INC09

Digital Twin-AI Driven Agent

CONTROL SYSTEMS AND INSTRUMENTATION ENGINEERING PROGRAM

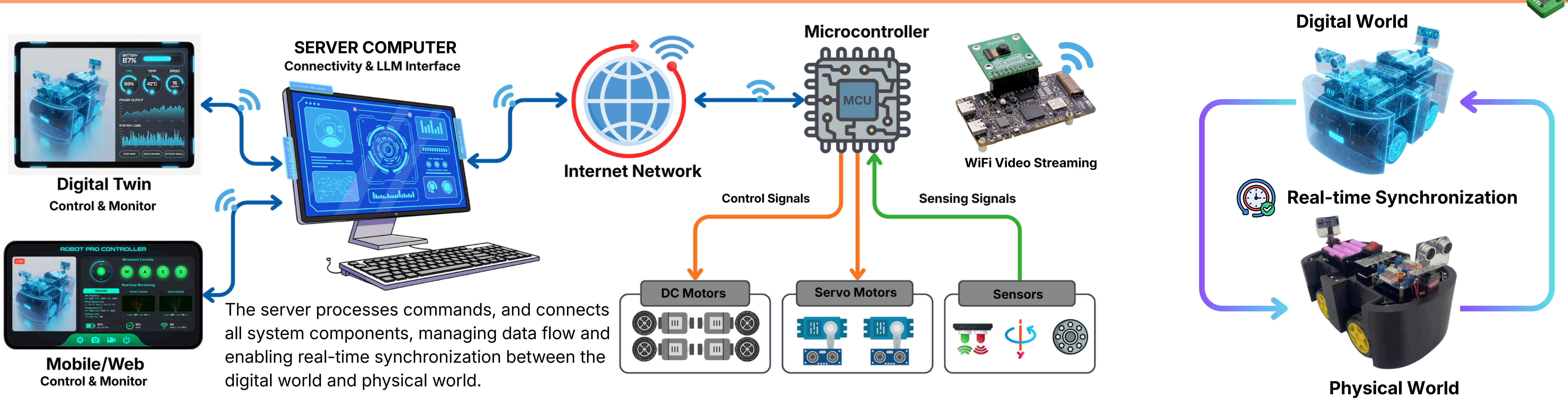
Mr. Nattawat Putthaprasert, Mr. Chindanai Suksalee | Advisor : Asst.Prof.Dr. Santi Nuratch

Abstract

As robotics advances toward greater autonomy, the integration of Artificial Intelligence (AI) and Digital Twin technology has become a key enabler of smart automation. This project presents an AI-driven Digital Twin framework for an autonomous 4WD mobile robot. Unlike conventional systems, the proposed platform incorporates a Large Language Model (LLM) as a high-level AI agent, capable of interpreting natural language commands and translating them into precise navigation actions. The hardware system is built on an ESP32 microcontroller, supporting real-time control and sensor integration, including ultrasonic radar for environmental perception. A low-latency, bi-directional communication link based on HTTP/JSON ensures continuous synchronization between the physical robot and its 3D virtual counterpart. Experimental results demonstrate an intuitive and responsive system, where the Digital Twin not only enables real-time monitoring but also enhances operational safety through autonomous obstacle avoidance. The proposed framework offers a scalable and flexible solution for future smart warehouse and industrial automation applications.

Keywords: Digital Twin Framework, AI-based Reasoning, ESP32, Real-time Monitoring, Industrial Automation

System Overview



The proposed system introduces an AI-driven Digital Twin architecture that enables real-time, closed-loop monitoring and control of a mobile robot through the integration of cloud computing, embedded systems, and intelligent reasoning. The system consists of four main components: a user interaction layer, a server computer with LLM integration, a communication network, and an embedded control system. Users interact via a Digital Twin dashboard and mobile/web interface, allowing real-time visualization and command input. The server acts as the central unit, integrating a Large Language Model (LLM) to interpret commands and generate control signals. Communication is achieved through a bi-directional HTTP/JSON protocol, ensuring continuous data exchange between the server and the robot. The ESP32-based system executes control commands and collects sensor data, including ultrasonic sensors and an IMU. The Digital Twin maintains real-time synchronization with the robot, reflecting its state, position, and environment for accurate monitoring and responsive control.

Methodology

System Architecture & Intelligence Layer

The system is designed using a layered architecture, where a Large Language Model (LLM) functions as the central intelligence and reasoning engine. It interprets high-level natural language commands and translates them into structured control actions in real time, enabling intuitive human–robot interaction and adaptive, context-aware decision-making.

Hardware Implementation

The physical platform is a 4WD mobile robot controlled by an ESP32 microcontroller. The system integrates DC motors for movement, servo motors for actuation, and sensors including ultrasonic sensors and an IMU for environmental perception and motion tracking, enabling real-time operation.

Communication & Data Synchronization

A bi-directional communication framework is implemented using HTTP/JSON over an Internet network. Control signals are transmitted from the server to the robot, while sensor data is continuously returned. This ensures low-latency communication and real-time synchronization between the physical robot and its Digital Twin.

Digital Twin Visualization & Control

A web-based Digital Twin interface is developed to provide real-time 3D visualization of the robot's state. The virtual model reflects position, orientation, and sensor data, enabling continuous monitoring and remote control within a closed-loop system.

Experimental Results

Real-Time Digital Twin Synchronization

The system achieves accurate real-time synchronization between the physical robot and its Digital Twin. Sensor data, including position, orientation, and ultrasonic measurements, is continuously transmitted and reflected in the virtual model with low latency. The Digital Twin maintains consistent state updates, demonstrating reliable bi-directional data flow and precise system representation.

Autonomous Obstacle Avoidance Performance

The robot successfully performs autonomous obstacle avoidance using ultrasonic sensing and real-time control. When obstacles are detected within a predefined threshold, the system responds immediately with corrective actions. Experimental trials demonstrate stable and consistent performance, ensuring safe navigation in dynamic environments.

LLM-Based Command Interpretation

The integrated LLM interprets natural language commands and translates them into control actions. Users can issue high-level instructions, which are executed accurately by the system. This demonstrates intuitive human–robot interaction without requiring low-level programming.

System Responsiveness & Reliability

The overall system exhibits low-latency response and stable operation under continuous data exchange. The closed-loop architecture ensures timely feedback between the physical robot and the Digital Twin, resulting in responsive control and reliable system performance.

Conclusion

This project demonstrates an AI-driven Digital Twin framework for real-time monitoring and control of a mobile robot. By integrating a Large Language Model (LLM) with a bi-directional communication architecture, the system enables intuitive human–robot interaction and reliable closed-loop control. The Digital Twin maintains accurate real-time synchronization, enhancing system awareness and operational safety through autonomous obstacle avoidance. The results validate the effectiveness of the proposed approach and highlight its potential for scalable deployment in smart warehouse and industrial automation applications.

References

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