Integrating Innovative Technologies in Mechanical Engineering Education: Case Study of an Arduino-Powered Robotic Arm for Quality Assurance in Automotive Manufacturing

Suzilawati Muhamud-Kayat, Universiti Teknologi MARA (UiTM), Malaysia
Mohd Hazri Mohd Rusli, Universiti Teknologi MARA (UiTM), Malaysia
Danish Afdal Azman, Universiti Teknologi MARA (UiTM), Malaysia
Joshua Goh, Pyrocell Sdn. Bhd. Malaysia

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Abstract
Integrating innovative technologies in mechanical engineering education is crucial for equipping students with the skills and knowledge required in modern industrial environments. This research presents the design, implementation, and assessment of an educational framework that incorporates Computer-Aided Design (CAD) and Simulation Software, Additive Manufacturing (3D Printing), Robotics and Automation, Mechatronics and Embedded Systems, with a specific focus on an Arduino-powered robotic arm for automated precision inspection in automotive manufacturing. The problem addressed was the existing gap in hands-on educational experiences that connect theoretical knowledge with practical applications, particularly in the context of quality assurance in manufacturing. The study explores the development of a robotic arm system designed to inspect Checking Fixture Jigs (CF-Jigs) used in automotive production, using Arduino as a cost-effective, open-source platform. This system was integrated into the curriculum to provide students with real-world experience in design, prototyping, and automation. The objectives included enhancing students' understanding of CAD modeling, 3D printing, and robotics while addressing the industry's need for efficient, accurate quality assurance tools. The methodology involved student-led projects, where students needed to design and implement the robotic arm, simulate its operations using CAD software, and produce physical prototypes through 3D printing. The system's performance was then evaluated in a simulated manufacturing environment. Findings indicated that this approach could improve students' technical skills and prepare them for challenges in modern manufacturing. Future work will focus on refining the educational framework, incorporating advanced technologies like machine learning, and expanding its application to broader engineering disciplines.

Keywords: Computer-Aided Design (CAD), Simulation Software, Additive Manufacturing, Robotics, Mechatronics and Embedded Systems

Introduction

The rapid advancement of Industry 4.0 technologies, such as automation, robotics, and additive manufacturing, has redefined the competencies required of mechanical engineers (Smith & Brown, 2021). In modern industrial environments, mechanical engineering curricula must evolve to meet industry needs. However, traditional curricula often fail to provide adequate hands-on experience in these areas (Patel & Sharma, 2020). Quality assurance (QA) in automotive manufacturing is a critical area where robotics and IoT technologies play a pivotal role. Integrating these technologies into education prepares students for emerging challenges and equips them with practical skills. To address this gap, this study presents an educational framework incorporating innovative tools and techniques, with an Arduino-powered robotic arm designed for quality assurance in automotive manufacturing. The initiative aligns with Industry 4.0 principles and aims to equip students with practical skills relevant to contemporary industrial challenges (Smith & Brown, 2021).

Research Background

Quality assurance is pivotal in automotive manufacturing, where precision and accuracy are paramount. Checking Fixture Jigs (CF-Jigs) plays a crucial role in verifying the dimensional accuracy of components (Patel & Sharma, 2020). Despite their importance, engineering curricula often overlook practical training in quality assurance and robotics, leaving graduates unprepared for industry demands (Johnson, 2019). This gap highlights the need for integrating innovative educational methods that connect theoretical knowledge with practical applications (Kumar & Gupta, 2021). The Arduino platform provides an ideal foundation for introducing students to automation and robotics because of its cost-effectiveness and open-source flexibility (Al-Hamadi & Al-Salti, 2021). The automotive sector heavily relies on precision in manufacturing processes, with CF-Jigs ensuring dimensional accuracy (Kumar & Gupta, 2021). Integrating Arduino into the curriculum provides students with valuable hands-on experience in CAD, mechatronics, and automation. This integration bridges the gap between academic knowledge and industrial requirements, equipping graduates with skills essential for meeting the demands of contemporary manufacturing environments (Wang & Zhou, 2019).

Research Objectives

The primary objectives of this study are:

1. To develop an Arduino-powered robotic arm framework for teaching quality assurance and automation in mechanical engineering education.
2. To enhance students' hands-on learning experience by integrating CAD, robotics, and automation technologies.
3. To assess the effectiveness of project-based learning in bridging the gap between academic knowledge and industrial applications.

Methodology

Educational Framework Design

The educational framework was meticulously designed to provide a comprehensive and immersive learning experience, emphasizing hands-on skills and practical applications in alignment with Industry 4.0 principles. The framework was designed to provide hands-on learning through four key components as listed in Table 1.

Table 1: Key Components for Framework Design

Key Components	**Description**
CAD and Simulation	Students used CAD software to design the robotic arm and simulated its movements to optimize performance and identify potential improvements (Chandra & Patel, 2019).
Additive Manufacturing (3D Printing)	Robotic arm components were fabricated using 3D printing, ensuring cost-effective production and customization (Al-Hamadi & Al-Salti, 2021).
Robotics and Automation	Arduino served as the control platform, integrating sensors and actuators to automate quality assurance tasks such as defect detection (Lee & Park, 2020).
Embedded Systems	Students programmed the robotic arm to inspect Checking Fixture Jigs (CF-Jigs), applying practical knowledge of automation and control systems to real-world scenarios (Li & Tan, 2022).

Implementation Process

The implementation process was carried out in five key phases to develop the robotic arm and ensure its effectiveness in quality assurance tasks. This structured process allowed students to apply theoretical knowledge to real-world challenges while gaining practical experience in design, manufacturing, and automation. The five key phases for the implementation process are tabulated in Table 2.

Table 2: Five Key Phases for the Implementation Process

Key Phase	Description
Phase 1: Conceptualization	Students began by analyzing quality assurance requirements and defining the specifications for the robotic arm. This phase involved understanding industry needs and brainstorming solutions to address them effectively
Phase 2: Design and Simulation	Using CAD software, students designed the robotic arm and simulated its movements. This step helped identify and address potential design flaws, ensuring the arm's functionality and efficiency before physical production.
Phase 3: Prototyping	The robotic arm's components were manufactured using 3D printing. After fabrication, the parts were assembled into a functional prototype, providing students with hands-on experience in prototyping and assembly.
Phase 4: Programming and Integration	Students programmed the robotic arm using Arduino to perform quality assurance tasks such as dimensional measurements and defect detection. Sensors and actuators were integrated to enhance the arm's capabilities, ensuring precision and reliability.
Phase 5: Testing and Evaluation	The final phase involved testing the robotic arm in a simulated manufacturing environment. Students evaluated its accuracy, reliability, and performance, making necessary adjustments to improve its operation.

Assessment Methods

The educational framework was evaluated using two main methods: rubrics and demonstrations. These approaches provided a comprehensive assessment, covering the technical, collaborative, and practical aspects.

Rubric.

The critical project components, including CAD design, programming accuracy, system functionality, and teamwork were evaluated using a structured rubric. CAD designs were assessed for clarity, precision, and optimization, while programming accuracy was judged on the effectiveness and reliability of the Arduino code. System functionality focused on the robotic arm's ability to perform tasks such as defect detection and dimensional measurement. Teamwork was also evaluated based on collaboration, communication, and problem-solving efforts. Each criterion was rated on a 5-point scale to provide clear and measurable feedback.

Demonstrations.

Each team presented their robotic arm in a live demonstration, showcasing its functionality and explaining design choices. The robotic arm's performance in quality assurance, defect detection, and dimensional accuracy was observed and evaluated. Faculty and industry professionals assessed the presentations on innovation, practicality, and technical execution, ensuring a well-rounded evaluation of the project's success.

These assessment methods provided a comprehensive overview of the framework's impact, combining objective performance metrics with student reflections and live evaluations to ensure a thorough review of both learning and application.

Results and Discussion

The robotic arm demonstrated an impressive accuracy rate of 95% in inspecting Checking Fixture Jigs (CF-Jigs) for both dimensional errors and surface defects. Figure 1 illustrates the 3D printing process for fabricating the robotic arm components. This additive manufacturing approach provided a cost-effective and efficient method for producing complex parts, allowing for rapid prototyping and refinement of the robotic arm's design. The 3D printing enabled the development of customized components, ensuring they met the specifications for the system's functionality.

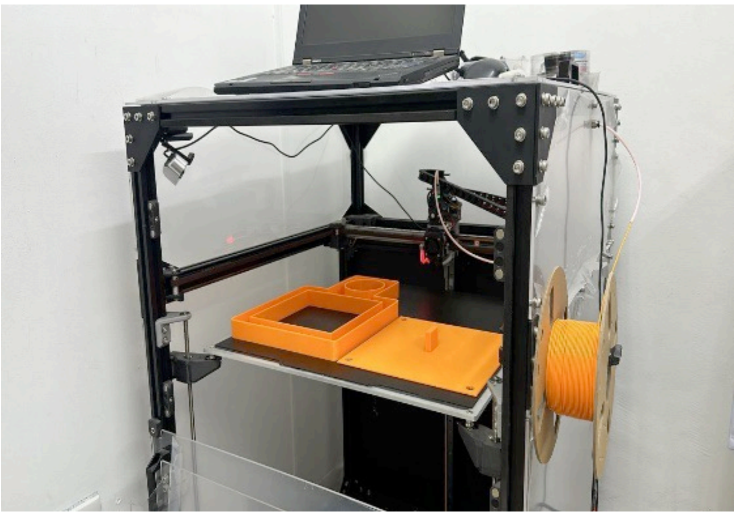
Figure 1: 3D Printing Process

Figure 2 shows the final prototype of the robotic arm, highlighting key mechanical and electronic components, such as the Arduino platform, sensors, and actuators. The design modularity allows for easy adjustments and upgrades, offering flexibility in adapting the system to various manufacturing requirements. The system also benefits from both affordability and ease of maintenance by using Arduino, a cost-effective and open-source platform.

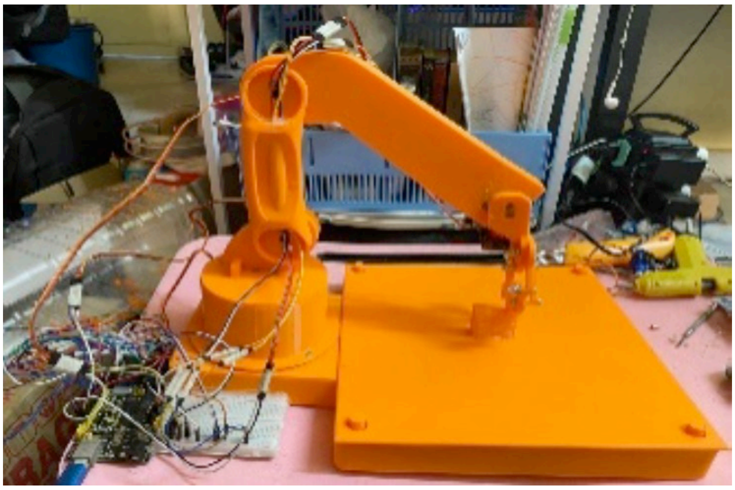
Figure 2: The Final Prototype of the Robotic Arm System

The combination of 3D printing for component fabrication and a modular design for system integration contributed to the robotic arm's high performance, offering a practical and affordable solution for quality inspections in industrial settings.

Conclusion

This study highlights the significant impact of incorporating innovative technologies into mechanical engineering education. The Arduino-powered robotic arm project was crucial in offering students valuable hands-on learning experiences that deepened their comprehension of theoretical concepts and also showcased how these concepts are applied in real-world industrial environments. By combining theoretical knowledge with practical application, students gained a more profound understanding of engineering principles, while enhancing their problem-solving abilities and technical skills.

Future research will aim to refine this framework by integrating machine learning techniques to forecast potential defects, thereby boosting the system's efficiency and reliability. Furthermore, this approach will be extended to other engineering disciplines, allowing for a wider application of these technologies. This will foster a more comprehensive understanding of the role of innovative technologies in modern engineering education and practice.

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Contact email: suzilawati6191@uitm.edu.my