Hardware in the loop simulation of a three-channel flight control system for an aerial vehicle using an integrated INS/GPS navigation system

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ABSTRACT

This paper presents the development of a Hardware-in-the-Loop (HiL) simulation model for a three-channel flight control system of an aerial vehicle equipped with an integrated INS/GPS navigation system. The proposed HiL framework is built upon a previously developed numerical simulation model of the vehicle's guidance and control system. In this framework, the six-degree-of-freedom (6-DOF) flight dynamics model is implemented in MATLAB/Simulink, while the INS/GPS navigation module, autopilot controller, and actuator subsystems are deployed on real hardware operating in a closed-loop real-time environment. The HiL system is designed to verify the implementation and performance of guidance and control algorithms on embedded hardware prior to field testing. The effectiveness of the proposed model is evaluated through comparisons between numerical simulation and HiL simulation results in terms of navigation parameters, control surface feedback signals, flight trajectories, and impact-point errors. The results demonstrate that the HiL model accurately reproduces the behavior of the guidance and control system under real-time operating conditions, showing a high level of agreement with the numerical simulation. The study confirms the feasibility and effectiveness of the proposed HiL framework as a reliable platform for the development, validation, and refinement of INS/GPS-based flight guidance and control systems before practical flight experiments.

Keywords: Hardware-in-the-Loop; INS/GPS integrated navigation; Flight control system; Autopilot; Real-time simulation; Six-degree-of-freedom model; Aerial vehicle.

1. INTRODUCTION

The practical significance of the HiL simulation is that it may close the gap between theoretical design and real-world deployment. This approach allows to obtain a comprehensive, quantitative assessment of the effect of such important physical parameters as mass variation, moments of inertia, sensor characteristics, and actuator dynamics on the system performance, by integrating them into the simulation framework. This increases the reliability of validation and reduces the risks of real flight testing, showing the novelty and applicability of the research in the field of modern flight control systems. Modern aerial vehicles, including guided missiles, require high accuracy, robust stability and reliable operation under complex dynamic conditions. For missiles with integrated Inertial Navigation System/Global Positioning System (INS/GPS) guidance, the interaction of flight dynamics, guidance algorithms, autopilot controllers, on-board sensors and actuator subsystems has a significant effect on the overall system performance. Thus, the creation of simulation and testing environments for the design, verification and evaluation of guidance and control systems before flight testing has already become a necessary requirement [1, 2].

Traditional numerical simulations can be used effectively for preliminary evaluation of guidance and control algorithms. However, they are not able to model real-time constraints and computation delays, effects of hardware communication and the real characteristics of embedded processors and actuators. However, flight testing is generally costly, time-consuming and operationally risky, which makes repeated experimentation during the controller development

process infeasible [1, 3]. Thus, HiL simulation has emerged as a practical solution that integrates mathematical models and real hardware in a closed-loop real-time setting, thereby enhancing the reliability and trustworthiness of system design and validation procedures [4].

There are a number of recent studies concerning the use of HiL simulation for control systems of missiles and aerial vehicles [2, 4, 9]. But in Vietnam, research on HiL simulation of INS/GPS based missile guidance and control systems is still limited, especially the integrated frameworks which combine simultaneously 6-DOF flight dynamics, INS/GPS navigation, three-channel autopilot control, actuator dynamics and real-time simulation architecture in a unified closed-loop environment. Most of the existing research is devoted to the simulation of algorithms in isolation or to purely numerical models, which are not enough to consider real-time execution constraints, hardware interfaces and the behaviour of practical control systems [5-8]. Thus, the development of a comprehensive HiL platform for analysis, verification and evaluation of INS/GPS guided missile control systems is of great scientific and practical significance.

Motivated by these problems, this paper proposes a HiL simulation framework for a three-channel missile control system with an integrated INS/GPS navigation system. Model development and performance evaluation are based on the E missile as the reference vehicle. The proposed framework is built upon a 6-DOF flight dynamics model with engine thrust, aerodynamic characteristics, time-varying mass properties and inertia parameters. Furthermore, INS/GPS navigation system, a three-channel autopilot controller, an actuator subsystem and embedded hardware modules are integrated into a real-time simulation environment to conduct closed-loop HiL testing.

The proposed framework is evaluated through a comparative study between pure numerical simulation and Hardware-in-the-Loop simulation. In the numerical simulation environment, all functional components such as flight dynamics, INS/GPS navigation, autopilot algorithms and actuator models are fully implemented in MATLAB/Simulink. For the HiL configuration, the INS/GPS navigation computations and the missile autopilot functions, i.e., the three-channel control algorithm and the fin actuation subsystem, are performed on real embedded hardware in real time and interact with the 6-DOF flight dynamics model in a closed-loop architecture. The performance assessment is done by comparing the flight trajectories, attitude responses, control commands and fin actuator responses obtained from the two simulation approaches.

The main contribution of this work is the development of a Hardware-in-the-Loop simulation model of a three-channel missile control system based on integrated INS/GPS navigation, extending the numerical simulation framework previously developed by the authors [5-8]. The proposed HiL platform aims to verify the implementation and real-time operation of guidance, navigation, control and actuator algorithms prior to practical deployment. The effectiveness is demonstrated by comparative analyses of the numerical simulation and HiL simulation results for the E missile control system.

2. NUMERICAL MODELING AND DEVELOPMENT OF THE HARDWARE-IN-THE-LOOP SIMULATION FRAMEWORK

In this section, we present the numerical modelling of the E missile guidance and control system and the design of the proposed HiL simulation framework. First, the reference model, the numerical simulation model composed of the 6-DOF flight dynamics, INS/GPS integrated navigation system, autopilot controller and fin actuation subsystem, is briefly introduced. The architecture and hardware implementation of the HiL platform is then presented, emphasising the integration of real navigation and control hardware with the flight dynamics simulation in a real-time closed-loop environment.

2.1. Numerical simulation model of the E missile control system

To construct the HiL simulation platform, a complete numerical simulation model of the missile control system based on MATLAB/Simulink has to be first established as the reference system for validation and verification. The model was developed and published earlier by the authors in previous studies [5-8]. Only a brief overview of the model is provided as a basis for the development of the proposed HiL framework in this paper. The overall architecture of the simulation model is shown in Figure 1. The model consists of five major functional modules: 6-DOF flight dynamics model, integrated INS/GPS navigation system, flight guidance program, autopilot controller and fin actuator subsystems. The proposed simulation framework utilises the 6-DOF flight dynamics model to generate the missile state variables, which are further used to simulate the measurements of the inertial sensors, e.g., the angular rate gyroscopes, the accelerometers and the GPS receivers. The simulated sensor data are then processed by the integrated navigation system of INS/GPS to estimate the missile position, velocity and attitude. For each flight phase, the obtained navigation information is used to generate the corresponding control commands by the flight guidance program and the autopilot controller. These commands are transmitted to the actuator subsystem, which changes the deflection angles of the aerodynamic control fins. The resulting aerodynamic forces and control moments are then feedback to the flight dynamics model, thus constituting a closed-loop guidance and control system.

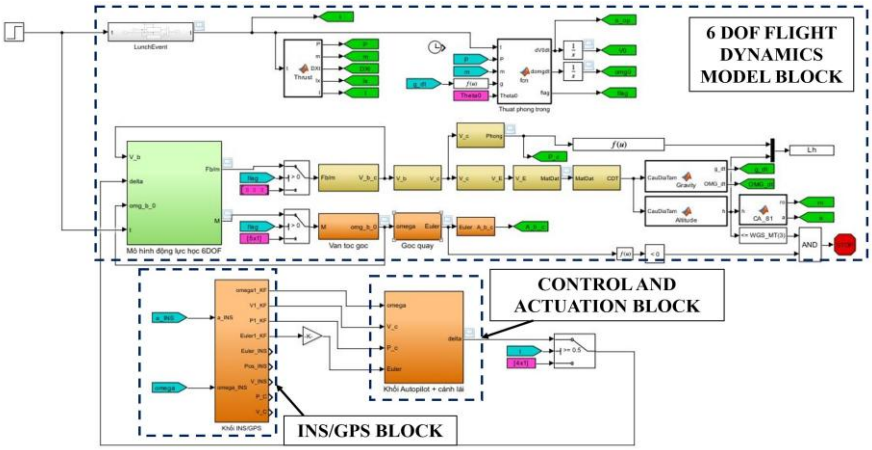


Figure 1. *Overall architecture of the numerical simulation model of the missile control system.*

The E missile flight dynamics model is developed based on a 6-DOF formulation (Figure 2), which provides a comprehensive representation of both the translational and rotational motions of the missile in three-dimensional space. The model accounts for the effects of engine thrust, gravitational forces, aerodynamic forces, and aerodynamic moments. In addition, variations in missile mass and moments of inertia resulting from fuel consumption during the boost phase are incorporated into the dynamic model. The state variables generated by the flight dynamics model serve as inputs to the guidance, navigation, and control (GNC) system. A detailed mathematical description of the 6-DOF flight dynamics model can be found in the authors' previous work [5].

The navigation system consists of an Inertial Measurement Unit (IMU), a GPS signal model, and an INS/GPS data fusion algorithm implemented using an Extended Kalman Filter (EKF). The INS subsystem estimates missile attitude, velocity, and position from accelerometer and gyroscope data, while the GPS subsystem corrects inertial drift with position and velocity updates. Integrating both systems enhances navigation accuracy and stability over standalone INS (see Figure 3, [7]). The INS/GPS model supports HiL simulation and real-time verification of a three-channel control system (pitch, yaw, roll). The flight control program operates in three phases ballistic, range extension, and terminal dive, with proportional navigation applied as shown in Figure 4.

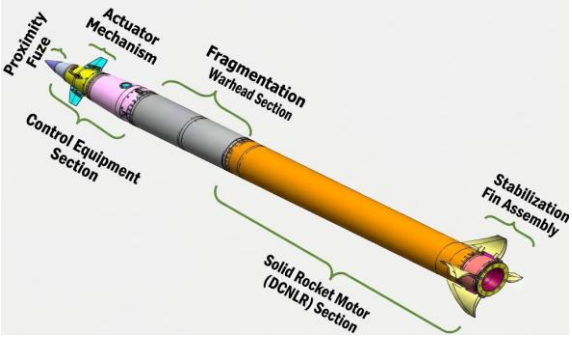


Figure 2. *Layout of the onboard subsystems in the E missile.*

The autopilot computes control commands for the required trajectory, with detailed algorithms described in [5].

The autopilot module generates control commands that are sent to the fin actuator subsystem via a power amplifier. The actuator subsystem drives the aerodynamic control fins by means of servo motors according to the commands issued by the autopilot controller. The resulting fin deflections create the aerodynamic forces and control moments required for missile manoeuvrability. These forces and moments are then applied to the 6-DOF flight dynamics model, thereby affecting the missile motion and closing the guidance and control loop.

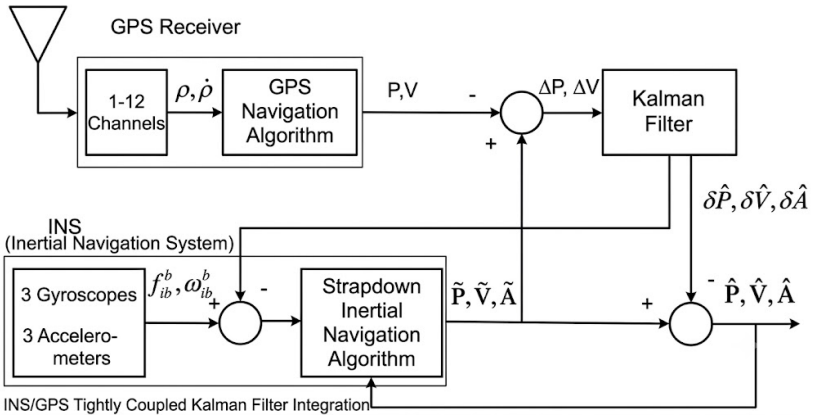


Figure 3. *Block diagram of the loosely coupled INS/GPS Kalman filter.*

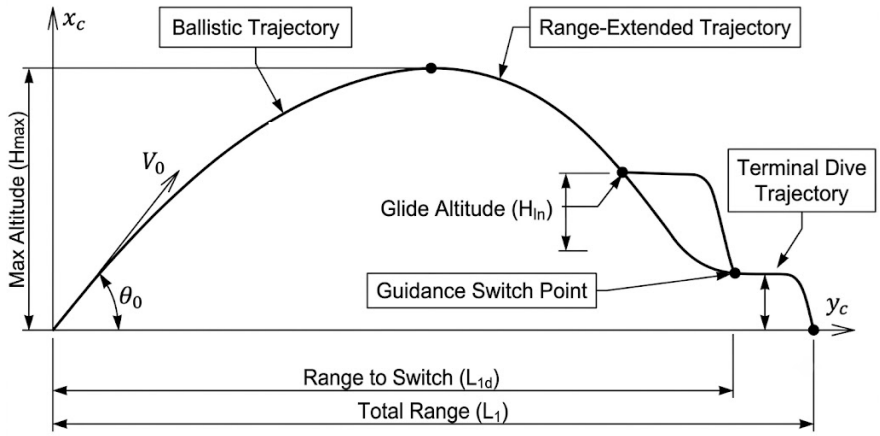


Figure 4. *Flight profile and trajectory of the E missile.*

The numerical simulation model is used as a reference benchmark for the development and performance evaluation of the HiL simulation system presented in the next section.

2.2. Design and implementation of the hardware-in-the-loop simulation framework

2.2.1. Overall system architecture of the proposed HiL platform

A HiL simulation system, based on the numerical model in Section 2.1, is developed to assess missile guidance and control performance under realistic conditions. The 6-DOF flight dynamics model runs in MATLAB/Simulink, while guidance and control algorithms operate on physical hardware. As shown in Figure 5, the 6-DOF model generates missile motion states, which are used to simulate onboard sensor outputs. The flight dynamics model adds sensor noise to acceleration and angular-rate signals before sending them to the INS module, where inertial navigation is performed. At the same time, synthetic GPS data with measurement noise is sent to the GPS emulator. The navigation processor fuses INS and GPS data to estimate missile position, velocity, and attitude. These state estimates are used by the autopilot to calculate control commands for pitch, yaw, and roll, which are sent to the fin actuators to generate aerodynamic forces and moments, closing the real-time guidance and control loop with the 6-DOF model.

2.2.2. Hardware components of the HiL system

The hardware platform is designed to emulate the onboard missile guidance and control architecture and comprises the following main functional modules: the INS unit, the GPS emulator, the INS/GPS navigation processor, the autopilot controller, the fin actuator subsystem and the central distribution unit. The general layout of the built HiL simulation system is shown in Figure 6. The integration of these hardware components allows running navigation, guidance and control algorithms on real embedded devices while maintaining the real-time closed-loop interaction with the 6-DOF flight dynamics model. This architecture offers a realistic environment for system verification and performance assessment before field testing.

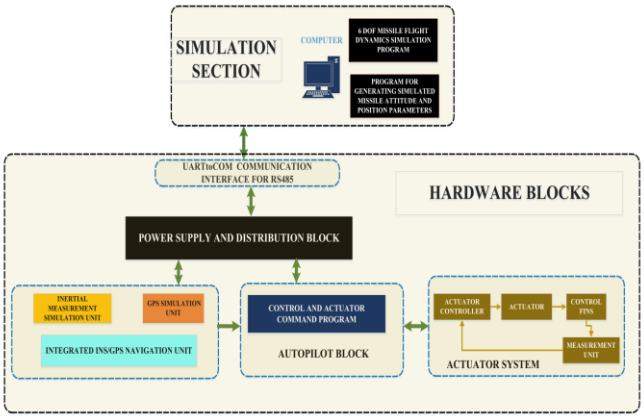


Figure 5. *Overall architecture of the proposed hardware-in-the-loop simulation framework.*

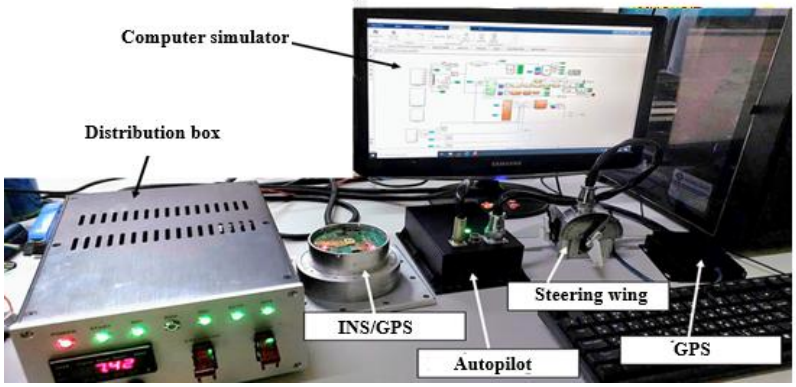


Figure 6. *Experimental setup of the proposed hardware-in-the-loop system.*

The INS unit includes an enclosure and a processing board with an STM32F407 microcontroller, running inertial navigation algorithms based on simulated acceleration and angular-rate data. The GPS emulator uses the same microcontroller to process position and velocity data from the flight dynamics model, generating realistic GPS-like measurements. The integrated INS/GPS algorithm is executed on the INS unit's onboard computer, providing position, velocity, and attitude estimates for the autopilot to generate fin control commands. The actuator assembly, with servo motors, feedback sensors, and control fins, accurately simulates missile fin dynamics. Control performance is evaluated via actuator feedback signals. The HiL system also features a central distribution unit for power management, operational control, launch command generation, and status monitoring. In the developed HiL system, all data exchange between the simulation model and the hardware components is performed via the RS485 communication standard using UART-to-COM modules. To ensure synchronization between the simulation model and the hardware, the 6-DOF flight dynamics model is solved in fixed-step mode at a computational frequency of 1000 Hz using the fourth-order Runge–Kutta method.

3. SIMULATION RESULTS AND PERFORMANCE EVALUATION

The simulation results and performance evaluation of the proposed HiL framework are presented in this section. The evaluation is performed by a comparative study between the numerical simulation model and the HiL implementation for similar flight scenarios. The evaluation is based on three main points: the accuracy of the INS/GPS navigation system, the performance of the autopilot controller and fin actuation subsystem, and the overall behaviour of the closed-loop guidance and control system. The proposed framework's performance is evaluated in terms of the major performance indicators, i.e. navigation states, control responses, flight trajectories and missile impact-point errors.

3.1. Evaluation of the INS/GPS navigation module

The objective of this experiment is to evaluate the implementation of the INS/GPS navigation algorithm on physical hardware by comparing the navigation outputs obtained from the numerical simulation and the HiL simulation platform. During the tests, an identical flight scenario was employed for both simulation environments. Inertial sensor measurements and GPS data were generated by the 6-DOF flight dynamics model and subsequently provided as inputs to the corresponding navigation systems.

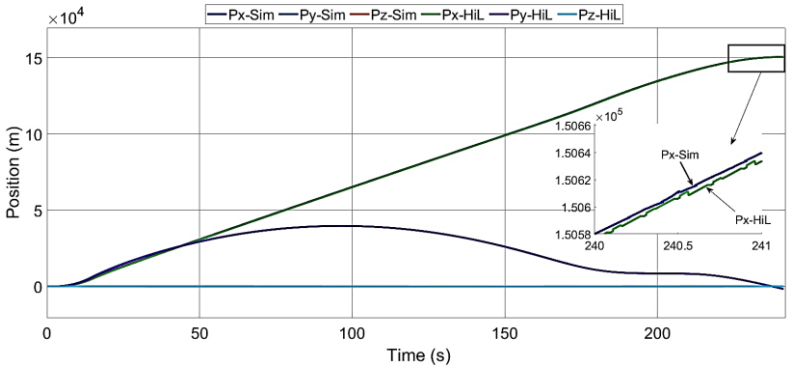
The comparison results for missile position, velocity, and attitude estimates obtained from the two simulation approaches are presented in Figures 7(a) and 7(b). It can be observed that the corresponding response curves exhibit an almost perfect overlap throughout the entire flight mission. This high level of agreement demonstrates that the INS/GPS navigation algorithm implemented on the physical hardware accurately reproduces the behavior and estimation performance of the numerical simulation model.

The results confirm the correctness of the hardware implementation and indicate that the proposed HiL platform is capable of providing reliable real-time execution of the INS/GPS navigation algorithm without introducing significant deviations from the reference simulation model.

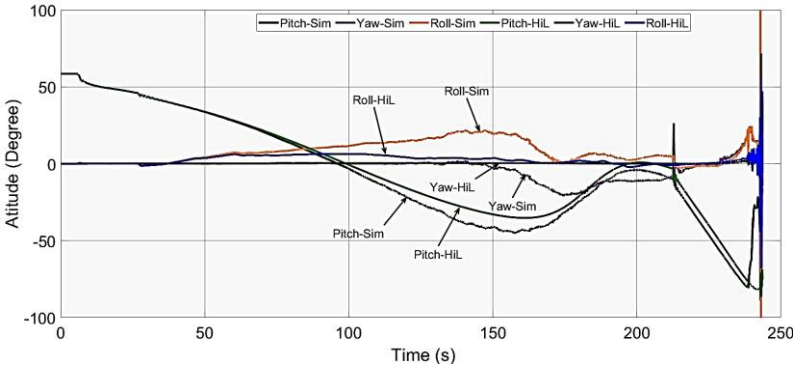
The obtained results indicate that the outputs of the INS/GPS navigation system implemented on physical hardware exhibit a high degree of consistency with those generated by the numerical simulation model. The discrepancies between the two approaches remain within the allowable system tolerances, namely 10 m for position estimation and 5° for attitude estimation. These results demonstrate that the navigation algorithm maintains its state-estimation accuracy after deployment on embedded hardware and is capable of operating reliably under real-time conditions.

Furthermore, the findings validate the effectiveness of the proposed INS/GPS hardware integration strategy within the HiL simulation framework. The close agreement between the

numerical and HiL simulation results confirms the correctness of the hardware implementation and provides a solid foundation for the testing, verification, and refinement of the navigation system prior to deployment on an actual missile platform.



a) Position graph.



b) Angle graph.

Figure 7. *Comparison of INS/GPS navigation parameters between the numerical simulation and the hardware-in-the-loop simulation.*

3.2. Evaluation of the autopilot controller and fin actuation system

To evaluate the performance of the control system implemented on physical hardware, a comparison was conducted between the fin deflection commands obtained from the numerical simulation model and the actual feedback signals measured from the actuator subsystem in the HiL platform. The signals were recorded under the same flight scenario and identical initial conditions. The comparison results are presented in Figure 8.

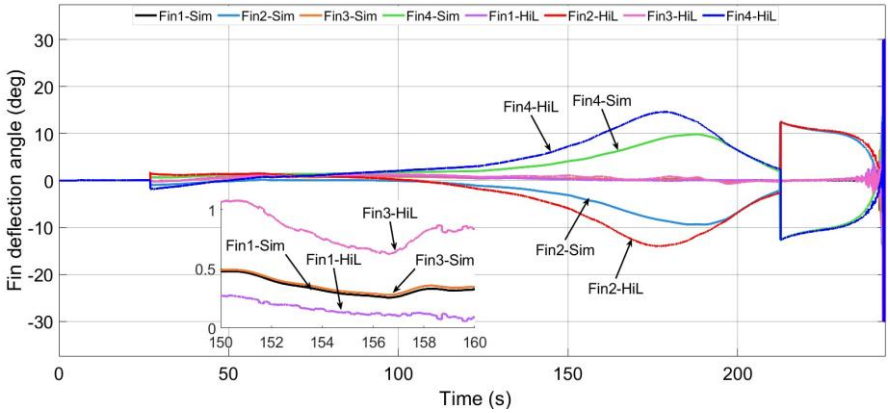


Figure 8. *Comparison of control fin deflection angles between the numerical simulation and the HiL.*

It can be observed that the fin deflection responses generated by the HiL system closely match those obtained from the numerical simulation throughout the entire flight mission. The timing of control actions, as well as the overall variation trends of the fin deflection angles, are highly consistent between the two cases. This close agreement demonstrates that the hardware-implemented autopilot and actuator subsystems accurately reproduce the intended control behavior and faithfully reflect the dynamic characteristics of the designed missile control system.

3.3. Evaluation of the closed-loop control system

The effectiveness of the proposed HiL framework is assessed by comparing the results obtained from the numerical simulation and the HiL simulation under an identical flight scenario (Figure 7a). In the HiL model, the control loop operates at a data exchange rate of 100 Hz, while the INS and GPS are updated at 100 Hz and 5 Hz, respectively. These frequencies are selected based on the operational requirements of the system and are kept constant throughout the experiment. The use of different computational and update rates allows the HiL model to more closely reproduce the actual operating conditions of the navigation and control units. Therefore, the HiL results not only assess the suitability of the proposed algorithm but also verify the ability of the entire control loop to maintain stable operation with the specified update and data exchange rates under real-time conditions. The results indicate that the flight trajectory generated by the HiL system closely follows that of the numerical simulation throughout the entire flight mission, demonstrating the capability of the proposed platform to accurately reproduce the behavior of the missile guidance and control system in a real-time environment.

To provide a quantitative assessment, a series of simulation experiments were conducted for different target ranges. Table 1 summarizes the missile impact-point errors relative to the target coordinates for both simulation approaches. The missile and target coordinates are expressed in the launch-site reference frame ($OX_cY_cZ_c$), which is fixed to the launcher at the launch location.

The comparison of the impact-point errors provides an important measure of the overall performance of the integrated guidance, navigation, and control system, as well as the fidelity of the proposed HiL simulation framework with respect to the reference numerical model.

Table 1. *Comparison of impact-point accuracy between numerical simulation and HiL simulation.*

N_0	**Shooting range (km)**	**Target coordinates (m)**			**Simulated missile drop coordinates (m)**			**Missile coordinates according to HiL (m)**		
		X_MT	Y_MT	Z_MT	X_TL	Y_TL	Z_TL	X_TL	Y_TL	Z_TL
1	150	150067	-1788	-2	150059	-1782	-3.2	150072	-1785	-1.5
2	100	100045	-456	-1.2	100053	-452	-1	100048	-162	-2.1
3	70	70032	-132	-0.5	70036	-129	-0.8	70028	-134	-1.2
4	50	50029	-52	-0.2	50034	-56	-0.1	50025	-49	-0.5

The results indicate that the missile impact-point errors obtained from the HiL simulation are highly consistent with those produced by the numerical simulation across all test scenarios. The discrepancies between the two approaches remain within 10 m along all coordinate axes. These findings demonstrate that, with the established computational, data-exchange, and INS/GPS update rates, the proposed HiL framework is capable of accurately reproducing the behavior of the integrated guidance and control system under real-time operating conditions. The strong correlation between numerical and HiL results demonstrates the simulation platform's

reliability, making it effective for verifying and refining guidance and control algorithms before real flight tests.

4. CONCLUSIONS

In this paper, a HiL simulation framework of a three-channel control system of an aerial vehicle using an integrated INS/GPS navigation system has been developed successfully, and the E missile is taken as the reference platform. The proposed framework enables the integration of physical hardware modules such as the INS/GPS navigation system, autopilot controller and fin actuation subsystem in a real-time closed-loop control. The comparison results between the numerical simulation and the HiL simulation show good agreement of the navigation states, the control signals, the flight trajectories and the missile impact-point errors. The obtained results confirm that the proposed HiL platform is able to faithfully replicate the behaviour of the integrated guidance, navigation and control system in real-time operating conditions. The use of HIL simulation in conjunction with stringent physical parameter evaluation represents a significant leap forward in the development and validation of flight guidance and control systems. This provides a realistic and cost-effective platform to detect and fix any potential problems before practical implementation. These contributions demonstrate the originality and practical value of this study towards improving the design, testing and readiness of advanced aerial vehicle control systems with INS/GPS-based navigation. The results demonstrate the correctness, fidelity and practical utility of the developed framework as an effective tool for the development, verification, validation and refinement of missile guidance and control systems prior to actual flight testing. Therefore, the proposed HiL platform is a reliable and cost-effective environment for reducing the development risk and increasing the readiness of the system prior to deploying it in real-world applications.

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TÓM TẮT

Mô hình mô phỏng bán tự nhiên hệ thống điều khiển ba kênh trên thiết bị bay sử dụng hệ thống dẫn đường kết hợp INS/GPS

Bài báo trình bày việc xây dựng mô hình mô phỏng bán tự nhiên Hardware-in-the-Loop (HiL) cho hệ thống điều khiển ba kênh của thiết bị bay (TBB) sử dụng hệ dẫn đường tích hợp INS/GPS. Mô hình HiL được xây dựng trên cơ sở mô hình mô phỏng số hệ thống dẫn đường – điều khiển TBB đã được nhóm tác giả công bố trong các nghiên cứu trước đây, trong đó mô hình động lực học bay sáu bậc tự do (6DOF) được thực hiện trên Matlab/Simulink, còn các khối dẫn đường INS/GPS, bộ điều khiển autopilot và cơ cấu chấp hành được triển khai trên phần cứng thực và làm việc trong vòng kín thời gian thực. Hệ thống HiL được xây dựng nhằm kiểm chứng khả năng triển khai các thuật toán dẫn đường và điều khiển trên phần cứng trước khi thử nghiệm thực tế. Hiệu quả của mô hình được đánh giá thông qua việc so sánh kết quả giữa mô phỏng số và mô phỏng HiL đối với các tham số dẫn đường, tín hiệu phản hồi cánh lái, quỹ đạo bay và sai số điểm rơi của TBB. Kết quả cho thấy mô hình HiL có khả năng tái hiện chính xác hoạt động của hệ thống dẫn đường – điều khiển trong điều kiện thời gian thực, với mức độ tương đồng cao so với mô phỏng số. Kết quả nghiên cứu khẳng định tính khả thi của mô hình đề xuất trong nghiên cứu, kiểm chứng và hoàn thiện các hệ thống điều khiển TBB sử dụng dẫn đường INS/GPS trước khi triển khai thử nghiệm thực tế.

Từ khoá: Thiết bị bay; Mô phỏng bán tự nhiên; Hardware-in-the-Loop; Hệ thống dẫn đường kết hợp INS/GPS; Hệ thống điều khiển.