The Design, Development and Testing of a Propulsion System for the SNAP-1 Nanosatellite

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Abstract

It has frequently been proposed to use very small nanosatellites for missions requiring orbital agility. Whether it be swarms of satellites for scientific or remote-sensing measurements, constellations for communications or single satellites for remote inspection, all require some way of modifying their respective orbits. Novel, high-technology solutions to this requirement have been proposed from MEMS to solar sails. Notwithstanding the eventual availability of such advanced nanosatellite propulsion technologies, the Surrey Space Centre has developed a miniature propulsion subsystem using technology readily available today.

On 28th June 2000 Surrey launched SNAP-1, the first in a series of Surrey Nanosatellite Application Platform missions. Amongst other features of this new 6.5 kg nanosatellite is a butane liquefied gas propulsion subsystem to meet the spacecraft's mission requirement of 1 m/s delta V.

With a total mass budget of 450 grams, including propellant, dry mass, structural support and drive electronics, this propulsion system will be one of the smallest ever to have flown on a spacecraft.

This paper describes some of the interesting challenges in producing such a small system, especially in a seven month "concept to launch site" program. The flight propulsion system will be described, including novel techniques such as using a coiled tube in the place of a conventional propellant tank. The choice of butane as a propellant will be discussed.

Introduction

As electronic technology improves, satellites can be manufactured in ever smaller packages. It is foreseen that many more nanosatellites (<10 kg mass) will be produced in the next few years. Decreasing payload sizes will increase demand for smaller, more capable platforms, including the ability to manoeuvre and change orbit. Hence the need for small propulsion systems. Such propulsive missions could include :-

- Remote inspector to rendezvous and manoeuvre around a host spacecraft
- Constellations on the same launch vehicle requiring separation
- De-orbiting of space junk requiring rendezvous, docking and orbit changing

In addition to low cost, low mass and short delivery some more specific requirements for these propulsion systems include :-

- Low power consumption
- Low, controllable thrust
- High propellant I_{sp}
- High density I_{sp}

Currently propulsion technology is developing rapidly towards miniaturised systems. Most notable is MEMS technology. However MEMS systems have not yet flown, and although they are likely to figure prominently in the long term, they are not a current solution. Presently, traditional technology is also becoming smaller and the best current option for flight is miniature conventional technology, as was used on SNAP-1. Future trends towards MEMS will need careful evaluation at system level. When considering system mass as a whole, a large fraction of it is usually propellant and tankage. Hence reducing mass by changing from conventional technology to MEMS may make a relatively small reduction in overall system mass.

SNAP-1 requirements

In November 1999 Surrey Satellite technology Ltd (SSTL) initiated its first nano spacecraft, SNAP-1 to demonstrate the technology and mission feasibility. With a launch date of June 2000, the programme would also demonstrate SSTL's ability to go from concept to launch site in 7 months.

The basic mission to be demonstrated by SNAP-1 is that of an inspection vehicle. The spacecraft is to be launched on 28th of June 2000 with another SSTL built spacecraft, Tsinghua-1. SNAP-1 will image Tsinghua-1 as it is deployed from the launch vehicle. The spacecraft will drift apart during a 10 day period, in which time the SNAP-1 attitude will be brought under control and 3 axis stabilisation achieved. After which time, using an inter-satellite link and relative GPS positioning, the SNAP-1 on-board propulsion will be used to attempt to bring the two spacecraft back together, to a range at which SNAP-1 can further image Tsinghua-1.

Hence, to rendezvous the two satellites a propulsion system is essential. The calculated ΔV requirement was 1 m/s, using a single axial thruster, firing as closely as possible through the Centre of Gravity of the spacecraft. Further requirements placed on the propulsion system by the mission were :-

- temperature range 0°C to 40°C
- multiple firings
- maximum thrust of 100 mN
- minimum impulse bit < 1 mNsec
- 7.2 to 9 Vdc
- low power consumption

The other requirements, needless to say, were low cost and a very tight delivery schedule. As the project was funded by in-house R & D budgets, there was significant emphasis to find a low cost solution. This constraint is also very important given the future constellation market potential, as a very low recurring price will be necessary to ensure the viability of propulsion on such spacecraft.

System description

Figure 1 shows a picture of the SNAP platform. It is constructed from 3 sets of electronic module boxes, connected together to form a triangular structure. The payload panel fits on the top of the modules and the propulsion system inside the module boxes.

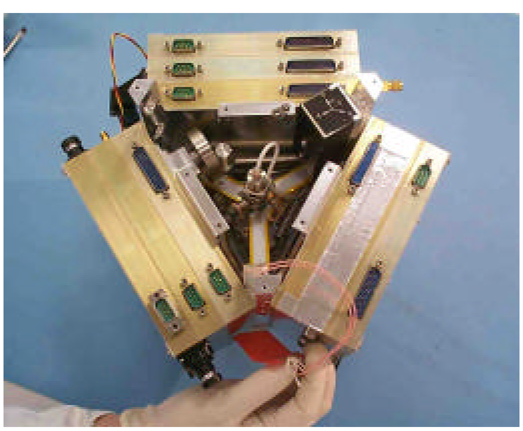

Figure 1 : SNAP-1 in build

Hence the propulsion system had to fit within the triangular volume shown in figure 1, with the thruster at the centre. This placed a limitation on the system as the propellant could not be stored in a single central propellant tank.

The extremely tight schedule placed a number of constraints on selection of equipments:-

- No US suppliers were considered for propulsion equipment as it was felt that there was a very high risk associated with obtaining an export license in the existing climate
- Existing off the shelf designs were necessary
- Hardware on the shelf would be a positive benefit

Polyflex Aerospace Limited was selected as the valve supplier. They had a cold gas thruster, recently developed under a BNSC program in conjunction with SSTL. This thruster was to be used on SSTL's ESAT program and consequently most of the parts were available.

The choice of Polyflex's cold gas thruster placed some limitations on the system immediately. The valve is designed for use with regulated nitrogen, giving 100 mN thrust at 4 bar chamber pressure. At greater than 16 bar, pressure forces make the valve difficult to open, especially with the low voltages available on SNAP-1. High pressure nitrogen, nitrous oxide or carbon dioxide propellants would all require some form of pressure regulation, hence additional costly valves, and additional volume and mass constraints. The propellant choices were reduced to ammonia, propane (both < 16 bar at 40°C) and butane (< 4 bar pressure at 40°C). Propellant choice will be further discussed later.

Figure 2 : pipework assembly

The most obvious feature of the complete propulsion pipework assembly, as seen in figure 2, is that there is no propellant tank. The propellant is stored in 1.1 meter of coiled titanium tube, providing 65 cm^3 of storage volume.

This has a number of advantages over a conventional "tank" :-

- Easily verified compliance with MIL-STD-1522A (and follow on regulations), as the system does not contain a pressure vessel, only pipework and fittings. Compliance with the standard merely requires a minimum burst of 4 x Maximum Operating Pressure, which is demonstrated in the system proof test.
- Low material costs, standard Airbus titanium tubing was used
- Even distribution of mass

A fill valve is welded directly to one end of the coiled tube assembly. The other end is connected to a titanium manifold. The manifold contains a pressure transducer and temperature sensors for system monitoring. Additionally inside the manifold are stainless steel mesh discs, which act as filters and also heat transfer elements. The manifold has an external heater (a 15Ω commercially available resistor) which ensures propellant vaporisation during firings. Finally an isolation valve and a thruster valve are fitted in the manifold. Figure 3 shows the propulsion schematic.

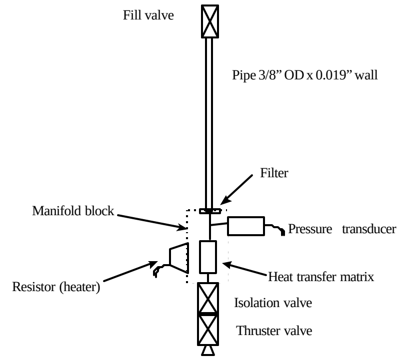

Figure 3 : Propulsion system schematic

As the system has only a small volume of propellant it could be sensitive to leakage. Consequently all joints in the system are welded or contain double seals and the isolation valve protects against a thruster leakage.

Propellant choices

As mentioned previously there was a choice of propellant to be made. Table 1 shows a trade-off between different propellants. The calculations are based upon a 6.5 kg spacecraft. The propulsion system has a volume of 65cm^3, a maximum pressure of 16 bar and a 5% ullage on all liquids.

Table 1 : Comparison of propellant performance in the SNAP-1 propulsion system

Propellant	Ammonia (liquefied gas)	Propane (liquefied gas)	Butane (liquefied gas)	Nitrogen (gaseous)	Xenon (gaseous)
Pressure / bar abs	15.6 bar at 40°C	14.5 bar at 40°C	3.8 bar at 40°C	16	16
Specific Impulse / sec	105	76	69	71	31
Propellant mass / grams	33.8	26.8	32.9	1.2	5.61
Total impulse / Nsec	34.8	19.9	22.6	0.84	1.68
Spacecraft ΔV / m/s	5.36	3.07	3.47	0.13	0.26

It is clear that the two gases (nitrogen and xenon) have inferior overall performance due to the pressure being limited by the hardware choice. The three remaining options are the liquefied gases identified previously. Ammonia gives the best total impulse and would be the optimum choice if maximum performance was a system requirement. However ammonia is a toxic substance and that would have safety implications, hence additional cost. Additionally, there is a brazed joint inside the thruster valve which, according to the literature, is not compatible with ammonia, even though testing suggested no problems. As the two alternatives could meet the mission requirements with margin it was decided not to use ammonia. However it is still considered a potential propellant for future missions.

The two remaining choices have fewer safety issues, although they are flammable rather than toxic. Propane has a 10% higher specific impulse, however it is 20% less dense, so for a fixed system volume butane will give the spacecraft a greater total impulse, at the penalty of an additional 6.1 grams of propellant. The other advantage butane has over propane is that it has a vapour pressure of 3.8 bar at 40°C rather than 14.5 bar for propane. As the thruster is optimised for 4 bar operation, the propane would need an additional flow restrictor to drop the line pressure to a reasonable chamber pressure. Butane does not need this and therefore the butane system is simpler.

The final advantage of butane is that the low pressure gives very large safety factors. The titanium tube is rated at 12,000 psi minimum burst, which is a factor of greater than 200. The lowest rated equipment is the isolation vale which has a minimum design burst of 48 bar, hence a safety factor of 12. With these margins in hand, it was agreed that the propulsion system could be shipped to launch site loaded with propellant. Consequently the propulsion system was loaded with 32.6 grams of butane 3 weeks prior to the spacecraft being shipped to launch site. The propulsion system was shipped integrated to the spacecraft and no further launch site operations were required.

Equipment descriptions

Thruster & Isolation valve

The thrust valve was originally designed by Polyflex Aerospace Ltd to meet the requirements of a NASA specification for small thrusters. Initial development and manufacture of demonstrator valves was completed with support through the UK Department of Trade and Industry 'SMART' programme. Subsequent encouragement and support from British National Space Centre (BNSC) enabled qualification to space standards and demonstrated suitability for platform applications such as E-SAT and SNAP. Continued refinement of the original design has lead to the development of a small, lightweight, compact isolation valve for use in cold gas propulsion systems such as that used on SNAP. Close coupling the Isolation valve and the thruster valve provides a compact dual redundant seal assembly with minimum dead volume between the seals.

The thruster valve is a solenoid operated valve comprising of a fixed pole and a suspended moving pole/armature, to which is attached the sealing feature (poppet) of the valve. The moving pole utilises a flexure guidance mechanism so that there are no sliding surfaces when the valve is energised / de-energised, thereby minimising the risk of any particulate generation.

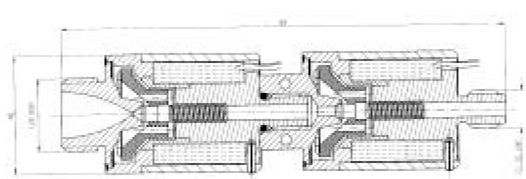

Figure 4 : Thruster & Isolation Valve Assembly (approximately full size)

The valve incorporates a single coil design, rated to make the possibility of failure very unlikely. The valve is constructed from 316L stainless steel, Radiometal and PTFE for the seal and features a welded closure to ensure maximum leak integrity. The design of the poppet/seat interface ensures minimal flow discontinuities and therefore reducing susceptibility to contamination induced failures and minimises pressure losses.

The valves are opened by energising the coil, the resulting force generated by the induced magnetic flux, will cause the armature to move towards the 'fixed pole' in so doing will retract the poppet from its seat. The valve is closed when the coil is de-energised collapsing the generated magnetic field. The armature will now move the poppet to the closed position under the influence of the helical spring. It then remains closed under the combined influence of the spring and forces applied by the working fluid.

Fill Valve

In order to meet time and cost constraints the Fill Valve is based on an existing Polyflex design as used on SSTL's UoSAT-12 spacecraft. The valve is constructed from stainless steel and incorporates a spring loaded Vespel seal.

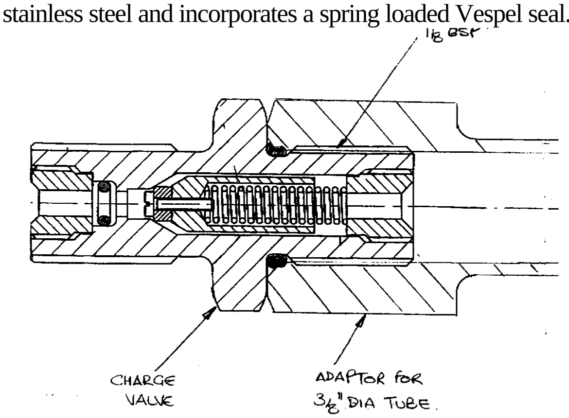

Figure 5 : Section view of the Fill Valve

The valve was subjected to a qualification programme to verify cleanliness and leakage performance in accordance with typical space requirements. The valve successfully met these requirements and is mounted using screw joint onto one end of the pipework assembly. The valve is operated by means of a charge adapter that screws into the valve outlet.

Pressure transducer

The pressure transducer was supplied by Kulite Sensors Ltd. It was a standard off-the-shelf unit, model number ETM-362.

Pipework assembly

The tubing was supplied by TW metals Ltd. It is standard 3000 psi rated 3/8" titanium alloy tube as used by Airbus. The tube lengths used were off-cuts and obtained from the scrap bin (although the tube itself was not scrap). Two 1.1 meter lengths were used, one flight and one forming practice. The pipework assembly was formed by RSM Aerospace Ltd. They were also responsible for the welding of the fill valve housing and the manifold to the pipe ends. The welds were TIG and performed by hand.

Manifold, heater, matrix

The filter disc and heat transfer discs were produced from sintered stainless steel mesh of nominal rating 40 microns. The heater was a resistor procured from the RS catalogue.

Integrated system

Figure 6 shows an exploded view of the above equipment in the propulsion plumbing assembly

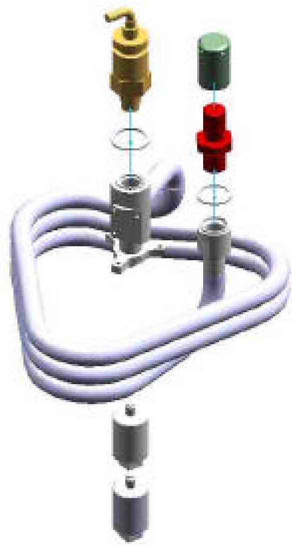

Figure 6 : Exploded view of propulsion assembly

Drive electronics

The drive electronics are mounted on a flexi-rigid PCB located inside the formed tube assembly, see figure 7. The electronic devices are all commercial off-the-shelf (COTS) as is typical of SSTL spacecraft. All propulsion equipment run on raw battery voltage. An additional boost voltage is available in flight, in the event of a solenoid having operating difficulties. This will also permit usage of the same circuit, without modification, for operation of the valves at higher pressures of up to 16 bar if alternative propellants are used in the future.

The drive electronics are operated from a Siemens C515c microcontroller. This derives its commands and feeds back telemetry via a CAN (Control Area Network) interface. It also controls the manifold heater, which ensures that the propellant is vaporised. The use of CAN controller allows a reduction of wiring harness to the propulsion module, with only 6 wires required :-

+ ve battery voltage
+ 5 V supply for CAN chip
Common return
CAN Hi
CAN Lo
Chassis (earth)

System integration

The Propulsion system is a stand alone module at spacecraft level. The whole assembly is built on a triangular panel (aluminium skinned & aluminium honeycomb) measuring 140 mm on each side. Three corner supports are fitted to the panel. The pipework assembly, figure 2, fixes to the outside of the corner supports, with the thruster clamped at the point it passes through the centre of the panel. The drive electronics PCB is fitted to the corner supports on the inside, and electrical connections are made. Access to the fill valve is from the top of the system, so once integrated into the spacecraft the fill valve is not accessible. Figure 7 shows the integrated propulsion module.

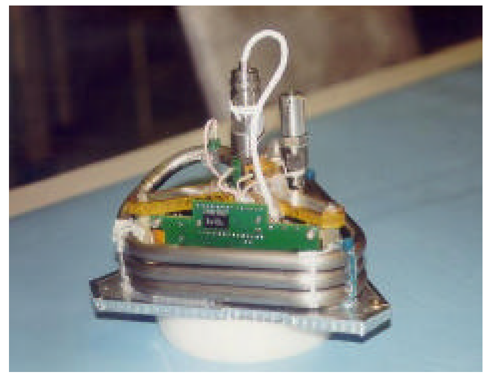

Figure 7 : SNAP-1 propulsion module

The propulsion module connects to the spacecraft by three M3 screws, one at each corner. Electrical connection is by a standard D type 9 pin plug on the underside of the panel. The spacecraft harness passes round the edge of the panel and is looped back to connect to the D type connector once the panel is in place.

System level testing

Following module integration, system electrical checkout and valve operations were performed using a PC and CAN card. Mechanical integrity was verified by a continual pressure decay monitoring. The highest decay rate was observed during environmental testing. However it was only 0.22 std cm^3 of Nitrogen / hour total from the complete system. The propulsion module was installed in the spacecraft during its environmental testing of vibration and thermal vacuum (-20°C to 50°C).

Propellant loading

As mentioned in a previous section the propellant was loaded 3 weeks prior to the spacecraft being shipped to launch site. The operation was performed in a fume cupboard in the propulsion lab at the Surrey Space Centre and took 2 engineers 3 hours to perform. Due to the low toxicity of butane, no additional personnel safety equipment was required, the major precaution being to avoid any potential ignition source.

The operation took place with the system sitting on a set of scales accurate to 0.1 gram. The system was evacuated through the fill valve and filled with butane under its own vapour pressure plus 1 bar of nitrogen. This loaded slightly more propellant than required, so the excess was fired through the thruster until the desired load level of 32.6 grams was obtained. The system was left for 48 hours on the scales and zero mass loss was verified. Subsequent to the loading operation there was no additional valve operations until post launch.

This operation sequence ensured that no propulsion operations were required at launch site. For future programmes this could be a significant advantage. If a constellation of SNAPs is being launched, there will be a significant cost saving by loading prior to shipping to launch site.

Summary

A low cost propulsion system has been designed and built for the SNAP-1 spacecraft in 7 months from concept to launch site. It utilises butane stored as a liquid and operating in a cold gas mode. Miniature conventional technology was used for the valves. The propellant was stored in a formed titanium tube, rather than a tank, giving a low cost solution. The spacecraft was loaded with 32.6 grams of butane prior to shipping it to launch site. SNAP-1 was successfully launched on 28th June 2000. The in-orbit performance of the propulsion system will be the subject of a future paper.

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More Information

More information on the organisations involved in this project can be found at :-
Surrey Satellite Technology Ltd, the system prime
www.sstl.co.uk
Polyflex Aerospace Ltd , supplier of the solenoid and fill valves - www.polyflex.co.uk
Kulite Sensors, suppliers of the pressure transducer - www.kulite.com
RSM Aerospace, manufacturer of the pipework assembly - www.rsmaerospace.co.uk
TW Metals, supplier of the titanium tube - www.twmetals.co.uk
British National Space Centre, supported development of thruster valve - www.bnsc.gov.uk

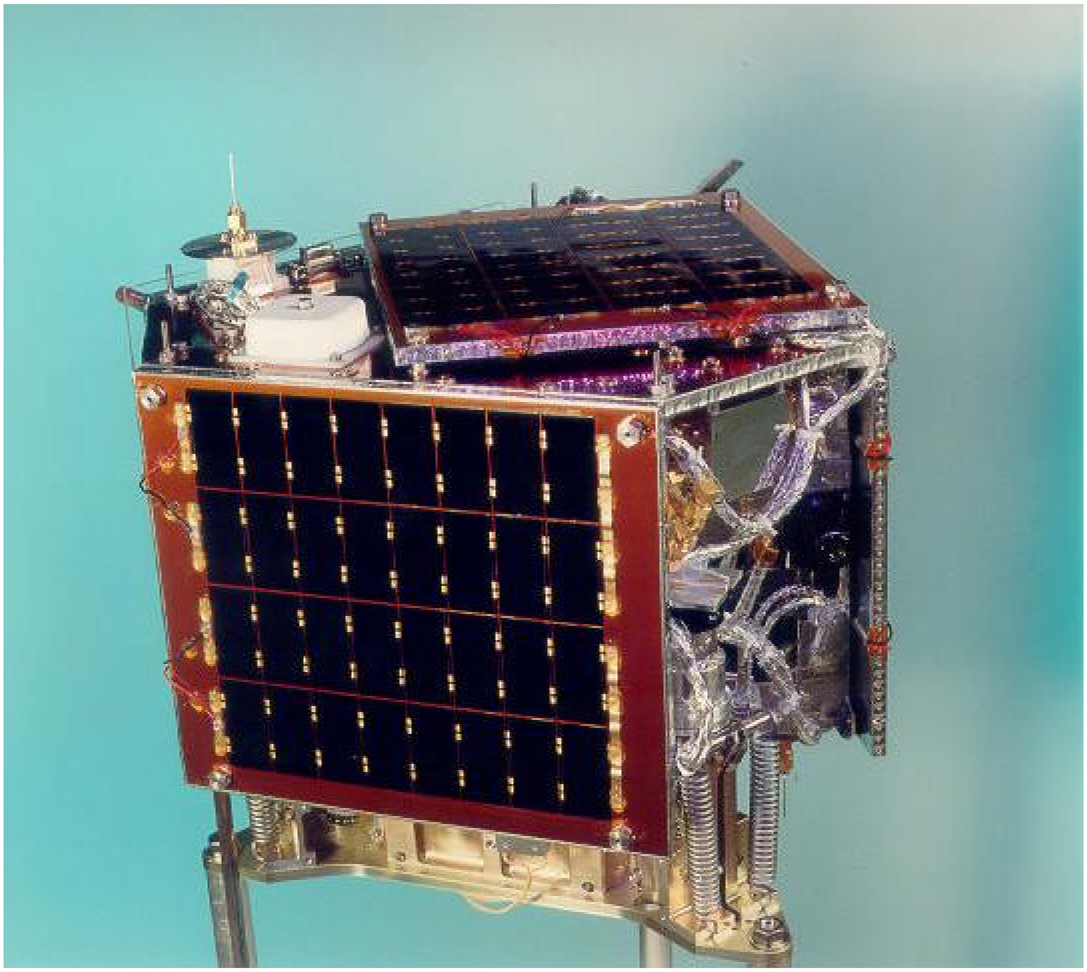

Figure 8 : SNAP-1 in flight configuration