AUGMENTED REALITY-ASSISTED PLC LEARNING: A COMPARATIVE ANALYSIS OF STUDENT MOTIVATION

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ABSTRACT

Laboratory experience is crucial in engineering education, as it enables students to design and conduct real experiments, fostering the development of their specific skills and aptitudes. However, students often face challenges when working with complex laboratory equipment, leading to longer experiment completion times. Augmented Reality (AR) and Mixed Reality (MR) offer the potential to enhance the learning experience by alleviating these difficulties. These technologies also improve concept comprehension and overall understanding of experiments. In this paper, we present an augmented reality application for a PLC (Programmable Logic Controller) experiment, designed to assist students in operating laboratory equipment more easily. The study investigates the impact of AR on students' laboratory skills, learning methods, and motivation through effectiveness results. A total of 35 participants from the Department of Mechanical and Manufacturing Engineering were introduced to AR technology. The study validates the effectiveness of AR using a questionnaire-based survey completed at the end of the experiment. Additionally, the study provides a comparative analysis of improvement percentages (POI) by examining data such as Task Completion Time (TCT), error counts, and the number of hints used in both paper-based and AR-based instruction experiments. Furthermore, this study assesses the understanding of MR applications. The findings suggest that AR and MR technologies are highly suitable for engineering education, offering efficiency and substantial benefits to students.

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Keywords: *Augmented Reality, Mixed Reality, Programmable Logic Controller.*

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1.0 INTRODUCTION

Augmented Reality (AR) is not a new concept, but its technology has become increasingly accessible to the general public in recent years. Researchers have accelerated the development of this field, driven by consumer and industrial demand, with the potential to fundamentally change how we solve problems and interact with the world. AR technology has paved the way for advancements in various sectors, including maintenance, manufacturing, oil and gas, and education, by making tasks significantly easier. AR is a

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technologically enhanced version of the real world, created through the integration of digital visual elements, auditory cues, or other sensory stimuli. By combining real-time data with computer-generated information, AR enriches the user's perception of reality. The result is an engaging and dynamic experience, powered by hardware devices such as smart glasses, smart lenses, and mobile devices.

Understanding textual instructions, teaching courses with spatial components, and technical gesture training (particularly in science, engineering, and medicine) can all be simplified through the use of augmented reality (AR) technology [1]. Currently, many educational institutions continue to rely on traditional methods, which are often perceived as monotonous. A study suggests that AR's ability to incorporate elements of curiosity, fantasy, and control may be a key factor in increasing student engagement [2]. By incorporating unique features into AR applications, educators can attract students and enhance their motivation to complete tasks. According to [3], AR technologies enable students to absorb knowledge more effectively, helping them develop skills that are challenging to acquire using conventional teaching methods. Moreover, utilizing AR as a learning tool can spark students' interest and motivation to better understand specific topics. To further address this, the development of a Mixed Reality (MR) environment has emerged. MR blends the physical and digital worlds, allowing physical objects and virtual entities to interact in meaningful ways, creating immersive and practical experiences for the user [4].

This work focuses on introducing an alternative teaching method as a new way of learning an experiment which is offered by the Department of Mechanical and Manufacturing Engineering. Typically, the experiments used paper instructions or assistant engineers to guide students on how to execute the procedures. The time consumption to complete is long albeit the tedious work of students in understanding the experiment. Based on a study by [5], 73% of the participants agreed that the use of AR applications guided them in experimenting. With the data of Task Completion Time (TCT), error counts, number of hints obtained, and survey feedback, the application was proved to be of good usability. By utilizing AR and MR technologies, students can better retain information and gain a deeper understanding of the mechanisms involved in the experiment.

The difficulty in comprehending laboratory work among students has significantly increased due to the tedious procedures involved in experiments. As a result, students are more prone to errors, as they often do not fully understand the experimental procedures, leading to extended time spent on tasks [6]. According to [7], discrepancies in active learning activities can arise from unclear definitions and inconsistent terminology. The limited time available for laboratory assistants to manage large groups of students may further contribute to this issue. Despite these challenges, paper-based instructions and demonstrations remain the primary methods for conveying the necessary information for conducting experiments. In the Department of Mechanical and Manufacturing Engineering, students must navigate complex procedures to understand how an experiment should be conducted. Following this, assistant engineers provide brief explanations and demonstrations. However, many students still struggle to grasp the procedures, which not only prolongs the time needed to complete the laboratory work but also increases the likelihood of errors, ultimately leading to suboptimal results [8].

This study presents applications developed for a Programmable Logic Controller (PLC) experiment, utilizing both augmented reality (AR) and mixed reality (MR) technologies. The experiment involves a PLC relay, a Human-Machine Interface (HMI) panel, and buzzer/light switches. It begins with the creation of a program called "Logic Ladder" that integrates with the HMI panel. For the experiment to function correctly, wire connections must be made according to the designed program. However, students often encounter difficulties in identifying the correct wire connections due to a lack of understanding. Addressing this issue can offer researchers and educators valuable insights into improving the effectiveness of laboratory experiences.

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The objectives of this study are: (1) to develop an AR application for PLC laboratory work using a smartphone, (2) to create an MR application for PLC laboratory work using Microsoft HoloLens 2, (3) to evaluate the effectiveness of the developed AR application for PLC laboratory work, and (4) to assess students' understanding of MR using Microsoft HoloLens 2.

2.0 BACKGROUND STUDY

Augmented Reality (AR) is defined as a technique to enhance the existing reality by using technology to observe and create an environment that is beyond the human's eyes perceive and feel, all while remaining in the real world [9]. A computer scientist, Ivan Sutherland was one of the first to build a virtual reality (VR) system back in 1965 [10]. The 'Sword of Damocles' became a reality in 1968 thanks to donations from Harvard University and the Massachusetts Institute of Technology (MIT): cumbersome spectacles with two cathode-ray tubes gave a 40-degree field of vision in a primitive virtual realm [11]. This invention is regarded as the foundation of augmented reality (AR) and has served as a blueprint for modern AR technology.

In 1992, an AR technology was introduced by creating a "see-through" virtual reality goggle and using this device to enhance the worker's visual field of view with valuable and dynamically changing information [12]. The project employed a heads-up (see-through) display headset (HUD), which tracked the user's head motions and gave them six degrees of freedom (6DOF), allowing them to compensate for variations in user position and view direction. The HDU technology was built as a proof of concept by applying AR to the industrial area in this project.

Over the years, many companies used the blueprint for AR to continue developing this technology. Augmented reality is created by overlaying a computer graphic onto a picture, making it easier to create and hence more accessible than virtual reality [13]. Recently, Pokémon Go has been a prominent AR application in the gaming industry. The Pokémon GO app is a multi-player, location-based augmented reality game that uses smartphone technology to bring mythical creatures known as Pokémon into the real world [14]. Another example of today's AR application is the Google Lens that was created for mobile devices Snapchat has integrated 'Lenses,' an in-app augmented reality (AR) feature that layers visuals and designs over real-world items when viewed through the camera of a smartphone, with in-app consumption opportunities [15].

2.1 Types of Augmented Reality

Currently, there are various types of AR technology that are used by developers. With the advancements in technology, more ways of developing AR are discovered.

Marker-based tracking augmented reality

Marker-based AR is also known as image recognition. This type of AR utilizes the camera and a visual marker that is in the form of a template marker, a 2D barcode (QR code) marker, circular marker or image marker. Markers have distinct patterns that the camera can detect and process recognition. When the camera scanned the marker, this triggers an AR experience that can appear in the form of object, text, video or animation. For the AR to work, the marker detection algorithm will be activated.

VR training with haptic feedback provides better results and the combination of learning method using AR system and training method using VR system also yield better results. The combination of learning and training in AR VR group enhanced users in mastering the assembly procedure and maximize their skill performance [16]. Figure 1 shows the utilization of AR applications in computers. Figure 2 shows the type of markers used for experiment setup.

DOI 10.11113/jm.v48.566

Figure 1: Utilization of AR application in components of computers [17]

Figure 2: The image marker used in experiment setup [18]

Markerless augmented reality

Markerless AR also known as location-based reality is a type of AR that allows users to be provided with data based on their current location and is collected via a digital compass, accelerometer, velocity meter, or GPS [19]. Markerless approaches utilise natural properties present in the picture, such as planes, edges, or corner points, which are taken from the environment and are suitable for putting virtual objects into the actual world [20].

Recently, a revolutionary markerless AR technology known as SLAM (Simultaneous Localization and Mapping) has become widely used in smartphones. SLAM is a tracking technology that does not require the addition of any physical objects to the environment [21]. SLAM detects the environment around them and calculates the camera's or device's position and orientation in the real world [22]. An example of the application of SLAM is the Microsoft Kinect depth sensor demonstrated that the surface reconstruction can be a normal element of a live SLAM pipeline, using GPU-accelerated algorithms for rapid dense reconstruction and tracking [23]. Figure 3 shows a markless AR application.

Figure 3: Utilization of AR application in components of computers [24]

Projection-based augmented reality

Projection-based AR also known as spatial AR allows artificial light projected onto real-world things [19]. This type of AR does not restrict the users from head-mounted or hand-held devices. The projector will be able to omit artificial light onto irregular surfaces using projection mapping. This approach allows for the manipulation of an object's perception

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and the creation of optical illusions [25]. Figure 4 shows the stepping exercise using a projection-based AR application.

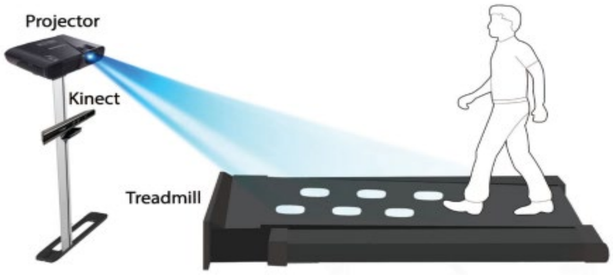

Figure 4: Stepping exercise using projection-based AR application [25]

Currently, extensive research is being conducted on projection-based AR, as this technology offers a highly interactive user experience. A study by [26] developed a projection-based AR application specifically for use in physiotherapy classrooms. In the study, the AR system uses pen-based interactions to put virtual skeletal and muscular models onto a person. Figure 5 shows the projection-based AR application during Geography class.

Figure 5: Projection-based AR application during Geography class [27]

Superimposition-based augmented reality

Superimposition-based AR is a technology in which the original object's features are partially or completely changed with new augmented features put on the same research item [27]. When replacing a view of an object with an augmented view, object recognition is critical [28]. Unlike marker-based AR, which overlays augmented information on top of specifically developed fiducial markers, superimposition-based AR identifies the entire item. This sort of AR is diverse, with uses ranging from assisting doctors to entertaining tourists by overlaying old images of the places they visit, allowing them to perceive the changes made in the period in between [29]. Figure 6 shows the superimposition-based AR for historical site education.

Figure 6: A superimposition-based AR for historical site education

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2.2 Mobile Augmented Reality

Mainstream smartphones continue to be the most popular computing platform for giving users Mobile Augmented Reality experiences, with applications that are rapidly increasing in popularity. Nearly everyone owns a smartphone, making access to augmented reality applications easier on this platform. For example, Snapchat, an app valued at approximately $1 billion, includes augmented reality features that allow users to enhance images with computer-generated animations [5]. Table 1 presents several examples of augmented reality applications used across different industries.

Table 1: Past studies for Mobile AR technology for various industrial applications

Sources	Topic	Type of Augmented Reality Application	Industry
[30]	Mobile Augmented Reality Applications for Construction Projects	Marker-based Augmented Reality	Construction
[31]	Integration of Mobile Augmented Reality (MAR) Applications into Biology Laboratory: Anatomic Structure of Heart	Marker-based Augmented Reality	Biology Education
[32]	Mobile Augmented Reality for Campus Visualization Using Markerless Tracking in an Indonesian Private University	Markerless Augmented Reality	Education

2.3 Augmented Reality for Programmable Logic Controller (PLC) Experiment in Engineering Education

Several studies were made specifically in developing AR applications for PLC experiments in engineering education. Table 2 shows past studies for AR technology for PLC experiments in engineering education.

Table 2: Past studies for AR technology for PLC experiments in engineering education

Sources	Topic	Findings	Evaluation method
[33]	Programming and Testing a PLC control a Scalable Industrial Plant in Remote Way	A proposed remote lab for the PLC experiment	-
[34]	Augmented Reality in Automation	The AR has helped students to understand the difficult experiment concepts	Survey questionnaire
[35]	Analysis of Student Motivation in the use of a Physics Augmented Reality Remote Lab During the COVID-19 Pandemic	AR lab has improved the student experience and learning	Survey questionnaire

3.0 MATERIALS AND METHODS

This section discusses the methods of developing the Augmented Reality (AR) application and the process needed to evaluate the data obtained. The flow of the project and the requirements for the project are explained in detail.

3.1 Project Workflow

In developing the AR and MR applications, there were two main steps required which are modelling all components needed and designing the scene in the application. For the 3D

DOI 10.11113/jm.v48.566

model, SolidWorks was used meanwhile Blender 2.93.6 was used to make the colouring of the components. The next stage was the development of the AR and MR applications when the modelling and colouring process was finished. The development of the AR and MR applications was done in Unity 3D where the software used to develop the AR and MR applications where all the components and 3D objects were imported and scenes were created in the project space. The AR and MR application were then imported into the smartphone and Microsoft HoloLens 2 respectively. A group of mechanical engineering students from Universiti Putra Malaysia were asked to conduct a PLC experiment under two conditions: paper-based instruction and AR-based training, to assess the application's performance. The completion time, data error counts and number of hints were recorded during the experiment. After the experiment, the participants must complete a survey to assess the user experience under both scenarios.

3.2 Hardware Requirement

In developing the AR application, Samsung Note 10+ was required. Samsung Note 10+ is a smartphone that has a variety of features that are suitable for AR applications. The smartphone can deliver a high-quality AR viewing experience providing maximum comfort to users. In developing the MR application, a Microsoft HoloLens 2 was required. This device is a Head-Mounted Device (HMD) that specializes in Mixed Reality applications. This device is equipped with see-through lenses that assist people in viewing holographic images. With the help of the hand tracking feature, the user can touch, grasp and move holograms in ways that feel natural. The PLC components were required for paper-based instruction such as power supply, connecting wires, switch and buzzer. All these components will be set up based on the experiment is undergoing.

3.3 Software Requirement

In developing the AR and MR applications, the software required such as SolidWorks, Blender and Unity 3D. SolidWorks is one of the Computer-Aided Design (CAD) software that is currently being used in the market. This software is used in modelling the 3D object. This software is used to draw power supply, connecting wires, switch and buzzer in 3D format. The 3D models have the same dimension as the real object to give a better user experience. Blender is an open-source 3D computer graphics software suite that may be used to make animated features, visuals, art, 3D printed replicas, motion graphics, interactive 3D apps, virtual reality, and computer games. 3D models from SolidWorks are imported to Blender before the model is transferred to Unity 3D. Unity is a game engine platform that has been developed by Unity Technologies and can be used in various platforms such as Windows and macOS. Unity allows users to create 2D and 3D games and experiences, and the engine includes a core scripting API written in C# for both the Unity editor and the applications themselves, as well as drag-and-drop capability.

3.4 Participants

The participants for this project were 35 students from the Department of Mechanical and Manufacturing Engineering at Universiti Putra Malaysia. Both female and male participants were involved in this project from the range of 19 to 24 years old. Each of the participants will attend the experimental sessions that will last approximately 10 to 30 minutes. All participants have experience in doing a mechanical lab using the current typical teaching method.

3.5 Questionnaire Setup

For this project, the questionnaire will be divided into four sections which are Section A, Section B, Section C and Section D. Section A will consist of pre-study questions which ask about the general knowledge of participants about AR and knowledge about PLC. Section B and Section C are post-study questions where Section B is for AR-based

DOI 10.11113/jm.v48.566

instruction and Section C is for paper-based instruction in doing the laboratory experiment. This section then is divided into three parts which consist of device interaction, learning experience, and overall recommendation. The final section, which is Section D will ask the participants which method is preferable to be used in the PLC lab.

4.0 RESULTS AND DISCUSSION

The development of Augmented Reality (AR) requires a few procedures. Details of the procedures are explained in this section.

4.1 Design and Development of Augmented Reality System Programmable Logic Controller (PLC) 3D Modelling Components

In modelling the PLC components, SolidWorks is used due to the user-friendly and flexibility. The components are modelled by the author as close to real objects to avoid confusion when experimented with in the laboratory. Figure 7 shows the completed 3D models for the push button, PLC box unit and buzzer.

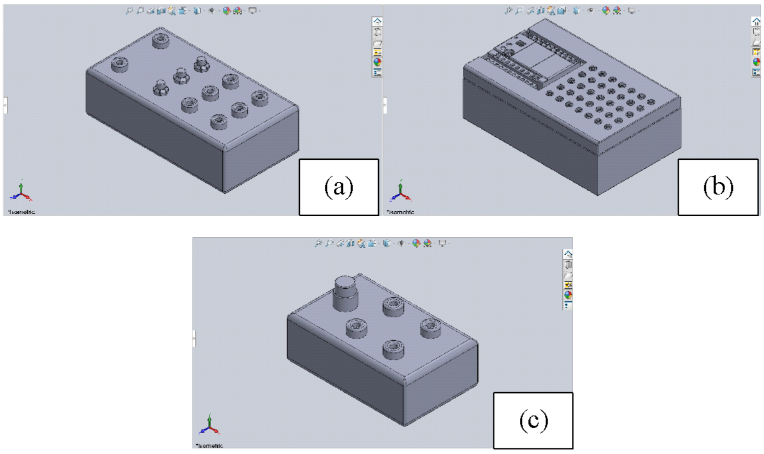

Figure 7: The completed 3D models consist of (a) LED buzzer unit (b) PLC box unit (c) push button

4.2 Colouring and File Format Changes

To colour the 3D object, the 3D object was imported in .stl format into the workspace. Materials were added to the object where each material was assigned to a specific surface based on the desired colour. When the colouring process is finished, the file will be exported in .fbx format where Unity 3D was able to read the 3D model properly. This is due to Unity 3D cannot support all file formats. The file format that can be read by Unity 3D are .fbx, .dae, .dxf, .obj and .skp formats. Figure 8 shows the completed colouring 3D models for the push button, PLC box unit and buzzer.

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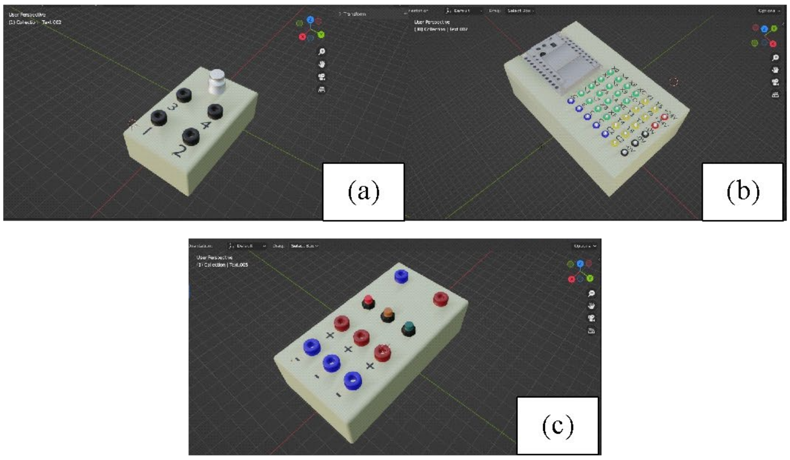

Figure 8: The completed colouring 3D models for the (a) push button (b) PLC box unit (c) LED buzzer output

4.3 Game Scene Building

The game engine Unity 3D was used to create augmented reality environments. The 3D components were imported into the workspace. Other features such as a gaming system, sound system and light feature were added to enhance the user interface and experience. Figure 9 shows some of the scenes that were built using Unity 3D.

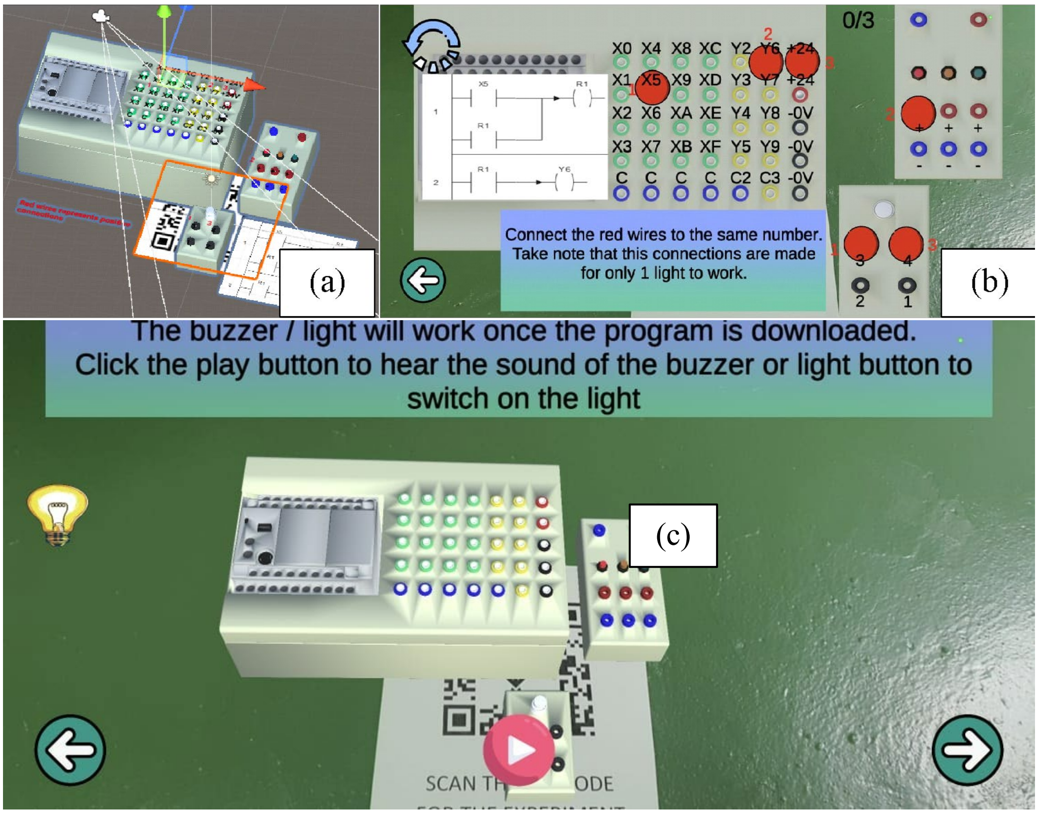

Figure 9: Scenes from the application (a) Placement of 3D models (b) Gaming system of the application (c) Outcome of the experiment

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4.4 Evaluation of the Effectiveness of Developed Virtual Reality Application Data Analysis

The average Task Completion Time (TCT) for the students to complete the experiment using paper-based instruction is higher than using AR-based instruction. Most of the participants required a longer time to complete the experiment compared to using AR instruction. However, in some cases where participants used as short time in completing the experiment using the paper-based is due to the usage of hints that were given during the experiment. In this matter, participants were unfamiliar with the experiment concept and lack of understanding of how to experiment correctly. Figure 10 shows the graph of frequency against Task Completion Time (TCT). Most of the participants that used the paper-based instruction took a time that ranges from approximately 3 to 23 minutes as compared to those using augmented reality-based instruction which ranges from 3 to 8 minutes.

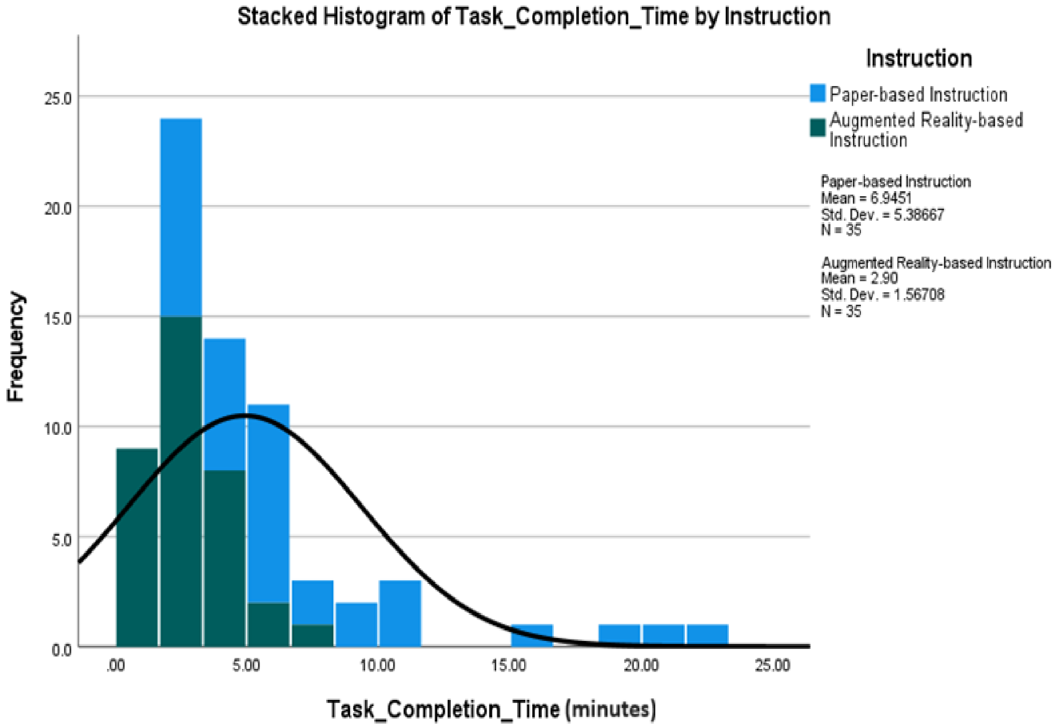

Figure 10: The graph of frequency against Task Completion Time (TCT)

The average error counts that were made by the participants using paper-based instruction is greater than using augmented reality-based instruction. The higher average of error counts in using paper-based instruction was obtained because the participants tend to connect the wires incorrectly. The participants were able to correctly connect the wires using the augmented reality-based application as the instructions of the application were clear and there were indications on how to connect the wires. Figure 11 shows the graph of frequency against error counts. The higher average of error counts in using paper-based instruction was obtained because the participants tend to connect the wires incorrectly.

DOI 10.11113/jm.v48.566

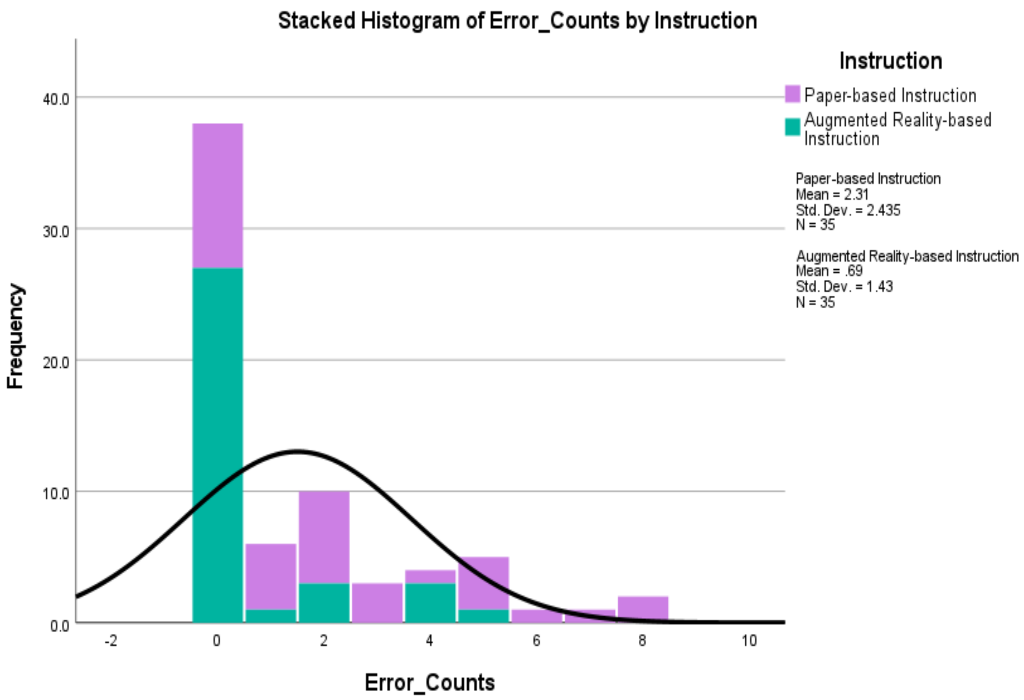

Figure 11: Frequency against error counts

To evaluate the performance, the Percentage of improvement (POI) for TCT, error counts and number of hints were calculated. Based on the Task Completion Time, error counts and number of hints, a Percentage of Improvement (POI) is calculated using the following formula.

$$Percentage\ of\ Improvement\ (POI) = \left|\frac{Score\ for\ AR\ based\ instruction - Score\ for\ paper\ based\ instuction}{Score\ for\ paper\ based\ instruction}\right| \times 100\%$$

The data on the Percentage of Improvements (POI) are represented in Table 3. The POI of the TCT is improved by 58.24 % for the AR-based instruction, and the POI of the error counts was reduced by 70.13 % as the group in AR instruction can follow the step-by-step procedure given with the help of the User Interface (UI) to make it more clear and understandable; meanwhile, the POI for the number of hints reduced to 92.63 % due to the participant able to experiment without guidance as they managed to perform the task by following every instruction given in AR. However, the participants in the paper-based instruction faced difficulties with paper instruction where they need to read the manual carefully and analyze the diagram given where they need to think more to organize all the wires.

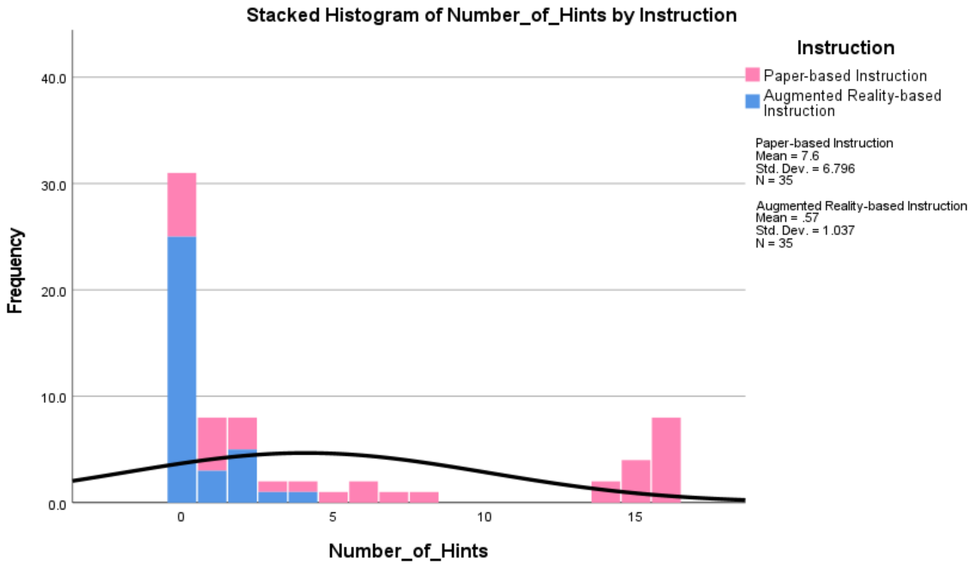

Figure 12: The graph of frequency against the number of hints

Table 3: The data of Percentage of Improvements (POI)

Data	Augmented Reality-based Instruction (%)
Task Completion Time (TCT) (mins)	58.24 (improved)
Error counts	70.13 (reduced)
Number of hints	92.63 (reduced)

4.5 Survey Analysis

The mean rating for the questions from AR-based instruction and paper-based instruction are recorded and tabulated as shown in Table 4.

Table 4: Mean of Each Question of AR-based and Paper-based Instruction

Subsection of survey	Device Interaction Section A			Learning Method Section B			Overall Section C		
Group	1	2	3	4	5	6	7	8	9
Paper-based	.34	.43	.06	.00	.03	.14	.97	.91	.51
Augmented reality-based	.34	.57	.43	.49	.34	.49	.37	.51	.63

The mean value of each question based on participant response in Part A which is represented as device interaction shows that most participants rated high for AR instruction compared to paper instruction. Part A consists of three questions asking about the difficulty in performing the task (Q1), how clear the instruction was viewed (Q2) and did the 2D instructions and 3D models easy to be recognized (Q3).

Next, the mean value of each question based on participant response in Part B which represented a learning experience shows that many participants rated high for AR instruction compared to paper instruction. The questions from this part B consist of the effectiveness of the learning method (Q4), assisting level of the medium instruction (Q5) and interest level towards the method approached the subject (Q6). Lastly, the mean value of each question based on participant response in Part C, which represented an overall recommendation shows that many participants also rated high for AR instruction compared

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to paper instruction. The final part of the survey consists of three questions which are about the recommendation applied for other laboratory tasks (Q7), apply for instructor to use in teaching (Q8) and participant confidence level in completing the PLC experiment (Q9). However, through this analysis, the mean is slightly significant, especially questions from Section B as compared to Section A and Section C. This is due to the participants being more comfortable using the traditional way of learning.

4.6 Design and Development of Mixed Reality System Game Scene Building

The game engine Unity 3D was used to create augmented reality environments. The 3D components were imported into the workspace. Other features such as holographic features, sound system, animation and light feature were added to enhance the user interface and experience. Figure 13 shows the view of the application from the user's perspective using Hololens 2. Figure 14 shows the hand tracking system that was implemented in the application. Figure 15 shows the user experimenting with the PLC using the MR application.

4.7 Assessment of the Mixed Reality Application

This application was experimented with in a trial run. Through this trial run, the participant was able to understand the wiring system of the Programmable Logic Controller (PLC) using the holographic guidelines provided. The animation of the holographic guidelines helped the participant to visualize how the wiring should be done. Figure 15 shows the participant doing the PLC experiment using the MR application.

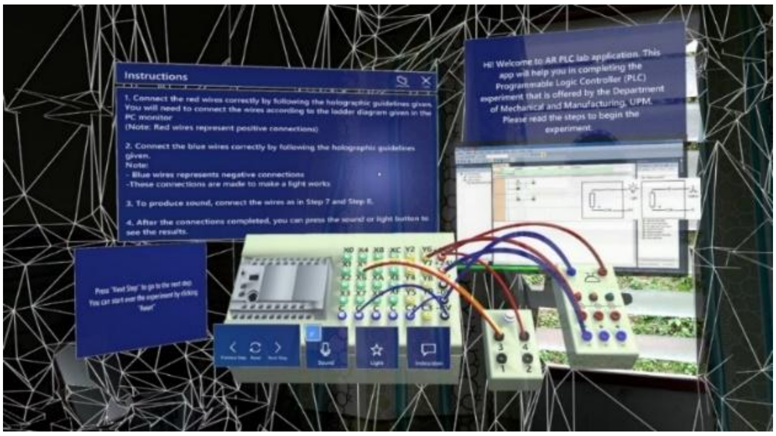

Figure 13: The view of the application from the user's perspective using the HoloLens 2

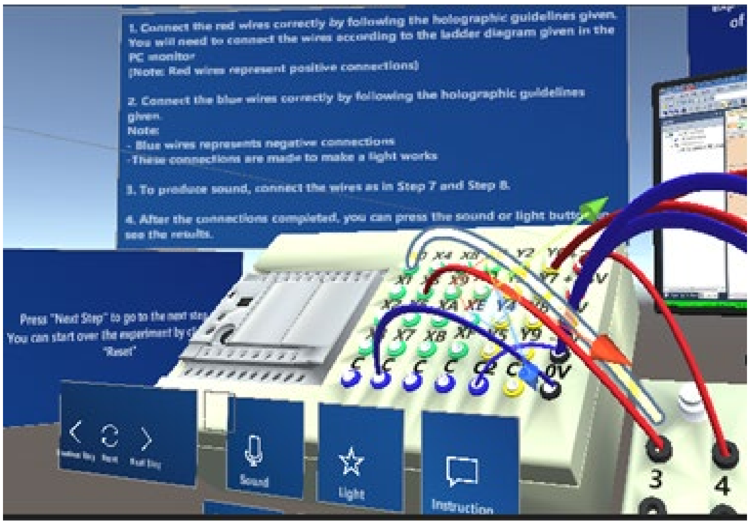

Figure 14: The holographic wires are used for the MR application

DOI 10.11113/jm.v48.566

Figure 15: The user is experimenting with the PLC using the MR application

5.0 CONCLUSION

The Augmented Reality (AR) and Mixed Reality (MR) application with a holographic guideline for Programmable Logic Controller (PLC) laboratory work was developed by using open source software which was Unity 3D where the 3D models of the PLC components were designed using the SolidWorks as similar to the real objects and the colouring of the models was done in Blender software were also used to change the format of the objects from .stl to .fbx format to ensure that the 3D models can be read and opened in Unity 3D; meanwhile, the hologram feature was added during game scene building. The effectiveness of the developed Augmented Reality (AR) application was evaluated by analysing the data that have been recorded which were Task Completion Time (TCT), error counts and the number of hints used and analysed the survey questionnaire that has been provided which consists of device interaction, learning experience and overall recommendation which the results of both analyses showed positive and good feedback from the participants.

The developed MR application was successfully assessed for application usability and functionality. Using AR and MR helps in achieving Goal number 4 (Quality Education) from 17 Sustainable Development Goals (SDGs) which ensure all students have access to high-quality, inclusive education and encourage possibilities for lifelong 86 learning. The SDGs can be achieved by examining the difficulties, opportunities, and developments in Information and Communication Technology (ICT) implementation in education, focusing on AR and MR learning environments and their potential in the classroom. Usage of AR and MR also gives benefits for a better environment since the Programmable Logic Controller (PLC) experiment used direct electricity, and the usage of AR and MR application has minimised the use of electricity. These innovations cut down on the amount of electricity needed and speed up usage. Using less power results in less consumption of fossil fuels, which lowers the amount of carbon dioxide in the atmosphere. However, AR and MR can physically and mentally harm society as the application may cause the users to get distracted from their surroundings and addicted to using the technologies. This happens as a result of the user being less aware of their surroundings and having less time to take action before an unexpected incident happens, which also causes social anxiety.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the publication of this paper.

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