

Modeling and Validation of a Digital Twin for a 3DOF Parallel Manipulator Ball Balancing System

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Abstract

Cyber-physical robotic systems play a critical role in modern aerospace applications where precision, reliability, and predictive monitoring are essential. This research presents the development of a digital twin of a three-degree-of-freedom (3DOF) ball balancing robot using Simscape Multibody, designed to replicate the dynamic behavior of a parallel manipulator-based stabilization platform. The study aims to create a virtual model capable of mirroring the physical system's motion, control response, and interaction between mechanical and electronic components.

The methodology involves constructing a detailed multibody model of the 3DOF robotic mechanism, including link dynamics, actuator motion, and sensor-based feedback for ball position detection. The digital twin integrates a closed-loop control strategy to maintain platform stability and regulate ball motion under varying disturbances. Realistic system parameters and control algorithms are incorporated to ensure accurate synchronization between simulated and physical system behavior. The developed model enables testing of control strategies, performance optimization, and system response evaluation in a safe virtual environment.

The results indicate that the digital twin successfully reproduces the stabilization characteristics of the physical robot, demonstrating dependable prediction of system behaviour and effective visualization of dynamic responses. The model supports controller tuning, fault analysis, and performance validation without requiring continuous physical experimentation.

This work highlights the potential of digital twin technology in enhancing cyber-physical robotic systems for aerospace applications, particularly in areas such as precision motion control, system validation, and predictive maintenance, thereby improving development efficiency and operational safety.

Index Terms

Digital Twin, Cyber-Physical Systems, Simscape Multibody, Parallel Manipulator, Dynamic Modeling