From Cold-Gas to Bipropellant Microthrusters Prototyping in the Context of Micro and Nanospacecrafts

G.Manzoni[1], S.Heisig[2], S.Matsumoto[2], R.Maeda[2]

1) Microspace Srl, Via Filzi 6, Trieste, ITALY- giulio.manzoni@micro-space.org
2) National Institute of Advanced Industrial Science and Technology (AIST), MEMS group, Tsukuba - JAPAN

Introduction

The context of micro and nanospacecrafts is first of all dominated by the vision, introduced about 10 years ago and not yet realized, of a fully integrated silicon nano or microsatellite; conversely, only some simple components, not even subsystems, are really available for assembly on the few attempts of small satellites, still based on rather conventional architectures. Nevertheless many people (we included) are still promoting the use of micro and nanotechnology for aerospace.
Why are we in this situation ? Maybe we have to ask ourselves "what is our target ?"; do we want a very small satellite or a satellite made by a certain arbitrarily given technology ? It is our opinion that technologies should be at the service of the function, not vice versa.
The selection of a technology may be done according to many criteria: the selected technology must be available (already developed, affordable, reliable); it must be necessary (without it we can not make the product); it must be sufficient (it is enough to fulfill a requirement) and must be economical (financially justified by the selling price of the application and cheaper than other equivalent solutions).
Now, is the integration of all the components and subsystems on the same substrate, mainly made by the same material, the right solution ? What about each small function made in a completely different technology (including some parts integrated at Chip level) and then assembled in a hybrid system ? The following table compares the two cases and this paper will illustrate our position on the matter.

	Full system integration on silicon	Hybrid integration of different technologies
Available	Not completely	Yes
Necessary	No	Almost in any case
Sufficient	Could be for almost all	Yes
Economical	No	Cheapest at the moment
Flexible (easily changeable)	No	Yes
Customizable	Very difficult	Yes
Reparable	No	Yes
Progressively developable	No	Yes
Transferable to other fields	Very specific or sub parts	Very broad

The technology selection

The motivations for a micropropulsion system are to control the attitude of the satellite, to perform small changes of altitude and inclination plane in view of formation fly, mother spacecraft observation or docking for maintenance operations, observations and measurements on a controlled baseline.
For all such maneuvers, we must have enough Δv on board and we also need a very precise control of the impulse generated at each nozzle firing, variable from almost zero thrust to a nominal value big enough for important maneuvers, say from 10 microN to 10 mN and we do not want to have a variable position of the thrust vector. For all these reasons, the only choice for fine attitude control is a Gas based-valve controlled system in combination with various gas storage technologies, with or without a way to heat up the gas, which, in fact, is the class of systems extensively used on big S/C till now.
We must notice that the use of such small thrust allows both fine attitude control and orbital maneuvers distributed over long mission time. Moreover, a common small value of thrust allows using the same engines for orbital maneuver and for attitude control.
Nevertheless, many research groups prefer to consider only impulsive maneuvers, with the consequence that they can still keep working on quite big thrust levels (in the order of 1N), but this is often related to technological difficulties to realize very small and efficient thrust.
If we analyze the basic elements of a micropropulsion system based on the expulsion of gas from a nozzle and transformation of gas energy in speed and thrust.
The basic elements of a micropropulsion system are easily defined: we need to transform the gas energy in thrust, therefore we need a nozzle, we need a valve to control the flow, the pressure and therefore the thrust and the impulse, we need a pressure sensor (at least at laboratory level) to characterize nozzle behavior and learn how to control the thrust by means of the valve.
We can take the same elements and expand them few levels in order to obtain a higher specific impulse…we add a heating module based on a resistor and we can double it, we add a second feed line with a heat regenerator and a microreactor (or combustion chamber) and we obtain a bipropellant microrocket that can triple the specific impulse or we just feed the heated thruster with a pressurized liquid and we make a vaporizing microthruster with and increase of several orders of magnitude in the Δv with the same Isp. We should not worry too much about the electrical power for the heating since it can be contained in the power budget of the satellite, especially for the short time necessary for the maneuver. In any case we can still try to use a microturbine based electrical generator to recover part of the heat lost, but we should very carefully analyze the benefit of such solution in comparison with a much simpler addition of few solar panels and heat recycling as fuel preheating.
Now, based on our experience, we analyze what are the main technologies necessary to manufacture the identified elements and we can divide them in 3 big classes: nano, micro and precision engineering.

The figure represents the topologic organization of micropropulsion elements in a modularly growing microthruster family, with an indication of which technologies are necessary (coloured modules: green-precision engineering, blue-microfabrication, pink-nanotechnology, white-none).

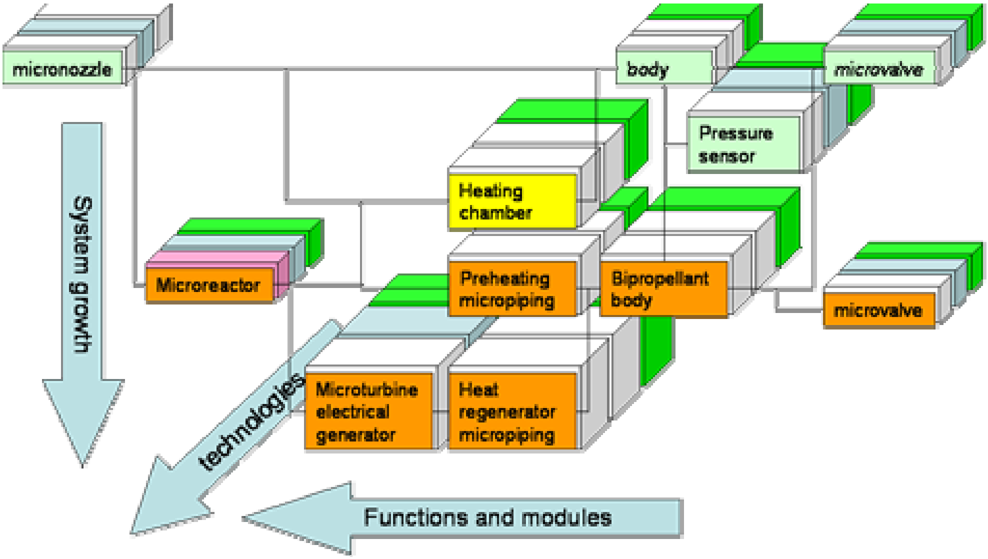

Fig. 1 – Microthruster synopsis

We recognize, from a preliminary basic dimensioning of the micronozzle, that the throat size must be in the range of 10 micronmeter, so Microtechnology is here a must. For the control of the thrust and impulse we recognize also that the valve must be very small, in order to have a very small volume between the nozzle and the valve, so Microtechnology is necessary here. The only place where nanotechnology really could make a difference is in the reaction chamber, in form of nanoparticle catalyst. For the rest of the components, precision engineering is more than enough, provided the overall mass and volume budget are satisfied. In fact, if we take the smallest S/C today really manufactured, the Cubesat class, there is enough space to make some small precision engineered propulsion components… in any case most of the space will be occupied by the tank.

Having decided which element will be done with which technology, the step is quite easy, we need to exercise our creativity and design the different element in a modular way, in order to be easily assembled and exchanged. Following our inclination to product design, we where naturally inclined to abandon as soon as possible the 2D constraints imposed by silicon micromachining and therefore, among different possibilities, we decided to use a miniature bolted assembly aluminum structure that can be expanded in a modular way. And

then we developed the family of our thrusters, the first “Cold-Gas”, the second evolved “Warm-Gas”- “Vaporizing thruster” and the latest born, the “Bipropellant”.
The picture represents the first “Cold-Gas prototype together with a Scanning Electron Microscope image of one of the micronozzles before bonding and dicing.

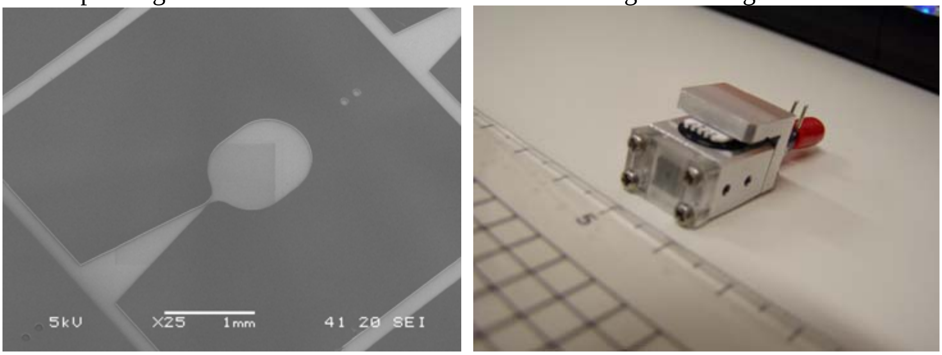

Fig. 2 – SEM of micronozzle and microthruster module

The main performances of the micthrusters are listed in the table with reference to a storage system using about 20% of the S/C volume and an indication of the development advancement status.

engine	Cold-Gas	Warm-Gas	Vaporizing	Bipropellant
Thrust (mN)	0.01 - 0.5	0.01 - 0.5	0.1 - 10	0.1 - 10
Specific impulse (s)	30 - 50	60 - 100	60 - 100	100 - 200
Δv (m/s)	1 m/s	2 m/s	200 m/s	300 m/s
status	Mission ready	Mission ready	Testing	Prototyping

Development methodology

The development methodology will be described by using the Warm-Gas Thruster as an example.
The first step is the gas-dynamic design of the nozzle. Here any book of Rocketry can be sufficient, but actually none can really tell us how to properly estimate the losses in the micronozzle. Even if the literature is full of papers, including ours, that describe how to calculate such losses, in principle it is better not fully trust such calculations when the nozzle has few microns of cross section and is characterized by a flat prismatic geometry.
After a rough tentative geometry has been established, we must proceed with Computer Fluid-Dynamics simulations, in order to have a better estimation of the flow in the nozzle, observing the point where the expansion ends and therefore were the viscous losses (very high at the small Reynolds numbers) will start to waste the energy and finally finding the final design geometry. When the geometry is finally defined, is time to design the mask for

the lithography and this can be done automatically just "assembling" the wafer from the desired micronozzle dices.
The manufacturing of the masks is a job that can be easily subcontracted. Then we have to spend some time in the clean room for the microfabrication of the micronozzles by means of few steps of lithography and Deep Reactive Ion Etching, Bonding and Dicing.

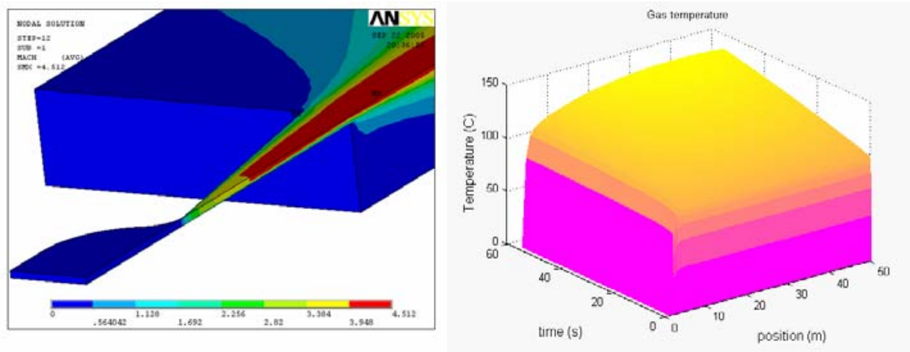

Fig. 3 – FEM CFD (mach number) and Transient Thermal Simulation

Finally we have the micronozzles, the apparently more difficult step is done… but the true hard job begins right now ! In fact, till now, we just used some sophisticated, but absolutely standard processes. Either you have the right equipment, or you do not have it. In other words, this was just "grammar"… the art has yet to come !
It is now that we have to create the thruster around the nozzle, we have to integrate in the simplest and smartest way commercial components such as microvalves and pressure sensors with zero leaks and with a system that can withstand high temperatures. Also, we are designing and prototyping a Warm-Gas thruster, therefore we have to study the transient behavior. The simplest way is to make a lumped capacitance thermal model, by dividing the heating chamber in slices where we can evaluate the gas temperatures by integrating the heat and mass transfer equations. The figure shows the transient behavior by plotting the gas temperature profiles along an non-dimensional coordinate (m). Now, the heating chamber is designed, we have to manufacture the heating resistor integrated in the chamber… another tricky business ! So, after few attempts we learn how to handle such integration and we have a thruster to test.

Testing

The main testing will be the measure in vacuum of the thrust and of the specific impulse. For such measure there are no commercial systems available, so we built our own microbalance, based on an elastic beam with a laser displacement measurement system. Our balance is very reliable and robust, it has a resolution of few micronmeters and a total

error below 10 microN, it allows continuous measurement of thrust in vacuum for unlimited time and monitoring of the pressure and temperature in the nozzle as well as control of the valve and the thruster resistors of the nozzle.
But since we are dealing with the heated thruster we must verify the temperatures distribution and the thermal transient, therefore we proceed with a thermovision experiment, and we verify the time constants of the heating transients that have been previously estimated, as well as the chamber and nozzle temperature distributions.

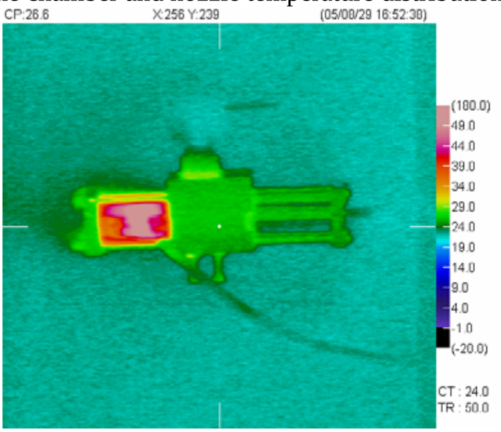

Fig. 4 – Thermovision of the Warm-Gas microthruster under operation

The picture shows the external temperature of the Warm-Gas thruster body, from which the internal temperatures can be deducted in combination with the thermal model.
Finally we have our measures of thrust and by blowing the gas from a tank of given volume we can calculate the mass flow rate and the specific impulse… here we observe 3 different heating situations with zero, 0.5 and 2 W of power… the tank is the same, the thrust remains the same, but it lasts at least double time in the second case: by spending 2 W we doubled the specific impulse.

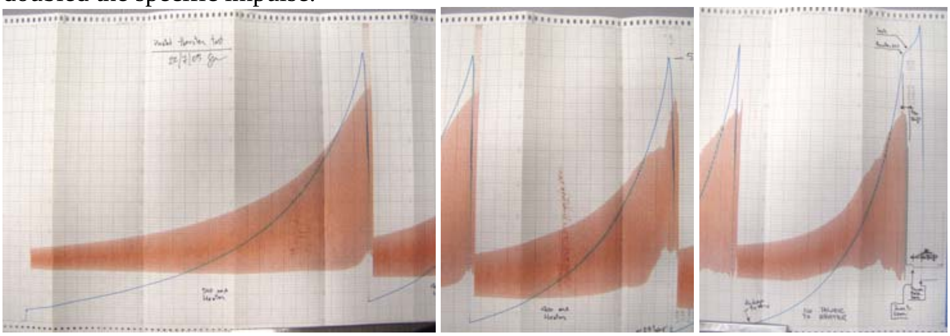

Fig. 5 – Experimental data records of the Warm-Gas thrusters performance

This is a very modest sacrifice for a microsatellite which can count on about 15W of continuous power: so a total budget of 3W (another 1W is needed to operate the micropropulsion electronic and the microvalves) can be very well spent. For smaller satellites we just have to use in a very rational and intelligent way the batteries or… install some additional deployable solar panels (another very interesting task for smart precision engineers).
Obviously, the pressure in the tank is not constant, but it is no problem, we just operate the valves with the proper duty cycle and we can modulate the thrust at any desired value, for any kind of maneuver at any time of the mission.
After the development of the thruster is done we have to fight with the other subsystem engineers and possibly find some good allied in the mission designers and program managers to get as much as possible of the mass and volume budget on board… if they want Δv, they have to give us place for the tank and they have to miniaturize other things, like OBDC, power electronic, radio and so on (a modern PDA can easily find place inside a Cubesat and can surely handle very difficult computational tasks if properly programmed !
On a typical Cubesat architecture, a full micropropulsion system will occupy about 25% of the volume and between 5% and 15% of the mass, depending if we install also the bipropellant thrusters; still more than 70% of the volume is available for other subsystems.
The picture shows the 3D model and the Satellite Mockup of the full microropulsion system including: (1) two modulesof 3 microthrusters for Attitude Control, (2) the complete tank system, (3) two Bipropellant modules and (4) the ACS electronic; at the moment the satellite has been built only as Mockup for dimensional verifications and to host the functional testing of the micropropulsion system.

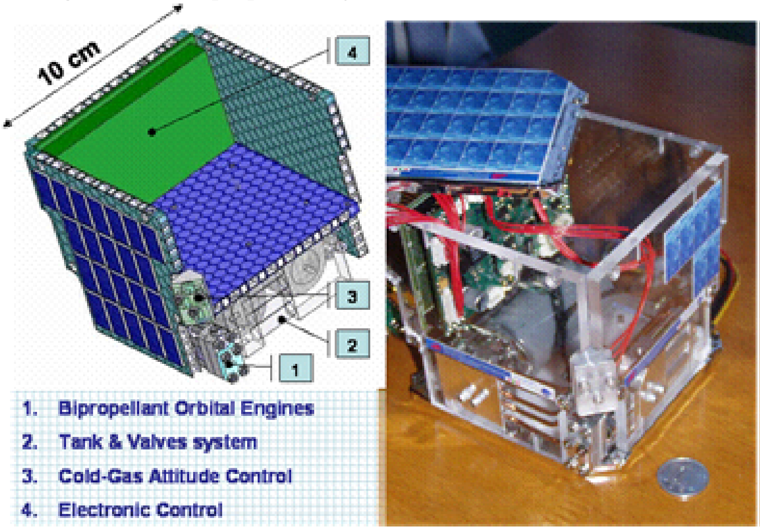

Fig. 6 – Cubesat with micropropulsion system 3D model and functional Mock-Up

Conclusion

In conclusion, we can try to compare the effort of developing a micropropulsion system by means of a wise mix of standard and advanced technologies, with the effort necessary if we are going to integrate everything on silicon. Just thinking that for each wafer at least 5 to 6 masks (typical market price about 10K) would be necessary, probably about 10 different wafers are necessary to complete the system and at least 1Week per wafer in the clean room when the processes are fully stabilized, plus several man/year for the design and related use of software and clean room facilities rental. It is clear that the cost of such fully integrated approach would be in the order of 10 MEuro ! But such money is invested in industry for expected production of million of devices.
How many nanosatellites have been launched yet ? Not enough to justify such enormous effort… this is the answer to the initial question about the satellite on chip: instead of satellites on chip we should talk about cheap satellites !!!
Our personal conclusion, at Microspace, is: the use of micro and nanotechnologies is of primary importance to enable miniaturized, fully functional, cheap spacecrafts, but we must not overdo it !
On the other hand we have to be careful that when micro-nano technology are not strictly necessary, insisting to use it may induce unnecessary problems and costs.
More practically, at Microspace, our aim is to offer to our customers the most innovative, and available solutions, therefore, all considered, we selected long time ago the "Hybrid approach" where micro or nanotechnologies are really necessary and not just used as superficial justifications to acquire funding. In particular, we would suggest redirecting the spending of public R&D funding from micro-rockets with no true or useful "micro- nano content" to more meaningful activities. For example, we initially promoted a microturbine bipropellant based system, but we later realized that it could not bring any benefit to our microrocket due to the inherent inefficiency of the turbine at the small sizes required or, conversely, the big size necessary to keep the efficiency at a reasonable level. Therefore, we happily stopped the realization of such system and opted for the simpler use of the electrical power available on board. We wish the organizations delivering research funding would have the same care on strategic directions.

References

[1] G.Manzoni "Design of a highly integrated micropropulsion system for microsatellites attitude control" - JPC 2000, Hunstville (USA), 2000.
[2] G.Manzoni, L.Vaccari, E.Di Fabrizio, "Design and Prototyping of a highly integrated micropropulsion system for microsatellites attitude control"- MST2001, Düsseldorf (D) [3] F. De Bona, G. Manzoni "Measurement system for mN forces" AMST 2002 – Udine
[4] G.Manzoni, S.Matsumoto, R.Maeda "Microthrusters and Microturbines Technologies and Prototypes: a Roadmap for Nanosatellites Propulsion and Power", ISTS24, Miyazaki (Jp), 2004.