MASARYK UNIVERSITY

FACULTY OF INFORMATICS

Intuitive VR Control Interface of Heavy Machinery

Bachelor's Thesis

ALENA NEUMANNOVÁ

Brno, Fall 2024

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Advisor: Ing. Matěj Lang

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FACULTAS ARTIS INFORMATICÆ • UNIVERSITAS MASARYKIANA •

Declaration

Hereby I declare that this paper is my original authorial work, which I have worked out on my own. All sources, references, and literature used or excerpted during elaboration of this work are properly cited and listed in complete reference to the due source.

During the preparation of this thesis, I utilized the following AI tools to assist my work:

- **ChatGPT** (`https://chat.openai.com/`): Used for rephrasing thoughts, asking clarifying questions, citation generation, and text/code corrections.
- **GitHub Copilot**: Employed for code assistance to streamline development and improve coding efficiency.
- **Writefull Integration in Overleaf**: Applied for grammar and spelling checks throughout the text.
- **Perplexity**: Used for research purposes, including topic exploration and identifying relevant papers.

The tools were applied throughout the thesis, enhancing the clarity, correctness, and efficiency of my work. I manually reviewed, verified, and edited all outputs generated by these tools to ensure their alignment with the principles of academic integrity and the quality requirements of this thesis.

I take full responsibility for the content of this work.

Alena Neumannová

Advisor: Ing. Matěj Lang

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I am grateful to my advisor, Ing. Matěj Lang, for his invaluable guidance, advice, and continuous feedback throughout this thesis. I deeply appreciate the time and effort he dedicated to ensuring the success of this project.

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Lastly, I wish to extend my sincere appreciation to all the participants who took part in the User Study. Their time, effort, and willingness to engage with the tasks were invaluable in gathering the necessary data and validating the results of this work.

Abstract

Virtual reality enables the creation of User Interfaces that are difficult or impractical to implement in the real world. This thesis focuses on designing and implementing an intuitive Virtual Reality (VR) control system for operating heavy construction machinery, such as excavators and loaders. Traditional control systems rely on a complex combination of levers, switches, and buttons, which require extensive training and pose challenges for new users.

The proposed VR Control Interface simplifies this process by providing an immersive and intuitive control system that allows users to interact with a virtual model of the construction machine in a realistic manner. The system visualizes the machine's inertia and the positional difference between the current and desired states, enabling users to better understand and predict the machine's movements.

A User Study was conducted to evaluate the performance of the VR Control Interface in comparison to traditional controls. The study examines key metrics such as task completion time, accuracy, and error rates, highlighting the potential of VR Control Interfaces to reduce learning time, improve operational accuracy, and enhance User Experience in Heavy Machinery operation.

Keywords

VR, Teleoperation, User Interface, Unity, Heavy Machinery, 3D Models

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Introduction

As Virtual Reality (VR) gains widespread recognition, it presents new concepts and methods to interact with our environment.

Although its crucial role in entertainment is broadly acknowledged, the potential benefits it offers in various sectors beyond entertainment are beginning to attract interest.

Virtual reality fosters creativity in multiple fields such as healthcare, entertainment, education, military, manufacturing, and engineering. It acts as a groundbreaking tool for training, exercise, and entertainment, as well as a research instrument in neuroscience and psychology [1].

As society generates increasing volumes of data, the advantages of VR are particularly appreciated, including the ability to convey substantial amounts of information in a clear and intuitive manner [2].

By giving our interactions a new dimension and bringing interfaces from a 2D to a 3D space, Virtual reality creates an opportunity for the development of new intuitive user interfaces that would not be possible with traditional methods. The immersive capabilities of VR allow users to interact with digital environments in a natural and intuitive way, enhancing the overall user experience [2, 3].

This is especially interesting within the domains of teleoperation. These domains represent pivotal fields in which virtual reality has the potential to substantially enhance user interface experiences. Through the utilization of VR technology, operators can manipulate robotic systems remotely with greater accuracy and convenience, thereby increasing the efficacy of teleoperation frameworks [3, 4].

This thesis aims to explore new and easy ways to control hydraulic excavators remotely through a virtual reality interface with the goal to improve efficiency and accuracy in control operations as well as reducing cognitive load.

This thesis is composed of seven main chapters, each addressing different aspects of the research and development process. The first chapter reviews related work, focusing on Virtual Reality User Interfaces, Teleoperation Techniques, and the Role of Digital Twins in enhancing human-robot interaction. The second chapter introduces the technologies used in the development of the VR application, including hardware, software frameworks, and prefabricated models.

The third chapter details the implementation process, covering movement types, control interfaces, and the design of the virtual environment. The fourth chapter presents the user study conducted to evaluate the application, describing the hypotheses, experimental setup, testing procedures, and data processing methods.

Chapter five analyzes the results, examining performance metrics such as speed, accuracy, and error rates, along with user feedback from various questionnaires.

The sixth chapter discusses the findings, limitations, and implications, offering insight for future improvements.

Finally, the conclusion summarizes the results of the thesis and highlights potential directions for further research.

1 Related Work

This chapter reviews existing research and developments related to virtual reality user interfaces (VRUIs), teleoperation, and digital twins, which form the foundation of this thesis.

The discussion begins with the key characteristics and advantages of VRUIs, highlighting their potential to enhance user performance and interaction.

Then it explores the challenges associated with traditional teleoperation methods and examines how VR-based techniques address these limitations, focusing on their applications in various domains.

The chapter concludes by introducing the concept of digital twins and their integration with inverse kinematics, emphasizing their role in improving precision and control in teleoperation tasks.

These topics provide essential context for understanding the contributions of this thesis in the advancement of VR-based teleoperation control systems.

1.1 Virtual Reality User Interfaces

Virtual Reality User Interfaces, abbreviated as VRUIs, represent a sophisticated category of interfaces that utilize advanced capabilities of virtual reality technology in order to create and enhance the interaction dynamics between human users and complex computer systems. These innovative interfaces immerse users deeply within a detailed three-dimensional (3D) environment, which not only provides a sense of presence but also facilitates interactions that are far more natural and intuitive when compared to the more conventional and flat two-dimensional interfaces that have been widely used in the past. These systems allow users to interact with virtual environments using natural and intuitive methods, such as gestures, voice commands, and body movements [2].

The aim of VRUIs is to make data perceptible and interactions natural, leveraging human sensory input and real-world interaction experiences to improve usability and reduce cognitive load.

The design of an effective VR User Interface is crucial, as it not only influences user engagement but also determines the overall effectiveness of the virtual experience in various applications, from gaming to training simulations.

1.1.1 Key Characteristics

VRUIs incorporate several key characteristics that make them effective for various applications. Simulation in VR includes visual, acoustic, and haptic elements to create realistic environments, often used in scientific simulations and virtual prototyping. Visualization allows users to perceive information intuitively, enabling an experiential understanding of the data. Natural interaction enables users to interact with the system in ways that mimic real-world actions, reducing cognitive load, and reserving mental resources for the task at hand. The immersive nature of VRUIs engages multiple senses, such as vision, hearing, and touch, while tracking detailed bodily movements for input [2].

1.1.2 Advantages

VRUIs offer several advantages over traditional two-dimensional (2D) interfaces, particularly in terms of accuracy, performance, task completion time, and cognitive workload. Research has shown that users achieve significantly higher accuracy when interacting with VRUIs, with an 83% improvement in positional accuracy and a 48% increase in orientation accuracy, enabling precise navigation and alignment within virtual environments [5].

Furthermore, task completion times are notably reduced, with users completing tasks 64% faster compared to using 2D interfaces, demonstrating the efficiency and speed that VRUIs bring to various applications. Studies also highlight a 37% reduction in subjective cognitive workload, measured by NASA-TLX scores, indicating that VRUIs are less mentally taxing and more intuitive for users. These findings underscore the potential of VRUIs to improve user performance, optimize workflows, and improve satisfaction in demanding scenarios that require accuracy, speed, and reduced mental effort.

1.2 Teleoperation

Teleoperation is the process of remotely controlling a machine or system from a safe distance using real-time input from a human operator. This technology enables precise manipulation and interaction with remote environments, allowing operators to perform complex tasks in hazardous or inaccessible locations such as space, underwater, or areas with dangerous materials. Teleoperation systems typically involve a user interface that translates human commands into robotic actions, ensuring immediate responsiveness and accuracy. This approach is widely used in industrial automation, medical surgery, and exploration, where direct human intervention is impractical or unsafe [6].

1.2.1 Challenges in Traditional Teleoperation

Traditional teleoperation methods, which rely heavily on levers and joysticks, present several challenges that can hinder operator performance. These tools often require complex hand-eye coordination and spatial reasoning, significantly increasing cognitive workload and the risk of operator fatigue. The 2D interfaces commonly used in such systems limit depth perception and spatial awareness, making precise movements difficult to execute in remote environments. This limitation can lead to higher stress levels and reduced efficiency, particularly in high-pressure scenarios where accuracy and speed are critical [3, 5].

Additionally, mastering traditional control methods involves challenges, as operators must manage their view of the scene and control the robot actuators using keyboard and mouse systems, which can be cumbersome and slow, as described by Whitney et al. [7]. 2D interfaces used in teleoperation require significant effort for precise manipulation due to their inherent limitations in providing intuitive feedback.

1.2.2 Teleoperation Techniques Used in VR

Virtual Reality User Interfaces support various teleoperation techniques that enhance user experience and performance in remote operations.

Immersive visualization in VR systems enhances situational awareness and improves the perception-action loop in teleoperation tasks, enabling users to perceive remote environments with high realism. The concept of "viewpoint-independent motion mapping" is a central feature of the Vicarios interface introduced by Naceri et al. [8], allowing users to freely change their viewpoint without re-mapping gestures, which enhances task performance in complex teleoperation scenarios. The flexibility of the VR interface, including teleporting features for changing viewpoints, supports both ego-centric (first-person) and robot-centric (third-person) perspectives during teleoperation tasks.

Natural action teleoperation interfaces, such as hand controllers that mimic human arm movements, make control intuitive and reduce the learning curve [9].

1.2.3 Applications of VR Teleoperation

VR teleoperation is applied in various domains, enhancing user capabilities and safety in challenging environments.

Applications in hazardous environments, such as nuclear reactor navigation, bomb disposal, and space station repairs, allow operators to manage tasks remotely, minimizing the risk to human life [10].

In the medical sector, VRUIs teleoperation techniques facilitate intuitive and precise control in tasks that require accuracy and user engagement such as rehabilitation [5]. To seamlessly integrate with surgical simulators, a teleoperation system has been developed enabling remote training through expert guidance provided via audio-visual cues [11].

Finally, VR teleoperation systems have been developed for remote control of robots in space missions. This allows operators on Earth to manipulate robots in extraterrestrial environments with improved situational awareness [12].

1.3 Digital Twins

A digital twin is a virtual representation of a physical robot that is synchronized in real-time to reflect the robot's state and movements.

This concept enables intuitive and precise control by allowing users to manipulate the virtual counterpart, which in turn controls the physical robot [13].

In the context of VR and teleoperation, digital twins provide an immersive environment where users can interact with the virtual model, enhancing situational awareness and improving the overall teleoperation experience [3].

1.3.1 Inverse Kinematics

Inverse kinematics plays an important role in the functionality of digital twins by determining the joint movements required to position an end effector at a specific target location. This process ensures that the movements of the virtual robot are synchronized with the physical counterpart, enabling accurate execution of tasks [13].

The system continuously solves forward and inverse kinematics equations to maintain real-time synchronization, allowing for precise control and real-time adjustments. This alignment is essential for enhancing the responsiveness and efficiency of robotic systems, supporting a wide range of applications, including industrial automation and robotic surgery [3].

1.3.2 Digital Twins for Teleoperation

Several research projects have explored the use of digital twins to enhance teleoperation in virtual and augmented reality environments.

One project used an augmented reality (AR) interface with HoloLens 2 to enable intuitive control of industrial robots by overlaying the digital twin onto the physical robot. Gesture-based interactions improved user immersion and control during tasks such as disassembling end-of-life batteries [4].

Another study used an AR interface for robot manipulator teleoperation, where the digital twin represented the robot in a mixed reality environment. This approach reduced task load and enhanced efficiency and accuracy in teleoperation tasks [3].

In the mining sector, researchers developed a VR interface using Unity3D to simulate a mobile manipulator as a digital twin, replicating the robot and its environment. This system addressed control latency issues and demonstrated improvements in user performance metrics, particularly for novice operators, while facilitating human-robot collaboration and data collection [5].

Additionally, a project combined ROS-enabled robotic platforms with high-performance VR interfaces to enable gesture tracking and bi-manual manipulation through a digital twin created using Unity3D and ROS bridge. This integration supported trajectory planning and real-time interaction for complex robotic tasks [8].

2 Technology Used

This chapter provides an overview of the key technologies and tools that form the foundation of the virtual reality control system. It begins by introducing the hardware utilized for immersive interaction and precise tracking, followed by a discussion of the software frameworks that facilitated the development of the virtual environment and user interface. In addition, prefabricated models used to improve system realism and functionality are described.

2.1 Hardware Used

The virtual reality control system was developed using the Meta Quest 2 headset and its accompanying motion controllers. The headset provides an immersive VR experience by tracking the user's position and orientation through built-in sensors, including accelerometers, gyroscopes, and cameras. Motion controllers serve as primary input devices, enabling intuitive interaction within the virtual environment. Together, these devices deliver precise tracking and responsive feedback, forming the hardware backbone of the system.

2.2 Unity Engine

Unity Engine is a cross-platform game engine that provides a powerful framework for creating interactive 2D, 3D, virtual reality, and augmented reality applications. Built on a component-based architecture, it uses GameObjects [14] as fundamental building blocks, enhanced by Components [15] to define behavior, visuals, and interactivity. The projects are organized into scenes [16], hierarchical structures where GameObjects maintain parent-child relationships, facilitating modular and scalable design.

To enhance user interface design, the Unity UI Toolkit [17] is employed, offering a flexible framework to build interactive menus, panels, and HUDs. Text rendering within the project leverages TextMesh-Pro (TMPro) [18], a text rendering system that provides advanced typographic features and high-quality visual fidelity, making it suitable for both standard UI elements and immersive virtual environments.

2.3 Microsoft Mixed Reality Toolkit

The Microsoft Mixed Reality Toolkit (MRTK) [19] is an open source framework designed to simplify the development of mixed reality applications. MRTK provides a set of features and tools that enable seamless interaction and user experience design in virtual and augmented reality environments. It includes various interaction systems, user interface controls, and experimental features to accelerate the development process.

In this project, MRTK's NonNative Keyboard prefab was utilized to create an interactive and dynamic text input system. The keyboard prefab, included as part of the experimental features of MRTK, allowed a straightforward integration with Unity's UI system while enabling a customizable and responsive input mechanism within the virtual reality environment.

The NonNative Keyboard, provided as an experimental feature in MRTK, was modified for this project to meet specific requirements. A standalone version of the keyboard, maintained by Ayfel [20], was used for ease of integration and customization. This implementation enabled text entry functionality in the virtual control system, allowing users to input commands or labels directly within the VR environment.

2.4 XR Interaction Toolkit

The XR Interaction Toolkit (XRI) is a high-level Unity package designed to simplify the creation of virtual and augmented reality applications. It provides a robust interaction framework that integrates seamlessly with Unity's interaction system, allowing developers to handle user input from a wide variety of XR devices, such as VR controllers or AR touch inputs [21].

In this project, the XR Origin Rig set-up [22], provided in the sample scenes of the XR Interaction Toolkit, is used to manage camera and controller tracking. The XR device simulator [23] is used to simulate the input of the XR device to test interactions without the need for physical hardware during implementation. Key components such as the XR Grab Interactive and XR Joystick scripts [24] were utilized to enable object interaction and dynamic control mechanisms. Additionally, pre-made components such as the XRI Examples package [25] joystick were integrated into the application, offering pre-designed interactive elements that align with XR best practices.

2.5 Prefabricated Models

The implementation of the VR control system incorporated several prefabricated models to enhance the realism and functionality of the simulation. These assets provided ready-to-use elements that simplified development and contributed to a professional and immersive user experience.

The *3D Excavator Rigged Model* [26] was central to the implementation of the system. This model is based on the real Caterpillar 390F LME Excavator. It has a complex design where all moving parts, such as the boom, arm, and bucket, are carefully positioned within a bone structure. This setup allows for realistic movements, making it easy to control the excavator by adjusting the positions and rotations of specific bones.

The *Stone Model* [27] was used to create individual stone objects within the virtual environment. These objects served as dynamic elements for testing the Excavator's precision and manipulation capabilities, enhancing the realism of user interactions.

The *Stones Pile Model* [28] consisted of a predesigned collection of stones, forming a complex pile.

3 Implementation

This chapter describes the design and implementation of the virtual reality control system for the Caterpillar 390F LME Excavator. It begins by presenting the two primary movement types used in the system: physics-based movement and inverse kinematics-based movement, detailing their calculations and applications. Following this, the chapter introduces the control interfaces, including the traditional joystick-based interface and the newly developed intuitive virtual control system. The final section focuses on the control perspective and the environment, explaining how an external perspective enhances usability and safety in the operation of the Excavator. This structure ensures a comprehensive explanation of the functionality of the system and highlights the integration of movement, control, and user interaction in the implementation.

3.1 Excavator Movement Types

This section explores the two approaches to implementing control systems for the Excavator model in the virtual environment and explains how these calculations are translated into movements of the virtual bones of the Excavator in Unity. The first approach employs a physics-based methodology to simulate real-world dynamics by directly manipulating the bones and joints of the Excavator based on physical properties. The second approach leverages inverse kinematics to achieve smooth, goal-oriented movements by calculating optimal joint angles.

The Excavator model, illustrated in Figure 3.1, consists of several key components essential for its operation and simulation. The base serves as the foundation of the machine, supporting its structure, and allowing rotational movement through the swing mechanism. Connected to the base is the boom, a large arm structure that facilitates vertical lifting and lowering. Attached to the boom is the stick, which extends the reach of the machine and allows the bucket to be placed precisely. The bucket, located at the end of the stick, is used for digging and material handling. In addition, the hydraulic cylinders for the boom, stick, and bucket, play a critical role in enabling controlled

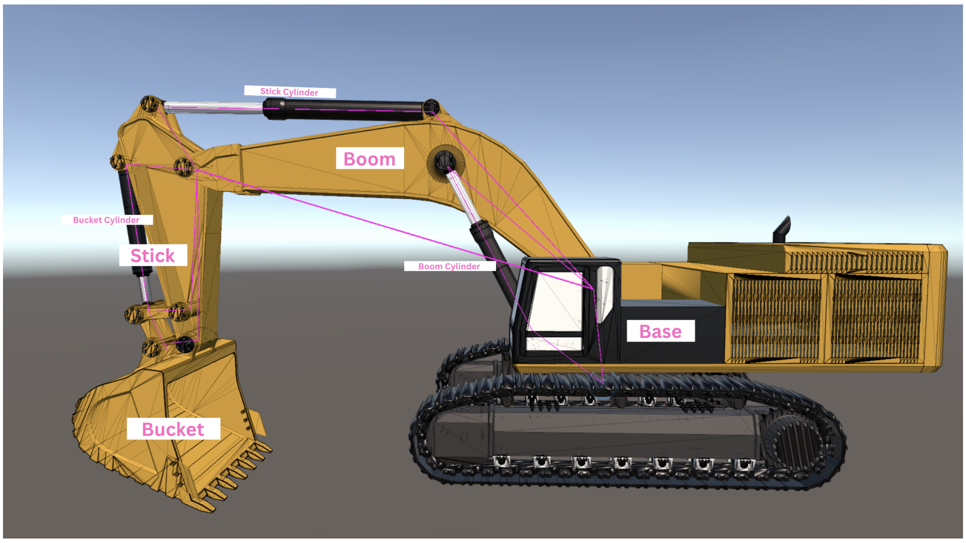

Figure 3.1: Excavator Model

movements by applying hydraulic forces to these components. These parts are integral to the functionality of the Excavator and are used in both physics-based and inverse kinematics-based simulations.

3.1.1 Physics-Based Movement

The simulation is grounded in values obtained from the Excavator manual [29] and uses these to perform calculations that replicate the physical behavior of the hydraulic and mechanical systems of the machine. The following tables state the values obtained from this manual to ensure realistic Excavator movement.

Table 3.1: Weight Distribution of the Excavator

Component	**Weight (kg)**
Base machine	67,950
Boom (including hydraulic cylinders)	8,310
Stick (with linkage and cylinders)	4,930
Bucket (estimated)	2,293
Smaller components (not modeled)	1,792
Total Weight	**87,070**

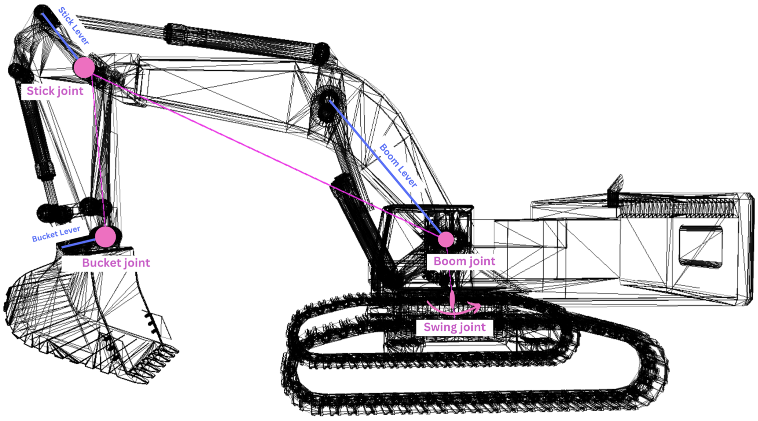

Figure 3.2: Physics-based Excavator

The Excavator has a total weight of 87,070 kg, distributed among its major components, as shown in Table 3.1. The base machine, boom, stick, and bucket weights are derived from the Excavator manual. The remaining weight is distributed across smaller components of the Excavator, which are modeled in the simulation but do not require detailed consideration for this implementation. These masses were used to simulate realistic load dynamics and force distribution in the virtual environment.

Table 3.2: Swing Parameters

Parameter	**Value**
Maximum Swing Torque	260,000 N·m
Maximum Swing Angular Velocity	6.2 RPM

The Table 3.2 lists the swing parameters, including the maximum swing torque and the maximum angular velocity of the Excavator swing mechanism. These values are critical for simulating realistic rotational dynamics.

The dimensions of the hydraulic cylinders are presented in Table 3.3, detailing the bore and stroke of the boom, stick, and bucket

Table 3.3: Hydraulic Cylinder Parameters

Cylinder	Bore (mm)	Stroke (mm)
Boom	210	1967
Stick	220	2262
Bucket	220	1586

cylinders. These values are used to calculate the force exerted by the hydraulic system and the movement of the cylinders.

Table 3.4: Hydraulic System Parameters

Parameter	Value
Maximum Cylinder Pressure	350 Bar
Oil Flow Rate	980 L/s

The Table 3.4 summarizes the hydraulic system specifications, including the maximum cylinder pressure and the oil flow rate. These parameters are essential for determining the cylinder velocities and simulating hydraulic behavior in the virtual environment.

These values form the foundation for the physical calculations that drive the realistic simulation of the Excavator's movement in the implementation.

The load of the Excavator stone has been estimated at $12,000\,\text{kg}$. This value represents a load that the Excavator can safely pick up without the risk of overloading. This estimated value has been used in calculations to adjust the Excavator's movement when the bucket is loaded.

Physical Calculations

The physical movement of the Excavator is simulated by calculating hydraulic forces, cylinder velocities, and joint torques, which are adjusted based on the load carried by the bucket.

Hydraulic force is a critical component of the control system and is calculated using the pressure of the cylinder and the area of the piston. The force exerted by a hydraulic cylinder is given by:

$$F = P \cdot A$$

where P is the maximum cylinder pressure in pascals, converted from bars, and A is the area of the piston in square meters. The piston area is determined using the bore diameter of the cylinder:

$$A = \pi \cdot \left(\frac{\text{bore}}{2}\right)^2$$

where the bore diameter is converted from millimeters to meters for consistency in units.

The hydraulic cylinder velocity is also calculated. The volume of the cylinder, given by:

$$\text{Volume} = A \cdot \text{Stroke}$$

where the stroke is also converted from millimeters to meters, is used to determine the time required to fully pressurize the cylinder based on the oil flow rate:

$$\text{Time} = \frac{\text{Volume}}{\text{Oil Flow Rate}}$$

The linear velocity of the cylinder is then derived by dividing the length of the stroke by the pressurization time:

$$\text{Linear Velocity} = \frac{\text{Stroke}}{\text{Time}}$$

This velocity is converted into angular velocity using the length of the Excavator joint lever:

$$\omega = \frac{\text{Linear Velocity}}{\text{Lever Length}} \cdot \frac{180}{\pi}$$

to express the angular velocity in degrees per second.

The torque required to lift a load is calculated to simulate the effects of weight on movement. When the bucket is loaded, an additional mass is added to the system, representing the sand or material being transported:

$$\text{Load Mass} = m_{\text{structure}} + m_{\text{sand (if filled)}}$$

The torque required to lift this load is given by:

$$\tau_{\text{required}} = \text{Load Mass} \cdot g \cdot l \cdot |\sin(\theta)|$$

where g is the gravitational acceleration ($9.81\,\text{m/s}^2$), l is the length of the lever and θ is the angle of the joint. The torque available from the hydraulic motor is calculated as

$$\tau_{\text{motor}} = F \cdot l \cdot |\sin(\theta)|$$

and is further scaled by the value of the input of the joystick to account for user control.

To determine the effect of the load on movement, a load factor is computed as the ratio of the required torque to the motor torque:

$$\text{Load Factor} = \frac{\tau_{\text{required}}}{\tau_{\text{motor}}}$$

This load factor, clamped between 0 and 1, adjusts the angular velocity, slowing the motion as the load increases:

$$\text{Adjusted Angular Velocity} = \omega \cdot (1 - \text{Load Factor})$$

Finally, the adjusted angular velocity is used to calculate the rotation step for each frame:

$$\Delta\theta = \text{Adjusted Angular Velocity} \cdot \Delta t \cdot \text{Input Value}$$

The calculated rotation step is further modified by the value from the controlling interface, which either speeds up or slows down the movement based on user input. This adjusted step is then applied to the Excavator joints in Unity using the following code:

```
jointTransform.Rotate(Vector3.right, rotationStep);
```

By incorporating these adjustments and calculations, the system effectively simulates the combined effects of hydraulic pressure, cylinder dimensions, load dynamics, and user input, resulting in realistic Excavator movement.

3.1.2 Inverse Kinematics Based Movement

This chapter explains the implementation of the IK control system for the Excavator. The IK system calculates joint rotations to achieve desired positions for two primary targets: the stick target and the bucket target. By calculating the necessary joint angles, the IK system enables a smooth and precise movement of the Excavator arm, ensuring that it reaches specified positions in the virtual environment.

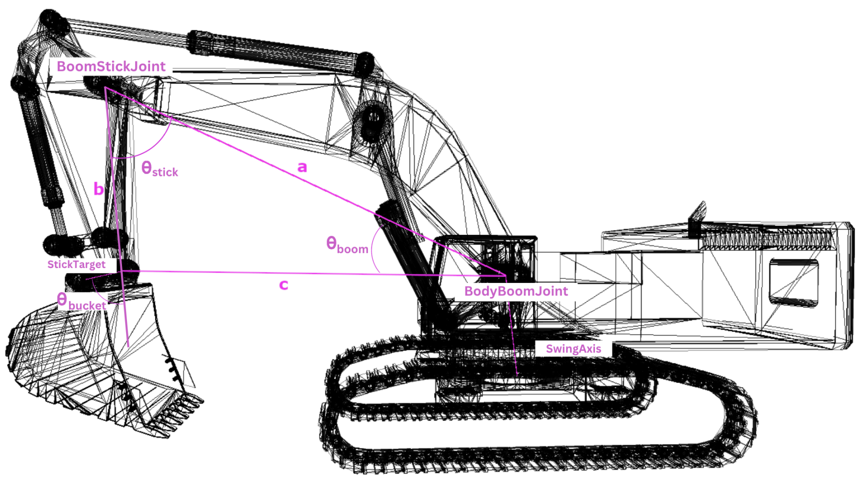

Figure 3.3: IK-based Excavator

The calculated angles are directly applied as rotations to the bones of the rigged Excavator model, allowing realistic articulation of the arm components in Unity. Each joint movement is limited to specific axes to replicate the mechanical limitations of the real Excavator, resulting in realistic and controlled motion.

The swing angle determines the horizontal rotation of the Excavator's upper body to align the boom with the stick target. This is calculated by determining the angle between the current forward direction of the Excavator and the direction to the stick target:

```
var directionToTarget = stickTarget - excavatorObj.
    SwingAxis.position;
directionToTarget.y = 0; // Project to x-z plane

```

```
var forwardDirection = excavatorObj.SwingAxis.
    forward;
forwardDirection.y = 0; // Project to x-z plane

directionToTarget.Normalize();
forwardDirection.Normalize();

var pSwingAngle = Vector3.SignedAngle(
    forwardDirection, directionToTarget, Vector3.up);
```

The calculated angle, `pSwingAngle`, is added to the Excavator's current swing rotation and applied as a rotation to the corresponding bone of the rigged model. This rotation is applied only to the y coordinate of the swing joint, ensuring lateral movement of the Excavator body along the horizontal plane. This constraint ensures that the swing mechanism operates in accordance with the mechanical capabilities of the real Excavator.

The boom and stick angles are calculated using trigonometric relationships based on the lengths of the boom and stick, as well as the distance to the stick target. The law of cosines is used to compute the angles between these components.

The distance from the boom joint to the stick target is calculated as:

$$c = \|\text{stickTarget} - \text{BodyBoomJoint.position}\|$$

The angle of the boom is calculated as:

$$\theta_{\text{boom}} = \cos^{-1}\left(\frac{a^2 + c^2 - b^2}{2 \cdot a \cdot c}\right)$$

where a is the boom length, b is the length of the stick, and c is the distance to the target of the stick. Similarly, the angle for the stick is calculated as:

$$\theta_{\text{stick}} = \cos^{-1}\left(\frac{b^2 + a^2 - c^2}{2 \cdot a \cdot b}\right)$$

The angle of the bucket determines the orientation of the bucket relative to the positions of the stick target and the bucket target. It is calculated as the signed angle between the vector from the stick target to the bucket target and the vector from the boom-stick joint to the stick target:

```
var bucketDirection = bucketTarget - stickTarget;

var stickDirection = stickTarget - excavatorObj.
    BoomStickJoint.position;

var bucketAngle = Vector3.SignedAngle(
    bucketDirection, stickDirection, excavatorObj.
    BucketAxis.right);
```

All angles are adjusted to ensure alignment with the vertical axis of the Excavator and are clamped within the mechanical constraints of the machine. These calculated angles are applied to the local rotations of the boom, stick and bucket bones, restricted to the x coordinate. This ensures that all components move only in one direction, mimicking the behavior of the hydraulic joints in the real Excavator.

Achieving the Goal Orientation

The combination of lateral rotation of the swing along the y coordinate, vertical rotation of the boom and stick along the x coordinate, and controlled articulation of the bucket along the x coordinate—results in the Excavator arm reaching the desired orientation.

3.2 Excavator Control Interfaces

3.2.1 Joysticks Control Interface

Modern excavators are equipped with joystick control interfaces that manage key movements, including swing, boom, stick, and bucket operations. These interfaces are standardized to ensure safety, ease of use, and consistency across various models and manufacturers, enabling operators to adapt quickly regardless of the machine. Two widely recognized standards define the design and configuration of these controls: the ISO 10968 standard, issued by the International Organization for Standardization, and the SAE J1177 standard, established by the Society of Automotive Engineers.

The ISO 10968 standard [30] specifies the layout and functionality of operator controls for earth moving machinery, ensuring a uniform control pattern between machines. Under this standard, the left-hand joystick is responsible for the stick and swing functions. Moving the joystick forward extends the dipper, pulling it back retracts it, and moving it left or right swings the Excavator's cab. The right-hand joystick controls the boom and bucket. Pushing the joystick forwards lowers the boom, pulling it back raises it, moving it left curls (closes) the bucket, and moving it right dumps (opens) the bucket.

In contrast, the SAE J1177Z [31] standard defines an alternative control layout, which is also widely used in specific regions or by certain manufacturers. Although the SAE configuration offers the same functionality, it varies in joystick mapping and control operations.

This project utilizes the ISO 10968 standard for implementing joystick controls, as it aligns more closely with the goals of creating a globally recognizable and consistent control system.

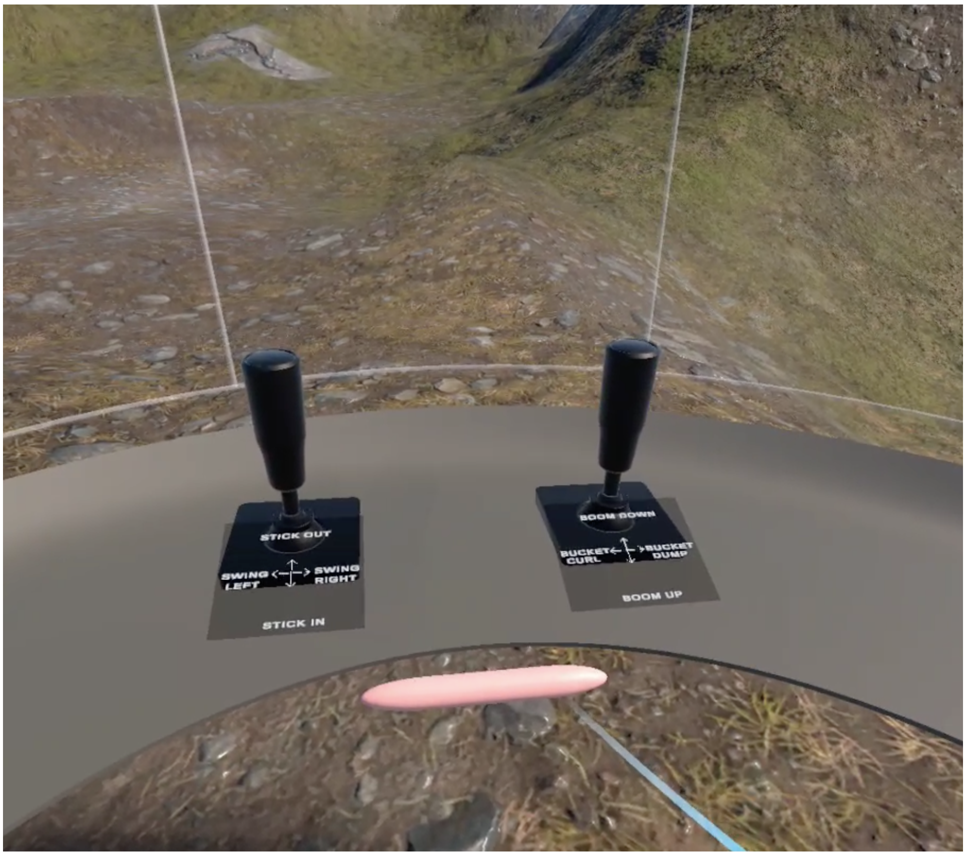

Figure 3.4: Virtual Joystick Control Interface

The virtual joystick controls, illustrated in Figure 3.4, are integrated into the simulation environment through Unity XRI. These controls utilize prefabricated components provided by the toolkit, ensuring accurate and realistic interaction mechanics. To enhance usability, directional labels based on the ISO 10968 standard have been incorporated into the design. These labels are persistently displayed, providing clear guidance for users and ensuring that the controls are intuitive and accessible for operation.

3.2.2 Intuitive Virtual Control System

This subsection introduces a novel approach to the control of excavators, focusing on implementing a more intuitive control interface, referred to as the Miniature Control Interface.

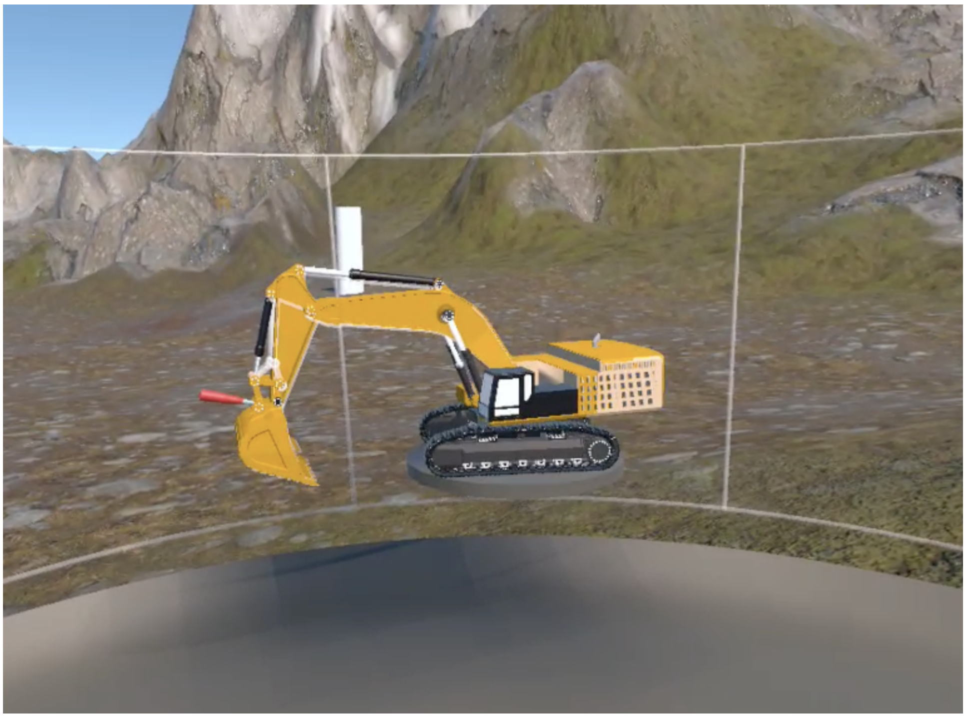

Figure 3.5: Virtual Miniature Control Interface

This control system is centered on a scaled-down interactive model of an Excavator, serving as a "toy-like" digital twin for the real machine.

This control interface, shown in Figure 3.5, replaces traditional joystick controls with a more natural and immersive method of operation.

The Miniature Control Interface leverages the digital twin concept, allowing users to intuitively manipulate the virtual Excavator in a physics-based environment. This enables precise positioning and orientation in real time, bridging the gap between play and real-life operation. By offering an accessible and engaging user experience, this interface enhances learning and usability, making the control process more efficient and enjoyable.

Handle Controller

The Handle Controller is designed to provide an intuitive and efficient mechanism for operating the IK-based Miniature Excavator controller, reducing control by consolidating all key movements into a single interface.

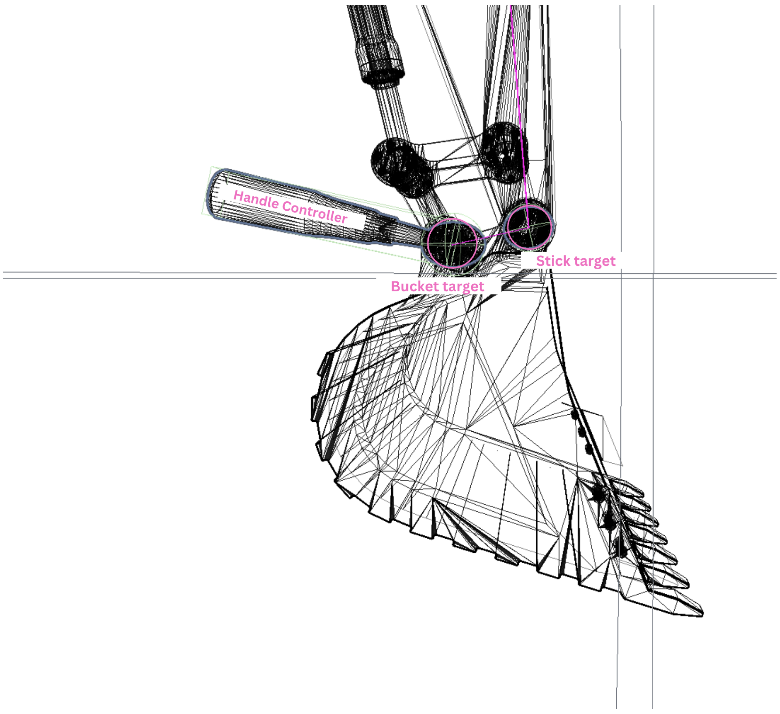

Figure 3.6: Handle Controller

The Handle Controller, shown in Figure 3.6, maps its motion to specific Excavator functions. Vertical movement of the handle adjusts the boom and stick angles along the Excavator's vertical axis, simulating natural upward and downward arm positioning. Lateral movement rotates the Excavator around its Y-axis, controlling the swing angle for side-to-side arm motion. Additionally, rotational motion of the handle adjusts the bucket angle, controlling curling (scooping) and dumping (releasing) actions. These combined movements correspond to the two control points, the stick and the bucket targets, effectively managing the swing, boom, stick, and bucket angles simultaneously.

The core functionality of the Handle Controller is implemented using a Follow Controller function, which dynamically updates the positions and rotations of the IK targets in real time based on the handle's movements. The bucket target's position is set directly to the handle's position, ensuring that it follows the handle accurately in the virtual environment.

The bucket target's rotation is determined by aligning its global orientation with the Excavator's frame of reference while adjusting its local rotation based on the handle's orientation.

```
var angle = Vector3.SignedAngle(transform.up,
    Vector3.up, bucketTarget.right);

bucketTarget.rotation = excDirection.transform.
    rotation;

bucketTarget.localRotation = Quaternion.Euler(-angle
    , 0, 0);
```

The stick target is positioned relative to the bucket target, maintaining a fixed distance that corresponds to the physical connection between the stick and the bucket. This alignment ensures smooth coordination of the arm's components:

```
stickTarget.position = handlePosition + bucketTarget
    .forward * initialTargetDistance;
```

The Handle Controller not only enables seamless operation of the Excavator in the virtual environment, but also ensures precise motion synchronization between the handle and the Excavator's IK targets.

Real-time updates provide users with accurate and responsive control, enhancing the overall usability and realism of the system.

Real-Time Synchronization

The Miniature Excavator dynamically responds to inputs from the user's Handle Controller in the virtual environment. As the user manipulates the handle, the IK-based Miniature adjusts its position and orientation in real time.

The operated virtual physics-based Excavator then tries to match the positioning of the Miniature while maintaining realistic movement, including factors such as inertia and joint constraints.

To further enhance precision and maintain the advantage of the joysticks' ability to adjust movement speed based on pressure, a similar functionality is introduced to the Miniature Control Interface. The system dynamically reduces the speed as the angle difference between the Miniature controller and the realistic Excavator decreases. This ensures smooth and accurate motion matching.

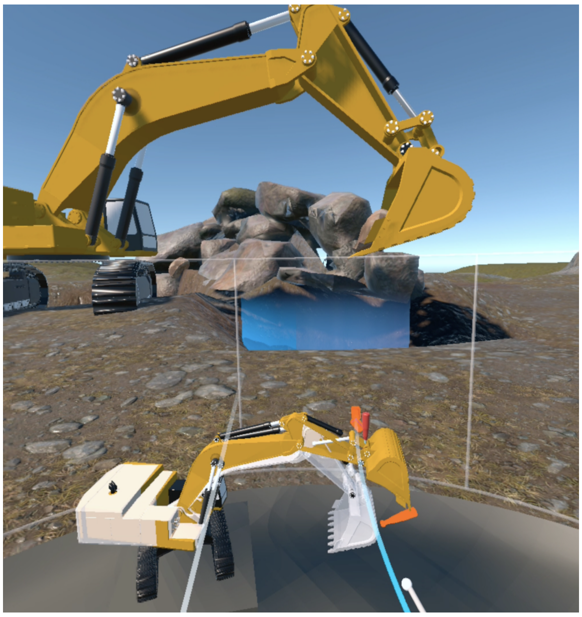

Figure 3.7: Miniature Controller Synchronization visualization

Introducing a ghost Excavator overlay in the virtual environment provides a visual representation of the current position of the operated Excavator superimposed on the Miniature controller, allowing users to easily identify discrepancies such as lagging, overshooting, or misalignment.

This visualization, displayed in Figure 3.7, improves operational precision by making it immediately clear how the physical Excavator responds to user input, allowing operators to adjust their movements for smoother and more accurate synchronization. By providing real-time feedback on the differences between the desired and actual positions, the overlay helps users anticipate the Excavator's behavior, ensuring better control and improved performance during complex tasks.

3.3 Control Perspective and Environment

Operating the Excavator from an external perspective, rather than from within the machine, offers significant advantages in terms of control, precision, and user experience. By leveraging virtual reality and remote operation, this approach provides a flexible and intuitive environment that enhances both safety and efficiency. One major benefit is the enhanced field of view, allowing operators to observe the entire machine and its surroundings, including areas that would typically be blind spots when seated in the cabin. This broader perspective is particularly valuable in complex or confined workspaces, where situational awareness is critical to safe and effective operation.

Additionally, the ability to reposition within the virtual environment offers unparalleled flexibility. Operators can teleport to different vantage points, enabling optimal views for precise tasks such as loading materials or navigating near obstacles. This freedom eliminates the constraints of a fixed cabin perspective and enhances coordination between the Excavator and its surroundings. Remote operation further improves safety by allowing users to control the machine from a distance, reducing exposure to hazardous environments such as unstable terrain or extreme weather. This combination of versatility, accessibility, and improved visibility makes the external perspective an essential feature for modern Excavator control systems.

4 User Study

This chapter presents the user study conducted to evaluate the performance and usability of the newly developed Miniature Control Interface for Excavator operation. The primary aim of this chapter is to assess whether the implemented interface provides measurable advantages over the traditional joystick-based control system. The key aspects under evaluation include operational speed, accuracy, error rates, and user intuitiveness. The findings of this study are intended to provide insights into the practical efficacy of the proposed interface and its potential to improve operator performance in real world scenarios.

4.1 Hypotheses

The user study aimed to assess whether this set of formulated hypotheses could be confirmed.

H1 The Miniature Control Interface will enable users to complete Excavator operation tasks faster than the traditional joystick-based control system.

H2 The Miniature Control Interface will result in greater precision during Excavator operation compared to the traditional joystick-based control system.

H3 Users will make fewer operational errors when using the Miniature Control Interface compared to the traditional joystick-based control system.

H4 The Miniature Control Interface will impose a lower cognitive workload on users compared to the traditional joystick-based control system.

4.2 Apparatus

The user study was conducted using a combination of hardware and software tools designed to create an immersive and controlled testing environment. The Oculus Meta Quest 2 headset, along with its accompanying controllers, served as the primary hardware platform to interact with the virtual Excavator control system. To collect feedback and demographic data, participants were asked to complete questionnaires developed in Google Forms. In addition, a testing application was specifically designed and implemented using the Unity engine to simulate Excavator operation and record performance metrics for the study.

4.3 The Testing Application

4.3.1 Environment

The main scene of the application features a detailed virtual Excavator, which the user operates to complete various tasks. The environment includes a terrain where users can move and teleport to different locations, allowing flexibility in task execution. A pile of stones is placed within the terrain, which can be used as an objective to load the Excavator bucket.

A central feature of the environment is a table equipped with a user interface that guides participants through the tasks they need to perform. This UI provides clear instructions and displays the currently active control mechanism for the task. The virtual controllers appear on the table, ensuring that users are always aware of the specific input device they must use for the given task.

4.3.2 Testing Process

The testing process begins with an introduction phase, where the user is familiarized with the virtual environment and the available control interfaces. During this phase, participants can explore the scene at their own pace. They are encouraged to practice teleporting and moving around the terrain to understand the spatial layout and operational mechanics of the testing application.

Participants are also encouraged to experiment with both control interfaces: the Miniature Control Interface and traditional joystick-based controls. They can use this time to operate the Excavator, practice its movement, and understand how the interfaces work in different scenarios. There is no time limit imposed during this familiarization phase, allowing users to take as much time as they need to feel confident and ready for the formal testing phase. Once the participant indicates that they are comfortable and sufficiently familiar with the environment and controls, they can proceed with the testing tasks.

The test phase consists of two types of tasks, each designed to evaluate different aspects of user performance. Each task type is completed twice: first using the traditional joystick controller and then using the Miniature Control Interface. For each type, the tasks are performed in three rounds at varying positions and targets. The first round serves as a practice session to help the participant become familiar with the specific requirements of the task and is not measured. The subsequent two rounds are measured for speed, accuracy and error rates. The collected data is used for analysis in the study.

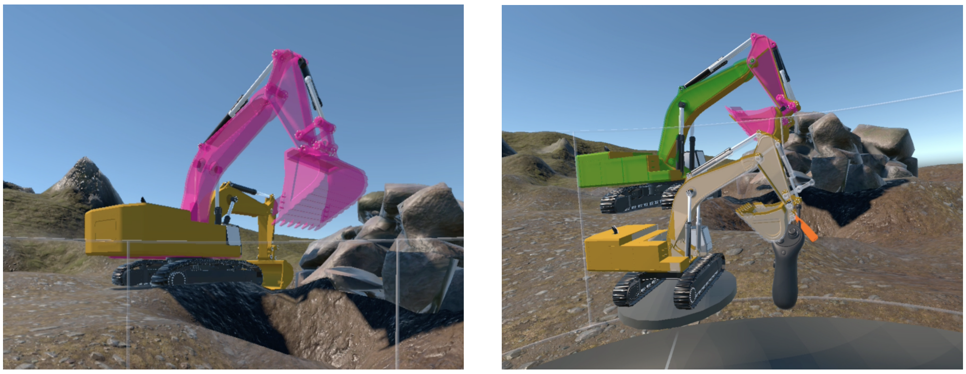

Figure 4.1: Ghost Task

The Figure 4.1 shows the first type of task, referred to as the **Ghost Task**. This task is designed to test the user's ability to position the Excavator accurately. In this task, a colored "ghost" Excavator appears in the virtual environment, representing the target position. The user's objective is to maneuver the Excavator to align as accurately as possible with the ghost model. As parts of the Excavator align correctly, they turn green, providing immediate visual feedback. This task assesses the user's spatial control and precision in positioning the Excavator in different scenarios.

The second type of task, called the **Bucket Task**, is displayed in Figure 4.2. This task simulates real-world operations by requiring the

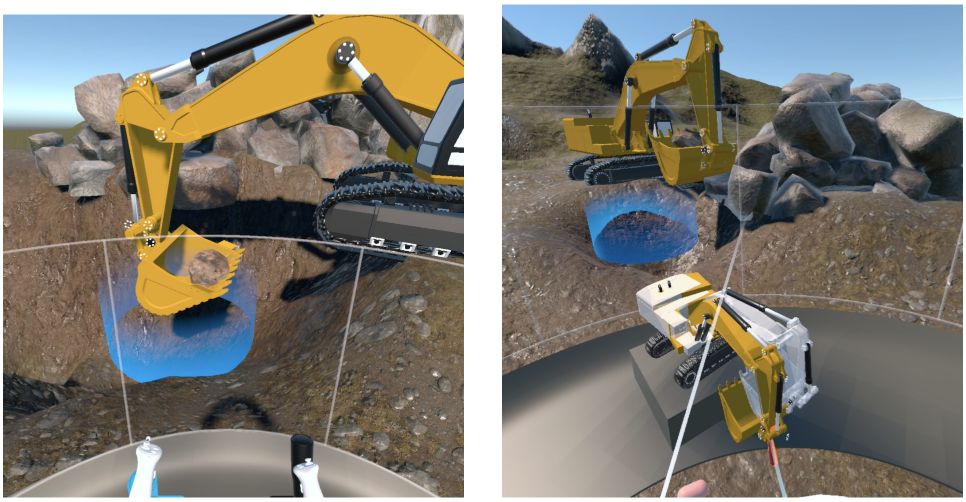

Figure 4.2: Bucket Task

user to load and unload materials with the Excavator. In this task, the participant is instructed to load stones from a designated pile into the Excavator's bucket and then transport and deposit them into a target circle on the terrain. This task evaluates the user's ability to perform complex operations that combine spatial awareness, precision, and control of Excavator movements in a realistic context.

4.4 Questionnaires

As part of the User Study, participants completed four questionnaires at different stages of the testing process. These questionnaires were designed to gather demographic data, assess user experience, and compare the two control interfaces based on participant feedback.

Before starting the study, each participant was required to agree to the **consent form** A.2. Upon giving their consent, the participants completed the **initial questionnaire** A.3, which included demographic questions.

The second and third questionnaires were identical and administered after completion of the tasks with each control interface. These questionnaires collected data for the **NASA Task Load Index** A.4 to assess cognitive workload and the **System Usability Scale** A.5 to measure the usability of each interface. Participants filled out these questionnaires after completing all tasks with the joystick controllers, took a pause if needed, and then repeated the process for the Miniature Control Interface. This approach enabled a comparative assessment of both systems based on standardized metrics.

The fourth questionnaire, the **likability questionnaire** A.6, was administered at the end of the study. This questionnaire combined open-ended questions with a series of statements rated on a 5-point Likert scale, ranging from "strongly disagree" to "strongly agree." The scaled questions assessed participants' general preferences, perceived ease of use, and satisfaction with each control interface. The open questions provided an opportunity for participants to share qualitative feedback, elaborate on their preferences, and suggest improvements for control systems.

4.5 Procedure

The entire user study was conducted in a controlled and safe environment, free of external distractions, to ensure that participants could focus fully on the tasks. Upon arrival, each participant was introduced and explained the objectives, tasks, and equipment. This introductory phase included a hands-on familiarization session with the VR headset and controllers to help participants feel comfortable with the technology before starting the testing process.

The entire procedure, including introduction, familiarization, questionnaires, task execution, and feedback collection, took approximately 60 minutes to complete for each participant.

4.6 Participants

The study included $N = 9$ participants, aged 25 to 57 years, with a median age of 30 years. Four participants were female, while the rest were male, representing diverse professional backgrounds, including fields such as IT, medicine, and business. Familiarity with VR varied between participants, with the majority ($n = 6$) reporting that they were not at all familiar with VR, two participants identifying as somewhat familiar, and one participant as very familiar. Four participants had previous VR experience.

The gaming experience also varied, with one participant never playing video games, four playing them rarely, two playing them frequently, and one playing occasionally. Regarding experience with heavy machinery, only one participant had prior exposure, reporting experience operating CNC milling machines, a Piper 2-motor airplane, and a tractor. Most of the participants ($n = 8$) reported no prior experience with heavy machinery or joystick-based controls.

4.7 Data Processing

Each user study generated four log files capturing task details such as start and end times, used control interface, distances, positional differences, and failed attempts. These raw files were processed to organize the data in a structured format suitable for analysis. During the second Bucket Task, the user with ID '1IM9' encountered errors with the Miniature controller when the bucket jumped unexpectedly. This issue was caused by an implementation error that was fixed after it was reported. Since this error was not the fault of the user, the faulty record was removed from the data set prior to processing to ensure that the analysis accurately reflected the user's performance. The distance calculations and other metrics were then performed to evaluate performance, allowing a comparison of speed, accuracy, and error rates between the Miniature Control Interface and the traditional joystick control interface.

5 Results

In this chapter, the findings of the research will be presented and analyzed in detail. The data collected from the user study, which includes system log files and user questionnaires, has been systematically processed and subjected to statistical analysis. This analysis aims to test the hypotheses outlined in the study by identifying statistically significant differences in performance, precision, error rates, and cognitive workload between the proposed Miniature Control Interface and the traditional joystick-based system. By examining these results, this chapter provides insight into the efficacy and potential advantages of the newly designed control system.

5.1 Speed Test

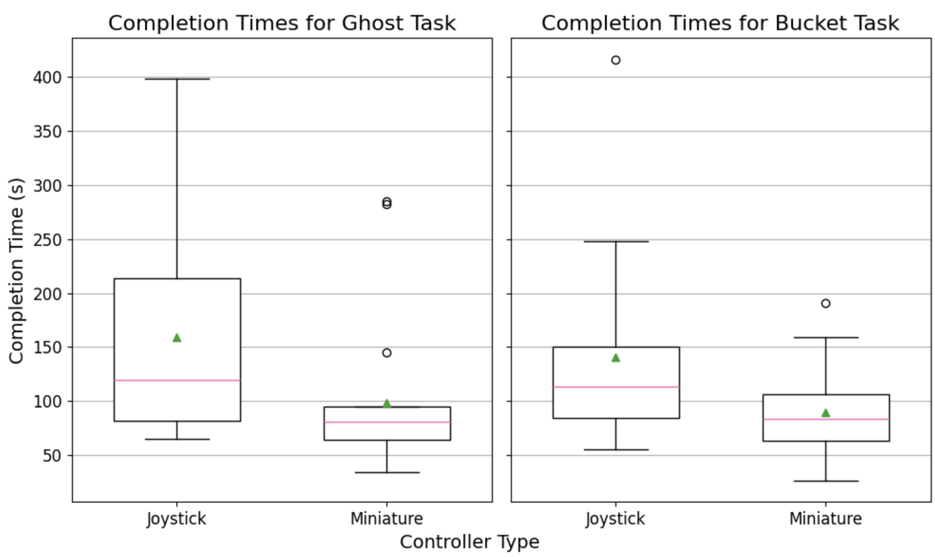

Figure 5.1: Speed Test times

The results of the Bucket Task demonstrate a clear advantage for the Miniature controller over the joystick controller in terms of speed. As shown in Figure 5.1, the box plot for the Bucket Task highlights that the median completion time for the Miniature controller is significantly lower than that of the joystick controller. Furthermore, the interquartile range for the Miniature controller is narrower, indicating less variability in the performance of the participants. The joystick controller, on the contrary, exhibits a broader spread of completion times, reflecting higher inconsistency among users. Descriptive statistics further confirm these observations, with a median completion time of 83.25 seconds for the Miniature controller compared to 113.03 seconds for the joystick controller. The mean completion times reinforce this trend, with the Miniature controller averaging 89.67 seconds versus 140.41 seconds for the joystick controller. The standard deviation values of 45.40 seconds for the Miniature controller and 89.20 seconds for the joystick controller indicate that the Miniature controller also provides a more consistent user experience.

Similarly, the results for the Ghost Task, depicted in Figure 5.1, align with the findings from the Bucket Task. The box plot for the Ghost Task shows a lower median completion time for the Miniature controller compared to the joystick controller, with the former displaying a more compact interquartile range. The joystick controller again shows greater variability in task completion times. The descriptive statistics reveal that the median completion time for the Miniature controller is 80.58 seconds, while the median for the joystick controller is 119.16 seconds. The mean completion times further emphasize the difference, with 98.39 seconds for the Miniature controller compared to 159.14 seconds for the joystick controller. The standard deviation for the Miniature controller is 72.54 seconds, significantly less than the joystick controller's 101.45 seconds, underscoring the Miniature controller's ability to deliver consistent performance.

The results of the Bucket and Ghost Tasks strongly support the hypotheses **H1**, stating that the Miniature Control Interface enables faster task completion than the traditional joystick-based control system. The statistical analyses, descriptive data, and visual evidence from the box plots collectively indicate that the Miniature controller not only allows participants to complete tasks more quickly but also provides a more stable and predictable user experience. Therefore, the hypotheses is accepted, affirming the superiority of the Miniature controller in task completion speed.

5.2 Accuracy test

The results of the accuracy test offer insight into the comparative precision of the Miniature controller and the joystick controller across the tasks.

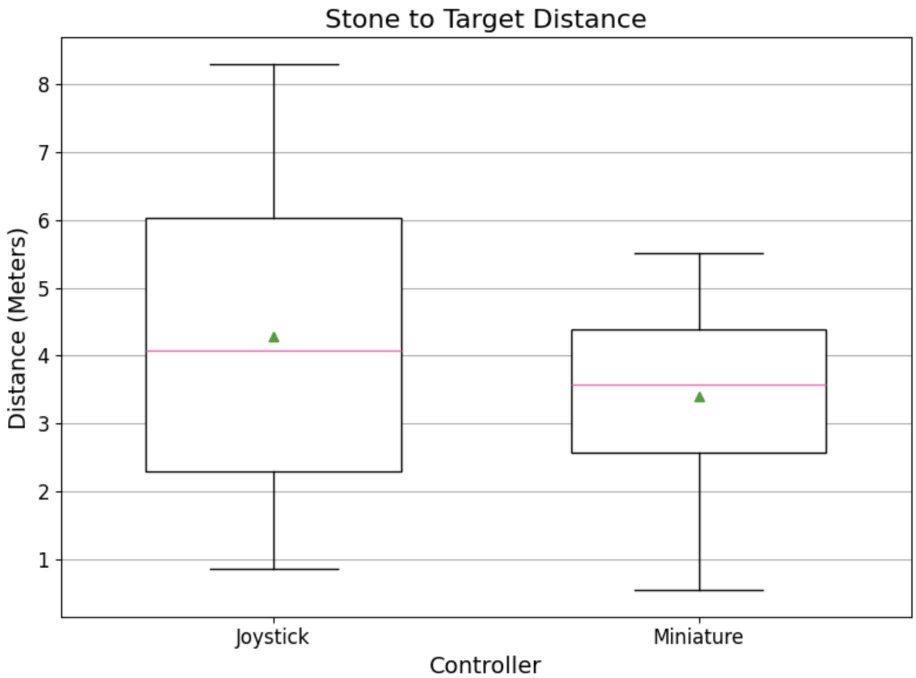

Figure 5.2: Accuracy Test for the Bucket Task

In the Bucket Task, the precision of each controller was measured in terms of distance. The box plot for this task, presented in Figure 5.2, shows a slightly lower median distance for the Miniature controller compared to the joystick controller. However, the overlap in the interquartile ranges suggests substantial variability in the results for both controllers. The Wilcoxon Signed-Rank test yielded a test statistic of 123.0 and a p-value of 0.054, which, while indicative of a trend toward improved precision with the Miniature controller, does not meet the threshold for statistical significance. These results suggest that, while the Miniature controller may offer a slight advantage in precision, the difference is not robust enough to be conclusive.

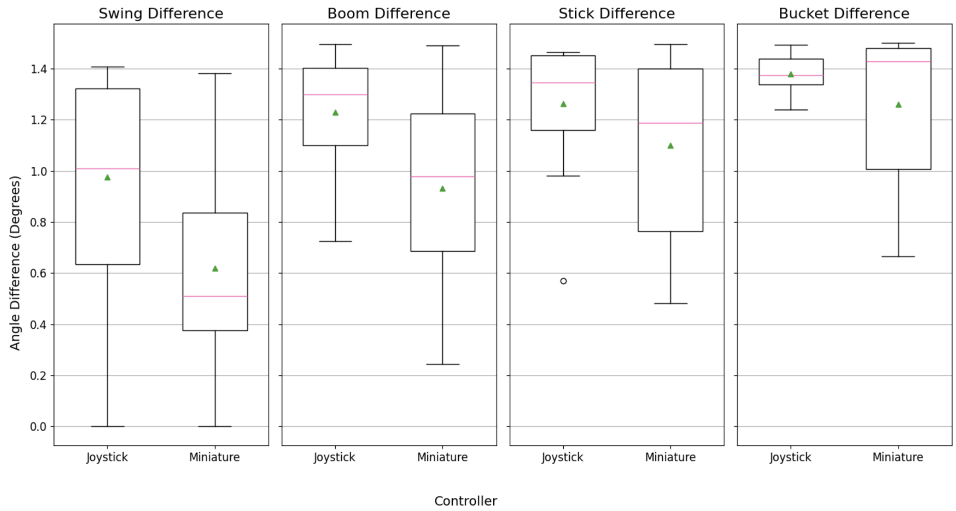

Figure 5.3: Accuracy Test for the Ghost Task

In the Ghost Task, the results are more nuanced, as precision was assessed across four parameters: swing difference, boom difference, stick difference, and bucket difference. The box plots for these metrics are shown in Figure 5.3. For the swing and boom differences, the Miniature controller demonstrated statistically significant improvements in precision. The medians for these parameters were lower for the Miniature controller, with narrower interquartile ranges indicating less variability in performance. The Wilcoxon Signed-Rank Test further supported these findings, with test statistics of 136.0 ($p = 0.013$) for swing difference and 131.0 ($p = 0.024$) for boom difference, both below the significance threshold of 0.05.

In contrast, the results for the stick and bucket Differences were not statistically significant between the two controllers. The medians and interquartile ranges for these metrics were similar, as confirmed by descriptive statistics and the results of the Wilcoxon Signed Rank Test. For stick difference, the test statistic was 121.0, with a p-value of 0.065, while for bucket difference, the test statistic was 98.0, with a p-value of 0.305. These findings indicate that in these aspects of the Ghost Task, the Miniature controller does not outperform the joystick controller in terms of precision.

The hypotheses H2, saying that the Miniature Control Interface results in greater precision during Excavator operation is partially accepted. For the Ghost Task, the Miniature controller demonstrated significant improvements in precision for swing and boom adjustments, supported by statistical and descriptive evidence. However, no significant differences were found for stick and bucket adjustments in the Ghost Task, or for the distance metric in the Bucket Task. These results suggest that, while the Miniature controller excels in certain aspects of precision, its performance is not uniformly superior across all metrics.

5.3 Error Test

The error test was conducted to evaluate whether users made fewer operational errors with the Miniature controller compared to the joystick controller during the Bucket Task. Errors were recorded as discrete count data, and McNemar's test was applied to analyze the paired nature of the data.

The results of McNemar's test indicate a statistically significant difference in error rates between the two controllers. The contingency table highlights the distribution of errors: 9 users made no errors with either controller, 8 users made errors only with the Miniature controller, 1 user made errors only with the joystick controller, and no users made errors with both controllers. The p-value obtained from the test was 0.015625, which is well below the significance threshold of 0.05. This result suggests that users were more likely to make errors with the Miniature controller than with the joystick controller.

Descriptive statistics provide further insight into the raw error counts. The mean error count for the Miniature controller was 0.94, compared to 0.11 for the joystick controller, with most users not making errors. However, the Miniature controller exhibited a wider range of error counts, with values ranging from 0 to 4, while the joystick controller showed a range from 0 to 2. This variability is visually apparent in the box plot Figure 5.4, which depicts a compact distribution at zero for the joystick controller, while the Miniature controller shows a greater spread and occasional outliers.

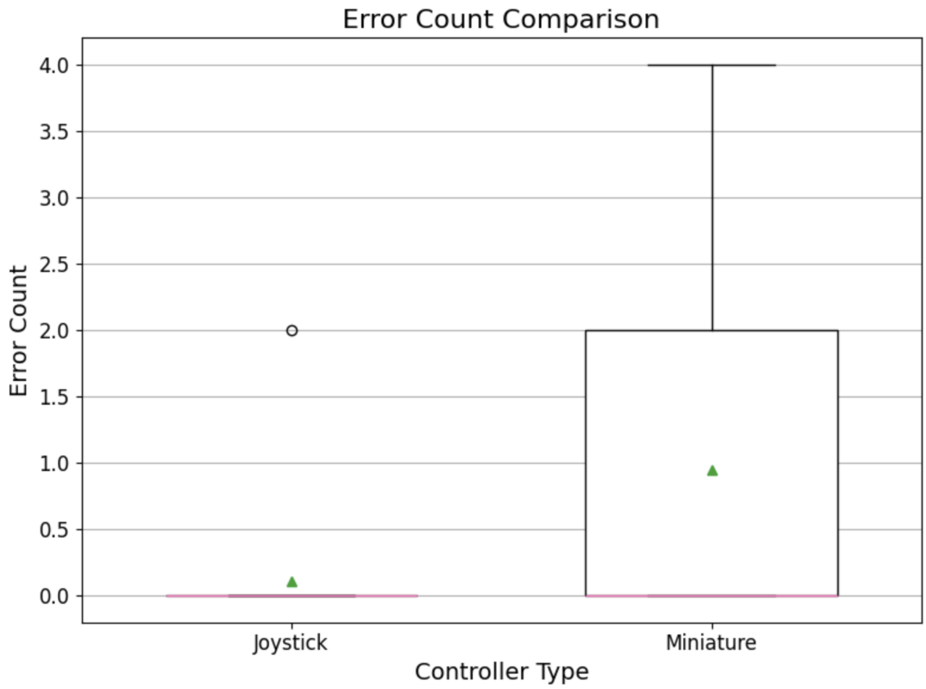

Figure 5.4: Error Test

The findings of both statistical and descriptive analyzes indicate that the joystick controller performs better in terms of error rate. Therefore, the H3, saying that the Miniature controller would result in fewer operational errors, is rejected. The data consistently demonstrate that users made fewer errors with the joystick controller during the Bucket Task.

5.4 User Feedback

5.4.1 NASA-TLX Questionnaire

The cognitive workload analysis began with the evaluation of the NASA-TLX Questionnaire results, which compared perceived workload between the joystick and Miniature controllers. The scores for both controllers were normally distributed, which makes a paired t-test an appropriate method for statistical comparison.

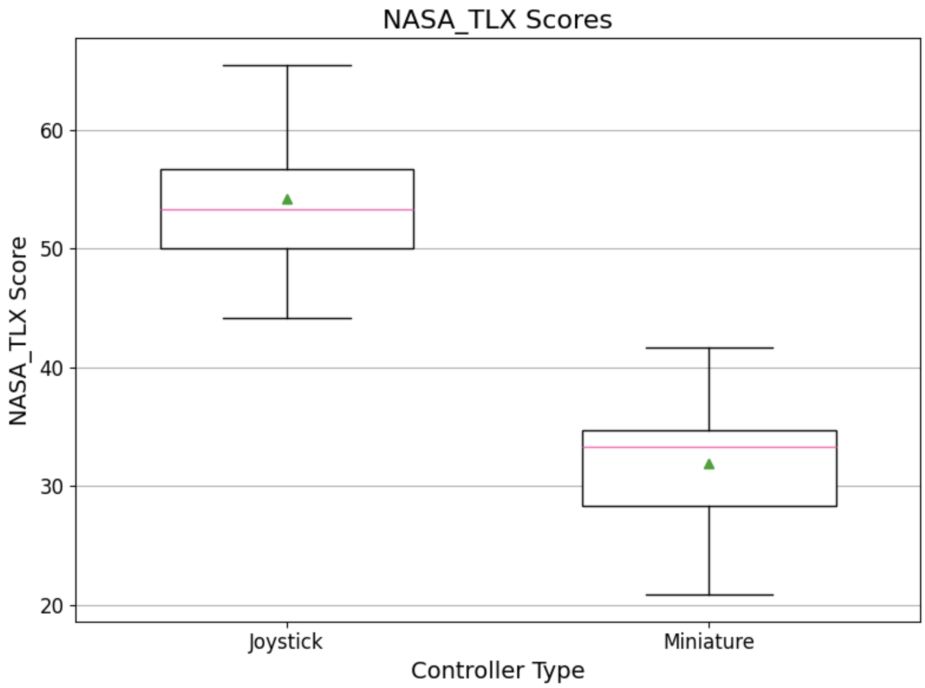

Figure 5.5: NASA-TLX Questionnaire results

A box plot, displayed in Figure 5.5, visually represents the distribution of NASA-TLX scores for the two controllers, providing a clear comparison of user experiences.

The results indicate a substantial difference in perceived workload between the two controllers. The joystick controller had higher mean and median scores, reflecting a greater cognitive burden on users. Specifically, the joystick controller's mean score was 54.22, with a median of 53.33. The scores ranged from 44.17 to 65.50, with a standard deviation of 6.49, suggesting a consistently high workload experienced by the participants. In contrast, the Miniature controller demonstrated lower workload scores, with a mean of 31.91 and a median of 33.33. The scores for the Miniature controller ranged from 20.83 to 41.67, with a standard deviation of 6.34, indicating both a lower cognitive burden.

The paired t-test reinforced these observations, with a t-statistic of 6.18 and a p-value of 0.00026, confirming that the difference in

NASA-TLX scores between the controllers was statistically significant. This significant reduction in perceived workload for the Miniature controller is further illustrated in Figure 5.4. The box plot shows the NASA-TLX scores for the joystick controller distributed around higher values, with a broader spread reflecting greater cognitive demands and variability. In contrast, the Miniature controller scores are tightly clustered around lower values, illustrating a more uniform and reduced cognitive workload among participants.

5.4.2 SUS Questionnaire

The analysis of the SUS scores demonstrates a clear difference in perceived usability between the joystick and Miniature controllers. Since the scores for both controllers were normally distributed, a paired t-test was used to compare their usability.

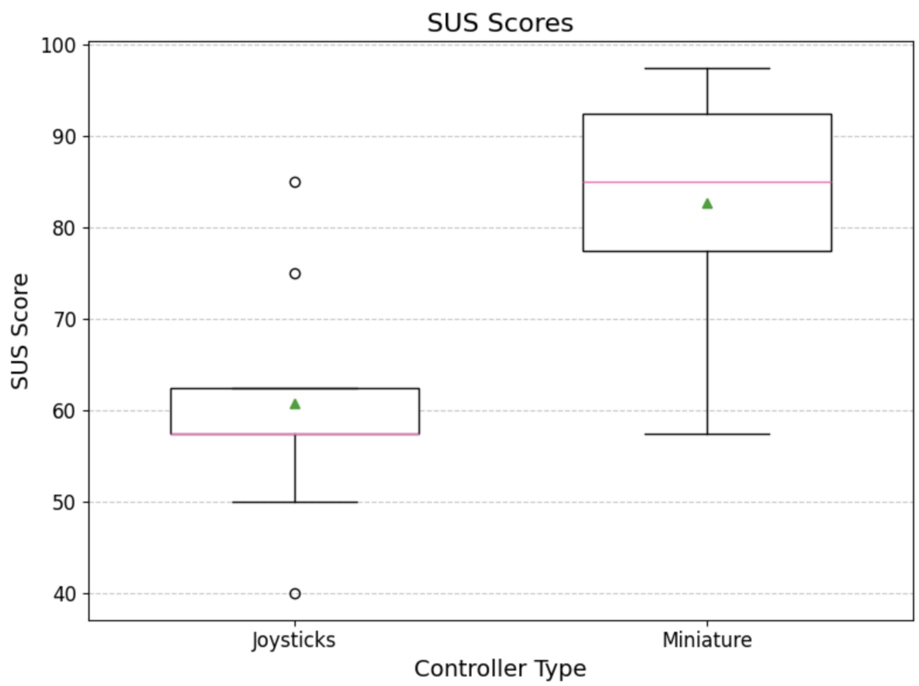

Figure 5.6: SUS Questionnaire results

The results reveal a significant preference for the Miniature controller, as shown in the box plot in Figure 5.6, which illustrates the differences in the score distributions.

The descriptive statistics show that the Miniature controller achieved consistently higher usability scores. Its mean SUS score was 82.78, indicating high usability, with a median of 85.0. The scores ranged from 57.5 to 97.5, with a standard deviation of 12.59, suggesting that the user ratings for the Miniature controller were relatively consistent. For comparison, the joystick controller had a mean score of 60.83, reflecting moderate usability, with a median of 57.5. The joystick controller scores ranged more widely, from 40.0 to 85.0, and had a higher standard deviation of 13.11, indicating greater variability in user feedback. These results suggest that the Miniature controller provided a more consistently positive experience.

The paired t-test confirmed the statistical significance of these differences, with a t-statistic of -4.59 and a p-value of 0.0018. The negative t-statistic indicates that the SUS scores for the Miniature controller were significantly higher than those for the joystick controller.

5.4.3 Likability Questionnaire

Given the distribution characteristics of the Likability scores were normally distributed for the joystick controller and not normally distributed for the Miniature controller, a nonparametric test was deemed the most appropriate. The Wilcoxon Signed-Rank test was selected for its suitability in comparing paired samples where one distribution does not meet the assumptions of normality. This test assesses differences in the median ranks of the two groups, providing a robust comparison of Likability scores between the two controllers.

A box plot, presented in Figure 5.7, visually represents the score distributions, offering additional insight into the findings.

The descriptive statistics reveal a pronounced contrast in the likability scores between the two controllers. The joystick controller had a mean score of 3.50, with a median of 3.5, suggesting moderate likability. The scores for this controller ranged from 2.5 to 4.5, with a standard deviation of 0.61, indicating moderate variability between the ratings of the participants. In contrast, the Miniature controller exhibited a mean score of 4.63 and a median score of 5.0, indicating a

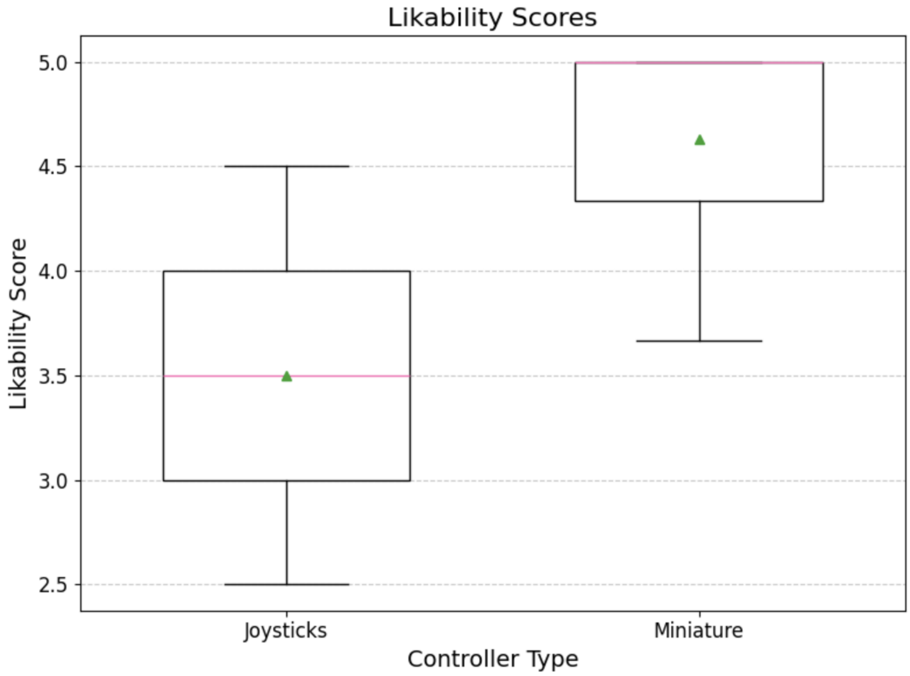

Figure 5.7: Likability Questionnaire results

very high likability. The range of scores for the Miniature controller was narrower, from 3.67 to 5.0, and the standard deviation was 0.51, reflecting greater consistency in the preferences of the participants.

The Wilcoxon Signed-Rank test confirmed these observations statistically, with a test statistic of 3.0 and a p-value of 0.035. This result indicates a statistically significant difference in Likability scores, which favors the Miniature controller. The box plot in Figure 5.7 further illustrates this difference, showing a higher median and a more compact distribution for the Miniature controller. In contrast, the joystick controller scores are more widely spread and are centered on lower values, indicating mixed opinions about its likability.

These findings provide clear evidence of the stronger preference of participants for the Miniature controller in terms of likability. Together, statistical and visual analyzes underscore the success of the Miniature controller in meeting user expectations and providing a more favorable user experience.

5.4.4 User Feedback Findings

The results of the NASA-TLX, SUS, and Likability questionnaires strongly support the hypotheses **H4**, stating that the Miniature Control Interface imposes a lower cognitive workload on users compared to the traditional joystick-based control system. NASA-TLX analysis revealed significantly lower cognitive effort required by the Miniature controller, while the SUS scores demonstrated its superior usability, with higher and more consistent ratings. The likability analysis also highlighted the preference of participants for the Miniature controller, with higher median, average scores, and less variability. The statistical significance across all metrics confirms that the Miniature controller not only reduces cognitive workload but also provides a more user-friendly and likable experience, leading to acceptance of the hypotheses.

6 Discussion

This chapter interprets the findings of the study, providing a deeper understanding of the performance, strengths, and limitations of the two control systems across the evaluated tasks. By examining the results of the Bucket and Ghost Tasks, alongside user feedback and limitations of the study, this chapter highlights critical trade-offs between speed, accuracy, and usability. The discussion further explores how these findings align with real-world Excavator operations, offering insights into the practical implications of the Miniature controller. Finally, potential directions for future research and system improvements are proposed to enhance the effectiveness and robustness of control systems in practical applications.

6.1 Bucket Task

The Bucket Task closely mirrors real-world Excavator operations, emphasizing the practical usability of the control systems. In this task, the Miniature controller outperformed the joystick in terms of speed, confirming the hypotheses **H1**, stating that it allows for faster task completion. However, the higher error rate observed with the Miniature controller highlights a key challenge: the need to control multiple angles simultaneously. Participants frequently reported difficulties in ensuring that the bucket remained closed while focusing on other aspects of the task. In contrast, the joystick controller allowed users to isolate movements, such as fully closing the bucket and ensuring that it remained closed while taking care of other controls. This feature reduced the likelihood of accidental actions, such as dropping the stone.

These findings emphasize the Miniature controller's potential for improving task efficiency, while also revealing areas where design refinements are necessary to enhance stability and reduce errors in tasks with multiple degrees of freedom.

6.2 Ghost Task

The Ghost Task required precise alignment of Excavator components with a virtual target, which required high accuracy at all angles. Despite these challenges, the Miniature controller still outperformed the joystick in terms of speed, aligning with hypotheses **H1**, stating that the Miniature Control Interface enables faster task completion. However, the accuracy hypotheses **H2** were only partially accepted, as the Miniature controller demonstrated superior performance in some accuracy metrics, but not consistently in all.

The limitations of the Miniature interface in this task stem from the need to control all angles simultaneously, which increased cognitive demand and occasionally hindered precise adjustments. In contrast, the joystick controller, with its ability to isolate individual movements, provided an advantage in tasks focused on accuracy. Users could adjust one or two angles at a time without having to monitor or stabilize others, making the joystick particularly effective for tasks that require precise alignment.

However, the heightened accuracy required in the Ghost Task does not necessarily reflect the demands of real-world Excavator operations, where precision to this degree is rarely necessary. Instead, operational efficiency and task completion speed often take precedence, areas where the Miniature controller excelled. These findings highlight the trade-offs in the design of the two control systems, with the joystick excelling in precision under controlled conditions but the Miniature controller offering broader usability and performance advantages in more practical contexts.

6.3 User Feedback and Insights

Participants feedback offers critical insights into the usability of the two control systems. Informal discussions after the study revealed that users overwhelmingly found the Miniature controller easier to learn and more intuitive. They appreciated not having to translate the directions of the joystick into the desired movements, which made the Miniature interface feel more natural and allowed them to focus on the objectives of the task rather than the mechanical operation.

However, users also reported frustrations with the Miniature controller, particularly its demand for constant attention to all angles during tasks. In contrast, while the joystick interface was less intuitive and more difficult to master, its ability to isolate movements made it advantageous in tasks requiring precision, such as the Ghost Task.

This feedback underscores a key trade-off: Although the Miniature controller improves the user experience and reduces the learning curve, its complexity in managing simultaneous movements can hinder performance in tasks demanding high precision.

6.4 Limitations

This study has several limitations that should be considered when interpreting the results. The sample size and diversity of the participants were limited, which can affect the applicability of the findings. The tasks included in the study were designed to evaluate specific aspects of the performance of the control system, but may not fully reflect the range of challenges encountered in real-world applications.

Addressing these limitations in future research will be crucial for obtaining a more comprehensive evaluation.

6.5 Implications and Future Directions

The findings of this study highlight important trade-offs in the design of control systems for construction machinery. The Miniature controller's strengths in speed and user preference make it a promising alternative to traditional joystick systems. However, its higher error rates and cognitive demands during tasks that require high precision, such as Ghost Task, indicate areas for improvement.

Future research should focus on refining the Miniature controller to address these limitations. Potential enhancements could include mechanisms to isolate specific angles during operation or haptic feedback to guide users and prevent unintentional actions. Expanding the scope of tasks and increasing participant diversity will also provide a more holistic understanding of the controller's capabilities.

By addressing these areas, the Miniature controller could evolve into a more robust and versatile control system, balancing speed, accuracy, and usability to meet the demands of real-world applications.

7 Conclusion

This thesis aimed to explore new and intuitive control interfaces for heavy machinery, leveraging the capabilities of Virtual Reality to overcome the limitations of traditional systems. Through the use of immersive 3D environments, the research demonstrated the potential of VR to simplify complex operations, reduce the learning curve, and enhance user experiences. By rethinking how operators interact with machinery, this work highlights the transformative possibilities of VR in creating more efficient and user-friendly teleoperation systems.

The findings contribute to the fields of teleoperation and human-robot interaction by emphasizing the advantages of VR-based interfaces over conventional methods. This study underscores the importance of designing systems that balance ease of use with precision, ensuring both speed and accuracy in operation. Furthermore, the work highlights task-specific considerations, showing how different interface designs can influence performance depending on the context and demands of the task.

Future research should focus on refining the proposed control interfaces to address observed challenges, such as improving error rates and managing cognitive workload. Incorporating features such as haptic feedback or adaptive control mechanisms could further enhance usability and precision. Expanding the scope of tasks and participant diversity will also provide a deeper understanding of the potential of the interface across different scenarios. With these advancements, VR-based control systems could significantly improve the usability and accessibility of heavy machinery, making them a valuable tool in various industrial applications.

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A An Appendix

A.1 Appended Files

The IS MU archive includes the following files, which document the implementation, analysis, and results of the conducted user study:

- **VR Excavator Unity Project** – The complete Unity project files are archived as `/vr-excavator.zip`.
- **User Study Logs** – Logs collected during the user study sessions, stored in the directory `/logs`.
- **Jupyter Notebook for Log Pre-Processing** – A Jupyter notebook used to preprocess the collected logs, located at `/data_analysis/VREX_LOGS_Processing.ipynb`.
- **Jupyter Notebook for Data Analysis** – The primary Jupyter notebook for analyzing the user study data, available at `/data_analysis/VREX_Analysis.ipynb`.
- **Questionnaires** – Copies of the questionnaires distributed through Google Forms, stored in `/questionnaires/google_forms`.
- **Questionnaire Pre-Processing File** – An Excel file containing pre-processed questionnaire data for analysis, located at `/questionnaires/google_forms_processing.xlsx`.

A.2 Consent Form

By filling out this form you acknowledge that you are voluntarily agreeing to participate in the VR Excavator Controlling Interface study. This participation includes your consent to the collection and processing of data related to your experiences during the study. Your involvement is entirely voluntary, and you have the right to withdraw from the study at any time, for any reason, without incurring any penalties or negative consequences.

The study will take place in a controlled, safe environment specifically designed for the tasks involved. However, please be aware that participation in virtual reality activities may carry inherent risks, including but not limited to potential discomfort, motion sickness, or physical strain. You participate in this study at your own risk. It is important to listen to your body and prioritize your well-being.

You are encouraged to ask questions about the study at any time, whether before, during, or after your participation. Additionally, you are free to take breaks whenever you feel it necessary, ensuring you are comfortable throughout the process. Should you experience any feelings of motion sickness or discomfort while using the VR equipment, please inform the researcher immediately. Your health and safety are of utmost importance, and appropriate measures will be taken to address any concerns you may have.

As part of the study, you consent to the recording of images and/or video footage of you while you are performing the tasks and using the VR equipment. These recordings may be used for research purposes, including presentations, publications, and educational materials. All collected personal information will be used solely for research purposes and will be handled with strict confidentiality. Your identity will not be disclosed in any reports or publications resulting from this study without your explicit permission.

A.3 Initial Questionnaire

The initial questionnaire collected demographic data and user experience information. The following questions were asked:

1. Age
2. Gender
3. Current field of work or study?
4. How familiar are you with virtual reality? (Options: Not at all familiar, Somewhat familiar, Very familiar)
5. Have you used VR for gaming, training, or other applications? (Yes/No)
6. If yes, did you experience discomfort or motion sickness while using VR or playing video games? (Open-ended)

7. How often do you play video games? (Options: Daily, Weekly, Monthly, Rarely, Never)
8. Have you ever operated heavy machinery? (Yes/No)
9. If yes, what type of heavy machinery have you operated? (Open-ended)
10. How many hours of experience do you have operating heavy machinery? (Numeric response)
11. Have you ever operated an Excavator? (Yes/No)
12. If yes, please specify your experience level: (Open-ended)
13. How comfortable are you using new technologies? (Scale: 1 - Not Comfortable to 5 - Very Comfortable)
14. How do you prefer to learn new skills? (Options: Hands-on practice, Reading, Watching videos, Other)
15. How often do you use a joystick or similar control device? (Options: Frequently, Occasionally, Rarely, Never)

A.4 NASA-TLX Questionnaire

Participants were asked to rate each dimension on a scale from 0 (Low) to 100 (High):

1. How mentally demanding was the task?
2. How physically demanding was the task?
3. How hurried or rushed was the pace of the task?
4. How successful were you in accomplishing the task? (0 - Very Poor, 100 - Excellent)
5. How hard did you have to work to accomplish your level of performance?
6. How frustrated, discouraged, irritated, stressed, and annoyed did you feel performing the task?

A.5 System Usability Scale Questionnaire

Participants rated each statement on a 5-point Likert scale from 1 (Strongly Disagree) to 5 (Strongly Agree):

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

A.6 Likability Questionnaire

The following questions were asked to evaluate the likability of the controllers:

1. I enjoyed using the Miniature controlling interface. (Scale: 1 - Strongly Disagree to 5 - Strongly Agree)
2. I enjoyed using the joystick controlling interface. (Scale: 1 - Strongly Disagree to 5 - Strongly Agree)
3. I would recommend the Miniature controlling interface to others. (Scale: 1 - Strongly Disagree to 5 - Strongly Agree)

4. I felt satisfied with the overall experience of using the Miniature control system. (Scale: 1 - Strongly Disagree to 5 - Strongly Agree)

5. I felt satisfied with the overall experience of using the joystick control system. (Scale: 1 - Strongly Disagree to 5 - Strongly Agree)

6. What did you like most about the Miniature control system? (Open-ended)

7. What did you like most about the joystick control system? (Open-ended)

8. I would prefer to use the Miniature control system over the joysticks. (Scale: 1 - Strongly Disagree to 5 - Strongly Agree)

9. I felt that the Miniature control system was more enjoyable overall. (Scale: 1 - Strongly Disagree to 5 - Strongly Agree)

10. What aspects of the Miniature controlling interface did you find frustrating or unappealing? (Open-ended)

11. What aspects of the joystick controlling interface did you find frustrating or unappealing? (Open-ended)

12. If you could change one thing about the Miniature controlling interface, what would it be? (Open-ended)