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Enhancing STEM Learning through Augmented Reality: Introducing Robotics to the Next Generation

***Abstract*—This paper presents the development and evaluation of an innovative educational application using Augmented Reality (AR) and robotic kit called ”Edarr” that leverages to enhance STEM (Science, Technology, Engineering, and Mathematics) learning among children and young people. The application is designed to introduce foundational concepts in robotics and related STEM areas through interactive and immersive AR experiences. By combining visual engagement with hands-on activities, the project aims to foster curiosity, improve understanding, and face one of the biggest challenges in technology education: bridge the gap between theoretical knowledge and practical application. Initial testing with target age groups indicates increased motivation, higher retention of concepts, and a more inclusive learning environment. This project highlights the potential of AR as a transformative tool in education, particularly for preparing the next generation for the challenges of a technology-driven world.**

***Keywords*—Augmented Reality, Robotics Kit, STEM Education, Arduino, Unity, 3D Printing.**

I. Introduction

A few years ago, the integration of technology into education has transformed the way students engage with scientific and technical subjects. Among these innovations, Augmented Reality (AR) has emerged as a powerful tool to create immersive, interactive learning environments that can meaningly enhance student motivation and understanding. The area STEM (Science, Technology, Engineering, and Mathematics) is a global and demanded skill, that has been demonstrated an increment need for educational approaches that not only teach complex concepts effectively but also inspire younger generations to pursue careers in these fields. Likewise, implementing the OARA (Learning Objects with Augmented Reality) methodology will enhance every stage of the familiarization with new technologies [1].

This paper presents a project focused on the development of an Augmented Reality application designed to introduce children and young people to STEM world, specially to robotics. The goal is to offer an engaging and accessible educational experience that bridges the gap between theoretical knowledge and hands-on exploration. By implementing AR technology from Vuforia and Unity that provide tools and integrations to built application for different devices, and a DIY Kit robot using 3D printed parts and an Arduino; the project ”Edarr” allows students to interact with virtual robotic components. This enhances cognitive connections and encourages the practice and experimentation. Additionally, it cultivates and develops the concept of a digital twin in the robotic so they can simultaneously interact with the robot, virtually and physically.

The proposed solution aims to address several educational challenges, such as limited access to laboratory spaces, low engagement in traditional learning environments (paper and pencil or just a visual presentation like videos or non-touch components), and the difficulty of contextualizing abstract scientific concepts in robotic and electronic. Moreover, it supports inclusive learning by catering to different learning styles and promoting equitable access to enhanced technology for education, this application it is accessible to anyone who has a smartphone, and also for people that has other resources to explore Virtual Reality as oculus glasses.

This idea was brought to reality, so we aimed to demonstrate how AR can be effectively implemented as a pedagogical tool to improve learning and teaching outcomes, and empower the next generation of innovators, our children and youths. The project is rentable and sustainable, this means, that can be modified and updated to bring new technologies or new robot kits to built using the guidance of the application. The following sections describe the design methodology, educational framework, technical implementation, and preliminary results gathered from pilot testing with students in STEM Robotics Academy and Don Bosco University, in El Salvador where the project was tested.

II. Methodology

This project followed the *Design Thinking methodology*, a human-centered approach used to develop both the physical robotic kit and the augmented reality (AR) mobile application. The process was divided into five key stages: Empathize, Define, Ideate, Prototype, and Test, with iterative feedback loops at each step to refine the final solution.

A. Empathize: Understanding Users’ Needs

To begin, we focused on understanding the real needs of students and educators involved in STEM education. We conducted informal interviews with students and teachers after their classes at the STEM Robotics Academy in San Salvador. This field research allowed us to empathize with the users and gather first-hand insights into the challenges they face in both learning and teaching technical concepts.

From the students' perspective, we identified a key issue: traditional teaching tools such as PowerPoint presentations and pre-recorded videos often failed to support student comprehension. One student in particular expressed difficulty understanding how a robot functions just by watching videos, indicating the need for hands-on, interactive learning tools that allow for active engagement and clearer visualization of robotic mechanisms.

In parallel, teachers highlighted the limitations of current pedagogical resources. During a conversation with Bryan Vásquez, an instructor at the academy, we learned that while technology continues to advance rapidly, educational methods are not evolving at the same pace. He emphasized the urgent need for affordable, modern teaching tools that keep up with Industry 4.0 demands and bridge the gap between theoretical concepts and practical application.

B. *Define: Identifying Key Challenges*

Based on the insights collected, we defined two main challenges:

- **For students**: the need for an accessible, engaging tool that enhances understanding through physical interaction and real-time visualization.
- **For teachers**: the need for a low-cost, scalable resource that supports the explanation of complex STEM topics with modern technologies.

These challenges helped us set a clear vision for the project: to develop an educational solution that combines a buildable robot kit with augmented reality to deliver a meaningful, interactive learning experience.

C. *Ideate: Planning the Solution*

With these goals in mind, we explored possible ways to merge our knowledge in mechatronics, 3D modeling, electronics, and software development. We brainstormed feasible solutions that aligned with the constraints of accessibility, simplicity, and educational impact.

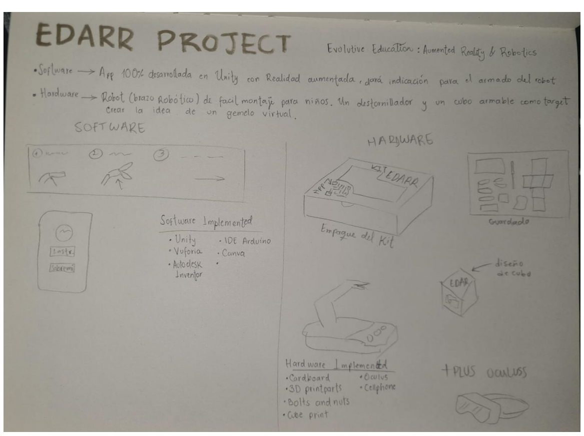

Fig. 1: Brainstorm and sketch for the project creation

The core idea emerged: a Do-It-Yourself (DIY) robotic arm kit designed for students to assemble, complemented by an AR mobile application that serves as a digital twin to guide the assembly process and simulate movement.

D. *Prototype: Building the Robot and the App*

Using Autodesk Inventor, we designed a small robotic arm composed of several 3D-printed components, from the base to the gripper. The robot's control system is based on Arduino, with potentiometers to manipulate each joint and buttons to record movements and create looping routines.

In parallel, we developed an AR mobile application using Unity and Vuforia Engine. The app allows users to scan a printed target and display 3D models of the robot's parts in real time, providing step-by-step visual instructions and interaction with the virtual model.

E. *Test: Preliminary Validation*

The initial prototype was tested with students at the Robotics Academy, where we collected early feedback on usability and educational value. The response confirmed that students found the physical assembly more intuitive and engaging when guided by AR, while teachers appreciated the potential for using the app as a modern instructional tool in the classroom.

III. Related Works

Several recent projects have explored the integration of Augmented Reality (AR) and robotics for educational purposes. These works demonstrate the potential of combining immersive technologies with hands-on learning to improve student engagement and conceptual understanding in STEM fields.

In [2], the authors developed an AR platform to teach reinforcement learning through interactive robot simulations. The system allowed K-12 students to visualize state transitions and decision-making processes in a gamified environment.

Technologies Used: Unity, Vuforia, Raspberry Pi, robot simulators.

Relevant Conclusions: AR improves comprehension of abstract algorithms like reinforcement learning by making internal processes visible and interactive.

In [3], Noriega and Zapata implemented an AR system combined with educational robotics in Ecuador. The project focused on improving the academic performance and motivation of mechatronics students through guided robot assembly and simulation.

Technologies Used: Unity, Vuforia, Arduino-based robots.

Relevant Conclusions: The use of AR significantly improved students' practical skills and engagement compared to traditional instructional methods.

[4] presents the design of an AR application integrated with ROS (Robot Operating System) to teach mechanisms and robotics. The system allows users to simulate and visualize robot movements over real-world scenes.

Technologies Used: Unity, Vuforia, ROS, SolidWorks.

Relevant Conclusions: The integration of AR with professional robotics platforms like ROS enhances students' understanding of kinematics and control.

[5] is a comprehensive survey on the use of AR in Human-Robot Interaction (HRI), classifying over 400 studies. The work provides a taxonomy based on interaction style, AR placement, and feedback mechanisms.

Technologies Reviewed: Unity, Microsoft HoloLens, smartphone-based AR.

Relevant Conclusions: AR improves transparency in robot behaviors and enhances communication between humans and machines in both industrial and educational settings.

[6] explores the development of an AR-assisted system to help students assemble a robotic platform. The mobile app provides step-by-step instructions through a digital twin of the robot.

Technologies Used: Unity, Vuforia, Android devices.

Relevant Conclusions: Visualizing the robot in AR before and during assembly reduces errors and increases learning retention.

In [7], the authors created a hybrid virtual and augmented reality environment for robotics education. The app simulates both the hardware and software of the robot, enabling full experimentation without physical components.

Technologies Used: Unity, MIT RACECAR MN platform, VR/AR integration.

Relevant Conclusions: Virtual twins of robotic systems allow students to train and test code even without direct access to physical robots.

Finally, [7] describes a real-world case in which AR was used to support the teaching of robotic arm kinematics in a high school setting. The study found that AR made the learning process more intuitive and less intimidating for students with no prior experience in programming or electronics.

Technologies Used: Vuforia, Unity, simple robotic kits.

Relevant Conclusions: AR can serve as a bridge between theory and practice, especially for beginners in STEM disciplines.

IV. Design and System

This section presents a detailed overview of the technical components and structure of the proposed solution, which integrates a physical robotic kit with an augmented reality (AR) mobile application. The system was designed with a focus on accessibility, modularity, and educational effectiveness. It combines mechanical design, electronic control, and software development to deliver an interactive and engaging learning experience for students. The following subsections describe the mechanical design of the robotic arm, the electronic circuitry and control logic, as well as the development and functionality of the AR application.

A. Robot Design in Autodesk Inventor

First, we needed a Do-It-Yourself robot kit in order to be manipulated and easy to build up with children and youths. For this, we put in practice what we learned from Mechatronics Engineering degree in 3D Technical Design and Electronic Applications. We design in Autodesk Inventor the parts of a little robotic arm, from the base to the grip.

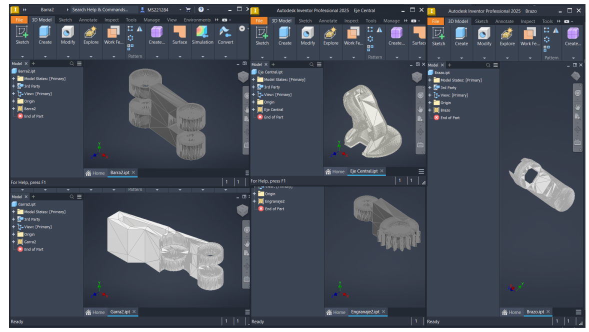

Fig. 2: 3D Parts of the Robotic Arm built on Autodesk Inventor 2025

B. Circuit Design and Building

Additionally, we develop the idea of a simple circuit using potentiometers, buttons, servomotors and the microcontroller Arduino Nano to reduce the cost of the project and future production of the basic kit.

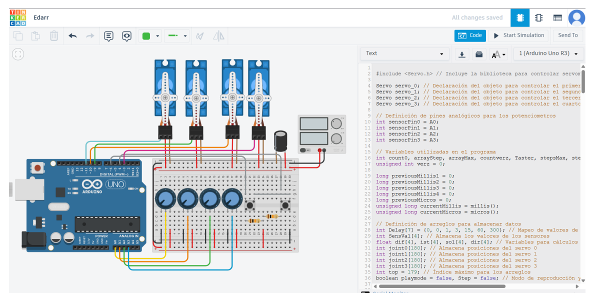

Fig. 3: Simulation of the Circuit in Tinkercad

Although the circuit is relatively simple, the real functionality lies in the code: potentiometers control each joint of the robotic arm, while buttons are used to record sequences of movements, enabling the creation of repetitive loops for basic tasks. This initial prototype has been integrated into a custom PCB to facilitate easier assembly and greater reliability. Its design serves as an accessible entry point for introducing future generations to advanced technologies and robotics.

C. Design in Unity and the creation of the guide

The application developed in Unity and integrated with Vuforia helps as guide to build up the robot (Environment: Cellphone and Robot), additionally, the digital twin function can be added to the cellphone (however, the hardware should be modified and add Bluetooth sensor or Wi-Fi module).

For the development of the application and the implementation of Augmented Reality (AR) features, we used the Unity development platform in combination with the Vuforia Engine. Unity [8] was selected for its powerful 3D rendering capabilities, its intuitive interface for interactive content creation, and its wide compatibility across devices, including smartphones and tablets.

Vuforia, an AR Software Development Kit (SDK), was integrated into Unity through its official package, which allows

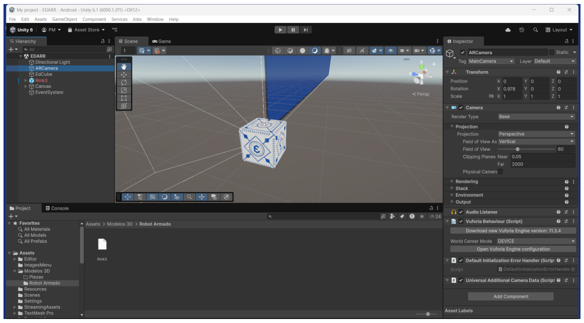

Fig. 4: Development process in Unity

developers to create AR experiences by recognizing real-world images, also known as image targets. These targets act as physical markers that, when detected by the camera of a mobile device, trigger the display of 3D virtual content anchored to the real environment.

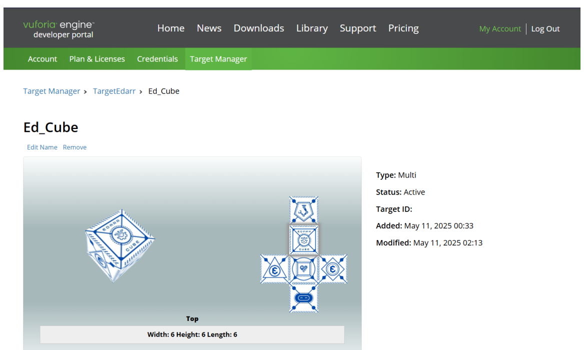

Fig. 5: Target Generation in Vuforia

Based on [9], the process begins by uploading an image (e.g., a printed marker or a visual from the robot assembly kit) to the Vuforia Target Manager, an online platform that generates a unique identifier (ID) and a tracking database. This database is then imported into Unity and linked to virtual 3D models—such as robotic components or animations. During runtime, when the application recognizes the target through the device camera, it overlays the corresponding 3D content in real-time, allowing users to interact with it as if it were part of the physical world.

This AR integration not only enhances the user experience but also facilitates intuitive, step-by-step assembly instructions through the concept of a digital twin. Users can visualize each part of the robot in spatial context before physically assembling it, reducing confusion and promoting deeper understanding.

V. Results

Functionality:

- **AR-Guided Assembly:** The mobile application successfully provided step-by-step instructions through 3D visualization of each robotic component, helping users understand how to assemble the robot accurately.

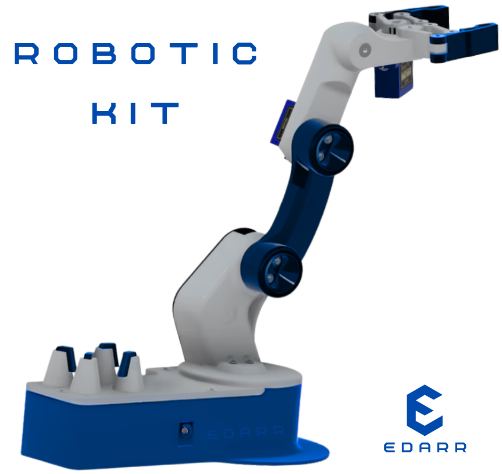

Fig. 6: Last assembly of the project in Autodesk Inventor and Canva

- **Digital Twin Interaction:** The robot could be manipulated both physically and virtually. Users could observe the robot's real-time joint movements mirrored in the AR environment.
- **Manual Programming via Interface:** The robot's motions were programmed using potentiometers and saved with button inputs to create simple action loops, enabling users to test repetitive tasks.

A. Test Scenario

Testing was conducted at the STEM Robotics Academy in a controlled classroom setting with a small group of students (ages 14–17) and an instructor. The focus was to evaluate the educational impact, usability, and technical performance of both the robot and the AR application.

Objective: Assess how effectively the application supports robot assembly, user interaction, and conceptual understanding of robotic movement.

Method: Students were given the disassembled robot and the AR app. They followed the digital instructions to assemble the kit, tested movement recording features, and answered a short usability and learning perception survey after the session.

B. Test Results

- **Assembly Accuracy:** 87% of students completed the full assembly without instructor intervention.
- **Time to Completion:** Average time to assemble the robot using the AR guide was 28 minutes.
- **Digital Twin Synchronization Delay:** 1.2 seconds average between physical motion and virtual display.
- **User Feedback:**
  - Students reported that the AR visualization made the assembly process clearer and more enjoyable.

– Most users found the interface intuitive and felt more confident understanding the robot's structure.
– Teachers expressed interest in using the app as a support tool for introductory robotics classes.

Conclusion: The prototype proved effective in enhancing the educational experience through hands-on learning and AR visualization. Further iterations will focus on improving the response time of the digital twin and expanding interactivity features within the app.

VI. Discussions

A. Technology and Functionality

- **Augmented Reality:** The integration of Unity and Vuforia enables real-time visualization of the robotic arm's components and movements, creating an immersive experience that reinforces understanding of mechanical concepts.

- **Physical and Virtual Synchronization:** The use of potentiometers and servo motors allows real-time interaction between the physical robot and its digital counterpart, fostering intuitive learning through experimentation.

- **Educational Interactivity:** The mobile application provides step-by-step assembly guidance and interactive visualization, making the learning process more accessible to students with varying levels of prior knowledge.

B. Economic Accessibility

- **Low-Cost Materials:** The use of widely available and affordable components, such as Arduino boards, basic servos, and 3D-printed parts, ensures the solution remains economically viable for educational institutions with limited resources.

- **Scalability and Reusability:** The modular nature of the robot and the reusability of the app across multiple devices contribute to long-term cost-effectiveness.

C. Compact and Modular Design

- **Assembly and Portability:** The robotic arm was designed with compactness and ease of assembly in mind, allowing students to quickly build and transport the kit without specialized tools.

- **Durability and Maintenance:** The 3D-printed parts and simple circuitry were chosen to minimize maintenance needs, while remaining robust enough for repeated classroom use.

D. Educational and Social Impact

- **Bridging the Theory–Practice Gap:** By combining AR visualization with hands-on assembly and control, students are better able to link abstract concepts with real-world applications, enhancing their motivation and retention.

- **Inspiring Future Innovators:** This type of solution encourages early exposure to robotics and engineering in an accessible way, potentially inspiring more students—especially from underrepresented groups—to pursue STEM careers.

E. Challenges and Ethical Considerations

- **Technical Limitations:** The system currently has a minor delay in synchronization between the physical and virtual robot. Further optimization is required to improve responsiveness and interactivity.

- **Digital Divide:** Although the app runs on smartphones, access to mobile devices and internet connectivity may still be a barrier for some educational contexts. Future efforts should consider fully offline-compatible solutions.

- **Inclusive Design:** While designed to be intuitive, additional accessibility features (e.g., voice instructions, multilingual options) could further broaden its reach and usability among diverse student populations.

VII. Conclusions

The development of an educational robotic kit supported by Augmented Reality (AR), combining physical assembly with a mobile application, represents a significant innovation in the way students interact with STEM content. By integrating technologies such as Arduino, Unity, Vuforia, and 3D printing, this solution bridges the gap between theory and practice, offering an engaging, step-by-step learning experience.

The mobile application not only provides interactive assembly guidance through AR, but also introduces the concept of a digital twin, allowing users to observe and interact with the robot both physically and virtually. This dual experience enhances understanding of mechanical and electronic systems, while promoting active learning and problem-solving skills.

Among the most relevant educational benefits are increased motivation, improved comprehension, and greater independence in the learning process. The tool fosters curiosity and creativity, empowering students to explore engineering concepts at their own pace.

From a social perspective, the solution contributes to educational equity by using low-cost, widely available components. This ensures that schools and learning centers, even in resource-limited environments, can adopt innovative tools that align with the needs of the Industry 4.0 era.

Furthermore, the modularity and accessibility of the system make it adaptable to different learning styles and age groups, reinforcing inclusive education.

In summary, this project not only enhances the quality of STEM education through accessible and immersive technologies, but also lays the foundation for a new generation of students equipped with the skills and confidence to innovate in a rapidly evolving technological world.

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