PRECISION FORMATION FLIGHT: THE CANX-4 AND CANX-5 DUAL NANOSATELLITE MISSION

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Abstract

Autonomous formation flight has long been studied as a means to provide high resolution sensing from multiple satellites equipped with lower resolution sensors. The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies (UTIAS) is developing enabling technologies in collaboration with the University of Calgary for future precise formation flying missions. These technologies will be validated on two nanosatellites under development as part of SFL's Canadian Advanced Nanospace eXperiment (CanX) program. These nanosatellites, named CanX-4 and CanX-5, will be launched together to be among the first to demonstrate autonomous formation flight in orbit. With a mass of only 7kg and size of 20x20x20 cm, these identical satellites will achieve position determination to within a few centimeters, while controlling their relative position to an accuracy of less than one meter. The short development cycle and low cost of nanosatellites make them an ideal platform for demonstrating formation flight provided certain enabling technologies are made available. This paper describes the enabling nanosatellite technologies that have been developed at UTIAS/SFL for this mission, including formation flying control algorithms, a low power intersatellite communication system, a liquid-fuel cold-gas propulsion system, a three-axis attitude control system, and an intersatellite separation system. CanX-4&5 will fly four individual formations during the mission at separation distances ranging from 50m to 1000m. CanX-4&5 are currently targeting a 2009 launch.

Introduction

Currently under development at the University of Toronto Institute for Aerospace Studies Space Flight Laboratory (UTIAS/SFL) are two identical nanosatellites called CanX-4 and CanX-5 (CanX-4&5). This mission will demonstrate autonomous formation flying with nanosatellites weighing less than 7kg. CanX-4&5 will achieve relative position determination on the order of centimeters allowing for sub-meter formation control. All formation maneuvers will be achieved autonomously with no operator intervention required.

The short development time and low cost of nanosatellites make them attractive candidates for a variety of missions. Until now, autonomous satellite formation flying has only been attainable on larger and more expensive spacecraft such as Orbital Express.[1] Achieving satellite formation flying at this level of precision on a nanosatellite platform requires several key enabling technologies. These technologies will be flown, and their performance evaluated, on the current CanX-2 mission (shown in Figure 1). They include: a propulsion system, a commercial GPS receiver and a 3-axis attitude determination and control system. The CanX-2 nanosatellite will launch in April 2008.

The CanX Program

The Space Flight Laboratory (SFL) is a research laboratory with the objective of providing affordable and low cost access to space for research and development using nanosatellites. The Canadian Advanced Nanospace eXperiment (CanX) was established in order to develop new state-of-the-art nanosatellite technology and train graduate students through exposure to real nanosatellite missions. Each CanX nanosatellite is developed over a period of two years which coincides with the time it takes to complete a master's degree. The team consists of students with backgrounds in aerospace, mechanical, electrical, and computer engineering under the close supervision of experienced staff engineers. Students are exposed to all aspects of a satellite development from mission conceptualization to on-orbit operations.

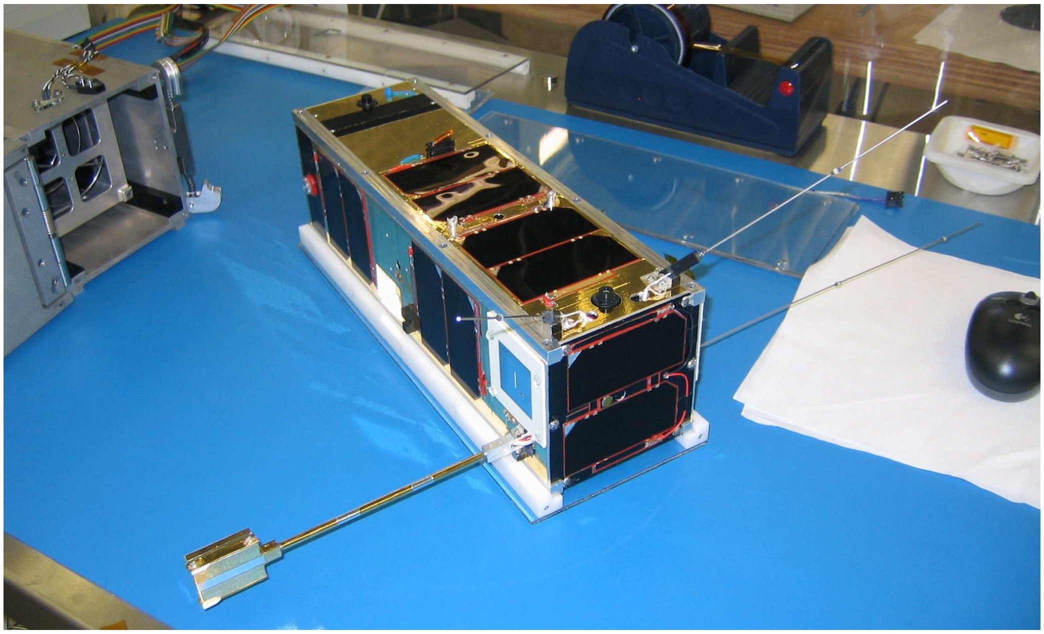

Figure 1: Integrated CanX-2 Nanosatellite

The CanX program follows a philosophy of low cost and rapid development along with aggressive experimentation. CanX nanosatellites use Commercial Off The Shelf (COTS) components in order to take advantage of the latest technologies and to benefit from their significantly reduced cost compared to radiation hardened components. To help mitigate risk due to rapid development, CanX nanosatellites use a staged approach where new technologies are developed and proven on current satellites which then become the baseline for future nanosatellite missions.[2]

In addition to the two CanX formation flying demonstration missions, a third nanosatellite mission is currently under development at SFL. CanX-3, also known as the BRIght Target Explorer or BRITE, will be a stellar photometry mission that will measure the oscillations of stars on a timescale of minutes to months. To maximize coverage of a given target field, a constellation of up to four BRITE nanosatellites will be used.[3] In order to save recurring engineering costs and minimize development time, both BRITE and CanX-4&5 will be implemented on the Generic Nanosatellite Bus (GNB). The GNB is a CanX nanosatellite bus designed to support a variety of science and technology demonstration missions.

The Canx-4 and Canx-5 Mission

The CanX-4&5 mission will demonstrate autonomous formation flying with CanX nanosatellites. Construction of CanX-4&5 will begin shortly with the recent completion of the critical design review. CanX-4&5 are on-track for a launch in 2009. These two identical nanosatellites will separate from the launch vehicle in an attached configuration. Following commissioning of both satellites, they will separate and the formation flying mission will begin. The CanX-4&5 mission patch is shown in Figure 2.

Many of the technologies used by CanX-4&5 will have gained space heritage on the CanX-2 mission. As formation flying is a complex and unforgiving endeavor, prior validation of these technologies in space is crucial for this mission. The CanX-2 nanosatellite will demonstrate the technology required for: producing formation flying control thrusts, accurate relative satellite position determination and 3-axis attitude control.

Figure 2: CanX-4 and CanX-5 Mission Patch

The CanX-4&5 mission objectives are as follows:

- Demonstrate the autonomous achievement and maintenance of several dual satellite formations.
- Demonstrate carrier phase differential GPS techniques to perform relative position determination measurements with accuracies of 10cm or less.
- Demonstrate sub-meter position control.
- Develop and validate fuel efficient formation flying algorithms.
- Demonstrate an intersatellite communication system.

Performance Requirements

Precisely achieving and maintaining a satellite formation requires precise relative position determination and accurate thrusting. The total ΔV and relative position determination requirements are driven by the desired degree of precision for the satellite formation control.[2] The CanX-4&5 thrusters are located on one face only. Therefore, attitude pointing requirements are placed on the attitude determination and control system for accurate thruster pointing. In addition, the two satellites must communicate with each other to relay position, velocity and attitude information. The intersatellite communication system must accommodate the desired relative distance of the satellites in each formation as well as the required data rates. Table 1 lists the parameters required to meet the formation flying requirements of the CanX-4&5 nanosatellites.

Table 1: CanX-4&5 Formation Flying Performance Requirements

Performance Requirement	**Minimum Requirement**
Position Control	1m
Relative Position Determination	10cm
Minimum Relative Distance	50m
Maximum Relative Distance	1000m
Attitude Determination	0.5°
Attitude Control	1°
Intersatellite Link Range	5km
Intersatellite Link Date Rate	10kbps
Total ΔV	14m/s
Specific Impulse	35s
Thrust	5mN
Minimum Impulse Bit	0.1mN·s

Formation Flying

Two different types of formation maneuvers will be demonstrated by CanX-4&5: Along Track Orbit (ATO) and Projected Circular Orbit (PCO) formations. In the ATO formation, both satellites will be in the same orbit but with the one satellite leading the other by a chosen time constant. Following the completion of this formation, one satellite will then perform a plane change in order to maneuver into the PCO formation. In the PCO formation one satellite appears to be orbiting the second as viewed from the Earth as shown in Figure 3.

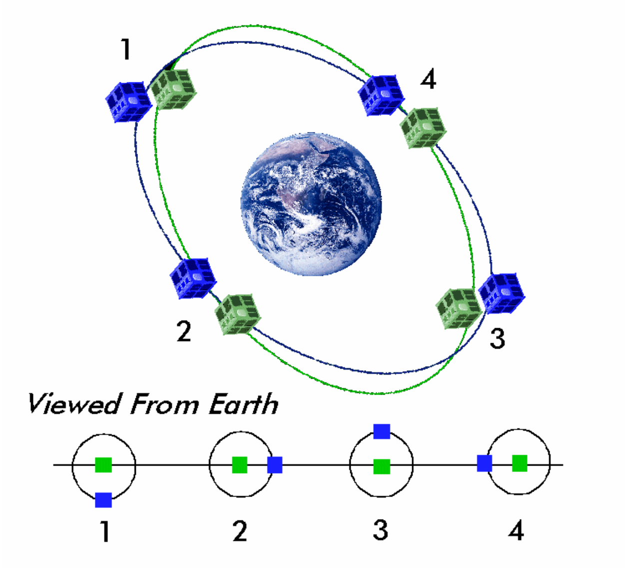

Figure 3: CanX-4&5 in Projected Circular Orbit

Each satellite will take on one of two roles, the chief or the deputy. The deputy satellite will perform thrusting maneuvers to maintain the formation with the uncontrolled chief satellite. At the same time the chief satellite will mimic the attitude of the deputy satellite to ensure the same GPS satellites are visible to both spacecraft.

Immediately after separation from the launch vehicle the satellites will be in a connected configuration. After commissioning of both satellites is complete, the intersatellite separation system will impart a ΔV of approximately 2.6cm/s on each satellite in the along track direction, causing them to separate in opposite directions. Any excess ΔV will be absorbed by separating the satellites partially in the orbit-normal direction. This initial ΔV will be sufficient after 1 orbit to place the satellites in their first ATO formation.

Over the course of the mission, two ATO and two PCO configurations will be flown with varied baseline distances. These formations will be flown in the following sequence: a 1000m ATO, a 500m ATO, a 50m PCO, and a 100m PCO. Each formation configuration will be flown for approximately 50 orbits. A series of impulsive maneuvers will be performed by the deputy satellite to transition into each new formation. The transition maneuvers will be performed at a specific phase in each orbit.[4]

There is sufficient propulsion system fuel in the deputy satellite alone to satisfy the baseline mission requirements. The unused fuel in the chief satellite (which will change roles with the deputy satellite at the end of the primary mission) will be used to perform additional formation flying experiments. These could include long duration formation flying (i.e. more than 100 orbits in a single formation), inspection maneuvers, and J_2-invarient formations for extremely long duration formation flying.

Experiment Verification

Two criteria will be used to determine the performance of CanX-4&5 over the course of the mission. First, the level of accuracy to which the satellites are able to control their relative position in each formation configuration will be determined. Second, the ability of the deputy satellite to minimize its fuel consumption by correcting for secular perturbations in the orbit while ignoring any periodic changes will be evaluated.

Each satellite will determine their absolute position and velocity using an onboard GPS receiver. This data will be logged by the satellite and downloaded by the ground station. This data can then be analyzed to accurately determine the relative distance of each satellite over time. In addition, orbital elements from NORAD will be used as a coarse means of verifying performance early in the mission.

Generic Nanosatellite Bus

The CanX-4&5 nanosatellite design is based on the Generic Nanosatellite Bus (GNB) developed at SFL. The GNB is a low cost spacecraft bus ideal for scientific and technology demonstration missions. The GNB has a 20cm cubic form factor with nearly 30% of its mass and volume dedicated to mission specific payloads. Power is generated by multiple strings of body mounted triple-junction solar cells with energy storage in an on-board lithium-ion battery. The GNB also comes equipped with a suite of 3-axis attitude determination and control components to provide high precision pointing. The following sections give an overview of the subsystems and technologies used on the GNB.

Structure

The GNB structure consists of two trays and six external panels. A dual tray structure was selected in order to maximize the payload bay and provide ease of integration. The trays and panels can be manufactured from either aluminum or magnesium alloys, depending on the mass requirements of the mission. The two trays contain all the necessary components for a basic satellite mission, including communications, attitude determination and control, power and thermal/structural components.

The external layout of the satellite is malleable in order to meet specific mission goals. The typical external panel will contain 3 pairs of solar cells, a coarse and a fine sun sensor, and area for mission specific components such as patch antennas, a GPS antenna, or camera optics. External views of the GNB structure configured for the CanX-4&5 mission are shown in Figure 4.

The thermal controls are incorporated into the structure of the satellite. In order to conserve power and reduce complexity of operations, the GNB employs mostly passive thermal controls in the form of coatings and structures. As the battery possesses the most stringent thermal requirements, it requires thermal isolation and a trim heater in order to meet a large variety of orbital scenarios.[5]

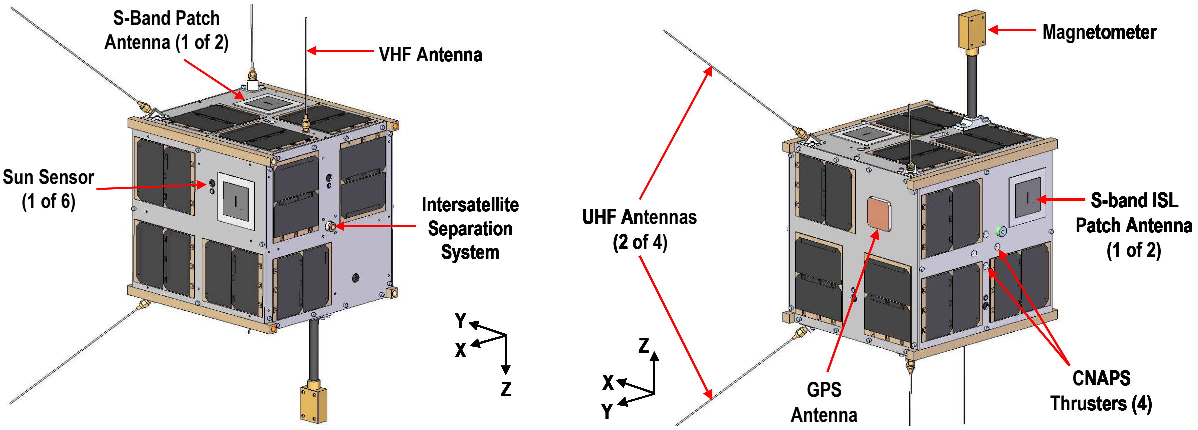

Figure 4: Opposing Views of the External CanX-4&5 GNB Structure

On-Board Computers

The GNB is equipped with two on-board computers (OBC) plus space for one additional mission specific OBC. Each OBC features an ARM7 microcontroller, 2MB of EDAC protected SRAM and 256MB of flash memory. The Housekeeping computer is responsible for communications with the ground station and collecting satellite telemetry. The Attitude Control System (ACS) computer interfaces with the attitude sensors and actuators and runs the attitude control algorithms. On CanX-4&5, a mission specific Formation Flying computer will be responsible for interfacing with the propulsion system and GPS receiver and running the formation flying algorithms. Each OBC runs a custom made multi-threaded operating system (called the Canadian Advanced Nanospace Operating Environment - CANOE) allowing it to divide processing time between multiple tasks in parallel.

Power

Power is generated on the GNB with 36 body mounted triple junction $GaInP_2$/GaAs/Ge solar cells. These cells have a beginning of life efficiency of 26.8% delivering up to 967mW at their peak power point at 28°C. Energy is stored in two 5.3Ah lithium-ion batteries allowing the satellite to operate in extended eclipse periods. The power system architecture is a peak power tracking system which provides switched power to the loads and power regulation where required. Finally, over current protection is provided to prevent damage to the payloads.

A Battery Charge and Discharge Regulator (BCDR) is connected in series with each battery. The BCDRs provide the peak power tracking for the solar array while regulating the charge and discharge of the batteries. The solar array is connected to the main power bus in a Direct Energy Transfer (DET) configuration. Therefore, by regulating the main bus voltage the BCDRs can maximize the power produced by the solar array when required for optimal battery charging.

Radios

Three different radios are used on the GNB nanosatellites: a UHF receiver, an S-Band transmitter and a VHF beacon. The UHF receiver is used for data uplink from the ground station and operates in the amateur band with a data rate of 4000bps. The UHF receiver uses four quad-canted monopole antennas which provide near omni-directional coverage. The S-Band transmitter will be used for data downlink and is capable of data rates between 32 and 256kbps. The S-Band transmitter operates in the space sciences S-Band and uses two patch antennas mounted on opposite sides of the satellite. Finally the VHF beacon will continually transmit satellite identification and basic telemetry in Morse code during the early stages of the mission to assist in commissioning the satellites.[6]

Attitude Determination and Control

A full 3-axis attitude determination and control system provides attitude stabilization and fine pointing for the GNB. Attitude sensors consist of six coarse/fine sun sensors, a magnetometer and three rate sensors. The combination of these sensors provides sub-degree level attitude determination throughout the orbit. Three orthogonally mounted reaction wheels and three magnetorquer coils provide the attitude actuation for the nanosatellite. The magnetorquer coils are used for detumbling and momentum dumping from the reaction wheels while the reaction wheels provide fine attitude pointing capability.

Canx-4 and Canx-5 GNB Payloads

Both the CanX-4 and CanX-5 nanosatellite will be equipped with the same mission specific GNB payloads required for formation flying. These payloads include: an intersatellite separation system, a propulsion system, a GPS receiver, and an intersatellite link. The majority of these payloads were directly derived from technologies developed for the CanX-2 mission. The following sections give a detailed description of the payloads equipped on the GNB.

Intersatellite Separation System

The Intersatellite Separation System (ISS) proved to be a great opportunity for innovation. The satellites are required to remain connected using no power, to separate from the launch vehicle in a joined configuration, operate to a maximum of six months while in the commissioning phase and then finally to separate in order to begin formation flying. Furthermore, the driving requirements for the design included low mass, low power, small footprint, low complexity and low cost.

The ISS consists of two identical halves (with the exception of the cup/cone interface) with one half located on each of the two nanosatellites (see Figure 5). In order to meet the extensive requirements, the design employs an electrically de-bonding agent. The ISS works by effectively gluing the two satellites together at the common cup/cone interface. When the satellites are ready to separate, a low voltage is applied to the mechanism and the glue weakens enough to allow the preloaded cup/cone interface to separate. Additionally, knowing the strength of the preload, the weight of the mechanism and the characteristics of the system allow it to be tailored to provide a predetermined velocity to each satellite.[7]

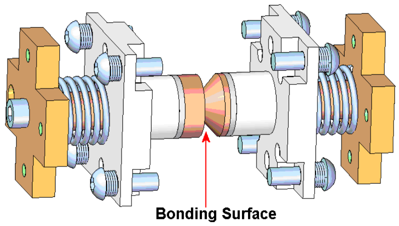

Figure 5: The Intersatellite Separation System

GPS Receiver

An on-board NovAtel dual band GPS receiver and an AeroAntenna dual-band GPS antenna provide absolute position and velocity information to each satellite. The GPS antenna is located on a face perpendicular to the thrust axis to allow antennae pointing control about this axis during thrusting. This control will be used to keep the GPS antennae pointed as close to Zenith as possible, maximizing the viewable GPS satellites at any given time.

With single point GPS processing, each satellite will be able to determine its absolute position and velocity to an accuracy of 2-5m (RMS) and 5-10cm/s (RMS) respectively. By combining the coarse absolute position information from both satellites, the deputy satellite will be able to compute precise relative position and velocity information using a special algorithm developed at the University of Calgary Department of Geomatics Engineering. This algorithm employs carrier phase and doppler data with differential techniques to determine the relative position and velocity of the satellites to within 2-5cm (RMS) and 1-3cm/s (RMS) respectively.[8] The algorithm requires that both nanosatellites maintain contact with the same GPS satellites. Therefore, the chief satellite will mirror the attitude of the deputy satellite during the formation flying maneuvers.

Intersatellite Link

The Intersatellite Link (ISL) is an S-Band radio transceiver carried by each satellite that permits them to share their absolute position, velocity and attitude information. A data rate of 10kbps can be achieved at a maximum separation distance of 5km between the two satellites. Omni-directional coverage is provided by two identical patch antennas mounted on opposite sides of the satellites.[9]

Propulsion System

The deputy satellite will use its on-board propulsion system to perform the thrusting maneuvers required for formation flying. This propulsion system is called the Canadian Nanosatellite Advanced Propulsion System (CNAPS). CNAPS uses liquefied sulfur hexafluoride (SF_6) as a propellant and will be able to achieve a specific impulse of at least 35s.[10]

The thrust is produced by four independently controlled thrusters, all of which are located on the same face. Each thruster produces a constant thrust magnitude of 5mN. The four thruster system helps minimize unwanted torques during thrusting as the thrust duration of each thruster can be individually calibrated.

A total of 300cc of fuel will be carried by the CNAPS on each satellite. This quantity of fuel is sufficient to produce a total ΔV of 14m/s.[10] Each satellite has enough ΔV to achieve the full base-line mission goals on its own. Therefore, in the nominal situation, the fuel remaining in the chief satellite can then be used for extended mission goals. A solid model of the fully integrated propulsion system is shown in Figure 6.

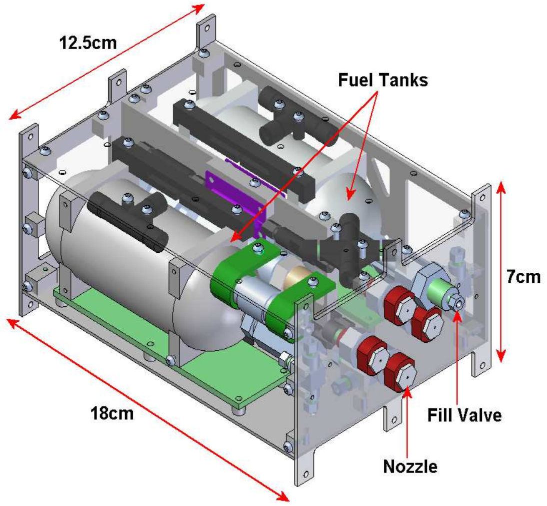

Figure 6: CNAPS Cold-Gas Propulsion System

Formation Flying Algorithm

Both nanosatellites will be equipped with a dedicated computer to run the formation flying control algorithm, FIONA (Formation flying Integrated Onboard Nanosatellite Algorithm). The principle objective of FIONA is to control the trajectory of the deputy satellite to an accuracy of better than 1m for minimum fuel consumption. To achieve this, FIONA regularly determines the tracking error of the deputy satellite and computes an optimal thrust to mitigate this error. For each thrust FIONA will pass the pointing target to the ACS computer and the thruster on time to the propulsion system. Since the nanosatellites will suffer a differential orbital perturbation due to the J_2 gravitational harmonic (an effect caused by the oblate shape of the Earth), this active control is necessary to keep the formation together over extended periods of time.

Reference Trajectories

The Hill reference frame, a rotating body-fixed coordinate frame centered on the chief satellite, is used extensively in formation flying calculations. Formation flying is primarily concerned with producing periodic relative motion of the deputy with respect to the chief satellite in the Hill frame. However, the relative dynamics of the deputy are non-linear and no periodic solutions to the equations have been found. A good approximation is the Hill's equations, a set of linearized ordinary differential equations of motion with periodic solutions.[11] The Hill's equations are useful for controller design, and the solutions to the equations provide circular reference trajectories for the controller to track in the Hill Frame.

The circular reference trajectories, however, provide only a very simple approximation to the natural perturbed motion of the deputy in the Hill frame in the presence of the J_2 effect. If either the eccentricity of the nanosatellites' orbit about the Earth increases, or if the separation distance between the nanosatellites increases (resulting in a linear increase in the differential J_2 effect), the circular approximation breaks down and the tracking errors and ΔV requirements rise substantially. In these cases, a better alternative are Lawden's elliptical equations of motion, whose periodic solutions form elliptical reference trajectories.[12] Both circular and elliptical reference trajectories can be readily adapted to PCO and ATO formations. Since the PCO orbits will be performed at low separation distances and the ATO orbits at high separation distances, the controller will track circular trajectories in the PCO formations, and elliptical trajectories in the ATO formations.

Linear State- Feedback Control

The CanX-4&5 mission utilizes a linear state-feedback solution to the control problem. The relative Hill dynamics are used in conjunction with predefined **Q** and **R** weighting matrices (representing state and input costs respectively) in a linear quadratic regulator (LQR) method to determine an optimal controller gain matrix **K**. **Q** and **R** can be adjusted to alter the performance of the controller towards tighter tracking at the expense of greater ΔV, or vice versa. Prior to each thrust, a tracking error term—the difference between the actual relative state of the deputy and the reference trajectories—is determined, and multiplied by –**K** to yield the control accelerations necessary to mitigate the tracking error. This information is used to compute the pointing target vector for the ADC computer, and a thruster on time for the propulsion system.

PWM Thrusting

Since the thruster on CanX-4&5 can only thrust at a constant 5mN, it is necessary to use a pulse width modulation (PWM) technique, whereby the thrust is held constant but the on time is varied. As long as the time between thrusts (i.e. the PWM period) is small compared to the rate of the dynamics, the PWM technique accurate approximates a continuous thrust method. The CanX-4&5 controller has a PWM period of 65 seconds.

Using a PWM technique on an actual spacecraft becomes problematic, however, when attitude determination and control is taken into consideration. If the thrust were performed as soon as the new pointing vector is calculated, it allows no time for the spacecraft to actually slew to this new pointing vector. Alternatively, if the pointing vector is determined at the beginning of the PWM period (immediately after the preceding thrust), and the deputy slews to that target and thrusts at the end of the PWM period, then by the time the deputy has reached the target it will have drifted and that target will no longer be valid. The solution to this problem is to begin the PWM period by propagating the state of the spacecraft forward in time to T_{PWM}=50s, predicting the required pointing vector for that time, and then passing this target to the ADC computer at T_{PWM}=0s. The deputy slews to that target over the next 50s, and then uses real-time GPS measurements to adjust its attitude slightly every 5 seconds until it finally performs the thrust at $T_{PWM}\approx$65s.

GPS Measurements

One of the key elements of the CanX-4&5 formation flying mission is the use of GPS satellites to determine the absolute and relative position and velocity of each CanX satellite. Under normal circumstances, the real-time GPS data can be fed directly into the formation flying computer where the University of Calgary's (U of C) algorithm determines the relative state of the deputy to a very high accuracy.[8] However, in the cases where either the chief, the deputy or both satellites fail to see 4 or more GPS satellites, a GPS blackout situation will occur and the U of C algorithm will have insufficient information to operate. Although the blackout periods are predicted to last no longer than 15 minutes, it is necessary to continue the formation flying mission throughout the blackout. As a result, an orbital simulator will be included in FIONA to predict the position and velocity of both satellites. An extended Kalman filter (EKF) will be used to combine the simulator data with the real-time GPS data.[13] The resulting "best estimate" is both more accurate than the lower-fidelity simulator data and less noisy than the GPS measurements.

The 3 possible modes of GPS data acquisition are:

1) *Full Coverage*. Here both the chief and deputy can receive data from ≥4 GPS satellites. This is the nominal mode of operation. The GPS data is used to compute the relative data via the U of C algorithm; the EKF output is passed back to the simulator.

2) *Insufficient Deputy*. In this case the chief can see ≥4 or more GPS satellites, but the deputy sees <4. The chief's absolute state is still available and is used to update the EKF, but the relative data is produced from the output of the EKF.

3) *Insufficient Chief/No Data Link*. This case occurs if either the chief receives data from <4 GPS satellites or the chief and deputy have lost contact via the intersatellite radio. In this case FIONA runs entirely on the last output of the EKF, cycled through the simulator.

EKF-Assisted Control

As noted previously, using the raw GPS measurements in the U of C algorithm will produce noisy relative measurements of the deputy. The linear state-feedback controller is robust to sensor noise on the relative position measurements, but suffers an unacceptably high ΔV and tracking error penalty for virtually any noise on the relative velocity measurements. To circumvent this problem, the controller uses the GPS data to produce the relative position measurements but uses the latest estimate from the EKF to produce the relative velocity measurements.[4] Since the EKF output has been smoothed by the noise-free simulator measurements and kept up-to-date by the GPS data, the resulting relative velocity measurements are both noise-free and accurate yielding excellent results.

Reconfiguration Maneuvers

CanX-4&5 will be attached during the launch and commissioning phases of the mission. At the start of formation flying, the ISS will separate the satellites, imparting a small ΔV (~2.6cm/s) to each in the along track direction. Since the precise value of the separation impulse will not be known, FIONA has been designed to accommodate any separation ΔV. The algorithm will determine on the fly how many orbits it needs to drift and what impulsive thrust is required to halt the drift. If the satellites miss their 1000m separation target, FIONA will decide whether it should use the controller to bring itself back to that target, or just use its current position as the new target.

Once the separation maneuver is concluded, the deputy will commence station-keeping, reconfiguring its formation after 50 orbits in each of the ATO and PCO formations. Since each reference trajectory describes either a circle or an ellipse for the deputy to track in the Hill frame, it is very important that each reconfiguration maneuver begin at an appropriate relative phase angle. The ATO→ATO and the ATO→PCO maneuvers must begin at an angle of 90˚ (corresponding to 0.25 of an orbit) and the PCO→PCO must begin at a phase of 180˚.

Simulation Results

FIONA was developed as flight code written in C, but embedded within a Simulink environment to reproduce the GPS measurements, thruster errors, etc. The formation flying simulation results for each configuration (on a per orbit basis) and each reconfiguration maneuver are presented in Table 2.

Table 2: CanX-4&5 Formation Flying Simulation Results

Metric	**ΔV (m/s)**	**Tracking/Overshoot Error (m)**
1000m ATO	0.059	0.23
ATO→ATO	0.088	67.0
500m ATO	0.029	0.12
ATO→PCO	0.16	37.2
50m PCO	0.013	0.11
PCO→PCO	0.072	2.57
100m PCO	0.027	0.17

The overall ΔV requirement for the baseline CanX-4&5 mission is anticipated to be approximately 7.5m/s, well beneath the 14m/s ΔV available onboard the deputy satellite.

Formation Flying Applications

The technology developed for the CanX-4&5 will open the doors to numerous future formation flying missions. Nanosatellites could one day be used to perform on-orbit servicing to larger, more expensive satellites.[2] The nanosatellite could fly in formation with the client satellite and image the satellite for diagnostic purposes. The nanosatellite could also dock with the client satellite and replace damaged or degraded parts such as batteries or on-board computers. As satellite complexity and cost continue to rise, on-orbit servicing and repair of damaged satellites could be a viable option when compared to the cost of a replacement.

Another important application of formation flying is remote sensing. High-resolution images can be produced by combining images from multiple satellites each equipped with lower resolution sensors. Satellites in formation can provide virtual instrumentation with an unlimited aperture size as the baseline between satellites can be varied as desired. Accurate formation flying techniques are important for this application as the quality of the composite image from multiple satellites is directly proportional to the accuracy to which their relative distance can be determined and maintained. Several remote sensing applications include: interferometric sensing, Earth imaging and ground moving target indication.

Finally, a constellation of multiple low-cost nanosatellites or microsatellites flying in formation could be used in place of a single larger satellite. Multiple satellites working together maximizes flexibility and provides the potential for increased coverage relative to a single satellite. If a satellite in the constellation fails, the other satellites can reorganize their positions to compensate for the lost satellite without loss of the mission. Then, as the as satellites become damaged or obsolete they can be seamlessly replaced with new satellites over time. Therefore, formation flying technology is an important stepping stone to the increased utilization of small satellites in future missions.

Conclusion

The success of the CanX-4 and CanX-5 mission will represent a major milestone in demonstrating the viability of precise formation flying with small, inexpensive satellites. CanX-4&5 will also help demonstrate the versatility of the Generic Nanosatellite Bus which is capable of supporting multiple missions. Several key enabling technologies required for formation flying, such as centimeter-level GPS relative position determination, formation flying algorithms, a propulsion system, and an intersatellite communication system, will be space proven on this mission. The majority of these technologies could be scaled to larger satellites, such as microsatellites, to further broaden the possible scope of formation flying missions. These future missions could include remote imaging and on-orbit servicing.

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