions of a satellite bus.

For each ignition, a maximum time of 120 seconds was allowed to achieve ignition.

### *8.3 Results*

For the first two tests, a single gas generator was directly connected to the second power source, the electrical interface being used only for pressure monitoring and valve actuation. Ignition was unsuccessful.

The gas generator was replaced for the second test with different voltage and current settings. After ignition, the pressure variation indicated a total decomposition of the charge. A small leakage was observed, but it was decided that this was no problem for the engineering model test series. The valve was actuated through the electrical interface to release the gas.

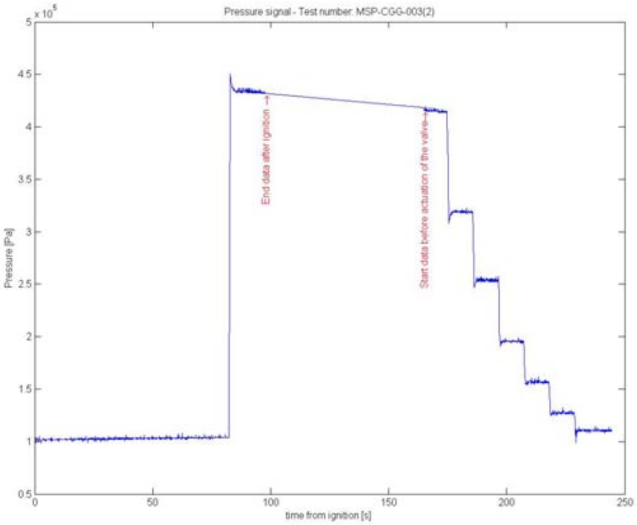

**Figure 10 – Pressure profile of an integrated test with CGG firing and gas release by the valve**

Following tests were performed using the electrical interface to control ignition of gas generators. Not all gas generators ignited due to problems with the resistance wire. When ignition was achieved, the pressure was released by actuating the valve for several pulses of 500ms every 10 seconds, see Figure 10.

### *8.4 Conclusion of the test series*

The first test series verified that most of the requirements are already met. Indeed, the electrical interface, the pressure transducer and the valve performed as expected. Mass and volume requirements for the engineering model are fulfilled. With small modifications the overall mass and volume requirements can be met.

Three ignitions from the test series were successful, proving that the concept works. Nonetheless, the reproducibility of the ignition needs to be improved. Several propositions have already been formulated to improve the design of the gas generator and especially the ignition device which is thought to be the main cause of ignition failure. For example, development tests of gas generators demonstrated that the addition of an energetic layer on top of the charge allows activating gas generators with a lower energy requirement. This solution could be used to decrease the energy required for ignition if other solutions such as the modification of the ignition device do not have a sufficient effect.

Further tests are required to test the impact of the various solutions that have been suggested to improve the reliability and the reproducibility of the ignition of the gas generators.

Furthermore, some specifications still have to be measured. Those are for example the leak rate, the minimum and total impulse bits, and the response time. Thermal and vacuum tests are required to confirm that the system can perform in the space environment.

## 9. Future developments

The next step in the development is to improve the Engineering Model with improved ignition for the cool gasgenerators. Also small improvements in the microcontroller software are planned. Last but not least the micro valve module including filter, valve, pressure transducer and nozzle developed at UTwente will be added (Figure 11). This module is 15 mm in diameter and 15 mm long and carries the components integrated in three silicon wafers[10]. By replacing the present valve, pressure transducer and nozzle with this new module, the total mass will be reduced to less than 100 grams. The performances of the micro-nozzles are already tested at TU Delft test facility.

The upgraded engineering model will be subjected to a new test series which will include mechanical and environmental tests.

The subsequent step will be a flight test of the micro propulsion system which is foreseen in 2009 / 2010 on board of a cubesat.

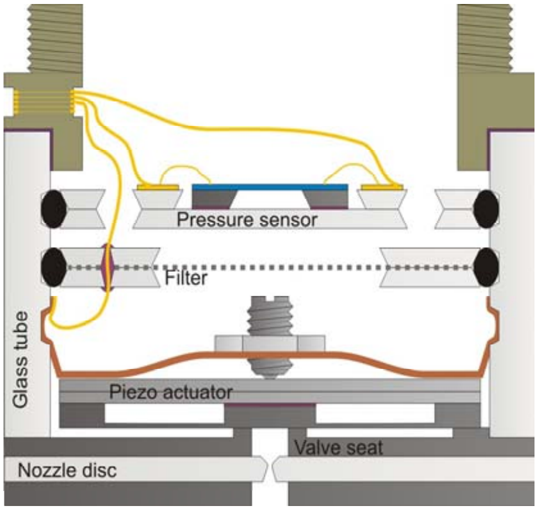

**Figure 11 - Drawing of the compact integrated feeding and thruster system as designed by UTwente**

**Figure 12 - Engineering model of the glass tube including valve and nozzle**

When the system is flight demonstrated, commercialisation will start. The commercialisation phase is already in preparation as discussions with companies in the Netherlands have started.

The team of TNO, TUDelft and UTwente will then concentrate on future advanced, these are:

- Advanced cool gas generators that can boost the total impulse with a factor of two
- Optimised design to lower the mass
- Hot gas thrusters that offer a higher specific impulse

## 10. Conclusion

Providing micropropulsion capacities to microsatellites would considerably enlarge the range of applications of that kind of spacecraft. It has been shown that propulsion systems, based on state-of-the-art space-qualified components, for very small satellites are not feasible. Particularly current pressure transducers and valves are too big to be accommodated on board of very small satellites. New technologies concerning compact storage of propellants (using CGG technology) and compact, highly integrated feeding and thruster systems (using MST) offer major mass and volume savings and are enabling technologies for propulsion onboard of very small satellites.

With the manufacturing and the assembly of the engineering model of T$^3$μPS and the tests that were performed, it has been demonstrated that such a new kind of micropropulsion system based on cool gas generators is particularly suitable for microsatellites. Indeed, the low mass, low volume, low cost, T$^3$μPS is a modular system that can easily be integrated in a CubeSat as a plug-and-play module.

## Acknowledgements

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