HARDWARE-IN-THE-LOOP TESTING OF CONTINUOUS CONTROL ALGORITHMS FOR A PRECISION FORMATION FLYING DEMONSTRATION MISSION

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ABSTRACT

A sample mission sequence is defined for a low earth orbit demonstration of Precision Formation Flying (PFF). Various guidance navigation and control strategies are discussed for use in the PFF experiment phases. A sample PFF experiment is implemented and tested in a realistic Hardware-in-the-Loop (HWIL) simulation using the Formation Flying Test Bed (FFTB) at NASA's Goddard Space Flight Center.

1. INTRODUCTION

Precision Formation Flying (PFF) refers to the class of distributed spacecraft missions that require precise, continuous control of the relative motion of multiple spacecraft, implemented through inter-satellite crosslinks. PFF technology will enable advanced science missions by using spacecraft Guidance, Navigation, and Control (GNC) systems to place distributed optics and detectors at distances not feasible on traditional spacecraft. Examples of PFF missions include Terrestrial Planet Finder, MicroArcsecond X-ray Imaging Mission, and Stellar Imager. While these missions will most likely occur in orbits near libration points, or in deep space, preliminary on-orbit demonstration of PFF technology is likely to occur in Low Earth Orbit (LEO) (for example in the proposed PFF version of New Millennium Program's Space Technology 9 mission).

In Section 2, we present a plan for demonstration of Precision Formation Flying in low earth orbit, and discuss the guidance and control issues associated with such an experiment. In Section 3, we present the current status of the Formation Flying Test Bed (FFTB) at the NASA Goddard Space Flight Center. In Section 4 we present results from a sample Precision Formation Flying experiment performed using both a non-real time simulation using the FreeFlyer™ software package, and a real-time, hardware-in-the-loop simulation using the FFTB.

2. LOW EARTH ORBIT PRECISION FORMATION FLYING DEMONSTRATION

Demonstration of PFF in LEO requires a unique combination of formation flying guidance and control strategies. These strategies must consider the relatively large differential gravitational and atmospheric effects present in LEO, while providing a test environment relevant to more distant orbital regimes. To this end, these strategies must include the use of naturally stable formations for staging and parking, as well as brief experimental periods with formations defined by slight deviations from natural motion so that continuous control is required but not prohibitively expensive.

The mission sequence for a LEO PFF demonstration can be broken into 6 distinct phases: 1) launch and early checkout; 2) stack separation; 3) period matching and individual spacecraft checkout; 4) precision formation flying experiments; 5) transfer to, and maintenance of stable parking formations for staging between experiments; 6) safe disposal. In this work we are interested in the precision formation flying experiment phases, and the staging required before and after each experiment.

2.1 Formation Dynamics in Low Earth Orbit

Naturally stable formations in LEO, and fuel-efficient means for maintaining these formations in the presence of perturbations and navigation uncertainly have been the subject of a number of recent works. These works present strategies for defining and maintaining relative motion trajectories that will not degrade in the presence of navigation errors and differential perturbations from reference orbit eccentricity, higher order gravitational effects, and drag. A continuing theme in these works is the realization that in order for formation flying in LEO to be feasible, control algorithms must not fight naturally occurring short period relative motion caused by nonspherical gravitational effects (primarily the effect of Earth oblateness, commonly referred to as the J_2 effect). Instead, they must seek to place the spacecraft on relative trajectories that will, on average, maintain a desired geometry. This requirement steers LEO formation designers away from any strategy that requires fixed separations between spacecraft.

A PFF demonstration mission must take advantage of this work to achieve safe and stable parking formations. As dictated by available fuel, the majority of the mission of a PFF demonstration in LEO must be spent in parking formations that are not inherently fuel-intensive. These formations should include coarsely maintained stable geometries such as in-plane or in-track separations, as in the LandSat-7, EarthObserving-1 formation, or relative elliptical formations in [1], with initial conditions defined to minimize long term secular drift (for example, by using the principle of J_2 invariance as described in [2].) Each of these arrangements would require infrequent control with maneuvers every few orbits to cancel the dominant sources of secular drift for this type of formation: usually navigation error and differential drag effects.

2.2 Precision Formation Flying Experiment

While natural formations with non-fixed separations may be acceptable for LEO formations, they are less appealing for Precision Formation Flying missions. Most PFF missions require inter-spacecraft separations to be prescribed and maintained with little regard for the local perturbation environment, and without allowing short period deviations. Since we would like to demonstrate the hardware and algorithms necessary to fly a PFF mission, it is our goal to design experimental trajectories that require continuous control. To limit the fuel required to perform experiments, the experiment durations are limited to 8 hours. Some possible PFF experiment formations are:

- Precise constant in-plane separation, with reference trajectory defined as differences in true latitude or by constant separations in the velocity direction using Hill's equations.
- Precise circular or projected circular formations with reference trajectory defined using disturbance accommodating techniques and conditions for periodic motion as described in [3], and [4].
- Precise circular motion, with reference trajectory very similar to the circular formation, but with strictly maintained, constant inter-spacecraft ranges.

2.3 Sample PFF experiment

Ideally, a PFF demonstration mission would include at least 4 spacecraft, allowing simulation of three-dimensional formations. A formation of at least 3 spacecraft would allow testing of complex multiple-vehicle cooperative control algorithms. For simplicity, and to defer the complexities involved with control of multiple distributed spacecraft to a future work, we simulate a 2 spacecraft formation launched as a stack to a nearly circular orbit with mean semi-major axis of 6823 km, and mean inclination of 28 degrees. The spacecraft are identical, with masses of 100kg, areas of $1m^2$, thrust provided by 10mN cold gas thrusters with specific impulse of 70s, and available ΔV of 70 m/s each.

The sample experiment is broken into three stages: 1) transfer from a safe parking formation to the experiment configuration; 2) continuous closed-loop control in a precise circular motion trajectory; and 3) transfer to a new parking formation.

The initial parking formation is defined by a 1km in-plane separation, with the maneuvering spacecraft trailing. The transfer to the experiment initial configuration is performed using two maneuvers separated by half the orbital period. The first maneuver is a combination radial and out-of-plane burn, which puts the maneuvering spacecraft on course to a point 100 meters ahead of and 100m out-of-plane from the passive spacecraft. The maneuver is performed at the point of maximum latitude so that out-of-plane motion is restricted to right ascension difference only (i.e. no inclination difference), so that no secular drift is introduced due to differential J_2 effects. The second maneuver is a radial burn half an orbital period after the first burn to achieve a natural circular formation with relative position and velocity defined to satisfy Lawden's [5] period matching constraint as given by Eqn. 1, where the variables x, and y are the radial and in-track separation, as defined in the rotating, spacecraft fixed Hill's frame, and e and n are the reference orbit eccentricity and mean motion, respectively.

$$\frac{\dot{y}(0)}{x(0)} = -\frac{n(2+e)}{(1+e)^{1/2}(1-e)^{3/2}} \tag{1}$$

The precise circular motion trajectory is defined by a fixed separation, and a time varying phase angle within the plane of relative motion of the circular formation. The initial phase angle is chosen based on the spacecraft state at initiation of closed-loop control. Subsequent phase angles are defined as a function of time by a constant angular rate, equal to the mean motion. In a more complex scenario, the phase angle could be defined through a formation control law, as described in [6] and [7], or by using a more "optimal" angular rate, as described in [4].

Upon completion of the 8-hour experiment, the safe dispersion of the formation is accomplished by a combination out-of-plane and in-track burn, which places the maneuvering spacecraft on a walking safety ellipse, similar to the safety ellipse briefly described in [8] for use in rendezvous operations. The maneuver to acquire the walking safety ellipse is performed when the radial separation between the spacecraft is maximized (approximately k + 1/4, or k + 3/4 orbits after the second burn in the optimal transfer phase, where k is any integer), such that the maneuvering spacecraft is at a point of maximum out-of-plane separation whenever it crosses the cross-track, in-track plane of the passive satellite. This dispersion technique is not required (we could just as easily perform a two burn escape in the same manner as in the transfer to the experiment configuration), but is presented as a simple safe escape plan which could be implemented with little or no knowledge of the current relative states.

3. FORMATION FLYING TEST BED

The Formation Flying Test Bed provides an excellent forum for testing Guidance Navigation and Control algorithms in as realistic an environment as is currently available for space flight dynamicists. The FFTB is composed of a GPS simulator, GPS receivers, flight computers, crosslink transceivers, the Crosslink Channel Simulator (CCS), and computers for providing true environment data and visualization. The FFTB supports up to four GPS receivers, flight computers, and crosslinks, to simulate a formation of four spacecraft. Simulation of larger formations may be supported in the future. Note that the CCS, currently under development [9], exists as a prototype in the FFTB and is not yet fully integrated. Consequently, it has not been utilized in this work. The FFTB hardware suite and their interfaces are shown in Fig. 1. A detailed description of the FFTB hardware components can be found in [10]. A brief summary follows.

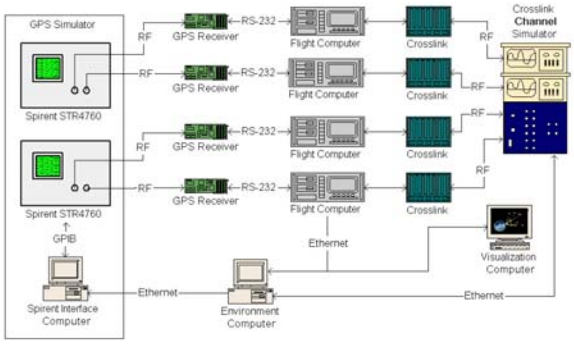

Fig. 1. FFTB Simulation environment

3.1 STARS Truth Environment

The Spacecraft Trajectory and Attitude Real-time Simulator (STARS) Suite runs on the Environment Computer, and provides the true spacecraft state and environment data for the simulation. The data are provided via Ethernet local area network (LAN) connections to the GPS simulator and CCS in order to drive the simulation. The Environment Computer also receives spacecraft maneuver information from the flight computers.

3.2 Spirent GPS Signal Simulator

The GPS simulator is composed of two Spirent STR4760 GPS signal generators and the Spirent Interface Computer. The Spirent Interface Computer is either a Windows XP computer or a Compaq computer running VMS. The STR4760 GPS signal generators produce the RF signals according to the GPS ICD-200 specification. The FFTB currently supports the Pivot, Orion, and Ashtech GPS receivers. However, the FFTB can readily be modified to support any GPS receiver. The GPS receivers are connected to the flight computers by a serial RS-232 interface. For this work, we use the FFTB in a two spacecraft configuration with two Orion GPS receivers from the DLR German Space Operations Center (GSOC) in a configuration similar to the one described in [11].

3.3 Flight Executive

The flight computers host the guidance, navigation and control algorithms, which use the measurement data provided by the GPS receivers and provide maneuver commands to control the spacecraft and the formation. The Flight Executive, the top level process running on the flight computers, manages the incoming data, calls the navigation and control processes, and sends the output back to the STARS truth environment.

3.4 Formation Flying Test Bed Simulator

An all-software, non-real-time simulation has been developed to mimic the performance of FFTB real-time, hardware-in-the-loop simulation. This simulation, henceforth referred to as FFTBSim, is a software version of the FFTB which provides an interface identical to the Flight Executive control interface to allow users to test FFTB guidance and control code in non-real-time. The simulation is driven by the FreeFlyer™ orbit software [12], and includes high-fidelity gravity, drag, and solar radiation pressure dynamics, as well as measurement noise affecting the estimated states.

4. RESULTS OF SAMPLE PFF EXPERIMENT

Hardware-in-the-loop testing of formation navigation and control software is a vital step in the evolution of formation flying technology. To demonstrate closed loop control for a PFF mission, we perform a simulation in the FFTB that includes an actively controlled spacecraft and a passive spacecraft, each connected to an Orion GPS receiver. The receivers are in turn connected to the RF output of the GPS Signal Simulator. Absolute orbit determination is performed on the active spacecraft flight computer using the GPS Enhanced Onboard Navigation System (GEONS) [13], which processes pseudorange data from one of the Orion GPS receivers in an Extended Kalman Filter (EKF). For this scenario, GEONS estimates the receiver clock error bias and drift, absolute position and velocity, and drag coefficient. Control accelerations are handled in the EKF by including the accelerations in the state propagation, and by increasing the position and velocity covariance whenever control is applied.

Relative navigation is performed by the Orion receivers, which exchange raw measurements over a serial port, and output time and relative position and velocity with respect to the Radial, Transverse, Orbit-Normal (RTN) frame of the host satellite. The relative navigation algorithm, and results from other hardware-in-the-loop tests are described in more detail in [14] and [11].

Control is computed for the active spacecraft using a Matlab™ function call commanded by the Flight Executive, which has as inputs, time, and absolute and relative states, and as outputs, spacecraft control acceleration in the Radial, In-Track, Cross-Track (RIC) frame. For the purposes of this control force, the RTN, RIC, and Hill's frames are identical[1].

The control law implemented in this study is a simple proportional-derivative feedback of the difference between the desired trajectory and the relative state information provided by the relative navigation system. Absolute state estimates are not used directly in the control feedback, but are available for computation of coordinate transformations. Thrust is assumed to be equally available in any direction, with magnitude limited to 10mN. Control is calculated and applied at a frequency of 1Hz.

4.1 Simulated and Hardware-in-the-Loop Results

Closed-loop control of the precise circular motion trajectory is simulated in FFTBSim with relative position and velocity noise of 1m and 0.5 cm/s, and in the FFTB hardware-in-the-loop (HWIL) simulation described above.

Absolute and relative state estimation errors from a 4-hour hardware-in-the-loop FFTB simulation of closed loop formation control are presented in Table 1. The table presents steady-state values from the final 3 hours of the simulation. The GEONS absolute state estimation results are as expected, with position errors on the order of a meter, and velocity errors on the order of tenths of centimeters. The relative state error of the Orion receivers is considerably larger than expected. Comparing absolute state errors from the two Orion solutions, we see that the mean state error is considerably larger for the maneuvering spacecraft than for the passive spacecraft. In hindsight this result is not surprising. We are seeing the effect of noisy control application on the navigation accuracy. The receiver has no knowledge of the control being applied, and cannot be expected to perform as well in such a perturbed environment. We would see a similar effect in the GEONS output accuracy if the filter had no knowledge of the control acceleration being applied.

Fig. 2 shows uncontrolled inter-spacecraft ranges, as well as controlled inter-spacecraft ranges from both all-software (FFTBSim) and FFTB hardware-in-the-loop (HWIL) simulations. Initial condition errors in this simulation are due to navigation and thrust performance errors in the transfer to the PFF experiment configuration.

[1] All relative velocities described in this paper are assumed to be *with respect to the rotating reference frame*

Table 1: Hardware-in-the-loop steady-state estimation errors for a 4 hour simulation

Navigation Type	Position Estimation Error [m]		Velocity Estimation Error [cm/s]	
	Mean	Max	Mean	Max
GEONS absolute state estimate	1.08	2.36	0.218	0.494
Orion abs. state est. (maneuvering s/c)	1.29	8.67	3.058	22.162
Orion abs. State est. (passive s/c)	0.23	35.93	2.772	40.503
Orion relative state estimate	0.99	8.06	0.510	2.400

Table 2 compares the control performance for the software-only and hardware-in-the-loop simulations. The HWIL mean range error is about 2.5 times worse than the FFTBSim result. This inconsistency is due to a number of effects, including improper modelling of the state estimation error in FFTBSim, and inconsistent real-time performance in the Flight Executive.

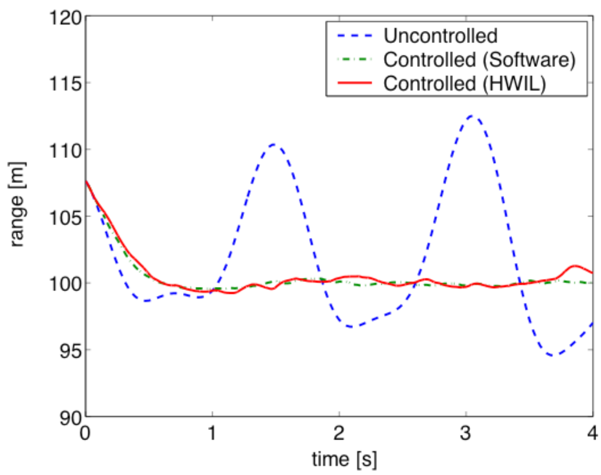

Fig. 2: Controlled and uncontrolled inter-spacecraft range, with proportional derivative control targeting 100m separation

Table 2: Control performance results for software-only (FFTBSim) and hardware-in-the-loop (HWIL) simulations

Simulation Type	Inter-Spacecraft Range Error [cm]		Total ΔV	Thruster Duty Cycle
	Mean	Max	[m/s]	[%]
FFTBSim	13.24	44.92	1.396	97.0
HWIL	31.14	126.30	0.777	51.8

Perhaps the most notable data from Table 2 are the thruster duty cycles and total ΔV values. Thrust is being applied about half as often in the HWIL simulation as in the software-only simulation. Upon further inspection it is clear that the Flight Executive software is failing to call the control law once per second (the system is not hard real-time), resulting in reduced control output and impaired performance. It is interesting to note that in a software-only simulation with control applied at 0.5Hz, the control law fails to maintain the 100 meter separation.

4.2 Future work

With these results in hand, we move forward to improved test facilities, and improved guidance, navigation, and control algorithms for Precision Formation Flying. The next steps for this effort will focus on the following goals:

- Incorporate GEONS relative state estimation capability to reduce measurement noise and allow inclusion of control accelerations and additional measurement sources.
- Include Crosslink Channel Simulator measurements into the EKF to improve relative navigation performance and test two-stage navigation and control algorithms.
- Improve guidance and control algorithms, making them more representative of future PFF missions
- Improve real-time performance of the Flight Executive.
- Improve error modelling in the FFTB Simulator to facilitate off-line testing that is more representative of the HWIL simulation environment.

5. CONCLUSIONS

Demonstration of Precision Formation Flying in low Earth orbit will provide a valuable stepping stone to the eventual deployment of a distributed spacecraft system. This work presents a simple timeline for a PFF demonstration mission in LEO, as well as some sample PFF experiments. These experiments are designed to allow testing of spacecraft technologies for multi-staged navigation and control for PFF missions, while accommodating the increased perturbations of the low Earth orbit environment.

A sample experiment performed in the Formation Flying Test Bed at NASA's Goddard Space Flight Center demonstrates control to a third of a meter using GPS measurements, and a simple proportional-derivative control law. Results from this simulation demonstrate the need for hardware-in-the-loop testing to identify modelling errors and refine our understanding of this revolutionary new technology.

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