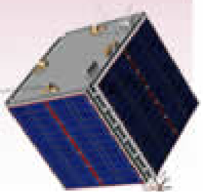
ALMASat Alma Mater Satellite



Cold Gas MicroPropulsion Experimental Activities at the University of Bologna

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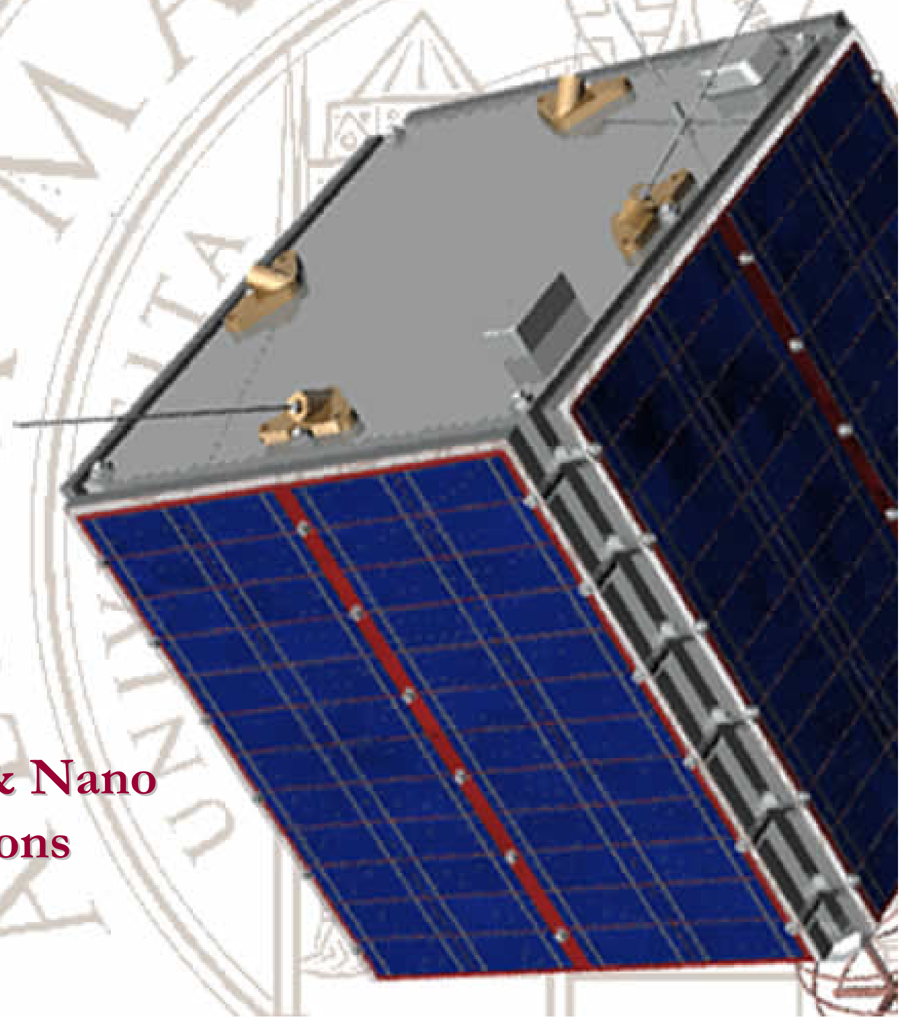
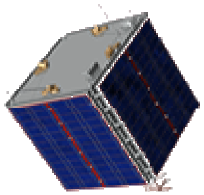


6th ESA Round Table on Micro & Nano Technologies for Space Applications
8 - 12 October 2007 ESA/ESTEC

Summary



- ALMASat-1 Microsatellite Project;
- Cold Gas Micropropulsion Target and Requirements;
- Micropropulsion Components and their Layout;
- Thruster – Valve Group;
- In Orbit Experiments;
- Experimental Activities: Valve Leakage, Isolation Valve, Thrust Measurements;
- State of the Art;
- Conclusion and Future Work.

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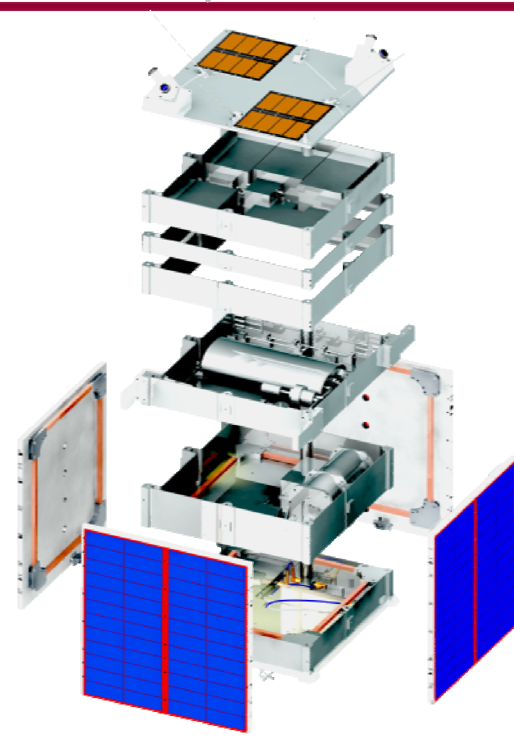
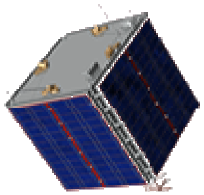
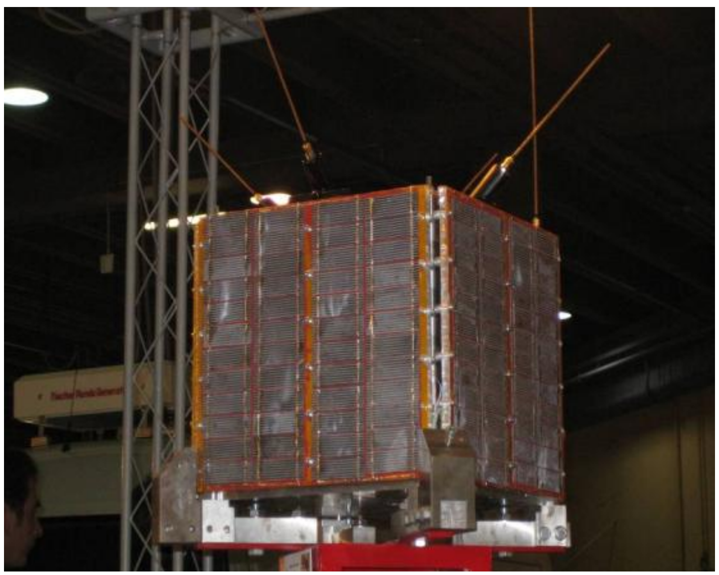
ALMASat Microsatellite: Project Context

University Microsatellite

- Dimensions: 300 x 300 x 300 mm;
- Modular Structure:
  6 shop machined Al trays;
- Total Mass: 12 kg;
- Available Power: ~15 W;
- Thermal Control: passive;





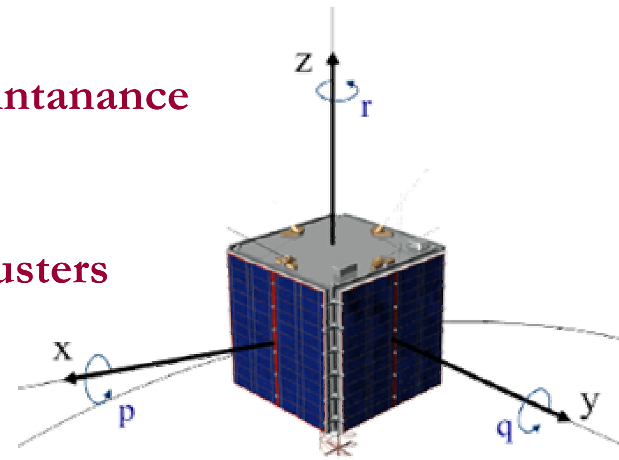


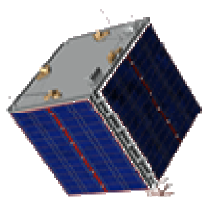
- Attitude Control System:
  three-axis stabilized using
  1) a momentum wheel;
  2) three orthogonal magnetic coils;
  3) micropropulsion system;
- Payload: Cold Gas Micropropulsion System (40g of Nitrogen gas) with 12 microthruster grouped in 4 clusters of 3 and about 1 mN thrust level.

Cold Gas Micropropulsion

Target:

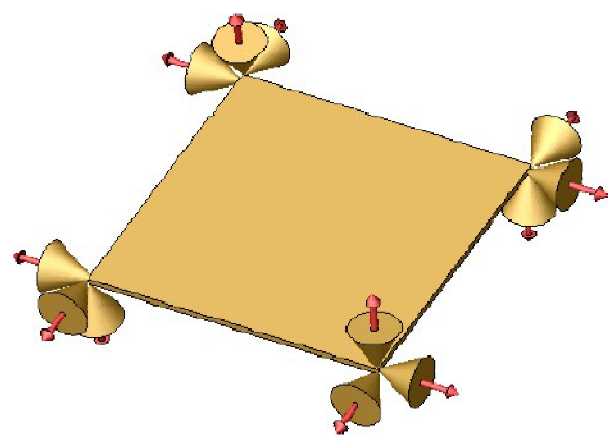
- To develop a Cold Gas Micropropulsion system to be flown on ALMASat-1 microsatellite
- Three-axis stabilization and nominal attitude maintanance
- Momentum Wheel Desaturation
- Small orbital manoeuvre will make use of two thrusters firing continuously until the gas runs out.





Requirement:

- Available dimensions: 300 x 300 x 50 mm
- Micropropulsion Firing Time: 20.000 s
- Gas Tank Volume: larger than 0.4 liters
- Power Consumption during operation: < 5 W
- Overall System Mass: < 1000 g
- Total Impulse: at least 15 N·s
- Impulse bit: at least 0.1 mN·s



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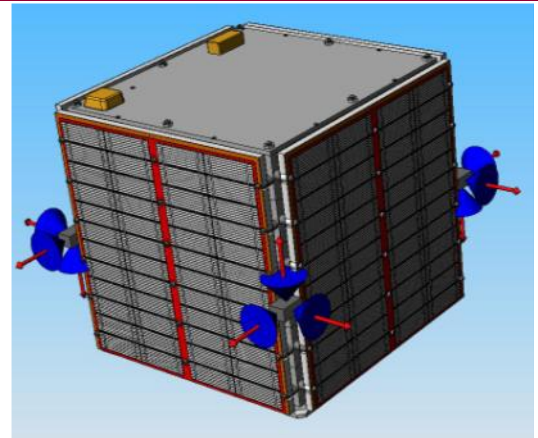
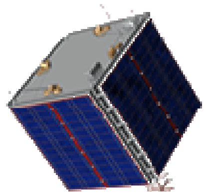
Thrust Level Determination

•In order to evaluate the thrust level required for ALMASat-1 mission, the pointing error and the manoeuvre acquisition time are take in account.

•From the accuracy point of view, a very low thrust concur to obtain high pointing accuracy, but the acquisition time as well as greater how much the satellite inertia is high.





Weight / Thrust	10 kg	100 kg	1000 kg
1 mN	Pointing Error: 1-2° Acquisition Time: 10^3s	Pointing Error: 2° Acquisition Time: 10^4-10^5 s	Thrust not sufficient
30 mN	Pointing Error: 3-4° Acquisition Time: 10^2s	Pointing Error: 1-2° Acquisition Time: 10^3s	Pointing Error: 1-2° Acquisition Time: 10^5s
100 mN	Unstable	Pointing Error: 1-2° Acquisition Time: 10^2s	Pointing Error: 1-2° Acquisition Time: 10^3-10^4 s

The 1 mN thrust level has been chosen for the ALMASat-1 microsatellite mission requirements.

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Micropropulsion System Layout

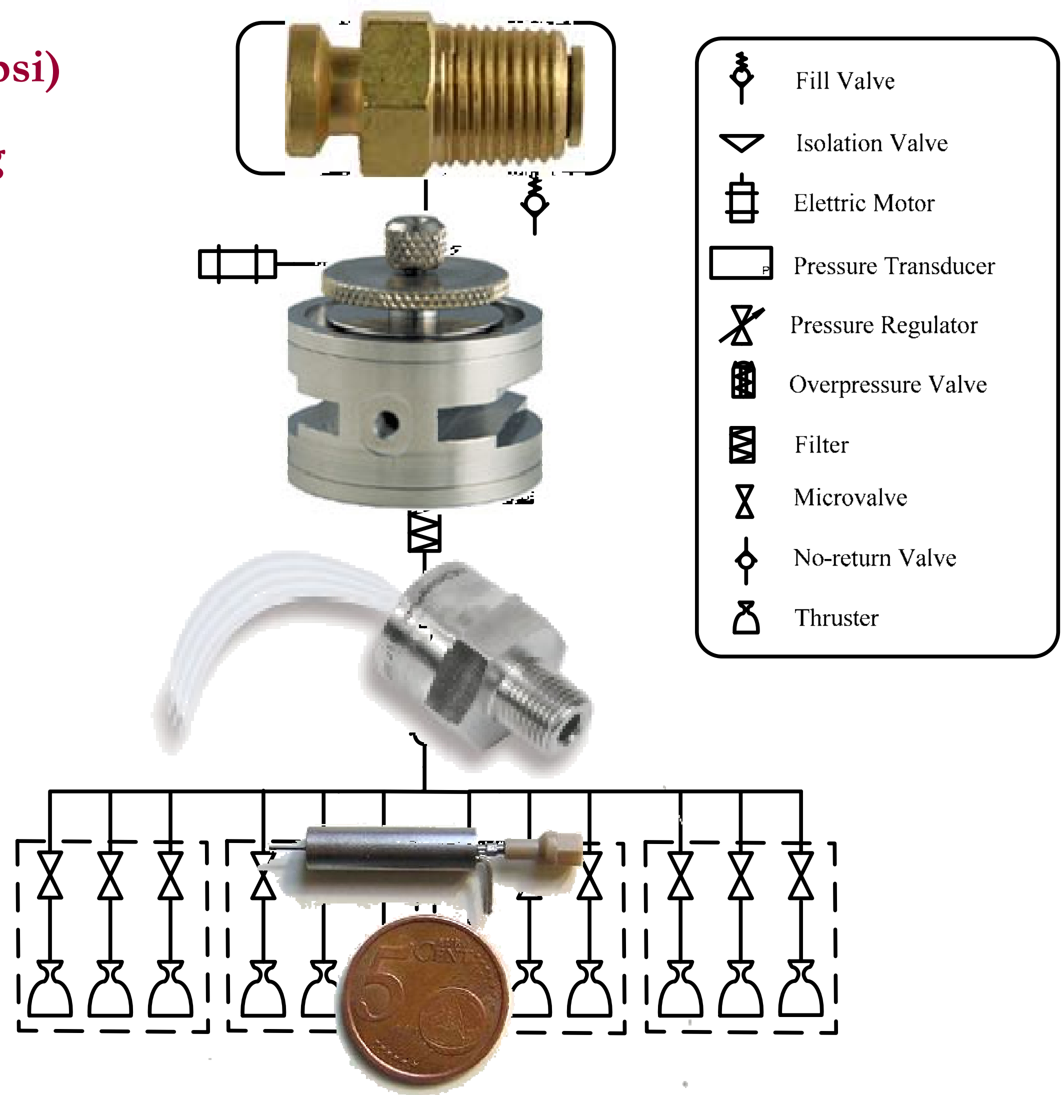
•Elliptical shape Tank: 0.7 liters

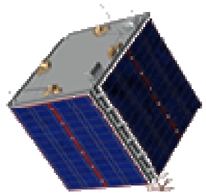
•Pressure Tank: 35 bar (500 psi)

•Propellent Mass (N_2): 27.5 g

•Estimate Total Mass: 950 g

•Firing Time: 25000 s





Commercial Component:

- Fill Valve: inlet 500 psi
- Pressure Regulator:
  Inlet: 500 psi
  Oulet: 0 - 30 psi
- Pressure transducer:
  range 0 - 1000 psi
- Solenoid Valve:
  range 0 - 100 psi

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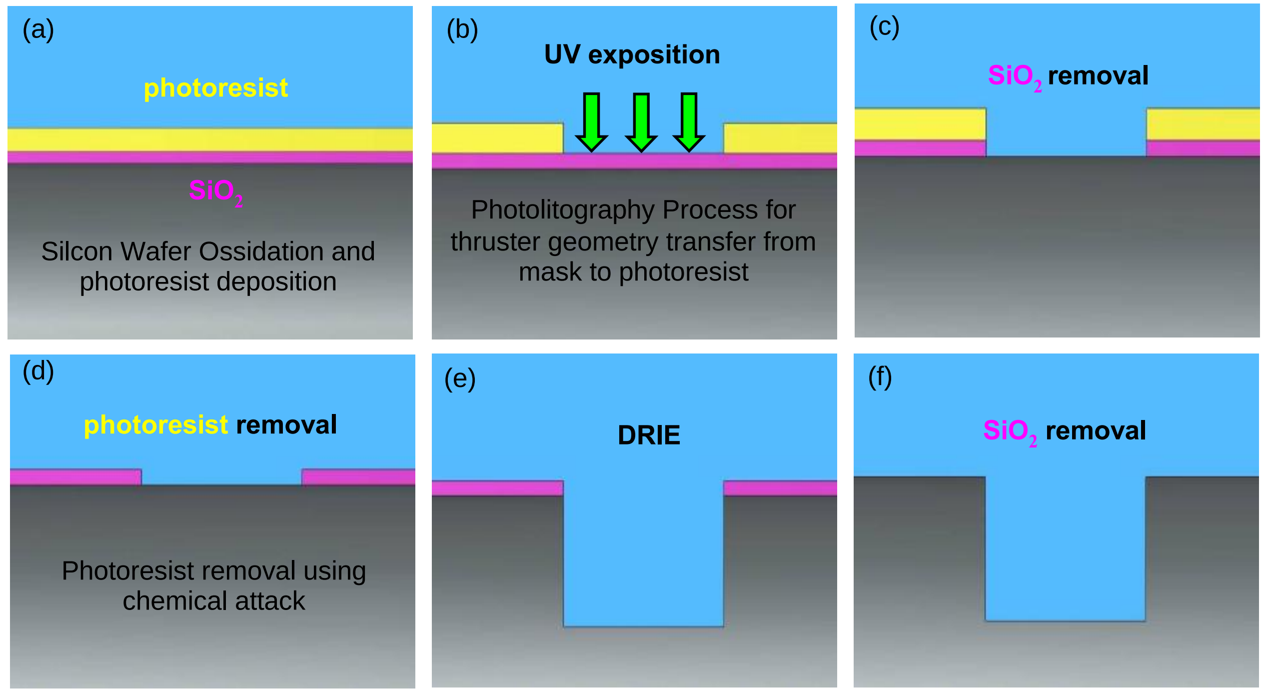
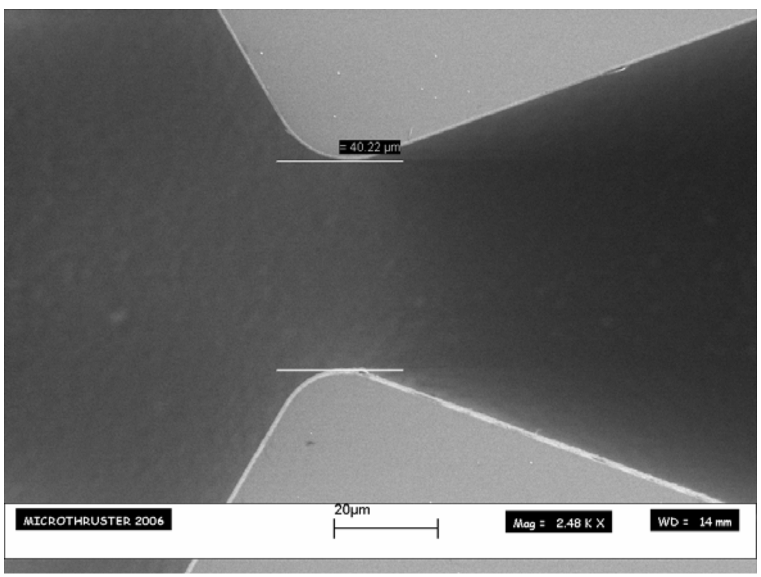
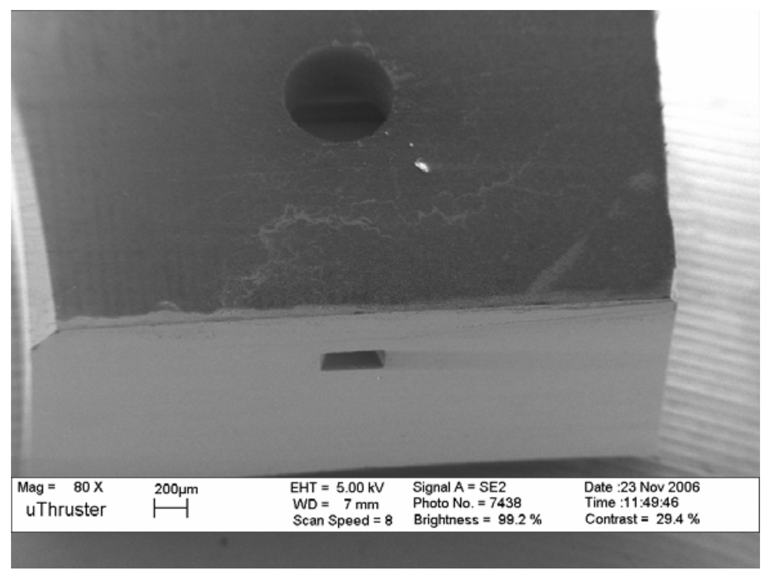
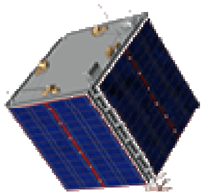
Microthruster Realization

- In collaboration with Carlo Gavazzi Space S.p.a
- Bonding Si - Si
- Microthruster Dimension:
  Dg = 40 micron
  H = 200 micron
  AR = 10

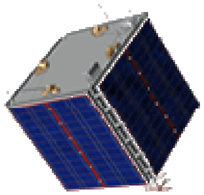








Valve Leakage Measurement

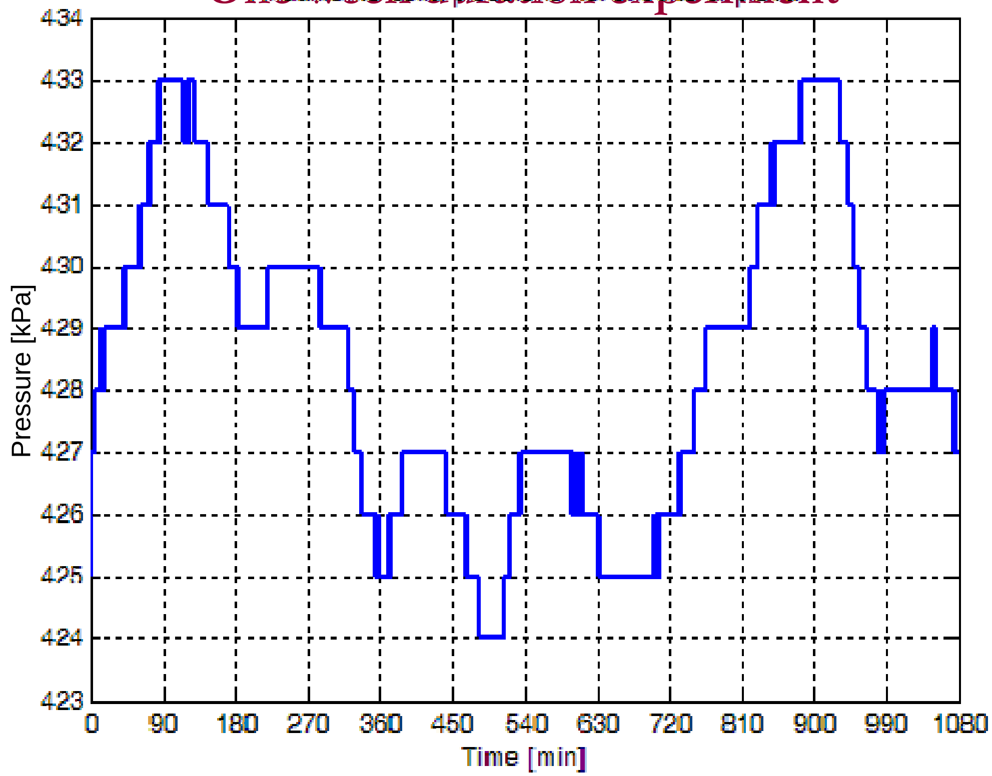


Target: to evaluate the valve leakage and to guarantee the microthruster feed during the entire mission.

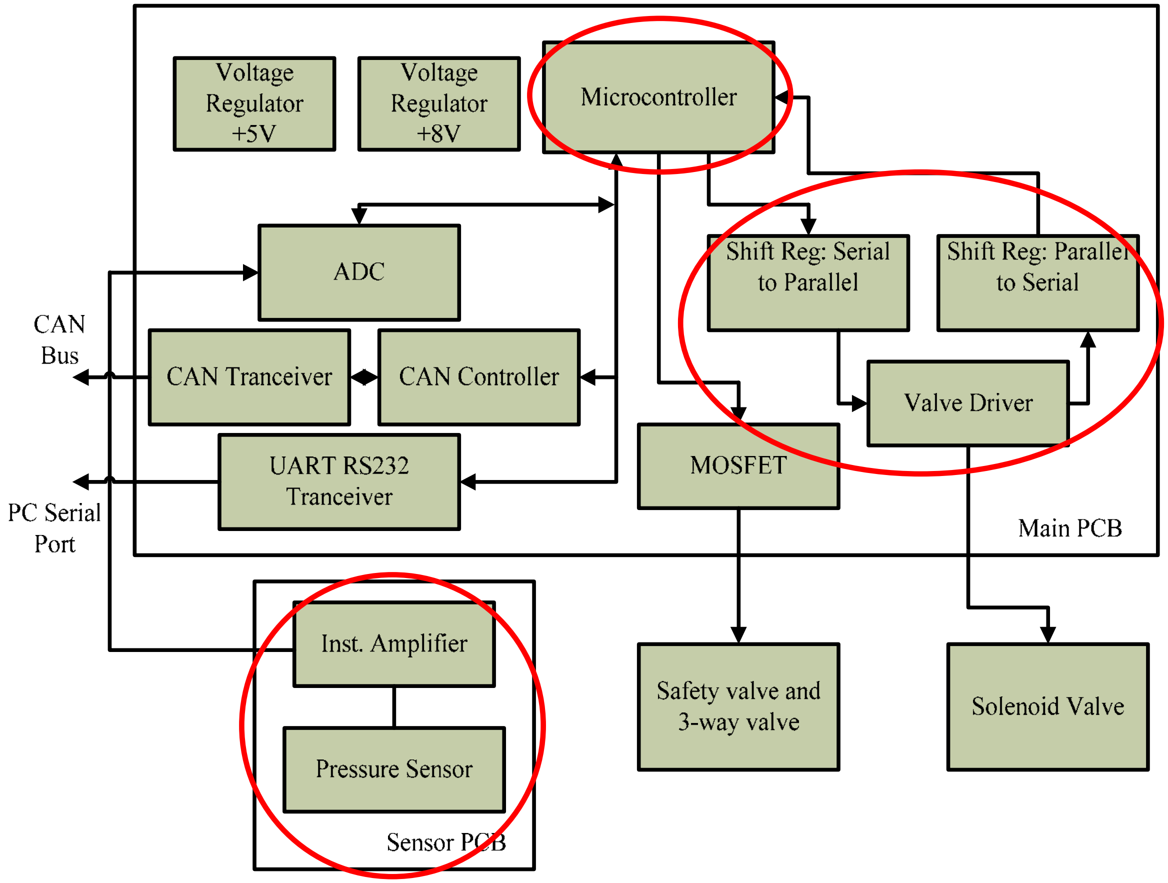
The losses mass flow rate are in the order of: 2.3×10^{-4} mg/sec

The time required to empty entirely the tank, with 30 g of N_2, is about 4 years.

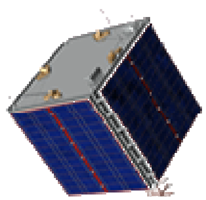
One week duration experiment



Control Electronics



8 bits microcontroller: collect data from pressure sensors, control the valves, communicate with other subsystems and execute the algorithms needed to perform attitude control manoeuvres.



Amplify the voltage signal produced by the pressure sensors. The amplified signal (0÷5 V) is translated into a 12-bit digital signal by the ADC. This information is transferred through a SPI (Serial Peripheral Inteface) bus to the microcontroller, that can collect data or send them to the Ground Control Station using the radio link of the microsatellite platform.

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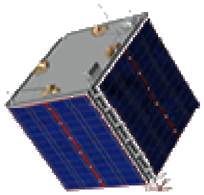
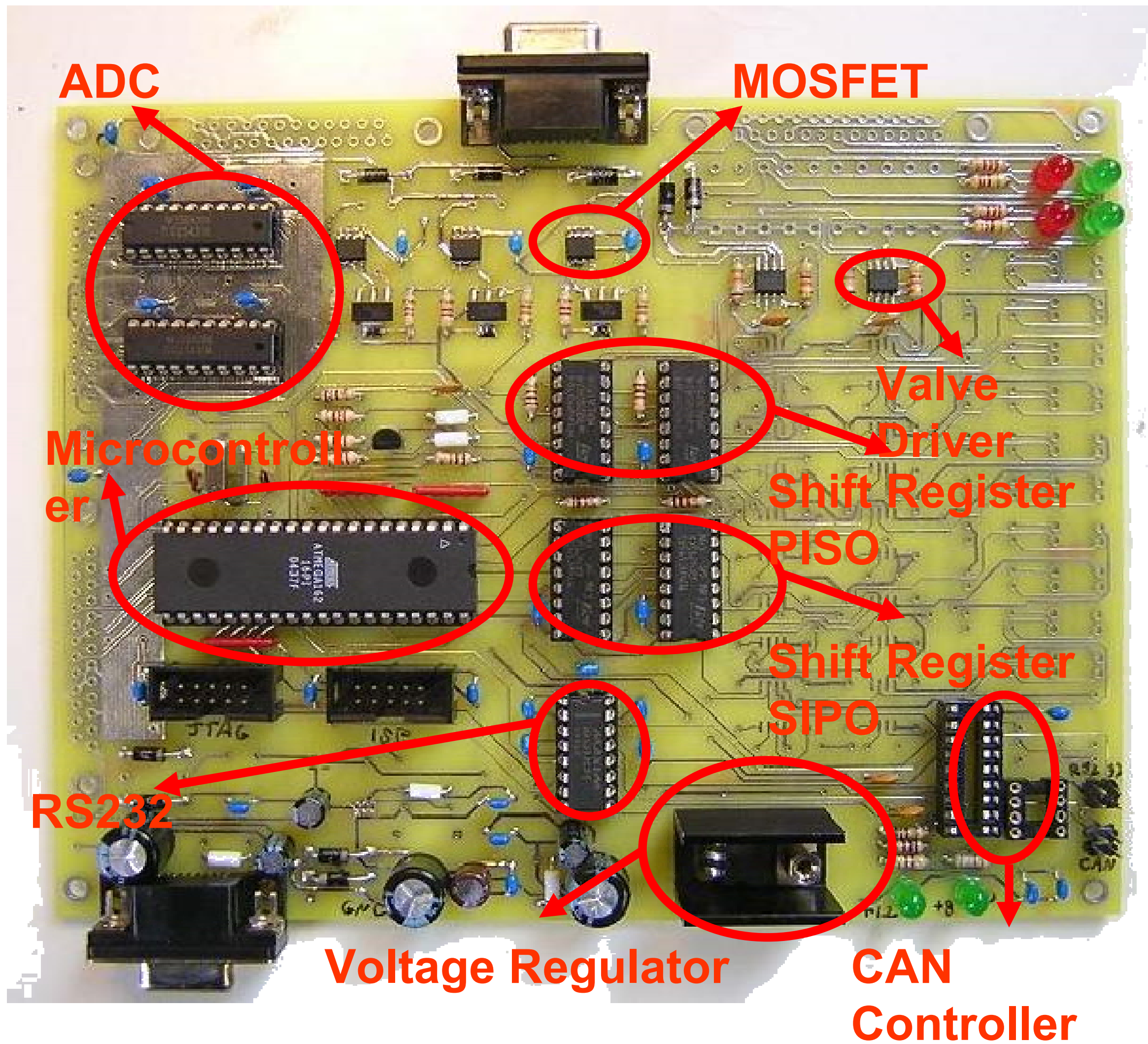
Control Electronics – PCB

The valve drivers create the signal necessary to open the valve:

- Spike impulse at 12 V for 2 ms;
- Hold phase at 2.3 V (0.5 W consumption) that keeps the valve opened.

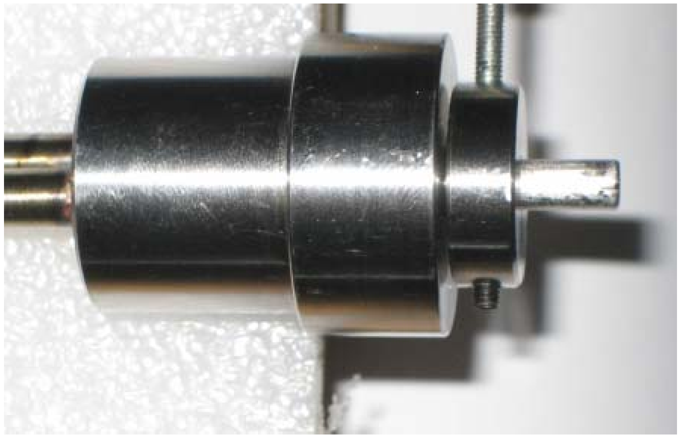


Because of the large amount of valves a combination of Shift Register SIPO (Serial In Parallel Out) and PISO (Parallel In Serial Out) is used to actuate the valve drivers form the microcontroller.

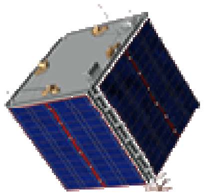


Laboratory Prototype

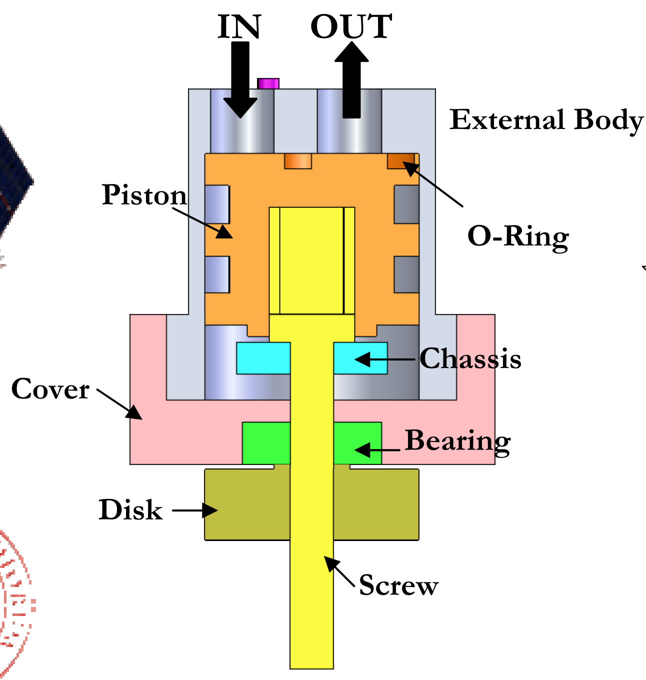
Isolation Valve



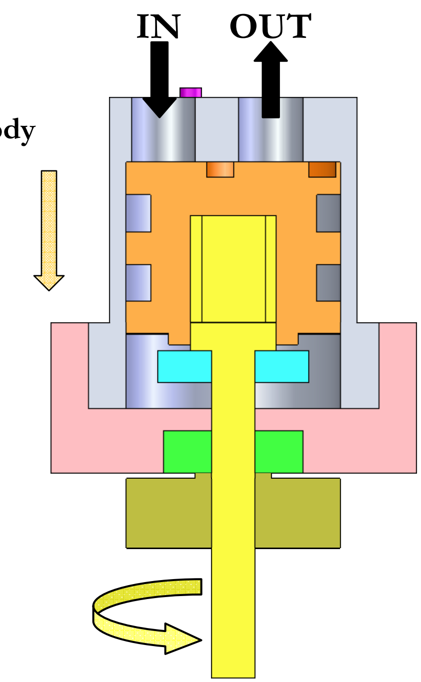
- Entirely developed in the aerospace laboratory of the University of Bologna.
- Mass: <100 g
- Dimensions: ø=30 mm; h=40 mm
- Open Torque: 175 mN*m



Close configuration



Open configuration



Leakage Measurement:

- Inlet Pressure: 35 bar
- Duration Test: 3 weeks
- No leakage

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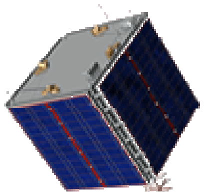
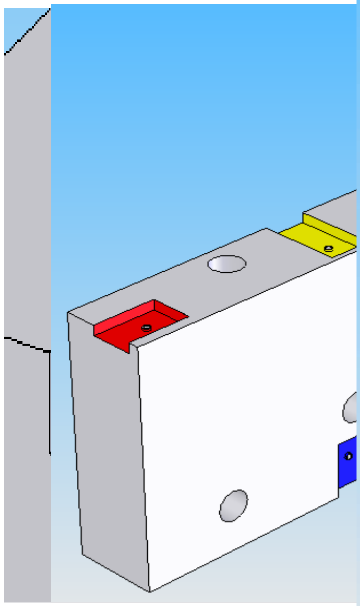
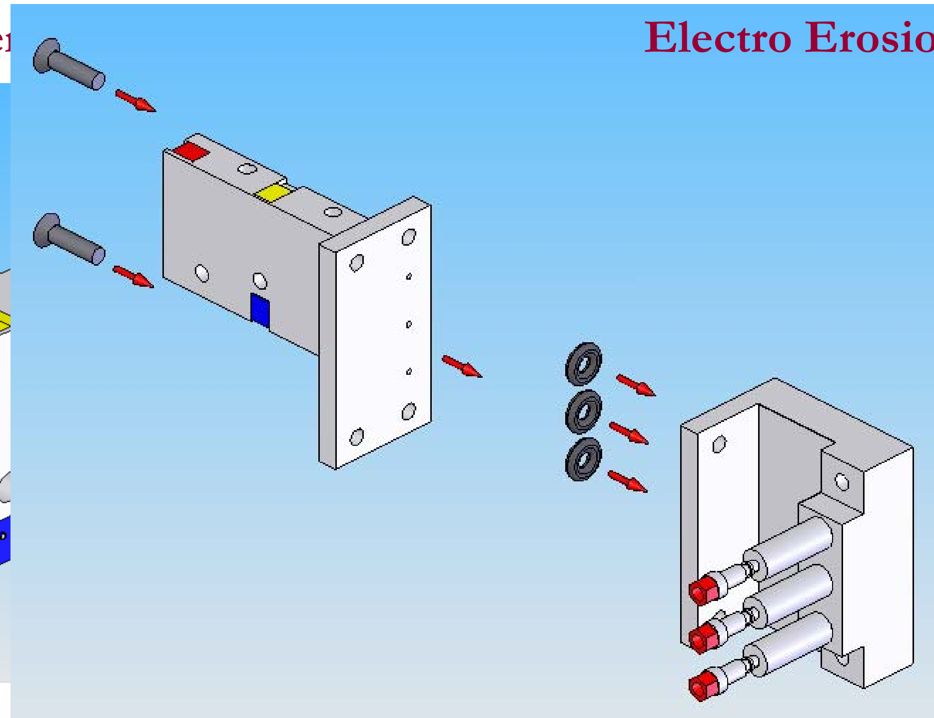


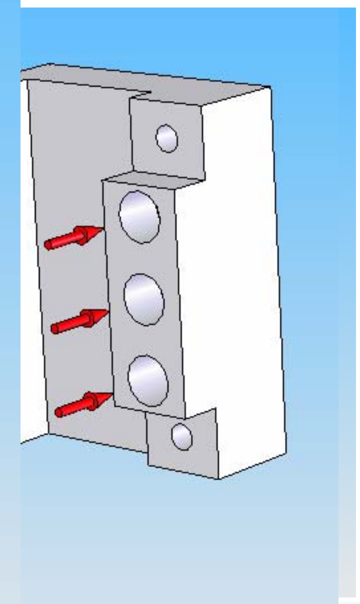
Thruster - Valve Group

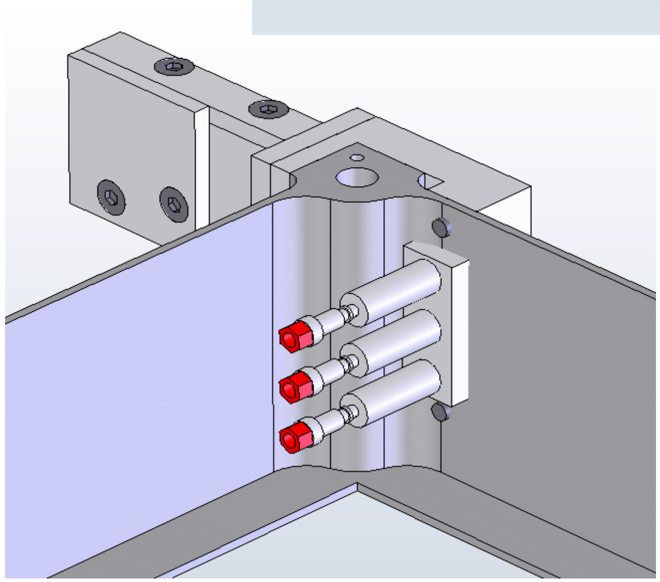
Thruster

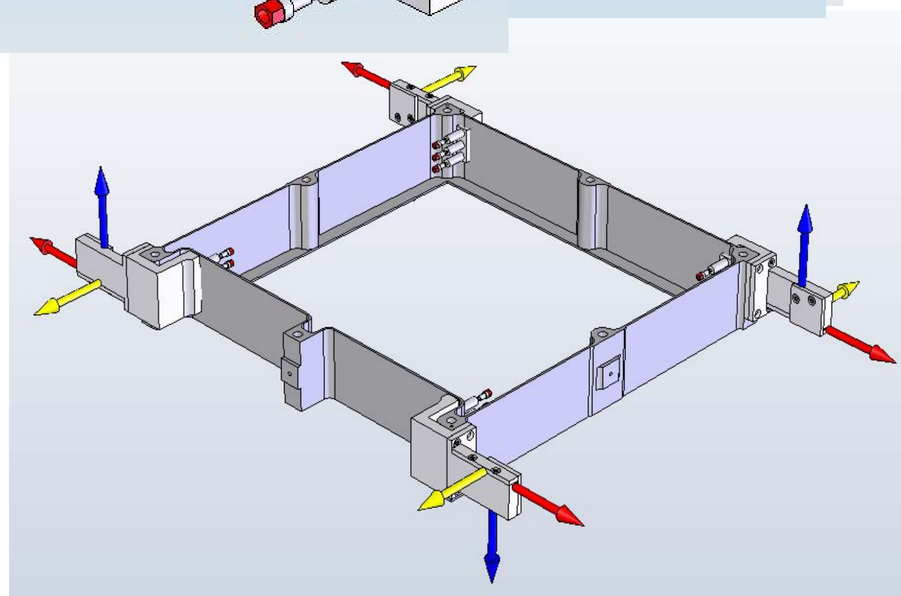
Electro Erosion Machine











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In-orbit Micropropulsion Experiments (1/3)

Three-axis stabilization and nominal attitude maintanance:

- Momentum Wheel Switch-off beginning from an attitude acquisition and maintained configuration;

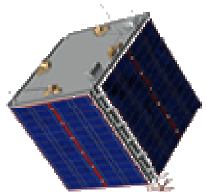
Satellite Mass: 12 kg; **Thrust: 1 mN;** **Impulse Bit: 1 mNs;**

Moment of Inertia:

$I_x = 0.4\ kg\cdot m^2$;

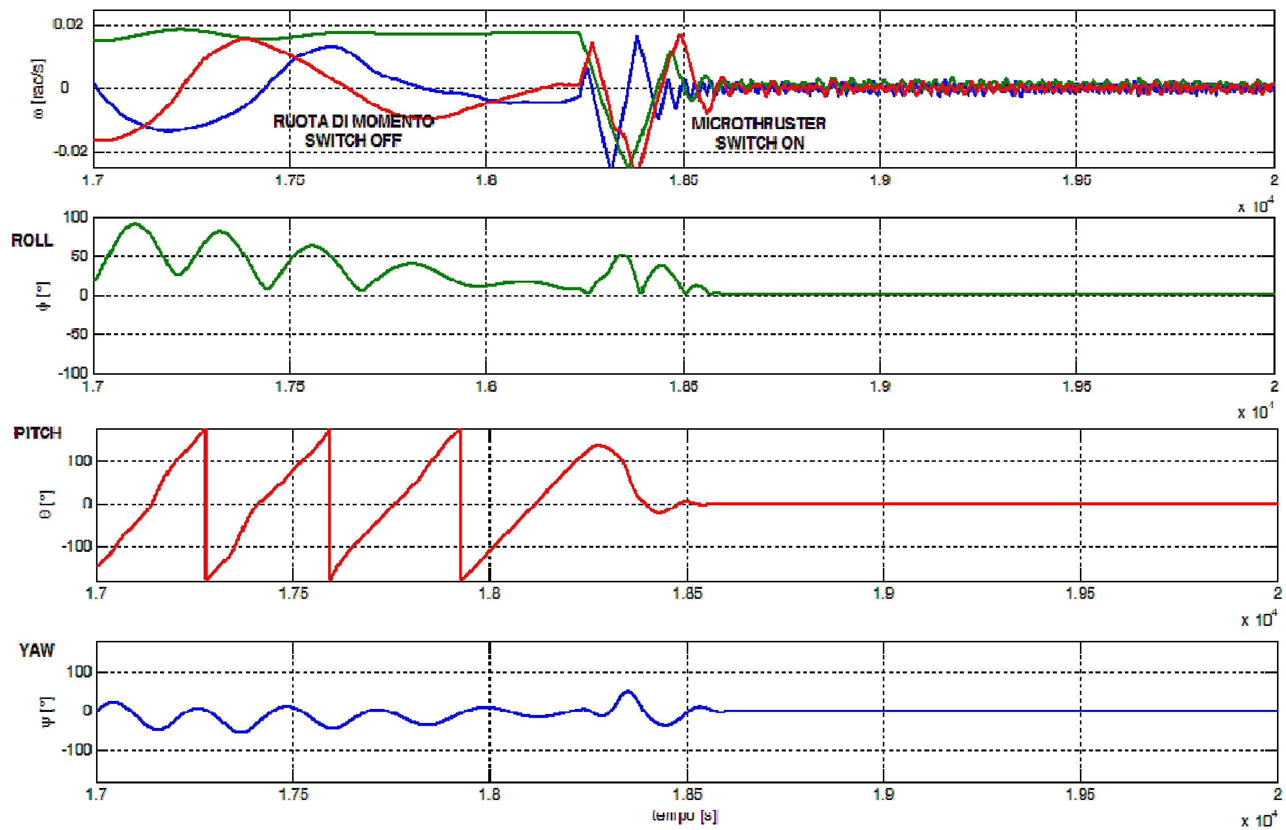
$I_y = 0.6\ kg\cdot m^2$;

$I_z = 0.5\ kg\cdot m^2$;



1ª phase: pointing losses due to momentum wheel switch-off and momentum transfer from wheel to satellite;

2ª phase: microthruster switch-on and stabilization;



Accuracy: +/- 1°

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In-orbit Micropropulsion Experiments (2/3)

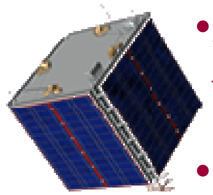
Momentum wheel desaturation:

- When the momentum wheel exits from its velocity range (effect due to environment space disturbances), the momentum wheel requires a desaturation operation.
- Usually this operation is obtained generating a torque around the wheel axis using magnetic coils.

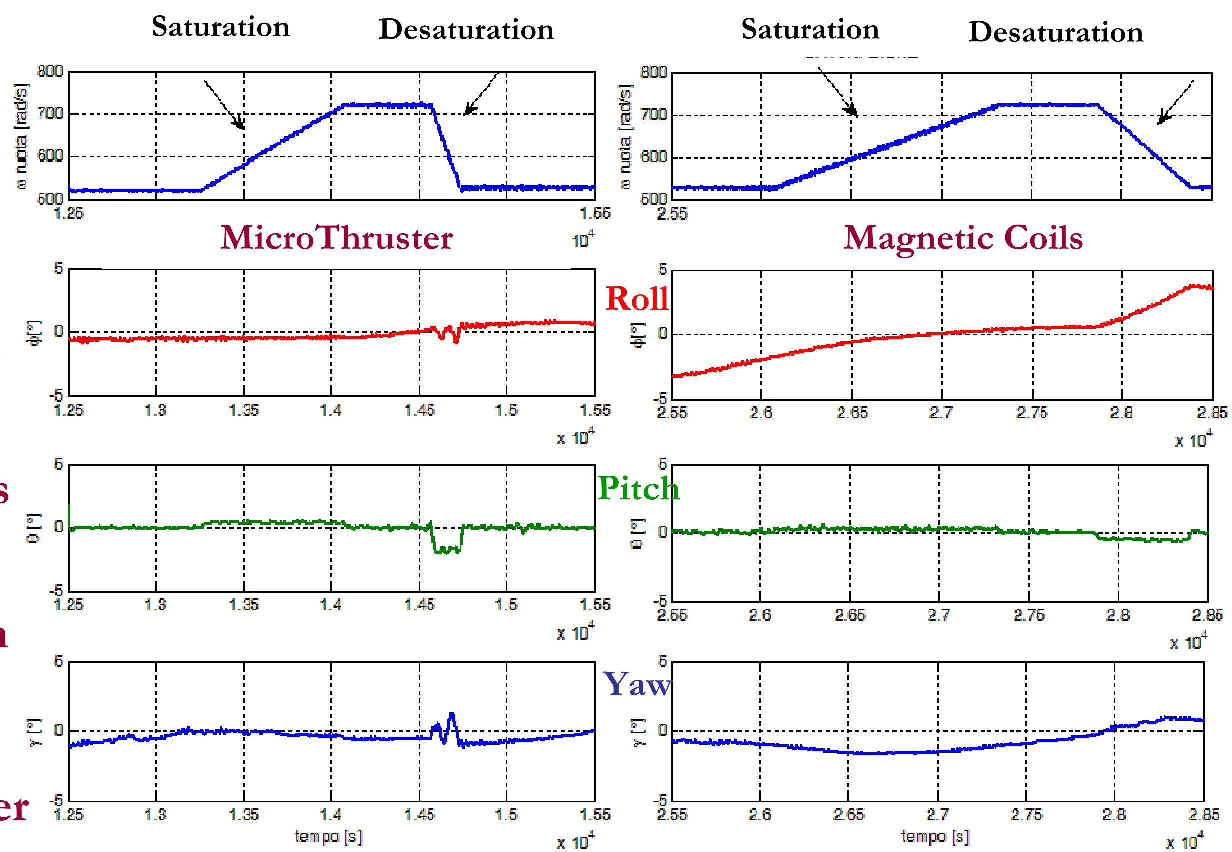
Desaturation Time:

Thruster: 200 s;

Magnetic Coils: 500 s;



- Less time required with micropropulsion
- External disturbance on the microsatellite is smaller
- The effect is visible in the roll angle which is less disturbed than in the magnetic maneuver



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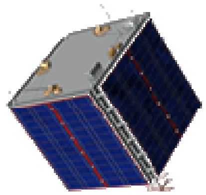
In-orbit Micropropulsion Experiments (3/3)

Small orbital manoeuvre, aimed at raising the S/C altitude (semi-major axis) will make use of two thruster firing continuously until the gas runs out:

- **Implementation of a Numerical Integrator of the orbital dynamics to simulate the maneuver efficiency and the J2 orbital perturbation;**
- **Microthruster Time Firing: 6000 s;**
- **Propellent Mass Consumption: about 10 g;**

$$\Delta v = \frac{\Delta a}{2v} \cdot \frac{\mu_{terra}}{\left(h + r_{terra}\right)^2} = 0.83 \text{ m/s}$$



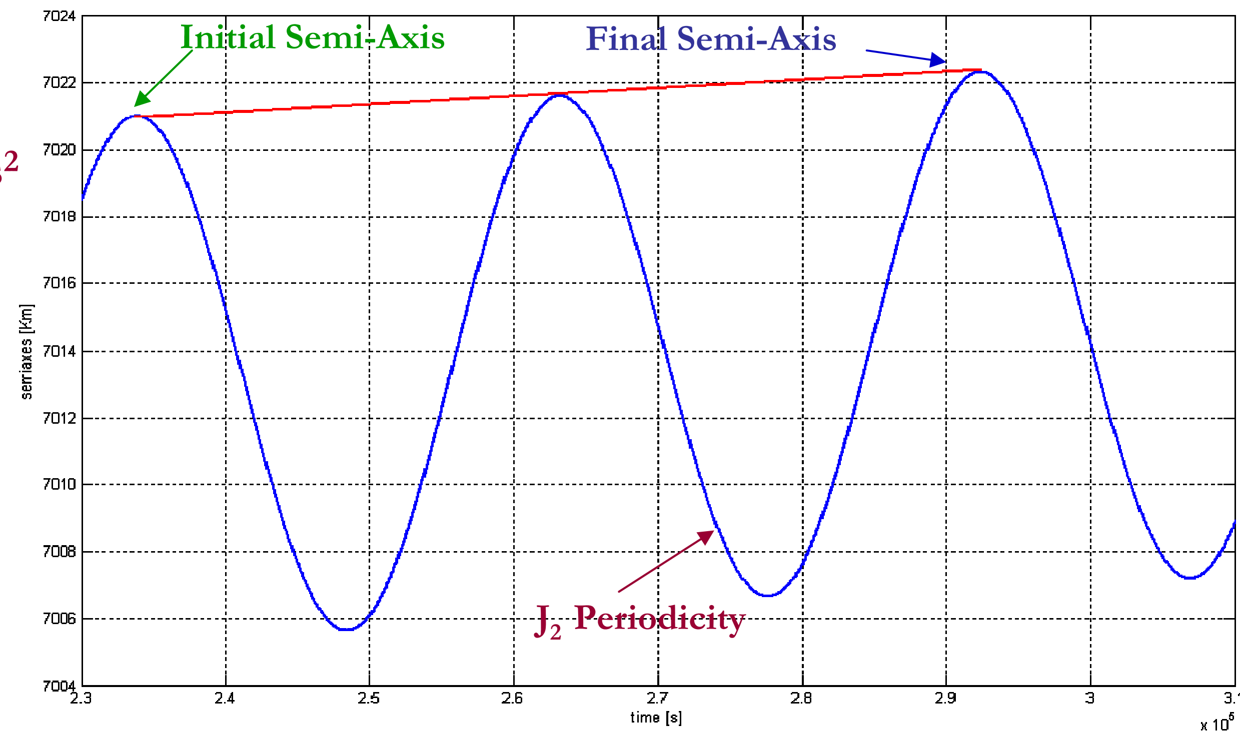
r_{terra} = 6372,8 km

μ_{terra} = 398604 km^3/s^2

h = orbit altitude

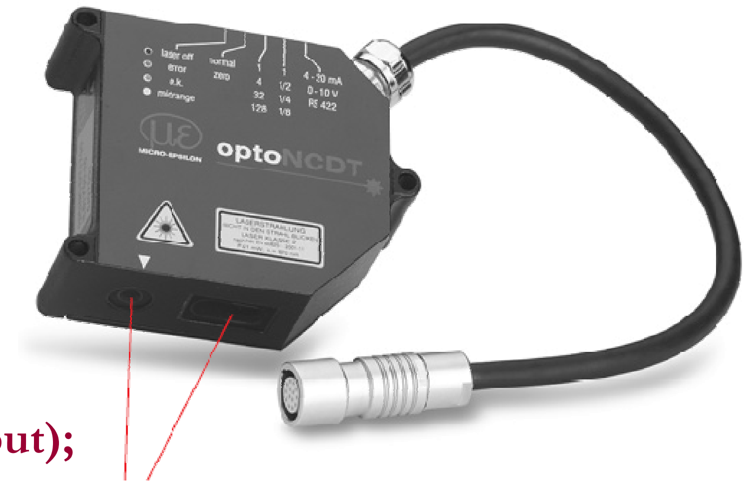
$v \sim 8$ km/s

$\Delta a = 1.5$ km



MicroBalance OverView: Sensor

Micro Epsilon OptoNCDT 1700 Laser Optical Displacement Sensor

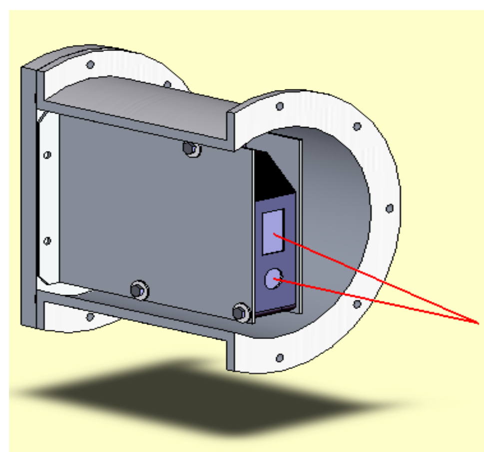


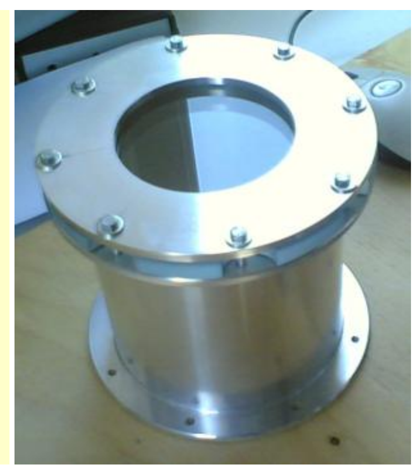
- Optical triangulation principle;
- Measure Range (*MR*): 100 mm;
- Resolution: 6 µm;
- Linearity:+/- 0.08% *FSO* (Full Scale Output);
- Measurement Frequency: 2500, 1250, 625, 312.5 Hz;
- RS422 serial interface;

Not suitable to operate in Vacuum condition → pressurized box

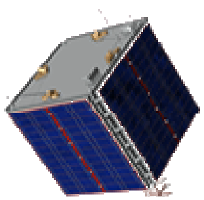
$$x[mm] = \left(digital_{OUT} \cdot \frac{1.02}{16368} - 0.01 \right) \cdot MR[mm]$$

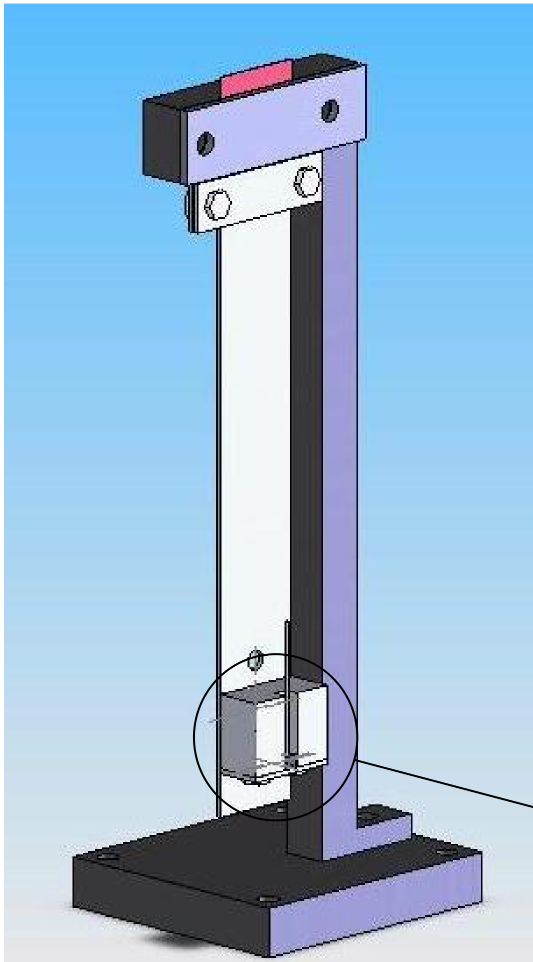
The sensor uses the above formula to convert a digital value (range $digital_{OUT}$ = 161 ÷ 16207) in a measurement value (mm).





MicroBalance OverView: Pendulum





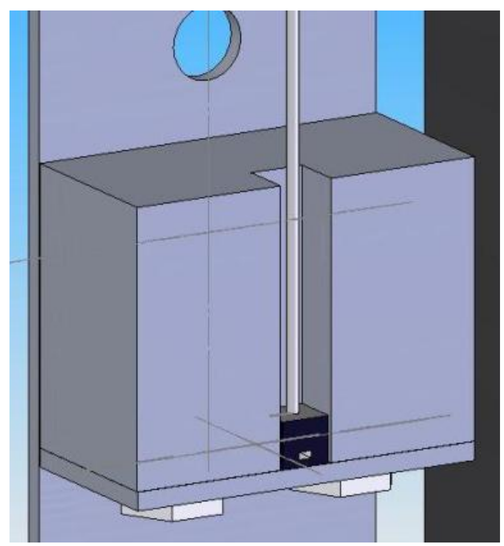
The pendulum transduces the thrust generated by the microthruster in a finite and proportional displacement measured by the laser trasducer.

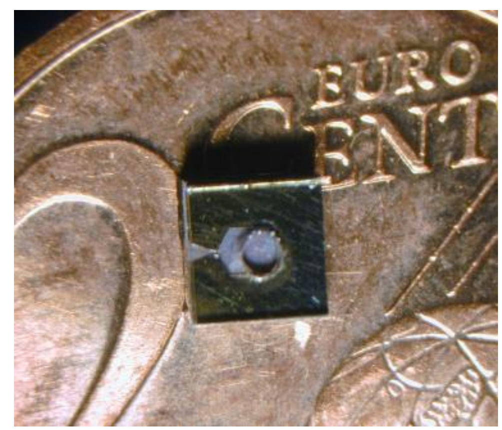
It consists of a:

•rigid support;

•rigid Arm;

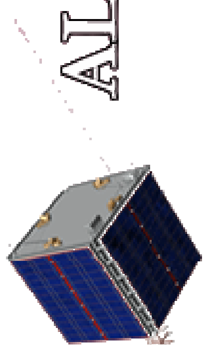
•Microthruster block support



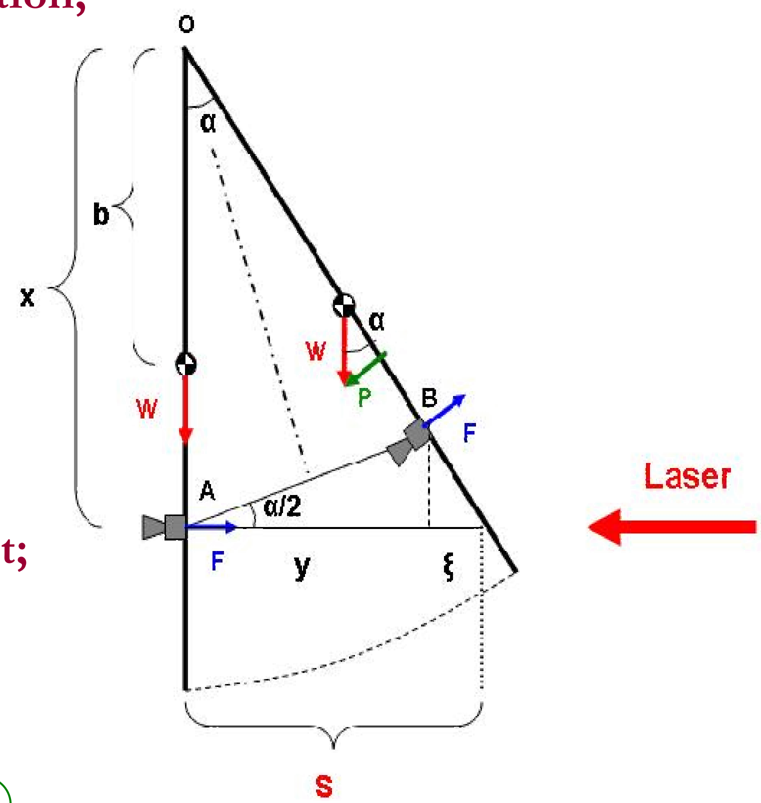


The hinge is an Aluminum sheet in order to minimize the friction

Measurement Principle



- P = weight component along thrust direction;
- W = pendulum total weight;
- F = microthruster thrust;
- α = oscillation pendulum angle;
- b = distance between center of mass and hinge point;
- x = pendulum arm;
- S = transducer displacement measurement;
- ξ = difference between S and y (S-y);
- AB = microthruster real displacement



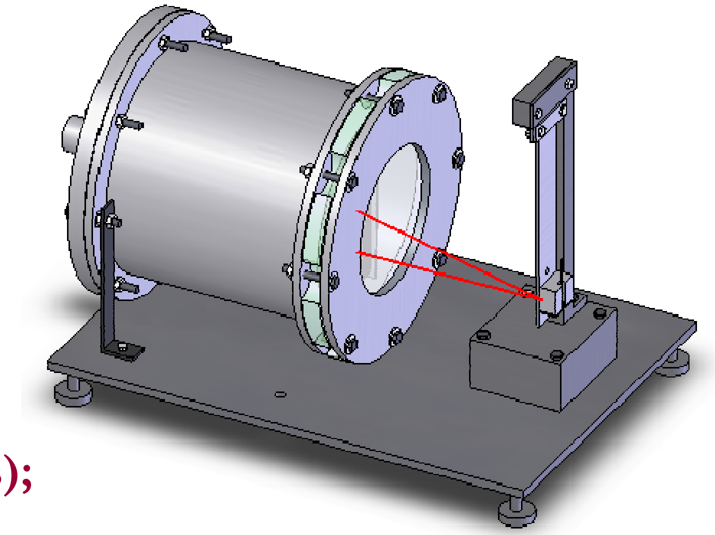
$$F = P \cdot \frac{b}{x} = W \cdot \sin\alpha \cdot \frac{b}{x}$$

$$\alpha = 2 \cdot \arcsin\left(\frac{S}{\left(1 + tg\left(\alpha/2\right) \cdot tg(\alpha)\right) \cdot \cos\left(\alpha/2\right) \cdot 2x} \right)$$

Iterative solution

MicroBalance Resolution (1/3)

$$\Delta F = W \cdot \frac{b}{x} \cdot \sin\left(2 \cdot \arcsin\left(\frac{\frac{\Delta y}{\cos\left(\alpha/2\right)}}{2 \cdot x}\right)\right)$$



Where:

W = 334 mN (oscillating system total mass);

b = 77 mm (center of mass);

x = 120 mm (pendulum arm);

Δy = 6 micron (sensor resolution);

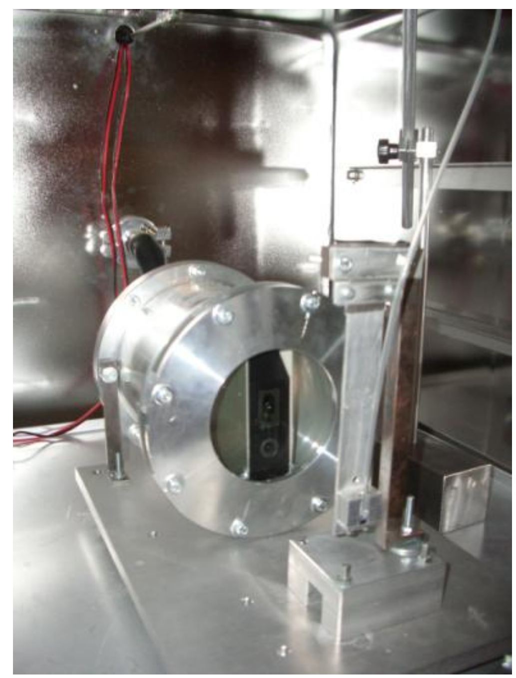
α = 0.005° (minimum angle due to resolution);

↓

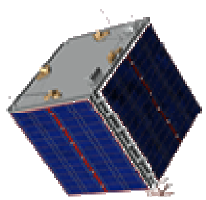
Theoretical Resolution

$$\Delta F = 0.0107\ mN$$

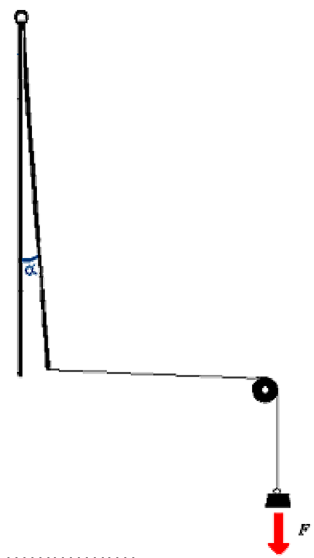
The center of mass is evaluated using the SolidWorks 2006 property mass Toolbox. In the real case the gas pipe adduction dislocation changes the center of mass position.



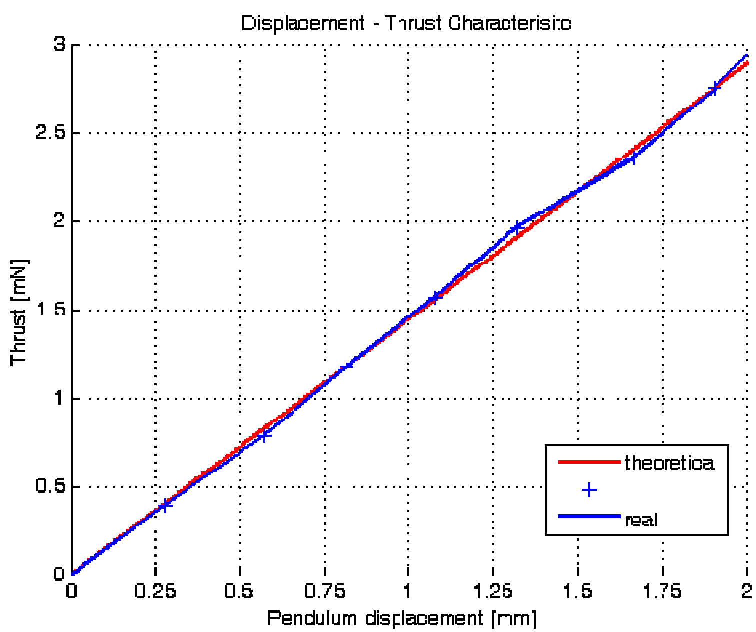
MicroBalance Resolution (2/3)



A "calibration method" with needles of known weight (0.04 g) is used in order to evaluate the position of the center of mass of the total system (pendulum and pipe for gas flow).



For every needles hung, the sensor measures the displacement of the pendulum. So a real characteristic in term of displacement – thrust can be plotted in order to evaluate the difference between the real case and the theoretical case (linear behavior).



$$\Delta F = 0.0098\ mN$$
$$b = 73\ mm$$
$$x = 122\ mm$$

The thrust resolution error using the SolidWorks Toolbox or the calibration method for evaluating the center of mass is below the 8%.

MicroBalance Resolution (3/3)

Since the thrust and resolution depends on pendulum weight and geometry we introduce the adimensional value:

$$\Delta y^* = \frac{\Delta y}{x} = 5 \cdot 10^{-5}$$

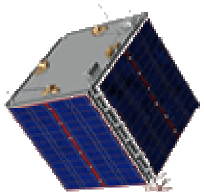
Adimensional Displacement Resolution

Adimensional Thrust Resolution

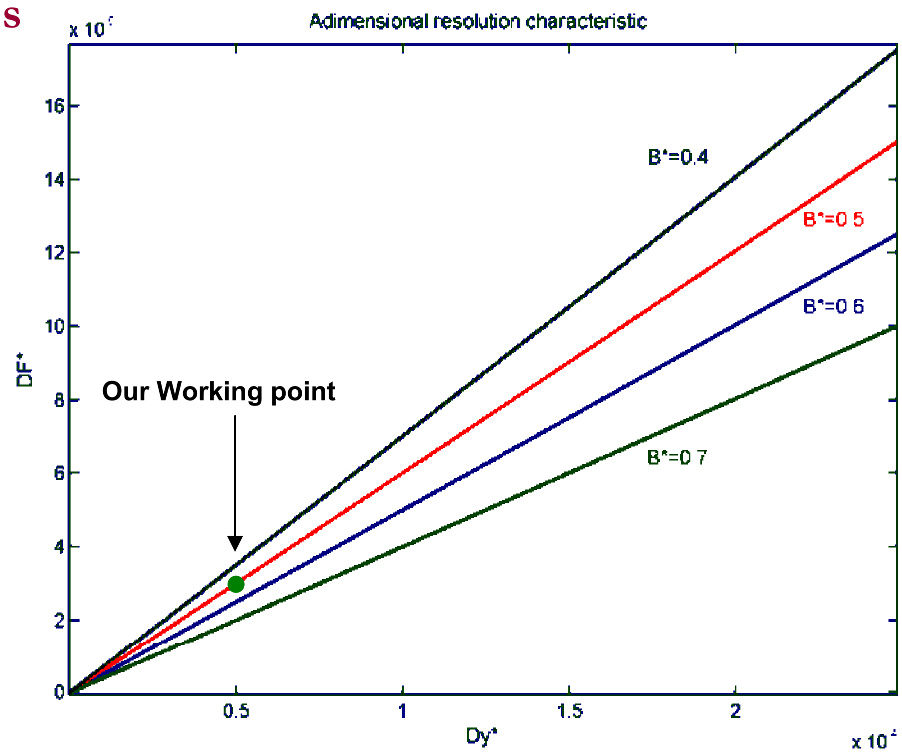
$$\Delta F^* = \frac{\Delta F}{W} = B^* \cdot \sin\left(2 \cdot \arcsin\left(\frac{\frac{\Delta y^*}{\cos\left(\alpha/2\right)}}{2}\right)\right) \approx 3 \cdot 10^{-5}$$

$$B^* = b/x = (0.6284 \pm 0.03)$$

Adimensional Center of Mass



The resolution of the system improves when the characteristic falls near the origin of the axes; this means that small values of **Δ**y* guarantee a better resolution. Since **Δ**y is a constant (fixed by the displacement sensor technology), the only way to get to an optimal point, with the same weight, is to make the pendulum arm as long as possible.



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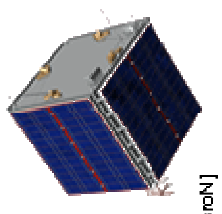
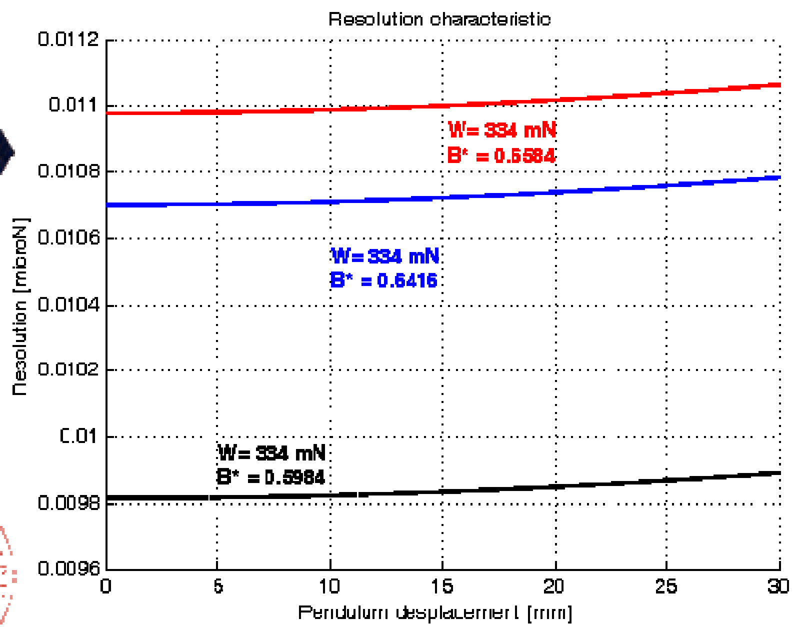
MicroBalance Accuracy

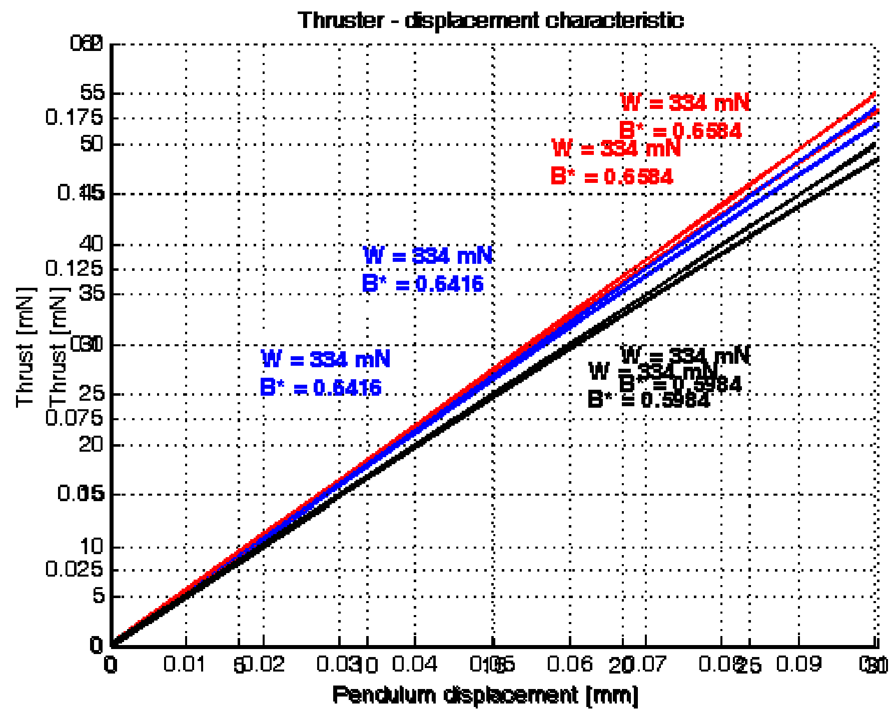
$$F = P\cdot\frac{b}{x} = W\cdot\sin\alpha\cdot\frac{b}{x} \Longrightarrow \begin{cases} F = \sin\alpha\cdot(333.54\pm1)\cdot(0.6284\pm0.03) \\ F_{min} = \sin\alpha\cdot198.99 \\ F_{max} = \sin\alpha\cdot220.26 \end{cases}$$

10% difference

The thrust evaluation error is quite small (below 10%). For a range of displacements $y = 0 \div 30$ mm, the resolution is confined around the value of 0.0098 ÷ 0.0110 mN.







Measurement System Characterisitic

- Thrust Resolution: ~ 0.01 mN
- Accuracy: ± 10%

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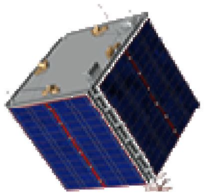
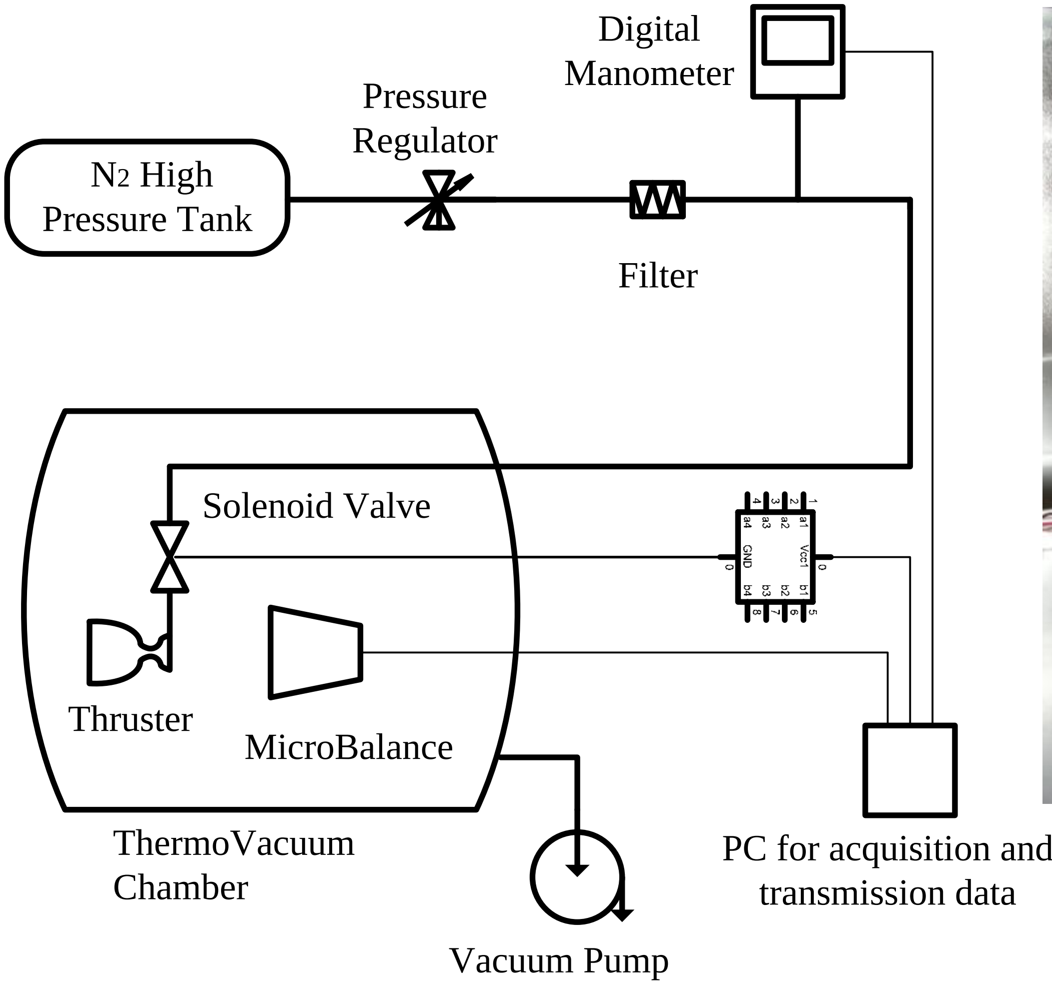
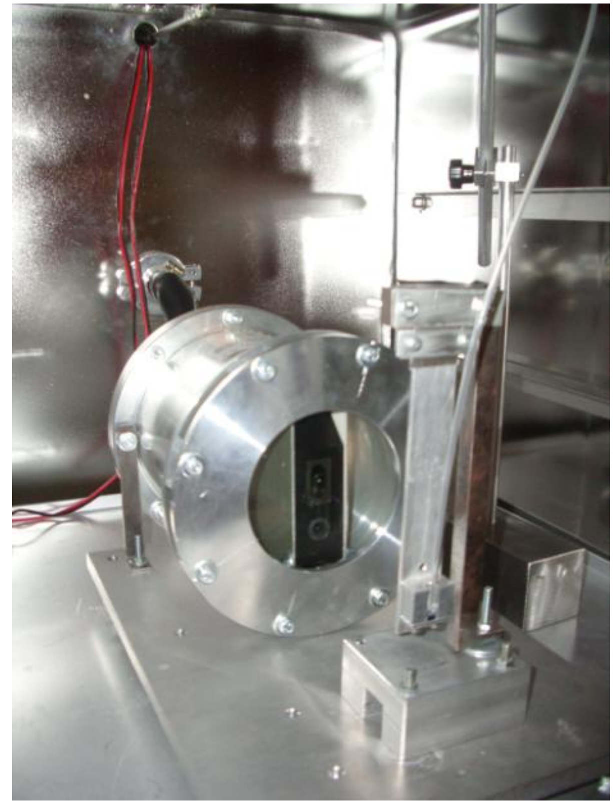


Thrust Measurement System Layout





Experimental test conducted in a thermo-vacuum chamber with ultimate vacuum level of 10^{-2}mbar and at different feed pressure in order to evaluate the thrust generated by the microthruster.

Microthruster Dimension:

Dt = 40 μm; H = 200 μm; AR = 10;

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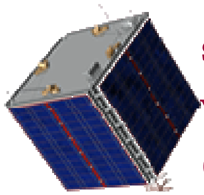
Real Time Thrust Measurement (RTTM)

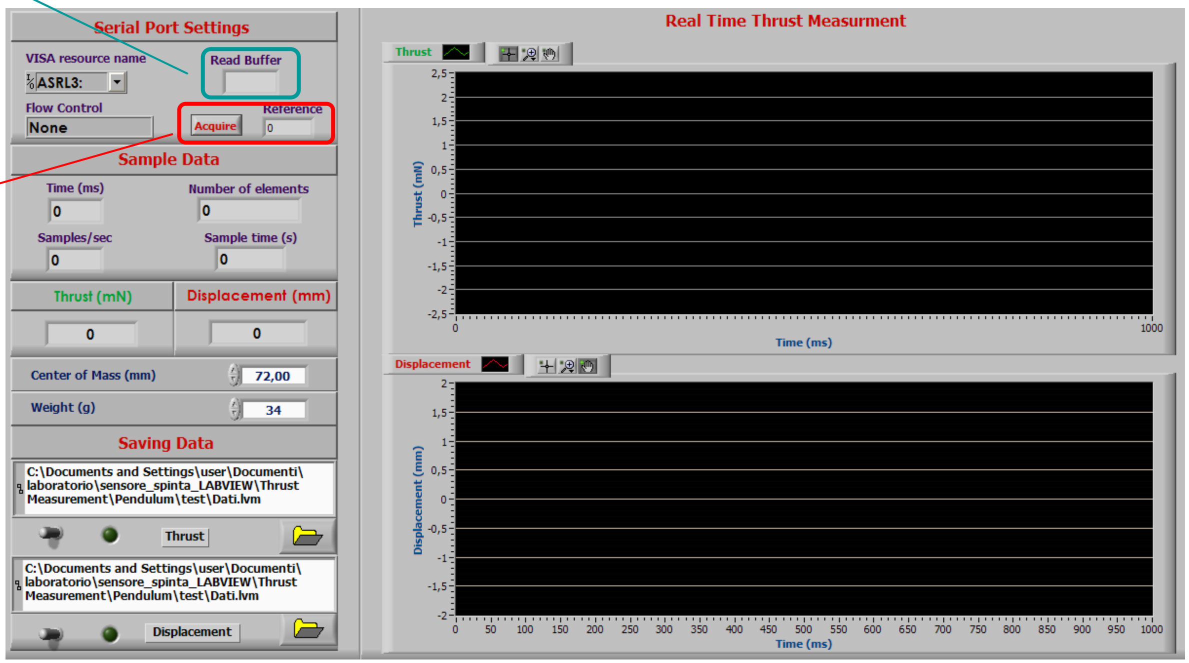
- Software developed in LABView environment;
- Real Time Thrust calculation and Visualization;
- The test result in term of displacement and thrust measure are saved in text file and loaded in Matlab environment for the post-processing.

$$x[mm] = \left(digital_{OUT} \cdot \frac{1.02}{16368} - 0.01 \right) \cdot MR[mm] \quad \Longrightarrow \quad MR = 100\ mm, \quad digital_{OUT} = 161 \div 16207$$

reads and acquires the digital values from sensor



The "acquire" button, saves the current digital value from sensor ("zero-reference"). In the thrust calculation the zero-reference value is subtracted from all successive values from the sensor, in order to calculate the relative displacements.



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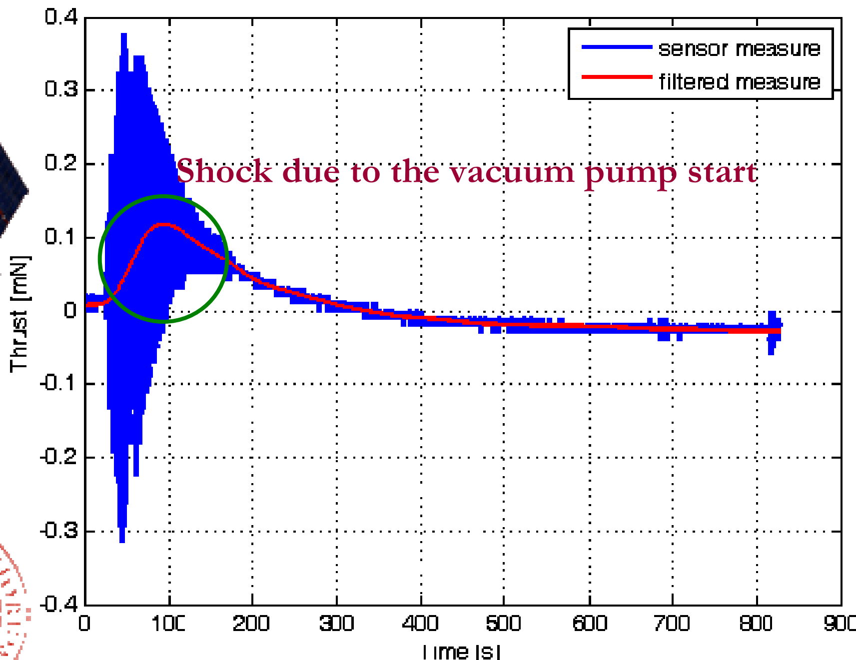
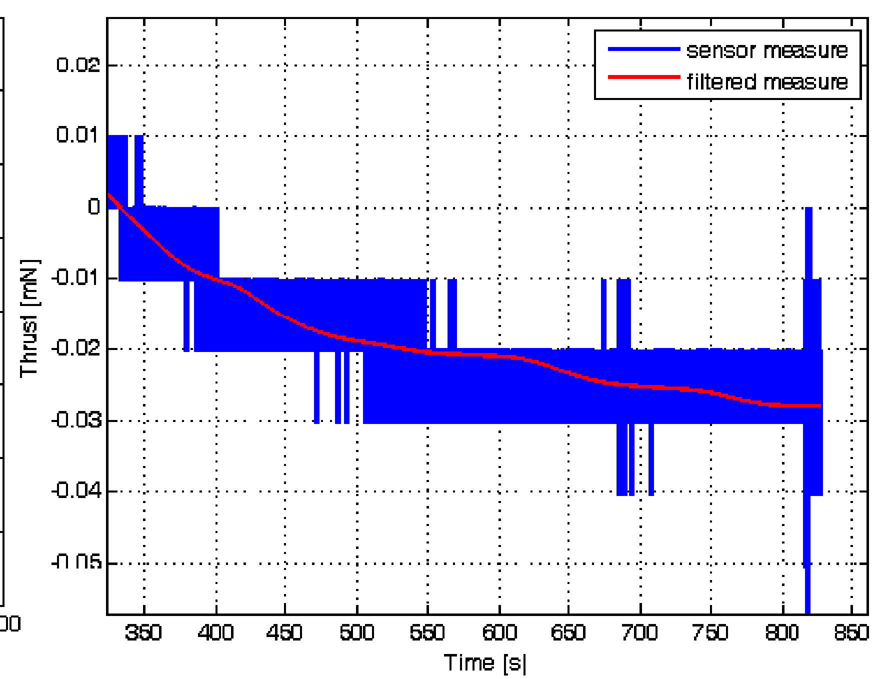
Zero Reference Value

The preliminary step is the acquisition of the displacement (or thrust) data during the reaching of vacuum conditions. This operation allows us to verify if the zero reference condition changes or not in vacuum. The change in zero reference condition is very small (about 0.03 mN), and depends on the air residual present in the pipe upstream (ambient pressure) and downstream (vacuum condition) the microvalve. So the center of mass can be considered for practical reasons coincident with the center of mass evaluated at ambient pressure.





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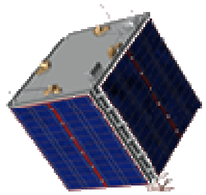


Some Thrust Measurement

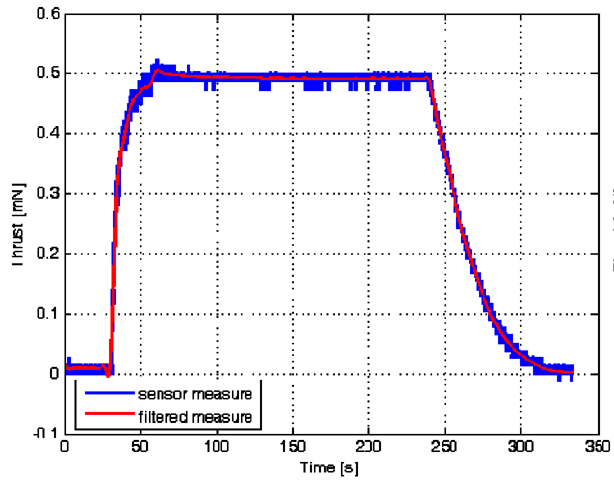
Two different Feed Pressure:

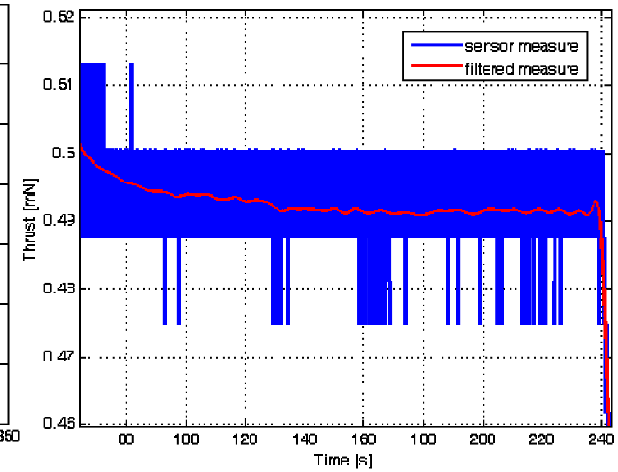
52 kPa (up)

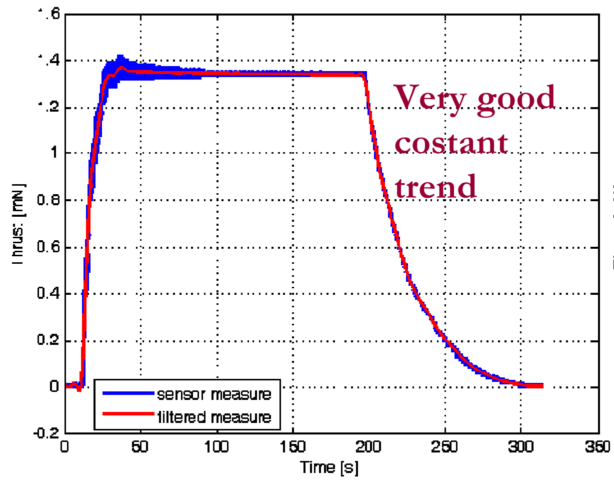
125 kPa (down)

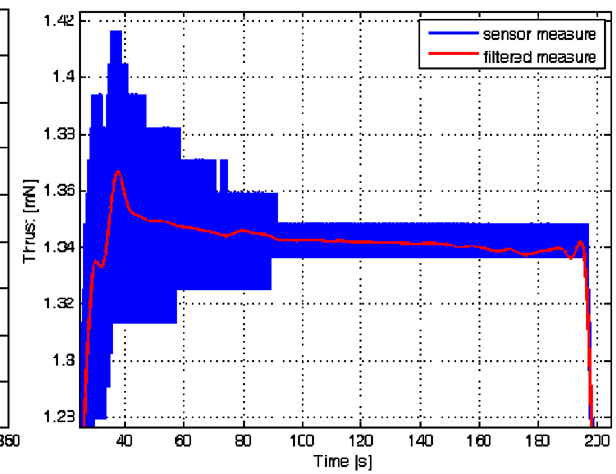
In both test the valve is opened and closed after 200 s.

Thrust measurement very well determined: quantization error of about 0.01 mN.









Capability to determine in a unique test the thrust values of a microthruster at different pressures without changing the system configuration, changing the outlet pressure regulator with a resoution of 1 kPa.

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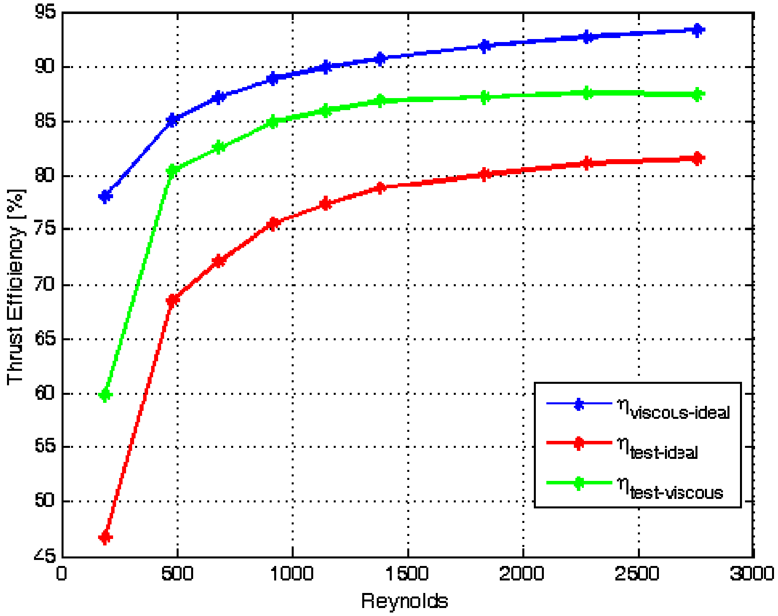
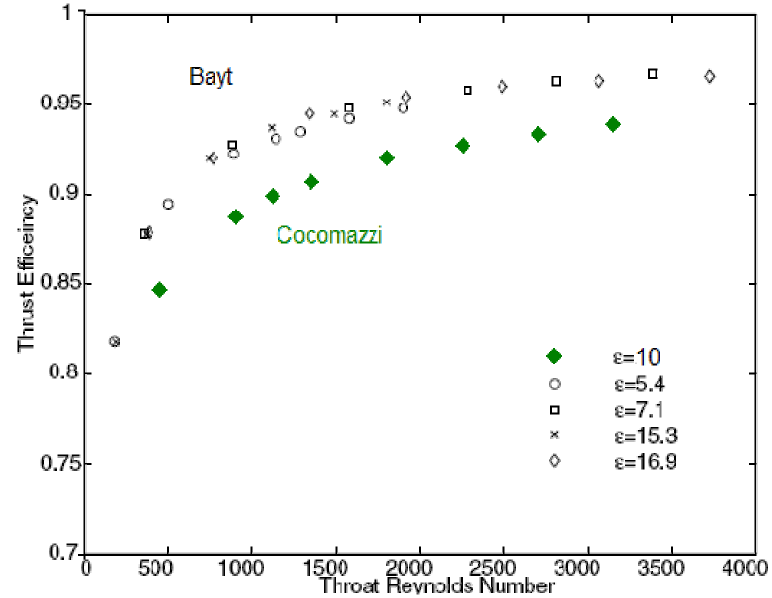
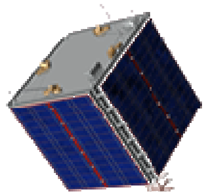
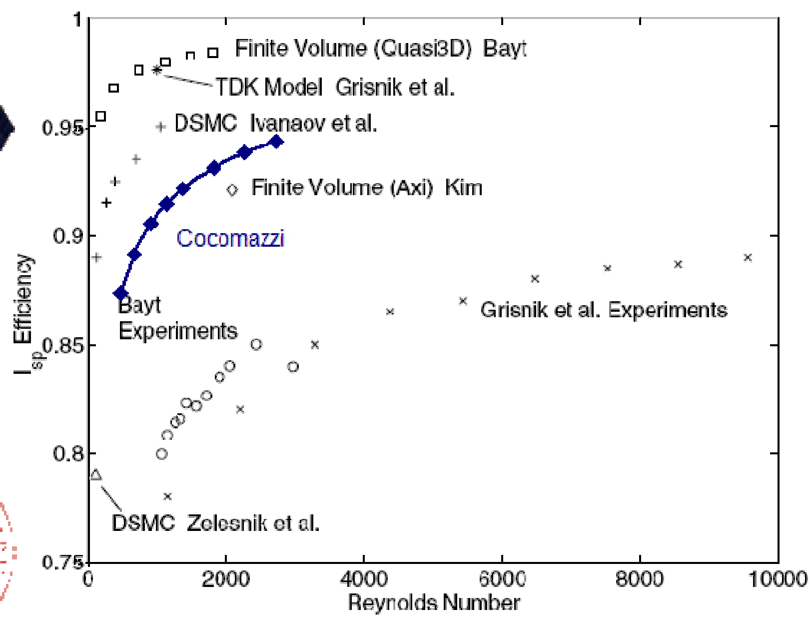
Comparison of Results









•The thrust efficiency increases as the Reynolds number increase in accordance with literature data;

•Below Re=500 the thrust efficiency is very low due to the viscous loss effect;

•Comparison between experimental results and simulations shows that the differences are confined around 10%.

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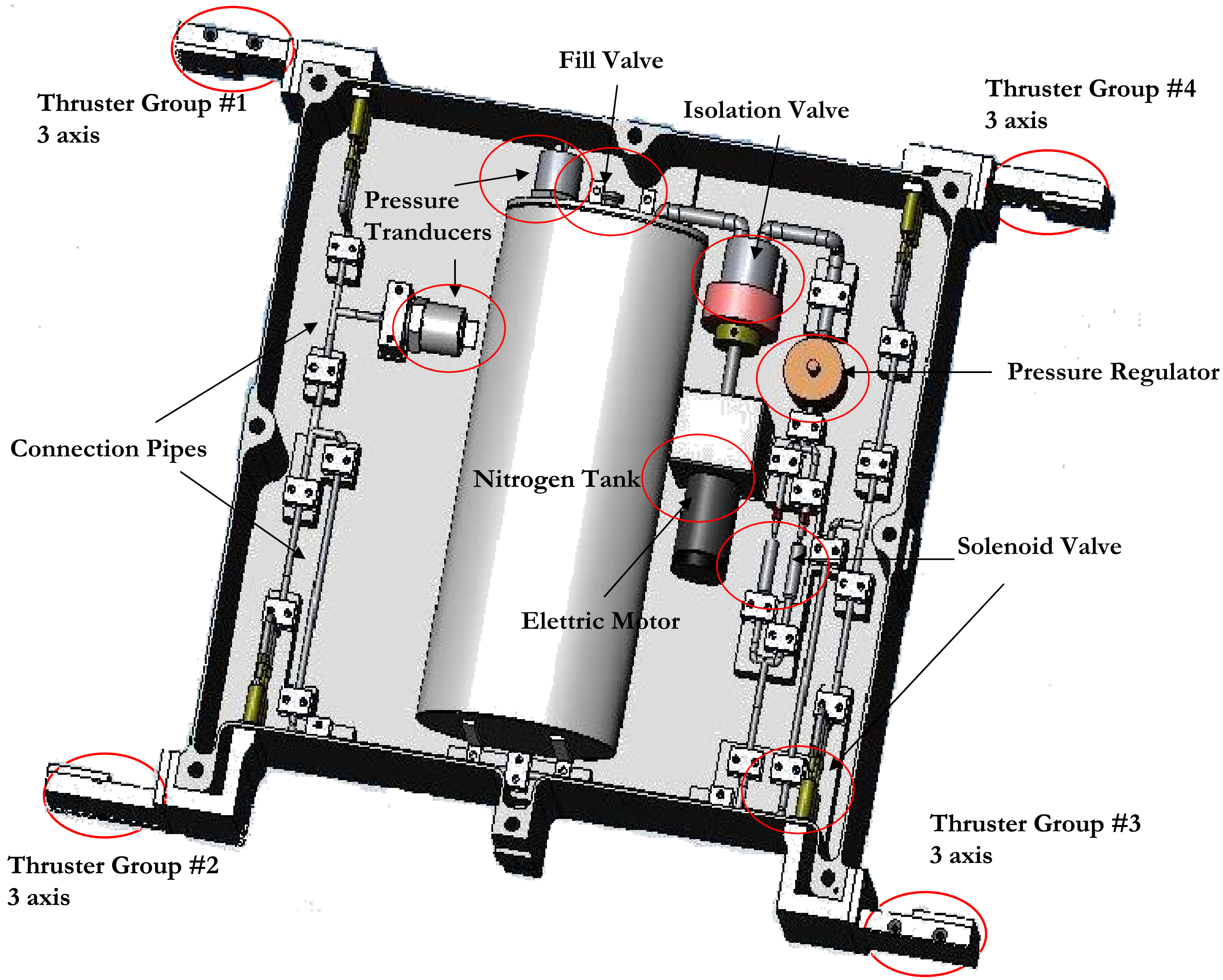
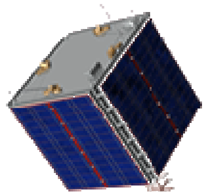
State of the Art





Conclusions and Future Work

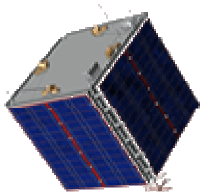
Conclusion

- Every Component of the Entire Micropropulsion System has been Frozen for the Mission;
- The Valve and its Electronics, Microthruster and Connection Group has been Tested in Thermo-Vacuum Chamber;
- The Isolation Valve has been Tested at a Maximum Pressure of 35 bar: No Leakage in 3 Week.
- Actually the Overall System Mass is about 900 g.

Future Work

- Mass Flow Meter Acquisition for Specific Impulse Measurements;
- Tank Realization and Fill Valve Test;
- Entire System Assembly inside the Tray and Vibration Test;

Contacts



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