A STUDY OF THE EFFECTIVENESS OF A FORKLIFT DRIVING SIMULATION: A COMPARISON BETWEEN VIRTUAL REALITY CONTROLLERS AND MOBILE-BASED CONTROLLERS

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MASTER OF SCIENCE

IN

DIGITAL TRANSFORMATION TECHNOLOGY

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Independent Study Title: A Study of the Effectiveness of a Forklift Driving Simulation: A Comparison Between Virtual Reality Controllers and Mobile-based Controllers

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Natkitta Kongkaewvorasit

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ABSTRACT

Forklift operation training carries inherent safety risks and high costs. To address this, this study developed a simulation system integrating a miniature forklift with IoT and Virtual Reality (VR) within a Digital Twin framework. The research compared operational effectiveness and user satisfaction between VR controllers and mobile-based controllers. Drawing from a continuous research framework (Protocol Number: EC 25067-13), participants performed navigation and pallet handling tasks using a learning-by-doing approach. The findings indicate that while both modalities facilitate conceptual understanding, the VR-based interaction demonstrated notably higher engagement and situational awareness due to its immersive nature. The study concludes that VR-based simulation effectively enhances procedural skills and provides a safe, engaging platform for technical and vocational education.

Keywords: Forklift Simulation, Virtual Reality (VR), Internet of Things (IoT), Digital Twin, Vocational Education

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ABBREVIATIONS AND SYMBOLS

VR	Virtual Reality
IoT	Internet of Things
HMD	Head-Mounted Display
XR	Extended Reality (includes VR, AR, and MR)
UI	User Interface
UX	User Experience
SDLC	System Development Life Cycle
MQTT	Message Queuing Telemetry Transport
WebSocket	Full-duplex communication protocol over a single TCP connection
PC	Personal Computer
FPV	First-Person View
WLAN	Wireless Local Area Network
HTTP	Hypertext Transfer Protocol
MJPEG	Motion Joint Photographic Experts Group (Video Format)
GPIO	General-Purpose Input/Output
PWM	Pulse Width Modulation
DC	Direct Current
LED	Light Emitting Diode
OS	Operating System
App	Application
EC	Ethics Committee (Protocol/Approval Code)
Vs.	Versus
etc.	Et cetera (and so forth)
p. (pp.)	page (pages)

CHAPTER 1

INTRODUCTION

1.1 Background and Importance of the Research Problem

In the industrial sector, forklift operation is an essential skill, as forklifts are key equipment used for moving materials and goods in warehouses, factories, and various workplaces (1). However, training beginners to operate forklifts in real-world environments from the outset may pose significant safety risks, including accidents, injuries, and property damage caused by trainee errors (2).

Meanwhile, Virtual Reality (VR) technology has rapidly advanced and gained popularity in training and education, especially for skillsets that require hands-on practice but involve high risk or cost (1). Applying VR technology to forklift training presents a highly promising solution.

Based on this concept, the research team has developed a VR-based forklift driving simulation system, integrated with a miniature forklift model capable of interacting with a virtual environment. This is achieved using IoT devices, which connect the trainee's physical actions with their corresponding controls in the VR system (3). The environment simulates realistic conditions in a scaled-down setting, allowing learners to practice, experience, and understand real-life scenarios without the risks typically associated with real-world forklift training, consistent with the principles of experiential learning (4).

1.2 Research Objectives

To develop and evaluate a forklift driving simulation system, specifically comparing the effectiveness of control via VR controllers and mobile-based applications.

1.3 The Importance of Research

1.3.1 Academic Significance: Contributes to the body of knowledge regarding the use of VR and IoT in skill training.

1.3.2 Applicational Significance: Provides a safe training alternative to reduce real-world accidents and improve preparedness.

1.4 Research Hypothesis

Using a VR-integrated forklift simulator can significantly enhance learning outcomes and operational skill acquisition compared to traditional methods.

1.5 Scope of Research

1.5.1 Population: High school students aged 15–18 years *(N=77)*.

1.5.2 Variables:

1. Independent Variable: Control method (VR Controller vs. Mobile Application).

2. Dependent Variables: Task performance (time, error rate), user satisfaction, and conceptual understanding.

1.5.3 Content: Simulation of forklift operations including basic navigation, pallet handling, and timed operational challenges.

1.5.4 Tools: Miniature forklift model, ESP32-CAM microcontroller, Oculus Quest 2 (VR), and Android tablets.

1.6 Preliminary Agreement

All participants volunteered and provided informed consent before participating. This study is a continuous part of a previously approved research project titled “Educational virtual reality to enhance knowledge and understanding of learning to drive a forklift for practice in working before actually working” (Protocol Number: EC 25067-13). The instruments used, including questionnaires, were verified for content validity and reliability by experts.

1.7 Research Limitations

The findings of this study are based on participants within a specific continuous research framework, which may affect the generalizability of professional industrial operators with extensive experience. Furthermore, hardware constraints and network latency inherent in miniature IoT models may slightly influence the degree of realism compared to full-scale industrial simulation systems.

1.8 Terminology Definition

1.8.1 VR (Virtual Reality): A computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way (5).

1.8.2 Forklift Simulator: A system combining hardware and software to replicate the experience of operating a forklift truck.

1.8.3 IoT (Internet of Things): A network of physical objects embedded with sensors and software for the purpose of connecting and exchanging data with other devices over the internet (2).

CHAPTER 2

LITERATURE REVIEW

2.1 Theoretical Background

2.1.1 Forklift/Robot Control

The core of the simulation system lies in the integration of hardware control through ESP32-CAM microcontrollers, which enable real-time interaction with physical systems. The ESP32-CAM is a low-cost, Wi-Fi-enabled microcontroller that also supports image transmission via its built-in camera (7). In this study, it serves as the key component for receiving control signals from mobile apps or VR controllers through protocols such as WebSocket or MQTT, both of which are efficient for low-latency communication (3). This architecture facilitates seamless interaction between user inputs and the behavior of the physical forklift model (2). Such real-time control mirrors principles found in robotics, where sensors, actuators, and communication layers form an integrated control system. The approach supports IoT-based learning systems, where hardware manipulation is embedded in the learning process.

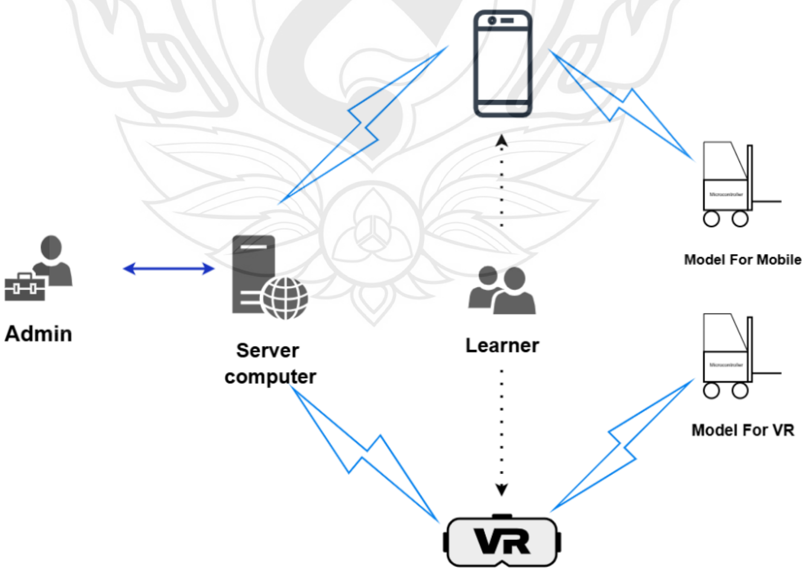
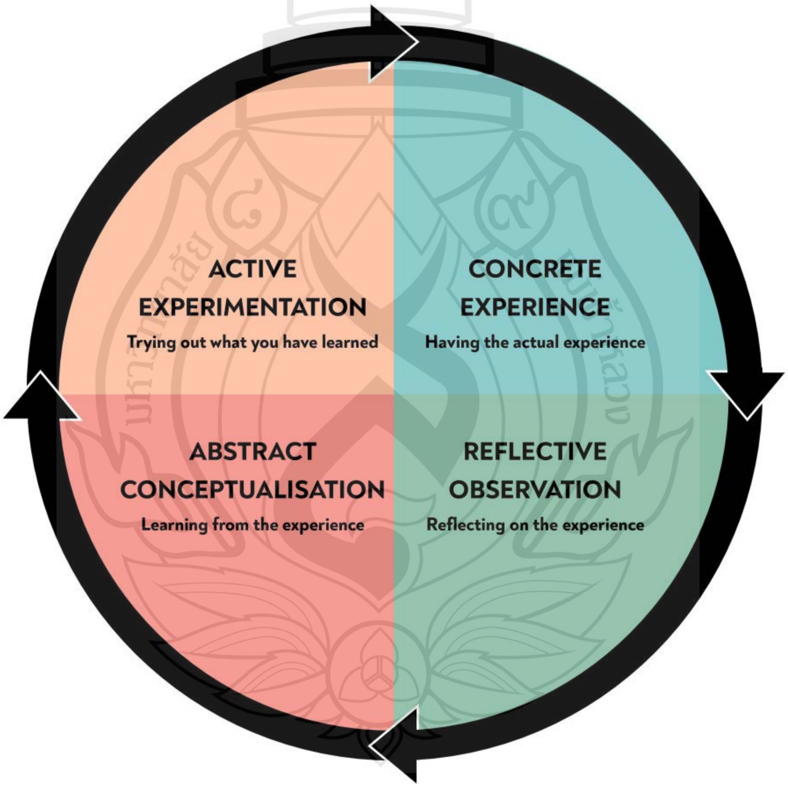


Figure 2.1 Overall System Architecture of the VR-integrated Forklift Driving Simulator.

2.1.2 Learning by Doing

Kolb's Experiential Learning Theory (1984) forms the pedagogical foundation of this research (4). This model emphasizes that learners gain deeper understanding when they engage directly with simulated tasks, reflect on their actions, and apply their understanding to practical challenges. In this study, the theory is applied to evaluate how different control interfaces affect the experiential learning process in forklift operation. The theory outlines a four-stage cycle:

1. Concrete Experience
2. Reflective Observation
3. Abstract Conceptualization
4. Active Experimentation (4)



Source Adapted from Kolb (1984)

Figure 2.2 Kolb's Experiential Learning Cycle.

This model emphasizes that learners gain deeper understanding when they engage directly with real or simulated tasks, reflect on their actions, conceptualize the experience, and apply their understanding to new challenges (4). In the context of this study, learners interact with a simulated forklift in a VR environment, making decisions and learning from outcomes in a safe, feedback-rich context—perfectly aligned with the experiential learning cycle.

2.1.3 Systems Thinking Development

Simulation-based learning involving hardware and software integration encourages systems thinking—the ability to see complex systems as interconnected components. When learners engage with Digital Twin models, where real-time input affects both virtual and physical outcomes, they must understand feedback loops, dependencies, and consequences of their actions (2-3). This holistic thinking is essential in modern engineering, logistics, and automation tasks, where systems rarely operate in isolation (1). The ability to mentally model system behavior, make predictions, and adjust actions based on system-wide understanding is one of the key outcomes expected from learners using this simulator (4).

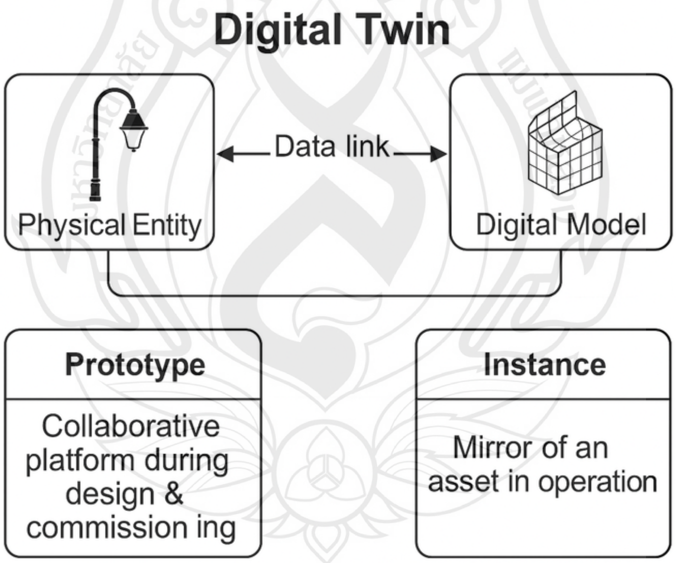


Figure 2.3 Conceptual Framework of the Digital Twin interaction between physical and virtual environments.

2.1.4 Vocational and Skill-Based Training

In professional training, hands-on engagement is central. Active learning strategies involving simulated systems result in better retention and deeper conceptual understanding (6). This simulator integrates these practices by allowing learners to work within a Digital Twin environment, fostering critical thinking and technical competency through physical-virtual interaction (8-9).

2.2 Related Works

This study draws on prior research and concepts from three key areas: IoT-based forklift control systems, VR driving simulation, and Experiential Learning in Technical Education

2.2.1 Research: System Control of Prototype Forklift Using Android and ESP32 Based on MQTT Communication

This study presents the development of a prototype forklift controlled via an ESP32 microcontroller and an Android device using MQTT for real-time communication (2). The system allows users to issue movement commands—forward, backward, turn, and lift—remotely and reliably.

The relevance of this work lies in demonstrating how IoT and microcontrollers can enable low-latency, real-time control for physical devices (2). These principles are directly applied in the current project, especially using the ESP32-CAM module, which enables live video streaming and interactive feedback in the simulation system.

2.2.2 Research: VR Driving Simulator

VR-based driving simulators have gained wide adoption in industrial training and education. Systems such as VR Forklift Trainer, Logistics Driving Simulator, or warehouse VR platforms allow learners to practice vehicle operation in immersive, safe environments (1).

Research shows that users trained in VR environments exhibit higher focus, faster reaction times, and improved coordination compared to traditional training methods (1). VR also allows flexible scenario design, such as obstacle-rich paths or emergency simulations, which are not always safe or practical to create in real life. These findings support the effectiveness of integrating VR into forklift simulation to enhance training outcomes.

2.2.3. Research: Experiential Learning in Technical Education

Experiential learning is a core pedagogical approach in technical and vocational education. Studies demonstrate that learners involved in physical simulations develop deeper understanding and greater motivation compared to passive instruction (6). This project applies this approach within a Digital Twin framework, enabling learners to control real hardware synchronized with a virtual environment to enhance training outcomes.

Table 2.1 Related Works

Related Works	**Focus Area**	**Technology Used**	**Key Relevance to This Study**
IoT-based Control Systems (2), (3)	IoT Architecture & Communication	ESP32, MQTT, WebSocket, Android	Provides the framework for low-latency hardware communication and mobile-based control.
VR Driving Simulator (1)	Immersive Vocational Training	Unity 3D, VR Headset, XR Interaction Toolkit	Demonstrates the efficacy of VR in simulating industrial tasks for safe learning.
Experiential Learning in Technical Education (6)	Pedagogical Methodology	Physical Simulations, Active Learning	Validates "Learning-by-Doing" as an effective strategy for technical skill acquisition.

Figure 2.4 Comparison of User Interfaces and Interaction Modes: (Left) Mobile-based Application Interface; (Right) VR-based Immersive Interaction.

Figure 2.4 illustrates the two distinct control modalities evaluated in this study. The Mobile-based Application Interface (left) employs a traditional 2D Graphical User Interface (GUI), utilizing on-screen virtual joysticks and touch-sensitive buttons for forklift maneuverability and lift control. This mode relies on a third-person perspective, where the user monitors the physical prototype directly while providing inputs via a handheld device.

In contrast, the VR-based Immersive Interaction (right) utilizes the XR Interaction Toolkit within a 3D simulated environment. This mode provides a first-person perspective through a Head-Mounted Display (HMD), allowing the user to interact with the forklift controls using spatial VR controllers. The VR system maps the user's hand movements to virtual levers and steering mechanisms, creating a Digital Twin experience that synchronizes virtual actions with the physical prototype's movements via IoT protocols. This comparison is central to assessing the effectiveness of spatial awareness and tactile-visual feedback in vocational training. The detailed technical development and experimental procedures for evaluating these two interfaces are further elaborated in Chapter 3: Research Methodology

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Research Process Overview

The development and evaluation of the forklift simulation system follow a structured research process:

3.1.1 Design and develop a miniature forklift simulation system utilizing Virtual Reality (VR) and Internet of Things (IoT) technologies.

3.1.2 Select participants from the continuous research framework based on defined criteria.

3.1.3 Execute forklift operation tasks within the simulated environment using two different control modalities.

3.1.4 Collect and analyze system log data and user performance metrics.

3.1.5 Distribute post-training questionnaires to evaluate user satisfaction and perceived learning outcomes.

3.1.6 Perform statistical analysis to compare the effectiveness of the control interfaces.

3.2 Research Design

The research follows the System Development Life Cycle (SDLC) combined with an experimental study approach. The process is divided into four main phases:

3.2.1 Requirement Analysis & Design: Analyzing the kinematics of forklift operations and designing the system architecture.

3.2.2 System Development: Constructing miniature forklift hardware and developing the software control interfaces (VR and Mobile) using Unity.

3.2.3 Experimental Phase: Conducting trials with high school students to collect performance data and user feedback.

3.2.4 Evaluation & Analysis: Analyzing quantitative data (time, errors) and qualitative data (satisfaction) to draw conclusions.

3.3 Population and Sample Subjects

The sample for this study was obtained from the continuous research project titled “Educational virtual reality to enhance knowledge and understanding of learning to drive a forklift for practice in working before actually working” (Protocol Number: EC 25067-13). The subjects consist of participants with no prior forklift operating experience. The experimental process focuses on testing and comparing the effectiveness between the VR Controller and the Mobile Application interfaces.

3.4 Instruments

3.4.1 Hardware Architecture: Miniature Forklift Model

The physical component of this study is a custom-built miniature forklift designed to replicate the kinematic movements of a standard industrial forklift. A 1:16 scale miniature forklift was custom-built to simulate physical constraints. Constructed from laser-cut 3-5mm acrylic sheets for durability. The hardware integration focuses on cost-effectiveness and IoT capability. The key components include:

3.4.1.1 Microcontroller (ESP32-CAM): The core processing unit is the AI-Thinker ESP32-CAM module. This board was selected for its integrated Wi-Fi + Bluetooth capabilities and its on-board OV2640 camera interface, allowing it to act as both a control server and a video streaming device simultaneously.

3.4.1.2 Actuation System:

1. Propulsion: Two DC gear motors (TT Motors) are used for the drive train, enabling forward, backward, and turning movements via differential steering.

2. Lifting Mechanism: A separate high-torque DC motor controls the fork's vertical movement (elevation and depression) via a gear and pulley system.

3. Motor Driver: An L298N Dual H-Bridge Motor Driver module is interfaced between the microcontroller and the motors to manage the high current and

voltage required for actuation, allowing for Pulse Width Modulation (PWM) speed control.

3.4.1.3 Chassis and Power: The structural frame is constructed from laser-cut acrylic sheets to ensure stability. The system is powered by18650 Lithium-ion batteries (7.4V, 3000mAh) to ensure sufficient runtime for experimental trials.

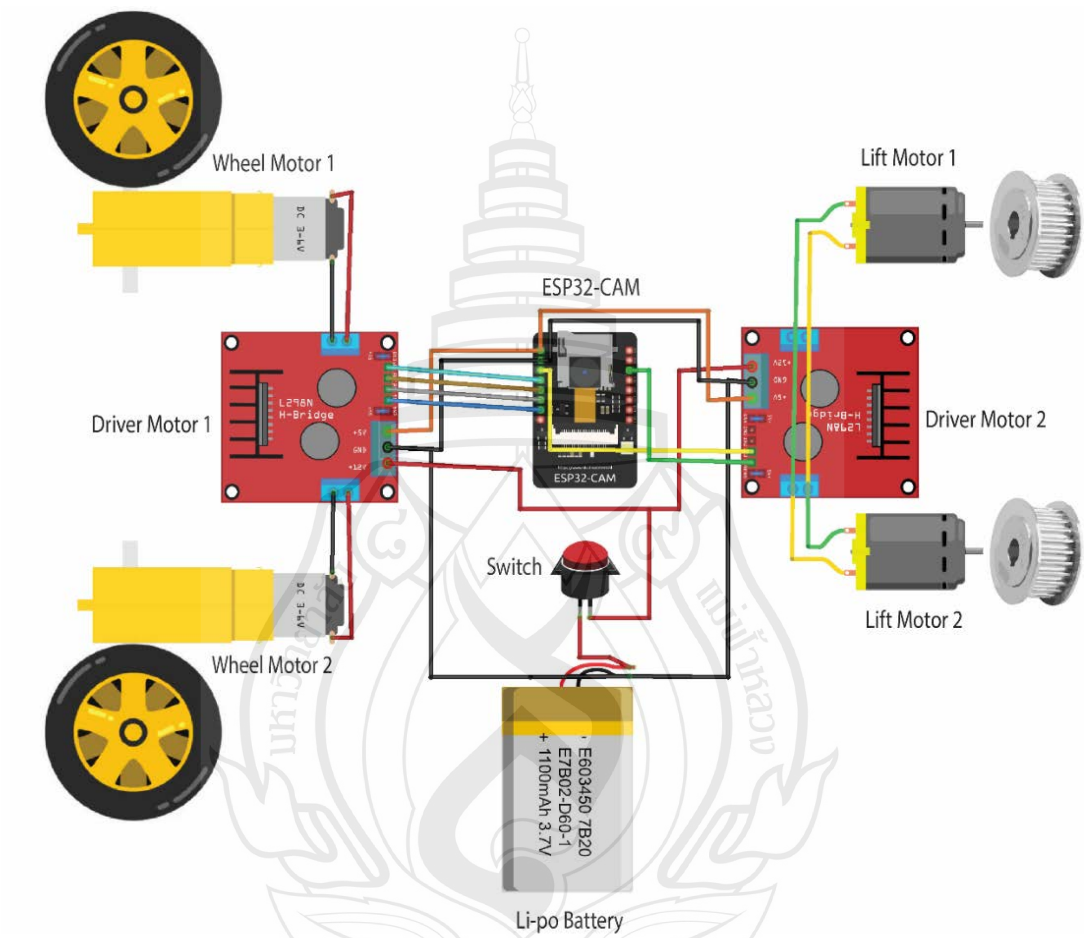


Figure 3.1 Schematic Diagram of the Miniature Forklift Electronics and Wiring Integration.

The electronic integration of the miniature forklift, as illustrated in Figure 3.1, centers around the ESP32-CAM microcontroller. It coordinates the movement of two DC gear motors for propulsion via the first L298N motor driver, while a second driver manages the dual lift motors responsible for the vertical movement of the fork mechanism. The entire system is powered by a Lithium-ion battery circuit regulated by a manual power switch to ensure safety and portability during the experiments. This hardware configuration ensures that control signals received from the VR or mobile interfaces are translated into physical actions with minimal latency.

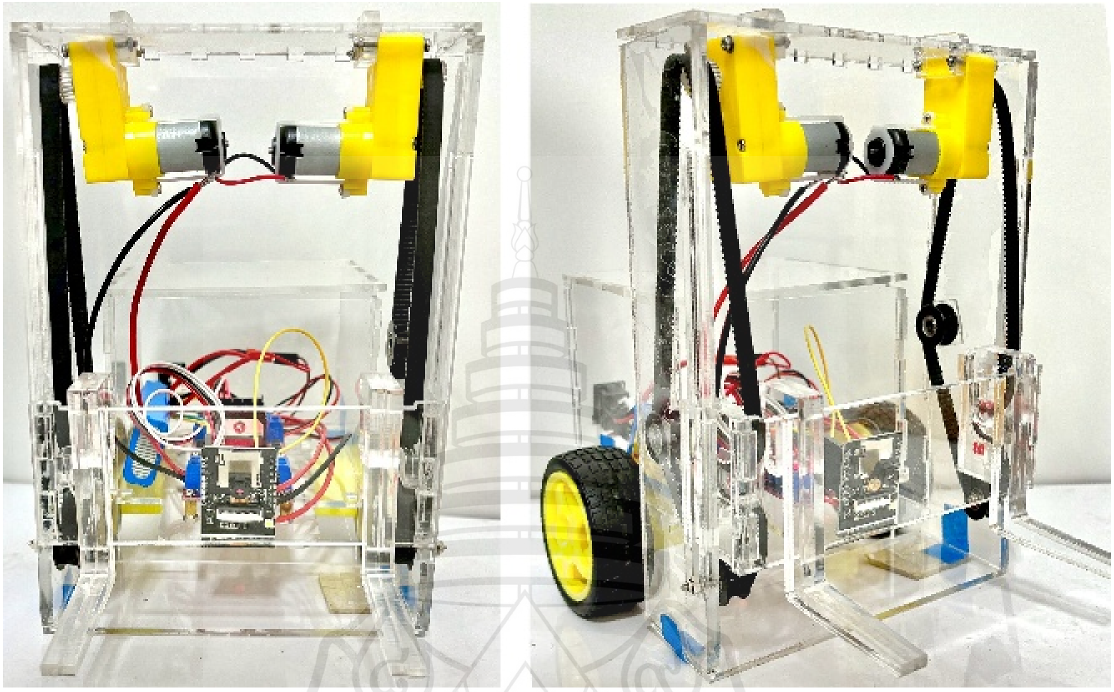


Figure 3.2 The Miniature Forklift Prototype.

A fully assembled miniature forklift prototype serves as the primary physical instrument for this study. Built upon a custom chassis integrated with an ESP32-CAM microcontroller, the model features a dual-motor lifting system for pallet manipulation and a rear-wheel steering configuration to emulate the kinematics of industrial forklifts. Functioning as a Digital Twin, this physical unit maintains real-time synchronization with the VR environment, providing a tangible interface for experiential learning through physical-virtual interaction.

3.4.2 Software Development

The software ecosystem was developed using the Unity Game Engine (Version 2021.3 LTS), utilizing C# as the primary scripting language due to its robust support for object-oriented programming and cross-platform compilation. Two distinct client applications were created to serve the experimental groups:

3.4.2.1 Mobile Application (Android Platform): The mobile control interface was compiled specifically for the Android operating system (Target API Level

30) to ensure compatibility with modern smartphones and tablets. The development focused on three key modules:

1. User Interface (UI) & Control Input: The application operates in landscape orientation to maximize screen real estate. It features a Virtual Analog Joystick implemented via Unity’s UI Event System. The joystick maps the user's touch coordinates (x, y) into normalized vectors (-1.0 to +1.0). These vectors are then algorithmically converted into differential drive commands (Left/Right motor speeds) before being transmitted to the robot. Additionally, vertical slides are used to control the forklifting mechanism with precision.

2. Real-Time Video Rendering (FPV System): To simulate a "First-Person View" (FPV) experience, the application implements a custom texture rendering system. It utilizes the UnityWebRequest class to fetch the MJPEG video stream from the ESP32-CAM via HTTP. The incoming data is decoded frame-by-frame into a Texture2D object and rendered onto a RawImage component in the background layer, ensuring the operator sees exactly what the forklift sees with minimal latency (<200ms).

3. Network Communication Layer: The app integrates the WebSocketSharp library to establish a full-duplex communication channel with the robot. Unlike traditional HTTP requests, this persistent connection allows for high-frequency command transmission (up to 20 packets/second), ensuring that the simulated forklift responds instantly to the user’s finger movements.

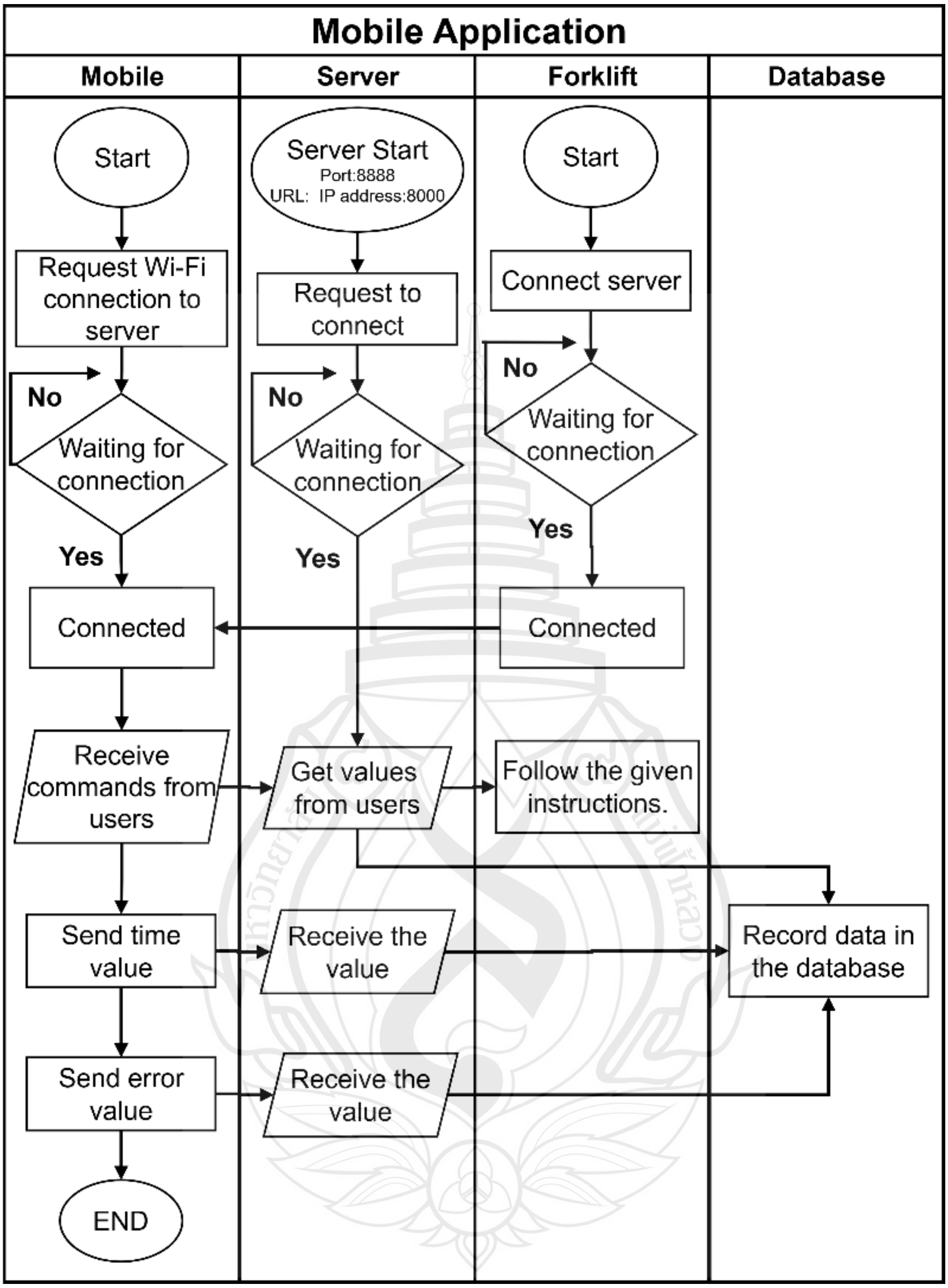


Figure 3.3 Flowchart of the Mobile Application Workflow.

3.4.2.2 Virtual Reality Application (VR Platform): The Virtual Reality control interface was developed specifically for the Meta Quest 2 (formerly Oculus

Quest 2) headset to leverage its standalone processing capabilities and 6DoF (Six Degrees of Freedom) tracking. The development highlights include:

1. XR Interaction Toolkit: The system utilizes Unity’s XR Interaction Toolkit as the core framework for handling user inputs. The script maps the physical inputs from the VR Touch Controllers—specifically the thumbstick axes for directional drive and the triggers for the lifting mechanism—directly to the robot’s movement commands via the WebSocket connection.

2. Immersive Environment: To simulate the atmosphere of a real industrial workplace, the application renders a realistic virtual warehouse environment. A key feature of this interface is the implementation of a "Virtual Screen" (Diegetic UI) floating inside the VR world. This screen displays the real-time video feed fetched from the physical robot’s camera, allowing the user to operate the forklift from a remote perspective while remaining immersed in the virtual simulation.

3. Immersive Visual System: Unlike the mobile interface, the VR system places the user inside a 3D Virtual Cockpit. Through Stereoscopic Rendering, the user perceives depth and distance naturally. The live camera feed from the physical robot is projected onto a "Virtual Dashboard Screen" located inside the virtual forklift cabin. This design choice—known as a Diegetic UI—helps ground the user in the virtual world while allowing them to monitor the physical robot's path, significantly reducing the likelihood of simulator sickness compared to a direct full-screen camera projection.

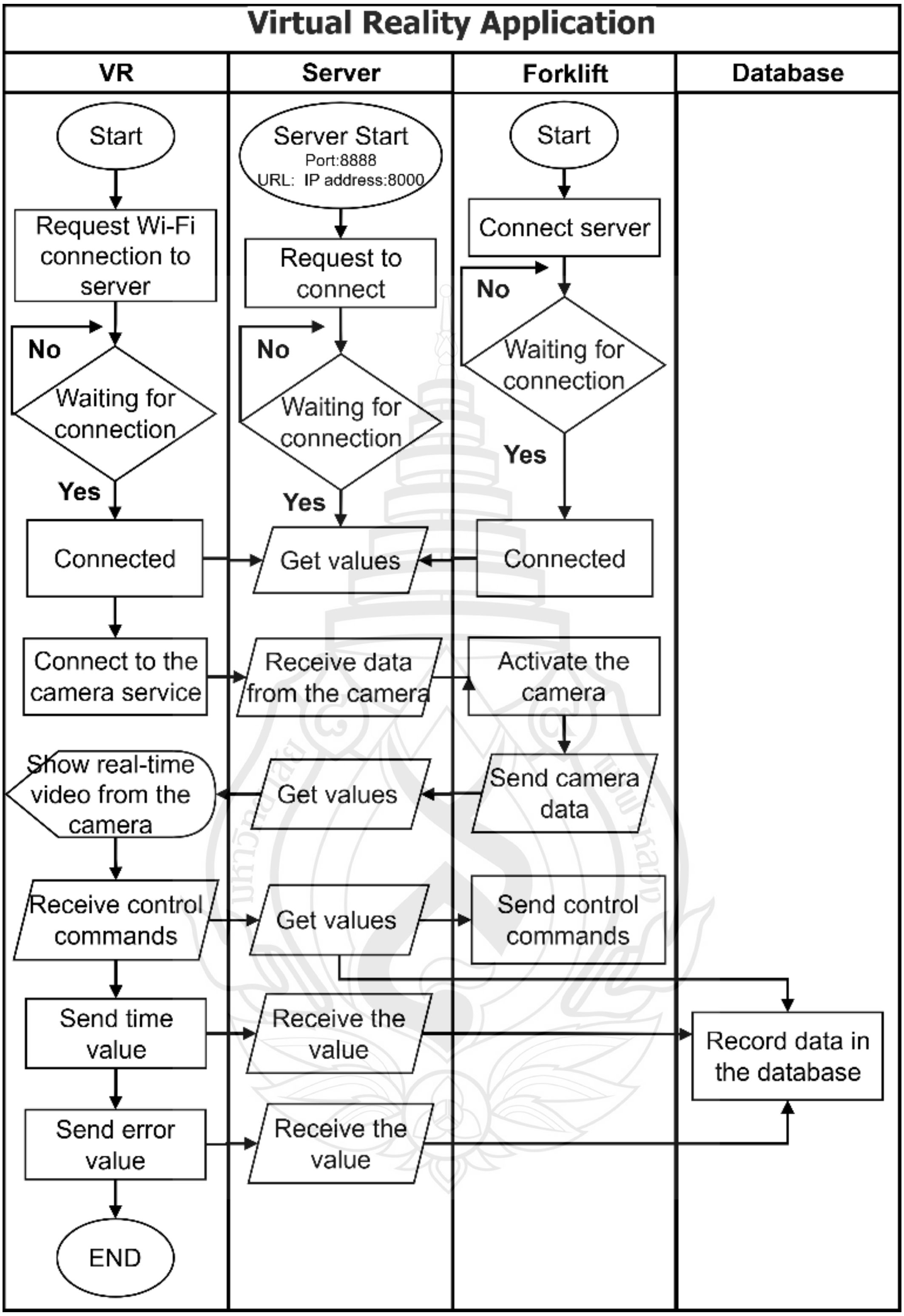


Figure 3.4 Flowchart of the Virtual Reality (VR) Application Workflow.

3.4.3 Network Architecture

To ensure real-time responsiveness and visual feedback, a dual-protocol communication architecture was established over a local Wi-Fi network (WLAN). The ESP32-CAM operates in Station Mode (STA), connecting to a central router.

3.4.3.1 Command Transmission (WebSocket Protocol): To achieve real-time control with minimal delay, the system employs the WebSocket Protocol over TCP/IP for command transmission.

1. Persistent Full-Duplex Connection: Unlike standard HTTP (Hypertext Transfer Protocol), which requires a new connection handshake for every request (stateless), WebSocket establishes a single, persistent connection between the Client (Unity Application) and the Server (ESP32). This allows for Full-Duplex communication, enabling data to flow in both directions simultaneously.

2. Latency Optimization: By eliminating the overhead of repeated HTTP headers and handshakes, the system significantly reduces latency (Round-Trip Time). This is critical for teleoperation, ensuring that control strings such as "FORWARD", "STOP", or "LIFT_UP" are transmitted and executed instantly.

3. Reliability: Since WebSocket runs over TCP, it ensures packet delivery, guaranteeing that critical safety commands (e.g., stopping the vehicle) are not lost during transmission.

3.4.3.2 Video Streaming (HTTP/MJPEG): Visual feedback is provided via an HTTP MJPEG (Motion JPEG) Stream, which serves as the "eyes" of the operator.

1. Streaming Mechanism: The ESP32-CAM acts as a web server that captures frames from the OV2640 sensor. These frames are compressed as JPEG images and transmitted sequentially using the multipart/x-mixed-replace content type. This tells the client (browser or Unity app) to continuously replace the current frame with the new one, creating a moving video effect.

2. The ESP32-CAM captures frames and sends them as a continuous stream of JPEG images. This method was chosen for its lightweight processing requirements, ensuring a smooth frame rate (approximately 20-30 FPS) suitable for remote driving.

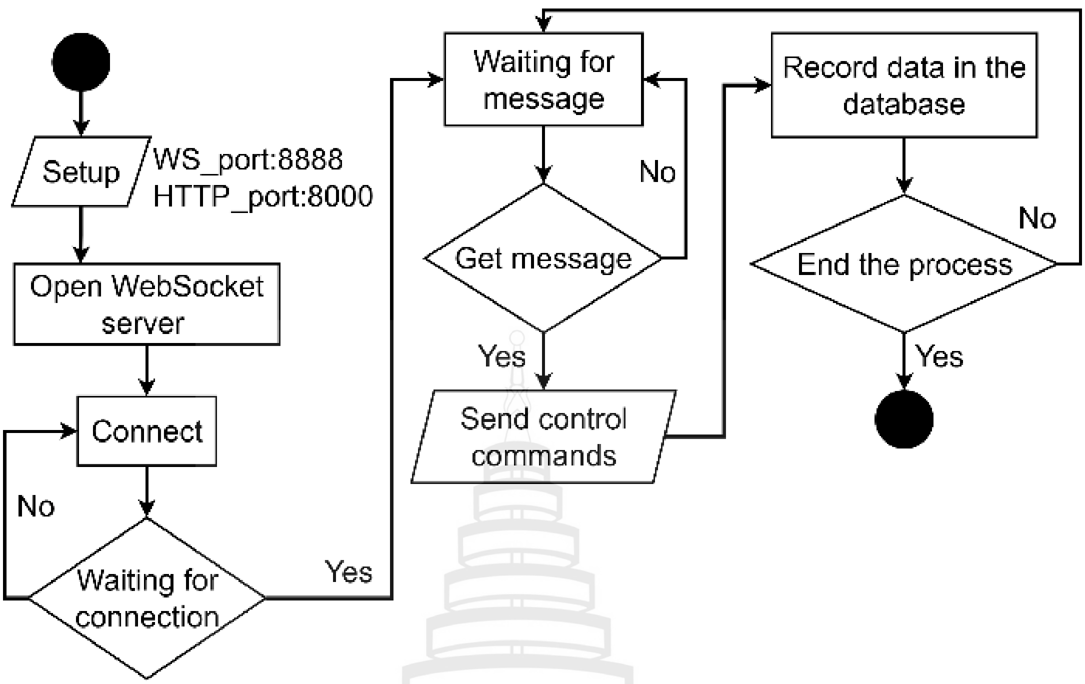


Figure 3.5 Flowchart of the Server Service Logic.

3.4.4 Learning Outcome and Satisfaction Questionnaire: Developed by the researchers and validated by subject matter experts.

3.5 Scenario Design

The simulation includes three key missions:

3.5.1 Basic Navigation: Maneuvering through a predefined obstacle course.

3.5.2 Pallet Handling: Precise operation of the fork to lift and place pallets.

3.5.3 Operational Challenge: A timed mission combining navigation and handling tasks.

3.6 Data Collection Procedure

The data collection process was conducted in a controlled environment to ensure consistency. The procedure is divided into the following steps:

3.6.1 Orientation and Informed Consent: Participants are briefed on the research objectives and safety guidelines. Informed consent is obtained in accordance with the ethical approval (Protocol Number: EC 25067-13).

3.6.2 Pre-task Familiarization: Participants are given a short period to familiarize themselves with the basic controls of both the VR Controller and the Mobile Application interfaces.

3.6.3 Experimental Task Execution: Each participant performs a standardized set of forklift maneuvers (e.g., driving, lifting, and pallet placement) using both control modalities. The order of use is counterbalanced to minimize learning bias.

3.6.4 Real-time Data Logging: During task execution, the system automatically records performance metrics, including task completion time and the frequency of operational errors, via the IoT-integrated backend.

3.6.5 Post-session Evaluation: Upon completion of the physical tasks, participants complete a structured questionnaire to provide feedback on user experience, perceived ease of use, and level of immersion for each interface.

3.7 Data Analysis

The data collected from the simulation trials and user feedback are analyzed as follows:

3.7.1 Performance Analysis: Task completion time and error frequency are compiled and presented through comparative tables and charts to identify operational trends between the two control modalities.

3.7.2 User Satisfaction Analysis: Feedback from questionnaires is synthesized to evaluate the overall user experience, focusing on ease of use, immersion, and perceived learning benefits.

3.7.3 Comparative Synthesis: A descriptive comparison is conducted to highlight the strengths and limitations of each interface, providing a comprehensive overview of their effectiveness in a training context.

3.8 Research Plan

Table 3.1 Research Plan

Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Requirement gathering	x	x									
Mission design & system planning		x	x								
System development (VR + Mobile)			x	x	x	x					
Testing simulation system							x				
Data collection and analysis							x	x			
Paper writing & submission					x	x	x	x	x	x	
Conference											x

3.9 Evaluation Methods

3.9.1 Evaluation Criteria

The simulation system and user interaction are evaluated based on the following criteria:

1. Operational Performance: Measured through task completion success and frequency of errors recorded by the system logs.

2. User Engagement & Experience: Evaluated based on participant feedback regarding immersion and ease of use for both VR and mobile interfaces.

3. Perceived Learning Outcomes: Assessed through the participants' self-reported understanding of forklift kinematics and operational safety after the session.

4. Expert Review: The system’s functionality and educational content are verified by experts to ensure reliability and technical accuracy.

3.9.2 Statistical Methods

Instead of traditional inferential statistics, this study employs the following methods:

1. Descriptive Comparison: Data from system logs (time and errors) are compiled into comparative tables and charts to illustrate performance trends between the two control modalities. Independent sample T-tests for comparing two groups

2. Qualitative Thematic Analysis: Feedback from open-ended questionnaire sections is categorized into themes to understand user preferences and identify potential areas for system improvement.

3. Observation Synthesis: Insights gained from observing participants during the trials are summarized to provide context for the performance data.

3.10 Expected Research Outcomes

3.10.1 A functional Digital Twin forklift simulation system integrated with physical hardware and a virtual environment. A comprehensive comparative analysis regarding the effectiveness of VR-based controllers and mobile-based interfaces in vocational training.

3.10.2 An academic manuscript documenting the findings, suitable for submission to peer-reviewed journals or international conferences.

3.10.3 An enhanced training framework that leverages immersive technology to improve spatial awareness and operational skills in forklift driving.

3.10.4 Practical insights and design recommendations for the development of future VR-integrated educational systems in technical and vocational fields.

CHAPTER 4

RESEARCH RESULT

4.1 Overview of the Experiment Results

The comparative analysis of the forklift driving simulation system focused on evaluating two distinct control modalities: the VR Controller and the Mobile Application interface. The results were derived from participant performance data recorded by the system logs and qualitative feedback from post-training evaluations. The study aimed to identify operational trends, user preferences, and the effectiveness of each interface within a Digital Twin framework.

4.2 Comparative Performance and Learning Experience

4.2.1 Operational Efficiency and Accuracy

Data from the system logs indicated that both control interfaces enabled participants to complete the designated forklift maneuvers successfully. However, distinct trends were observed:

1. VR Controller Interface: Participants demonstrated higher spatial awareness during complex tasks, such as pallet placement. The immersive first-person perspective allowed for more precise depth perception, resulting in a lower frequency of collisions with virtual obstacles compared to the mobile interface.

2. Mobile Application Interface: While effective for basic movement, this modality showed a slightly higher time-to-completion for precision-based tasks. The third-person perspective required participants to mentally map 2D inputs to 3D movements, which initially posed a steeper learning curve for some participants.

4.2.2 Engagement and Immersion

Qualitative feedback revealed a clear preference for the VR system in terms of engagement. Participants reported a high sense of "presence" and realism, which contributed to increased interest in the training process. In contrast, the Mobile Application was praised for its accessibility and lower technical complexity, making it a suitable tool for quick familiarization with forklift kinematics.

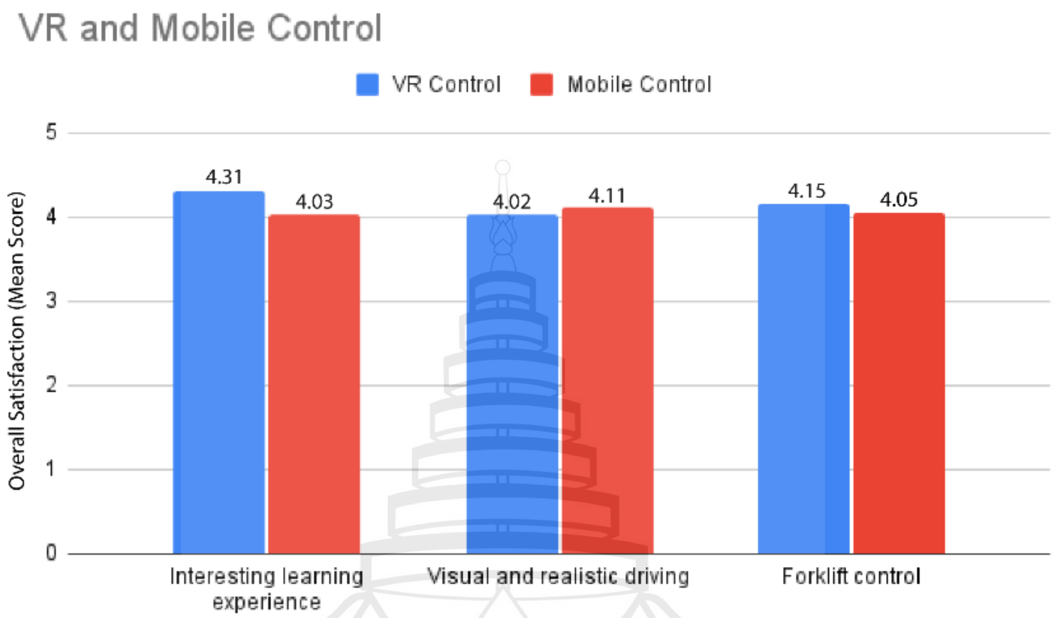


Figure 4.1 Comparative Ratings of Specific User Experience Aspects.

Figure 4.1 presents a comparative overview of user feedback across three key dimensions. The data indicates that the VR Controller excels in "Engagement and Interest," reflecting the high immersion of the system. In contrast, the Mobile Application shows a slight advantage in "Visual Clarity," while both systems perform similarly in "Control Usability," suggesting that both interfaces are intuitive for the participants.

4.3 Analysis of User Satisfaction

The synthesis of questionnaire responses focused on three key areas:

4.3.1 Usability: Both systems were rated as highly intuitive. The VR controllers provided a more "natural" feel, mimicking real-world hand-eye coordination, whereas the mobile interface benefited from the participants' existing familiarity with touchscreen devices.

4.3.2 Visual Clarity: Participants noted that while VR offered superior immersion, the mobile interface provided consistent visual clarity, as it was not subject to the lens-focusing requirements inherent in VR headsets.

4.3.3 Educational Value: Participants consistently reported that the simulation, regardless of the controller used, significantly enhanced their understanding of forklift safety and operational logic without the risks associated with real-world practice.

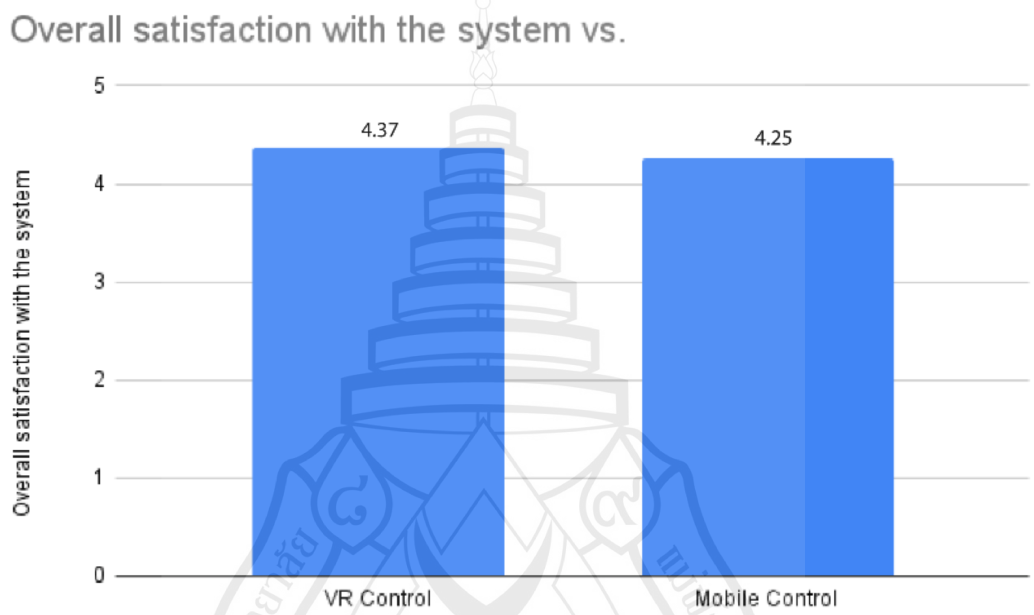


Figure 4.2 Overall User Satisfaction with the System

The overall satisfaction trends shown in Figure 4.2 suggest that participants perceived the VR-based system as more engaging and enjoyable for long-term training. However, the high scores for the mobile interface confirm its effectiveness as a reliable supplementary tool for quick-access vocational orientation.

CHAPTER 5

CONCLUSION AND DISCUSSION

5.1 Conclusion

This study successfully developed and evaluated a forklift simulation system that integrates Digital Twin technology through VR and IoT interfaces. The research aimed to compare the effectiveness of two control modalities: VR Controllers and Mobile-based applications. The findings demonstrate that both interfaces are effective for training, but they serve different strengths.

VR-based interaction significantly enhances procedural engagement and spatial awareness, providing a first-person perspective that mimics real-world operation. Conversely, the Mobile-based interface offers a reliable and accessible alternative for introductory learning, providing clear visual feedback and ease of use. Overall, the system achieves the objective of providing a safe, risk-free environment for acquiring forklift operational knowledge, consistent with the continuous research framework (Protocol Number: EC 25067-13).

5.2 Discussion

The results of this study align with Kolb's Experiential Learning Theory, emphasizing that "learning-by-doing" in a simulated environment fosters deeper conceptual understanding. The immersion provided by VR allows participants to experience "presence," which is crucial for understanding the kinematics of heavy machinery.

A key observation from the comparative analysis is the trade-off between immersion and accessibility. While VR provides superior spatial feedback, the mobile interface utilizes the participants' existing familiarity with touchscreen technology, reducing the initial technical barrier. This suggests that a multi-modal training approach—starting with mobile orientation followed by immersive VR practice—could be a highly effective model for technical education. However, minor limitations such as network latency and the physical scale of the prototype were noted, which may influence the absolute realism of the experience.

5.3 Suggestions for Future Research

5.3.1 Scale Expansion: Future studies should transition from miniature models to full-scale industrial forklift simulations to further validate the training effectiveness in real-world scenarios.

5.3.2 Long-term Retention: Research should be conducted to evaluate the long-term retention of skills acquired through VR versus mobile-based simulations.

5.3.3 Advanced Haptics: Integrating more advanced haptic feedback mechanisms into the VR controllers could further bridge the gap between virtual and physical practice.

5.3.4 Target Audience Diversity: Expanding the participant pool to include professional industrial workers would provide deeper insights into how immersive technology can support professional upskilling.

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APPENDIX A

CERTIFICATE OF ETHICAL APPROVAL

เรียน อาจารย์ ดร.เขมชาติ เขมาวุฒานนท์

ตามที่ ท่านได้ส่งโครงการวิจัย ฉบับแก้ไขครั้งที่ 1 เรื่อง การศึกษาเสมือนจริงเพื่อเสริมสร้างความรู้ความเข้าใจในการขับรถยกของ เพื่อการฝึกฝนในการปฏิบัติงานก่อนปฏิบัติงานจริง (Educational virtual reality to enhance knowledge and understanding of learning to drive a forklift for practice in working before actually working) รหัสโครงการวิจัย ***EC 25067-13*** *โดยเอกสารครบถ้วนเมื่อวันที่ 14 กรกฎาคม พ.ศ. 2568 นั้น คณะกรรมการฯ ได้พิจารณาโครงการวิจัยดังกล่าวเห็นสมควรดังนี้*

รับรอง (Approval)

ทั้งนี้ ท่านสามารถติดต่อสอบถามได้ที่ นายชาญณรงค์ คำแสน เพื่อรับหนังสือรับรองจริยธรรมการวิจัย (Certificate of Approval) ที่สำนักงานคณะกรรมการจริยธรรมการวิจัยในมนุษย์ มหาวิทยาลัยแม่ฟ้าหลวง อาคารบริการวิชาการ (AS) ชั้น 4 หมายเลขโทรศัพท์ (053) 917-170 ถึง 7171 และ (053) 916-551 โทรสาร (053) 917-170 อีเมล rec.human@mfu.ac.th

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มหาวิทยาลัยแม่ฟ้าหลวง

ด้วยความนับถือ

นายชาญณรงค์ คำแสน

เจ้าหน้าที่ประสานงาน

053-917-170

APPENDIX B

QUESTIONNAIRE ON THE EFFECTIVENESS OF A FORKLIFT DRIVING SIMULATION: A COMPARISON BETWEEN VIRTUAL REALITY CONTROLLERS AND MOBILE-BASED CONTROLLERS

Ethical Approval Reference: This questionnaire and its data collection process are conducted under the continuous research framework of the project titled *"Educational virtual reality to enhance knowledge and understanding of learning to drive a forklift for practice in working before actually working"*, which has been officially approved by the Ethics Committee (Protocol Number: EC 25067-13).

Explanation: This questionnaire is designed to collect data for an Independent Study research project. Your responses will be kept strictly confidential, anonymized, and used for educational and research purposes only. Please mark ✓ in the box that best matches your experience and opinion.

Part 1: General Information

Gender: ☐ Male ☐ Female ☐ Other

Part 2: System Usability & User Experience

Rating Scale: 5 = Highest, 4 = High, 3 = Moderate, 2 = Low, 1 = Lowest

Evaluation Items	5	4	3	2	1
A. Design & Realism					
1. Aesthetic and modernity of the application interface.					
2. Realism of the simulated forklift movement physics.					
3. Visual clarity of the display (VR Environment / Mobile Screen).					
B. Control & Responsiveness					
4. Appropriateness of the control layout (Buttons/Joystick).					
5. Responsiveness of the vehicle to control commands (Low Latency).					
6. Ease of learning the controls					

Part 3: Learning Effectiveness

Evaluation Items	5	4	3	2	1
1. I have gained a better understanding of basic forklift mechanisms.					
2. My ability to estimate distance and control direction has improved.					
3. The system raised my awareness regarding operational safety.					
4. I feel more confident about training with a real forklift in the future.					
5. I felt engaged and focused during the training (Engagement).					

Part 5: Suggestions & Feedback

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

APPENDIX C

TECHNICAL SPECIFICATIONS

Source Code:
ESP32CAM C++

```
#include "esp_camera.h"
#include <WiFi.h>
#include <ArduinoWebsockets.h>

#define CAMERA_MODEL_AI_THINKER
#include "camera_pins.h"

#define MOTOR_LF 14
#define MOTOR_LB 2
#define MOTOR_RF 13
#define MOTOR_RB 15
#define LIFT_UP_PIN 12
#define LIFT_DOWN_PIN 3
#define LED_PIN 4

const char* ssid = "S7A-211-1";
const char* password = "211211211";
const char* websocket_server_host = "10.1.82.56";
const uint16_t websocket_server_port = 8888;

using namespace websockets;
WebsocketsClient client;

void move(int lf, int lb, int rf, int rb) {
…
}
void lift(int up, int down) {
…}

void onMessageCallback(WebsocketsMessage message) {
    String command = message.data();
    Serial.printf("Received: %s\n", command.c_str());

    if (command == "GO") {
        move(LOW, HIGH, HIGH, LOW);
    } …
}
```

```
void setup() {
    Serial.begin(115200);
    Serial.setDebugOutput(true);
    Serial.println();


    esp_err_t err = esp_camera_init(&config);
    if (err != ESP_OK) {
        Serial.printf("Camera init failed with error 0x%x", err);
        return;

    WiFi.begin(ssid, password);
    while (WiFi.status() != WL_CONNECTED) {
        delay(500);
        Serial.print(".");
    }
    Serial.println("\nWiFi Connected");


    client.onMessage(onMessageCallback);
    while (!client.connect(websocket_server_host,
websocket_server_port, "/")) {
        delay(500);
        Serial.print(".");
    }
    Serial.println("WebSocket Connected");
}

void loop() {
    client.poll();
    camera_fb_t *fb = esp_camera_fb_get();
    if(!fb){
        Serial.println("Camera capture failed");
        esp_camera_fb_return(fb);
    return;
  }
    if(fb->format != PIXFORMAT_JPEG){
        Serial.println("Non-JPEG data not implemented");
    return;
  }
}
```

WebSocket

```
const path = require("path");
const express = require("express");
const WebSocket = require("ws");
const app = express();
const WS_PORT = 8888;
const HTTP_PORT = 8000;
const wsServer = new WebSocket.Server({ port: WS_PORT }, () => console.log(`WS Server
is listening at ${WS_PORT}`));

let connectedClients = [];
wsServer.on("connection", (ws) => {
  console.log("Connected");
  connectedClients.push(ws);

  ws.on("message", (data) => {
    console.log("Received:", data.toString());

    connectedClients.forEach((client) => {
      if (client.readyState === WebSocket.OPEN) {
        client.send(data);
      }
    });
  });

  ws.on("close", () => {
    connectedClients = connectedClients.filter(client => client !== ws);
  });
  ws.on("error", () => {
    connectedClients = connectedClients.filter(client => client !== ws);
  });
});
app.get("/client", (req, res) => res.sendFile(path.resolve(__dirname, "./client.html")));
app.listen(HTTP_PORT, () => console.log(`HTTP server listening at ${HTTP_PORT}`));
```

Unity C#

```
using UnityEngine;
using NativeWebSocket;
using UnityEngine.UI;
using UnityEngine.EventSystems;
using System.Threading.Tasks;

public class ESP32WebSocketControl : MonoBehaviour
{
    private WebSocket _webSocket;

    [Header("Movement Buttons")]
    public Button goButton, backButton, leftButton, rightButton, stopButton;
    [Header("Lift Buttons")]
    public Button liftUpButton, liftDownButton, liftStopButton;
    [Header("LED Button")]
    public Button toggleLightButton;
    public Text toggleLightButtonText;
    [Header("Camera View")]
    public RawImage cameraView;

    public string esp32IP = "ws://10.1.82.56:8888";
    private bool isLedOn = false;

    async void Start()
    {
        Debug.Log("Start called");
        _webSocket = new WebSocket(esp32IP);

        _webSocket.OnOpen += () => Debug.Log("WebSocket Connected");
        _webSocket.OnMessage += (bytes) =>
        {
```

```
            Debug.Log("Bytes received: " + bytes.Length);
            if (bytes.Length > 4 && bytes[0] == 0xFF && bytes[1] == 0xD8)
            {
                Texture2D tex = new Texture2D(2, 2);
                bool loaded = tex.LoadImage(bytes);
                if (loaded && cameraView != null)
                {
                    cameraView.texture = tex;
                }
            }
            else
            {
                string msg = System.Text.Encoding.UTF8.GetString(bytes);
                Debug.Log("Received: " + msg);
            }
        };
        _webSocket.OnError += (error) => Debug.LogError("WebSocket Error: " +
error);
        _webSocket.OnClose += (code) => Debug.Log("WebSocket Disconnected");

        await _webSocket.Connect();

        AddDirectionalButton(goButton, "GO");
        AddDirectionalButton(backButton, "BACK");
        AddDirectionalButton(leftButton, "LEFT");
        AddDirectionalButton(rightButton, "RIGHT");
        AddDirectionalButton(liftUpButton, "LIFT_UP");
        AddDirectionalButton(liftDownButton, "LIFT_DOWN");

        if (liftStopButton != null)
            liftStopButton.onClick.AddListener(async () => await
SendCommand("LIFT_STOP"));
```

```
        if (stopButton != null)
            stopButton.onClick.AddListener(async () => await SendCommand("STOP"));

        // LED
        if (toggleLightButton != null)
            toggleLightButton.onClick.AddListener(ToggleLED);

        if (toggleLightButtonText != null)
            toggleLightButtonText.text = "LED_OFF";
    }
    void AddDirectionalButton(Button button, string command)
    {
        if (button == null)
        {
            Debug.LogWarning($"Button for {command} is null!");
            return;
        }
        Debug.Log($"Add DirectionalButtonHoldControl to {button.gameObject.name}");
        var holdHandler = button.gameObject.AddComponent<DirectionalButtonHoldControl>();
        holdHandler.esp32Controller = this;
        holdHandler.directionCommand = command;
    }
    public async Task SendCommand(string command)
    {
        Debug.Log("SendCommand: " + command);
        if (_webSocket != null && _webSocket.State == WebSocketState.Open)
        {
            await _webSocket.SendText(command);
            Debug.Log("Sent: " + command);
        }
```

```
        else
        {
            Debug.LogError("WebSocket not connected");
        }
    }
    public async void SendSTOP() { await SendCommand("STOP"); }
    public async void SendLIFT_STOP() { await SendCommand("LIFT_STOP"); }
    public async void ToggleLED()
    {
        isLedOn = !isLedOn;
        string command = isLedOn ? "LED_ON" : "LED_OFF";

        await SendCommand(command);

        if (toggleLightButtonText != null)
            toggleLightButtonText.text = command;
    }
    void Update()
    {
#if !UNITY_WEBGL || UNITY_EDITOR
        _webSocket?.DispatchMessageQueue();
#endif
    }

    async void OnApplicationQuit()
    {
        await _webSocket.Close();
    }
}
```

APPENDIX D

ADDITIONAL PHOTOGRAPHS

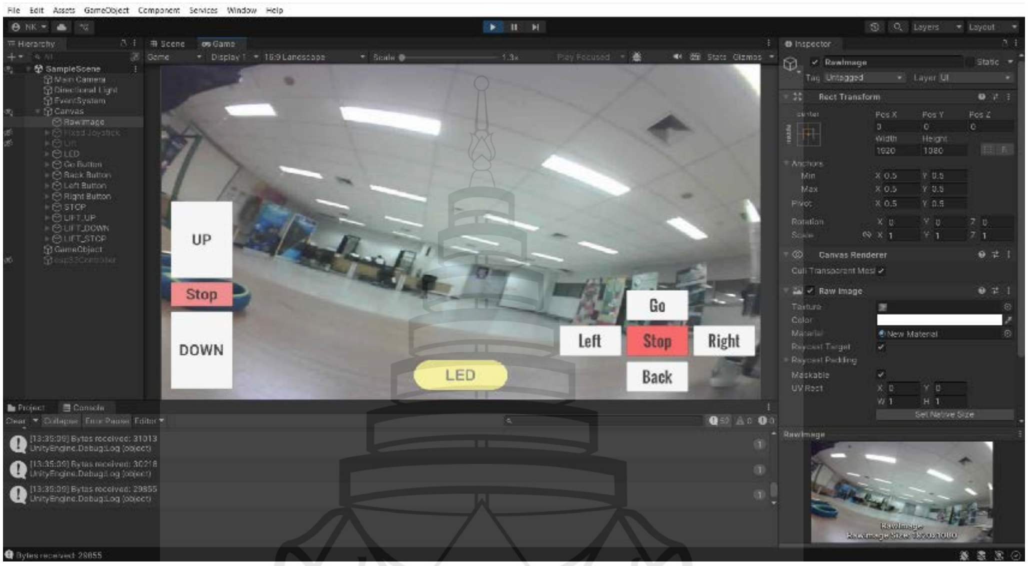

Figure D1 The Mobile Control Interface Featuring Real-Time Video Streaming.

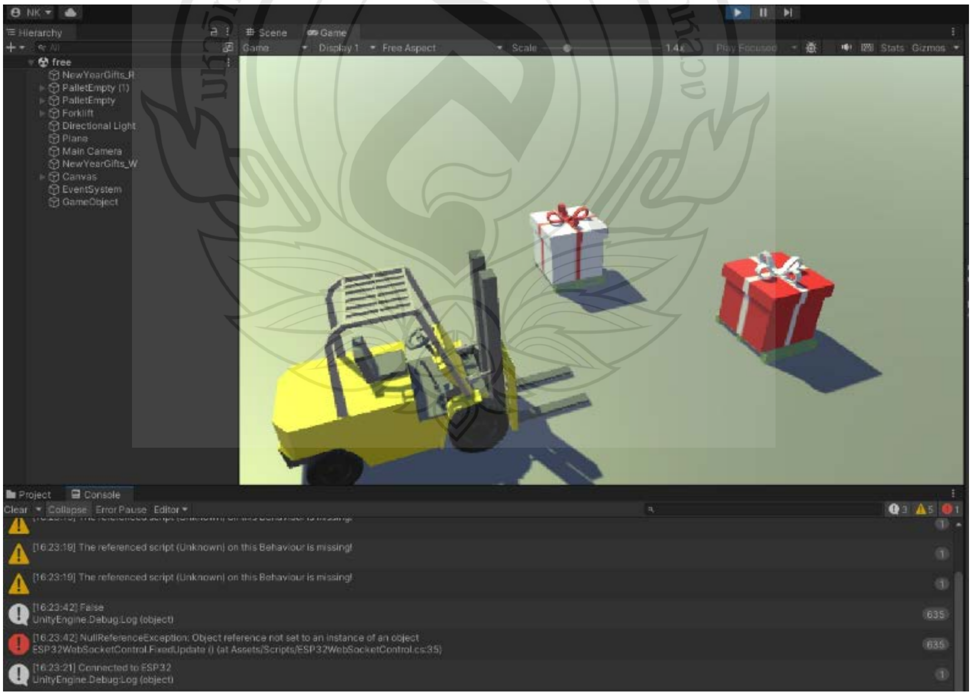

Figure D2 The Immersive Virtual Warehouse Environment in the VR Application.

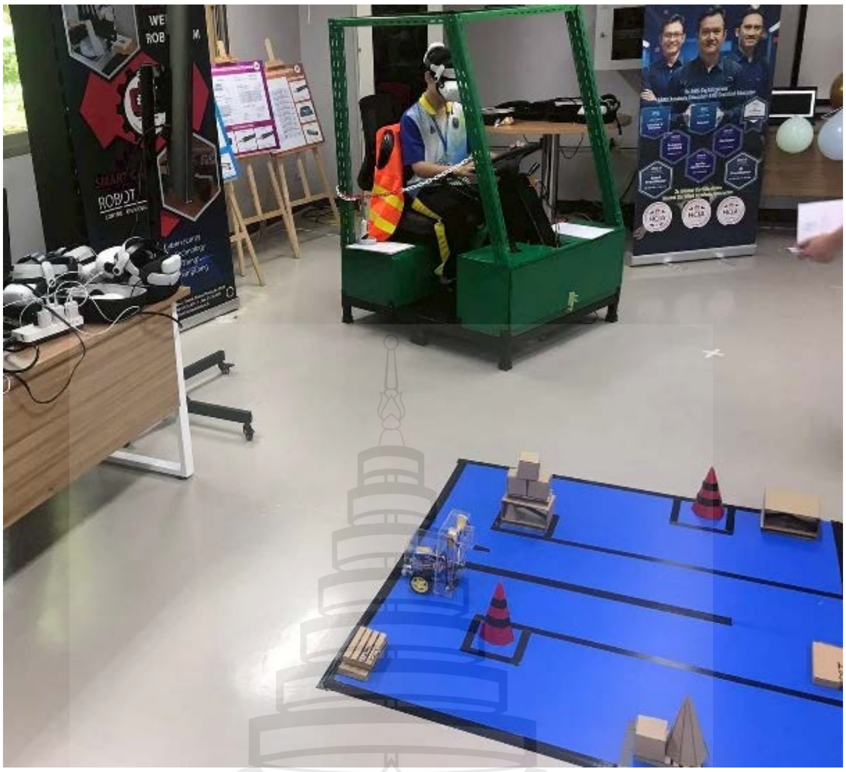

Figure D3 Simulation Scenario Design for Forklift Skill Evaluation.

Figure D4 A Participant Operating the Forklift Simulator Using the Virtual Reality (VR) Controller.

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