

# RECENT DEVELOPMENTS IN HARDWARE-IN-THE-LOOP FORMATION NAVIGATION AND CONTROL

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## Abstract

The Formation Flying Test-Bed (FFTB) at NASA Goddard Space Flight Center (GSFC) provides a hardware-in-the-loop test environment for formation navigation and control. The facility is evolving as a modular, hybrid, dynamic simulation facility for end-to-end guidance, navigation, and control (GN&C) design and analysis of formation flying spacecraft. The core capabilities of the FFTB, as a platform for testing critical hardware and software algorithms in-the-loop, are reviewed with a focus on many recent improvements. Two significant upgrades to the FFTB are a message-oriented middleware (MOM) architecture, and a software crosslink for inter-spacecraft ranging. The MOM architecture provides a common messaging bus for software agents, easing integration, and supporting the GSFC Mission Services Evolution Center (GMSEC) architecture via software bridge. Additionally, the FFTB's hardware capabilities are expanding. Recently, two pairs of crosslink transceivers been introduced into the FFTB. These crosslinks will be connected to a modified Crosslink Channel Simulator (CCS), which applies realistic space-environment effects to the Radio Frequency (RF) signals produced by the transceivers.

## INTRODUCTION

Spacecraft formation flying is a concept that continues to attract significant attention; Fig. 1. The advantages of formation flying are manifold. The President's Commission on Implementation of United States Space Exploration Policy [2] identifies formation flying as one of seventeen enabling technologies needed to meet exploration objectives.

Both NASA and ESA are evaluating formation flying concepts for numerous planned missions. A brief list of currently planned missions include, NASA: Magnetospheric Multi-scale (MMS) [20], Constellation-X Observatory [22], Micro-Arcsecond X-Ray Imaging Mission [23], Submillimeter Probe of the Evolution of Cosmic Structure [16], Terrestrial Planet Finder [15], Stellar Imager [6]; ESA: X-ray Evolving Universe Spectroscopy [9]. In addition, *precision formation flying* was chosen as one of the five candidate technology capability areas for the New Millennium Program's Space Technology 9 Project [10, 4].

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**Fig. 1.** Artist's concept of formation flying spacecraft exchanging information via crosslink.

## PRIOR CAPABILITIES REVIEW

The Formation Flying Testbed (FFTB) at NASA Goddard Space Flight Center (GSFC) allows formation flying navigation and control algorithms to be tested while interacting in real-time with the required flight hardware, such as GPS receivers and crosslink transceivers. By including hardware directly in the closed-loop testing, researchers and engineers can gain valuable information about the interaction and performance of their algorithms, and of the performance of the required hardware.

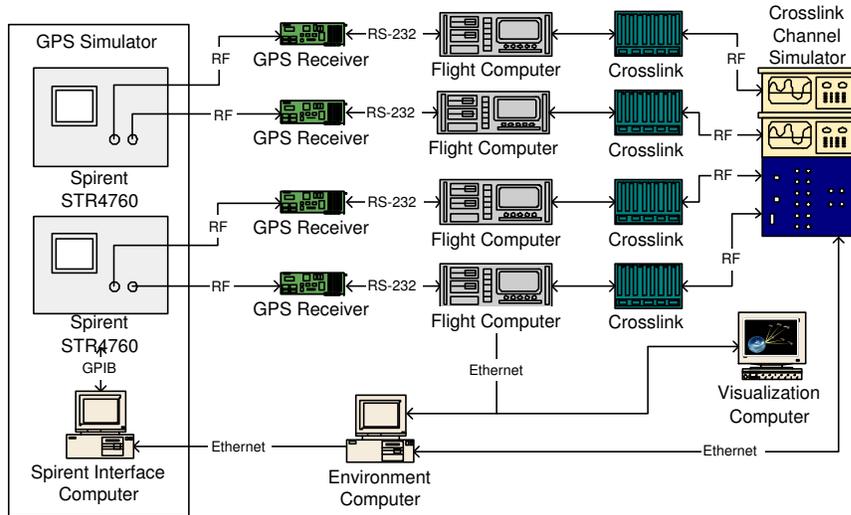
The following is a brief summary of previously discussed FFTB capabilities.

### Hardware

A graphical depiction of FFTB hardware connectivity is shown in Fig. 2. The individual hardware elements are described in the following, including the FFTB integration status.

*GPS Receivers* Currently, the FFTB includes GPS receivers in-the-loop: two Orion receivers, four PiVoT receivers, and a single Ashtech G-12. The Orion receivers from the German Space Operations Center possess a direct relative navigation feature where GPS measurements are exchanged directly via RS-232. The Ashtech receiver is reserved for calibration activities.

*GPS Simulator* A Spirent<sup>®</sup> STR4760, with four Radio Frequency (RF) outputs, provides simulated GPS constellation signals that stimulate GPS receivers. Each receiver's antenna pattern is configurable.



**Fig. 2.** Hardware interfaces.

*Crosslink Channel Simulator* The Crosslink Channel Simulator (CCS) [14] simulates the space environment for RF signals used for inter-spacecraft communication and ranging. The CCS applies delay, Doppler shift, and attenuation for an RF crosslink between two spacecraft, see Fig. 3. At present, the CCS is being modified to support the MMS mission [20]. Modifications are nearly complete. The device is expected to be re-integrated into the FFTB in the near future.

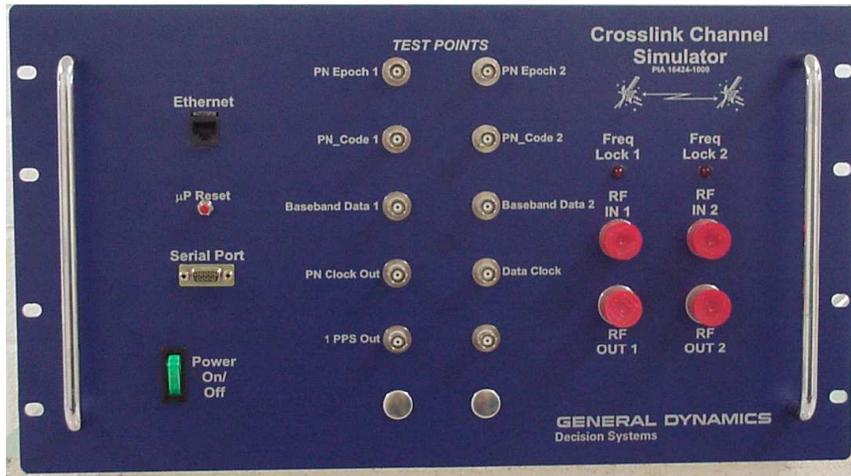
*Crosslink Transceivers* To meet science data collection requirements, on-board spacecraft formation controllers must maintain position knowledge. This requires sufficient inter-spacecraft communications. To control a formation on the order of kilometers to centimeters, RF communication can be used. Two pairs of RF transceivers are in the process of being fully integrated into the FFTB. The Nanosat Cross Link Transceiver (NCLT), developed by the Johns Hopkins University Applied Physics Lab, supports integrated crosslink communication and relative navigation. The Low-Power Transceiver (LPT), developed by ITT, provides integrated Tracking and Data Relay Satellite System (TDRSS) link and ranging.

## SOFTWARE ARCHITECTURE

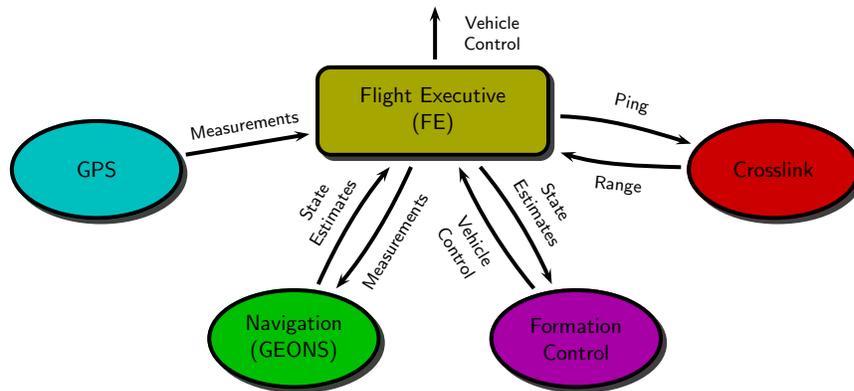
The FFTB software drives soft Real-Time Hardware-in-the-Loop simulations. The simulation software components are dividend into the following areas.

### Environment

The Spacecraft Trajectory and Attitude Real-time Simulation (STARS) drives the truth spacecraft environment in the FFTB. STARS provides truth orbit and attitude trajectories to the overall simulation at a 10 Hz update rate, synchronized to a 1PPS signal provided



**Fig. 3.** Crosslink Channel Simulator hardware interface.



**Fig. 4.** Flight Executive connectivity diagram.

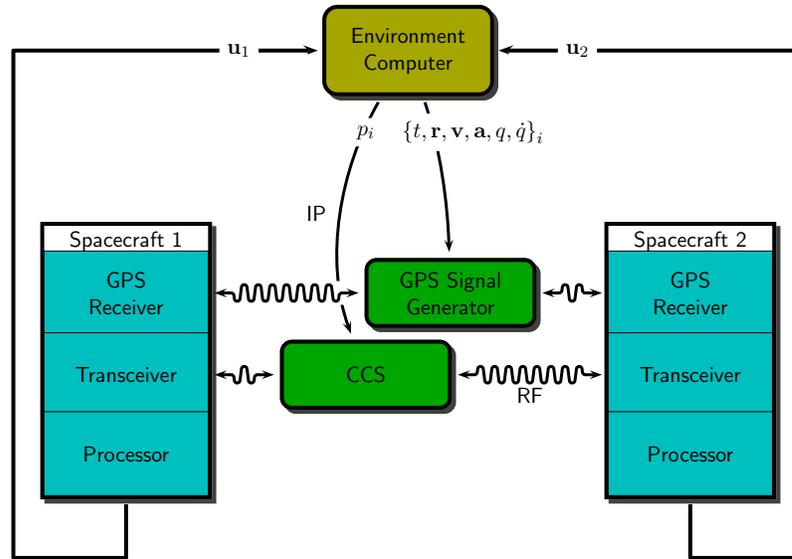
by the Spirent<sup>®</sup> hardware described previously. Maneuver inputs are accepted by STARS in a vehicle’s local reference frame.

*GPS Simulator* SimGEN<sup>®</sup> drives the Spirent<sup>®</sup> GPS Simulators. STARS feeds true vehicle state information directly to SimGEN<sup>®</sup>, stimulating realistic RF GPS signals.

*Crosslink Channel Simulator* The CCS software provides the interface to control the hardware described previously. This control is performed with User Datagram Protocol (UDP) messages over Ethernet.

## Flight Software

From Fig. 2, each flight computer instantiates a Flight Executive (FE), composed of a collection of Java/C/C++ programs and MATLAB scripts; see Fig. 4. The FE accepts GPS or



**Fig. 5.** Information flow diagram for two satellite simulation with crosslink.

other sensor measurements and processes them with GEONS [19] for orbit determination for navigation and control. A flexible formation controller interface accommodates MATLAB, Java, C and C++.

In the absence of the hardware crosslinks and the CCS, a software crosslink ranging model is available to augment position measurements to improve formation knowledge and control. Fig. 5 shows the information flow for a two satellite configuration using crosslinks.

Each FE runs, individually, on a dual-processor Pentium III, clocked at 500 MHz. The choice of processor type and speed was intended to emulate the type of on-board computational resources available to a physical spacecraft, while permitting a reasonable development ability.

## Visualization

Full 3-D scene visualization of the real-time simulation data is accomplished with the Satellite Tool Kit<sup>®</sup> [3] in combination with FFTB's adapter software using STKConnect.

## RECENT WORK

Within the last year, considerable effort was invested to upgrade the FFTB infrastructure to provide more computing and simulation hardware resources, as well as to ease component integration for customers.

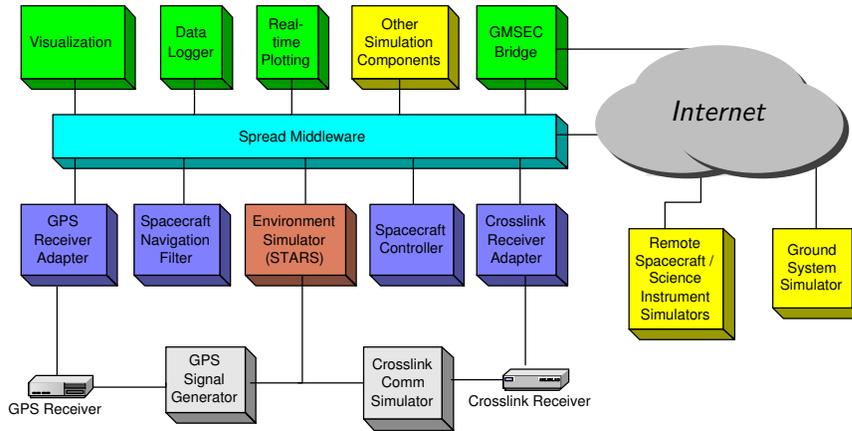


Fig. 6. FFTB Messaging System software architecture.

## Computing Infrastructure

One component of the recent work is a general modernization of the network and computing facilities.

*Network* Previously, the FFTB internal network was a hub based, 10/100 Mbps, private Class C network. This has been replaced with a single switch based, Gigabit, Class C network that can operate at full-duplex between capable hardware. For hardware with a fixed Ethernet interface of 10/100 Mbps, the network is fully auto-negotiated.

*Computational Resources* The software development process in the FFTB has become more resource intensive, particularly for the flight software. This prompted the replacement of the existing flight computers with single processor HyperThreaded Pentium 4 (6-series) units, clocked at 3 GHz. These units contribute to a much more comfortable development environment.

To emulate the computational power of typical flight computers, the updated flight computers can be stepped down using Intel's SpeedStep<sup>®</sup> technology via the Linux `cpufreq` module [5]. The 6-series processors offer eight frequency steps for clocking (kHz): 3000, 2625, 2250, 1875, 1500, 1125, 750, 375, so providing a range of on-board computing resources.

## Software

*Message-Oriented Middleware* One of the most useful recent developments is the introduction of a Message-Oriented Middleware (MOM) layer called the FFTB Messaging System (FMS). The goal of introducing the FMS MOM is to significantly reduce the development burden when integrating software components into the existing software infrastructure. This becomes particularly useful for collaborators that wish to test algorithms within the FFTB, allowing more time for testing and evaluation, and reducing component integration time.

The FMS architecture, Fig. 6, uses a customized form of the open-source Spread Toolkit [21] as the foundation of a *publish/subscribe* messaging system, with message definitions maintained by the FMS Interface Control Document (ICD) [11]. In the publish/subscribe model, producers publish their messages to clearly defined subject names that follow the naming convention prescribed by the GSFC Mission Services Evolution Center (GMSEC) Interface Specification Document [7]. The message consumers then subscribe to the desired subject, receiving each message published to that subject. The naming convention states that subject names will be a dot (.) delimited string, consisting of upper-case alphanumeric characters, the underscore (-), and the dash (-). The subject elements are strictly ordered as: System, Mission (constellation or scenario name), Satellite ID, Message Type, Message Subtype, Component Name, Message Name. Individual messages are formatted in XML version 1.0 [1], where entries are composed of empty-element tags containing (*key,type,value*) attributes.

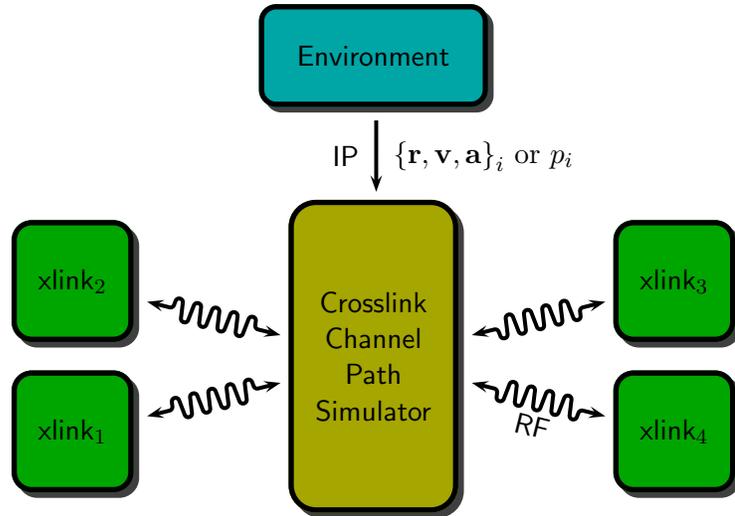
The FMS libraries are available in both Java and C++, and include support for XML marshalling and unmarshalling as well as other supporting functionality, e.g. input file parsing, state file reader, etc.

Although the FMS follows the GMSEC subject naming convention, it is not GMSEC compliant. Currently, there is no open-source GMSEC compliant middleware available. However, FMS and GMSEC messages can be exchanged, Fig. 6, via a GMSEC bridge.

*Software Crosslinks* As a precursor to implementing hardware crosslinks within the FFTB, a software-only crosslink was constructed. This software crosslink clearly defines the interface and functionality requirements necessary for the hardware crosslink to function in the FE. The crosslink channel model is simplistic, and merely corrupts the computed range truth with a user defined noise model. The software crosslink subscribes to STARS state messages from each of two spacecraft, computes the true range, corrupts the true range with noise, and publishes that data with a crosslink subject name, e.g. `...MSG.RTSD.CROSSLINK.2WAY`. The FE accepts a crosslink *enabled* configuration option, and subscribes to the specified crosslink subject. When the FE receives a crosslink measurement, it informs GEONS of the measurement type, and provides the measurement for processing.

With hardware crosslinks and the CCS integrated into the FFTB, the FE treats crosslink measurements in the same way. However, the component computing crosslink measurements increases in complexity due to multiple hardware interfaces. This complexity is reduced by abstracting the higher level functionality as an interface. Thus, hardware specific code is not repeated within the FE components. This approach is used to address various GPS receivers used within the FFTB.

*Visualization* In addition to the previously mentioned 3-D full scene visualization developed with Satellite Took Kit<sup>®</sup> and STKConnect, there are several new options for visualization. Full scene 3-D visualization can now be performed with the *Jatalizer*, which leverages the Java Astrodynamics Toolkit (JAT) [12] to perform visualization. In addition to full scene visualization, the FFTBPlot tool can be used to graph simulation data that is of interest. Since each of the applications is FMS enabled, their data stream can be real-time



**Fig. 7.** Operational diagram for Crosslink Channel Path Simulator.

or non-real-time depending on the operating mode of the message publisher.

## FUTURE ACTIVITIES

Future efforts in the FFTB could, for example, expand full-scene visualization or real-time plotting capabilities, add software and measurement models, support different orbit regimes, acquire new or improved hardware (GPS receivers, crosslinks, etc.), or improve computing infrastructure. At present, the FFTB is addressing the following activities.

### Channel Simulators

The next generation of crosslink simulator, the Crosslink Channel Path Simulator (CCPS) seen in Fig. 7, is currently being designed and will support the MMS mission. The CCPS will be capable of simulating the crosslinks between four satellites. The hardware is planned to have two modes of operation:

1. accept vehicle state data and compute channel path effect based on internal models,
2. accept values for Doppler shift, delay, and attenuation from externally computed models.

### Automated Rendezvous & Docking

In addition to formation flying, the President's Commission on Implementation of United States Space Exploration Policy [2] also identifies *Automated rendezvous and docking* (AR&D)

as an enabling technology. Extending the FFTB to study AR&D will require the addition of models for attitude sensing and algorithms for attitude determination and estimation. Once developed, the models and algorithms will require validation to ensure that they meet the specified requirements.

For this effort, the FFTB will maintain its emphasis on closed-loop relative navigation and control, and with the final integration of the previously described communication hardware and software, will include the effects of communication-in-the-loop on performance.

## **Libration Dynamics**

Several of the missions described in the Introduction are evaluating formation flying concepts with orbits about the collinear Libration points of the Sun-Earth or Earth-Moon systems. Modeling the orbital dynamics about a Libration point is considerably different from modeling the dynamics of spacecraft motion dominated by a massive central body subject to perturbations. Such work will require extension of the truth environment to accommodate new model dynamics, force models, and integrators. As with the AR&D, described above, this will also require attitude determination and estimation.

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