Cubesat Micropropulsion Characterization in Low Earth Orbit

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ABSTRACT

This paper describes the results of several orbital experiments of a proprietary micropropulsion system for nanosatellites developed by Microspace Rapid Pte Ltd of Singapore. A 3U cubesat named POPSAT-HIP1 has been developed by Microspace to demonstrate the functionality of multiple integrated payloads in orbit. One of the payloads is a Cold Gas Micropropulsion system based on the supersonic micronozzles developed by Microspace. The system has been integrated in the optical payload which serves also as pressurized propellant tank (1). Eight micronozzles have been placed on the corners and edges of the satellite to control three rotation axes and to allow for net force production for formation flight or station keeping along the orbit. The satellite has been launched on a Sun Synchronous Low Earth Orbit on 19th June 2014 by a DNEPR vehicle from Yasny in Russia. The propulsion system has been activated as soon as the satellite has reached orbit and has remained fully functional until the time of writing, 9 months after the launch. The nozzles have been fired under telecommand to produce ΔV in angular velocity which has been measured by the ADCS sensors: magnetometers, gyro and Sun sensors with data points collected every 3 to 5 seconds and transmitted to ground as telemetry data. Maneuvers results are presented and analyzed versus the expected values. The Conclusions present the estimation of the total ΔV produced during this mission, evaluated at about 2.25m/s and 3m/s.

INTRODUCTION

Micropropulsion is perhaps the latest of the building blocks on the way to become a standard feature of small satellites, nanosatellite and cubesats. The topic has been explored by several groups and some experiments have been performed in orbit although they have been usually short lived or used as preliminary assessment or partial demonstration only (2) (3), (4). On the other hand the literature on laboratory experiments or just conceptual designs is very vast almost suggesting that the topic is already a mature one. Certainly the intrinsic difficulties of realizing a micropropulsion system actually working in Space have been the cause of the delayed arrival of this technology on a real, long lived, orbiting nanosatellite. Among such difficulties we count not only the need to use very special manufacturing technologies for the construction of the micronozzles, but also the real or assumed resistance of launchers to allow the presence of a propellant on a class of satellites which is still perceived as a toy or just as an immature product that, because of lack of testing, may produce damages to the other elements of the mission. Microspace has been dealing with such issues one by one since the beginning of activities in year 2002, and has pursued a roadmap of development as shown in Figure 1 that was also adopted by ESA in its harmonization document (5).

We have focused initially on the development of the essential and unique element, which is the core of any micropropulsion system: the micronozzle, a high efficiency microfluidic device with micrometer sized features and sub-micrometer surface qualities. As we have previously documented (6), we have gone through 3 phases of development: technology feasibility demonstration, technology refinement and full scale engineering production involving facilities in Italy, Japan, and Singapore.

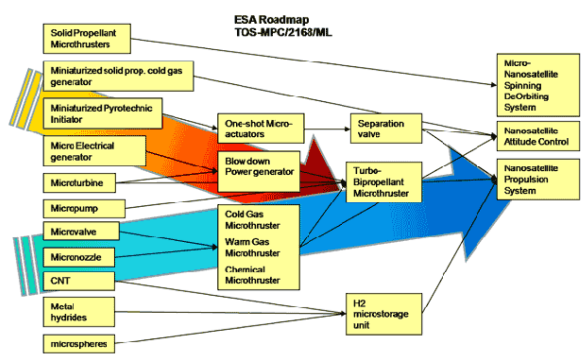


Figure 1: Micropropulsion Development Roadmap Outlined by Microspace

Once the micronozzle, its controls, and its characterization devices have been completed we have moved to the development of the complete miropropulsion system, made in a modular fashion to be suitable for the smallest possible satellite, the 1U Cubesat (7), and to be scaled-up to nano and microsatellites of up to 100kg mass. Subsequently we have developed POPSAT-HIP1: "Propulsion Operation Proof SATellite – High Performance 1" to achieve an in-orbit demonstration. Development of POPSAT started in 2010 and the launch was initially planned for end 2012 but it was postponed until the readiness of the selected launch vehicle, a DNEPR that took off from Yasny on 19th June 2014.

POPSAT-HIP1

POPSAT-HIP1 is a 3U Cubesat of 3.3kg mass. Its primary payload is built around Microspace micropropulsion system for attitude control with 6 micronozzles modules placed on the edges of the front face and 2 micronozzles placed along one of the long sides of the satellite as illustrated in Figure 2.

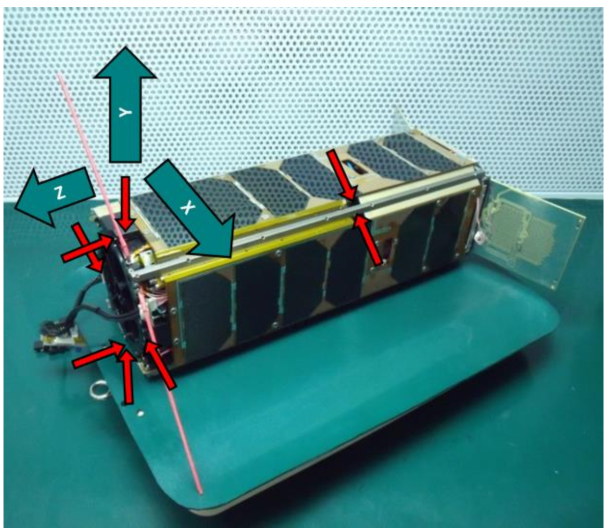


Figure 2: Position of the Thrust Vectors in POPSAT

One of the control axes has redundant nozzles that can be used also to produce net force for possible formation flight. Such configuration has been chosen to maximize the arm of the nozzles while occupying the least possible volume. All satellite electronics are arranged to occupy 1U of the satellite while the rest of the 2U are utilized for a pressurized tank containing Argon gas at about 8bar. The tank is completely customized and integrated in the secondary payload of the satellite for the most efficient use of the available volume. The secondary payload is a high resolution catadioptric optical system. The satellite is equipped with fixed and deployable solar panels and its primary attitude determination and control system is based on Magnetorquers, Magnetometers, Sun sensors and Gyroscopes. The communication is achieved by a UHF half-duplex transceiver using a simple deployable dipole antenna.

COLD GAS MICROPROPULSION SYSTEM

The Micropropulsion system utilizes 8 micronozzles of 1mN nominal thrust at 5 bar of Argon propellant. Each nozzle has been individually characterized on a microbalance built in house and operated in a vacuum chamber. Each nozzle is operated via an electromagnetic microvalve with shortest opening time of 1ms and unlimited longest opening time. The nozzles are fed via a low pressure manifold circuit which is connected to the main tank through a pressure regulator and an isolation valve. Pressures in the tank and on the nozzle supply line are measured by MEMS pressure sensors. Figure 3 shows the block diagram of the overall system.

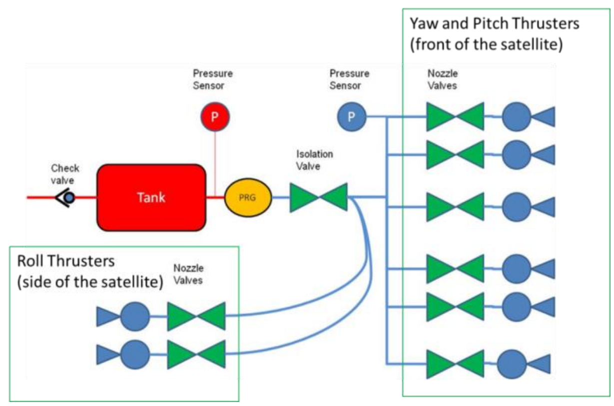


Figure 3: Block Diagram of the Micropropulsion System

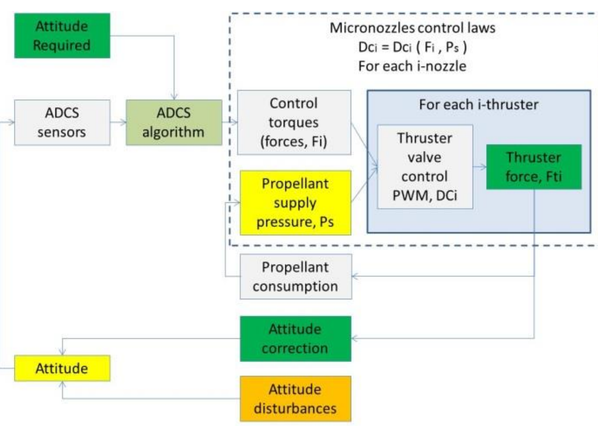


Figure 4: Micropropulsion Control Algorithm

The control of the micropropulsion system as shown in Figure 4 is integrated in the satellite ADCS algorithm. Based on the knowledge of the present attitude and the required attitude, the control torque can be calculated based on the available propellant pressure. The calculation can then be translated to the required duty cycle to produce the average force, which then affects the attitude of the satellite and reduces the available propellant. The new information is then fed back into the control and the calculation loop restarts.

SUPERSONIC MICRONOZZLE

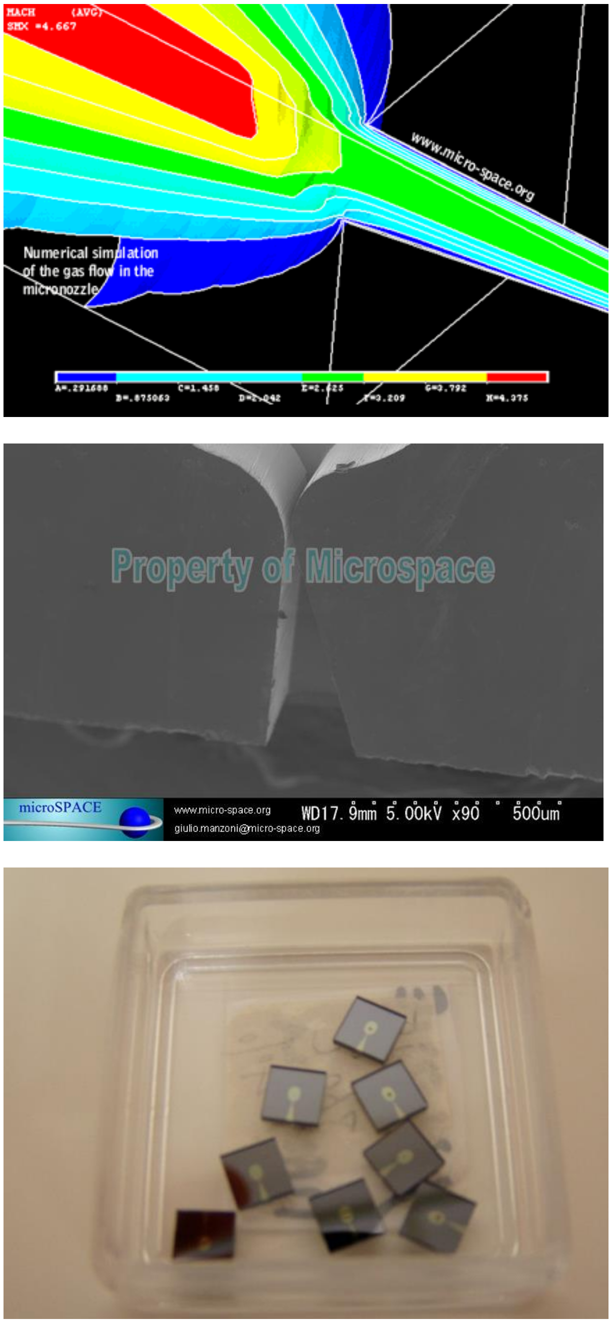


Figure 5: Micronozzle Fluid Dynamic Analysis, SEM Image, and some Nozzles Ready for Testing

The supersonic micronozzles are produced by Microlithography, Deep Reactive Ion Etching, Anodic Bonding and Dicing. The nozzles have been developed through a comprehensive project including Computational Fluid Dynamics by Finite Elements Analysis (CFD), microfabrication, and vacuum microbalance characterization of several different shapes to obtain the optimal geometry (8) as presented in Figure 5.

Each nozzle has been individually characterized on a microbalance built in house and operated in a vacuum chamber. Characterization includes mapping the nozzle thrust and specific impulse over the whole range of available pressure and microvalve opening control (i.e. duty cycle) in order to obtain the functions mapping of nozzle performances that are later utilized by the thrust control loop combined with the attitude control algorithms (8).

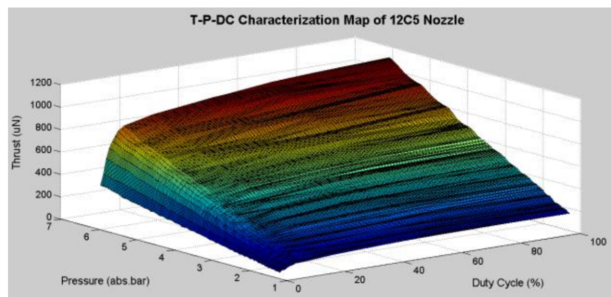


Figure 6: Characterization Map of a Micronozzle

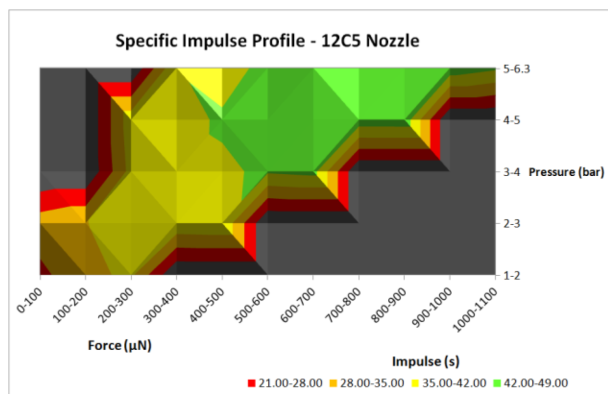


Figure 7: Laboratory Measurement of the Specific Impulse of a Micronozzle

PROPELLANT PRESSURE PROFILE

The tank system (i.e. high-pressure chamber) has been filled during the final check out operations at Yasny base just before inserting POPSAT in the Quadpack deployment system provided by ISL (9). The pressure stability has been monitored for 2 days to confirm the absence of leakages. For safety reasons and to minimize any risk, the pressure has been limited to 7.8bar even if the system can work up to 18bar with the present design.

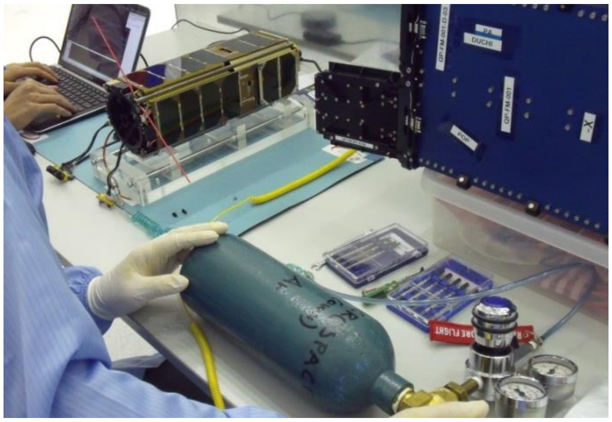


Figure 8: Propellant Filling Activity at the Launch Base

The satellite was launched 2 weeks later and micropropulsion operations have been conducted by telecommands from the Microspace Ground Station of Singapore. After initial verification of the satellite good condition during the first few days in orbit, the isolation valve has been opened and the increase in pressure of the low-pressure chamber is shown in Figure 9.

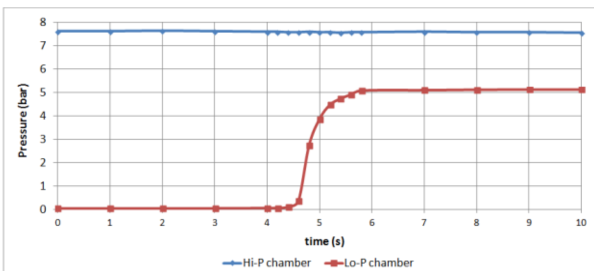


Figure 9: Pressure Profile for the Opening of Isolation Valve

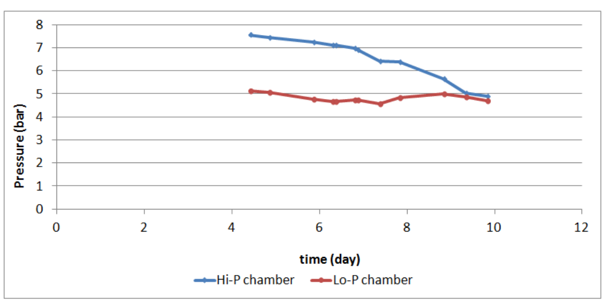


Figure 10: Pressure Profile after 10 Days Operation

Figure 11 shows the pressure profile of POPSAT since the opening of the isolation valve to the time of this article writing. Many micropropulsion experiments were heavily attempted in the first ten days and the corresponding reduction in pressure is shown in Figure 10. Nevertheless due to an unexpected software bug in the gyroscopes initialization, the micropropulsion effect could not be verified with the necessary accuracy. It should be noted that the pressure in the low pressure chamber varies around the set point of 5bar due to the pressure regulator internal adjustments.

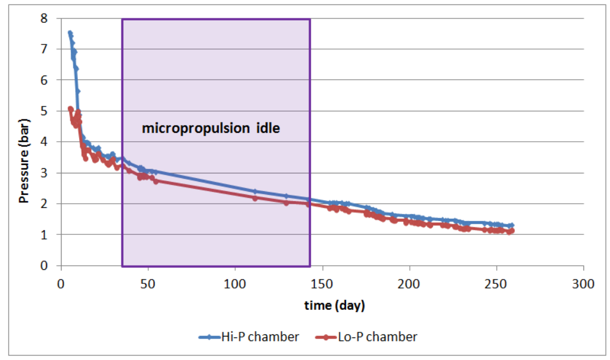


Figure 11: Overall Pressure Profile in Space

The micropropulsion experiment resumed 150 days later after a problem with the satellite internal I2C bus has been resolved. It can be seen from the pressure profile that the observed leakage of the low pressure chamber is 8mbar/day. Conservatively assuming a linear relationship, it will take another 170 days for the pressure to drop to 0.5bar, which can be considered the lower limit of the micropropulsion effectiveness.

ANALYSIS OF AN ANGULAR VELOCITY CHANGE MANEUVER

Table 1: POPSAT Inertia and Actuators

Inertia	**Unit**	**Value**
Mass	kg	3.3
Px	kgm^2	0.043
Py	kgm^2	0.045
Pz	kgm^2	0.009
Magnetorquers	**Reference Axis**	**Max. dipole moment – at 25°C (Am^2)**
A	X axis	0.145
B	Y axis	0.145
C	Z axis	0.110
Thrusters	**Reference Axis**	**Arm to C.O.M (m)**
S4	+X axis	0.167
12B5	+X axis redundant	0.052
7C5	+Y axis	0.180
V4	+Z axis	0.061
7E5	–X axis	0.167
V5	–X axis redundant	0.052
12C5	–Y axis	0.180
V1	–Z axis	0.061

The angular velocity change is the simplest maneuver. It is achieved by firing one thruster in the desired direction. The inertia of the satellite is given in Table 1. along with the arm of the thrusters with respect to the centre of mass (C.O.M) which is known by design and has been verified by means of balancing the satellite before the launch with an uncertainty of ~2mm.

The maneuver starts by ensuring that the gyroscopes are active, followed by powering the valves controller board through a series of telecommands, and by measuring the gas pressure in the tank to confirm the health of the system. The angular velocities of the satellite are subsequently measured repeatedly by means of gyroscopes readings to choose the firing direction. The maneuver attempt was initiated with a tumbling test to show that the micronozzle was really able to fire and cause angular velocity change of the satellite. The attempt examples can be seen in Figure 12.

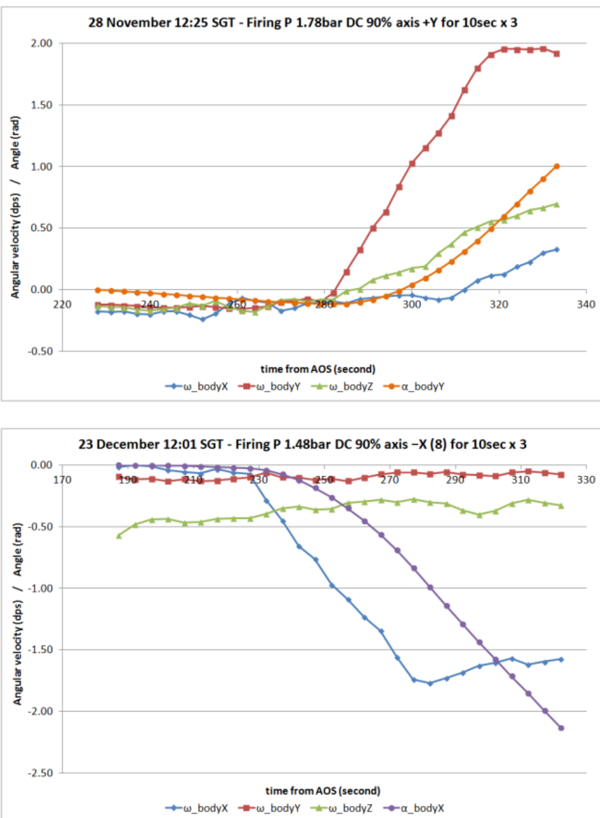


Figure 12: Single Axis Propulsion Tumbling Test

Subsequently it is for example interesting to stop a particular angular velocity in order to prepare for a clean attitude change maneuver as illustrated in Figure 13.

One simple example to discuss is the test conducted on 28th November 2014 as illustrated in Figure 12. The initial velocity of Y axis was -0.1°/sec and after a firing attempt in +Y axis at setting of 90% duty cycle for 30 seconds the final velocity was 1.95°/sec. This confirms the correct functioning of +Y axis thruster.

Another example is the test on 9th January 2015 as illustrated in Figure 13. In this case the purpose was to stabilize the satellite due to its tumbling state. The initial velocity of Y axis was 0.55°/sec and after a firing attempt in −Y axis at setting of 4% duty cycle for 10 seconds followed by 2% duty cycle for another 10 seconds, the final velocity was 0.09°/sec, which is generally sufficient within the resolution of the gyroscope to start a meaningful attitude change maneuver as described further in the next paragraphs.

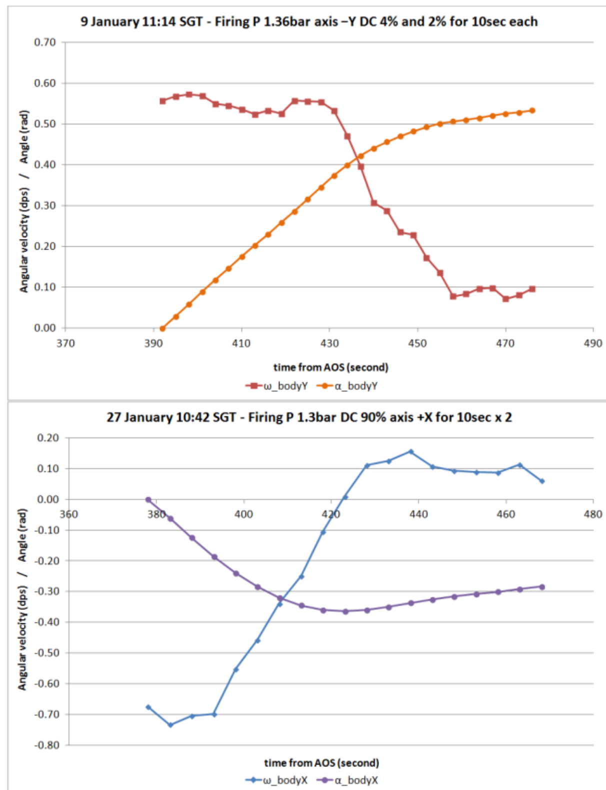


Figure 13: Single Axis Control Detumbling by Micropropulsion

It should be noted that the gas consumption for each propulsion attempt is very minimal and cannot be measured just by evaluating the pressure difference before and after the maneuver. Therefore only after several maneuvers can the average gas consumption be estimated.

Table 2: List of Maneuver Attempt Examples with Micropropulsion

Date	Pressure (bar)	Firing Axis	DC (%)	Duration (sec)	Δω (dps)
21/11/14	1.85	+Z	90	20	0.38
24/11/14	1.85	−Z	90	20	0.34
26/11/14	1.83	−Y	90	60	2.72
28/11/14	1.78	+Y	90	30	2.05
14/12/14	1.62	−Y	90	40	1.80
		+Y	90	30	2.04
15/12/14	1.61	+Y	90	25	1.65
		−Y	90	30	1.45
16/12/14	1.60	−X sa[1]	90	60	0.74
18/12/14	1.56	+X	90	30	1.18
		−X sa	90	50	1.06
23/12/14	1.48	−X	90	30	1.73
09/01/15	1.36	−Y	4	10	0.31
			2	10	0.15
27/01/15	1.30	+X	90	20	0.8
28/01/15	1.28	−X	80	20	0.6
		+X	8	10	0.35
			60	10	0.54
		−X	60	10	0.54
			8	10	0.36
01/02/15	1.21	+Y	2	10	0.21
			4	10	0.24
			10	10	0.46
		−Y	60	10	0.36
			10	10	0.30
			5	10	0.25
			2	10	0.19
01/03/15	1.15	+Y	2	10	0.20
			4	10	0.27
			8	10	0.38
		−Y	10	10	0.34
			5	10	0.24
			2	10	0.20

Depending on the available pressure in the tank, a different thrust will be available at varied valve duty cycle as already presented in Figure 6. The thrust needed to obtain the necessary velocity change is then calculated and the corresponding duty cycle is determined by the mapping of thrusters calibrations as performed in the laboratory. The necessary telecommand is sent to the satellite and after execution the new velocity is acquired from the gyroscope readings.

Table 2 shows the log of such maneuvers in several different objectives. Tumbling and detumbling tests are to show that the micropropulsion works in the particular axis, while bang-bang maneuver is to show that the satellite can be rotated according to the desired velocity and return to its stabilized state. Target pointing simulation is to show that the satellite is able to keep pointing at certain target by keeping adjusting its velocity by means of micropropulsion. The tests were kept in single axis control due to its simplicity in showing the effect of the micropropulsion.

ANALYSIS OF AN ATTITUDE CHANGE MANEUVER

Table 3: Calculation of the Expected Δω for –Y Axis Micropropulsion at 90% Duty Cycle

Δω (°/sec)		Time (second)				
P (bar)	**F (μN)**	**5**	**10**	**20**	**40**	**60**
1.0	83	0.10	0.19	0.38	0.76	1.14
1.6	204	0.23	0.47	0.94	1.87	2.81
2.0	280	0.32	0.64	1.28	2.55	3.83
3.0	470	0.54	1.08	2.17	4.34	6.51
4.0	670	0.77	1.53	3.06	6.13	9.19
5.0	860	0.99	1.98	3.96	7.92	11.9
6.0	1100	1.21	2.43	4.85	9.70	14.6

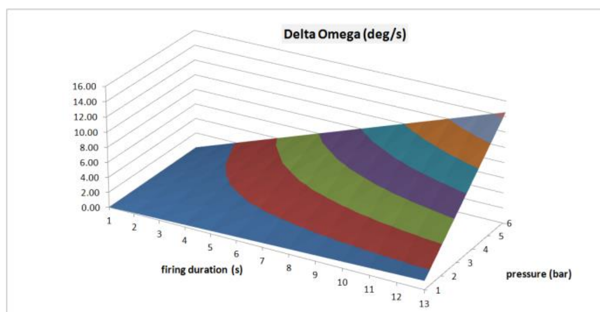


Figure 14: Surface Diagram of the Expected Δω for –Y Axis Micropropulsion at 90% Duty Cycle

The attitude change maneuver is a typical bang-bang with firing a certain number of times a given thruster followed by a waiting time and then firing the opposite thrusters for the necessary number of times. At beginning of life, when the pressure in the tank is still rather high, one firing at low duty cycle may be sufficient, depending of the desired speed of attitude change, while towards the end of life multiple firing at 100% duty cycle will be necessary if a fast attitude change is desired. Table 3 and Figure 14 illustrates the

[1] sa: short arm

expected change in the satellite angular velocity at a given pressure and firing duration for the –Y axis.

For example, at 2 bar of available pressure, a firing of 10s at 90% duty Cycle should produce a Δω on the Y axis of about 0.6°/s.

Figure 15 shows a maneuver executed after 6 months of life in orbit, when the available gas pressure was already reduced down to about 1.6bar. A rotation of 160 deg has been achieved in about 3 minutes time with a total firing time of 70 seconds by means of 4 times firing of the –Y axis thruster at 90% duty cycle and 3 times firing of the +Y axis thrusters at the same 90% duty cycle.

The observed change of angular velocity in −Y axis was 1.8°/s, corresponding to 0.45°/s per firing. Based on the expected values shown in Table 3, a pressure of 1.62bar corresponds to an expected 0.47°/s indicating a well characterized micronozzle of only a reduction of about 4% in the overall effectiveness of the maneuver. Based on Figure 7, it can subsequently be estimated that for this maneuver at low operative pressure, the specific impulse was 34s.

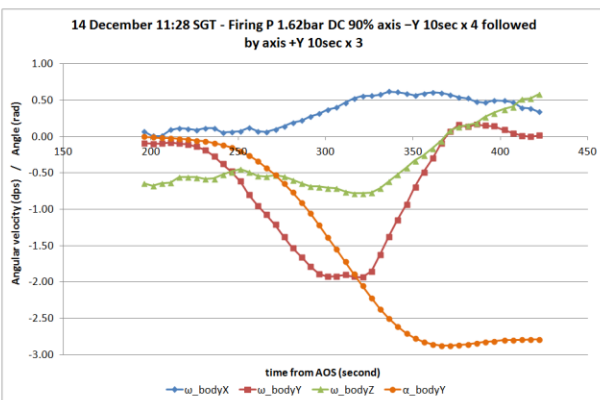


Figure 15: Y-axis Bang-Bang Maneuver with Micropropulsion

Another rotation of 130 deg has also been achieved in a total firing time of 60 seconds by means of 3 times firing of the +X axis thruster at 90% duty cycle and 5 times firing of the –X axis thrusters at the same 90% duty cycle. The shorter duration of the +X axis firing is due to the longer arm of the microthruster located in that particular axis.

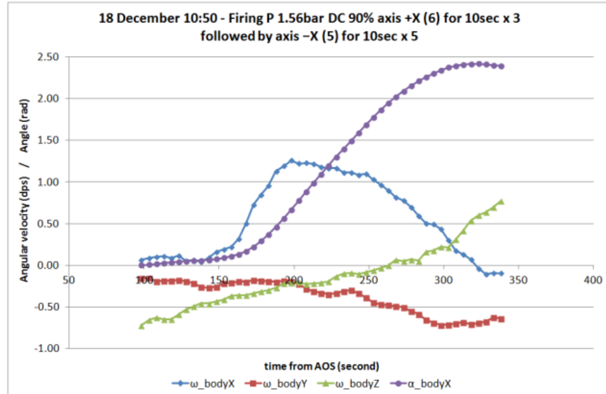


Figure 16: X-axis Bang-Bang Maneuver with Micropropulsion

The observed change of angular velocity in +X axis was 1.18°/s, corresponding to 0.39°/s per firing. Having a pressure of 1.56bar, it corresponds to an expected 0.42°/s indicating a reduction of about 7% in the overall effectiveness of the maneuver. It can be estimated that for this maneuver at low operative pressure the specific impulse was 33s.

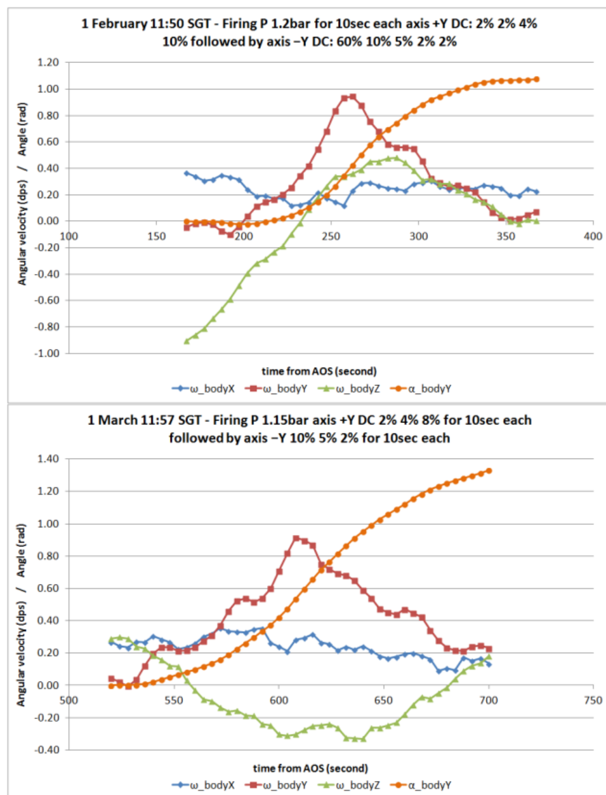
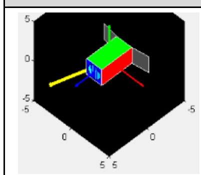
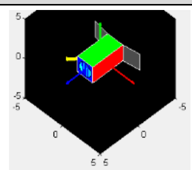
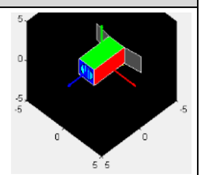
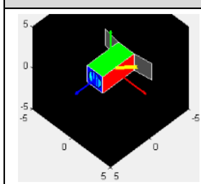
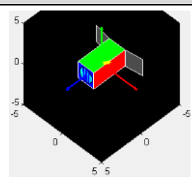
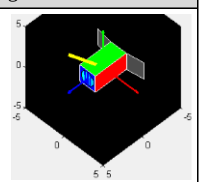
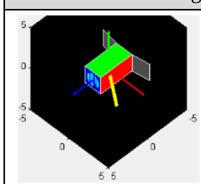
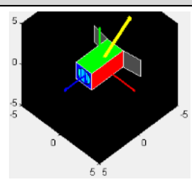
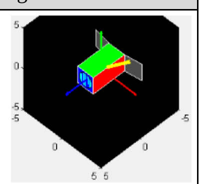


Figure 17: Single Axis Target Pointing Simulation with Micropropulsion

Figure 17 shows another example of bang-bang maneuver that specifically used to reproduce a target pointing activity, however only in single axis. In this case, different duty cycles were applied over the period range that the satellite has to keep pointing at a specific target.

The attitude change of the satellite can also be confirmed with the reading of other attitude sensors, such as magnetometer and sun sensors. Table 4 shows the vector change of the Sun vector, magnetic field, and angular velocity, after the target pointing attempted on the Y axis of the satellite.

Table 4: Vector Change after Y-axis Target Pointing with Micropropulsion

Before firing	Climax	After firing
Sun Vector Change		
		
Magnetic Field Vector Change		
		
Angular Velocity Vector Change		
		

TOTAL MISSION ΔV

An estimation of the total ΔV actually produced by the micropropulsion system during the 9 months of recorded operation can be attempted based on the impulse achieved on the various maneuvers reported here. For each maneuver the angular impulse is converted in equivalent linear impulse through the calculation of the force F that produced the Δω around the axis of inertia J in the firing time Δt. It can be represented in the following equations:

$$T = Fa = J\frac{\Delta\omega}{\Delta t} \quad (1)$$

$$F\Delta t = m\Delta v \quad (2)$$

$$\Delta v = \frac{J}{ma}\Delta\omega \quad (3)$$

where T = torque; a = linear acceleration; m = satellite mass.

Table 5 presents the calculation for each maneuver presented in this article.

Table 5 – ΔV Equivalents

experiment type			Δ ω	B-B	B	B	Δ ω	Δ ω	Δ ω	B-B	B-B
Axis			Y	Y	X	X-sa	X	Y	X	Y	Y
Inertia	J	kgm2	0.045	0.045	0.043	0.043	0.043	0.045	0.043	0.045	0.045
DeltaOmega	Dom	deg/s	2.05	3.84	1.18	1.06	1.73	0.46	0.8	2	1.63
		rad/s	0.036	0.067	0.021	0.018	0.030	0.008	0.014	0.035	0.028
Maneuver time	Mt	s	40	90	90		40	15	40	150	175
Delta T	Dt	s	30	70	30	50	30	20	20	70	60
Torque	T	Nm	5.4E-05	4.31E-05	3E-05	1.6E-05	4.33E-05	1.81E-05	3E-05	2.24E-05	2.13E-05
Arm	a	m	0.18	0.18	0.167	0.052	0.167	0.18	0.167	0.18	0.18
Thrust	F	N	0.0003	0.000239	0.00018	0.00031	0.000259	0.0001	0.00018	0.000125	0.000118
		mN	0.30	0.24	0.18	0.31	0.26	0.10	0.18	0.12	0.12
		µN	298	239	177	306	259	100	180	125	118
Impulse	I	Ns	0.00894	0.016747	0.0053	0.01529	0.007771	0.002006	0.003593	0.008722	0.007109
satellite mass	m	kg	3.3								
Equivalent DeltaV	Dv	m/s	0.00271	0.00507	0.00161	0.00463	0.00235	0.00061	0.00109	0.00264	0.00215
typical average/pass											
Thrust	F	N					0.00020				
DeltaV	Dv	m/s					0.0025				
DeltaV spread	Dv	m/s					0.0014				

In order to overcome the difficulty of knowing the exact gas consumption for each maneuver, averages of force produced and gas consumed have been taken for the combined maneuvers reported here. As shown in Table 6, the average specific impulse has been therefore estimated to be about 32s, which is in good agreement with the values recorded in laboratory testing for the relevant range of pressure as presented in Figure 7.

Table 6 – Specific Impulse Estimations

experiment date			28-Nov	14-Dec	18-Dec		23-Dec	9-Jan	27-Jan	1-Feb	1-Mar
experiment type			Δ ω	B-B	B	B	Δ ω	Δ ω	Δ ω	B-B	B-B
consumption estimations											
pressure		bar	1.78	1.62	1.56		1.48	1.36	1.30	1.28	1.15
total pressure drop		bar					0.63				
volume	V	m3	1.80E-03								
density at 1 bar	rho	kg/m3	1.7								
mass available	mp	kg	0.0054	0.0050	0.0048	0.0000	0.0045	0.0042	0.0040	0.0039	0.0035
total mass consumed		kg	0.0019								
		g	1.93								
total firing time		s	3000								
estimated total impulse		Ns	0.60								
Average Is on experiments	Is	s					31.8				

Finally, thanks to the good agreement of the laboratory measured specific impulse with the one observed in Space, the total ΔV that has been produced during the whole operation of the propulsion system can be estimated by extrapolating it from the average specific impulse of 43s observed in laboratory.

By means of such estimation, a lower limit of ΔV can be calculated at about 2.25m/s (using the conservative value of specific impulse = 32s) while a upper limit of ΔV can be calculated at 3.05m/s (with the specific impulse averaged over the whole mission = 43s) for the complete POPSAT micropropulsion operation over 9 months of mission. It must be noted that if the mission duration is kept much shorter (i.e. 1 month) the effect of the leakages will be much less and a higher ΔV may be achievable, perhaps up to 5m/s with exactly the same technology and architecture of POPSAT.

Table 7 – Total Mission ΔV

Average specific impulse on experiments	I_s	31.8	sec
Extrapolation on the Whole Mission			
Average specific impulse on mission		43.0	sec
Initial pressure	P_0	7.8	bar
Total mass	m_0	2.39E-02	kg
Total ΔV based on in-orbit experiments	Δv	2.25	m/sec
Total ΔV based on the whole mission	Δv	3.05	m/sec
Total ΔV for 1 month mission	Δv	5	m/sec

CONCLUSION

A micropropulsion system has been integrated in the payload of POPSAT-HIP1 3U Cubesat and has been operated in space up to 9 months at time of writing. Performances have been measured to confirm the functionality of the system for maneuvers of up to 4°/s with tank pressure reduced at 2bar. For higher supply pressures up to 5bar, maneuvers of up to 10°/s can be obtained. It is also worth to mention, that such changes of angular velocity or the corresponding satellite rotations are achieved rather quickly, hence allowing re-orientation of the satellite in less than one minute.

The overall operation has demonstrated a total ΔV of up to 3m/s available during 9 months in orbit, thereby ensuring attitude re-orientation on a daily basis for a one year mission or for about 1000 times.

If higher pressurizations levels are allowed by the rocket launcher, the ΔV can be increased about 10 times to 100 times just by adopting different tank technologies presently available at Engineering Model level at Microspace, thereby increasing the number of maneuvers, being target pointing or formation flight, orbital station keeping or small orbital changes.

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