

The Design and Test of a Compact Propulsion System for CanX Nanosatellite Formation Flying

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ABSTRACT: The NANOsatellite Propulsion System (NANOPS) is part of the CanX-2 (Canadian Advanced Nanospace eXperiment 2) mission to demonstrate enabling component technologies in support of future formation flying missions. Flight test results in 2006 from NANOPS on board CanX-2 will augment ground test results with the goal of refining the design to support the CanX-4 / CanX-5 formation flying mission in 2008. The CanX-2 version of NANOPS is a scaled prototype of what will be needed for the CanX-4 / CanX-5 mission. CanX-2 NANOPS uses liquefied sulfur hexafluoride (SF₆) as a propellant because of its high storage density. The target performance goals are 50 mN of thrust, a specific impulse of 45s, and a minimum impulse bit of 0.0005 Ns. The CanX-2 experiment will mainly involve attitude control maneuvers in order to evaluate the performance of the propulsion system through on-board attitude sensors. NANOPS is novel not only because it is the first of its kind in Canada, but also because it will pave the way for other propulsion systems to be developed for nanosatellites and microsatellites based on commercial off-the-shelf components. This paper describes the development methodology as well as the ground-based and space-based testing involved during the development of NANOPS, and its suitability for future missions.

INTRODUCTION

CanX-4 and -5 Formation Flying Mission

At the Space Flight Laboratory (SFL) located at the University of Toronto's Institute for Aerospace Studies (UTIAS), the development of a formation flying mission involving two nanosatellites is currently underway. As part of a continuing series of Canadian Advanced Nanospace eXperiment (CanX) satellites, CanX-4 and CanX-5 will be the fruition of an ambitious plan to demonstrate the viability of formation flying with nano-class (<10kg) satellites. This demonstration mission will open the door to operational formation flying missions involving multiple spacecraft that together act as a single mission spacecraft for coordinated observations, in situ measurements, or virtual instrumentation (e.g. interferometry, distributed sensing).

CanX-4 and -5 are planned for launch in 2008, and are intended to verify the performance of enabling hardware elements, and in addition, evaluate novel formation determination and control algorithms. The innovations of this mission include the demonstration of centimeter-level position determination and control enabled by a compact nanosatellite propulsion system and a three-axis attitude control system. As a consequence of following the CanX design approach (a mixture of microspace and "X" program philosophy), the mission

benefits from the low-cost and rapid design cycle typically associated with nanosatellite programs [1].

CanX-2

As the technology required for this type of mission is still in early development, UTIAS / SFL will be flying a precursor nanosatellite, CanX-2. CanX-4 and -5 will be largely based on CanX-2 but will incorporate improvements and upgrades suggested by the results of the CanX-2 mission. The CanX-2 mission is therefore intended to be a risk mitigation mission with the goal of improving the reliability of the critical components for the CanX-4 and -5 mission.

The primary elements of the CanX-2 spacecraft include:

- A 10x10x30 cm CanX nanosatellite bus including on-board computer, communications, structure, thermal and power subsystems
- A GPS receiver and antenna.
- An attitude control system consisting of a magnetometer, sun sensors, magnetorquers, and a nanosatellite reaction wheel
- A CMOS imaging system
- A nanopropulsion system capable of ΔV at least 2 m/s.

NANOPS and CanX-2

The NANOSatellite Propulsion System (NANOPS) is part of the CanX-2 mission to demonstrate enabling component technologies in support of future formation flying missions. Flight test results in 2006 from NANOPS on board CanX-2 will augment ground test results with the goal of refining the design to support the CanX-4 and -5 formation flying mission in 2008. The CanX-2 version of NANOPS is a scaled prototype of what will be needed for the CanX-4 and -5 mission. CanX-2 NANOPS uses liquefied sulfur hexafluoride (SF₆) as a propellant because of its high storage density. The target performance goals are 50 mN of thrust, a specific impulse of 45 s, and a minimum impulse bit less than 0.5mNs.

The requirements that drive the NANOPS design are derived from the preliminary CanX-4 and -5 propulsion requirements shown in Table 1. For the purpose of NANOPS, several requirement reductions are considered. These reductions are deemed necessary at this stage of the development in order to meet the CanX-2 accommodation requirements and development schedule. NANOPS aims to prove the general design methodology, the implementation strategy, and the individual component technologies. Once NANOPS is completed and the general design is verified, future propulsion systems based on NANOPS technology will be developed to meet the goals of the CanX-4 and -5 mission in addition to other UTIAS / SFL nanosatellite missions.

The requirement reductions include reductions in ΔV , I_{SP} , and overall wet mass. The ΔV requirement is reduced to 2 m/s mainly because of the volume and mass limitations of CanX-2. However, NANOPS will meet the lower specific impulse requirement of 50 s for the CanX-4 and -5 mission (see Table 1). This is attained with a simple cold-gas system. NANOPS is not currently optimized for mass.

In future NANOPS derivatives, improvements to ΔV can be obtained by increasing the amount of propellant, increasing I_{SP} , and/or the use of lighter weight components. NANOPS is currently designed with a small 10 mL stainless steel propellant storage tank. This could be expanded to accommodate 50 mL or more by increasing the size of the tank and/or using lighter materials such as titanium.

Table 1: CanX-4 and CanX-5 Propulsion System Requirements and the Augmented Propulsion System Requirements for NANOPS

Parameter	Requirements from CanX-4 and CanX-5	Augmented Requirements for CanX-2
ΔV	35 m/s	2 m/s
Specific Impulse (I_{SP})	~50 sec (cold gas) ~100 sec (warm gas)	~50 sec (cold gas)
Thrust	50-100 mN	50 mN
Minimum Impulse Bit (I_{BIT})	0.1 mN-sec	< 0.5 mN-sec
DC Power Consumption	3 W	4 W
Overall Wet Mass	500 grams	500 grams
Overall Volume	50x50x100 mm	50x50x100 mm
Material Cost	< CAD\$20k	< CAD\$20k

Improvements to I_{SP} in the future may be possible through the use of higher performance thruster cores such as an electrothermal thruster core where a heater would be used to add energy to the propellant. In addition, an improved nozzle design can be used to further increase I_{SP} . Finally, the NANOPS support structure could be optimized. As an example, 100 mL of propellant and an I_{SP} of 100 seconds would result in a total ΔV of 37 m/s on a 5-kg spacecraft.

The CanX-2 experiment involves mainly attitude control maneuvers that spin the satellite about one axis. The sensors aboard CanX-2, namely the magnetometer, the coarse sun sensors, and the fine sun sensors, should easily and effectively detect spacecraft rotation. The measured rotation rates and attitude can then be used to determine the performance of the propulsion system. The results of these tests can be compared to test results obtained before launch to verify predictions of the system characteristics. NANOPS is novel not only because it is the first of its kind in Canada, but also because it will pave the way for other propulsion systems to be developed for nanosatellites and microsattellites based on commercial off-the-shelf (COTS) components.

DESIGN METHODOLOGY

Propellant Selection

Several propellants were originally considered for use with NANOPS. They include traditional cold gas propellants such as Iso-Butane (C_4H_{10}) as well as unconventional options such as the refrigerant 1,1,1,2-Tetrafluoroethane/R134a and Sulfur Hexafluoride.

Table 2: Propellant Choices Considered for NANOPS

Liquid	Vapour Pressure (at 21°C)	Liquid Density (kg/m^3)	Critical Temperature (°C)
Acetone C_3H_6O	0.3 bar (4.5 psi)	790	172.0
Ammonia NH_3	8.8 bar (127 psi)	682	132.4
Carbon-Dioxide CO_2	62.0 bar (900 psi)	763	31.0
Iso-Butane C_4H_{10}	2.6 bar (38 psi)	556	134.9
Nitrous Oxide N_2O	50.0 bar (725 psi)	1223	36.4
R134a CH_2FCF_3	5.8 bar (84 psi)	1150	100.9
Sulphur Hexafluoride SF_6	21.7 bar (315 psi)	1880	45.5
Xenon Xe	53.5 bar (773 psi)	3057	16.5

The main drivers for the propellant selection were:

- Ease of use.
- Propellant safety.
- High storage density.
- Relevant to future NANOPS derivatives.
- Allows for sufficient testing of the NANOPS components.

The chosen propellant should be easily procured and safe to use in a university lab environment, without requiring extensive licensing or safety precautions. These principles point to the use of chemicals that are non-toxic and generally friendly to humans.

The propellant should be chemically inert to materials commonly found on spacecraft and launch vehicles. The propellant should also be easy to transport from the integration facility at SFL to the launch site.

When considering the limited available volume and mass in a nanosatellite, high-density propellants are

very desirable. Whereas storing gas at a high-pressure achieves this result, it places extra requirements on ground handling and the on-board pressure vessel. Therefore this favors the use of a liquefied gas that is stored at its vapor pressure. The propellant of choice would have to have a vapor pressure low enough so as to not to place any extra requirements on the system, but also high enough to overcome any internal flow losses within the NANOPS plumbing. A high vapor pressure is also desired, as it will ensure rapid transition to gas phase.

Each of the propellants to be considered complied with at least one of the selection criteria, however most of them also had at least one property that disqualified them outright. Rationale behind not choosing some of the more common propellants is summed up below:

- Ammonia is not considered at this time because of its toxicity.
- Acetone and iso-butane are not as desirable for NANOPS due to their low vapor pressure.
- Carbon dioxide and nitrous-oxide have a relatively high vapor pressure.
- Nitrous-oxide requires special licensing.

The refrigerant R134a is another attractive choice as propellant. It is widely used in portable dusters or blowers, and is widely available in pressurized cans. However it does require special licensing requirements and therefore conflicts with the rigorous NANOPS development timeline.

Xenon is also an attractive choice. It is widely used as propellant for high-efficiency Hall and Ion thrusters. It is not considered at this time because of its high vapor pressure and high cost.

In the end, sulfur hexafluoride (SF_6) was chosen to be the propellant for NANOPS. Sulfur hexafluoride is non-toxic, inert, and a known electrical insulator and thus was believed to be the best choice as a propellant for NANOPS.

It is important to note that NANOPS is not aiming to have optimized performance capabilities. It is true that other propellants would allow for greater thrust and/or specific impulse, but it was felt that having a propellant that would allow for many tests in orbit to verify the operation of the entire propulsion system was a more important feature at this stage in the development of a nanosatellite propulsion system. Future versions of NANOPS would then be able to use propellants that allow for greater performance once a dependable system has been designed, built and tested.

System Architecture

Within NANOPS, there are several factors that helped shape the final architecture of the system. The main limiting factor is the volume constraint imposed by the envelope provided by CanX-2 as it limits the types of component that may be used. In many cases, components are either unavailable in the sizes that are needed, or if they are, their price is significantly higher for that very reason. This constraint applies mainly to the key components such as the check valve, relief valve, solenoid valves, and the pressure sensor.

Another issue that has been addressed is how to make connections between the different components within NANOPS. The first concern is finding a method to attach the 1/16" ports off the solenoid valves. As most fluid control devices use piping with larger outer diameters, finding COTS components to interface with the solenoid valves has not been easy. Originally, welding the ports to custom manifolds was considered, but due to their relative small size and sensitivity, welding would be undesirable, as it would make replacing the solenoid valves difficult. Secondly, two stainless steel bosses would be needed to house the check and relief valves, adding more mass to the system. For these reasons, a strategy using nuts and ferrules has been chosen. Ferrules work by placing a sort of ring/sleeve around the end of the tubing, and through the compression of the nut, the ferrule creates a seal by biting down on the tubing and pressing on to the bottom of the fitting which the tubing is being routed into (see Figure 1).



Figure 1: Examples of Nut and Ferrule Connections

Through the use of a nut and ferrule scheme, connections can now be made between the 1/16" ports of the solenoid valves. Nut and ferrules connections are

also desirable because they allow for easy assembly and disassembly, and exchange of the NANOPS components during integration and testing. Nut and ferrules connections also eliminate the risk of heat damage to sensitive components that may arise during welding, while also permitting the possibility of using polymer components downstream of the storage volume and stainless steel in areas where propellant will be stored for extended periods of time, which in turns provides flexibility in the placement of the components.

Although it would have been desirable to have as many polymer (Tefzel or PEEK) components as possible, some stainless steel components are needed for two reasons. A supplier error resulted in solenoid valves that were longer than specified, but could only be remedied within the time available by substituting the PEEK tee unions with smaller stainless steel counterparts. The second reason is that using polymer tubing in any storage area would have resulted in propellant loss due to the permeability inherent in polymers. Figure 2 and Figure 3 show examples of what happens when storing propellant in polymer tubing over extended periods of time. As such, stainless steel tubing is required for any portion of the system where propellant is being stored.



Figure 2: Propellant Leakage Occurring Through a Ferruled Connection with PEEK Tubing

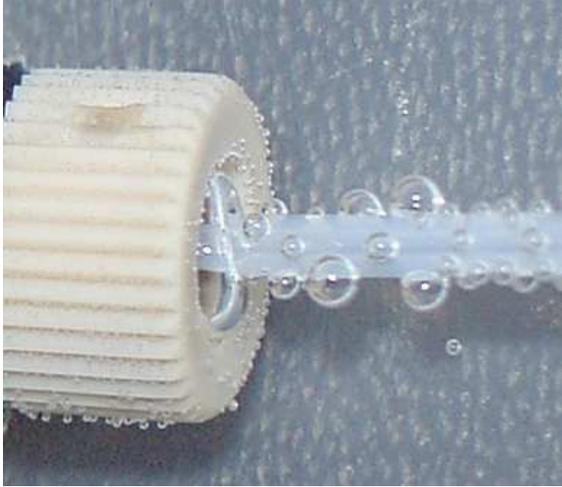


Figure 3: Example of Leakage Due to Tubing Tefzel Permeability

The expected operating pressure of the system is predicted to be ~21.7 bar (315 psi) however the initial pressure of the supply tank is 34.5 bar (500 psi). A positive pressure margin is desired for the system so all the selected components have been rated for operation at above 34.5 bar (500 psi) where possible.

Exceptions to this are the solenoid valves, the pressure transducer, and the relief valve. These three components are rated to operate at 34.5 bar (500 psi). However it should be noted that the burst pressure of these three components are higher than 34.5 bar (500 psi). The rest of the components in the system are all rated to pressures above 34.5 bar (500 psi) and do not limit the operation of the system.

There are very limited transducer choices that are compatible with the mass and volume constraints of NANOPS. It is also desired that the transducer can monitor the pressure decay as a thruster valve is activated with sufficient resolution. Because of these reasons the pressure transducer is selected for operation at this pressure level.

The relief valve is selected for operation at this pressure level such that it will relieve the excess pressure should the pressure increases above 34.5 bar (500 psi).

The solenoid valves are experimental prototypes that were modified from COTS valves and are currently guaranteed to work at 34.5 bar (500 psi), although they have been tested for operation at up to 48.3 bar (700 psi).

Another concern is the danger that the propulsion system poses to the satellite as the thrust produced by

NANOPS could potentially spin the satellite beyond its control limits. Several protective measures have been implemented to ensure this is not the case. First, the solenoid valves used as the regulator and thruster valves are designed to fail closed, limiting propellant flow should power suddenly fail on NANOPS. As these valves are in series, simultaneous failures would have to occur to cause a critical failure. A watchdog timer has also been included on the electronics board and will shut off the solenoid valves after 5.2 seconds. The 5.2 seconds time limit assumes a nominal thrust of 50 mN which will result in a nominal spacecraft spin of 60°/s. This is well below the maximum spin rate of 80°/s, which is defined as the maximum spin rate that can safely be managed by the spacecraft attitude control.

Finally, if an overpressure causes the relief valve to vent propellant, it will vent within the satellite. It is believed that with the various openings in the satellite's structure where other components have been fitted through the outer panels, any propellant released inside of CanX-2 will disperse through these openings causing very little, if any, rotation.

Magnetic Field & Dipole Considerations

There has also been a concern with regard to the possible magnetic dipole that may be caused by the solenoid valves used in NANOPS. Active attitude control will not be used while tests are performed with NANOPS, and one of the concerns is that any dipole emanating from the valves will throw off the results from the propulsion test. A residual dipole could also have adverse effects on the satellite even when NANOPS is not active. The presence of a magnetic field from the solenoid valves also presents a problem if the field intensity is strong enough to influence the magnetometer that is being flown aboard CanX-2.

Although preliminary tests have shown that there is no appreciable magnetic dipole being created during operation, it is desired that preventative measures be taken just in case the magnetic properties of the valves change after use. To minimize any magnetic effects, NANOPS was originally configured such that if four solenoid valves were to be used, the two redundant regulator valves would be oriented in the opposite directions in order to reduce their magnetic effects. This could not be done with the thruster valves due to orientation constraints. Currently NANOPS will be operating with only two valves due to budget constraints, thus canceling cannot occur, and for this reason, further tests will be performed to measure the magnetic dipole of the valves and any changes that may occur after time. If it is found that the dipole created by the solenoid valves will have an adverse effect, counter-

measures will have to be put into effect in the attitude control system. Depending on whether the dipole effect is permanent or not will determine the nature of the counter-measure.

Thermal Considerations

The thermal condition within NANOPS is difficult to estimate due to the uncertainty with the CanX-2 orbit. This is in part due to the fact that nanosatellite orbits are dependant on the orbits of the primary payloads on the launch.

From preliminary thermal analyses, NANOPS may experience temperatures anywhere from -20°C to 40°C as a worst-case scenario. Note that the maximum temperature expected should decrease by $\sim 5^{\circ}\text{C}$ once a final orbit has been selected for CanX-2 and proper thermal coatings can be selected for use on the exterior of the satellite. The limiting components for this temperature range are the temperature sensors at -25°C and the Tefzel tubing and relief valve, which are rated to 80°C . Testing has not yet been conducted with any of the tubing, however the temperature sensors have already been tested to -25°C , and were shown to still operate within acceptable limits. Testing will be conducted to ensure that the tubing does not fail at 50°C , which should prove NANOPS' ability to survive the expected temperature conditions.

Another factor to consider is the temperature's effect on the propellant. At lower temperatures, the only significant effect would be a decrease in the propulsion system's performance. At temperatures higher than $\sim 40^{\circ}\text{C}$, the saturation pressure of the sulfur hexafluoride would exceed the 34.5 bar (500 psi) pressure limit on the relief valve. While in orbit, this would cause the propellant to vent unexpectedly, but measures have been taken to ensure that no damage is inflicted upon NANOPS or CanX-2. Increased temperature could also increase the propulsion system's performance causing the satellite to spin faster than $80^{\circ}/\text{s}$, the maximum spin rate that the CanX-2 ADCS can handle. For this reason, operation of NANOPS has been restricted to times when the measured temperature of the system falls between 20°C to 35°C . Heaters will be incorporated in NANOPS to help warm the propellant prior to a test in the case of cold temperatures. If temperatures are found to be higher than 35°C , the duration of thrust times will be reduced accordingly.

From preliminary thermal analysis, it is believed that the by isolating NANOPS from the rest of the satellite, the effective temperature will fall within a smaller

range with diminished extremes. Reducing the amount of area that comes in contact with the CanX-2 mounting tray can increase this isolation further. Once a final orbit has been decided upon, the thermal isolation between NANOPS and the rest of the satellite will be optimized.

SYSTEM DESCRIPTION

Figure 4 below shows a block diagram of the propulsion. From the external sulfur hexafluoride supply tank, the propellant will enter NANOPS via the nozzle assembly (F). The original design called for a check valve and a separate fill port, but for simplicity it was decided to fill the system through its nozzle and reduce the number of connections. The propellant then flows through the rest of the system requiring that the thruster valve (E) and regulator valve (C) be open during the filling process. This allows the propellant tank (A) and the tubing up to the relief valve (B) to store the propellant upstream of the regulator valve. The rest of the system will be evacuated once the fill is complete

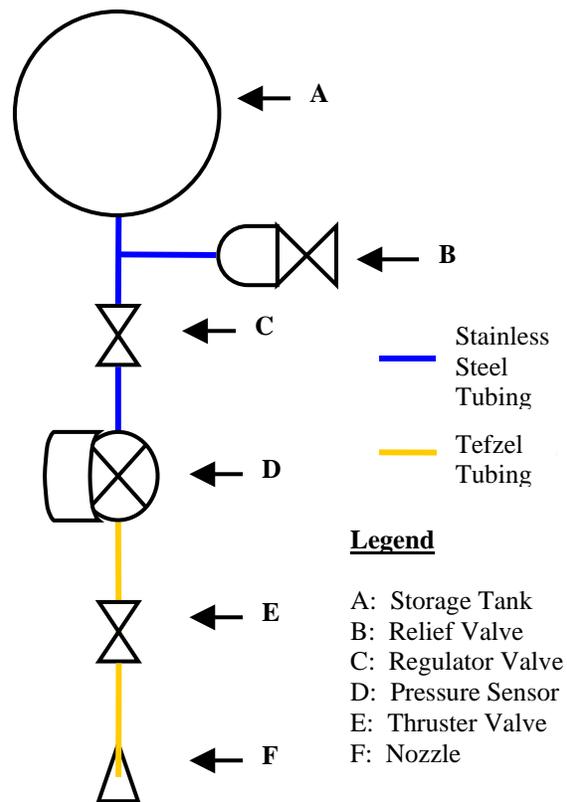


Figure 4: NANOPS System Architecture

Figure 5 through Figure 7 show the fully assembled NANOPS. Note that not all the tubing and electrical wiring have been included and the NANOPS Tray and Regulator Valve Support Bracket have been shown with a slight transparency for illustrative purposes.

COMPONENT TESTING

This first of three phases of testing is intended to find any faults with the hardware that would diminish the validity of any performance testing. The faults that should be detected should be the type that are more likely to stem from manufacturing defects or improper integration rather than ones that would be caused by induced failures such as vibration or thermal testing. All tests are intended to characterize the performance of components over the expected temperature range of -20°C to 40°C and therefore will be tested at -30°C, 25°C and at 50°C. The vacuum of space will also have an impact on how the system performs, and as such, each temperature will be tested at ambient atmospheric pressure and in high vacuum ($\sim 10^{-5}$ torr or $\sim 10^{-3}$ Pa).

Measurement Devices

Within NANOPS, there are three temperature sensors and one pressure sensor used for taking real-time pressure and temperature measurements at key

locations. While the pressure sensor is the only device that interacts with the propellant directly, the temperature sensors are placed on stainless steel components because of the material's higher thermal conductivity when compared to the PEEK or Tefzel components in the system. The aim of these tests is to verify the calibration process and accuracy of the various sensors.

Solenoid Valves

Two solenoid valves will be used within NANOPS to control propellant flow. Due to the fact that the solenoid valves use small electromagnets to control propellant flow, the magnetic dipole of these valves induce could impact CanX-2 attitude stability in a manner similar to what was experienced on the SNAP-1 nanosatellite [2]. According to the manufacturer, shielding has been put in place to minimize these effects, however no quantitative results are available. Therefore characterization of the valve's magnetic field intensity must be made.

Tests will be performed to characterize both the residual and active magnetic properties of the system.

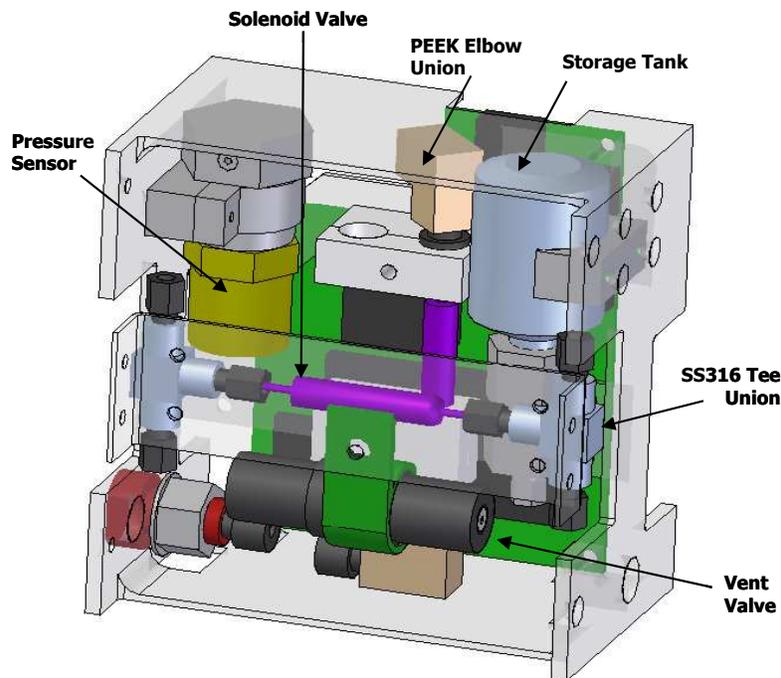


Figure 5: Solid Model of NANOPS (+Z Face)

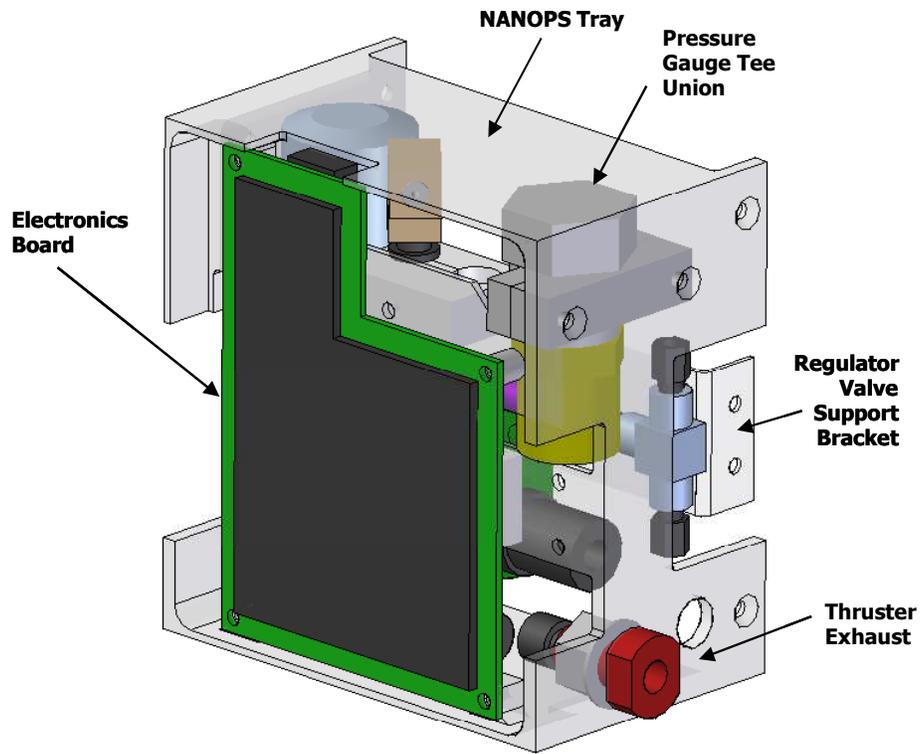


Figure 6: Solid Model of NANOPS (-Z Face)

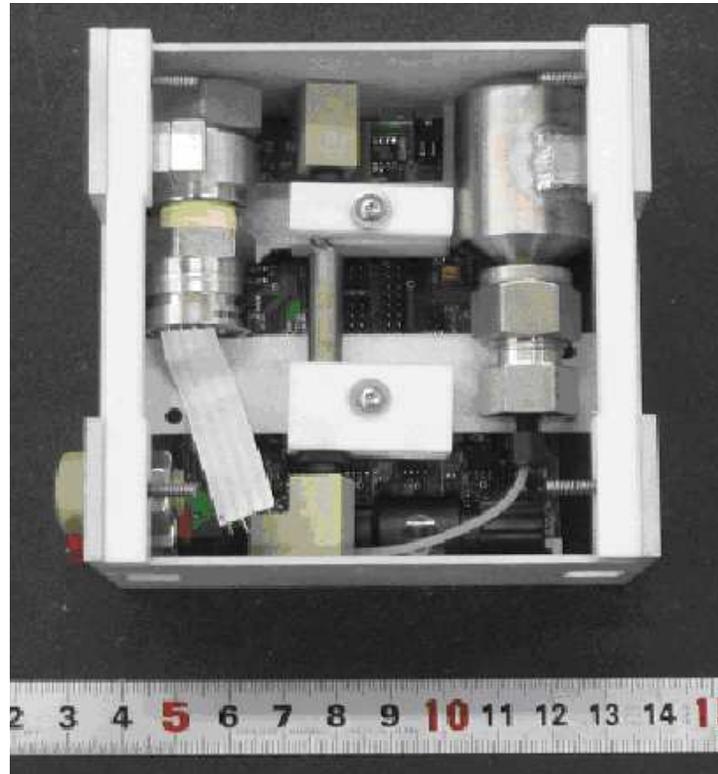


Figure 7: Photo of Partially Assembled NANOPS (Scale in cm)

The residual magnetic field tests will be conducted in order to detect any build-up in magnetic field intensity due to operation of the solenoid valves. Active magnetic field tests aim to compare the magnetic field while the valves are active to their inactive states. Due to the low mass of the CanX-2 satellite, strong enough magnetic dipoles created by the valves may alter how the satellites moves during a thrusting maneuver and may make fine maneuvering difficult.

Leakage

Once CanX-2 has been fully integrated into the launch vehicle, an appreciable amount of time will pass between then and when the NANOPS experiments can be performed. Mainly due to the fact that NANOPS is an amalgamation of several types of components, the chances of leaks occurring in the system increases with every connection point. Although not perfect, welded connections would have a lower likelihood of leaking, but as this was not an available option, ferruled connection types have been used as mentioned above. All connections are rated for at least a 68.9 bar (1000 psi) pressure difference, and tests will be conducted to verify that no leaks are present in the system, or if they are, at what rate the propellant will leak out. The vibration testing planned for NANOPS and CanX-2 will also act as a test for the reliability of these connections.

PRE-FLIGHT TESTING

These tests are intended to predict how NANOPS will perform while in orbit and also to act as a reference for comparison with the NANOPS theoretical model. These tests will help verify that NANOPS is performing within its expected parameters. As parameters such as thrust and mass flow rate are affected by ambient temperature and pressure, all tests described are intended to characterize the performance of components over their maximum temperature range of -20°C to +40°C.

System Thrust

In order to characterize NANOPS, the level of thrust that it can produce must be measured. Three thrusting modes will be tested: a full thrust mode, a pulse-width-modulated (PWM) mode, and a minimum impulse-bit mode. The measurements taken during these modes of operation are not only used to help determine how NANOPS will perform in orbit, but also as references to help validate the theoretical model currently being created.

The full thrust mode entails opening both the regulator and thruster valve and holding them in their open position for the duration of the thrusting. The PWM mode will be investigated through the use of pulse-width modulation in the regulator valve. Currently, the signal used in the PWM thrusting mode is a simple square wave with at a frequency of 10 Hz and a duty cycle of 20%. Fine-tuning of this pulse signal will take place concurrently with the pre-flight thrust tests in an attempt to provide consistent pressure regulation.

The minimum impulse bit will also be investigated. This is in concordance with the aim for NANOPS to provide fine control capabilities for future formation flying missions. The factors that determine the minimum impulse bit are the mechanics of the solenoid valve (the minimum open-and-close time) and the thrust available (which is dependant on the regulated pressure). The average specific impulse of the system can also be determined once the thrust and fuel consumption has been determined for each thrust test.

Durations for the tests will be limited to a maximum 2 s thrust times, as this is indicative of the testing to be performed in orbit due to the limitations imposed by the ACS.

System Pressure Profiling

During thrust periods, the pressure of the propellant flowing through the system may change differently than what is predicted by the theoretical model. By being able to determine the true pressure of the propellant at a point between the storage volume and nozzle throat, a comparison can be made with the predicted values at the same point in the model. An accurate means to predict system performance will allow for changes in the system to be evaluated without having to spend the time and money constructing a prototype, thus adhering to the low-cost and short development time of a nanosatellite program.

IN-FLIGHT TESTING

Once in orbit, tests will be performed with NANOPS in order to verify performance predictions and to assess the functionality of the system in the LEO environment. Performance tests will be conducted to find average values of thrust, specific impulse, and minimum impulse bit with telemetry data being recorded during these tests, and at intermittent times when thrusting is not occurring. This secondary data will be used to verify characteristics such as leakage rate and the survivability of the various components used in NANOPS. The testing environment of NANOPS will depend on the final orbit that is selected for CanX-2. It

is estimated that the temperature experienced by NANOPS will fall between -20°C to $+40^{\circ}\text{C}$, which would bring the saturation pressure of the SF_6 very close to the 34.5 bar pressure limit. Because the pressure would be very high at this point, testing during times of high temperature beyond 35°C will be avoided if possible or thrust durations will be reduced. The accuracy of CanX-2's ADCS imposes a limit to the accuracy of the test results as the current accuracy of the satellite's attitude and attitude rates are to within $\pm 1.0^{\circ}$ and $\pm 0.2^{\circ}/\text{s}$ respectively.

System Thrust

Similar to the pre-flight test, thrust produced by NANOPS and the minimum impulse bit must be measured. Also similar to pre-flight testing is the fact that full thrust and minimum impulse bit modes will be tested. It is predicted that after a full thrust firing, CanX-2 should be spinning at $\sim 60^{\circ}/\text{s}$ about its Z-axis (see Figure 8), however it is expected that some thrust misalignment may occur due to either manufacturing, integration inaccuracies, or as a result of launch loads. The changes in spin rates of the satellite will help determine if any misalignments are present and its severity.

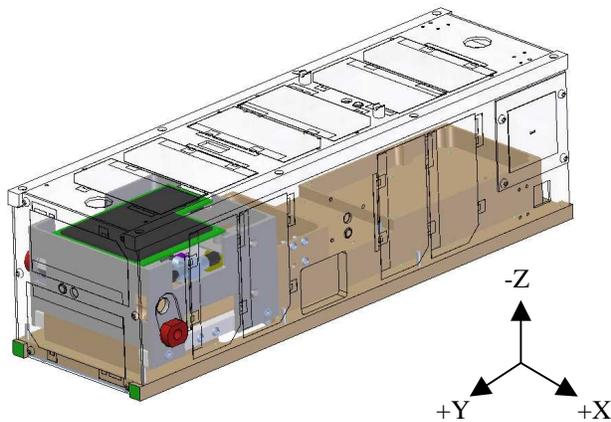


Figure 8: NANOPS Location Within CanX-2

Measuring the rotation rate resulting from firing a small, predetermined amount of propellant will determine the specific impulse.

GROUND TEST FACILITY

In order to perform pre-flight thrust tests, a thrust stand is needed for taking measurements. Traditional force and acceleration sensors were considered, however this option was too complex, as it would require some sort of a force-balanced support structure and a complete

signal conditioning system. A traditional thrust stand is considered to be outside of the current project budget, however it will be considered in the future.

It was decided that a commercial microbalance could provide the required resolution. A microbalance was selected which is capable of a resolution of 0.01 g, which is equivalent to a force of 0.1 mN. The microbalance has a stabilization time of only 1 s, maximum capacity of 2.1 kg, and comes integrated with conditioning circuit and computer interface

The downside to using commercial equipment for testing is that some modifications will be necessary to make it operable in a vacuum. The modifications will only involve the electrical interface between the force sensor and the microbalance control electronics, and does not involve alteration of the mechanical parts. The operable temperature range is also limited to 5°C to 40°C which means that the thermal conditions used for performance testing will be limited to that range.

Within SFL, there are two thermal cycling chambers that can be used for testing items within a temperature range of -70°C to $+180^{\circ}\text{C}$. SFL also possesses equipment to operate a small vacuum chamber that can be used within a thermal chamber. The vacuum chamber is capable of lowering pressure within the vessel to $\sim 10^{-7}$ torr, thus allowing in-house thermal-vacuum testing of specific components or the entire propulsion system assembly.

An air-bearing table is available for testing where low friction surfaces are required. Testing will be conducted using the air-bearing table to simulate on-orbit conditions to allow for rotation about the Z-axis of CanX-2 once NANOPS has been integrated with the rest of the satellite.

Vibration tests, that will be used to verify the mechanical integrity of NANOPS structure and seals, will be performed at an external facility.

PRELIMINARY TEST RESULTS

Leakage Tests

In order to verify the compatibility of tubing and nut and ferrule types, leakage tests have been conducted on a partially assembled version of NANOPS called FlatNOPS. This system consists of the storage tank, pressure sensor, and the two solenoid valves that would be incorporated into the final flight version of NANOPS, as well as the necessary unions and tubing needed to connect the components.

Results from tests conducted using stainless steel tubing showed that no significant leaks were present in the system, and are shown below in Figure 9. From these results, it can be seen that over nearly two days, the pressure in the system has fluctuated in a periodic fashion. This periodic fluctuation is explained by the changes in temperature in the test area over the course of two days. Further tests are planned to take place in a temperature-controlled environment where both mass and pressure will be recorded over the duration of the test.

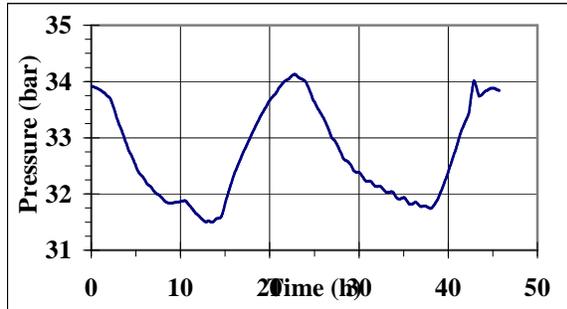


Figure 9: Leakage Test Results Using Stainless Steel Tubing

Magnetic Field Testing

Two sets of data have been collected from testing the NANOPS propulsion system for any magnetic fields that are created due to either the operation or the presence of the solenoid valves used to control propellant flow. A residual magnetic field test was conducted prior to and after an active magnetic field test where the valves were operated in the two thrust modes described in the *Pre-Flight: System Thrust Tests* section.

From the results, the residual magnetic field did change after operating the valves. Prior to operation, the largest magnetic field reading was measured to be 0.090 gauss while after the active test the largest reading was 0.110 gauss with an average change in field intensity of 0.013 gauss. To put these values in context, the smallest magnetic field intensity that may be experienced while in orbit can range from ~0.239 gauss to ~0.194 gauss at altitudes of 500 km and 1000km respectively. These values were obtained using the following relationship[3]:

$$B = \frac{B_o (1 + \sin^2 \lambda)^{1/2}}{R} \quad (1)$$

where B is the local magnetic field intensity, λ is the magnetic latitude, R is the radial distance in Earth radii, and B_o is the magnetic field at the equator at $R=1$.

These values indicate while the residual readings are <50% of the minimum expected magnetic field intensity due to the Earth, they are still significant enough that they may interfere with the magnetometer that will be flown aboard CanX-2. They also indicate that after running the valves, some residual magnetic charge remains in the solenoid valves. It is important to note that the valves were operated for several minutes continuously where as normal operation of the valves would only occur for several seconds at the most. Whether these effects are permanent or not have not yet been explored, but will be investigated further with continuing residual magnetic field tests.

Preliminary results from the active magnetic field test also show appreciable rises in field intensity during valve operation. In the case where the valves were operated in their full thrust mode (both valves held open), the largest magnetic field intensity reading was found to be 0.495 gauss. When the valves were operated in the PWM mode (one valve pulsing and the other held open), the maximum reading was 0.409 gauss. This seems counter intuitive as the PWM mode would be activating the regulator valve's induction coil more frequently and with a higher average current. It is believed that the sample rate of the magnetometer used during the tests might not have been fast enough to capture the 1ms opening pulse of the valve and more tests are scheduled to confirm this.

Despite the inconsistency with what was expected, the magnitudes of the results show that the magnetic field intensity of the valves during operation can be quite significant when compared to the theoretical Earth's field intensity. Field intensities of this magnitude could have negative effects on an attitude determination and control system if not properly considered.

Further higher fidelity testing will be done to determine whether additional countermeasure is needed to reduce the valve's active dipole and field intensity.

Thrust Profile

Preliminary thrust test have been performed with FlatNOPS. The tests and the results are considered preliminary, as the components used within FlatNOPS are not set-up in their flight configuration. As minor differences in the connections could have a significant impact on the system's performance, the results are still considered as preliminary as official test results will stem from a flight ready NANOPS propulsion system.

The preliminary thrust test is a complete blow-down test, where the thruster valve is opened until all of the propellant upstream is expelled. In FlatNOPS, this involves pressurizing a section of 1/16" tubing to 34.5 bar with SF₆. Once the tubing has been pressurized the external tank is disconnected. The thruster valve is positioned such that the resulting force is imparted against the microbalance.

The thrust profile shown in Figure 10 represents the average thrust measured by the microbalance over several trials. The initial pressure of the SF₆ was at 34.5 bar while the external pressure and temperature were ambient atmospheric pressure (1.01 bar) and 21°C respectively. No nozzle had been attached and as such, the propellant was vented through a 1.6mm opening in one of the PEEK elbow unions with the solenoid valves held fully open for the entire thrust duration.

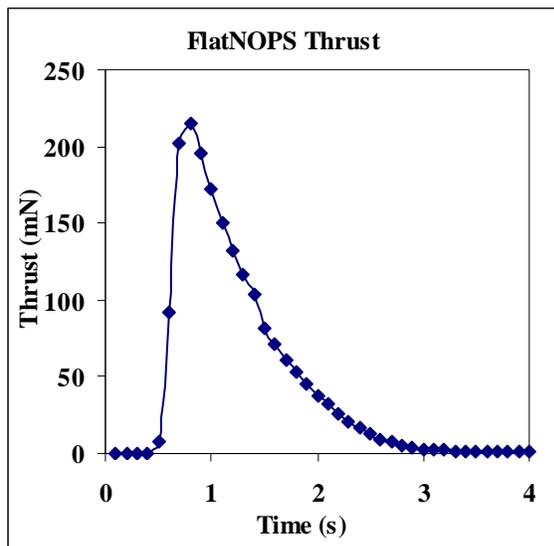


Figure 10: Preliminary FlatNOPS Thrust Profile

Comparing these results with the 50 mN thrust requirement as outlined above, a nozzle will most likely have to be used to reduce the throat area. This should have the effect of decreasing the thrust and exiting mass flow rate such that thrust levels are more stable over the duration of a thrust. A nozzle design has not been implemented at this time, as further investigation is required.

At the time of this writing, NANOPS is undergoing final integration tests and is progressing towards a full performance characterization.

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