Space Technology Transition Using Hardware in the Loop Simulation

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Abstract—This paper treats the development of a laboratory within the USAF Phillips Lab for the purpose of integrating component technologies and demonstrating spacecraft subsystem/payload level capabilities. The lab will facilitate the transition of technologies to flight. The infrastructure will be such that virtually any type of spacecraft payload or subsystem can be brought in, as long as the technologies are mature. Once the subsystem or payload is demonstrated successfully in the first phase, the second phase will be the integration of the payload or subsystem into a spacecraft model which consists of a hybrid of simulated spacecraft systems and subsystems and actual spacecraft hardware. A potential third phase would be actual flight qualifying of the system. Depending on both the individual project's requirements and the results of the first phase, it may not be necessary to follow on to the second or third phases. The emphasis here will be placed upon the second phase, or the hardware in the loop (HIL) simulation evaluation. End to end HIL simulation has several benefits within the Phillips Lab, including (1) bringing forth spacecraft integration problems before spending millions of dollars to put a system into space, (2) exploring scenarios for in-flight anomalies and hardware and software failures, (3) showing the utility of component technlogies and subsystems to the warfighter, (4) evaluating various potential mission concepts, (5) selling programs to upper management, (6) training of operators and educating lab personnel in how theater operations are performed with respect to obtaining data from space. Based on monetary constraints, the lab must leverage off of existing hardware in the loop facilities, such as Wright Lab's Kinetic Kill Vehicle HIL facility (KHILS), JPL's Flight System Testbed (FST), Arnolds Engineering Development Center (AEDC), etc., in terms of networking in, mimicking equipment, and utilizing lessons learned. The cost for setting up the HIL facility will be further reduced by building the lab based on requirements for the individual projects coming in, rather than up front construction of a HIL laboratory.

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1. INTRODUCTION

Due to the significant cost of putting a satellite into orbit and the extreme difficulty and cost for performing on orbit repairs or reconfigurations, it is essential to demonstrate a new payload or subsystem on the ground before launching into space. Furthermore, it is important

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to bring forth potential problems with the integrated spacecraft system on the ground and to explore "what if" scenarios for potential failures and anomalies which may occur on board. Finally, an end-to-end simulation can aid in the design of missions as well as for selling a program to upper management. The Integrated Ground Demonstration Laboratory (IGDL) will be a mechanism for merging component technologies to demonstrate an integrated spacecraft subsystem or payload on the ground, and potentially integrating the components of a spacecraft (hardware or simulation) to perform a simulated mission.

Phase 1 will be the "project" oriented part of the program, for which the goal is to demonstrate the payload or subsystem as an independent entity. Figure 1 shows the notional concept of a potential Phase 1 application involving optics, structures, thermal, and controls. Phase 2 will be the interfacing of the payload or subsystem with the simulated spacecraft in a hardware in the loop (HIL) sense and the concept is illustrated in Figure 2. Phase 3 could potentially represent flight qualifying of the spacecraft. The emphasis in this paper will be on the Phase 2 portion of the program. However, the Phase 1 project (specifically the UltraLITE program) will be discussed as an example to show the transition of specialized software and hardware from the project level to the end-to-end HIL simulation level in Phase 2. This transition emphasizes the capability to leverage a laboratory with a generic and wide purpose capability off of specialized individual projects.

2. LAB INFRASTRUCTURE

The laboratory equipment will consist of hardware and software to support the integration of components into a payload or subsystem in Phase 1 and HIL integration and mission simulation in Phase 2. Therefore, a significant factor in procuring project level equipment will be the applicability of the equipment to the HIL simulation facility.

Methodology

The software and hardware infrastructure will support all functions of operation for the ground demonstration. The framework will provide the capability of interchanging individual hardware components with "equivalent" software modules.

Architecture

The overall software structure will be for the most part composed of commercial, off-the-shelf (COTS) and existing government developed software. The COTS software will include software for modeling and dynamic simulation, pre and post simulation/test analysis, as well as control system analysis and design. Instrumentation can be handled in actual hardware or in COTS software such as LabView. The selection of the software will depend on such factors as overall cost, availability of related routines, flexibility of fidelity level, interfaceability, and robustness.

Although the initial consideration for payload and perhaps the first demonstration will be a lightweight optical system, the architecture will be generic in that virtually any payload or subsystem can be integrated for demonstrating a different technology or performing a new experiment. This is essential for the facility to be of long term value for the Phillips Lab.

Subsystems

In this paper, a subsystem is defined as any modular component which interacts with the rest of the vehicle and which essentially performs an independent function of the vehicle's or payload's operation. Examples include the vehicle attitude dynamics, the payload itself, the on-board processor, the Attitude Determination and Attitude Control System (ADACS), and the thermal control system, to name a few. Where applicable, each subsystem will be modeled such that an associated piece of software and hardware can be readily interchanged in the overall Hardware in the Loop architecture. Thus the interface between the particular subsystem and the overall scheme should be equiv-

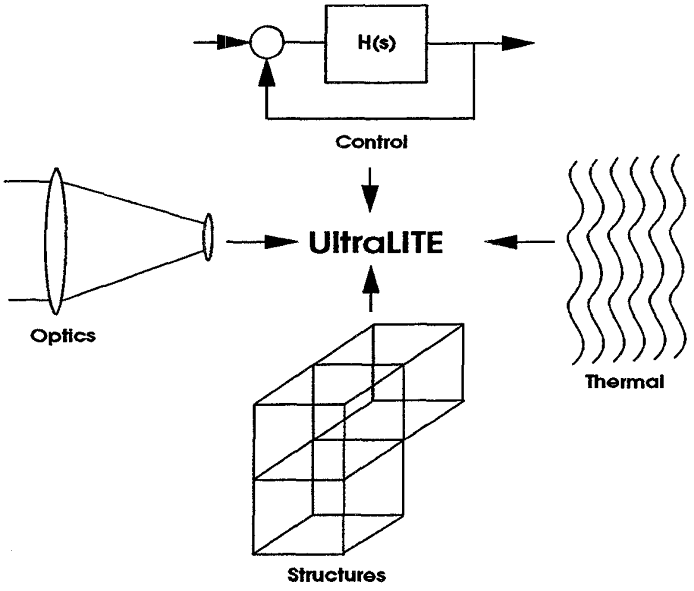

Figure 1: Phase 1 UltraLITE Concept for IGDL

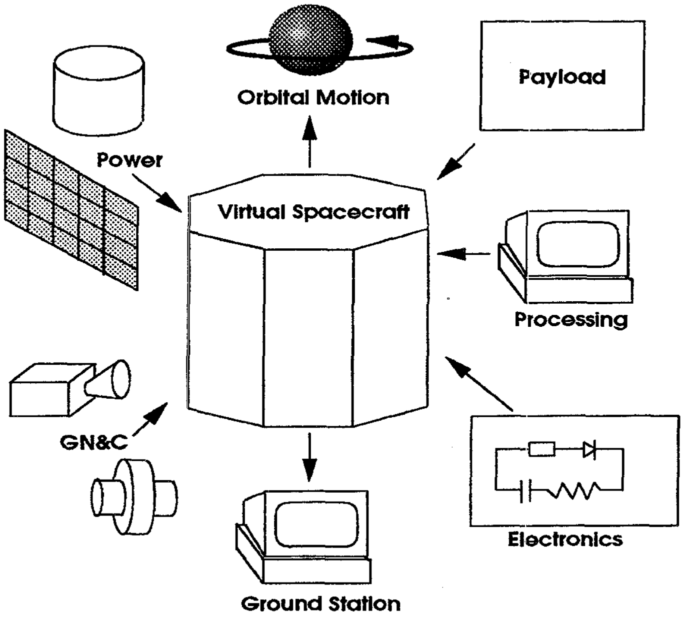

Figure 2: Phase 2 Concept for Hardware in the Loop

alent for the hardware module and the equivalent software module.

Vehicle Attitude Dynamics—The attitude dynamics subsystem will represent the six degree of freedom dynamics of the body. This system will receive inputs from the Space Environment, the Structural Dynamics, the Orbital Mechanics, the Thermal system, and the Guidance, Navigation, and Control (GN&C) subsystem. The attitude dynamics may either tie into a motion based platform or may be represented purely in simulation, depending on the requirements for the particular project. The attitude control sensors and hardware will be included in this subsystem and, where practical, will be interchangeable between actual hardware and software simulations. The outputs will enter the Vehicle Structural Dynamics, GN&C, Payload, Power, and Thermal Control subsystems.

Structural Dynamics and Vibrations—The structural dynamics subsystem will simulate the flexural modes of the spacecraft and the interaction with the sensors with possible inputs from a motion-based model. The inputs will come from the attitude dynamics and orbital mechanics subsystems and outputs will go to the GN&C subsystem.

Thermal Control and Cryocooling—The spacecraft thermal control system will exist purely in simulation except in the case where thermal control is the focus of the individual project, as in the demonstration of an advanced cryocooler. It is likely, however, that payload cryocooling may be performed at the project level in Phase 1, in particular for optical system demonstrations.

Orbital Mechanics—The orbital mechanics will be simulated to the level of fidelity required by the individual project and the desired mission. At this point it is likely that orbits will be analyzed from a two body problem sense with consideration of the earth oblateness (J2) perturbation and atmospheric drag. If necessary, gravitational influence of the moon can be included, but for typical Air Force missions, it is unlikely that other planets will influence the orbit. However, the level of fidelity will be flexible to possibly accommodate customers outside of the Air Force to emphasize the interest in dual use applications.

Onboard Software—As is the case for most hardware, the software will be an interchangeable subsystem, with the capability to replace the simulated onboard software with actual flight software, in which case programming efficiency and coordination with other on board processing requirements are essential. In particular, this will be a primary function if the technology to be demonstrated is an advanced flight computer. The software can be organized into the following classes:

- guidance, navigation, and control
- health and status
- fault tolerance
- payload operations
- subsystem specific requirements

Space Environment—The space environmental effects will be modeled to an appropriate extent based on the individual missions. The following effects may be modeled:

- atmospheric arag
- radiation, e.g., the Van Allen belts
- solar winds
- orbital debris considerations

Payload—In most cases, the payload will be the primary item of interest in the lab, and will therefore will be modeled to particularly high levels of fidelity. In the instances where the payload is the focus of the Phase 1, this module can potentially be broken down into simulated components and actual hardware in order to isolate the effects of individual elements of the payload. For example, if the project is a lightweight optics experiment designed for a geosynchronous earth orbit (GEO) mission, the payload module may be comprised of the actual hardware required to control a set of optical elements while the actual passing of photons through the optics is performed in simulation.

Ground Station—Spacecraft telemetry data will be formatted for retrieval at a simulated ground station or at DoD facilities such as the Research, Development, Test, and Evaluation Support Center (RSC) located at Phillips Lab, the Air Force Satellite Control Network (AFSCN) or other locations which are using standardized data. This will enhance the mission simulation capability and will enable the system to be used for training ground station crew members. It will also enhance the capability to demonstrate a potential Integrated Space Technology Flights (ISTD) mission before flight.

Onboard Processor—The onboard processor will be brought in to evaluate its capability to support the processing requirements of the payload and bus operations. A potential utility is to artificially try to overload the processor while on the ground to determine limitations and possibly requirements for additional computing power. For instance, it may be determined that a particular payload or subsystem will require its own processing rather than share the central spacecraft processor.

Power System—The power system will typically be a software simulation, potentially utilizing instrumentation software such as LabView. However, the power system module will permit the inclusion of actual hardware components such as a batteries, solar arrays, etc., in cases where it is desirable to evaluate new component technologies from an integration perspective.

Laboratory Software Requirements

This section specifies software required for an example project (in this case a lightweight imaging demonstration program) which is applicable also to Phase 2 demonstrations for performing subsystem level and postprocessing analysis.

Dynamic Analysis Software—This class of software, which includes Matlab, MatrixX, XMath, Program CC and others, will serve the purpose of off-line analysis and data processing, dynamic simulations, control system analysis, design, and pretesting, as well as image processing and interfacing with several other applicable routines for optical system analysis.

Optical Simulation Code—It is essential to define a metric in terms of image quality with which to decide what the limits are for displacements of optical elements. Given, these metrics, the optical simulation code can be used to determine an error budget and influence functions for the design of an optical control system. Several codes are available for this purpose, but JPL/BRO's COMP [1] (Controlled Optics Modeling Package) has been applied to several configurations in the scope of the IGDL's potential first project. COMP is a standalone code for optical analysis and model generation. It is particularly useful for system-level design and analysis tasks, as opposed to pure optical design. The performance takes into account optical, structural, thermal, and control system designs for an integrated optical system. COMP has significant ray-trace, differential ray-trace and diffraction capabilities. Point spread functions can be generated using individual diffraction planes or by going through each surface in the optical system.

Structural Analysis—Several fairly standard codes will be used for analyzing the structural properties of the system. In particular, NASTRAN may be used for modeling and modal analysis of the system, while CADA-X software is a potential tool for performing modal tests on the structure and LINK can be used validate the finite element model. These codes will most likely be involved in off-line analysis rather than being explicitly brought into a HIL setting.

Simulation of Integrated System—After performing off-line analysis and design on the optics, structure, and controls, it is important to evaluate the integrated system in Phase 1 before actually constructing hardware. Therefore, a code is required which integrates the aforementioned software, combines the results, or somehow includes the contributions from each of the technical areas to analyze the payload or subsystem as whole. One code available for this task is IMOS [2] (Integrated Modeling of Optical Systems). IMOS is a JPL/BRO developed collection of MATLAB functions used to evaluate performance of multidisciplinary models, including end-to-end spacecraft models of structural dynamics, optics, controls, and thermodynamics. This package includes a subset of the COMP software, a set of finite element tools comparable to NASTRAN functions, thermal analysis tools, and of course the dynamics, control, and simulation capability is available from MATLAB. The Phillips Laboratory simulation framework available for combining the results or including the contributions from each of the technical areas is the Spacecraft Simulation Tookit (SST). The SST includes an end-to-end, space-based, sensor simulation which integrates the following components:

- input scene physics (target, background, and intervening atmosphere)
- aperture/optical train effects on the image scene
- effects of structural/optical train vibrations
- detailed model of the focal plane array including quantum efficiency
- spectral responsivity, noise, and other detector characteristics
- scanning and sampling functions
- A/D (analog to digital) conversion process

This simulation produces an output image of the scene affected by the aforementioned noise/jitter sources which is then ready for post processing. The important characteristic of these codes or simulations is that all of the technical areas are talking to each other. Based on the results of this task, the program can either move into a redesign or slight modification, or proceed into hardware development to complete Phase 1.

Instrumentation and System Monitoring Software—The purpose of this software is basically to oversee the operations of the project in the ground demonstration facility. The code will provide simulated instrumentation for monitoring most of the integrated devices. In addition, this software will oversee the interaction of the various hardware components, monitoring inputs and outputs, saturations of actuators and other components, out of range parameters, etc.

Real Time Dynamic Simulation—When moving to Phase 2, it is important to consider the necessity to have a real time capability for simulation of spacecraft dynamics, which can interact with the rest of the spacescraft. There is a significant amount of such software available through many other existing HIL facilities available at little or no direct cost, e.g., the DART simulation used in JPL's FST [3]. The main issue is to ensure compatibility of the software with the simulation framework and the laboratory hardware.

Miscellaneous—Additional software will be required to provide the drivers for some of the required infrastructure hardware as well as to provide interfacing between the components. For example, an operating system such VXworks may be required for performing real time tests.

Laboratory Hardware Requirements

Potentially, HIL simulation evaluation can be performed with virtually no infrastructure hardware, meaning that the "project level" hardware is interfaced with computer simulation representing the spacecraft and space environment, as well as all required subsystems. In general, however, even at the project level (Phase 1), some infrastructure is required in order to evaluate the payload or subsystem in a realistic environment.

Hardware Interface Equipment—The essential requirement for performing HIL experiments is the basic equipment for interfacing hardware components with software in a real time setting. A common mechanism for this is the VME bus architecture, which allows the interface of processor boards, data retrieval systems, and other components and which can accommodate real time operation. However, currently under consideration is an 80486-based real time computer which interfaces with dSpace DSP (digital signal processing) boards in order to perform real time control and provide a direct interface between MATLAB software (for synthesizing and analyzing control systems) and control hardware. This setup, combined with associated dSpace software and MATLAB with Simulink and the Real Time Workshop allows real time changes in the control laws and automatic software generation to permit rapid transition from control design to real time implementation. In particular, this configuration provides a substantial capability at the Phase 1 level for real time control, while its use can extend to Phase 2 for performing HIL simulation.

Scene Projectors—Since most projects of interest would involve reconnaissance or surveillance type missions, scene projectors may play a significant role, particularly in the case where the project is an optical sensor or camera. Much work has been done in this area in the IR region (e.g., KHILS) but very little for simulating scenes and evaluating resolution of visible sensors from the ground. In particular, it may be a complicated task to simulate the collection of an image on the earth from low earth orbit (LEO) with a sensor located a short distance from a scene projector. This component has perhaps the smallest technology base and will require the most development before becoming ready for use in the lab. However, this technology could potentially have the most utility, both at the project (Phase 1) level and the lab (Phase 2) level.

Vibration Table, Motion-based Platform, or Air Bearing Table—An important component of any hardware test is the behavior of the system in a dynamic environment. The vibration table can be used to perform structural and modal evaluations on a system while motion based platforms and air bearing tables are useful for looking at vehicle attitude dynamics and vehicle or payload pointing and maneuvering problems. Typically these functions would be performed in simulation, but the physical tests could be performed if there is an emphasis in the project on the dynamic behavior or in order to validate simulation models.

Environmental Chambers—Environmental chambers may be required for either maintaining certain types of sensors in an appropriate environment for testing, e.g., low background radiation, or for evaluating effects of various environmental conditions on sensor or subsystem performance. Because of the high cost of performing this operation and existence of other facilities, such as AEDC, KHILS [4], and FST [5], it is likely that this functionality will be left to other facilities to perform and potentially interact with the IGDL HIL facility in real time.

Networking and External Communications—Because of the minimal budget for HIL simulation, it will be necessary to have the capability of interfacing in real time with other existing HIL facilities. This will require a multiline modem with encryption/decryption and secure data transfer capabilities. Under consideration are multiline Integrated Services Digital Network (ISDN) modems, direct T1 links, and standard internet (nonsecure) connections.

Potential Projects

There are several existing Phillips Lab projects as well as other concepts which have potential value for end-to-end spacecraft HIL evaluation. These will be briefly described in this section.

UltraLITE—The UltraLITE (Lightweight Imaging Technology Experiment) program represents the first project moving through the IGDL. At the project level, UltraLITE's goal is to demonstrate the capability to collect high resolution imagery of the earth from space at a fraction of the cost of monolithic optical systems. Some of the concepts being evaluated for the first project include sparsely populated arrays, systems with segmented primaries, and deployable monolithic or partially filled optics. The Phase 1 level evaluation will include the demonstration of the selected optical concept on the ground as an independent system. There is a potential interest to bring the program into the Phase 2 HIL demonstration, in which such aspects as payload integration and mission utility can be addressed.

MightySat—MightySat is a small satellite program within the Space Experiments Directorate at the Phillips Lab whose main goal is to fly a compendium of advanced technologies. Because of the many payloads and subsystems aboard which push technology, there is a significant interest in thorough evaluations of the integrated spacecraft on the ground.

Integrated Space Technology Demonstrations—Integrated Space Technology Demonstrations (ISTD) is another Phillips Lab Space Experiments program which combines requirements from Air Force Space Command (AFSPC) and the Space and Missile Warfare Center (SMWC) with technology push from the Phillips Lab in order to support the warfighter. The emphasis is to deliver timely information to the user in the field. A major aspect of the program is the requirement to leverage off of commercial, civil, or other DoD programs in order to reduce cost. This leveraging can consist of technical collaboration, piggybacking on flights, enhancing a commercial satellites capabilities (e.g., adding encryption), or just purchasing data from an existing system. Thus, in addition to the hardware integration issues as in the MightySat program, ISTD would have further HIL applications, such as evaluating and selling various mission scenarios, demonstrating capabilities to the representatives of the warfighter (e.g., SMWC, Air Combat Command, etc.), and evaluating the effects of flying potentially high precision equipment on 'noisy' satellites.

Evaluation of Advanced Guidance, Navigation, and Control Algorithms—Another example of a potential HIL application is the implementation of advanced control software on the ground, perhaps in conjunction with an actual flight processor. This is particularly important based on the emerging interest in satellite autonomy and high accuracy pointing control for Air Force space missions.

3. CONCLUSIONS

In this paper a methodology was presented for easing the transition of Phillips Lab technologies and for reducing risk for flying space experiments by the means of HIL simulation. Due to budget constraints, the emphasis is placed on leveraging capabilities of existing HIL facilities through networking, mimicking equipment and capabilities, and utilizing lessons learned. The HIL lab will facilitate to transition component technologies, subsystems, and payloads to flight, demonstrate the value of such instruments to the warfighter, and to bring forth potential integration or component interaction problems before flight. This will amount to significant risk reduction and cost savings before flight as well as during operations, because potential integration problems, failures, and anomalies can be thoroughly investigated and solution procedures can be determined.

4. REFERENCES

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5. ACKNOWLEDGMENT

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6. BIOGRAPHY

Jesse Leitner received the BS degree in Aerospace Engineering from the University of Texas at Austin in 1990 and the MS and PhD degrees from Georgia Tech in 1992 and 1995, respectively. He is currently an Aerospace Engineer with the USAF Phillips Lab, Space Experiments Directorate in Albuquerque, NM. His current areas of interest are in nonlinear, adaptive control, and neural networks, with application to helicopter flight controls, spacecraft GN&C, and optical systems.