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Design and Development of Hardware-In-Loop Remote Simulation Real-Time Testbed with MIL-STD 1773-Based Fiber Optics Data Acquisition System

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ABSTRACT

Performance evaluation of avionics software in conjunction with flight hardware is a critical process carried out using a specialized Hardware-In-Loop Simulation (HILS) platform. This platform integrates essential flight subsystems, such as actuators and navigation systems, to validate their performance under real-time conditions. A unique facility, the Flight Motion Simulator (FMS), plays a vital role in testing the dynamic behavior of navigation systems. However, challenges arise due to the physical separation of critical equipment like the FMS and actuator setups from the main HILS Test-bed, necessitating their integration across large distances. To address this, a remote simulation Test-bed has been designed and developed utilising the emerging MIL-STD 1773 protocol with fiber optics-based communication. This approach ensures real-time data transfer with minimal latency, preserving the high-performance requirements of HILS. The Fiber Optics Data Acquisition System (FODAS) facilitates seamless integration of remote flight subsystems with the HILS Test-bed, eliminating delays associated with relocating equipment and re-establishing setups. Additionally, it enables the connection of flight subsystems directly from integration hangers, enhancing testing efficiency and flexibility. This research outlines the design and development methodology of the MIL-STD 1773-based FODAS system integrated with the HILS Test-bed. It further provides performance analysis, advantages, and practical results from its implementation, demonstrating the system's capability to overcome existing limitations while improving operational efficiency.

Keywords: Fiber Optics based data acquisition system; Flight motion simulator; Hardware-in-loop simulation; MIL-STD 1773, Simulation computer

NOMENCLATURE

Θ, Φ, Ψ	: Euler angles to FMS (deg.).
Δθ	: Incremental Angles (deg).
ΔV	: Incremental Velocities (m/s).
Vx, Vy, Vz	: INS Velocities (m/sec).
X, Y, Z	: INS Positions (Mtrs)
P, q, r	: INS Rates (deg./sec)
ax, ay, az	: INS Acceleration (m/Sec2)

1. INTRODUCTION

Validating avionics system software and hardware is a critical and complex process in the aerospace industry, requiring meticulous evaluation to ensure reliability and performance under dynamic flight conditions. The Hardware-in-Loop Simulation (HILS) platform is a vital tool for assessing the interaction and functionality of interconnected subsystems in real time[1]. This platform is essential during developmental flight trials, as it replicates real-world operational conditions to test avionics systems, including the Inertial Navigation System (INS), Onboard Computer (OBC), and actuators. The OBC plays a central role by executing control and guidance algorithms using navigation data provided by the INS, subsequently transmitting delta commands to actuators for vehicle control. The dynamics of propulsion and other subsystems are modelled mathematically in the simulation environment, forming plant model used to compute 6Dof algorithm[2]. This setup enables a comprehensive assessment of various configurations of mission-critical software and hardware. The HILS framework encompasses different configurations tailored to validate specific subsystems[4]:

- OBC-In-Loop (OIL): In this configuration, the control and guidance algorithms reside solely within the OBC, while other subsystems such as actuators and INS are represented as mathematical models within the simulation computer. This setup focuses on validating the algorithms without requiring real hardware.
- Actuator-In-Loop (AIL)*:* Real actuators are integrated into the HILS platform, allowing the performance of physical actuators to be validated under simulated conditions[9].
- Sensor-In-Loop (SIL): The INS undergoes validation in this configuration. The Flight Motion Simulator (FMS), driven by trajectory dynamics, rotates in three axes, generating inputs that simulate flight conditions[2]. The INS processes these inputs to produce navigation data, which is then sent to the OBC for further computation of control and guidance algorithm.
- Sensor-Actuator-In-Loop (SAIL): This is the final and

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most comprehensive configuration, integrating the OBC, actuators, and INS in real-time for a complete end-to-end validation of the avionics system clearing the software.

These configurations rely on diverse communication protocols, such as RS-422, Ethernet, and MIL-STD 1553, alongside signal conversion interfaces like ADC and DAC. MIL-STD 1553 is preferred in avionics due to its redundancy and simple architecture, which ensures robust data exchange between subsystems[3].

Despite the advancements, two significant challenges persist:

1.1 Flight Motion Simulator (FMS) Accessibility

The FMS is a critical piece of equipment used for INS validation, capable of simulating high-dynamic rotational movements based on trajectory dynamics. Due to its complexity and operational requirements, the FMS is typically housed in a controlled and secure environment, often located far from the HILS laboratory[5]. Relocating HILS setups to the FMS site or establishing parallel setups introduces delays, operational inefficiencies, and potential safety risks due to proximity work conditions. Additionally, simultaneous usage of the FMS by multiple aerospace projects further complicates the scheduling and testing process.

1.2 Actuator Integration

Actuators, which are often installed in flight subsystems or undergoing testing in integration hangars, present logistical challenges for transportation and re-installation in the HILS laboratory. Their remote integration is critical to optimizing the testing process while maintaining real-time communication and feedback.

To address these challenges, this research proposes a novel Fiber Optics Data Acquisition System (FODAS) based on the MIL-STD 1773 communication protocol. This system enables real-time, low-latency data transfer over long distances using fiber-optic communication, ensuring seamless integration of critical subsystems with the HILS platform[6-7]. The proposed FODAS system is designed to encode and transmit both discrete and continuous signals over fiber-optic links, supporting a wide range of communication standards, including MIL-STD 1553 and RS-422[8].

Key benefits of the FODAS system include:

- Remote operation of the FMS for INS validation without requiring physical relocation of the HILS setup, thereby optimizing resource utilisation and eliminating setup re-establishment delays.
- Seamless integration of actuators located in distant integration hangars, enabling real-time testing with digital or analog feedback transmitted back to the HILS simulation computer.

This research outlines the design methodology and development of the FODAS system, considering the stringent requirements of aerospace safety standards such as AS9100. The proposed solution not only enhances the efficiency and flexibility of HILS testing but also ensures compliance with operational safety guidelines. By addressing the challenges of remote integration and communication, this approach facilitates faster project completion, reduces logistical complexities, and significantly improves the accuracy and reliability of avionics system validation. Detailed analysis, results, and conclusions from the implementation of the FODAS system are discussed in subsequent sections.

2. LITERATURE REVIEW

An extensive literature survey has been carried out about the remote simulation feasibility in the HILS area. A paper is studied on SCRAMNET Technology which is popularly used in the avionics field[7]. It is based on a shared memory interface card. The disadvantage of this network is that it is not an integrated solution with the other data communication interfaces like ADC, DAC, and RS-422 commonly used in the avionics field. It is only an I/O card integrated into the system. A research paper titled "Investigation into Network Architecture and modulation scheme for MIL-STD-1773 Optical Fiber Data Buses" focuses on the concept of the MIL-STD 1773 communication protocol[6]. Similarly, a paper titled "cPCI-based Hardware In Loop Simulation" explained about the I/O interfaces of the HILS system[3]. This is a detailed explanation of the system development for the HILS. These papers do not cover any development of MIL-STD 1773-related information for HILS application. So, the unique concept of a Fiber optics Data Acquisition System development based on MIL-STD 1773 for HILS remote simulation has been designed, developed, and deployed for the HILS application.

3. PROBLEM DEFINITION

3.1 Existing HILS Setup

The current Hardware-In-Loop Simulation (HILS) infrastructure has been extensively tested with various avionics-based configurations, ensuring robust performance under simulated flight conditions[9-10]. As illustrated in Fig. 1, different HILS setups are designated to specific locations and operate independently to validate various avionics subsystems[10].

During the Sensor-In-Loop (SIL) configuration, real hardware such as the Inertial Navigation System (INS) must be validated against simulated flight dynamics. To achieve this, the HILS setup often needs to be relocated temporarily to the Flight Motion Simulator (FMS) facility. The FMS, a critical piece of equipment used for simulating high-dynamic flight trajectories, is typically housed in a controlled and secure environment. Relocating the HILS test-bed close to the FMS for each project introduces significant challenges, including:

- Schedule Disruptions: Re-establishing the HILS setup for every project delays the testing timeline, affecting the overall project schedule.
- Operational Risks: Working in proximity to the FMS and other critical equipment can lead to unsafe conditions due to the complexity and scale of the machinery.
- Logistical Constraints: Frequent relocation of the HILS setup is labor-intensive and prone to errors, potentially leading to inefficiencies.

Similarly, actuators, which must be tested before launch, face logistical challenges. Once integrated into the flight

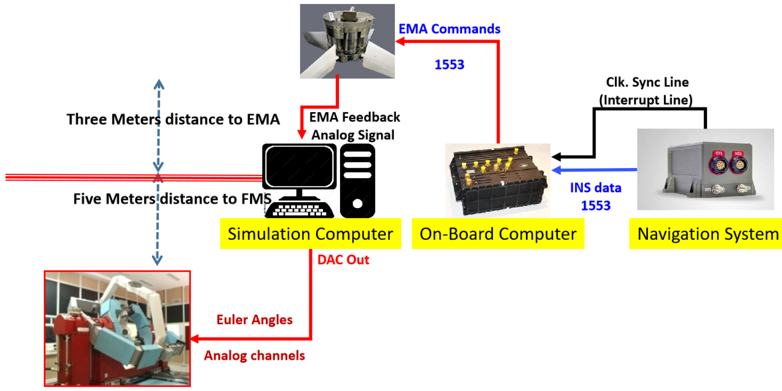


Figure 1. Existing HILS test-bed in proximity of FMS and Actuator.

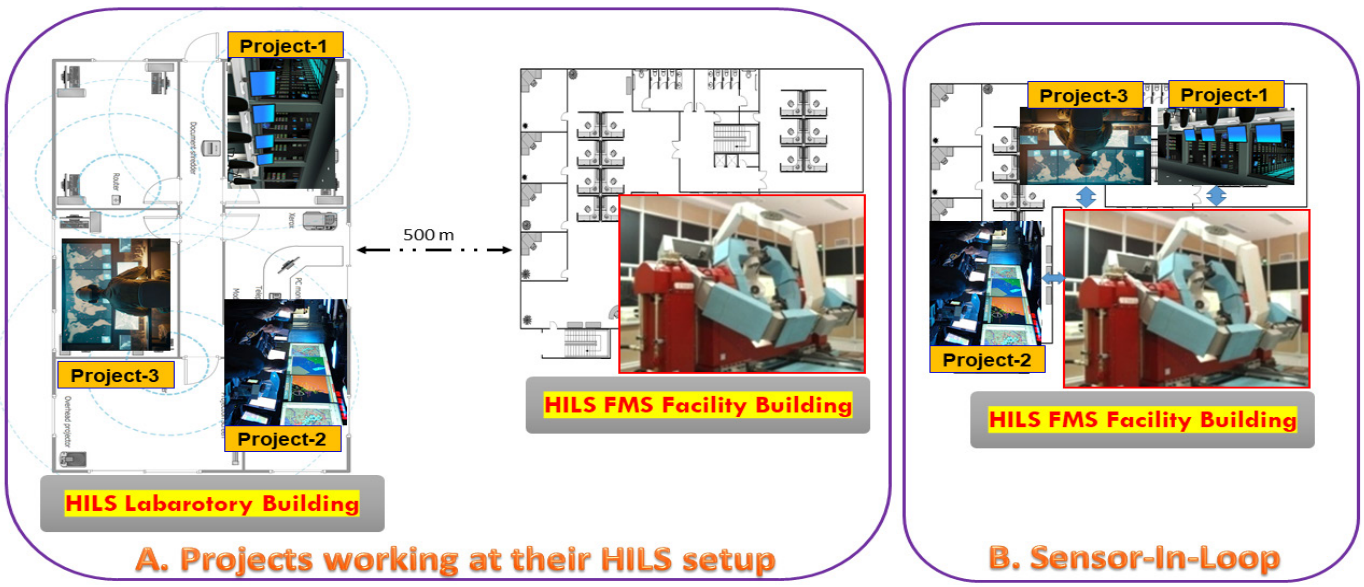


Figure 2. HILS testing of various avionics configuration, A. HILS Lab. B. Near FMS location.

vehicle's sub-system, transporting them to the HILS facility for validation becomes difficult. This process not only risks minor damages during transit but also requires extensive reassembly efforts, further delaying the testing schedule.

3.2 Proposed HILS Remote Simulation

To overcome these limitations, this research proposes a remote simulation methodology that leverages advanced communication and automation technologies to enable the remote operation of critical flight subsystems without compromising real-time performance[11]. Key features of the proposed solution include:

3.2.1 Remote Operation

Flight subsystems, such as actuators and the INS, can remain in their original locations while being integrated with the HILS test-bed. This eliminates the need for physical relocation, thereby reducing risks and delays.

3.2.2 Versatile Data Acquisition System

The system must support both analog and digital communication interfaces to seamlessly acquire data from a variety of avionics components. This ensures compatibility with existing systems while enabling future scalability.

3.3.3 All-in-One Communication Solution

An integrated, unified data communication system will be developed to handle multiple protocols, including analog, digital, and high-speed fiber-optic communication.

The implementation of this proposed remote simulation framework is expected to:

Significantly optimise the HILS testing schedule by reducing the time required for setup re-establishment.

Improve the safety and reliability of operations by minimizing handling and transportation risks associated with sensitive equipment.

Enhance flexibility and scalability, allowing for simultaneous testing of multiple projects without interference.

By addressing these challenges, the HILS remote simulation methodology represents a significant step toward a more efficient and robust testing framework for modern avionics systems. This development will ensure timely project delivery and maintain compliance with stringent quality standards in the aerospace industry[11-12].

4. METHODOLOGY

The architecture of the FODAS-based system is based on the processor and the interfaces. The software modifications have been done in the simulation computer to send and receive the data from FODAS systems. Design and development of hardware and software for remote simulation has been done in a phase-wise manner. Both the FODAS systems are the same in the hardware architecture. Only the difference is the BC and RT configuration that is done through the software[12]. The component of the full setup is explained point wise and then the integration and communication have been discussed in this section.

4.1 Brief Technical details of MIL-STD 1773

The foundation of the 1773 protocol is based on the MIL-STD 1553. It is a serial bus with redundancy and duplex communication architecture popularly used in avionics buses with Bus-Controller (BC) and Remote Terminal (RT) architecture. BC is responsible for scheduling the data messages to RT.

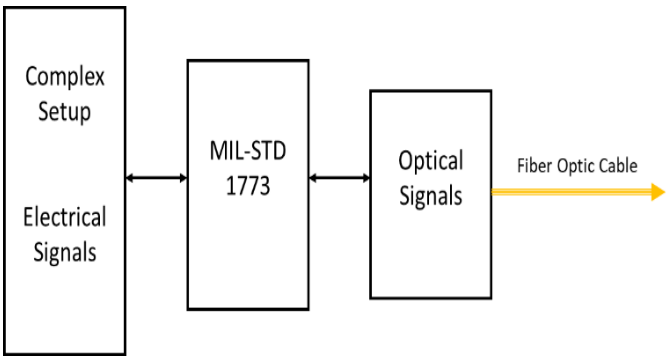


Figure 3. Basic diagram of MIL-STD 1773.

MIL-STD 1773 is a bus architecture with Fiber as a medium of transmission as shown in Fig. 3. The protocol wise it is the same as MIL_STD 1553. One side MIL-STD 1773 is the electrical bus of MIL-STD 1553 and the other side is the optical signals that are transmitted through optical Fiber cable. Optical Fiber is used to travel the distance at longer distances, immune to noise and electrical interference. The data rate is the same as MIL-STD 1553 which is 1 Mbps. MIL-STD 1773 protocol is used in the case of remote control, configuration, and operation. Mainly in the case of the avionics field, it is used to send signals at remote locations. This signal has been transmitted via Fiber optical cable.

4.2 Fiber Optics Communication

The Optical Fiber communication process transmits a signal in the form of light which is first converted into the light from electrical signals and transmitted, and then vice versa happens on the receiving side.

Fiber optic cable generally consists of a glass material covered by the cable.

4.3 MIL-STD 1553 to/from MIL-STD 1773

FODAS is a Fiber Optic Data Acquisition System as shown in Fig. 4. This is used to configure specific application requirements for remote operation by using the micro-controller-based software that resides in the ROM memory. This system will convert the 1553B Electrical data to Fiber optic 1773 and Analog IO, Digital IO, Muxing, and framing, converting into Fiber optic and vice versa. Separate two channels of RS-422 are configured for interrupt signal[8]. This unit finds applications requiring long-distance data transfer through MIL-STD-1553B protocol involving bus lengths of the order of 1-3 km. The unit also can be used for 1773 to MIL-STD 1553B conversions facilitating the testing of optical systems with existing MIL-STD-1553B test equipment. The unit also can be used for wire to/from Fiber Conversion applications. The unit facilitates the MIX and Match of MIL-STD-1553B/1773 Buses. The main Specifications are as follows:

- Processor: MC68LK332 (3.3V)
- 512 MB SRAM with 1 MB FLASH
- Digital Inputs/Outputs: 16 Channels, 28V
- Analog Inputs: 16 Channels, +/- 10V, 16 bit
- Analog Output: 16 Channels, +/- 10V, 16 bit
- RS-422 Channels: up to 115. Kbps
- 1553 Receiver: 01 Node, Redundant.
- 1553 Transmitter: 01 Node, Redundant.
- Fiber Optic Channels: 5 Nos, FC/ST/SC
- Easy interface connectivity to an external

MC68LK332 is a modular 32-bit micro-controller operating at 16.78 MHZ. It incorporates a central processing unit (CPU32), a system integration module (SIM), a queued serial module (QSM), a time processor unit (TPU), and a static 2K-byte static RAM module with TPU emulation capability. This is the main unit of FODAS and interfaces built with this micro-controller.

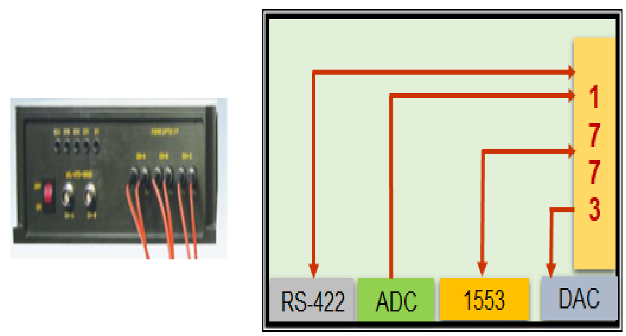


Figure 4. FODAS internal architecture.

Two FODAS systems have been developed that work in the Master and slave configuration. The software is developed according to the configuration. In the master configuration 1553 interface on FODAS is configured as BC and on the other side FODAS-2 is programmed to work as RT. The communication between FODAS-1 to FODAS-2 is via optical Fiber media and this does not affect the external interfaces and subsystems connected with this. The system is configured and integrated according to the vehicle configuration details. The number of channels for DAC, ADC, RS-422, and MIL-STD 1553 interface is explained below. All the required interfaces for the avionics integration is available with the FODAS. The resolution is 16 bit that offers the good sensitivity that is sensed by the FMS and the simulation is carried out with integration of the HILS test setup . This is cost effective solution for the data acquisition system integrated with the distance simulation and all the subsystems has been integrated and simulated with

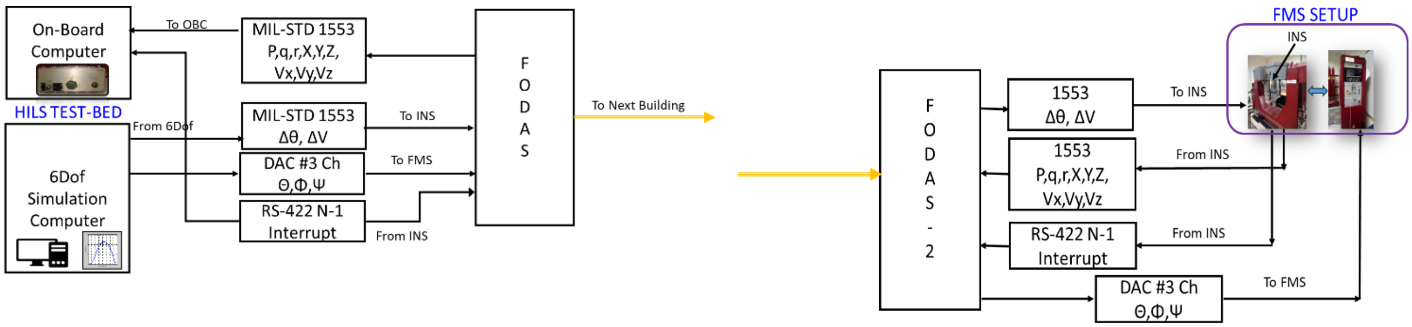


Figure 5. HILS test-bed interfaces to FODAS.

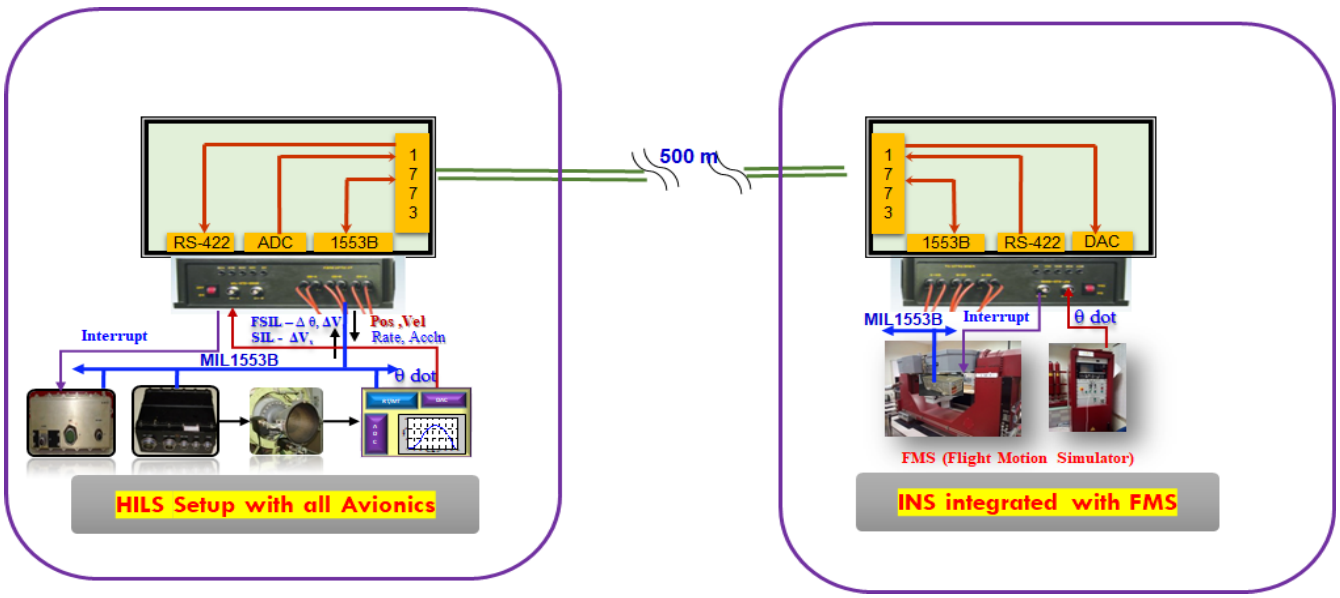


Figure 6. Remote Simulation Integrated Setup with FODAS system deployed at both sites.

the remote simulation. The following section explains the integration of hardware and software.

4.4 Test-bed Integration and Methodology

4.4.1 FODAS-1 (at HILS Testbed side)

The data communication from the HILS Testbed is interfaced with FODAS-1 to send incremental angles and velocities to INS, Euler angles to drive FMS, and RS-422 to receive clock sync to OBC. Both sides' configuration is shown in Fig. 5.

- Analog to Digital Channels: The Euler angle information is sent via DAC of the simulation computer and input as ADC to FODAS-1. 3 Channels are configured.
- MIL-STD 1553 Node-1: The incremental angle and velocities information is sent to INS via node-1. The INS information is received by the MIL-STD 1553 interface to OBC. OBC schedules the messages according to the algorithm on the mission node.
- RS-422 Interface: The clock synchronization of INS as a master to OBC is done by the RS-422 interface. At HILS side RS-422 receives the interrupt signal @2.5 ms and is connected with OBC via Digital Input.

4.4.2 FODAS-2 (at FMS side)

The processed information is sent back to the HILS Testbed by FODAS-2. The INS processed data that is position, and velocities have been sent. The Euler angles have received and interfaced with FMS as well as interrupt generated by the INS is sent for synchronization with OBC through the RS-422 interface.

- Analog to Digital Channels: The Euler angle information is sent via DAC of the simulation computer and input as ADC to FODAS-1.
- MIL-STD 1553 Node-1: The incremental angle and velocities information is sent to INS via node-1. The INS information is received by the MIL-STD 1553 interface to OBC.
- RS-422 Interface: The clock synchronisation of INS as a master to OBC is done by the RS-422 interface. At HILS side RS-422 receives the interrupt signal @2.5 ms and is connected with OBC via digital input.

There is no change in the avionics software as well as mission software. Plant Simulation Software Undergo the change in the software. In the broader view of the HILS process, for avionics subsystems, both the methodologies that are set up in the proximity of FMS and FODAS-based remote HILS simulation should show exact simulation performance. The newly developed methodology has been tested with several test cases with FSIL and SIL configurations.

The integrated remote simulation setup is shown in Fig. 6. The HILS setup is connected with FODAS with the

FMS simulation facility. The HILS Test-bed is located at about 500 mtr distance from the FMS and the FMS is operated in real time with the minimum latency that simulate the trajectory dynamics with high sampling rate.

5. METHODOLOGY

Interfacing software for the simulation computer is modified according to the new methodology of FODAS and the software is developed to test INS fully with different configurations. Two main configurations have been explained below.

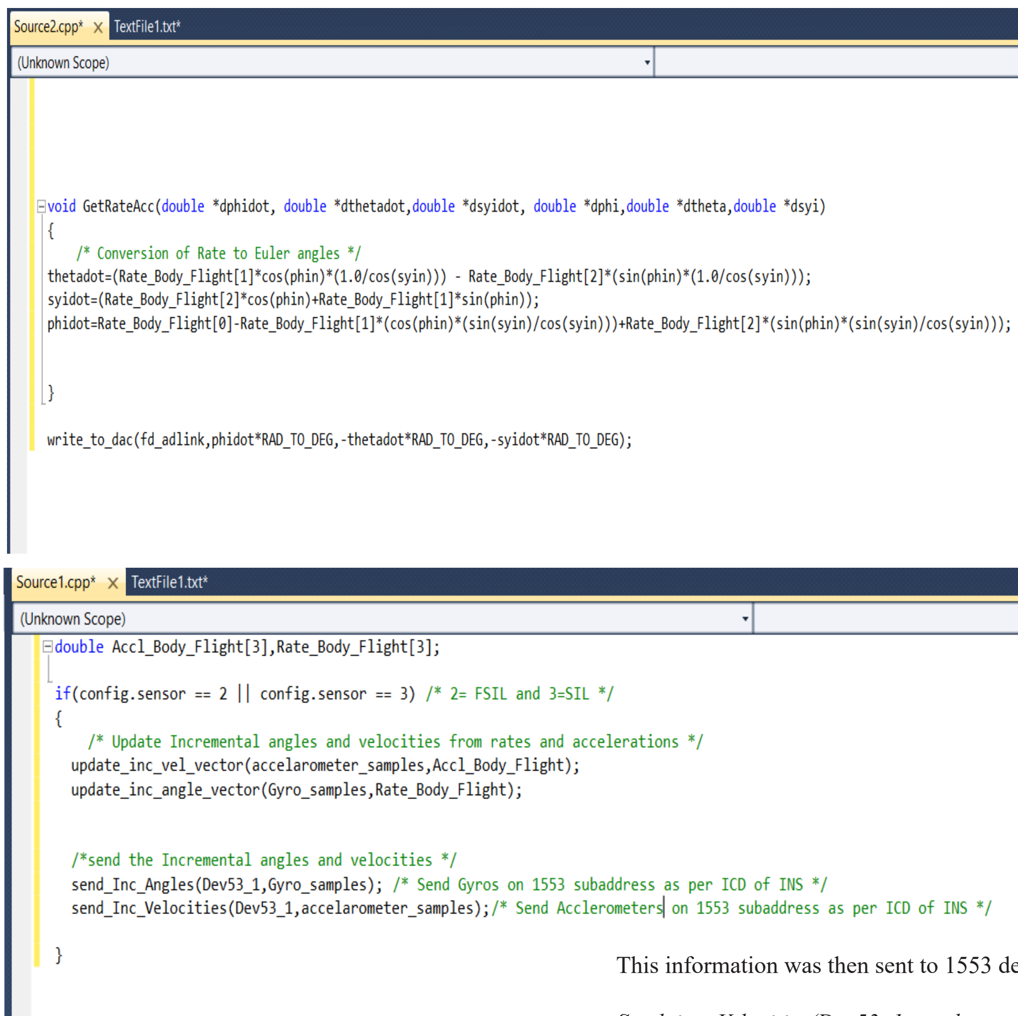
5.1 Full Stimulation-In-Loop (FSIL) Mode

In this configuration, only the navigation algorithm is validated. The raw data as measured by INS are incremental angles and velocities that have been sent (stimulated) by the simulation computer[10] to the navigation algorithm. So, the INS does not experience any dynamic movement or rotation but only the navigation algorithm is validated by using the simulation computer's information bypassing the real sensors. With the remote simulation setup, only the MIL-STD 1553 and interrupt on RS-422 in real-time are evaluated. The main focus is to establish the communication and evaluate the that real-time exchange of the data packets is being communicated properly without any delay and dropping of packets to and from FODAS systems.

In Fig. 7, the software interaction with FODAS is shown. When the run configuration flag is set to FSIL and SIL as 2/3 then the code is executed to compute the incremental angles and velocities.

Rate_Body_Flight[] is converted to *Gyro_Samples[]* by using the *update_inc_vel_vector()* function. Similarly, the accelerometer samples are computed based on the acceleration computation.

A number of test cases have been executed with FSIL mode to monitor the data consistency and latency. Data shows the exact match of the parameters throughout the trajectory[11]. The Jitter and latency values are within the limit that is observed maximum to be a maximum of 10 microseconds due to the Fiber optics communication that has not affected the real-time simulation run. This proves that the real-time communication performance is as per the trajectory scheduling and the delays are in the tolerance limit.



This information was then sent to 1553 devices by using:

Send_inc_Velocities(Dev53_1,accelerometer_samples);
Send_inc_Velocities(Dev53_1,Gyro_samples);
Where Dev53_1 is the driver ID of 1553 node-1.

Figure 7. Simulation computer's software flow.

5.2 Sensor-In-Loop Mode

The dynamic movement according to the trajectory[5] is simulated in this configuration and this is experienced by the sensors of the INS system. All the interfaces, 1553, ADC, DAC, and RS-422 have been utilized for SIL. The INS mounted on the FMS is driven by the simulation computer's Euler angles. In this case, the FMS is in a closed loop and the DAC output of the FODAS-2 is integrated with FMS. The sensed gyros rotations in three directions are being given to the INS algorithm and the navigation output is sent in the form of a 1553 message as FODAS-2 input. That information is decoded by FODAS-1 and given to OBC as shown in Fig. 7. In the SIL configuration, the additional software part is DAC and ADC interfaces. As shown in Fig. 8, thetadot, syidot, and phidot are computed and sent to DAC channel driver ID fd_adlink. This further sends the voltage to DAC channels. The voltage sensitivity is based on the dynamic range required by the simulation. In this case voltage range of DAC channels is +/- 10V for a +/- 57.3 deg/sec rate. So, for 1V FMS is commanded to 5.7 deg./sec rotation. The simulation in real time @2.5 ms.

The real-time sampling rate for rates output to DAC channels @2.5 ms and incremental rates and acceleration to 1553 is @2.5 ms remains unchanged. The interrupt of INS to OBC is synchronized @2.5 ms. So, the real-time data communication from HILS Setup to FODAS and Fiber optic communication should be minimal with latency and jitter values in tolerance limit that should not affect the real-time performance of close loop HILS testing.

6. TESTING AND VALIDATION

Before the deployment of the new methodology rigorous testing has been carried out with a number of test cases to create disturbance within the boundary limits of the dynamics[12]. The remote simulation test bed is established with the two buildings connecting with fiber optics interface. The real time data is sent and received with the HILS test setup. Following are the observations during the HILS simulation:

Table 1. HILS test-case matrix

Test cases	Trajectory-1	Trajectory-2	Trajectory-3
Full stimulation in loop			
FSIL Case-1	Pass	Pass	Pass
FSIL Case-2	Pass	Pass	Pass
FSIL Case-3	Pass	Pass	Pass
FSIL Case-4	Pass	Pass	Pass
FSIL Case-5	Pass	Pass	Pass
Actuator In Loop Simulation (AIL)			
AIL Case-1	Pass	Pass	Pass
AIL Case-2	Pass	Pass	Pass
AIL Case-3	Pass	Pass	Pass
AIL Case-4	Pass	Pass	Pass
AIL Case-5	Pass	Pass	Pass

6.1 Observations during HILS Runs

6.1.1 Grounding of the Test Setup

Noise affects the analog signal and the remote simulation is also affected because of the noise entered into the signal dominating the amplitude of the signal as the FODAS communication is mixed signal-based for simulation. The real-time performance is affected by the noise interference. Low-Pass-Filter (LPF) at the FODAS-2 Output side i.e. at the FMS side is designed to eliminate the noise at 50 Hz frequency. The values of the R= 1000 ohms and C=3.15 uF for the elimination of 50 Hz noise. After this additional circuit in the FMS input path, the analog signal noise was eliminated and the real-time performance of HILS runs has been assured with the same as close proximity run.

6.1.2 RS-422 Interface for Interrupt

The INS and OBC are synchronized by the clock signal of the INS. So, this signal has to be connected to the HILS test bed. In the initial development, the RS-422 interface for interrupt was not available with FODAS. The RS-422 interface is integrated as per the requirement of this application. It is tested and integrated.

6.2 Jitter and Latency in Real-Time

The latency observed is 10 us for the 1553 and 1773 channels and for the ADC and DAC channels, it is 12 us which is well within the limits of the execution cycle of the algorithm. This does not affect the performance of the HILS simulation in real-time. The delays of the fiber optics communication are negligible and the execution of the simulation algorithm data @2.5 ms

7. RESULTS ANALYSIS

Various parameters of the trajectory are analysed for the delay in communication, latency and drop in the packets. Before deployment of this new methodology, the old HILS run data (HILS set up in proximity to FMS) is compared with this new methodology. The simulation conditions are the same with the trajectory profile maintained the same. As shown in Fig. 8, the data is plotted in blue color representing the trajectory parameters for the new methodology, and in red color for the old data. The result analysis shows that both simulations are exactly matching. With remote simulation, the exact behaviour throughout the trajectory is observed even with the analog signal communicated with the MIL-STD 1773-based FODAS system. There are no effects of latency and noise on the performance and the methodology is accepted for the ongoing and future HILS setup to validate the avionics system.

8. CONCLUSION AND SUGGESTIONS

The FODAS scheme was conceptualized, designed, developed, and deployed indigenous. The results from real-time simulation runs demonstrate the system’s reliable performance, with no jitters and minimal latency. This product uses a single-node MIL-STD 1553 bus, which meets the requirements of various avionics test-beds. However, for broader use in avionics projects, configurations requiring a dual-node MIL-STD 1553 bus can be implemented. The remote integration of the subsystems are now possible with the FODAS based Test setup. Many of the test-cases have been tested and the performance of this setup is matching the legacy simulation. That prove that with the adoption of the new

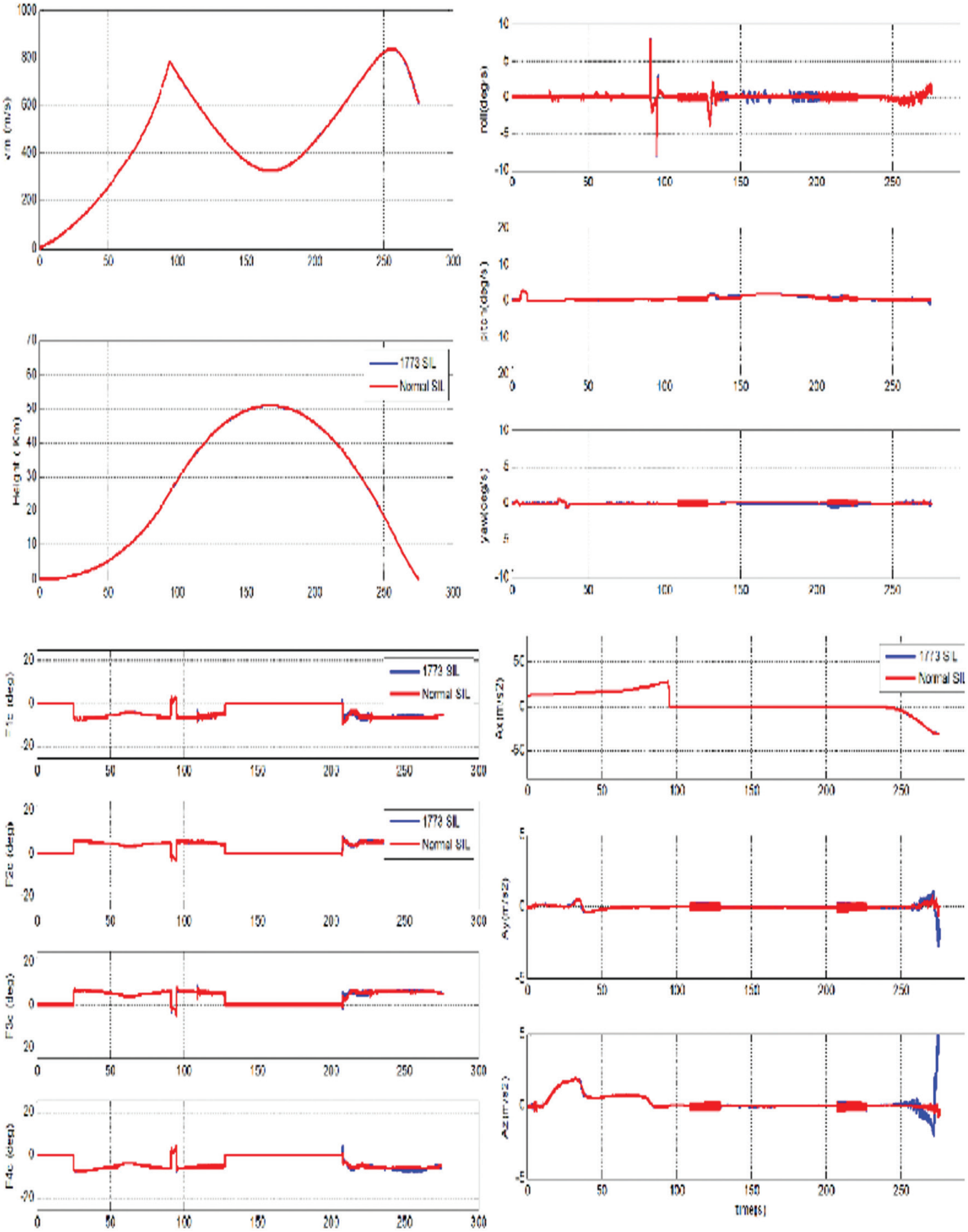


Figure 8. Result analysis with HILS simulation.

methodology has enhanced the performance of the simulation with the significant improvement in HILS technology.

Furthermore, the adaptation of newer interfaces to the FODAS hardware data acquisition architecture can be made to increase processing speed, aligning with the execution speed of weapon systems. This enhancement would make the FODAS system more agile and flexible, enabling its adoption for a wider range of applications.

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