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RESEARCH PAPER

Enhancing STEM Learning through Interactive Digital Twins: Architecture of a Low-Cost Web Solution for Robotics

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Abstract. Educational robotics is a powerful approach for developing STEM skills; however, its widespread adoption is often constrained by the high cost of commercial robotic kits and by the complexity of integrating physical hardware with virtual learning environments. In the context of Industry 4.0, the Digital Twin (DT) concept emerges as a strategic bridge between physical assets and virtual models, yet its application in basic and higher education remains limited by technical and financial barriers. *Purpose:* To address these challenges, this article presents a web-based Digital Twin architecture that utilizes the low-cost mobile educational platform URA (One Robot per Student) as a case study. The study aims to provide an accessible and scalable solution for real-time monitoring, simulation, and remote interaction, democratizing access to advanced robotics and IoT concepts. *Methods:* The proposed system integrates an ESP32-based physical robot with a web interface implemented using React.js and Three.js. Communication between the physical and virtual layers is achieved via the MQTT protocol to ensure low-latency data exchange. The platform includes a three-dimensional visualization module for state monitoring and an augmented reality component to support immersive interaction. The research methodology involved a technical evaluation focused on communication latency and synchronization fidelity between the robot's sensor data (ultrasonic, vibration, and magnetometer) and its virtual counterpart. Furthermore, the study analyzes the pedagogical alignment of the platform with constructivist and constructionist learning principles, emphasizing the importance of active experimentation. *Results:* Technical evaluations indicate that the system maintains responsiveness and synchronization accuracy within acceptable limits for educational applications, with average latency levels suitable for real-time user perception. The orientation error observed between the physical and virtual entities remained minimal, ensuring a high-fidelity representation. Additionally, the estimated cost of the essential electronic components is approximately US$24.72, which is substantially lower than that of commercial educational robotics platforms, such as Lego Mindstorms. This financial accessibility allows for the replication of the project in resource-constrained institutions. *Conclusion:* These results demonstrate that the proposed Digital Twin constitutes a viable and cost-effective solution for educational robotics. By enabling students to safely experiment in virtual environments before validating their solutions on real hardware, the platform effectively reduces financial and technical barriers in STEM education. The integration of web technologies and open-source hardware reinforces the scalability of the approach, contributing to the democratization of advanced simulation technologies in the teaching-learning process.

Keywords: Digital Twin, Educational Robotics, Low Cost, IoT, Web Interface, Engineering Education

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1 Introduction

The concept of a digital twin (DT) has emerged as a promising technological solution, establishing a bridge between the physical environment and its virtual counterpart. Through the collection and analysis of real-time data, combined with machine learning techniques, the digital twin allows dynamic modeling of asset behavior and performance, enabling continuous monitoring, diagnosis, and operational prognosis. As noted by Tao et al. (Tao *et al*. [2018]), the ability to simulate future scenarios and identify potential failures is a strategic differentiator for Industry 4.0 (Jamwal *et al*. [2021]), directly impacting productivity improvement and cost reduction.

However, the successful adoption of these technologies intrinsically depends on the availability of qualified professionals, which directs the focus toward the importance of educational training. Parallel to technological innovation in the productive environment, the relevance of education for the mastery and application of these emerging technologies is highlighted. Since the XX century, there has been an increase in the integration of automated tools into society, requiring individuals to develop skills related to programming, robotics, and computational thinking. Educational robotics emerges as a pedagogical approach that incorporates such technologies into teaching practices. By providing practical experiences in programming and manipulating robots, this teaching tool stimulates logical reasoning, problem solving, cognitive flexibility, and self-monitoring of learning, skills considered essential for the comprehensive education of students (Yang *et al*. [2022]). Such practices are aligned with the guidelines of the National Curricular Parameters (PCNs), which guide Brazilian basic education regarding the integration of technologies into the pedagogical process (Brazil [1998]).

However, the distribution of these pedagogical innovations remains uneven, facing barriers that hinder their democratization in basic education. The high cost of educational kits is a determining factor, as studies indicate that financial and infrastructure limitations are currently among the main obstacles. Evidence of this can be observed in a study involving 302 Greek teachers, in which 59.3% identified the cost of kits as the primary reason for not adopting robotics in educational settings (Gavrilas *et al.* [2025]). This technological gap creates a disconnect between the school curriculum and the competencies required by the labor market, affecting students' understanding of how these tools may influence their future careers.

Given this scenario, this research is articulated along two complementary axes: the first, dedicated to proposing a free and accessible technological solution for implementing digital twins with augmented and virtual reality support; the second, focused on enhancing technological education, promoting the development of skills necessary for the qualified insertion of students into the context of Industry 4.0. Thus, it is expected to contribute to the advancement of scientific and technological knowledge, as well as to the formation of capable and critical human capital, fit to act on the contemporary demands of the digital society.

In this context, the paper presents the development of a web-based digital twin platform. In this work, we present the architecture and software that were created for this platform. To validate our platform, we used the open-source URA robot as a real twin. The URA's robot is an educational mobile robot Torres *et al.* [2014], designed as a low-cost tool and developed within a university research laboratory. The project emphasizes accessibility and educational use, enabling real-time integration between a physical robot and its virtual counterpart through a web interface. The proposed environment aims to support the practical teaching of fundamental concepts in technology-oriented courses, such as the Internet of Things (IoT) Souza *et al.* [2025], robotics, programming, and system simulation, fostering active learning, interdisciplinary practices, and skills aligned with Industry 4.0.

At its current stage, the project has reached a functional prototype and includes an initial technical evaluation focusing on synchronization between the physical and virtual systems. Although the development is ongoing, the results obtained so far indicate the feasibility and educational suitability of the proposed approach. It is expected that the continued evolution of this work will further contribute to the democratization of digital twin technologies in educational contexts, expanding practical and formative opportunities for students.

This article presents an extended version of the work originally published in the Work in Progress (WIP) track of the 27th Symposium on Virtual and Augmented Reality (SVR 2025), entitled "A Proposal for a Low-Cost Educational Digital Twin with a Real-Time Web Interface." While the original version introduced the initial concept and architectural proposal, the present manuscript substantially expands the study by providing a more comprehensive discussion of related work, a detailed description of the digital platform with additional experiments and case studies, and an expanded analysis of the pedagogical alignment of the proposed solution. Moreover, this version reports preliminary experimental results obtained from the implemented prototype, characterizing the current stage of development while indicating that the system remains under ongoing refinement and evaluation. The main scientific contributions of this work are summarized as follows:

- **Development of a Novel Web-Based Digital Twin Architecture:** While the physical layer adopts the existing low-cost URA robot platform, this work introduces a newly developed software architecture that integrates React.js, Three.js, and the MQTT protocol to provide a seamless, low-latency bridge between physical and virtual environments.
- **Integrated Visualization and Augmented Reality (AR) Modules:** We developed original software components for real-time 3D state monitoring and immersive AR interaction, specifically tailored for resource-constrained educational settings.
- **Technical and Pedagogical Evaluation:** This study provides a new, comprehensive evaluation of synchronization fidelity and communication latency, alongside an expanded analysis of how this specific Digital Twin implementation could align with constructivist and constructionist learning principles.
- **Standardization of Low-Cost Frameworks:** By adapting standard web technologies for educational robotics, this work contributes a replicable framework that reduces the financial and technical barriers identified in prior research.

2 Related Works

The concept of Digital Twin (DT), originated in the aerospace industry and popularized in the context of Industry 4.0 (Tao *et al.* [2018]), represents a paradigm shift in how physical systems are designed, monitored, and managed. Essentially, a Digital Twin consists of a dynamic virtual representation of a physical object, process, or system, connected to its real counterpart through a bidirectional flow of real-time data. This connection allows for not only visualization of the current state of the physical system but also simulation of future scenarios, performance analysis, and early identification of potential failures or optimizations (Tao *et al.* [2018]). Unlike static models, such as those found in traditional Building Information Modeling (BIM) approaches, the dynamic and connected nature of a Digital Twin enables continuous and adaptive interaction with the physical world, reflecting its changes and behaviors in real-time.

The transformation potential of Digital Twins quickly surpassed the factory floor, finding promising applications in various sectors, including engineering and technology education. The ability of DTs to mirror complex real-world systems in a controlled virtual environment offers a range of significant pedagogical benefits. Recent studies demonstrate that the use of DTs can facilitate the visualization of abstract concepts and complex processes, making them more tangible and understandable for students (Lee *et al.* [2023]). In addition, DTs promote hands-on and experiential learning, allowing students to interact, manipulate, and experiment with virtual representations of real equipment or systems. This practical approach is crucial for developing technical skills but is often limited in traditional teaching due to cost, space, or safety constraints.

Safe experimentation is another key benefit provided by DTs. Students can test configurations, program control sequences, or simulate failure conditions in the virtual environment without the risk of damaging expensive physical hardware or compromising the safety of critical systems, such as power grids or industrial plants (Kandasamy *et al*. [2022]). This freedom to explore and make mistakes in a safe environment is fundamental for deep learning and the development of student confidence. Furthermore, the digital nature of DTs inherently facilitates remote and flexible access, allowing students to access virtual laboratory resources anytime, anywhere, overcoming geographical barriers or limitations of physical access to laboratories, a particularly relevant point in hybrid or distance learning scenarios. The interactivity and visualization capabilities of DTs have also been associated with increased student engagement and motivation, making the learning process more stimulating and effective (Liljaniemi and Paavilainen [2020]). Finally, DTs serve as excellent tools for teaching systems integration and technology, allowing students to visualize how different components (sensors, actuators, controllers, software) interact throughout the lifecycle of a product or process.

In the specific context of educational robotics, the literature points out that the use of Digital Twins is an emerging field, characterized mainly by experimental approaches and the construction of prototypes aimed at creating interactive and immersive learning environments. Several studies propose the combined use of three-dimensional models, physical sensors, and real-time simulation to replicate robotic systems in virtual environments, enabling remote control, monitoring, and even teleoperation (González-Herbón *et al*. [2024]; Kaarlela *et al*. [2022]). These initiatives seek to bring students closer to the actual behavior of the robot, even in the absence of direct physical contact with the equipment.

In this context, Magrin *et al*. [2021] propose a Digital Twin as an open-source learning tool for the development and study of mobile robots. Their approach uses a virtual model to support the evaluation of locomotion behavior and the analysis of different sensor configurations before the physical assembly of the robot. This strategy can reduce the costs and risks associated with early-stage experimentation while allowing students to explore mechanical, electronic, and programming concepts at different levels of knowledge. The work is particularly relevant to the present study because it demonstrates that Digital Twins can be used not only to monitor or replicate an existing physical system, but also as an educational resource for understanding, designing, and experimenting with mobile robotic platforms.

Remote educational infrastructures have also been extensively investigated, as exemplified by the Unibotics architecture proposed by Roldan-Alvarez et al. (Roldán-Àlvarez *et al*. [2024]), which allows students to solve robotic programming challenges in simulated scenarios through a web platform, mitigating limitations associated with the availability of physical hardware and direct contact with equipment. In the same vein, other research goes beyond traditional simulation by exploring the use of mixed reality technologies, with the aim of making interaction with digital twins more immersive and closer to the real physical environment. The study presented in (Lee *et al*. [2024]) investigates the convergence between mixed reality, the Internet of Things (IoT), and digital twins, highlighting technical challenges related to data synchronization, interoperability between heterogeneous platforms, and maintaining consistency between the physical world and its virtual representation. To address these limitations, the authors propose the concept of Mixed Reality Virtual Device (MRVD), an architecture that extends the traditional concept of digital twins by including mixed reality devices themselves as components of the digital world, delegating to them advanced processing, communication, and data management functions.

These approaches, based on remote simulation and mixed reality, complement purely virtual environments by providing richer educational experiences that are closer to interaction with the physical environment. Still, studies such as that by (Peidró *et al*. [2016]) demonstrate that simultaneous integration between virtual and physical environments can offer additional benefits to the learning process. This study presents a virtual and remote laboratory of parallel robots, consisting of a simulation and a real robot, in which students can simulate kinematic problems and then perform experiments on physical hardware, allowing them to observe nuances that are not apparent in the virtual environment (Peidró *et al*. [2016]). This integration between programming, real hardware, and the web environment reinforces the technical and pedagogical feasibility of using Digital Twins in distance learning of robotics and automation. González-Herbón *et al*. [2024]

Concrete examples of these educational applications can be found in various areas. In construction engineering, DTs of construction sites allow for virtual exploration and analysis of construction processes (Lee *et al*. [2023]). In electrical and computer engineering, DTs of electrical microgrids are used for cybersecurity training, enabling the simulation of attacks and validation of countermeasures in a safe and scalable environment (Kangisser *et al*. [2022]). In automation engineering, DTs of flexible manufacturing systems enable the programming and debugging of programmable logic controllers (PLCs) before implementation on physical hardware (Rodríguez-Rodríguez *et al*. [2017]). Even in mathematics education, the DT concept has been explored to create gamified models that represent and track student engagement and progress, personalizing the learning experience (Liljaniemi and Paavilainen [2020]). These diverse applications underscore the versatility and broad potential of Digital Twins as innovative pedagogical tools.

Despite the advances reported, the literature also highlights significant challenges associated with the implementation of Digital Twins in educational contexts. Among the main obstacles are the high cost of proprietary industrial platforms and the complexity involved in accurately modeling systems and efficiently integrating data Kangisser *et al*. [2022]. Similarly, Gavrilas *et al*. [2025] identified several barriers to the adoption of educational robotics, including infrastructure limitations (85.5%), high costs or limited availability of kits (59.3%), and limited teacher knowledge (49.3%). Additionally, approximately 81% of participants reported frequent dependence on technical support, suggesting that many current solutions require specialised assistance for deployment and maintenance.

These challenges reflect broader difficulties commonly observed in the adoption of innovative educational technologies. Initiatives such as the Ciberlândia project demonstrate that the high cost of robotics kits and the logistical difficulties associated with competitions may exclude schools and students with fewer financial resources. Furthermore, the shortage of teachers with adequate technical training to use these tools constitutes an additional barrier to their widespread adoption Rodríguez-Rodríguez *et al*. [2017].

The literature reveals that the ecosystem of Digital Twin solutions is not homogeneous. Existing approaches range from highly integrated industrial platforms to lightweight educational tools designed to prioritize accessibility, usability, and low-cost deployment. This heterogeneity highlights two important aspects. First, it demonstrates the relevance of distinguishing approaches that prioritize accessibility from those focused primarily on advanced functionality. Second, it reinforces the ongoing need for modular and low-cost solutions capable of balancing ease of use with sufficient fidelity for educational purposes. Therefore, although many Digital Twin implementations still involve significant technical demands, there remains a clear opportunity to expand and standardize accessible platforms that reduce both financial and technical barriers for educational institutions with limited infrastructure.

In this context, the proposed URA Digital Twin addresses these concerns through the coordination of physical sensing, MQTT-based communication, virtual-state representation, and web-based visualization. Rather than implementing a complete industrial Data Fusion Core, as discussed by (B. Correia *et al*. [2022]), the proposed platform adopts a lightweight data-integration strategy suitable for educational environments with limited computational and financial resources. This distinction positions the system as an accessible architecture that preserves the essential relationship between data acquisition, digital representation, monitoring, and control.

Table 1. Comparison between related works and the proposed URA Digital Twin

Project	Low-Cost	Educational	Interactive Visualization	Web-Based Simulation	Digital Twin Concept
Peidró *et al*. [2016]	-	Yes	Yes	-	-
Rodríguez-Rodríguez *et al*. [2017]	Yes	Yes	-	-	-
Tao *et al*. [2018]	-	-	Yes	Yes	Yes
Liljaniemi and Paavilainen [2020]	-	Yes	Yes	-	Yes
Kandasamy *et al*. [2022]	Yes	Yes	-	Yes	Yes
Kaarlela *et al*. [2022]	Yes	Yes	Yes	Yes	Yes
Kangisser *et al*. [2022]	-	Yes	Yes	-	Yes
González-Herbón *et al*. [2024]	Yes	Yes	Yes	Yes	Yes
Lee *et al*. [2023]	-	Yes	Yes	-	-
Roldán-Àlvarez *et al*. [2024]	Yes	Yes	Yes	-	-
Lee *et al*. [2024]	-	-	-	Yes	yes
Magrin *et al*. [2021]	-	Yes	Yes	-	yes
URA Digital Twin (Ours)	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

Although these studies demonstrate the potential of digital twins, remote laboratories, and mixed reality in educational robotics, many of them rely on complex infrastructures, proprietary solutions, or focus on isolated layers of the system. As noted by Lee *et al*. [2023], while Digital Twin applications in education have advanced in theoretical modeling and complex gamification software, there is still a lack of focus on how these systems can be made accessible for diverse educational backgrounds, especially regarding the costs of implementation. To address this gap, this work emphasizes an integrated, low-cost approach that combines physical hardware, web-based simulation, and digital twin concepts into a single educational platform.

Considering the analysis of related works, there are significant efforts aimed at developing low-cost hardware applied to educational robotics. However, there are still important gaps in the literature, especially regarding the standardization of frameworks, the modularity of architectures, and the efficient integration between different technologies in educational environments. Additionally, many of the proposed systems are highly complex to use, making it difficult for teachers without specialized technical training to adopt them. Given these limitations, the proposal of this work aligns with the identified trends by addressing the hardware and software layers in an integrated manner through accessible virtualization and simulation, culminating in the design of a web-based digital twin platform. To validate our platform, we conducted a case study using the open-source URA robot as a real-world twin and the physical layer of our platform.

3 The physical platform

This section details the development of the physical layer of our digital twin (DT) platform. The architecture of the proposed platform is divided into 3 distinct parts: the physical layer, the data layer, and the digital layer, represented by the three columns in the Figure 1.

At the physical layer, the platform's hardware, sensors, and microcontrollers were arranged. In this layer, controls and scripts are responsible for performing the main functions and routines inside the hardware. The storage, manipulation, and transport of data resulting from the control layer are used in the data layer.

The Data layer comprises a database management system, the MQTT protocol (Message Queuing Telemetry Transport), and other Data tools. Because it is simple and lightweight, MQTT receives data from the control layer and exchanges messages in the Publisher-Subscriber model, enabling two-way communication with the database.

The digital layer is represented by the web-based platform and will be described in the next section.

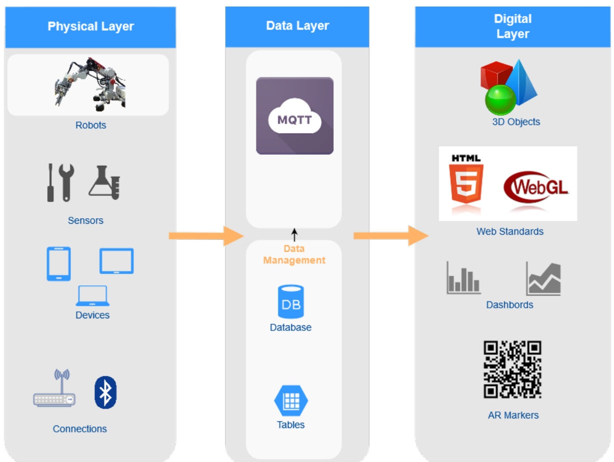

Figure 1. The system architecture: The architecture is composed of three modules: The physical layer (left), the data layer(middle) and the digital layer (right).

3.1 The URA robot

We chose the URA robot as the core of the physical layer with a focus on usability, accessibility, and effective support for the teaching-learning process. The URA (Um Robô por Aluno — *One Robot per Student*) is a low-cost mobile robot platform developed for educational purposes, using a smartphone as its primary control unit to reduce costs and leverage existing sensors and connectivity (Riedel-Kruse and Gerber [2017]). This robot, built as a low-cost platform, integrates various electronic and structural components to enable navigation and sensing functionality (as illustrated in Figure 2). The physical structure of the robot is manufactured using 3D printing techniques, an approach that is increasingly adopted in educational robotics because it allows rapid and accessible prototyping of customized components (Cabrera *et al*. [2022]).

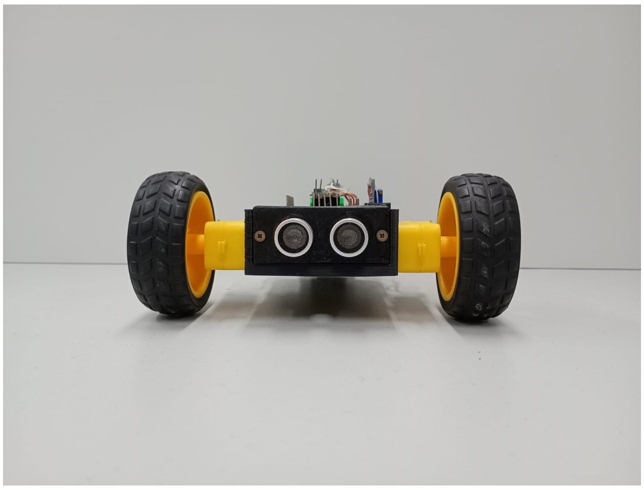

Figure 2. URA Robot: Front view showing the two wheels and an HC-04 sensor

The processing core of the URA is a development board based on the ESP32 microcontroller. This component was selected due to its intrinsic characteristics of low energy consumption, dual-core processing capability, and, crucially, integrated Wi-Fi and Bluetooth connectivity, making it ideal for Internet of Things (IoT) and educational robotics applications (Hercog *et al*. [2023]). For locomotion, the robot uses two DC motors with an attached reduction gearbox, aiming to increase the available torque. The directional and speed control of these motors is managed by an L298N H-bridge, a motor driver widely used in educational robotic projects for its ability to control two DC motors independently (HowToMechatronics [2025]).

The URA robot integrates a set of low-cost sensors and actuators that provide the necessary data to support both its physical operation and synchronization with the digital twin. These components enable basic perception, motion control, and state monitoring, supplying real-time information that is mirrored in the virtual environment. Rather than focusing on the individual technical characteristics of each sensor, this work emphasizes how such data streams are abstracted, transmitted, and represented within the digital twin platform.

The proposed digital twin for the URA aims to virtually replicate the state and behavior of the physical robot, allowing for remote visualization and interaction. The DT will be capable of displaying the robot's movement synchronized with the physical one, in addition to monitoring crucial data in real-time. Specifically, the system captures the position or speed of the motors (inferred or measured, depending on the implementation) and the readings from the ultrasonic and vibration sensors. Data communication between the physical robot (via ESP32) and the digital twin interface will be carried out using the MQTT (Message Queuing Telemetry Transport) protocol. MQTT is used as the communication backbone between the physical robot and the digital twin platform. This protocol enables near real-time synchronization of physical and virtual states, allowing the digital twin to reflect the robot's behavior and to operate as a bidirectional interface for monitoring and control within the web-based environment.

The digital twin is implemented as a web-based platform that serves as the primary interface between users and the robotic system. Through this platform, students and educators can remotely visualize the robot's behavior, interact with its virtual representation, and monitor sensor data in real-time. By abstracting the underlying hardware complexity, the platform allows users to focus on experimentation, algorithm development, and learning outcomes rather than low-level device configuration. In this context, the digital twin acts not only as a virtual replica but as an educational mediator that bridges physical hardware, simulation, and user interaction.

3.2 Educational Aspects

The synchronous interaction between the physical robot and its digital twin offers a dynamic platform for experimental learning. The control interface allows users to observe the direct correspondence between the commands sent and the actions executed by both the physical cart and its virtual representation. This simultaneous visualization of physical and virtual behavior is not limited to direct control; the virtual environment also enables simulations and exploratory tests without risk to the physical equipment. For example, students can virtually investigate the robot's operational limits, such as the maximum vibration level the structure can withstand before the SW-420 sensors are triggered, or simulate trajectories under different grip or inclination conditions (de Sena et al [2019]).

This pedagogical approach, combining virtual and physical experimentation, aligns with constructivist learning principles, emphasizing the importance of action and reflection in the educational process. Authentic praxis emerges from the dialectic between theory and practice, avoiding both "activism" (practice devoid of theoretical reflection) and "verbalism" (theory without concrete application) (Freire [1968]). This perspective is complemented by work on constructionism, which advocates learning through the construction of meaningful and manipulable artifacts. By allowing students to test hypotheses in the virtual environment before validating them in the physical world, the digital twin promotes an active learning cycle, where error is seen as an integral part of the investigative process. Recent research demonstrates that this capacity for safe and iterative experimentation not only deepens conceptual understanding but also significantly increases the motivation and engagement of both students and educators (Rodríguez-Rodríguez *et al*. [2017]).

The versatility of the URA digital twin allows its application in various educational contexts and teaching levels. In higher education, in disciplines such as electrical engineering, mechatronics, or computer science, the platform can be used to explore advanced concepts of embedded electronics, motor control, and real-time systems. Students can analyze the behavior of specific components, such as the response of motors to different PWM (Pulse Width Modulation) signals to control torque, or develop more sophisticated control algorithms. It has been highlighted that robotic kits with accessible components and open interfaces are particularly valuable in higher education, as they allow students to understand the fundamental principles of robotics without the limitations imposed by closed proprietary systems.

In high school, in physics classes, the URA robot and its digital twin can serve as experimental tools for studying kinematics and dynamics. The use of mobile robots in physics classes, through a project-based approach, has been shown to significantly increase student engagement and understanding of abstract physical concepts(de Sena et al [2019]). Students can program the cart to perform movements with different speeds and accelerations, collect position and time data (through sensors or the simulation itself), and graphically analyze the relationships between displacement, velocity, and acceleration, reinforcing the understanding of Newton's laws practically and visually. It has been observed that simultaneous visualization of physical movement and corresponding graphs facilitates the understanding of complex kinematic concepts.

Even at more elementary levels, such as primary education, the platform can be adapted for playful and interdisciplinary activities. For example, in geography or introductory programming classes, the intuitive remote control can be used to teach concepts of spatial orientation and cardinal points, where children program or guide the robot to navigate a map or maze, developing logical reasoning and notions of direction interactively and motivatingly. Recent research indicates that the effectiveness of such educational technologies varies according to the stages of cognitive development of the students, their pre-existing knowledge and experiences, and their personal worldviews (Xefteris and Palaigeorgiou [2019]), highlighting the importance of adaptable platforms that can accommodate diverse learning profiles.

The implementation of the URA digital twin as an educational tool directly addresses the barriers identified in the literature on educational robotics, particularly the issues of cost and accessibility highlighted by previous studies (Rodríguez-Rodríguez *et al*. [2017]). By offering a low-cost platform that integrates accessible physical components with a virtual simulation environment, the project provides a rich and multifaceted educational experience that can be adapted to different contexts and teaching levels, democratizing access to advanced simulation and control technologies.

3.3 Low Cost

One of the main objectives of this project is to offer an educational digital twin platform that is financially accessible, overcoming the cost barriers often associated with advanced simulation technologies and commercial robotic kits (Rodríguez-Rodríguez *et al*. [2017]). In the context of educational robotics, platforms such as Arduino and ESP32 are often considered low-cost, especially when compared to widely used commercial kits like Lego Mindstorms. The latter, for instance, has an approximate price of US$390 (Riedel-Kruse and Gerber [2017]). Although kits like Lego Mindstorms offer high-quality finishes and are well established in robotics education, low-cost platforms have emerged as a growing alternative in this domain. This popularity is mainly due to their flexibility, ease of use, and, most importantly, the associated low cost, which makes them a viable option for various educational contexts related to robotics.

To demonstrate the economic viability of the URA robot, a cost survey of the essential electronic components was conducted, as detailed in Table 2. It is important to note that the indicated prices are estimates based on specific suppliers at the time of consultation and may vary. However, the approximate total cost illustrates the potential for replicating the platform in institutions with limited resources.

Table 2. Estimated Cost of Essential Electronic Components for the URA Robot (May 2025)

Component Name	**Price (USD)**
HC-SR04 Ultrasonic Distance Sensor	$1.66
ESP32 Devkit V1 Board	$9.51
MT3608 Step-up Voltage Regulator	$1.32
L9110s H-Bridge	$0.88
DC Motor with Reduction Gearbox (x2)*	$2.64
SW-420 Vibration Sensor Module (x3)*	$3.42
HMC5883L Magnetometer Sensor	$5.29
Estimated Total Cost	**$24.72**

Table 3. Cost comparison between the proposed URA Digital Twin and a commercial platform

Platform	**Hardware Cost**	**Software Cost**	**Total (USD)**
LEGO Mindstorms Riedel-Kruse and Gerber [2017]	~US$390.00	Included	US$ 390.00
URA Digital Twin (Ours)	**US$ 24.72**	**Free (Open Source)**	**US$ 24.72**

4 The Digital Twin Web Platform

The web platform is a tool built with the goal of being the center of interactivity with the URA robot. It needs to help students send and receive data, simulate conditions, and help to interpret the robot's behaviour, making it a complete Digital Twin platform. To build it, the main libraries are React.js, for user interface (UI) and architecture, and Three.js, for three-dimentional (3D) rendering in browsers, these were chosen with acessibility in mind, so web development standards were adopted allowing cross-platform usage, and implementation of the Web Content Accessibility Guidelines (WCAG) 2.1, ensuring the tool can be used with most devices and by anyone.

At the current stage of development, the interface prioritizes functional integration and accessibility of the interaction modes. Future iterations will further explore pedagogical interface design strategies focused on reducing cognitive load, improving visual engagement, and enhancing usability for users with different educational backgrounds.

4.1 Web Development

As stated, React.js was used as a base for the architecture; it enforces the usage of components, allowing a modular approach, guiding the development philosophy by defining what features need to be built first and reusing existing ones. This component approach creates functionality silos where a single component encapsulates the scope for a specific feature, allowing faster development by requiring fewer changes in the code, but this creates the need for middleware to facilitate communication between components. Consequently, Zustand is utilized for its state engine and event system. Every component accesses this global state, while the event system permits the transfer of specific data between them (e.g., selecting a robot part in the sidebar and highlighting it in the 3D renderer). The global state, also called store, is structured as the following data:

- **Software mode:** Which mode the user wants to interact with (e.g, real-time, coding, simulation).
- **MQTT Instance:** The instantiated MQTT class.
- **MQTT Telemetry:** Real-time sensor inputs and device status updates.
- **3D References:** Pointers to specific meshes within the 3D scene graph.
- **Block Coding programs:** The code created by the user.

To visualize data, the system utilizes Three.js for 3D rendering. It enables complex visualizations, such as the 3D model of the physical URA robot. This environment facilitates the creation of visual cues to indicate data changes; for instance, modifying mesh colors to indicate temperature or animating wheel components to reflect rotations per minute (RPM). However, to implement this more efficiently, the React-Three-Fiber (R3F) library is utilized to ensure architectural compatibility with React.js. This is necessary because of the conflicting programming paradigms: while React.js is declarative, Three.js is imperative. In complex applications, these imperative data changes could cause redundant draw calls that impact visual fidelity and performance. The library solves this issue by allowing direct scene graph modifications, keeping the actual rendering process synchronized with the React.js lifecycle. This integration enables the software to offer multiple modes of interaction. These modes of interaction will be discussed in the next section.

5 Results and Discussion

This section presents the results obtained from the implementation and testing of the Digital Twin platform proposed in this work. These results focus on the functional integration of the different interaction modes planned for this platform and the technical performance of the web-based architecture.

As the center of interaction with the URA robot, the platform offers several interaction modes that enable data visualization and robot control. These modes are: Realtime, Coding, and Simulation. They enable the platform to operate as a Digital Twin by providing telemetry monitoring, simulation, and control of the robot. As a baseline, all modes receive real-time data via MQTT, can send it via application programming interfaces (APIs) to a database, and switch the interaction mode using a selector, keeping the UI always visible.

This section also presents the results of the development and technical validation of our Digital Twin platform. The results are categorized into three main pillars: the economic and structural feasibility of the hardware, the technical performance of the software synchronization, and the functional capabilities designed for educational scenarios.

5.1 Real-time Mode

Real-time is the default mode; its goal is to provide real-time monitoring of the robot so users can understand the current behaviour of the subject. The main visualization is a 3D viewer, shown in Figure **3**, which changes colors based on the data value and shows labels when the part is hovered, containing the text version of the data. At the top, there are two buttons and the mode selector. The left button allows connecting to a database to save and pull data from, and the right button connects to the robot via MQTT. The database button opens a UI in the right-side panel that allows the user to pull and reproduce data in the viewer. In the right-side panel, called the inspector, the user can select a specific part to enable its configuration; the available changes are the minimum and maximum values of that sensor and the colors representing those values, along with an area to visualize the chronologically ordered data of that specific part. The left side has a button with a phone icon, to enable the mixed-reality viewer, it shows a QR code to be scanned by a mobile device, and a button to download a PDF containing a marker for tracking. And on the bottom, there is a view cube to help the user understand the orientation of the viewer.

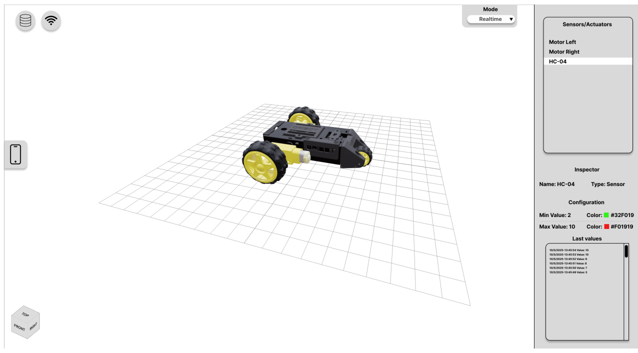

Figure 3. Real-time Mode Interface: The interface is composed of two primary sections: the central 3D viewport displaying the interactive digital twin of the robot on a grid, and the right sidebar displaying real-time sensor data and component configuration.

5.1.1 *Mixed Reality*

The augmented reality (AR) viewer is built using the open-source library AR.js; it is marker tracking-based and overlays real-time or database data in a mixed-reality setting for inspection of specific actuator or sensor behavior. Its UI is composed of the camera view, for the AR functionality, a button at the top to download the marker, and at the bottom, a gamepad-like interface that allows command execution to control the robot.

5.2 Coding Mode

The coding mode is an interface that allows the user to create a sequence of movements using block-based programming. The UI, represented in **Figure 4**, is composed of the main coding area, where the user will drag the code blocks from the bottom and connect them to the start block or the previously added block. At the top, it has the database, MQTT, and mode selection UI. A right-side bar, which indicates the program flow vertically, allows the user to configure each block individually or delete them, and at the bottom, there are import, export, and run code buttons. The draggable code blocks have a shape that indicates how they connect, different colors to easily identify their function, along with titles that describe what each one executes, and also indicate how long that command will run.

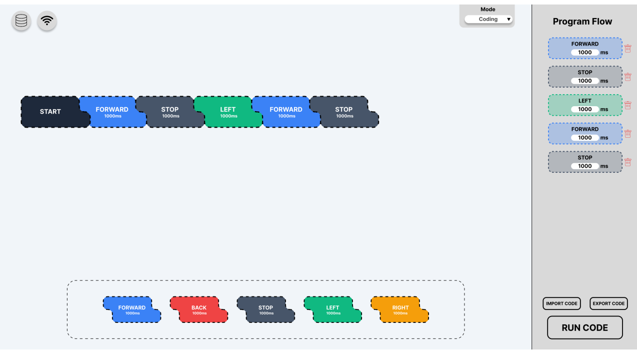

Figure 4. Coding Mode Interface: The interface enables users to program robot movements utilizing block-based programming. The central canvas displays the constructed sequence of commands, while the bottom shows the available movement blocks. The right sidebar outlines the overall program flow and includes options to run, import, and export the generated code.

5.2.1 *Code Execution*

As the code, the platform creates a JavaScript object notation (JSON) object that contains two keys, mode and steps. The mode key indicates that the robot should start the code loop, and the steps are an array containing objects that indicate what command it is and how long it will run. This JSON object can be generated previously and imported or exported. Once the user executes the code, the robot receives the JSON via MQTT and enters the code execution mode, then runs each command in order, even if the robot can not physically do it. In the future, sensor checks will be added, as code blocks, to stop or run alternative codes, for instance, if the ultrasonic detects an obstacle at a distance smaller than 40 centimeters, the robot starts an alternative code to go around the obstacle.

5.3 Simulation Mode

The Simulation Mode interface is designed to simulate and visualize the operating conditions of the URA robot. The UI, shown in Figure **5**, contains the top elements previously described. The center of the interface is the main area, which visualizes sensor and actuator values. A sidebar on the right allows users to select components and modify their configurations. The bottom region is divided into three sections: the Report section, for viewing or exporting generated data; the Recorded section, containing re-run and export controls; and the Code section, which allows for running and importing JSON code generated in Code Mode. In addition, the bottom of the main area features a control interface for executing robot movements, recording commands, and displaying the recorded commands chronologically, structured identically to the generated code.

5.3.1 *Simulating the Robot*

The main goal of the simulation is to show the user the hardware behavior during the robot's operation. In the main visualization area, there are two visual indicators: the boxes that represent the components, and the lines that represent their connections. If there is an issue with the component, the box becomes red; if there is an issue with the connection, the line

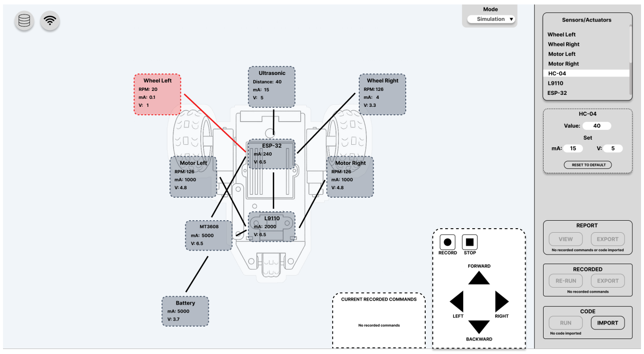

Figure 5. Simulation Mode Interface: The central visualization area displays the robot's hardware, using boxes for individual components and lines for their connections. The simulation monitors metrics such as voltage, amperage, and expected output, dynamically highlighting problematic components or connections in red. The right sidebar provides controls to adjust specific component parameters and options to view or export simulation reports.

becomes red. To decide the state of each visual component, the simulation considers three metrics: voltage, amperage, and, in the case of a sensor or an actuator, its expected output value, which is based on the component's datasheet. For instance, if the user changes the default value of the battery voltage to a number lower than 2.7 Volts, the system might not be able to sustain a heavy load, meaning the robot requires more torque to move, but the system does not have enough power to supply, then most of the system will become red, including connections. Another example, if there is an issue with the output value of the HC-SR04 ultrasonic sensor, but the input amperage and voltage are expected, the box representation will become red, but not the connections, since it is receiving the correct power. The final result from the simulation can later be visualized through a report.

5.3.2 *The Report*

To allow a better representation of the states of each component during the simulation, either by manual control or loading a code, the software outputs a report that contains a set of graphs of each metric, amperage, voltage, and output values for each component, overlayed with what command was running and how long, as well expected trajectory of the robot. To calculate the trajectory, the system uses the output RPMs from the encoders and the size of the wheel, obtaining how far forward and backward the robot can move, but for rotation, the system ignores the drag of the caster wheel. Then we can use differential drive kinematics to understand the robot's movement.

5.4 The Educational Use of the Interaction Modes

The system was designed as a tool that could be used by a single user or multiple users, meaning each student could use their own robot, or an entire class could use a single robot. There are multiple ways a collaborative approach could be used in classes; this section outlines a couple of suggestions of uses.

5.4.1 *The Class Approach*

Educational institutions often possess a computer laboratory, but may lack access to multiple robots, restricting the professor to one robot. In a class setting, the professor could ask each student to generate code to try on the robot since the connection via MQTT allows multiple clients on the same broker. The dynamic also allows the professor to control using the AR viewer or the Code Mode, while the students are connected in the Realtime Mode. Both dynamics are represented in order in **Figure 6**.

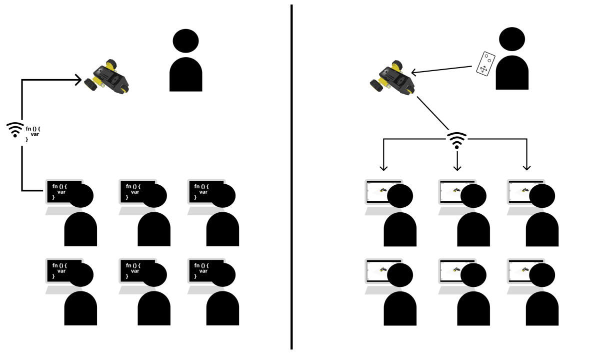

Figure 6. Suggestions to class dynamics with one robot. The left panel illustrates a scenario where multiple students generate and transmit code to a single shared robot via an MQTT connection. The right panel demonstrates an alternative dynamic where the professor directly controls the physical robot while students actively monitor its live telemetry and sensor data on their individual computers using the Realtime Mode interface.

5.4.2 *The Collaborative Approach*

Continuing in the class environment where there are not enough robots for all students, the professor could create a dynamic where one student uses the Simulation Mode to predict the robot's behavior based on the power constraints of available batteries and generate its recorded code. A second student could then review and fix the result in the Code Mode. Finally, both students can monitor the behavior of the physical robot using the Realtime mode, shown in **Figure 7**.

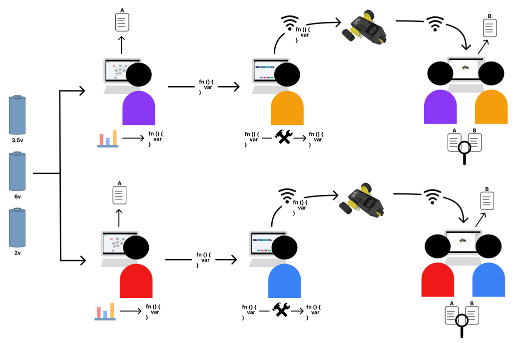

Figure 7. Suggested steps of the Collaborative Approach. The workflow illustrates a three-step learning dynamic: first, a student uses Simulation Mode (left) to evaluate battery power constraints and generate initial code alongside a predictive report. Next, a second student reviews and refines the code in Code Mode (center) before transmitting it to the physical robot. Finally, both students utilize Realtime Mode (right) to monitor live telemetry, allowing them to compare the initial simulated predictions against the actual hardware performance.

5.5 Hardware Feasibility and Economic Impact

The primary result of this research is the delivery of a functional, low-cost educational robotic platform. Through the strategic selection of open-source hardware components, such as the ESP32 microcontroller and accessible sensors, the total cost of the URA robot was optimized to approximately US$ 24.72. This cost represents a significant reduction compared to traditional commercial kits, such as Lego Mindstorms or VEX Robotics, which often exceed US$ 400.00 (Rodríguez-Rodríguez *et al*. [2017]). The successful integration of these components into a robust, 3D-printed chassis demonstrates that high-fidelity educational tools can be produced at a fraction of the market price, directly addressing the financial barriers to STEM education in resource-constrained environments.

5.6 Cyber-Physical Synchronization and Software Performance

The technical validation of the Digital Twin architecture focused on the synchronization between the physical URA robot and its virtual counterpart. Using the MQTT protocol as the communication backbone, the system achieved stable real-time data exchange. The virtual model implemented in Three.js successfully mirrored the physical robot's orientation and sensor states (e.g., ultrasonic distance and battery voltage) with low latency. This synchronization is a critical result, as it ensures that the "Digital Twin" experience is consistent, allowing students to trust the virtual representation for remote monitoring and simulation-based debugging before physical deployment.

5.7 Functional Capabilities for Educational Scenarios

Beyond the technical artifacts, the platform's design resulted in a versatile tool capable of supporting diverse pedagogical dynamics. The architecture was specifically engineered to enable:

- **Collaborative Learning under Hardware Scarcity:** The system allows multiple students to interact with a single physical robot through different virtual layers. While one student operates the physical unit, others can monitor its state or run parallel simulations in the web interface, maximizing the utility of limited hardware resources.
- **Hybrid Experimentation Cycle:** The platform enables a safe learning cycle where students can validate their logic in the "Simulation Mode" before executing it on the physical hardware. This capability reduces the risk of hardware damage and encourages autonomous experimentation.

These features demonstrate the platform's potential to foster constructionist learning environments. It is important to note that these scenarios presented in **Subsection 5.4** describe the system's functional capabilities; future work may involve formal user studies to evaluate the pedagogical impact on student learning outcomes, following institutional ethical guidelines.

Although the current tests demonstrated stable synchronization under the evaluated conditions, large-scale classroom scenarios involving dozens of simultaneous users connected through shared wireless infrastructure still require further investigation and constitute an important direction for future scalability evaluations.

6 System Usability Tests

To validate the approach and different interaction modes, a system usability test was conducted using the System Usability Scale(SUS) (Corrêa *et al*. [2025]). Firstly, each participant was informed how the test would be conducted, including how long it would take. Then, if they accepted, a presentation of the platform and functionalities was made, and they were asked to interact with the interface and try the features in a real robot. After they tried all the features, they were asked again if they wanted to participate in the anonymous questionnaire.

6.1 The participants

A total of eight people participated in the test, and all agreed to complete the anonymous questionnaire. Their education level ranged from completing a bachelor's or licenciature degree to doctorates, with 37.5% having finished higher education but not started a master's, and 25% concluding their doctorate. Also 87,5% were professors/teachers of multiple areas, ranging from Languages and Pedagogy to Computer Science where 62,5% never had any contact with robotics in education.

6.2 Results

The final results indicated an average score of 71.25 with a standard deviation of 10.3. According to the reference scale, the system obtained a "Good" qualitative rating, placing it above the average acceptable usability level. The standard deviation suggests a relatively consistent perception of usability among the participants, indicating that the user experience did not present significant disparities in opinion and reinforcing the platform's suitability for the evaluated audience.

Additionally, participants provided qualitative feedback emphasizing the importance of improving accessibility and ease of adoption for users with different technical backgrounds. The suggestions included the development of instructional materials, more visually engaging interface elements, alternative interaction flows for educational activities, and language localization features. These observations reinforce the relevance of designing educational technologies that are not only technically functional, but also intuitive and accessible for first-time users and educators. In response, future versions of the platform are expected to incorporate integrated tutorials, multilingual support, and interface refinements directly within the web environment.

Although the preliminary usability results indicate that the platform presents acceptable usability and educational potential, this validation still represents an initial stage of the project. Since the platform is currently evolving from a functional prototype toward a more mature educational tool, the present evaluation focused primarily on collecting feedback from participants with educational and academic backgrounds before large-scale classroom deployment.

The feedback obtained during this stage revealed important opportunities for improvement, including interface personalization, more visually engaging design elements, multilingual support, and the development of instructional materials to facilitate adoption by educators with different technical backgrounds. Future developments will therefore focus on refining the user experience, expanding accessibility features, and conducting broader pedagogical validations in real educational environments, including classroom-based studies involving students and learning outcome analysis.

7 Final Considerations

This work presents a concrete and viable contribution to the field of Educational Robotics by demonstrating the feasibility of a low-cost digital twin architecture integrated with a physical mobile robot. The results obtained indicate that the proposed system is capable of maintaining the level of synchronization and responsiveness required for educational applications involving control concepts, Internet of Things (IoT) fundamentals, and programming.

By combining an accessible physical platform with a web-based digital twin, the proposed solution effectively addresses two of the main barriers identified in the literature: high financial cost and excessive technical complexity. The use of open and widely adopted technologies, such as ESP32, MQTT, and web-based visualization, reinforces the replicability and scalability of the approach, making it suitable for adoption in institutions with limited resources.

From an educational perspective, the platform enables a meaningful integration between virtual simulation and physical experimentation. This dual interaction allows students to explore robotic behavior safely in the virtual environment before validating their solutions on real hardware, fostering an active learning process grounded in experimentation and immediate feedback. The preliminary technical evaluations demonstrate that the architecture supports this pedagogical workflow without requiring sophisticated infrastructure.

The limitations observed in this study, such as the current focus on a specific robot model and the preliminary nature of pedagogical validation, are inherent to the defined scope of the work and do not compromise its main contributions. Rather, they delineate clear directions for extension and adaptation of the proposed architecture to other robotic platforms and educational scenarios.

Overall, the results demonstrate that the proposed digital twin architecture constitutes a practical, accessible, and pedagogically meaningful solution for educational robotics, contributing to the democratization of advanced simulation and control technologies in teaching and learning contexts.

Future work includes expanding the scalability evaluation of the platform in classroom environments with multiple simultaneous users connected through shared wireless networks, as well as conducting broader usability and pedagogical studies involving teachers and students in real educational scenarios. Additional developments also include the implementation of multilingual support, integrated instructional guides, more accessible interface design strategies, and the expansion of the platform to support additional robotic architectures and educational use cases.

Declarations

Authors' Contributions

Maria Lago contributed to the conceptualization and methodology of the study, conducted the investigation, managed the project, and was responsible for the development and integration of the hardware components. Maria Lago also wrote the original draft of the manuscript. Daniel Oliveira contributed to the concept of interac-

tion modes, design, implementation, and validation of the software components and was responsible for writing the software section of the manuscript, in addition to participating in the review and editing process. Rummenigge supervised the research activities, contributed to the methodological guidance of the study, and participated in the review and editing of the manuscript. All authors read and approved the final version of the manuscript.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The web platform's public-facing source code is available at: `https://github.com/Carnaux/Arcad-URA`. Disclaimer: the repository may not yet reflect the latest development version, since the platform is still under active refinement before its complete public release.

The firmware and control code for the physical URA robot, including sensor integration and MQTT-based communication routines, are available at: `https://github.com/ProjetoGemeoDigitalUrinha/CarrinhoComESP32`. This repository contains the embedded software corresponding to the physical prototype described in this study.

The usability evaluation was conducted using a System Usability Scale (SUS) questionnaire adapted for this study. The collected responses are not publicly available, but anonymized materials and aggregated results may be provided by the authors upon request.

Both repositories are under active development and may evolve as the platform continues to be refined and expanded.

Further relevant information

Artificial Intelligence Disclaimer: Artificial Intelligence tools were used to create the first version of the user interface from Figma, and for grammar correction during the writing and editing of this paper.

Citation Diversity Statement: The authors are aware of the existence of citation biases in scientific publications and acknowledge the importance of promoting equitable citation practices. While no formal quantitative analysis of citation diversity was conducted, efforts were made to include references from a diverse range of authors, publication venues, and geographic contexts, considering relevance and contribution to the research topic.

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