Canadian Advanced

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The cost of launching a given mass into space is a driving factor for many of the design decisions made in space engineering. While some have focussed on reducing the cost per kilogram in next-generation launch vehicles, many university laboratories have concentrated on reducing the mass of the satellite to bring development and launch costs within reach of their budgets. By using smaller satellites with capabilities distilled to the essential needs, missions can be developed in a short period of time with a team of a few engineers and graduate students, further reducing the cost of development. These ideas are well known elements of the microspace philosophy [1].

At the University of Toronto Institute for Aerospace Studies, Space Flight Laboratory (UTIAS/SFL), the microspace philosophy has been combined with a staged, aggressive technology development program similar to that used by the U.S. Air Force in the development of the X planes in the 1950's. This program is the Canadian Advanced Nanospace eXperiment (CanX) program conceived in 2001 by Robert E. Zee, manager of UTIAS/SFL. The CanX program aims to achieve high-performance missions with emphasis on innovation and quick turnaround in exchange for moderate risks. [2]

CanX-2, a 3.5-kg satellite the size of a milk carton, is the second in this series of *nanosatellites*—a term used to refer to satellites with mass between 1 and 10 kg. Its primary mission is to evaluate on-orbit the core component technologies necessary for formation flight [3].

Formation flight refers to two or more satellites actively controlling their relative positions and orientations in order to achieve coordinated operations. Multiple small satellites in formation flight can perform tasks, such as Earth observation, that might otherwise require a larger and more costly single satellite. Formation flight also has applications in the orbital inspection and servicing areas. For example, a large spacecraft could contain a nanosatellite and deploy it when a problem occurs in order to fly in formation (with respect to the larger craft) and conduct an inspection.

Formation flight is not a new concept. Astronauts flew Gemini VI-A in formation with Gemini VII for over five hours in December 1965. What is novel in this research is that future satellites will perform *autonomous* and *precise* formation configuration and maintenance operations over a long period of time. The techniques under development aim to minimize fuel consumed while compensating for secular variations and allowing periodic fluctuations.

CanX-2 internals with Eric Caillibot

CanX-2 will evaluate several critical technologies in orbital space in preparation for a demonstration of actual formation flight by a pair of identical 5-kg nanosatellites called CanX-4 and CanX-5 that are planned for launch in 2008.

To achieve formation flight, it is necessary to determine accurately the relative states of the vehicles in real time, determine how to control the vehicles, and implement that control by pointing and thrusting the spacecrafts' propulsion systems.

The CanX-4 and CanX-5 mission will achieve real-time position determination by measuring and comparing the frequency and phase of GPS carrier signals from four GPS satellites. Carrier phase and frequency shift are proportional to the relative satellite distance and velocity, respectively. Others have shown that this technique is capable of positional accuracies on the centimetre level [4,5].

While CanX-4/-5 will fly with this technology, their mission will rely upon a GPS receiver tested in space by CanX-2 that will be used to assess the GPS hardware and data quality. Evaluation of the data from CanX-2 should enable the development of GPS data processing algorithms employing standard techniques to allow CanX-4/-5 to achieve positional accuracies on the order of 5-10 m. Subsequently, refinements to the position algorithms incorporating carrier-phase observables are expected to provide relative position accuracies on the order of 5 cm. This work is being developed by our collaborators Susan Skone and Elizabeth Cannon at the University of Calgary.

Orbital propagation and orbital control algorithms shall be required prior to flying CanX-4/-5 in formation. The Hill equations, whose solutions describe suitable trajectories for the lead (chief) and following (deputy) satellites, form the starting point for formation-flight algorithms. These linearized equations are valid for motions in a circular orbit. One solution of the Hill equations is a constant relative separation in the along-track direction and a zero relative distance in the radial and cross-track directions. Essentially, the chief and deputy occupy the same orbit but with different true anomalies; i.e., one satellite follows the other. Another solution to the Hill equations, termed *halo orbit*, is one where the motion in the along-track and cross-track plane is a circle; i.e. the deputy circles the chief satellite. These solutions also show that the relative separation will increase over time; however, this secular variation can be avoided under certain initial conditions.

The Hill equations provide solutions

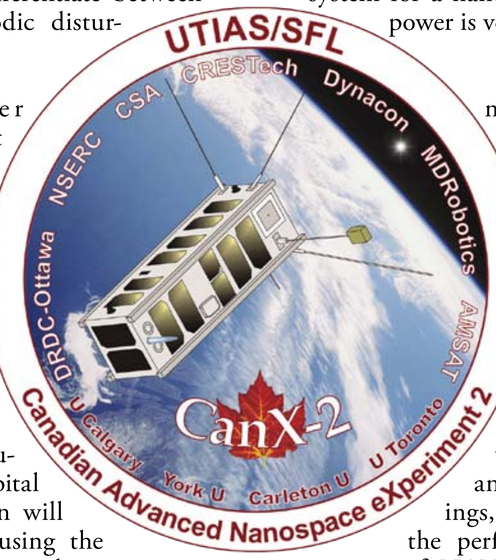
for circular orbits when there are no perturbative forces. When high accuracy is required, it is necessary to predict the effect of disturbance forces. The main perturbation is caused by the oblateness of Earth: the so-called J2 effect. Although both the chief and deputy are affected by the J2 effect, each is affected differently, leading to a slow break-up in formation. When this perturbation is included, it results in a non-linear replacement of the Hill equations.

Aside from solving analytically for the dynamics of these perturbations, the algorithms derived from the modified Hill equations must also incorporate active feedback control in order to deal with secular and periodic disturbances and small errors in the initial conditions. In the interest of conserving fuel, only the secular motions will be accommodated by the feedback control system; the trade-off is a sacrifice in positional accuracy. The replacement Hill equations must therefore differentiate between secular and periodic disturbances.

Christopher Damaren at UTIAS is currently developing modified Hill equations that take into account the differential effects of J2. The CanX-2 mission will serve to verify the accuracy of this orbital model. Verification will be accomplished using the satellite's GPS receiver, by treating CanX-2 as the deputy spacecraft relative to a virtual chief in a reference orbit. The CanX-4/-5 formation flight algorithms will build upon these verified orbital dynamic equations and incorporate feedback control laws.

The formation flight control algorithms will be implemented using impulsive maneuvers from an on-board propulsion system. To point the propulsion system thrusters, a suitable attitude control system is required. Both CanX-4 and CanX-5 will have full three-axis pointing capability afforded by nanosatellite reaction wheels (*or nanowheels*) developed by Dynacon Inc. CanX-2 will be the first spacecraft to demonstrate in space the capability of the nanowheel (5 cm in diameter, 125 g in mass, with 0.35 mN·m torque capacity) by using a single wheel to achieve momentum bias control.

The CanX-4/-5 propulsion system will be based on the NANOsatellite Propulsion System (NANOPS) aboard CanX-2. NANOPS is a cold-gas propulsion system developed at UTIAS/SFL. It is designed to carry 12 g of liquid sulphur hexafluoride as propellant and is self-pressurized. The system is designed to have a total ΔV of 35 m/s, a specific impulse (ISP) in the range of 50 to 100 s, and a thrust in the range of 50 to 100 mN. Although the cold-gas system has a relatively low specific impulse, it is more attractive than an electric propulsion system for a nanosatellite, given that power is very limited.



NANOPS has one nozzle oriented off-axis, so that thrusting will impart a major-axis spin to the satellite. A series of experiments will measure the spin with the attitude determination system. That motion, combined with pressure, flow and temperature readings, will be used to infer the performance characteristics of NANOPS. The lessons learned here will help to improve the development of the larger variant flown on CanX-4/-5.

The promise of spacecraft formation flight in a variety of applications has generated a surge of interest and development within the international community. The Space Flight Laboratory is at the forefront of this development. We have created a series of spacecraft missions to demonstrate formation flight. By using nanosatellites to develop and verify the technologies required successfully to perform formation flying missions, the cost and risk of such missions can be significantly reduced. Many of the technologies developed on this scale are directly applicable to any class of spacecraft.

CanX-2 will be fully qualified and ready for launch in mid-2006. The launch arrangements for CanX-2 are still under negotiation, but a mid-2007 launch date is currently targeted.

The CanX-4 and CanX-5 project was started in September 2005 and the preliminary design review was held in June 2006. The CanX-4/-5 Mission is targeted for launch in late 2008.

This is the first of a series of three articles by Daniel Kekez and Robert Zee on the CanX development program. Next time: the CanX-2 science payload.

References and Further Reading

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