

A Proposal for a Low-Cost Educational Digital Twin with Real-Time Web Interface

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Abstract. *This paper presents a proposal for the development of a low-cost educational digital twin for the URA robot, featuring a real-time web interface. The initiative aims to democratize access to interactive technologies in STEM education, promoting practical learning through the integration of hardware, software, and digital simulation. The platform is expected to contribute to student engagement in investigative activities, promoting skills such as critical thinking and autonomy. This article describes the project’s motivations, architecture, and current results, which include a functional prototype of the robot, a web visualization platform, and a defined communication architecture using MQTT. Finally, it presents the next steps for integration and practical validation.*

1. Introduction

The concept of Digital Twin (DT) has emerged as a key technology in Industry 4.0, enabling real-time representation and monitoring of physical assets through virtual models [Tao et al. 2018, Jamwal et al. 2021]. Its predictive capabilities allow simulating future scenarios, identifying failures, and improving productivity and cost efficiency.

However, the adoption of such technologies requires qualified professionals, which highlights the role of education. Educational robotics has been recognized as an effective approach to develop skills such as programming, problem-solving, and computational thinking [Weipeng Yang 2022], in line with the National Curricular Parameters (PCNs) [Brazil, Secretariat of Fundamental Education 1998]. Nevertheless, high-cost kits remain a major barrier to widespread use in basic education [Guedes et al. 2012].

This work-in-progress addresses these challenges by proposing a low-cost digital twin for the URA educational robot [Torres et al. 2015], designed for real-time interaction via a web interface. The initiative aims to create a replicable platform for teaching IoT [Laghari et al. 2022], robotics, and system simulation, fostering active learning and Industry 4.0 skills. Currently, the project is in its initial phase, involving architecture design and prototype development, with the goal of democratizing DT technology in educational contexts.

2. Related Works

Digital Twin (DT) technology, central to Industry 4.0, involves dynamic virtual models connected to physical counterparts via real-time data, enabling continuous monitoring, simulation, and predictive analysis [Tao et al. 2018, Dai and Brell- okcan 2022].

In education, DTs offer pedagogical benefits like visualizing abstract concepts, hands-on experimentation, and safe testing, alongside remote access for enhanced engagement [Kandasamy et al. 2022, Lee et al. 2023, Liljaniemi and Paavilainen 2020]. Despite these advantages, adoption in educational settings is hindered by significant challenges. Commercial DT platforms, such as Siemens NX or NVIDIA Omniverse, offer powerful simulation capabilities but come with high licensing costs and require substantial computational resources, making them inaccessible for most educational institutions [Kangisser et al. 2022]. Furthermore, their complexity demands specialized training for both teachers and students, creating a steep learning curve that is often impractical for basic and secondary education [Rodríguez et al. 2017]. Our work addresses these challenges by proposing a low-cost DT solution for the URA robot, integrating affordable hardware with an accessible web-based simulation layer to democratize advanced technologies in education.

3. Proposed Work

This proposal details the development of a digital twin (DT) for the URA educational mobile robot, a low-cost platform using a smartphone as its primary control unit [Riedel-Kruse and Gerber 2017]. The robot's physical structure is 3D-printed [Cabrera et al. 2022], and its core is an ESP32 microcontroller, chosen for its low energy consumption, dual-core processing, and integrated Wi-Fi/Bluetooth, ideal for IoT and educational robotics [Hercog et al. 2023]. Locomotion is managed by two DC motors controlled by an L298N H-bridge

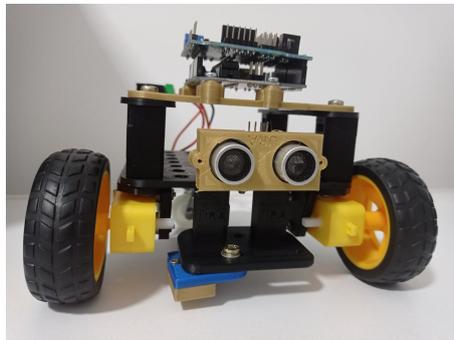


Figura 1. The URA physical robot prototype.

The proposed DT aims to virtually replicate the robot's state and behavior, enabling remote visualization and interaction. It will display synchronized movement and monitor real-time data from motors and sensors. Data communication will use MQTT, a lightweight protocol optimized for resource-limited devices and low-bandwidth networks, integrating well with the ESP32 ecosystem

Data communication will use the MQTT protocol, a lightweight solution optimized for devices with limited resources and low-bandwidth networks [Zhang et al. 2024]. This protocol was chosen because the classroom context perfectly matches the benefits that MQTT offers. This structure ensures efficient and organized data exchange between the physical robot and the web platform.

3.1. Educational Aspects

The synchronous interaction between the physical URA robot and its DT fosters experiential learning, allowing users to observe real-time correspondence between commands and actions, and perform risk-free simulations [de Sena et al. 2019]. This approach aligns with constructivist principles, promoting active learning and iterative experimentation, thereby increasing conceptual understanding and engagement [Freire 1987].

The platform’s versatility supports its use in higher education for embedded systems and real-time applications, in secondary education for physics concepts via project-based learning [de Sena et al. 2019], and at elementary levels for programming and spatial orientation [Xeferis and Palaigeorgiou 2019]. By integrating accessible physical components with virtual simulation, the URA DT addresses cost and accessibility barriers in educational robotics, offering a low-cost, scalable solution for diverse educational contexts [Rodríguez et al. 2017].

3.2. Low Cost

This project prioritizes financial accessibility, aiming to overcome the high costs of commercial kits like Lego Mindstorms (approx. US\$390) [Riedel-Kruse and Gerber 2017]. Low-cost platforms such as Arduino and ESP32 are favored for their flexibility and affordability. An estimated cost of essential components for the URA robot is approximately US\$24.72, highlighting its potential for replication in resource-constrained institutions.

4. The Digital Twin Web Platform

The platform aims to provide students with a free, easy-to-use, cross-platform tool to test and visualize the URA robot’s state. Developed as a website using technologies like Three.js and React.js, it requires only internet access, facilitating broad distribution without specialized hardware. Accessibility is a core consideration, following Web Content Accessibility Guidelines (WCAG) 2.1. Key features include 3D visualization of the URA robot, Augmented and Virtual Reality views, MQTT connectivity with the physical robot, real-time sensor and actuator state monitoring, and the ability to save and reproduce states virtually and physically by sending commands back to the robot.

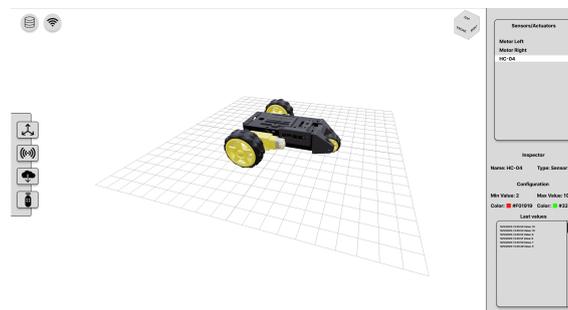


Figura 2. Editor UI and 3D model visualization

The application offers two main interaction modes: the editor (3D viewer) for setup and configuration, and the augmented reality (AR) viewer for quick behavior inspection. The editor interface features a top bar for MQTT and database connections and view manipulation, a left bar for adding and adjusting sensors, reproducing data in real-time or from the database, and launching the AR viewer. The AR viewer, built on AR.js,

uses marker tracking to overlay live or stored data in mixed reality and allows command execution for actuator and sensor control, acting like a remote joystick.

5. Development Planning

The development of the digital twin for the URA robot follows an iterative plan divided into phases, enabling continuous validation and adjustments. With the physical prototype and electronic components already defined, current efforts focus on hardware adaptation, software planning, integration, and validation.

5.1. Main Phases and Estimated Timeline

The project timeline includes four main phases: Phase 1, which involves component survey and testing; Phase 2, focused on physical-virtual integration and webcam incorporation; Phase 3, dedicated to system testing and validation; and Phase 4, covering documentation and preparation for demonstration.

5.2. Methodology

An agile Scrum methodology is adopted, organizing work into two-week sprints with an expected duration of six months [Cervone 2011]. Each sprint delivers testable features, including functionality tests (sensor readings, commands, visuals), integration tests (communication via MQTT between robot and web platform), and accuracy and performance tests (synchronization fidelity, latency). The development is guided by usability principles to facilitate future educational adoption, while formal pedagogical feedback remains planned as future work.

Formal pedagogical feedback, planned as future work, will be conducted through case studies with students and teachers. We intend to use surveys and observational methods to assess the platform's impact on student engagement and learning outcomes.

6. Results

The key outcomes achieved to date include:

- **Functional Robot Prototype:** The successful assembly and operation of the URA robot prototype, with its defined sensors and actuators, has been completed.
- **Web Platform for Digital Twin:** A web-based platform has been developed using Three.js and React, enabling real-time 3D visualization and control of the robot's virtual model (as shown in Figure 2).
- **System Architecture:** A robust architecture was designed, defining MQTT over Wi-Fi as the communication protocol for data exchange between the physical and virtual entities (illustrated in Figure 3).
- **Cost Analysis:** A comprehensive cost analysis confirmed the financial viability of the project, with an estimated component cost of under US\$25.
- **Literature Review:** A thorough literature review was conducted to ground the project's scope and validate its contribution to the field.

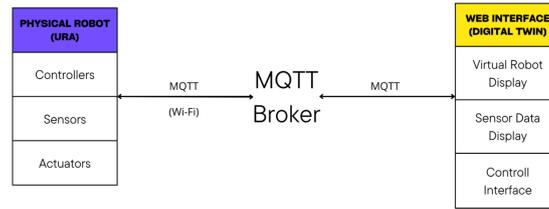


Figura 3. Digital Twin Architecture Diagram

6.1. Anticipated Challenges

- **Low Latency Communication:** Ensuring low latency and efficient MQTT communication is crucial for a smooth user experience. To address this, we will optimize data packet size and transmission frequency, and implement client-side interpolation algorithms to handle potential network jitter.
- **Synchronization Accuracy:** Achieving accurate synchronization between the physical and virtual robot states is critical. This will be managed by using synchronized timestamps (NTP) on all messages and developing a buffering mechanism on the web client to reorder any out-of-sequence data packets.
- **User Interface Design:** Balancing the simplicity of the user interface with sufficient educational functionality is a key challenge. We plan to conduct usability tests with target users (students and teachers) to gather feedback and iteratively refine the interface based on their input, focusing on clarity and ease of use.

7. Final Considerations

This ongoing work contributes to the field of Educational Robotics by proposing a low-cost and user-friendly digital twin platform designed to better prepare professionals for the challenges of Industry 4.0. Although some limitations remain, such as the fidelity of the simulation and the preliminary stage of pedagogical evaluation, the project establishes important foundations for accessible educational tools that integrate physical and virtual learning environments.

The immediate next phases of development include the physical-virtual integration and implementation of a webcam feature. Additionally, work will focus on developing mixed reality functionalities that combine virtual and real robot visualization. Finally, comprehensive functional and accuracy testing will be conducted, emphasizing system latency and synchronization between the physical and digital representations.

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