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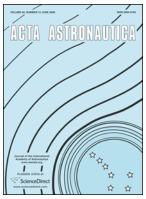

First results of PRECISE—Development of a MEMS-based monopropellant micro chemical propulsion system ☆

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ABSTRACT

PRECISE focuses on the research and development of a MEMS-based monopropellant micro chemical propulsion system for highly accurate attitude control of satellites. The availability of such propulsion systems forms the basis for defining new mission concepts such as formation flying and rendezvous manoeuvres. These concepts require propulsion systems for precise attitude and orbit control manoeuvrability. Application-oriented aspects are addressed by two end-users who are planning a formation flying mission for which the propulsion system is crucial. Basic research is conducted aiming at improving crucial MEMS technologies required for the propulsion system. Research and development also focuses on the efficiency and reliability of critical system components. System analysis tools are enhanced to complement the development stages. Finally, the propulsion system will be tested in a simulated space vacuum environment. These experiments will deliver data for the validation of the numerical models.

1. Introduction

PRECISE [1] (chemical μPRopulsion for an Efficient and accurate Control of Satellites for Space Exploration) aims for the advancement of research and technologies needed for the development, manufacturing and operation of Micro Electro Mechanical Systems (MEMS) based monopropellant Micro Chemical Propulsion Systems (μCPS). PRECISE combines European capabilities and know-how from universities, research organisations and experienced space companies for the research and development of a μCPS for future market demands. μCPS has been identified to fill the gap between state-of-the-art electrical and chemical propulsion due to its compactness, low power requirements and low system weight. Due to these reasons the MEMS-based μCPS is considered as one of the key technologies for future satellite missions.

All partners in the consortium possess a sound experience in the topics they are called for and they can all look back on various successful projects in their company's history. Two universities are involved, the University of Twente and the Surrey Space Center of the University of

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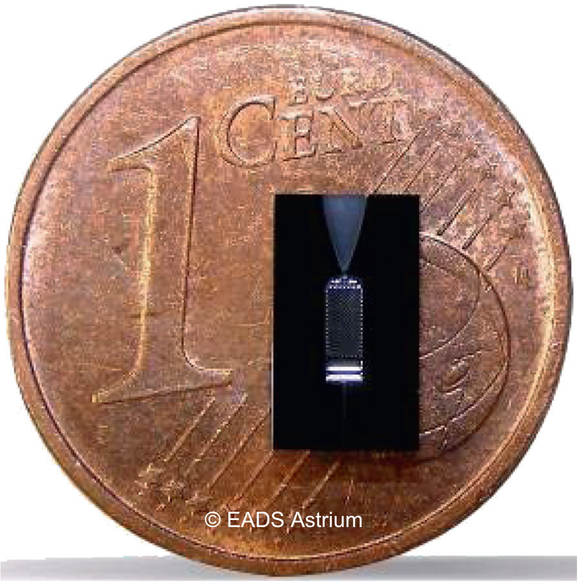

Fig. 1. Illustration of a μThruster in comparison to a one Cent coin.

Surrey. In addition, two large research organisations are participating, the National Center for Scientific Research (CNRS) and the German Aerospace Center (DLR) who is coordinating the project. Finally, three industrial partners namely EADS Astrium Space Transportation, NanoSpace and NPO Mashinostroyenia are completing the consortium.

The term chemical micro propulsion is used for propulsion systems with thrust levels in the order of microNewtons (μN) up to several milliNewtons (mN) and generating thrust primarily by means of chemical energy of the propellant itself. A revolutionary feature is the highly compact, lightweight and modular architecture. The micro thruster weighs only few grams and is etched on a silicon wafer as illustrated in Fig. 1. The thrust range is targeted to lie within $F=1$–10 mN with a minimum specific impulse of $I_{sp}=180$ s. This results in a mass flow rate of approximately 6 mg/s per thruster. The primary objective is the development of a μCPS necessary for highly accurate attitude control maneuvers of satellites as they were not feasible until today with propulsion systems of this size.

Several aspects need to be considered for a consistent development of the μCPS:

- Definition of requirements and specifications, comprising S/C demands.
- Research of critical propulsion aspects.
- Development of crucial components.
- Elaboration of the test facility infrastructure.
- Development of diagnostic tools.
- Further development of numerical flow simulation tools and comparison.
- Manufacturing, assembly, integration and testing of the μCPS.

The thoughts for a dedicated approach to build up a μCPS network were initiated in 2005 since potential application fields were recognized and the feasibility of MEMS technologies for space propulsion was demonstrated. The μCPS development roadmap was elaborated by ESA in the European Space Technology Harmonisation on Chemical Propulsion and Micro-Propulsion, with main emphasis on the harmonization of running European activities under the technical coordination of an industrial partner. On this basis the set-up of a competence network to advance the development of μCPS in Europe was started. Key partners were identified holding know-how and infrastructures for MEMS technologies and components, system aspects, satellites and mission design. Astrium has established a close cooperation with the consortium partners and aims to extend the collaboration with research and development initiatives along the μCPS roadmap to unite the activities and create synergies within one large μCPS European Technology Network.

2. Necessity of micro chemical propulsion systems

Formation flying on LEO and GEO trajectories as well as deep space missions for the realization of novel telecommunication concepts, utilization of flexible space based instruments or even earth observation are some typical applications which address the need for new approaches and place new demands on the propulsion system. Compared with the current technology of mono-spacecraft the realization of distributed systems entails obvious benefits like increasing reliability, flexibility, low cost solutions and a reduced development time. All these aspects are reflected in the current growth of satellites with masses in the range between 10 and 50 kg. Small satellite platforms as well as distributed formation flying require precise control capacities especially for:

- attitude control and de-orbiting.
- precise positioning of spacecraft(s) within satellite constellations and formation flying ‘swarms’, e.g. to provide the required fine adjustment of space based instruments.
- realization of precise proximity maneuvers for inspection and rendezvous.

Therefore, low thrust levels in the milli-Newton range and low impulse bits are required. For micro- and nano-spacecraft, the severe mass and volume limitations act as “bottlenecks” to the spacecraft capability. By developing a propulsion system that increases the impulse whilst at the same time decreasing the mass of the technology, the capability of the whole spacecraft can be immensely increased.

The need of propulsion systems capable of thrust levels in the range of a few μN to 1 N is emerging and has also been identified by ESA. Due to this reason, the roadmap for chemical propulsion/micropropulsion [1], was defined which specifies the proposed development approach. It is emphasized that the logical way of pursuing the development of high performance (MEMS) propulsion is to gradually increase the complexity by going from cold gas to hot gas to catalytic decomposition (monopropellant) and in the long run to more advanced miniaturized bipropellant systems.

Cold gas propulsion systems have some disadvantages due to

- the low energy density.
- the high specific mass.
- the large system complexity due to the high system pressure.

With monopropellant propulsion systems using hydrazine as propellant the specific impulse can almost be doubled due to the chemical energy of the liquid propellant. Thereby, the chemical decomposition can be initiated using suitable catalyst techniques. The efficient catalytic decomposition on micro scales is one challenge which μCPS have to cope with and is therefore addressed in PRECISE.

To improve the overall performance of the μCPS, further development on component level is necessary. Currently, the valves of hydrazine thrusters may take up more than 50% of the complete thruster weight. This fact clearly points out the opportunity for further weight reductions of the system. Therefore, component research and thus optimisation of the propulsion system is an important research pillar of this project.

Furthermore, the micro-fluidics and the fluid behaviour in the catalyst bed are investigated. Numerical flow solvers will be enhanced with applicable methods to simulate the flow in the μCPS and in addition to model the plume expansion.

3. First results

3.1. Model mission

The University of Surrey and NPO Mashinostroyenia complete the concept of PRECISE with their collaborative formation flight mission. For the realization of this mission the availability of a μCPS is crucial. The mission consists of two satellites where one of which carries a solar sail and the other is orbiting the solar sail unit for observation and inspection as illustrated in Fig. 2.

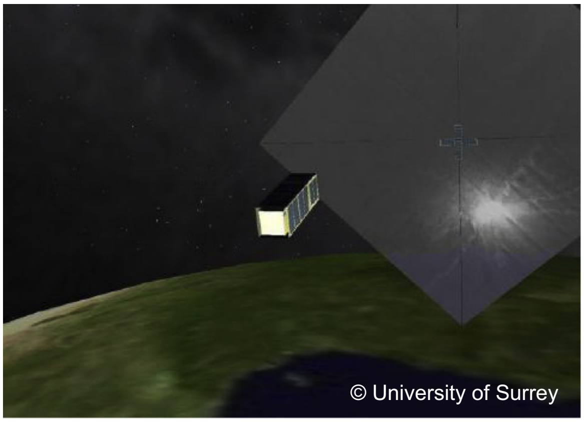

Fig. 2. Schematic of the solar sail spacecraft and the InspectorSat.

For the relative formation flying a sun-synchronous orbit is foreseen. Therefore, it is proposed that the mission orbit should be between 1500 and 2000 km to minimise propellant demands for atmospheric drag compensation. Additionally, minimisation of the effects of atmospheric drag is desirable in order to improve characterisation of solar radiation pressure (SRP). Characterisation of perturbations due to drag is accomplished by analysis of the relative motion of the two spacecraft. Assuming the solar sail spacecraft (SSSC) orbit is circular or nearly circular, by using a 2–1 safety ellipse trajectory relative to the SSSC the InspectorSat will remain within a range defined by its orbit. Successful execution of the SSSC observation will also allow the examination of the deployment dynamics and mechanical behaviours of the solar sail and study of the SRP effect on orbital motion.

It is proposed that the μCPS is used for all stages of the mission, this includes attitude manoeuvres including detumbling after launch vehicle separation, for rendezvous and orbital maintenance manoeuvres, thus demonstrating long thruster burns in addition to the shorter bursts required for attitude control. Finally, analysis of orbit maintenance and drift compensation manoeuvres will allow SRP on the solar sail spacecraft to be determined.

Analyses have shown that a ΔV budget which totals up to approximately 27 m/s for the whole mission results in a propellant requirement which is feasible within the spacecraft masses. The analyses indicated that the use of the μCPS thruster will provide an accurate, precise AOCS actuator with performance characteristics which are ideal for the on-orbit examination of co-orbital targets

3.2. μComponents

The technology of μValves is one of the key components providing reliable operation in terms of required fast response characteristics, constant injection quantities, high number of activations, tightness and propellant resistance. Furthermore, the components have to sustain chemically reactive liquids instead of inert gases. Despite known concepts of μValves based on MEMS techniques no prototypes for operation with liquid hydrazine in ultra-small dimensions exist. This requires significant development efforts in materials and manufacturing methods. Components which have to face high temperatures from combustion or decomposition of the propellant are another challenge that calls for radical design changes compared with the current state of the art.

A highly integrated μCPS is the most efficient way of achieving an extremely small and lightweight system that can meet the propulsion needs for future missions with advanced micro-, nano- and possibly even picosatellites. The Swedish consortium partner NanoSpace is responsible for the component development within PRECISE.

After the assessment of different μValve concepts it is concluded to continue and modify the Phase Change Material (PCM) actuated μValves with heritage from the cold gas (PRISMA [2]) project. PCM actuation mechanism is evidently a technique that can provide both large forces (>N) and displacements (>100 μm). The μValve will be normally-closed and weighs between 1 and 5 g. In a PCM actuator the volume change in the materials phase transition is used for an actuator function. Paraffin has been the active material in a number of fine-mechanical actuators. Compared to other miniature actuators such as e.g. piezoelectric materials or shape memory alloys used to create motion in µValves there is a need for miniature actuators which can deliver both large strokes and large forces. Here, dealing with a future miniaturized feed system in mind, the PCM-actuators may fulfil the criteria combining large flows and high pressures.

A crucial point will be the thermal insolation of the µValve from components having a higher temperature such as the µChamber. An insulation layer could be intercalated in order to reduce the heat flux. This kind of layer may drop the heat flux by more than 70% since the heat transfer at the microscale level is mainly generated by heat conduction [3].

Furthermore, the implementation of a µHeater to heat the µChamber is investigated to improve the performance during the start phases of a micro thruster at low operational temperatures. The primary selection criterion for µHeaters is not the melting point of the resistor material rather the compatibility with the rest of the fabrication steps. The heaters can be applied on the external surface of the MEMS component or inside the actual flow path or between component layers. The latter is referred to as internal heaters. These concepts are currently investigated. The final choice, however, depends strongly on the selected catalysis concept of hydrazine and the layout of the µThruster Fig. 3.

3.3. MEMS based mass flow sensors

In order to ensure the reliable characterization of micro propulsion systems generating the required ultra low thrust levels and impulse bits it is necessary to accurately measure and control the propellant mass flow. Therefore, a fluid channel technology is needed that is compatible with the used propellant hydrazine and that allows the integration of flow sensors in these channels. A suitable candidate is the so-called surface channel technology [4] which was developed at the University of Twente and results in channels with an almost circular cross-section and a channel wall of silicon nitride. The nearly circular cross-section results in low pressure drops. Furthermore, the thin silicon nitride wall (1 µm) allows integration of sensor and actuator structures very close to the fluid but without actual contact to the fluid. Fig. 4 shows a cross-section of a fabricated channel. Channel diameters ranging from 5 to 40 µm have been successfully demonstrated.

For propellant mass flow measurement, a particularly interesting solution is the so-called Coriolis flow sensor. An important advantage of Coriolis sensors is their sensitivity to the true mass flow, independent of flow profile, pressure, temperature and properties of the fluid (density, viscosity, etc.). Recently, significant effort has been put in the realization of a micro Coriolis flow sensor at the University of Twente. Fig. 5 shows a SEM photograph of

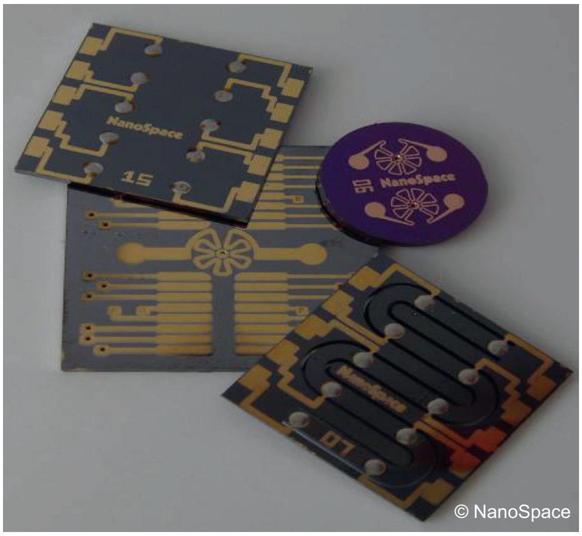

Fig. 3. Examples of MEMS-based fluid control components with the patented circular isolation valve ($\Phi = 12$ mm).

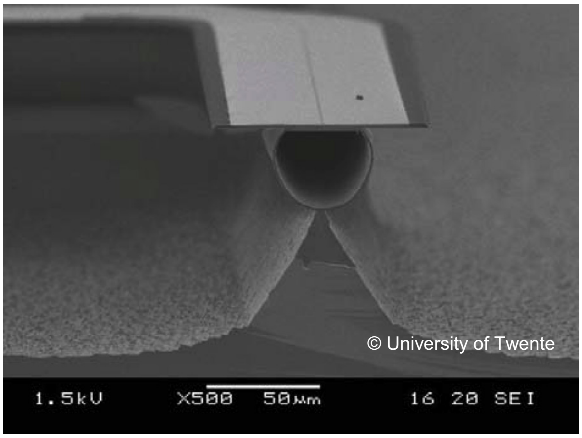

Fig. 4. SEM photograph of a fabricated surface channel with a diameter of about 20 µm and a silicon nitride wall thickness of 1 µm.

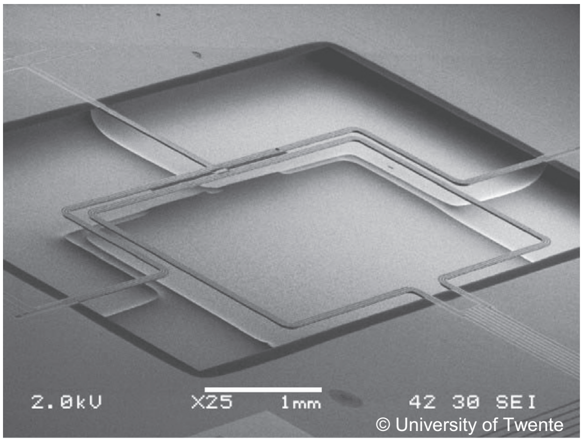

Fig. 5. SEM photograph of the micro Coriolis flow sensor fabricated at University of Twente.

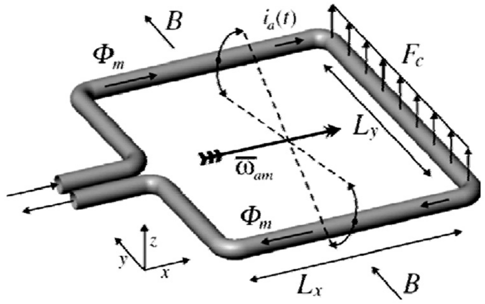

Fig. 6. Operating principle of the Coriolis mass flow sensor.

a realized Coriolis sensor based on a rectangular tube shape.

Fig. 6 shows a schematic drawing of a Coriolis sensor based on a rectangular tube shape [5]. The tube is actuated in a torsional mode indicated by ω_{am}, using the Lorentz force on an electrical ac-current i_a flowing through a metal track on top of the tube and a static external magnetic field B imposed by two permanent magnets. A mass flow Φ_m inside the tube results in a Coriolis force F_c. The Coriolis force is capacitively detected by its induced out of plane vibration mode with an amplitude proportional to the mass flow.

Up to this day, this sensor is the only micro Coriolis flow sensor ever presented which is capable of measuring such low mass flow levels ($\dot{m} < 1\ \mu g/s$). Within PRECISE, the micro Coriolis sensor will be redesigned and optimized for measuring propellant mass flow in the ground test facility during the hot firing tests.

3.4. Micro fluidics and hydrazine catalysis

The state of the art techniques of catalyst manufacturing as well as currently used configurations are not suitable to micro propulsion applications. Classical systems typically use three-dimensional components in contrary to the two-dimensional chip design of the proposed μCPS. When moving to a MEMS-based hydrazine μCPS, the size of the decomposition chamber and feeding part has to be decreased by at least one order of magnitude and some drawbacks can be identified when these aspects are considered:

- the current grain-based catalysts cannot be used in the decomposition chamber with diameter less than 1 mm.
- a reduction of the average size of the catalyst to about 50 μm will increase the pressure drop.
- micro-fluidic effects have to be taken into account.

These criteria demand for a radically new catalyst concept and design to implement the effective hydrazine decomposition processes in micro volumes. To trigger these problems special focus is on

- the decomposition process of hydrazine.
- the design of the decomposition chamber.
- the material compatibility.
- the surface coating techniques.

Hydrazine decomposition initiation is a key point for the operation of the μCatalyst. Various possibilities have to be taken into consideration:

- heat up of liquid hydrazine.
- direct vaporisation of gaseous hydrazine in the decomposition chamber.
- heat up and catalytic/thermal decomposition of gaseous hydrazine.

These different approaches to initiate the hydrazine decomposition are investigated within PRECISE. During the hydrazine decomposition process, hydrazine is decomposed into ammonia and nitrogen followed by a further decomposition of ammonia into hydrogen and nitrogen. Thus, it can basically be distinguished between a catalytic decomposition, a thermal decomposition or a mixture of the aforementioned processes. Thermal decomposition of liquid hydrazine alone, occurs at much higher temperatures than a catalytic decomposition. This requires more energy input compared to a catalytic decomposition since the liquid hydrazine must be pre-heated.

In order to minimise the energy catalytic decomposition appears to be a better choice. However, from a technological point of view this process implies several coatings and thus a challenging manufacturing process. On the other hand, high initial temperatures can be avoided from which the overall system might benefit and the efficiency of the catalyst is increased.

In order to maximize the reacting catalytic surface area the μCatalyst bed unit might be designed with either micro pillars or micro channels. The residual stresses and thus the stability of the final μCatalyst is highly dependent on the materials used for the coatings and on their deposition method. The coatings have to be deposited in different layers, e.g. catalyst and catalyst supporting layer, protective and adhesion layer. The PRECISE consortium partner IC2MP is investigating and testing various concepts in order to identify the best procedure, material and deposition method to produce the μCatalyst by ensuring both mechanical and thermal stabilities.

3.5. Numerical flow modelling of μCPS

Considering the integration of the monopropellant μCPS on a spacecraft, basically two different flow regimes can be identified:

- the internal continuum flow path and.
- the expansion of the thruster plume into space vacuum.

The continuum flow regime can be treated with the Navier-Stokes equations (NSE) whereas the expansion into vacuum requires the solution of the Boltzmann equations since the degree of rarefaction is too large for the Navier-Stokes-equations to be applicable.

The DLR TAU code will be utilised as the Computational Fluid Dynamics (CFD) platform for the internal μCPS flow path modelling, see Fig. 7. This hybrid structured/unstructured

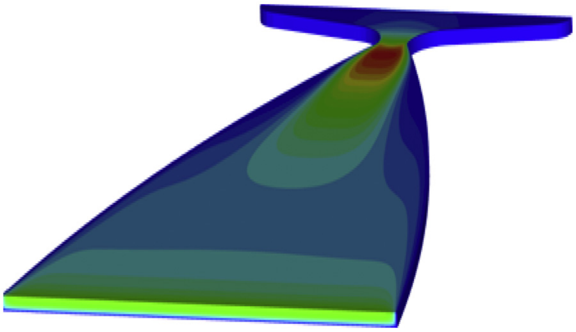

Fig. 7. CFD simulation of the flow in the μNozzle with Mach number contours (DLR TAU Code).

Euler/Navier-Stokes solver was validated for a wide range of steady and unsteady sub-, trans- and hypersonic flow cases [6–8]. The investigation of chemically reacting external and internal flows can be performed with the TAU code including the treatment of surface catalysity.

The physical phenomena that dominate the fluid dynamics in a μCPS have been defined and from this as a basis a roadmap for extending the available computational tools to model the fluid flow in such a system has been suggested.

The Reynolds numbers in the plenum and the throat indicate that turbulence modelling must be considered. Furthermore, internal friction in the fluid must be accurately modelled to investigate the boundary layer growth at the nozzle walls and its influence.

With Knudsen numbers well below a critical value of 0.01, it is safe to assume continuum flow at least up to the throat. How quickly the Knudsen number will rise in the nozzle depends on its geometry and is under investigation.

The focus of the numerical computations lies currently on the investigation of nozzle designs and the flow modelling through the catalyst. Initial computations have shown that the nozzle flow strongly depends on the hydrazine decomposition products.

3.6. *Hot firing of the μCPS*

The hot firings with hydrazine will be performed in the vacuum chamber STG-MT at the German Aerospace Center in Göttingen. The vacuum chamber has a volume of 1000 l which is a suitable size to accommodate the μCPS, the thrust measurement balance and plume measurement diagnostics. The chamber has a good accessibility through a big front door which eases the installation of the equipment as illustrated in Fig. 8.

Several pumps, including turbomolecular pumps, maintain a chamber pressure of 10^{-6} mbar. Optionally, a liquid helium cryo pump can be activated.

A thrust measurement balance will be developed by Astrium to measure the thrust during the hot firings in one axis. To obtain representative thrust histories, damping of vibrations and perturbations resulting from e.g. vacuum pumps, environment (traffic, building, other test stands, etc.) must be compensated since their amplitudes may be within the order of the displacements caused by the thrust forces. A system trade-off of various thrust measurement concepts has been performed and the selected concept is currently being finalised.

Fig. 8. Vacuum chamber STG-MT at DLR in Göttingen.

In addition, a sensor chip with thermistors based on the Pitot tube principle is designed by the University of Twente and will be employed for plume measurements during the hot firings. A MEMS-based Pitot tube sensor does not yet exist. One chip will consist of two sensors, one of which is used for the higher pressure range ($\geqslant$1 mbar) as expected at nozzle exit or inside the plume. The second sensor is used for the lower pressure range ($<$1 mbar) as expected in the backflow. First prototypes are currently manufactured.

The test infrastructure with the vacuum chamber STG-MT will allow a very close link between numerical modelling and experimental investigations of the μCPS prototype.

4. Summary

PRECISE aims for the development of a micro Chemical Propulsion System (μCPS) necessary for highly accurate attitude control of satellites.

The incorporated mission, which requires an AOCS capable of accurate and agile pointing of the spacecraft, has been defined in terms of high level objectives to demonstrate the utility of the PRECISE μCPS. The analyses indicate that the use of the μCPS thruster provides an accurate, precise attitude and orbit control actuator with performance characteristics which are ideal for the on-orbit examination of co-orbital targets.

Research and development focuses on critical MEMS-based system components, such as the μValve, the μHeater and the μCatalyst. μValves based on PCM actuation are investigated. The phase change mechanism is evidently a technique that can provide both large forces (>N) and displacements (>100 μm). Various heater concepts are analysed whose selection depend strongly on the catalyst and the decomposition process.

Furthermore, micro fluidic and hydrazine catalysis aspects are of great importance to select an efficient layout of the μCatalyst and its coatings by ensuring both mechanical and thermal stabilities. Different designs are proposed for the decomposition chamber and each system is currently investigated.

The numerical support for developing a μCPS aims at evaluating system performance and then optimising specific components with respect to performance. A roadmap is elaborated towards numerical modelling of the flow inside a micro-propulsive device. Step by step, extensions to the numerical capabilities are suggested and evaluated with regards to arising additional modelling capabilities.

The requirements for the test infrastructure and key diagnostic tools have been described at the very beginning of the project. From this as basis key diagnostic tools such as mass flow and plume measurement sensors and the thrust measurement balance are developed. The novel MEMS-based Coriolis mass flow and plume measurement sensors are currently manufactured. This equipment will be used during the final hot firings of the μCPS demonstrator in the vacuum chamber STG-MT at DLR in Göttingen.

Acknowledgements

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References

[1] M. Gauer, D. Telitschkin, U. Gotzig, Y. Battoneau, H. Johansson, M. Ivanov, P. Palmer, R. Wiegerink, R., PRECISE—development of a MEMS-based monopropellant micro chemical propulsion system, AIAA-2012-4072, in: 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Atlanta, Georgia, 29 July–1 August 2012.

[2] 〈http://www.prismasatellites.se〉.

[3] T. Yuan, A. Li, Design and fabrication of a MEMS-based millinewton level hydrazine thruster, in: 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Denver, Colorado, 2009, AIAA paper 2009-5201.

[4] M. Dijkstra, M.J. De Boer, J.W. Berenschot, T.S.J. Lammerink, R.J. Wiegerink, M. Elwenspoek, A versatile surface channel concept for microfluidic applications, J. Micromech. Microeng 17 (2007) 1971–1977.

[5] J. Haneveld, T.S.J. Lammerink, M.J. de Boer, R.G.P. Sanders, A. Mehendale, J.C. Lötters, M. Dijkstra, R.J. Wiegerink, Modeling, design, fabrication and characterization of a micro Coriolis mass flow sensor, J. Micromech. Microeng 20 (2010) 125001.

[6] D. Schwamborn, T. Gerhold, R. Heinrich, The DLR TAU-code: recent applications in research and industry, in: Proceedings of the European Conference on Computational Fluid Dynamics, ECCOMAS CFD, 2006.

[7] T. Gerhold, O. Friedrich, J. Evans, M. Galle, Calculation of Complex Three-Dimensional Configurations Employing the DLR-TAU-Code, AIAA-Paper 97-0167, 1997.

[8] B. Reimann, I. Johnston, V. Hannemann, The DLR TAU-code for high enthalpy flows, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, 87, Springer, 2004.