Adaptable, Multi-Mission Design of CanX Nanosatellites

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ABSTRACT: Through the development of a low-cost, 5 kg multi-mission nanosatellite bus at the University of Toronto Institute for Aerospace Studies' Space Flight Laboratory, a number of new and interesting applications are now possible on a nanosatellite platform. Two ventures currently underway that adopt the multi-mission nanosatellite bus are an astronomy mission, CanX-3 (also known as the BRight Target Explorer - BRITE), and a dual-satellite formation flight mission, CanX-4/5. CanX-3 is a space telescope that will monitor long-term light fluctuations from the brightest stars in our galaxy to study stellar structure and galactic evolution. CanX-4/5 will demonstrate precise formation flight by controlling position to the 1 m level, and by providing determination with an order of magnitude better accuracy, all via a commercial GPS receiver and a custom propulsion system. The driving force behind the multi-mission concept is the objective of reducing non-recurring engineering design costs. While this approach violates microspace philosophy by not tailoring to each specific mission, this paper argues that consideration and combination of the mission requirement sets allow a limited generic approach that holds to the basic tenets of the philosophy, allowing substantial cost savings to be realized, over and above the case of tailoring to specific mission interests.

INTRODUCTION

As humanity trepidly advances exploration of the final frontier, the cost of gaining access to, and operating in space continues to pose a formidable challenge. Not only is the cost of launch at tens of thousands of dollars per kilogram prohibitive, but the political adversity to risk tends to drive the cost of space missions ever upward. Nanosatellites, defined as having mass less than or equal to 10 kg, are no exception. Figure 1 shows a conservative estimate of the number of nanosatellites launched over the last fifteen years, with the overall slow pace of increase reflecting, among other issues, the cost barrier.



Figure 1: Nanosats Launched Since 1990^{6,7,8}

For more than five years, the University of Toronto's Space Flight Laboratory (SFL) has been developing low-cost nanosatellites. By adopting the microspace philosophy¹, the laboratory's Canadian Advanced Nanospace eXperiment (CanX) program has been able to reduce the costs associated with nanospace

missions. The overall aim of microspace philosophy is to focus on good design in consideration of the operating environment and to implement targeted quality assurance approaches. The means by which this is achieved is summarized by the following principles:

- redundancy through multiple missions is preferable to multiple components on a single mission;²
- multiple modest investments in experimental satellites developed with commercial components and good design practices leads to more science per dollar than otherwise would be possible;²
- reliability is related to complexity and that simple satellites are intrinsically more reliable and less expensive;⁵ and
- working in small, tightly-knit design teams that focus on cross-collaboration rather than on intense documentation.

By narrowing the design scope for a given satellite to a particular purpose, objective, or payload, the design envelope is greatly simplified. The quest for simplicity leads to cost reduction and risk mitigation, both of which allow more economic ventures into space science and engineering.

Historically, CanX satellites have successfully followed this philosophy without deviation. Attempting to further reduce mission costs, however, SFL is hoping to save non-recurring engineering design expenses by developing a generic nanosatellite bus (GNB). This goes against the normal drive to develop each nanosatellite for a particular mission, which is done for simplicity's sake, leading to cost reduction. That said, by advancing a generic bus with certain generic subsystems, and by adhering to the remaining precepts of microspace philosophy, SFL hopes to achieve greater financial efficiency than would otherwise be possible without compromising the tenets of the microspace philosophy.

Designing any product or service to be generic immediately leads to the problem of scope, i.e. how to constrain a generic design within a vast domain of possibility. Instead of considering a wide array of possibilities, SFL is limiting its generic design to a multi-mission approach, designing the GNB to meet the specific needs of the missions currently under way.

This paper seeks to lay out SFL's GNB requirements and design, based on the needs of the supported missions.

CANX PROGRAM

The Canadian Advanced Nanospace eXperiment (CanX) is at heart a master's level post-graduate training program, run and operated by SFL. It is not however, limited to academic studies. Nanosatellites are designed, built, tested, and implemented by graduate students under the guidance and mentorship of experienced staff. CanX seeks not only to provide an education, but to provide a service to the science and engineering communities in Canada and abroad.

The CanX program has three overarching functions that guide each phase of every mission. The first and foremost is to train students at the master's level, channelling their varied undergraduate backgrounds through hands-on training into highly qualified areas of expertise. In this way, the University of Toronto supports Canada's public and private space sectors through the continual supply of space engineers. The second function is to push the limits of scientific instrumentation and technical capability. Incorporating leading edge scientific experiments and prototype instruments serves to meet the university's mandate of academic excellence and to position Canada as a global leader in the nanospace field. As a corollary, the third function is to provide a low-cost. accessible means by which government agencies and industrial companies may prove miniature technologies in an orbital environment. Figure 2 shows the nanosatellites that have been, and are being, produced by the CanX program at the University of Toronto.



Figure 2: CanX Timeline by Launch Date

SFL is currently developing two tangent missions: CanX-3, a space astronomy mission, and CanX-4/5, a dual satellite formation flight mission. The capacity to produce multiple missions in tandem under the current infrastructure is the result of moving toward the GNB design that forms the subject matter of this paper. It is believed that evolution of the GNB will lead to many new and diverse missions in the future. The direction that the CanX program will continue to follow into the forseeable future is along the lines of incorporating the lastest commercial technology, simplifying design problems, and improving risk mitigation and management - quintesstially the microspace philosophy - with the goal of providing faster, better, and cheaper access to space on a nanospace scale.

GNB CONCEPT

The range of missions that SFL adopts is driven by the motivated partnership of university researchers and private industry who wish to pursue space-based interests. Equally driving the mission selection is the funding envelope that restricts design to the nanosatellite environment, though this is somewhat intentional considering the student-training function of the CanX program. In no way are the missions adopted by SFL a function of a particular platform, though the capabilities and limitations of available technologies are considered in a bottom-up approach. That is, the microspace philosophy of tailoring nanosatellites for specific missions and payloads is followed. The advent of the GNB does not contradict this precept, rather it tailors nanosatellite design to a limited number of missions, attempting to reduce non-recurring engineering costs across the fleet. To illuminate how SFL is approaching the use of a generic bus design without compromising the basic premises of microspace philosophy, the current missions being pursued by SFL are presented, along with the commonly-derived set of requirements that form

the basis of the GNB's design.

Space Astronomy

Much about stellar structure, evolution, and life-cycle matter contribution to the interstellar medium remains unknown, particularly with respect to the hot, massive, and luminous type O and B stars of the upper H-R diagram that are relatively rare with respect to the general population. Exploration of such areas is possible through photometry by examining oscillation modes to infer certain stellar properties and patterns, a form of astroseismology. SFL's CanX-3 mission hopes to shed light on some of these astronomical unknowns. Comprised of a four-nanosatellite constellation with two sets of filters, the BRIght Target Explorer (BRITE) nanosatellites will make differential photometric observations of the apparently brightest (and intrinsically luminous) stars in the galaxy. Examining variability with a precision at least ten times better than ground-based techniques, CanX-3 will systematically observe the most of the 286 stars with an apparent brightness of +3.5 or brighter to provide critical insight into the structure and processes (including rotation and convection) of massive stars, leading to a greater understanding of the evolution of the universe.



Figure 3: Stellar Density Around Orion

The science objectives will be achieved by using a small, custom-built, 24° by 25° field of view, CMOSbased telescope to perform differential photometry on multiple bright stars to a precision of 0.1%. Based on the BRITE telescope design, Figure 3 shows the stellar densities for one of the CanX-3 mission's regions of interest, the richly diverse and populous Orion consellation. The BRITE nanosatellites will monitor amplitude variation of these stars for campaigns of up to 100 days per target star field.

Complementing the main science objectives, the planned ancillary science is extensive, ranging from characterization of red-giant variability to the detection of planetary transits around stars much more massive than the Sun.

The major performance requirement for the BRITE nanostatellites is to be able to achieve arc-minute level pointing precision in order to achieve the target 0.1% accuracy on differential photometry. The use of components such as miniature reaction wheels (developed by Dynacon Inc. and being test-flown on CanX-2) and a precision star tracker will allow BRITE nanosatellites to achieve the ambitious and demanding attitude performance necessary to conduct their stellar photometry measurements.

The attitude performance goal of the CanX-3 mission also has the consequence that the telescope must be thermally isolated from the rest of the structure because gradients in temperature as well as sustained elevated temperatures would deteriorate the quality of data being collected or possibly damage the detector.

Formation Flight

The expensive nature of space flight has led many spacecraft programs to attempt risk mitigation through highly autonomous, highly fault-tolerant designs involving scores of skilled employees, very detailed documentation and space-proven components. Conversely, the concept of formation flight has come about in which a cluster of small satellites is implemented that allows for reduced cost (through lower mass totals and the spreading of non-recurring engineering expenses across the fleet) of space missions while increasing mission redundancy and reliability. Such formations may disperse the task of a single, large satellite over the few, smaller ones. The loss of any one due to failure may be compensated by reconfiguring the formation. The presence of more than one satellite opens up doors to ventures not possible with a single spacecraft, where satellites in formation can also be arranged in various configurations for the purposes of sparse aperture sensing or to adjust ground coverage and revisit times in order to accommodate evolving mission needs. Greater flexibility in system upgrades is also a by-product, since individual low-cost satellites can be added to increase, replenish, or even improve the overall functionality of the cluster. The ability to fly in formation is also the necessary foundation of missions with remote servicing objectives or similar veins of interest.

SFL's CanX-4/5 mission aims to demonstrate formation flight using two identical nanosatellites that will determine relative position on the cm level and control relative position with an accuracy of 1 m or better. Figure 4 shows one of the planned formation flight configurations, where a simple difference of inclination along with station-keeping leads to the perception from an Earth-based observer that one satellite is orbiting the other.



Figure 4: Formation Flight Halo Orbit

Led by Cannon and Skone at the University of Calgary, each identical nanosatellite will feature a GPS antenna and receiver that allow phase-differential comparisions to be made. This method drives the cm level relative position goal.

Both CanX-4 and CanX-5 will contain a gas propulsion system, the Canadian Nanosatellite Advanced Propulsion System (CNAPS), that will regulate the satellites' relative orbit. To ensure that thrusts do not impart angular velocity, the nozzle from the propulsion system will be aligned with the mass centroid. Moreover, it is necessary to ensure that fuel sloshing and changes in both the mass centroid and moment of inertia tensor due to fuel movement and consumption do not negatively impact controllability of the nanosatellites.

The CanX-4/5 mission has particular attitude requirements related to the propulsion system and formation flight algorithms. The attitude system is sized to provide quick and efficient large-angle slews in order to support the demands of the governing Hill and elliptical-orbit equations. Furthermore, a common attitude is maintained for both nanosatellites, even though only one thrusts at a give time. This meets the constraints of the GPS determination algorithms that require each nanosatellite to view the same set of five or more GPS satellites.

$Nanosatellite \ Deployment$

One of the ongoing projects at SFL that transcends any particular mission or nanosatellite is the development of reliable and effective deployment mechanisms that eject nanosatellites from the upper stages of launch vehicles in their final orbits. Known as eXperimental Push-Out Deployers (X-PODs), these ejection units are basically tubes that have a spring at the base. With an activation signal, a springloaded door is released, and the base spring pushes a nanosatellite out into orbit. Figure 5, shows that pre-deployed components such as CanX-4/5's magnetometers are able to translate freely as the nanosatellite deploys because two sides of the X-POD are completely open once the door has been unclasped.



Figure 5: X-POD with CanX-4/5

While accommodating a variety of form factors, the design of the X-POD imposes certain constraints on all nanosatellites using it as an ejection medium, namely the minimization of components that are mounted to the exterior shell that would (with specific expections for pre-deployed units) interfere with the case.

The Common Solution

The two missions presented represent vastly different functions and objectives, yet they share much in common in terms of the support infrastructure that enables them. By comparing and combining (where ever possible) the requirements of each, a multi-mission platform may be developed that significantly reduces non-recurring engineering costs.

The fact that both CanX-3 and CanX-4/5 will use the X-POD means that each bus must be able to slide out of the deployer without damage. This leads to a contact rail-based design where most nanosatellite components must be on the spacecraft's interior. Consideration of the isolation needs of the BRITE telescopes and the necessary location of CNAPS near the mass centroid lead to a central payload bay concept. These factors in part lead to a generic structural strategy.

All of the nanosatellites of the CanX-3 and CanX-4/5 missions have similar power needs. While not equivalent, their consumptions are on the same order of magnitude (< 10 W), meaning that a similar number of solar cells are necessary. In consideration of the lessons learned from CanX-2's anisotropic thermal situation, the desire is to adopt a cubic form factor. The power and thermal commonalities lead to further possibilities of similarities between the power subsystems, thermal control strategy, and structural layout for both CanX-3 and CanX-4/5.

While the attitude demands of CanX-3 are more stringent than those of CanX-4/5, both missions share common attitude attributes: the need for full three-axis control, slewing, momentum shedding, and coarse attitude estimation. By using similar sensors and actuators (and allowing for additions or deletions), the attitude subsystem implemented on one mission may be virtually identical to that used on the other. In a similar vein, risk mitigation leads to a communication strategy that doesn't depend on orientation (avoiding possible death-mode attitudes). That both the CanX-3 and CanX-4/5 missions follow this philosophy leads to a common design and implementation between the two.

It was the realization that both of SFL's current missions share certain aspects in common that led to the conceptualization of the GNB. It was the consideration and combination of the two sets of requirements that led to the practical implementation of the GNB that in the end continues to hold to the traditional microspace philosophy while achieving greater cost savings through the reduction of recurring engineering related expenses. The following section describes in more detail what exactly makes up SFL's GNB.

GNB DESIGN

The GNB will allow SFL to provide a platform that can support a range of potential payloads, even though the current design specifically considers only two missions. The following sections lay out the subsystems that make up and define the GNB.

Structure

The structure of the GNB will be constructed from Al 6061-T6. Shown in Figure 6, the design is based on a modular dual-tray concept that fits within the volume of a 20 cm/side cube and a mass of approximately 5 kg, including a payload.



Figure 6: Tray Structure Concept

By nature of the tray-based concept, the spacecraft bus is separated into segments that group similar systems within a tray. For example, one tray holds a stack of on-board computers and power regulation boards, while another tray acts as a mount for the attitude control hardware suite.



Figure 7: Tray Population

Figure 7 shows that population minimizes volume

consumption, where components are mounted to the inside and underside of each tray. The dual-tray design leaves a sizable, readily adaptable, and conveniently situated central payload bay. Thus, a modular tray-based design offers payload engineers critical design flexibility. Further motivation for a modular tray-based design came from the desire to ensure that enough internal structural mounting area exists to minimize the number of components mounted on the spacecraft's exterior shell.

Thermal Control

Protection of the GNB from the on-orbit thermal environment follows a passive thermal control strategy. Computer modeling and simulation facilitates prudent material selection, component placement and selection of external surface treatments. The thermal control strategy is effective over a wide range of orbits, which is a design requirement driven by the need to maximize launch opportunities. Unlike most other GNB subsystems, the thermal design may well be fairly mission specific, though it remains possible that one design will suit both missions. This is because each mission will likely contain differing orbital parameters, which drive the passive thermal control strategy.

Power

The GNB will make use of up to 36 high-efficiency triple junction GaAs solar cells in order to generate 5 to 10 W of power. Through a direct-energy transfer system, these cells will be used to charge a 5.3 Ah Liion battery pack that provides a nominal unregulated ≈ 4 V bus voltage to the subsystems, which then regulate the supply levels.

Computers

The GNB will employ a centralized computing architecture. Three separate 48MHz ARM7 computers, all using an identical design, are responsible for particular tasks. The first computer, the main OBC, will be responsible for most housekeeping tasks aboard the spacecraft such as collecting basic telemetry, coordinating the communications system and relaying data between various subsystems. A second computer will be employed for the attitude subsystem. Its main responsibility will be the execution of the attitude control algorithms as well as the control and sampling of all related actuators and sensors. Finally, a payload computer will be employed and configured specifically for each particular mission. The payload

computer for CanX-3 will be responsible for science data collection, processing and storage. For CanX-4/5 it will be responsible for the execution of the relative position determination and formation control algorithms. All three computers will have EDAC-protected memory specifially for both short and long term storage of programs and variable data.

The Canadian Advanced Nanospace Operating Environment (CANOE) is SFL's in-house developed, multi-threaded operating system that will be employed on these computers. CANOE will control all software aboard the spacecraft and provide ground station operators the ability to do tasks such as dynamically loading and executing new experimental software as required during the mission.

Attitude Determination and Control

The GNB's attitude determination and control subsystem is fundamentally a second iteration design of that for CanX-2, and allows mission specific modifications. It is a clear example of a modular system design that may be applied to a range of nanosatellite missions. To help solve the attitude problem the GNB will employ phototransistors as coarse sun sensors, digital pixel arrays as fine sun sensors and a three-axis magnetometer to measure the solar vector and the local magnetic field vector. These sensors were originally designed, tested, and built in-house at SFL, and represent design iterations that incorporate lessons learned during development for CanX-2.

As an example of the GNB's adaptability, a nanosatellite star tracker will be flown on CanX-3 in order to provide high accuracy attitude determination. This will allow CanX-3 to deliver three-axis attitude control with arc-minute stability, a new precedent for nanosatellites.

Oasys, the SFL's custom attitude software, uses an Extended Kalman Filter (EKF) that propagates attitude information over time and corrects the results (at discrete intervals in state-space) based on sensory measurements. This is especially useful for CanX satellites, where explicit rate information is not used, but which becomes available as a result of iterative updates. The inclusion of rate sensors as an additional sensor is being investigated. On-board ephemerides against which to compare the measured vectors, data reduction algorithms, failure path definitions and supportive libraries round out the software. On the control side of the system, three vacuum-core magnetorquers will be used to damp body rates, and shed momentum from the reaction wheels. Three orthogonally-mounted Dynacon NanoWheels will be used to implement three-axis control, commanded by a linear quadrative feedback regulator.

Communications

The GNB is designed to carry three separate communication systems. A VHF beacon will be a downlinkonly channel responsible for continually transmitting basic spacecraft telemetry such as temperature and bus voltage. The continuous-wave beacon will serve as a diagnostic tool and will allow tracking of the spacecraft. Data uplink to the spacecraft will be accomplished through the use of an SFL-developed 4 kbps UHF transceiver. This receiver is identical in design to the one flown aboard the CanX-2 mission. To obtain omni-directional coverage on this communication link, the system will make use of a quad canted, pre-deployed monopole antenna arrangement mounted at one end of the satellite. High-speed data downlinks will be accomplished using another SFLdeveloped radio, an S-band transmitter that is identical to the design used on CanX-2, and is capable of data rates of 32 kbps to 1Mbps. Transmission is made possible by a patch antenna set, with one antenna on one face of the satellite, and a second on the opposite face.

Additionally for CanX-4/5, an inter-satellite communication system is being developed because the two spacecraft must be able to communicate with each other to share GPS and attitude information. This system will make use of an existing commercial variable-speed system-on-a-chip communication device. Through this system and an additional patch antenna set, the spacecraft will be able to exchange information with each other regardless of their relative orientation.

Payload Bay

A relatively large and conveniently situated central payload bay, shown in Figure 8, is designed to accommodate mission-specific equipment, requiring little or no modification to the supporting bus.



Figure 8: GNB Payload Bay

This large central payload bay minimizes mission cost and development time by providing a volume that easily accommodates both missions. The payload bay can also accommodate the instruments of future CanX missions.

The GNB will be able to support the payload with a dedicated 47 MHz ARM7 computer to conduct mission-specific processes. This enables a great deal of flexibility in processor utilization and memory storage allocation, given that the general house-keeping and communication processes are handled on the GNB's main OBC and are not competing for processing time with payload applications. The adaptable nature of the attitude sensors and actuators means that the GNB is able to support basic Earth-pointing missions as well as high-precision, inertial-pointing objectives. The GNB will power the payload using an unregulated 4V bus voltage that will be able to provide roughly 2 to 7 W to a given mission instrument.

The payload bay design offers the mission payloads considerable flexibility. This is achieved by developing the bus to be adaptable to a payload provided that it meets the power, volume and mass budgets. As an example, the trays forming the upper and lower boundaries of the payload bay are stiffened by cross braces in order to support a payload that must be mounted along it's length rather than being fixed at its end, and may therefore protrude out of the GNB's outer surfaces. The payload bay is centralized to ensure that changes in the moment of inertia are minimal with different payloads in an effort to ensure that the attitude control system can be designed fairly independently of a particular payload.

As examples of how the payload bay will be used, Figure 9 shows how CanX-3 will employ a CMOS-based telescope and a nanosatellite star tracker within the payload volume.



Figure 9: Telescope in the Payload Bay

A CMOS array was chosen over a CCD counterpart for power reasons. The noise characteristics of modern CMOS detectors are acceptable for BRITE science. The 0.62 kg CMOS telescope will have a large field of view which is sized to maximize the probability that several bright stars are visible when pointing anywhere in inertial space. A star tracker, employing the same CMOS detector is required by the mission to achieve precise arc-minute level pointing. This 0.63 kg sensor is designed to view $M_v \approx +4.5$ stars over a 30° field of view, with an accuracy of about 30 arc-seconds about the transverse axes and 150 arcseconds about the normal vector.

CanX-4/5 will use the payload volume to carry a liquid-fuel cold-gas propulsion system. The Canadian Nanosatellite Advanced Propulsion System (CNAPS), shown in Figure 10, will be used to produce the thrust needed to make the changes in velocity required for formation flight control.



Figure 10: CNAPS Payload

Thrusting allows the spacecraft to be arranged in a particular formation and to provide control to maintain such configurations. The system is designed to yield a ΔV capability of 18 m/s. CNAPS mainly consists of off-the-shelf components, including pressure transducers and solenoid valves that act as pressure regulation and thrust valves. The propulsion system is configured to have two parallel lines that deliver two different thrust levels. The system will include a custom-designed tank that will be used to store 300 cc of sulphur hexafluoride (SF₆) fuel in liquid form in

order to maximize fuel storage. The overall wet mass of CNAPS is 1 kg, spanning the full payload volume and consuming up to 1.2 W of power.

Current Status

The GNB as applied to the CanX-3 and CanX-4/5 missions is currently in the detailed design phase. Many of the lessons learned from the design and test of CanX-2 have already been incorporated into the GNB's preliminary design. More will be included once CanX-2 is launched as scheduled in the second quarter of 2007. Formal research and development with industrial partners is proceeding, and will continue to expand as the potential applications of formation flying are realized.

CONCLUSION

The design of SFL's generic nanosatellite bus has been laid out, the missions that it supports have been described, and the means by which consideration and combination of various mission requirement sets lead to a common solution have been presented.

In pursuing the CanX-3 and CanX-4/5 missions with shared bus, SFL has contradicted the purest form of microspace philosophy that demands each nanosatellite to be tailored to the particular mission and spacecraft of interest, for the sake of simplicity that results in cost savings. However, by designing the GNB to consider the common requirement set of the particular missions at hand, and not designing to be generic beyond this scope, SFL has been able to reduce costs by sharing non-recurring engineering design expenses across multiple missions. With the possibility that the requirements of future missions will be used to evolve the GNB, SFL is not only ensuring that the CanX program is cost effective now, but that it will continue to be economically viable well into the future, allowing it to continue to fulfill its quintessential student-training and low-cost, rapid access to space mandate.

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