Instituto Tecnológico
y de Estudios Superiores de Occidente
Reconocimiento de validez oficial de estudios de nivel superior según acuerdo secretarial 15018, publicado en el Diario Oficial de la Federación del 29 de noviembre de 1976.

Departamento de Electrónica, Sistemas e Informática
Especialidad en Sistemas Embebidos

Digital Twin of a Stewart Platform for Embedded Control Testing Using HIL Simulation

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TRABAJO RECEPCIONAL que para obtener el **GRADO** de
ESPECIALISTA EN SISTEMAS EMBEBIDOS

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Tlaquepaque, Jalisco. agosto de 2026

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***Abstract*— This research mitigates the gap between theoretical control design and real-world implementation of Stewart platforms, where high system costs often limit experimental validation. The objective of this work is to develop a Stewart platform digital twin using Hardware-in-the-Loop simulation for control testing. To achieve this, a discretized model was implemented with a hardware controller for a closed-loop system. The digital twin was successfully tested with an embedded input using serial communication. This framework provides an accessible, low-risk environment for students and researchers to evaluate advanced control algorithms. Future developments could focus on the integration of middleware to expand the system's monitoring and training capabilities.**

Keywords—Stewart platform, Hardware-in-the-Loop, digital twin, controller validation

I. Introduction

The Stewart platform, a high-level, precision manipulator with six degrees of freedom, has become an indispensable technology in industrial sectors. Since its introduction in 1965 by Stewart [1], it has been widely adopted in fields ranging from aerospace flight simulators to robotic-assisted surgical systems due to its enhanced stiffness, accuracy, speed, and loading capacity compared to serial manipulators [2, 3]. In academia, it has also been studied extensively, leading to the development of numerous kinematic, dynamic, and control models. However, the leap from theoretical models to physical experimentation requires expensive hardware to guarantee performance reliability [4]. For instance, commercial platforms known as *Hexapods,* consisting of 6 telescoping legs cost over $20,000 USD [5]. Furthermore, while developing a low-cost prototype is possible, it would entail an additional stage for manufacturing and hardware assembly. The complexity of a parallel, six-degree-of-freedom system also poses a significant operational cost, as a minor error in control law implementation can lead to catastrophic hardware failure or safety hazards.

Hardware-in-the-Loop (HIL) methodologies, supported by high-fidelity mathematical simulations, emerge as a transformative solution that mitigates the gap between theory and practice. HIL simulation is a beneficial tool for optimization and debugging, which was first developed for military testing and nuclear reactor controllers [6]. Its use case in education, particularly for testing and validation, addresses the disadvantage of relying on physical systems and their acquisition costs. Therefore, HIL offers a framework where students can validate control algorithms without the risk of physical degradation or hardware depletion [7].

This paper presents the dynamic model for a 6-DOF Stewart platform, which serves as the core component of a digital twin architecture by providing a high-fidelity real-time representation of the physical system [8]. The development introduces Model-in-the-Loop performed in a simulation environment, where the plant is a mathematical model [9], while the controller is embedded in C.

The article is organized as follows: Section II provides a detailed description of the methodology employed for the Stewart platform digital twin, describing the continuous-time and discrete-time models, and the embedded controller. Section III describes the hardware setup and architecture of the HIL framework. Section IV outlines the results. Finally, Section V presents concluding remarks and future work.

II. Stewart Platform Digital Twin

There are various definitions of digital twin in the literature; however, the concept can be generalized as a digital model that can reflect the behavior of a physical object or process [10]. For the digital twin and HIL simulation to be an effective engineering tool and provide reliable results, it must integrate a full dynamic model of the Stewart Platform that operates under the timing constraints of the embedded controller. Therefore, the model is discretized in the time domain to ensure compatibility with the digital processors that drive modern control systems [11].

A. Continuous Dynamic Model

The continuous model of the Stewart platform is based on the formulations described by Bingul, et al. [12]. The Stewart platform considered in this project consists of six extendable legs that stem from a fixed base to an upper moving platform. The platform's pose is defined by the vector $X_{P-O} = [x, y, z, \alpha, \beta, \gamma]^T$, which represents the Cartesian position and the Euler angles (roll, pitch, and yaw) of the moving platform relative to the fixed base. The platform dynamics are described as:

$$J^T F = M_{P-O}\ddot{X}_{P-O} + V_{P-O}\dot{X}_{P-O} + G_{P-O} \tag{1}$$

where $M_{P-O} \in \mathbb{R}^{6\times 6}$ is the inertia matrix, $V_{P-O}\dot{X}_{P-O} \in \mathbb{R}^{6\times 6}$ contains the Coriolis-Centrifugal terms, and $G_{P-O} \in \mathbb{R}^{6\times 6}$ represents the gravitational forces, all are nonlinear functions of the generalized coordinates and velocities of the moving platform. J is the Jacobian matrix, and F is the vector of actuator forces. Solving for the platform's acceleration yields:

$$\ddot{X}_{P-O} = M_{P-O}{}^{-1}\left(J^T F - V_{P-O}\dot{X}_{P-O} - G_{P-O}\right). \quad (2)$$

The platform's velocity and pose are obtained by integrating the acceleration vector

$$\dot{X}_{P-O} = \int \ddot{X}_{P-O}\, dt \quad (3)$$

$$X_{P-O} = \int \dot{X}_{P-O}\, dt. \quad (4)$$

The resulting position and velocity are used to calculate actuator coordinates determined by the following kinematic relationships

$$\dot{L}_{1-6} = J\dot{X}_{P-O} \quad (5)$$

$$\ddot{L}_{1-6} = \dot{J}\dot{X}_{P-O} + J\ddot{X}_{P-O} \quad (6)$$

$\ddot{L}_{1-6}, \dot{L}_{1-6}$ denote the actuators' velocity and acceleration, while the position vector L_{1-6} is obtained as:

$$L_i = R_{XYZ} GT_i + P - B_i \quad (7)$$

where $\vec{P}$ represents the translation vector of the platform's center and R_{XYZ} is the rotation matrix defining its orientation. The terms $\overrightarrow{GT_i}$ and $\vec{B}_i$ denote the constant coordinates of the attachment points on the moving platform and the fixed base, respectively.

The electrical dynamics of the actuators are modeled based on the DC motor and ball-screw drive formulations by the following equation:

$$V = L\dot{I} + RI + K_b\dot{\theta}_m \quad (8)$$

where V and I are the applied motor voltage and current, L, R, K_b are the rotor inductance, terminal resistance, back-emf constant of the actuators. The angular velocity of the motor $\dot{\theta}_m$ is coupled to the linear velocity of the leg through the gear ratio n and pitch p

$$\dot{\theta}_m = \tfrac{2\pi n}{p}\dot{L}_{1-6}. \quad (9)$$

Substituting angular velocity into the voltage equation and for current gives:

$$\dot{I} = \frac{V}{L} - \frac{R}{L}I - \frac{K_b 2\pi n}{Lp}\dot{L}_{1-6}. \quad (10)$$

The mechanical interaction between motor torque τ_m and the platform is described by

$$\tau_m = K_t I \quad (11)$$

$$M_a\ddot{L}_{1-6} + N_a\dot{L}_{1-6} + K_a F = K_t I \quad (12)$$

$$\tau_m = M_a\ddot{L}_{1-6} + N_a\dot{L}_{1-6} + K_a F \quad (13)$$

where K_t is the torque constant and M_a, N_a and K_a are the inertia matrix, viscous damping coefficient and gain matrix of the actuator, respectively.

The mechanical actuator dynamics can relate the motor torque, isolating for the applied force yields:

$$F = \tfrac{K_t}{K_a}I - \tfrac{M_a}{K_a}\ddot{L}_{1-6} - \tfrac{N_a}{K_a}\dot{L}_{1-6}. \quad (14)$$

The resulting force is fed back into the platform dynamics, completing the continuous-time model used.

B. Discrete Dynamic Model

To enable real-time execution within the HIL environment, the continuous-time equations are discretized using the Forward Euler method [13]. Assuming a constant sampling period T, the states derivative is approximated by

$$\dot{x}(t) \approx \frac{x_{k+1} - x_k}{T} \quad (15)$$

where T denotes the sampling period. Hence, by means of (2)-(6) and (10), the discrete dynamics of the system are defined by

$$X_{P-O,k+1} = X_{P-O,k} + T\dot{X}_{P-O,k} \quad (16)$$

$$\dot{X}_{P-O,k+1} = \dot{X}_{P-O,k} + T\ddot{X}_{P-O,k} \quad (17)$$

$$I_{k+1} = \frac{T}{L}V_k + \frac{L - TR}{L}I_k - \frac{TK_b 2\pi n}{Lp}\dot{L}_{1-6,k} \quad (18)$$

with

$$\ddot{X}_{P-O,k} = \Psi^{-1}M_{P-O,k}{}^{-1}\left(J_k^T\Phi - V_{P-O,k}\dot{X}_{P-O,k} - G_{P-O,k}\right) \quad (19)$$

$$\dot{L}_{1-6,k} = \dot{J}_k\dot{X}_{P-O,k} \quad (20)$$

where $\Phi = \frac{K_t}{K_a}I_k - \frac{M_a}{K_a}\dot{J}_k\dot{X}_{P-O,k} - \frac{N_a}{K_a}\dot{L}_{1-6,k}$ and $\Psi = \mathbb{I}_6 + M_{P-O,k}{}^{-1}\frac{M_a}{K_a}J_k^T J_k$, which are solved considering the initial conditions $X_{P-O,0}$ and $\dot{X}_{P-O,0}$.

This recursive formulation is applied to each state variable of the Stewart platform model, resulting in a discrete-time representation suitable for integration with HIL architecture and the execution of digital control algorithms.

C. Controller Design

In controller design, two approaches are commonly adopted when a continuous-time plant model is available. The first involves designing a continuous-time controller based on plant dynamics and subsequently discretizing the controller for digital implementation. The second approach first discretizes the plant model and then designs a discrete controller [14]. Since both the plant and the controller are executed on digital hardware, the second approach is chosen to avoid discrepancies introduced by using a continuous-time model in the discrete-time domain. The Stewart platform plant is implemented using the discretized model described in the previous section, whereas the control algorithm is implemented in C as an independent software module. "Fig. 1" describes the controller side algorithm in pseudocode.

Algorithm 1 Discrete PID Control Algorithm

```
Initialize variables
Initialize UART and timer
while true do
    Receive plant output y_k
    Compute error: e_k ← r − y_k
    Compute proportional term:
    u_P ← K_p e_k
    Compute integral term:
    u_I ← K_i T e_{k−1} + u_{I,k−1}
    Compute derivative term:
    u_D ← K_d (e_k − e_{k−1}) / T
    Compute control signal:
    u_k ← u_P + u_I + u_D
    Update stored variables:
    e_{k−1} ← e_k
    u_{I,k−1} ← u_I
    Wait until next sampling period
    Transmit u_k to the plant
end while
```

Fig 1. Discrete-time controller pseudocode.

Functional testing of this HIL simulation is performed with a basic PID controller [15], which satisfies trajectory following for the moving platform. It is designed as:

$$u_k = K_P e_k + u_{I,k-1} + K_I T e_k + \frac{K_D}{T}(e_k - e_{k-1}). \tag{21}$$

Moreover, the embedded side controls the timing and synchronization during the HIL simulation, allowing the exchange of plant measurements and control commands at each sampling instant. During each sampling period, the embedded platform requests the current plant states, compares them with the reference input, and computes a corresponding control action described by:

$$u_k = u_{Pk} + u_{Ik} + u_{Dk}. \tag{22}$$

The resulting output, represented as actuator voltage, is transmitted back to the plant for the next state update.

III. HARDWARE-IN-THE-LOOP FRAMEWORK

The proposed HIL framework employs an NXP FRDM-MCXN947 development board as the embedded controller and a host computer executing the Stewart Platform model in MATLAB®.

A. Hardware setup

The hardware used consists of a NXP FRDM-MCXN947, which features Dual Arm® Cortex®-M33 cores at 150MHz each, 2 MB of on-chip Flash memory, 512 KB of SRAM, and multiple communication peripherals, including Ethernet, USB, SPI/I²C/UART, Wi-Fi connector and CAN [16]. These characteristics make the platform suitable for real-time control applications and rapid prototyping.

System control is managed by the embedded processor running C-based software developed with the MCUXpresso SDK. To facilitate HIL testing, the Stewart Platform model runs on a host computer, establishing a continuous data exchange with the embedded controller through an asynchronous UART interface at 115200 baud rate. *"Fig. 2"* illustrates the overall setup of the proposed HIL system.

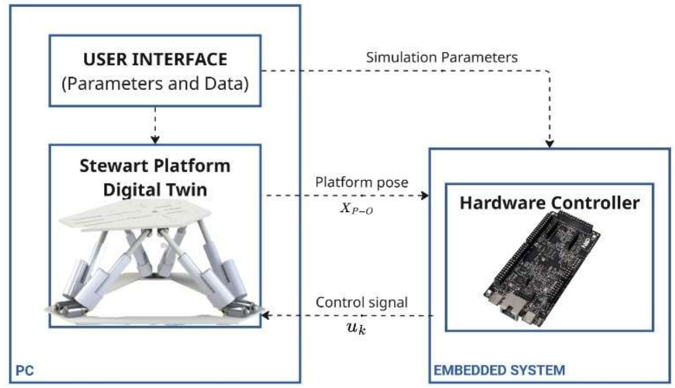

Fig 2. Stewart Platform and Hardware controller setup.

B. System Architecture

The proposed architecture enables the evaluation of control algorithms under conditions that closely resemble physical experimentation with an embedded system and a digital twin. Both components are integrated through a serial interface to achieve a closed-loop system illustrated in "Fig. 3".

Additionally, it maintains the flexibility of a simulation environment without modifying the plant model and provides a modular framework for performance comparison.

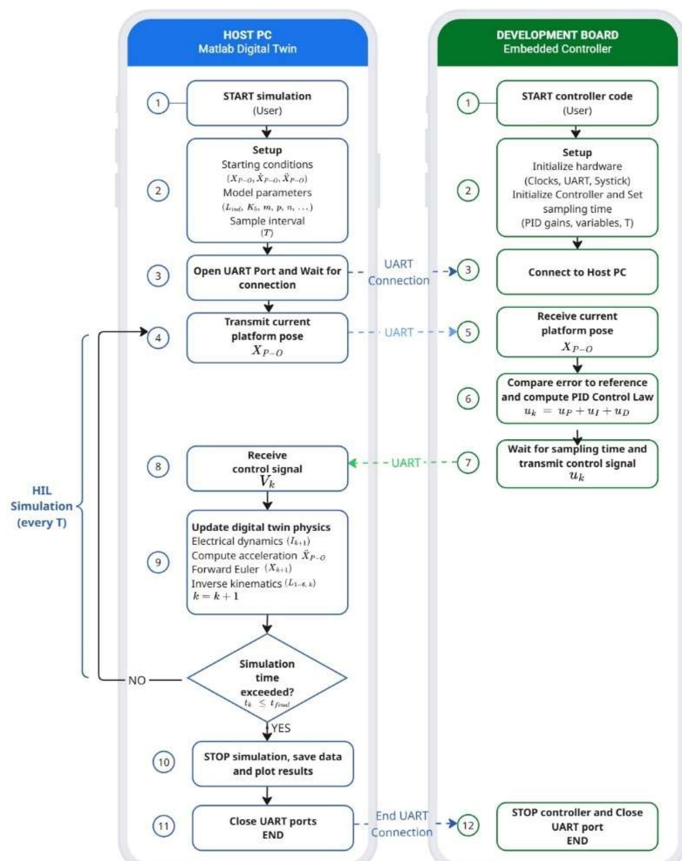

Fig 3. Stewart Platform and Hardware controller closed-loop system.

IV. RESULTS

Regarding the Stewart Platform digital twin, the continuous-time model was evaluated under several open-loop input signals. The resulting platform motion was analyzed to evaluate a physically consistent response with an initial pose condition of $X_{P-O} = [0, 0, 0.25, 0, 0, 0]$. *"Fig. 4"* shows the platform position increasing with a constant positive actuator voltage, which generates an upward displacement.

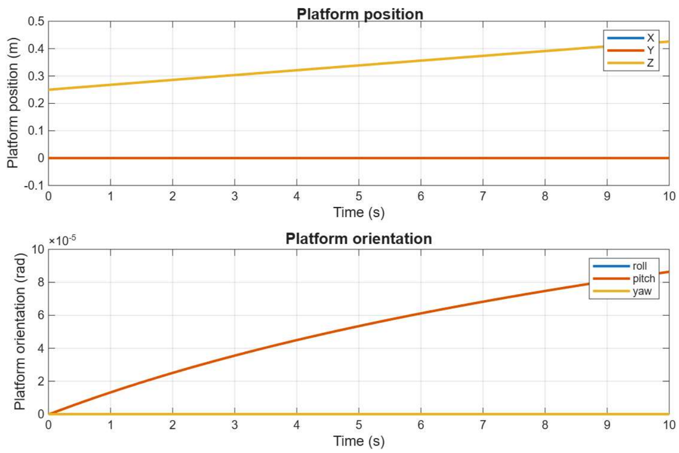

Fig 4. Continuous-time model response to positive constant voltage.

A constant zero voltage, where the generated actuator force is insufficient to support the platform weight, was then applied to validate both the continuous-time and discrete-time model. *"Fig. 5"* shows the position of the platform descending under gravitational forces while *"Fig. 6"* exhibits the same response for discrete-time.

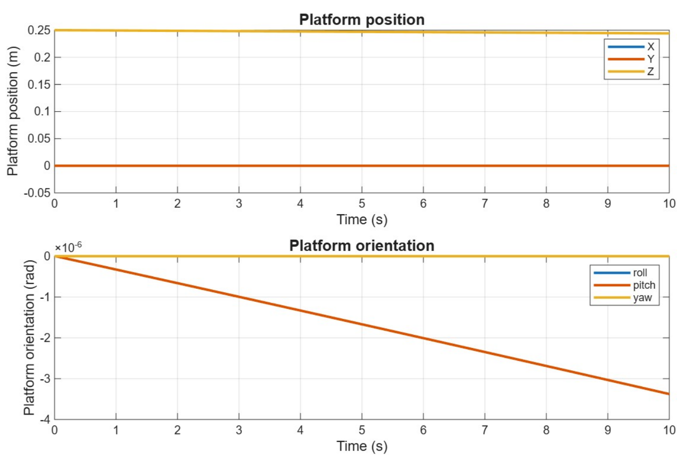

Fig 5. Continuous-time model response to zero constant voltage.

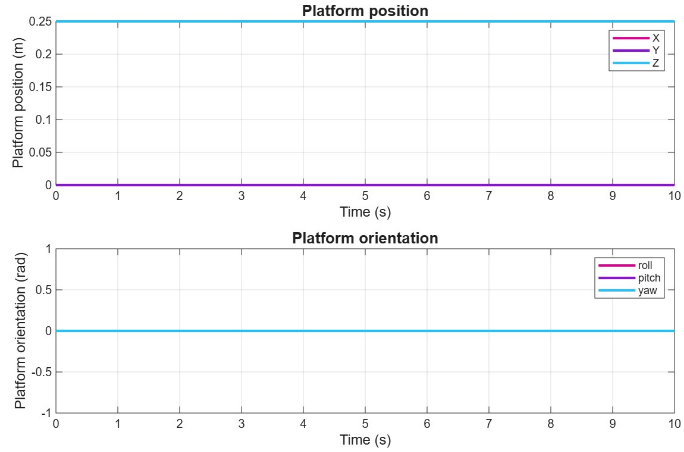

Fig 6. Discrete-time model response to zero constant voltage.

The HIL architecture was successfully validated by generating the actuator voltage commands on the embedded development board and transmitting them to the digital twin in real time. The platform response was consistent with the behavior obtained using equivalent constant voltage inputs applied directly in MATLAB, demonstrating the successful implementation of real-time communication between the digital twin and the development board.

V. CONCLUSIONS

This work presented the development of a Hardware-in-the-Loop framework designed for real-time simulation and control of a Stewart platform digital twin. This approach enables systematic testing, tuning, and validation of control schemes without requiring access to a physical parallel manipulator, thereby reducing cost, risk, and development time. Furthermore, the modular nature of the digital twin and HIL simulation allows for its use with other complex robotic and mechanical systems. Consequently, this proposal provides an accessible solution for students and researchers to explore advanced control strategies.

Future work could involve the integration of middleware like Robot Operating System (ROS) and Computer-Aided Design (CAD) models, which will enhance the digital twin's accuracy, providing a more robust and intuitive tool for testing advanced control algorithms.

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