Implementation and Evaluation of an HMI for Teleoperation

Implementierung und Bewertung eines HMIs für Teleoperation

Wissenschaftliche Arbeit zur Erlangung des Grades

M.Sc. Mechatronik und Robotik

an der TUM School of Engineering and Design der Technischen Universität München.

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Abstract

This master thesis investigates the design and effectiveness of a novel Human-Machine Interface (HMI) using a PlayStation 4 (PS4) controller for teleoperation in industrial manufacturing settings. The rise of collaborative robots (cobots) in manufacturing necessitates HMIs that enhance productivity while ensuring safety and reducing learning costs. Traditional teleoperation systems used in space and underwater explorations do not meet the demands of industrial environments where usability and integration into production processes are crucial.

This research aims to fill the gap in teleoperation HMI design for manufacturing by implementing and evaluating a PS4 controller-based interface against the traditional leader-follower configuration. The study was structured around two main objectives: the design and implementation of the PS4 controller-based HMI, and a within-subject user study to compare its performance, workload, and usability with that of the conventional system.

Participants in the study performed typical manufacturing tasks such as pick-and-place and peg-in-hole, with performance metrics including task completion time, grasp and drop attempts, alongside subjective workload and usability assessments through NASA-TLX and the System Usability Scale (SUS). The findings reveal that while the PS4 controller HMI showed potential in specific control aspects, it underperformed compared to the leader-follower HMI in terms of performance, workload, and usability.

These insights show the complexities of adapting gaming hardware for precision-driven industrial tasks and highlight the need for further research into bridging the gap between advanced teleoperation systems and user-friendly interfaces in manufacturing environments.

Kurzfassung

Diese Masterarbeit untersucht das Design und die Wirksamkeit einer neuartigen Mensch-Maschine-Schnittstelle (HMI) unter Verwendung eines PlayStation 4 (PS4) Controllers für die Teleoperation in industriellen Fertigungsumgebungen. Der Aufstieg kollaborativer Roboter (Cobots) in der Fertigung macht HMIs notwendig, die die Produktivität steigern, gleichzeitig Sicherheit gewährleisten und die Lernkosten senken. Traditionelle Teleoperationssysteme, die in der Raumfahrt und Unterwasserforschung verwendet werden, erfüllen nicht die Anforderungen industrieller Umgebungen, in denen Benutzerfreundlichkeit und Integration in Produktionsprozesse entscheidend sind.

Diese Forschung zielt darauf ab, die Lücke im Design von Teleoperations-HMIs für die Fertigung zu schließen, indem eine auf dem PS4-Controller basierende Schnittstelle implementiert and mit der traditionellen Leader-Follower-Konfiguration verglichen wird. Die Studie war um zwei Hauptziele strukturiert: das Design und die Implementierung des auf dem PS4-Controller basierenden HMI und eine benutzerinterne Studie, um dessen Leistung, Arbeitsbelastung und Benutzerfreundlichkeit mit dem herkömmlichen System zu vergleichen.

Teilnehmer der Studie führten typische Fertigungsaufgaben wie Pick-and-Place und Peg-in-Hole durch, wobei Leistungsmetriken wie die Aufgabenabschlusszeit, Greif- und Ablegeversuche sowie subjektive Arbeitsbelastungs- und Benutzerfreundlichkeitsbewertungen durch NASA-TLX und die System Usability Scale (SUS) erfasst wurden. Die Ergebnisse zeigen, dass das PS4-Controller HMI in bestimmten Steuerungsaspekten Potenzial aufwies, jedoch im Vergleich zum Leader-Follower HMI hinsichtlich Leistung, Arbeitsbelastung und Benutzerfreundlichkeit unterlegen war.

Diese Erkenntnisse zeigen die Komplexität der Anpassung von Spielhardware für präzisionsgetriebene industrielle Aufgaben und unterstreichen die Notwendigkeit weiterer Forschung zur Überbrückung der Lücke zwischen fortschrittlichen Teleoperationssystemen und benutzerfreundlichen Schnittstellen in Fertigungsumgebungen.

Contents

1. Introduction

1.1. Motivation and Task

Teleoperation has been widely applied for decades in areas such as space exploration and underwater operation, because it allows human operators to control the robot to complete tasks in environments dangerous to human(Rea & Seo, 2022). In recent years, however, teleoperation has found its way into the world of industrial manufacturing. As cobots (collaborative robots) starts gaining popularity in industrial manufacturing process, teleoperation becomes an option to connect human operators with the cobots. It offers many benefits such as increasing productivity, increasing time-space-flexibility and providing a safer working environment for the operators. Unlike traditional teleoperation system for space or underwater exploration, there is a higher requirement for the usability and learning cost of the teleoperation system for industrial manufacturing purpose. A well designed Human-Machine-Interface(HMI) is crucial for the teleoperation system to be integrated into the time-sensitive production processes(Prinz & Bengler, 2023). Some works have been done about teleoperation HMIs specified for manufacturing tasks, where a leader robot is used as the control input for a follower robot (Prinz & Bengler, 2023). However, there is still a research gap for teleoperation HMI designs specified for manufacturing tasks using other input devices, such as a PlayStation4 (PS4) controller.

To address this gap, this thesis is dedicated to exploring the possibility of designing an improved HMI specified for assembly tasks using the existing equipments in our laboratory. The research question posed in this thesis is:

- **For assembly tasks using a 7 DoFs robot, can an HMI using a PS4 controller as input outperform an HMI using a leader-follower configuration in terms of performance, workload, and usability?**

To answer this question, the study is divided into two main objectives:

1. Design and implement a novel teleoperation HMI based on a PS4 controller.
2. Conduct a within-subject user study to validate whether this new HMI outperforms the traditional HMI based on a leader-follower setup in terms of performance , workload, and usability through assembly tasks such as pick-and-place and peg-in-hole.

1.2. Outline of Thesis

This section provides a detailed outline of the thesis, describing the content and focus of each subsequent chapter.

1. **Chapter 1: Introduction** This chapter introduces the context and motivation for the research, outlining the importance of teleoperation in industrial settings and the need for effective HMIs. It defines the research question and objectives that guide the study. The chapter concludes with an overview of the thesis structure.

2. **Chapter 2: The State of the Art of HMI in Teleoperation Systems** This chapter reviews existing literature on teleoperation systems across various domains with emphasis on HMIs development.

3. **Chapter 3: HMI Design and Implementation** This chapter details the design and implementation of the novel PS4 controller-based HMI. It describes the design goals, system architecture, and the specific configurations used for the PS4 controller HMI. The development process of the HMI, including software and programming implementation details, is discussed. In the end of this chapter, an HMI parameter optimization experiment is also conducted.

4. **Chapter 4: User Study Design** This chapter outlines the methodology used in the user study, including research hypotheses, the design of the study, participant recruitment, and data collection methods. It explains the quantitative and qualitative measures used to evaluate the performance, workload, and usability of the new HMI compared to the traditional leader-follower HMI.

5. **Chapter 5: User Study Results** This chapter presents the results of the user study. It provides a detailed analysis of performance metrics such as task completion times, grasp, and drop attempts, as well as subjective assessments from NASA-TLX and SUS questionnaires. The chapter discusses the findings in the context of the PS4 controller's effectiveness as an HMI.

6. **Chapter 6: Discussion** This chapter discusses the implications of the study findings. It evaluates the research hypotheses based on the collected data, discusses the strengths and limitations of the PS4 controller HMI, and offers suggestions for improving HMI design in industrial applications.

7. **Chapter 7: Conclusion and Future Work** This chapter summarizes the main findings of the thesis and discusses their contributions to the field of teleoperation and HMI design. It highlights the practical implications of the research and identifies areas for future research and potential enhancements in the HMI design for teleoperation systems aimed for industrial manufacturing.

2. The State of the Art of HMI in Teleoperation Systems

Teleoperation has been widely applied in areas that are inaccessible to humans, such as space, ocean, and volcanoes. A typical teleoperation system consists of two sides: the operator side and the remote side. The operator interacts with the Human-Machine-Interface (HMI) on the operator side, sending control signals to the robot on the remote side. On the remote side, the robot will also send information feedback to the operator side, making the operator aware of the situation of the robot(Niemeyer, Günter Preusche, Carsten Hirzinger, 2008)(Boboc, Moga, & TALABĂ, 2012).

In the realm of teleoperation, various control designs have been implemented. On one end of the spectrum, there's direct or manual control, where the user maneuvers the robot without any automation. On the opposite end, supervisory control means the user provides high-level commands, and the robot possesses significant intelligence or autonomy. Falling between these two poles are shared control designs, granting a mix of user input and automated assistance(Sheridan, 1992). Many real-world systems incorporate at least some element of direct control, often utilizing a joystick or a similar tool to interpret user directives. A typical teleoperation configuration deploys a second robot on the local side as control interface, with which the user can interact. Within this setup, the local robot is termed the "leader", while the distant one is the "follower". Such configurations are often labeled leader-follower configurations. For direct control, the follower robot mimics the leader robot's movements, which are set by the user. It's not rare for the leader robot (or joystick) to mirror the slave robot's design, ensuring an instinctive user experience(Niemeyer, Günter Preusche, Carsten Hirzinger, 2008).

The ultimate goal of a teleoperation system is to realize "telepresence". This concept goes beyond just allowing users to interact with a robot in the distance, it lets them experience the distant environment as if they were there in person. The operator receives sufficient feedback and sensations that make them feel as though they're physically at the remote location. This experience integrates touch with other sensory perceptions, like sight, sound, and even possibly smell and taste. For industrial manufacturing purposes, telepresence primarily centers on the tactile aspect, which is facilitated by the robotic equipment and the design of HMI. When users feel so immersed that they overlook the intermediary technology, the system is said to be transparent(Niemeyer, Günter Preusche, Carsten Hirzinger, 2008).

The design of the HMI is crucial in bridging the gap between humans and robots and realizing the objective of telepresence in teleoperation systems utilized in production procedures. As shown in Figure 1, an HMI can be divided into two components: control input and feedback. Subsequent sections will provide an overview of present-day teleoperation HMI based on this categorization.

2.1. Control Input of HMI

A major function of the HMI is to accept commands input by the user. With the development of teleoperation over many years, the method of input have been continuously innovated. Depending on the input

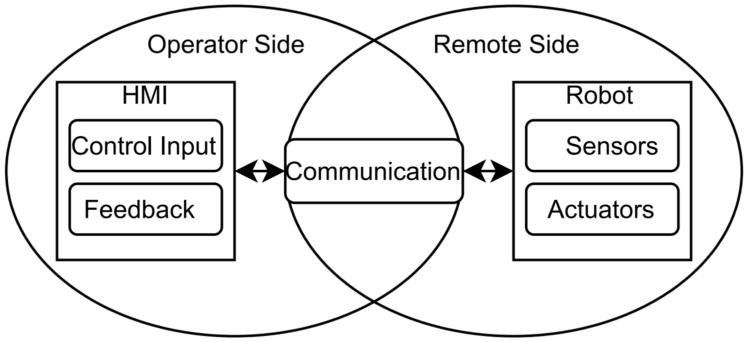

Figure 1: *Teleoperation configuration*(Boboc et al., 2012)

device, they can be roughly divided into two main categories: input based on mechanical devices (such as joysticks, keyboards, etc.) and input based on other modalities(such as visual, auditory, etc.)

2.1.1. Input Based on Mechanical Devices

A common input device for teleoperation HMI is the joystick. When the robot's movements are mapped to the joystick, users can directly guide the robot to specific Cartesian-space or joint-space positions. This allows for immediate control over joint velocity or Tool Center Point (TCP) speed(Niemeyer, Günter Preusche, Carsten Hirzinger, 2008). However, robots typically have more Degrees of Freedom (DoF) than a joystick can offer, meaning a single joystick can't control all robot joints simultaneously. One solution to this problem is to increase the DoF of the input by replacing the joystick with a replicate of the robot. In this setting, the robot replicate on the operator's side is called the leader robot, and the robot on the remote side is called the follower robot. Users can command desired robot pose by moving the leader robot, and the follower robot will follow the movements of the leader. This is one method to allow the user have full control of all the robot joints. Another method is to map the joystick's limited input to a specific set of the robot's DoF, termed a mode. By switching between these modes, users can control various subsets, a technique referred to as modal control. This way, users can also navigate the robot throughout its range, but can't leverage all its DoF concurrently(Herlant, Holladay, & Srinivasa, 2016).

2.1.2. Other Input Modalities

Apart from using mechanical input to control the robot, attempts have been made to adopt new input modalities in teleoperation HMIs. Kofman et al. proposed a vision-based HMI for teleoperation, which recognized the human gesture inputs through a stereo-camera system to manipulate a 6-DoFs robot to accomplish pick-and-place tasks(Kofman, Wu, Luu, & Verma, 2005).Compared to conventional interfaces such as joysticks and leader robot, the vision-based interface allowed the operator to interact with the robot more naturally and required less learning cost. However the drawback of this vision-based interface was also obvious: it required operators to wear markers for visual tracking, which might hinder the motion and operators might get occluded in some highly dexterous tasks(Du & Zhang, 2016). Markerless tracking could be a better option, but existing markerless human-limb tracking methods also face numerous challenges, making their application in robot teleoperation difficult. For example, lime pose recognition without using markers could be complex and time-consuming, and it was difficult to fulfill the real-time control requirements (Du, Zhang, Mai, & Li, 2012)(Du & Zhang, 2016). Therefore efforts have been made to solve this problem by combining visual input with other input signals. Wang et al. proposed an HMI which enables real-time control of a mobile humanoid robot arm in three-dimensional space by estimating the operator's upper limb movement through surface electromyography signals and the vision signals from a Microsoft Kinect sensor(Wang, Li, Ye, & Xie, 2012). Through the electromyography signals even disabled people could give commands to operate the robot(Wang et al., 2012). Du et al. put forwards a novel method combining 3D camera and an inertial measurement unit to determine the lime pose of the operator(Du & Zhang, 2016).

With the development of speech recognition technique, it is now possible to adopt voice command as an input modality in the HMI. Various studies focus on integrating speech recognition techniques into robotic system. In the study conducted by Barkana, a method of speech recognition was created for integrating patient responses into a robot-aided therapy system, achieving an accuracy rate of at least 90% (Barkana, Das, Wang, Groomes, & Sarkar, 2011). Poncela et al. developed an acoustic model for Spanish speakers to teleoperate a robot with a set of commands (Poncela & Gallardo-Estrella, 2015). Andrés Martín-Barrio et al. evaluated the integration of speech recognition in an immersive 3D interface for a hyper-redundant robot's teleoperation and reached the conclusion that using voice commands as control input could help reduce workloads of the operator and it was more user-friendly for operators with little robotic experience (Martín-Barrio, Roldán, Terrile, del Cerro, & Barrientos, 2020).

2.2. Feedback of HMI

For teleoperation applications, the feedback of robot system is crucial for human operators to gain situation awareness and for better robot performance. Some common feedbacks include haptic feedback and vision feedback. With the development of sensors and VR/AR technology, it is now a trend to integrate VR/AR technology into the HMI feedback of teleoperation systems(Moniruzzaman, Rassau, Chai, & Islam, 2022).

2.2.1. Haptic Feedback

Haptic force feedback has been a popular method to enable the operator to sense the interaction between robot and its environment. In order to generate haptic feedback, a haptic output device is required. A typical haptic device is the PS4 Dual-Shock controller, which can send vibration as haptic feedback to the user. In the classical leader-follower configuration, for example, the leader robot can provide haptic feedback. When the follower robot collides with the environment, the leader robot will provide the operator with appropriate force feedback, so that the operator knows the robot's situation intuitively. This is very helpful for teleoperation applications used in tasks where robot-environment-interaction is inevitable, such as assembly and debris retrieval. It can lessen the cognitive burden of the human operator and improve the safety and efficiency of operation (Mizuno, Tazaki, Hashimoto, & Yokokohji, 2023).

Besides leader robots, there are also other haptic devices. D. Brooks et al. proposed a haptic joystick design for mobile robot teleoperation based on a C.H. Products Flight stick (Brooks & Yanco, 2012). Music et al. put forwards a cooperative control framework using wearable haptic fingertip devices(Musić et al., 2019), which reduces the complexity of the leader robot while retaining the controllability of the robot.

2.2.2. Video Stream Feedback

Visual information is one of the most important information the user needs to operate a teleoperation robot. For applications whose remote site is separated from the operator's site with a vision barrier, the vision information is usually obtained through a camera mounted on the remote site and displayed to the operator on the monitor on the operator's site. When obtaining the video stream, the position of the camera determines the viewpoint of vision feedback, which can influence the perception of the operator. In a conventional teleoperation scenario, the camera is placed on the robot, which offers an egocentric view of the environment. An alternative to the ecocentric view is the exocentric view, which is also called third-person view. In such a scenario, the camera is placed somewhere else other than the operating robot on the remote site(Moniruzzaman et al., 2022). The shifting of viewpoint can offer benefits such as reducing the cognitive loads of the operator, but it could be difficult to obtain an exocentric view, especially for teleoperation systems operating in an unknown environment. One solution to this is to deploy other mobile robots to provide extra views, such as drones(Claret, Zaplana, & Basañez, 2016). For teleoperation specified for manufacturing purposes, however, obtaining an exocentric view is much easier. Because the manufacturing environment is known to the system, there are plenty of choices for camera position.

Besides video stream, visualized data such as force and robot position can also serve as useful visual feedback. A. Reveleu et al. designed a 3D interface where the interaction force between the robot and environment was visualized as graphic bars with varying colors and size (Reveleau, Ferland, Labbé, Létourneau, & Michaud, 2015). Compared to haptic force feedback, visualized force data can provide more accurate information for the user to process and thus enhance the performance of the teleoperation(Reveleau et al., 2015).

2.2.3. Virtual Reality and Augmented Reality

Virtual Reality (VR) refers to the creation or simulation of an environment that might not accurately replicate the real physical world. It enables a teleoperator to experience the environment of a robotic platform with high perceptual awareness(Moniruzzaman et al., 2022). Additionally, Augmented Reality (AR) is also considered a form of VR, in which 3D virtual objects are integrated into a 3D real environment in real-time(Azuma, 1997). The concept of VR and AR has been around since the 1960s, but has not been widely studied in the field of teleoperation until the last decade. This is due to the recent maturation of commercial VR devices. Compared to traditional video stream feedback displayed on 2D monitors, VR devices can provide a more immersive user experience, further reducing the cognitive load of the user, and allowing the user to interact more naturally with the robot at the remote side in the 3D VR space (Wonsick & Padir, 2020). VR/AR feedback in teleoperation applications can be achieved by 3D reconstructing a virtual environment based on the data collected by robot sensors and displaying the virtual environment using commercial VR devices such as VR headset(Moniruzzaman et al., 2022).VR environment becomes beneficial when a remote environment is unknown but can be modeled, it is therefore suitable for teleoperation tasks such as underwater exploration and navigation. In the last decade many studies have been focusing on the integration of teleoperation and VR, Murphy Wonsick classified them into 5 main categories: visualization, robot control and planning, interaction, usability, and infrastructure(Wonsick & Padir, 2020). Among these 5 categories, visualization, interaction, and usability are closely related to teleoperation HMI design. The visualization category aims to find the most effective ways to display visual information on VR devices, enhancing the user's situational awareness(Brizzi et al., 2018)(Kohn et al., 2018)(Wonsick & Padir, 2020). Research in the interaction category is dual-focused, exploring both innovative techniques for VR-based robot control and identifying optimal interaction methods(Wonsick & Padir, 2020). Finally, the usability group emphasizes improving user experience by comparing traditional robot interfaces with VR interfaces(Wonsick & Padir, 2020).

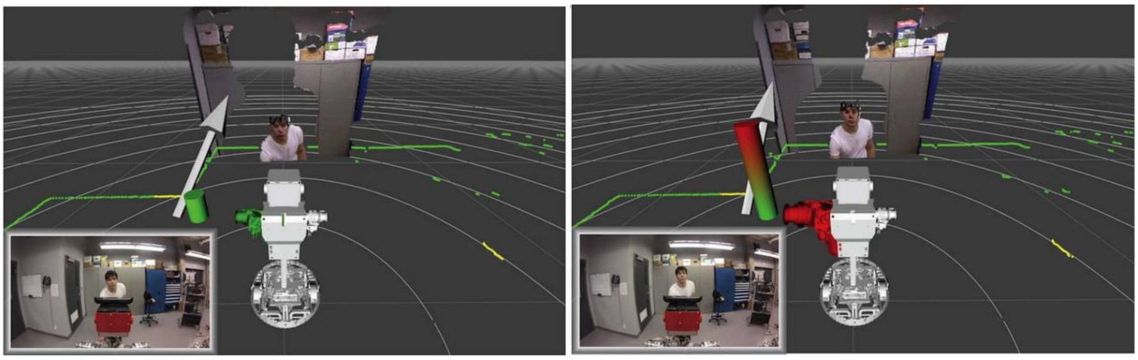

Figure 2: *The visualization of interaction force as bar graphs and arrows of varying colours and sizes based on their intensity.*(Reveleau et al., 2015)

3. HMI Design and Implementation

To answer the research question, the first step is to implement a new teleoperation HMI based on the available resource in the lab - a PlayStation4 dual-shock 4 game controller (PS4 controller). This chapter discusses the HMI design and implementation details. The structure of the chapter is as follows: first the overall design goal and design requirements of the HMI are defined in Section 3.1. The information on the teleoperation hardware for HMI is introduced and the choice of the robot control algorithm is considered in Section 3.2 and Section 3.3. After that, Section 3.4 and 3.5 closely discuss the new HMI concept and its software implementation using Python, followed by Section 3.6 discussing how to improve the HMI's motion performance by parameters optimal design. In the end, the last Section 3.7 provides an overview of the newly designed HMI.

3.1. Design Goal and Design Requirements

Based on the research question, the **design goal** of this teleoperation HMI can be formulated as this:

- **Design an HMI, with which any user without robotics knowledge can easily learn to operate and use to accomplish simple parts assembly tasks such as pick-and-place and peg-in-hole efficiently.**

This goal can be further broken down into the following **design requirements**:

1. The user can demand the robot gripper to move to a desired position with sufficient accuracy.
2. The user can demand the robot the gripper to rotate to a desired orientation with sufficient accuracy.
3. The user can control the robot gripper to grasp and release parts.
4. During the assembly process, the applied force and torque should be moderate and controllable, so that neither the robot nor the parts will be damaged.
5. The robot movement control interface should be simple and intuitive.
6. The information related to the robot's internals that users need to deal with should be minimized as much as possible.

The first 4 requirements are the basics for parts assembly, and last two requirements are to make the teleoperation application easy to use for non-expert users.

3.2. Equipment

A PlayStation4 dual-shock 4 game controller is chosen as the hardware for the new HMI. It provides 13 buttons for binary inputs, two joysticks, and two buttons for analog inputs. Besides, the robot on the remote side is a 7 DoFs robot from Franka Emika Robotics GmbH. It has a gripper with two parallel fingers, which are capable of grasping objects with diameter smaller than 80mm. These two equipments are shown in Figure 3.

(a) The PS4 game controller **(b) The Franka Emika Panda Robot**

Figure 3: The PlayStation4 dual-shock 4 game controller

3.3. Robot Control Algorithm

Currently, there are many mature robot control algorithms. These can be categorized based on the control space, into joint space control and Cartesian space control. Joint space control involves direct control over each robot joint's variables (such as position, torques, etc.), whereas Cartesian space control pertains to managing the state of the robot's end-effector within the Cartesian coordinate system. Additionally, depending on the type of variable being controlled, control algorithms can also be classified into position control, force control, and mixed control, which is a combination of position control can force control, including impedance control and admittance control. Considering the design requirements from the last section, the **Cartesian impedance control** is chosen for the new HMI . The reasons are as follows:

1. Cartesian impedance control satisfies design requirements 1 and 2.

2. Compared to joint space control, Cartesian space control is preferred because the assembly task is defined in Cartesian space, and the user can directly command Cartesian poses without un-

derstanding the complex transformation of inverse kinematics of the robot, thus satisfying design requirements 5 and 6.

3. Impedance control is a combined control of position and force. This concept is akin to controlling the relationship between force and motion, akin to the way a spring-damper system behaves. It makes the robot's movement feel more natural and compliant when it comes into contact with something, rather than rigid or unyielding. It can prevent damage to the robot and the interaction object during contact, thus it satisfies design requirements 4.

3.4. HMI Concept Design

Starting from the requirements 1-4, the HMI should at least have the following functions:

- **End-effector translation function**.
- **End-effector rotation function**.
- **End-effector grasp and release function**.
- **Error recovery function**.

The first three functions are sufficient to accomplish a simple assembly task. However, regarding the specific robot deployed in the study, an extra **error recovery function** is required. This is because the Franka Emika Panda robot has a self-protection mechanism. When the torques of the robot joints reach a preset limit, an internal reflex error will be triggered and the robot will stop moving to avoid potential damage. In the parts assembly process, the interaction between the robot and the environment may result in unforeseen large joint torques and trigger the reflex error, in this case user has to evaluate the robot's operating condition and recover the robot from error mode. That is when the error recovery function is needed.

The next subsections will discuss the design details of these four functions.

3.4.1. End-effector translation function design

An assembly task usually involves translation movements in 3 directions: X, Y and Z. According to requirement 1, the user should be able to give accurate demands for a desired position in Cartesian space. Thus at least 3 independent inputs on the PS4 controller are needed for this function. Design requirement 1 emphasizes accuracy in position control, which is important for assembly tasks. In this aspect, analog inputs are preferred over binary inputs. Because analog inputs can define finer movements, this makes more precise operations possible. The analog inputs on a PS4 dual-shock4 game controller include two joysticks, which provide 4 independent analog signals, and two analog buttons (L2 and L3). Considering requirement 4, the two joysticks are chosen as position inputs. The only question that remains is how to assign the 3 translational movement commands to 4 independent joystick inputs. The possible assignment combinations are listed in table 1 as follows:

Table 1: Possible assignment combinations

Option	Left joystick	Right joystick
1	X,Y	Z
2	X,Z	Y
3	Y,Z	X
4	Z	X,Y
5	Y	X,Z
6	X	Y,Z

Which of the 6 options is more intuitive is a subjective question. This thesis does not go into the details of this question but simply chooses option 1 as the final assignment. If other options can lead to better HMI performance could be a future research question.

After the assignment, the relationship of the analog input signal of the joystick j_x, j_y, j_z and the corresponding desired TCP velocity output v_{x_d}, v_{y_d}, v_{z_d} can be written as:

$$v_{x_d} = f(j_x) \tag{3.1}$$

$$v_{y_d} = f(j_y) \tag{3.2}$$

$$v_{z_d} = f(j_z) \tag{3.3}$$

Where $j_x, j_y, j_z \in [-1.0, 1.0]$, and $f(x)$ can be an arbitrary strictly increasing function. The design of the function $f(x)$ will be discussed in Section 3.6.

3.4.2. End-effector rotation function design

Unlike 3D translation movement, commanding 3D rotation movement can be a complex process. To simplify the HMI while retaining the basic functionality of rotation, only one direction of rotation is implemented in this thesis, that is, the rotation around the Z axis. This is sufficient for certain simple assembly tasks. Similar to the translation function, the rotation function also requires accuracy. So the two analog buttons L2 and R2 are chosen as the Z rotation inputs. The relationship between the desired robot end-effector rotation speed ω and the two analog input signals l_2, r_2 is as follows:

$$\omega_d = 0.03(l_2 - r_2) \tag{3.4}$$

The proportional coefficient of 0.03 is chosen by experience. An optimal design for this parameter could be a future research topic.

3.4.3. End-effector grasp and release function design

The grasp and release function is a logical function, so it is enough to use binary input buttons to define these two actions. The X button is chosen as the trigger for the grasp action, and the O button for the release action. When the X button is pressed, the grasp action starts. The two gripper fingers will move at a given speed toward each other, and exert a predefined grasp force when they contact any object during the process. A grasp action is successful if the grasping force reaches a predefined value and the position of the fingers lies within a predefined interval. The fingers will continue exerting this predefined grasping force on the grasped object until a release action is called. When the O button is pressed, the release action starts. The two gripper fingers will move at a given speed toward a predefined starting position. A release action is successful if the position is reached with predefined accuracy. The fingers will stop moving when the action is completed. Figure 4 illustrates the control logic of the grasp-release function interface.

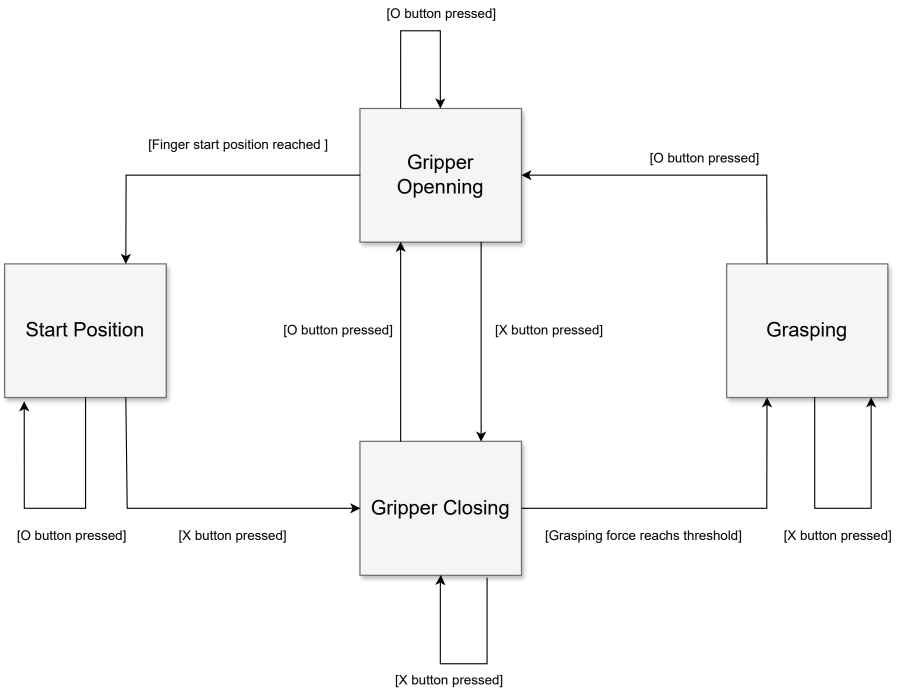

Figure 4: The flow chart of grasp and release function

3.4.4. Error recovery function design

The error recovery function is also a logical function. Only one binary button is needed for this function. Once the button is pressed, the software interface will launch a restart signal to the robot and recover it from the error state. The PS4 controller already provides a start button for turning on/off the PlayStation. So it is natural to adopt this button for the error recovery function. The button is shown in Figure 16 in Section 3.7.

3.5. HMI Software Implementation

The implementation of HMI is done using the Robot Operating System (ROS) in Ubuntu 20.04 environment. There are already existing ROS packages for interaction with the PS4 controller as well as the Franka Emika Panda robot (Joy, franka_ROS), so the task of this thesis is to create an HMI ROS package to incorporate with the existing ROS packages that communicate with each other through ROS topics. The software structure of the teleoperation system is illustrated in Figure 5. The ROS package Joy can collect the keypad signals sent from the PS4 controller and publish them in the form of ROS message in the ROS topic joy. The HMI package subscribes to this topic and processes the data, eventually sending the corresponding robot action message to the robot ROS topics at a frequency of 100 Hz. The franka_ROS package subscribes to the robot ROS topics and sends the final control signals to the robot.

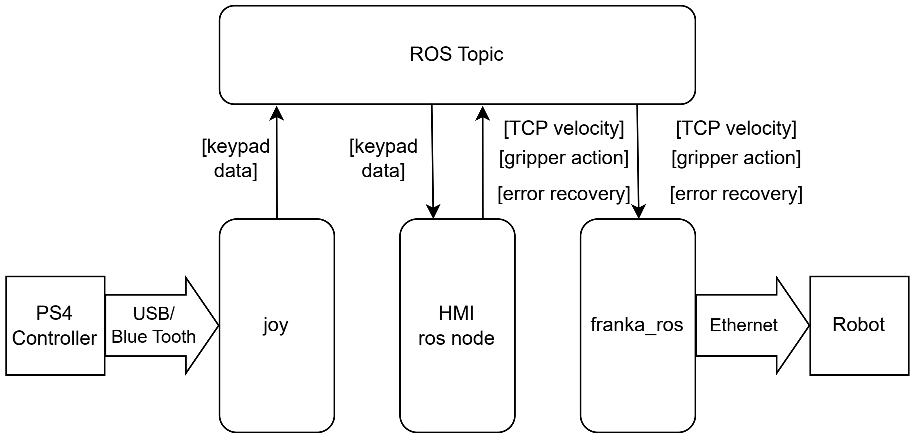

Figure 5: The HMI software structure

To realize the HMI functions defined before, a new HMI interface package has to be created, and the franka_ROS package also has to be modified to incorporate the new HMI interface package.

3.5.1. HMI interface package

This package is written in Python. It contains the following 3 types of functions: subscriber, data processor, and publisher. The subscriber receives the keypad data through ROS topic and passes them to the processor, the processor handles the data according to the logic of the 4 HMI functions and reformulates them into the message data type for the robot. In the end, the publisher publishes the data to the ROS topic. The whole process is illustrated in Figure 6 .

3.5.2. Franka ROS package

This meta-package is provided by Franka Robotics GmbH . It integrates the C++ implementation of the Franka Emika robot control interface with ROS and ROS control (FrankaRoboticsGmbH, 2023). It provides ROS nodes such as the gripper control node and the error recovery node, which can be easily utilized in the teleoperation system through ROS topic. A Cartesian position impedance controller is also available in the franka_ROS package, but it needs to be modified to integrate with the teleoperation system. Figure 7 illustrates this process. First, a new subscriber is implemented to receive the commands sent from the

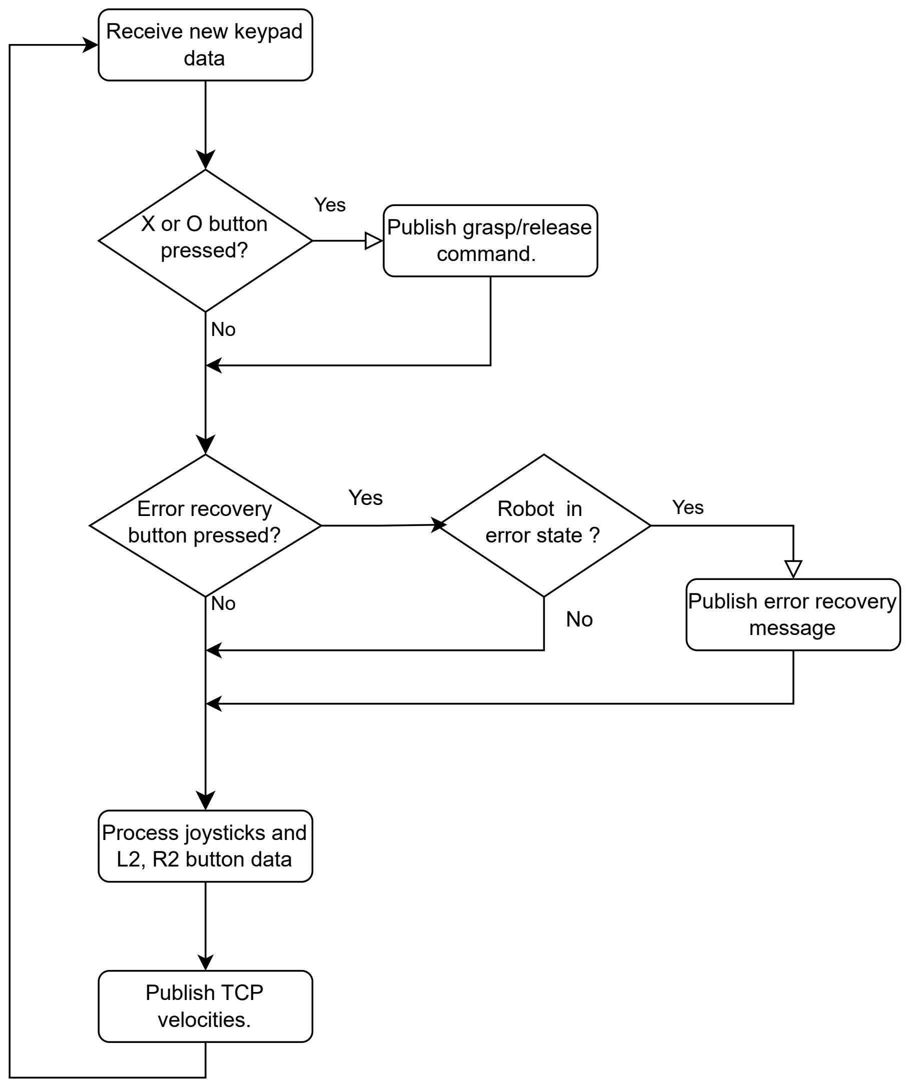

Figure 6: The HMI flow chart

HMI ROS node. Because the commands are TCP velocities, they have to be integrated to obtain the desired position and orientation of the robot end effector. To avoid collision and violation of the joints limit, a boundary check is implemented before the position and orientation values are passed to the control loop.

3.6. HMI Parameters Optimization

The framework of the new teleoperation HMI has been completed, the only design problem that remains is deciding the parameters for the HMI velocity control function $f(x)$, that is, deciding the relationship between the joystick input and the velocity output. The design goal requires the HMI to be capable of accomplishing peg-in-hole tasks efficiently. Peg-in-hole tasks require a minimum accuracy in robot movement. Thus, the parameter design problem can be treated as an optimization problem: optimization of motion control efficiency while meeting the minimum accuracy requirements. The idea behind the parameter optimization is that by changing the parameters of the control function $f(x)$ and observing

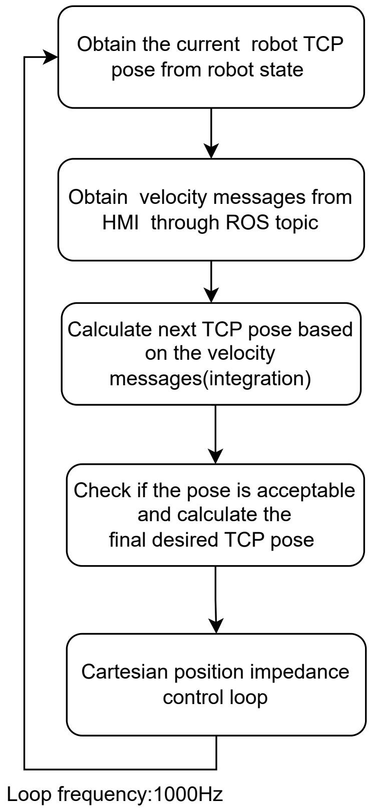

Figure 7: Thw integration between HMI and Franka ROS package

its influence on the robot motion's efficiency and accuracy, it can be determined which parameters are optimal for the new HMI. To do this, the variable $f(x)$ has to be defined, and a task has to be designed to evaluate the system's efficiency and accuracy. An experiment will be conducted to study the influence of the variable on the system. The results of the experiment will provide insight into designing the final control function.

3.6.1. Variable

The variable of this study is the function $f(x)$. Because it is a control function for the HMI, it needs to meet the following designed requirements:

- $f(x)$ has to be a strictly increasing function. Because the commanded TCP velocity shall always increase or decrease when the joystick is dragged in one direction.
- $f(x)$ has to be continuous in $[-1.0, 1.0]$. Because discontinuity of the function $f(x)$ may lead to abrupt changes in the TCP velocity and make it difficult to control.
- $f(x)$ has to be an odd function. Because the system's behavior should be symmetric concerning movement direction.

There are many choices of $f(x)$ that satisfy the above-mentioned requirements. Among them, the simplest one is the linear function:

$$f(x) = kx \tag{3.5}$$

Choosing the linear function as the control function offers the following advantages:

- Single variable. There is only one unknown parameter k in the linear function. The study of the influence of a single parameter on the system is easier than that of multiple parameters.
- It provides insight into the influence of the derivative on the controllability of the system. Because the parameter k is also the first derivative of k, understanding how the first derivative influences the system can be useful for designing more complex control functions.

For these reasons, the linear function $f(x) = kx$ is chosen as the control function for this experiment.

3.6.2. Evaluation Task

The task needs to be capable of evaluating both the accuracy and efficiency of the motion function of the HMI. A trajectory-tracking task can satisfy this requirement. To make the task simple, the goal trajectory is defined by 3 cylinder obstacles as shown in Figure 8. The task is to control the robot TCP through the HMI to follow the given trajectory without knocking out any of the three obstacles. The accuracy can be evaluated by adjusting the distance x between the obstacles and recording the successful rate of the task; the efficiency can be evaluated by the time needed to finish the task.

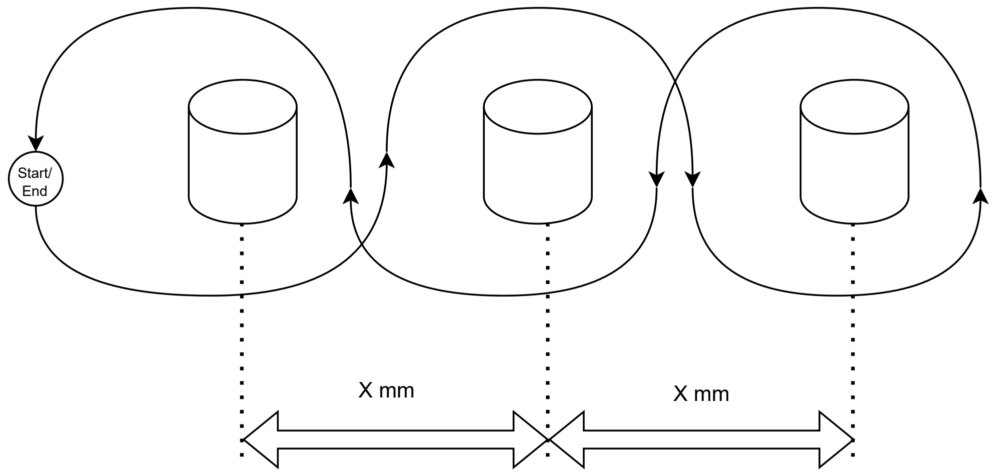

Figure 8: Evaluation task for robot motion control efficiency and accuracy

3.6.3. Experiment

Setting

The experiment settings are shown in Figure 9 and 10. The distance x between each cylinder is set as $200mm$ and $50mm$, testing the HMI control efficiency for both low-accuracy and high-accuracy scenarios. The robot grasps a pencil during the whole experiment process, whose tip represents the TCP. Out of experience and safety considerations, the test range of parameter k is chosen between $0.01m/s$ and $0.03m/s$.

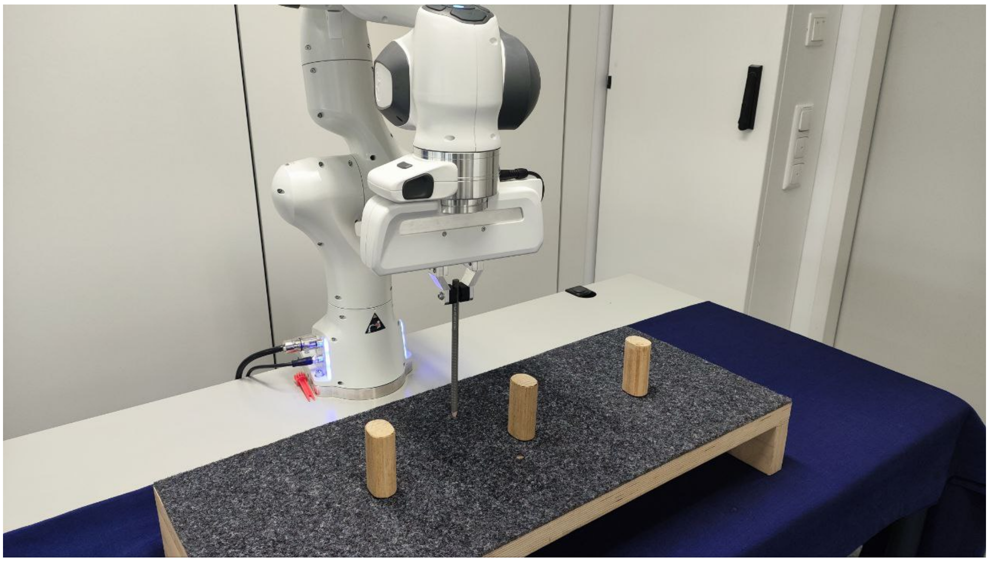

Figure 9: Experiment setting x = 200 mm

Figure 10: Experiment setting x = 50 mm

Participant

Because of time limitations, the author of this thesis is the only participant in this experiment.

Experiment Process

The experiment process is shown in Figure 11. To reduce the influence of the learning effect on the results, the experiment will first start from $k = 0.01$ and increase to $k = 0.03$; after that, it will start from $k = 0.03$ and decrease to 0.01 to measure the data again.

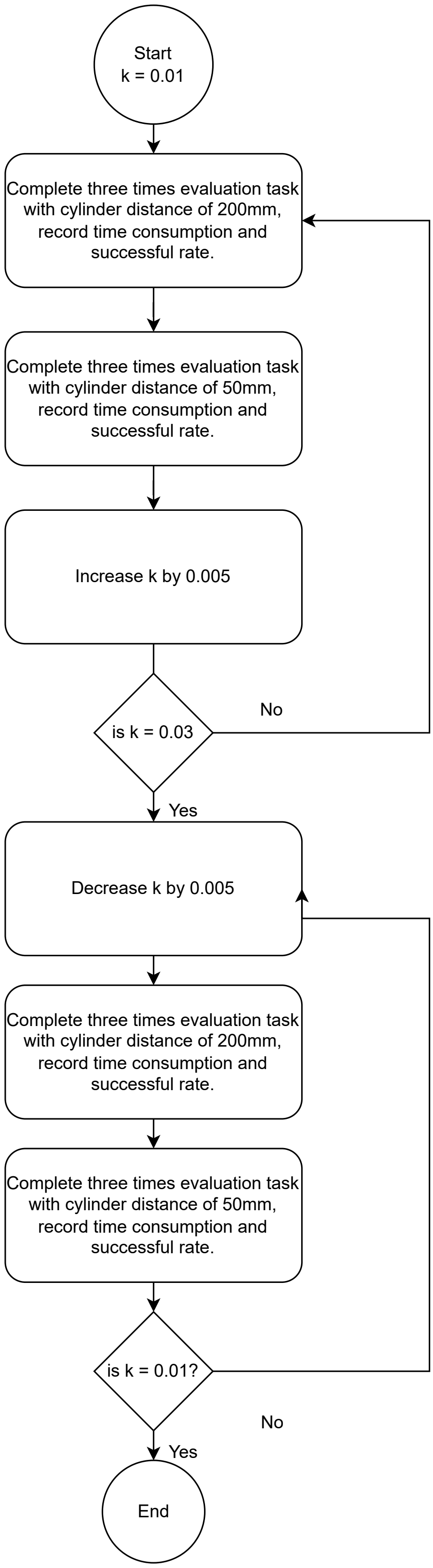

Figure 11: Evaluation task procedure

Results and Analysis

The data measured in the experiment is shown in Figure 12 and 13. As the parameter k increases, the completion time for the low-accuracy task drops, but for the high-accuracy task there is no significant change. However, the successful rate drops significantly for the high-accuracy task when k exceeds $0.02m/s$. The reason behind this phenomenon can be that when k is large, the maximum velocity output is also large. When the task required accuracy is low, larger output velocity leads to higher efficiency; however, larger k means that the first derivative of the control function is larger, and the output velocity will be more sensitive to the changes of the input signals, resulting in difficulty in performing accurate movements.

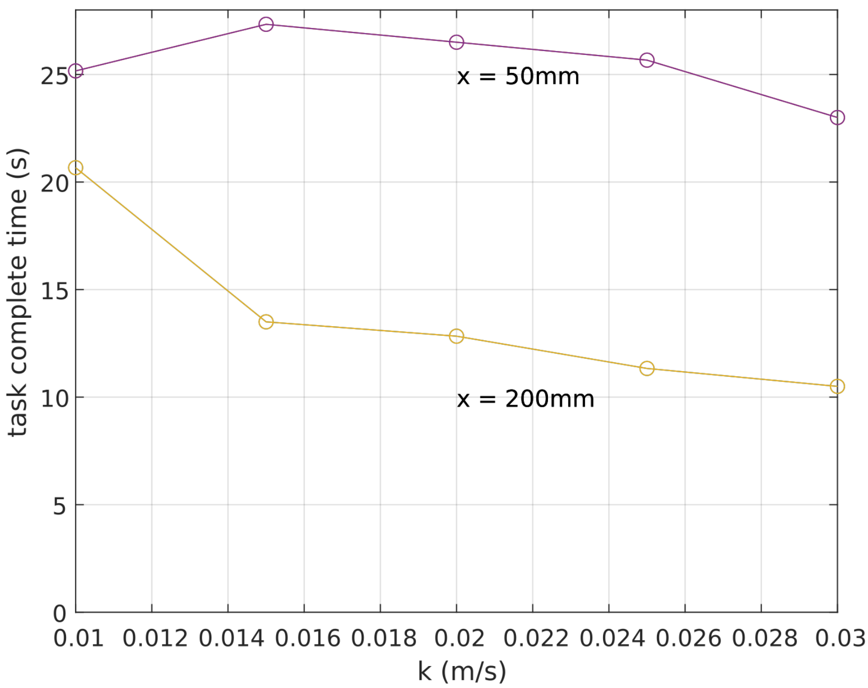

Figure 12: Relationship between k and task completion time

3.6.4. Control Function Design

The design goal of the HMI is for assembly tasks, which usually involve robot movements of different accuracy levels. Using a linear function as the control function is simple and intuitive, but it may not be suitable for tasks involving different levels of accuracy. A solution to this is designing a new control function with varying derivatives. The function shall begin with a small derivative to facilitate highly accurate movements and end with a larger velocity value to achieve higher efficiency for movements that don't require high accuracy. According to the results, $k = 0.01$ achieves the best performance for the high-accuracy task, while $k = 0.02$ (maximum velocity is $0.02m/s$) achieves the best performance in both efficiency and successful rate for the low-accuracy task. To design a control function combining these two features, the following boundary conditions need to be fulfilled:

- $f(0) = 0$

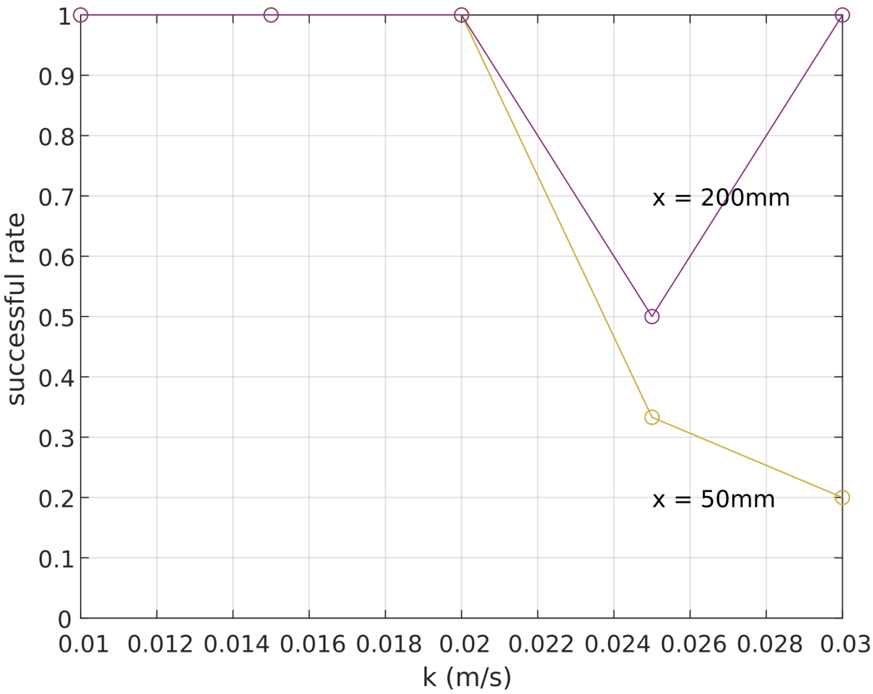

Figure 13: Relationship between k and task successful rate

- $f'(0) = 0.01$
- $f(1) = 0.02$
- $f(-1) = -0.02$

According to the Weierstrass Approximation Theorem, any continuous real-valued functions on a compact interval can be uniformly approximated by polynomials(Stone, 1937). The interval of interest of the control function is $[-1, 1]$, so theoretically it can be written in the form of polynomials:

$$f(x) = a_n x^n + a_{n-1} x^{n-1} + \ldots + a_1 x + a_0 \tag{3.6}$$

The first derivative of $f(x)$ is:

$$f'(x) = n a_n x^{n-1} + (n-1) a_{n-1} x^{n-2} + \ldots + a_1 \tag{3.7}$$

Using the boundary conditions, we have:

$$\begin{aligned} a_0 &= 0 \\ a_1 &= 0.01 \\ a_n + a_{n-1} + \ldots + a_1 &= 0.02 \end{aligned}$$

According to the design requirements, $f(x)$ is a strictly increasing odd function, we also have:

$$f'(x) > 0 \text{ for } -1 \leq x \leq 1$$
$$f(x) = -f(-x)$$

which leads to

$$a_0 = a_2 = a_4 = \ldots = a_k = 0 \tag{3.8}$$

where $k = n$ if n is an even number, $k = n - 1$ if n is an odd number. When $n > 3$, there are infinite solutions for $f(x)$. However, if we consider the situation of $n = 3$, there is only one solution:

$$f(x) = 0.01x^3 + 0.01x \tag{3.9}$$

This polynomial function can meet the boundary conditions with the minimal polynomial degree. It is an optimal balance between simplicity and compliance with the given constraints. Figure 14 illustrates the 3 control functions. The quadratic control function combines the advantages of the other two linear functions: a small derivative at the beginning to facilitate accurate control and a large maximum velocity output to enable efficient movements.

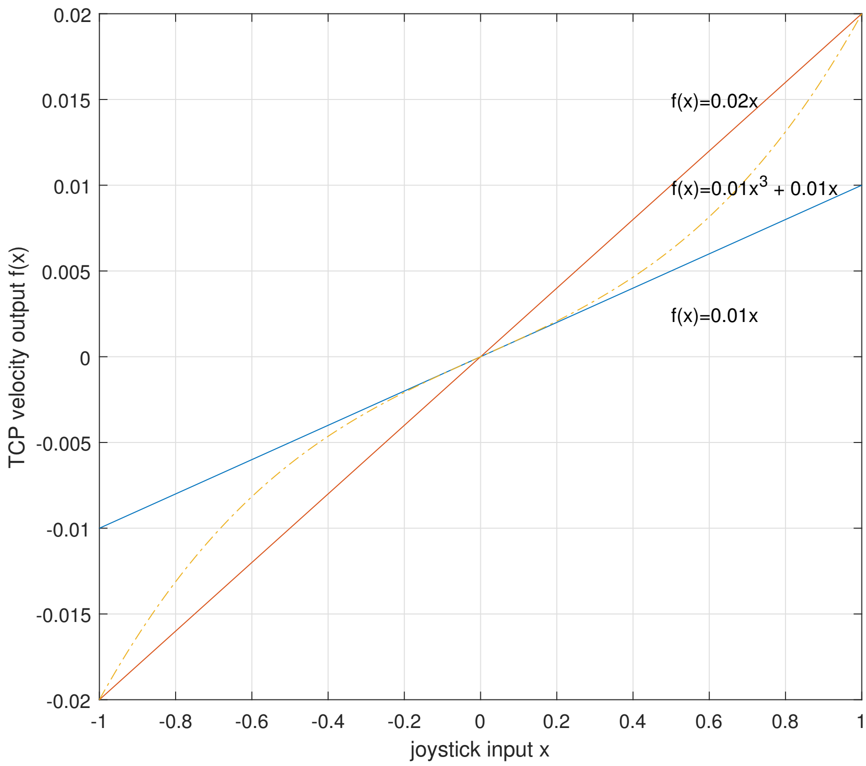

Figure 14: comparison of different control function $f(x)$

3.6.5. Validation

To check the performance of the newly designed control function, the same experiment is repeated again for the new control function. Figure 15 below illustrates the results. The new control function achieves almost the same performance for the low-accuracy task as the linear function with $k = 0.02$. And for the high-accuracy task, the time cost of the three functions are similar, with $f(x) = 0.01x$ and $f(x) = 0.01x^3 + 0.01x$ slightly better than $f(x) = 0.02x$. As for the successful rate, all three are 100%, but the control experience of $f(x) = 0.01x$ and $f(x) = 0.01x^3 + 0.01x$ are more relaxed, while with $f(x) = 0.02x$ the controlling experience is more tensed because the system reacts more abruptly. Due to the limited number of samples and participant, it is currently impossible to rigorously verify whether the new design control function has advantages over others. This could become one of the future research topics.

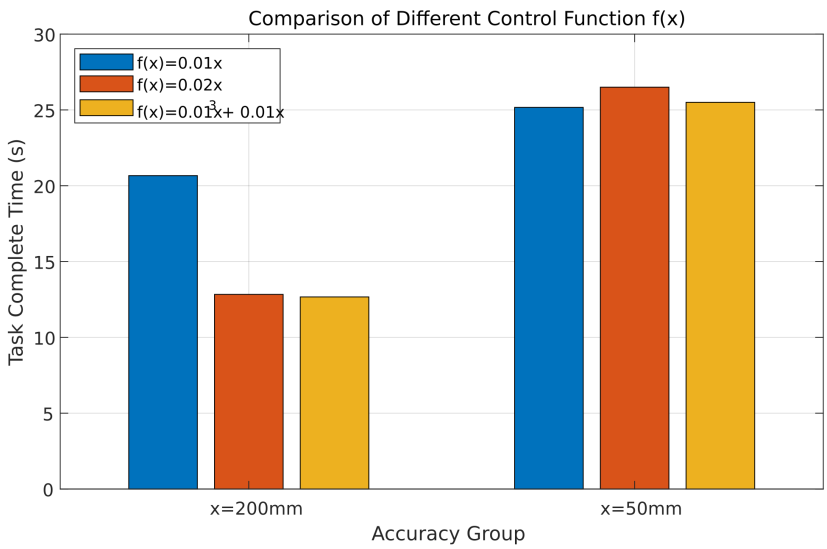

Figure 15: Validation of the new designed $f(x)$

3.7. HMI Final Design Overview

As the conclusion of this chapter, this section provides an overview of the newly designed HMI. The table 2 and Figure 16 shows the layout and function description of this HMI. All the buttons used in the interface are marked in Figure 16. And the coordinate system used for the robot is also defined in Figure 16.

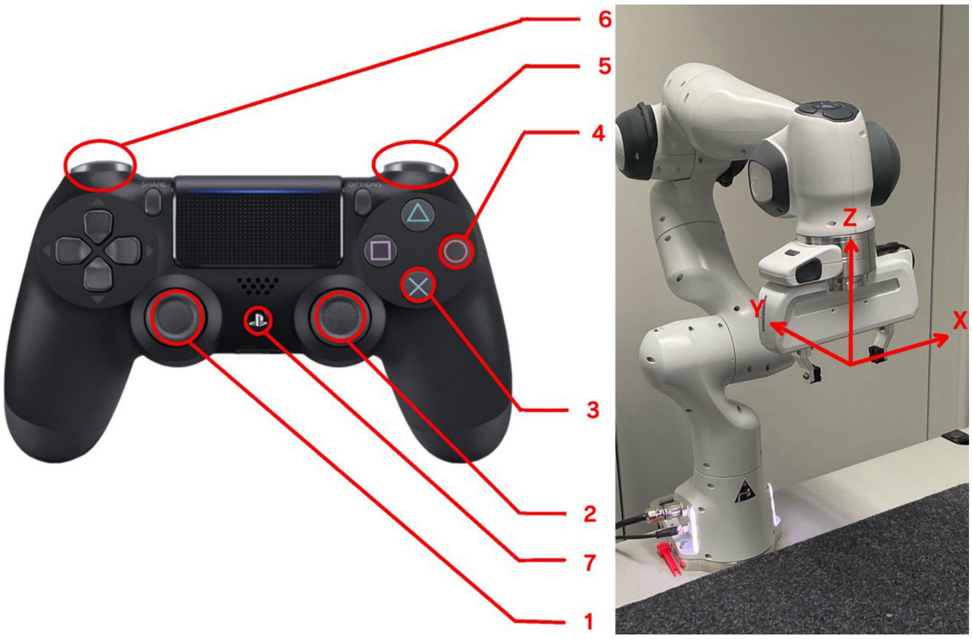

Figure 16: The layout of the PS4 controller-based HMI and the definition of the coordinate system of the robot. A closer description of the button functions is listed in table 2.

Table 2: The new HMI Function Description

Button Number	**Function Description**
1	Left joystick, controlling the translation motion of the robot TCP in X and Y directions.
2	Right joystick, controlling the translation motion of the robot TCP in Z direction.
3	X button, controlling the gripper to grasp.
4	O button, controlling the gripper to release.
5	R2 button, controlling the gripper to rotate in negative Z direction.
6	L2 button, controlling the gripper to rotate in positive Z direction.
7	Restart button for robot error recovery.

4. User Study Design

This chapter deals with the second task of this thesis, which involves designing a within-subject user study to verify whether the new PS4 controller HMI shows improvements in performance and workload compared to the previous leader-follower HMI . Prior to conducting the user study, three sets of hypotheses were formulated:

- **Null Hypothesis 1:** The PS4 controller HMI is equivalent to or better than the leader-follower HMI in terms of objective performance.
- **Alternative Hypothesis 1:** The PS4 controller HMI performs worse than the leader-follower HMI in terms of objective performance.
- **Null Hypothesis 2:** The subjective workload associated with the PS4 controller HMI is equivalent to or less than that of the leader-follower HMI.
- **Alternative Hypothesis 2:** The subjective workload associated with the PS4 controller HMI is greater than that of the leader-follower HMI.
- **Null Hypothesis 3:** The PS4 controller HMI is equivalent to or better than the leader-follower HMI in terms of perceived system usability.
- **Alternative Hypothesis 3:** The PS4 controller HMI performs worse than the leader-follower HMI in terms of perceived system usability.

To validate these hypotheses, it is necessary to first define the metrics for assessing performance, workload and usability, design tasks to collect data that can be used for evaluation, and verify the hypotheses through the data collected.

This chapter is structured as follows: it begins by introducing the variables used in the study in Section 4.1, including the independent variables, which are the two HMI configurations—the Leader-Follower and PS4 Controller setups. It then outlines the dependent variables that measure system performance, workload, and usability. The chapter proceeds to discuss the equipments, recruitment and ethical considerations for the participants involved in the user study in Section 4.2, Section 4.3 and Section 4.4. Finally, Section 4.5 and Section 4.6 detail the experiment procedure, briefly describing the setup, tasks, and data collection methodology, ensuring a clear understanding of how the study will be conducted to evaluate the effectiveness of the HMIs.

4.1. Variables

4.1.1. Independent Variables

We want to evaluate the performance of new HMI, so the HMI of the teleoperation system is set as the independent variable of this study. There are two kinds of HMIs adopted in the user study.

1. **HMI 1: Leader-Follower Configuration**:In this configuration two Franka Emika robots are used. The user can control the follower robot to do assembly tasks in the remote site by moving the leader robot in the local site. The movements of the follower robot are synchronized with the leader. And the interaction force of the follower robot with the environment will sent back to the user through the leader follower as haptic feedback. Figure 17 shows the experiment setting of this configuration.

2. **HMI 2: PS4 Controller Configuration**:In this configuration, The user can control the robot in the remote site using a PS4 controller. Figure 18 shows the experiment setting of this configuration.

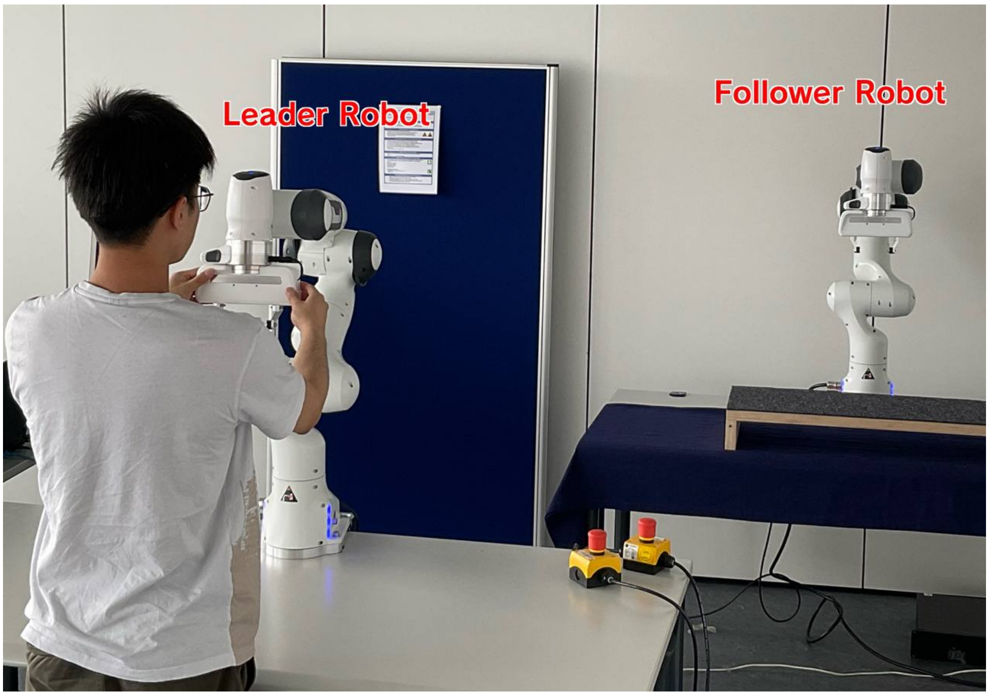

Figure 17: HMI1: The user can move the leader robot to control the follower robot.

4.1.2. Dependent Variables

The dependent variables in this study are the objective performance of the system, subjective workload of the participants and perceived usability of the system.

1. **Objective Performance**: Task Completion Time (TCT) is chosen as the main objective metric for measuring the performance of the HMI. This is because TCT has frequently been used as an evaluation metric in previous experiments involving the same teleoperation system (Prinz & Bengler, 2023) (Prinz & Bengler, 2024). In addition to TCT, grasp attempts and drop attempts are also used

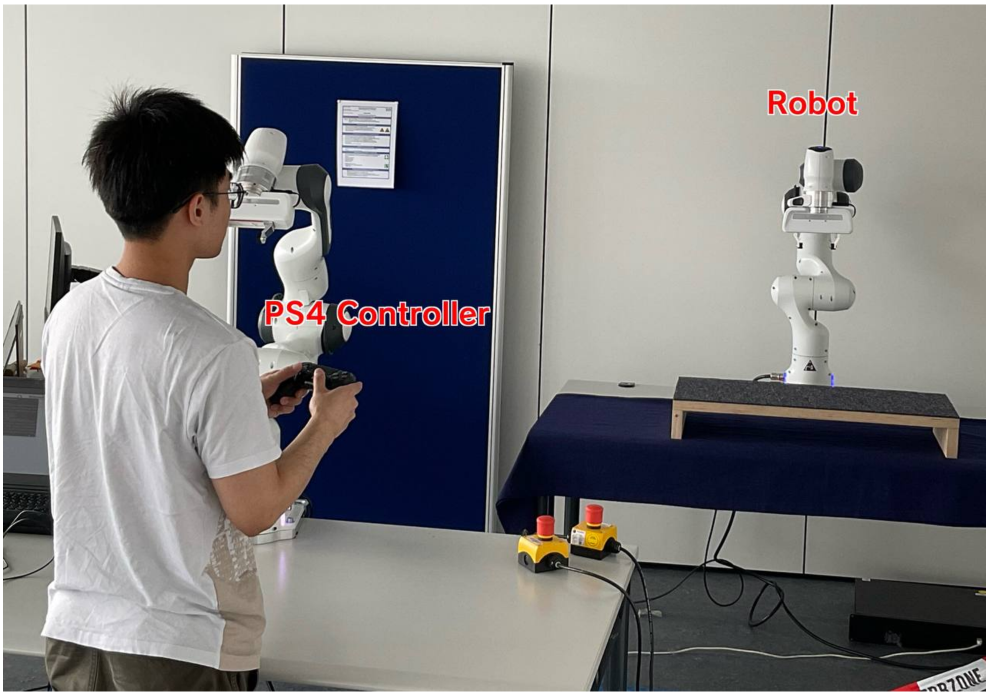

Figure 18: HMI2: The user can use a PS4 controller to control the robot.

as reference metrics to evaluate HMI performance, which are described in more detail in Chapter 6.1.

2. **Subjective Workload**: The subjective workload is measured through the NASA Task Load Index (NASA-TLX), which is a widely used tool designed to assess subjective workload experienced by individuals when performing various tasks. Developed by the Human Performance Group at NASA's Ames Research Center, this multidimensional scale evaluates workload through six key dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration level. By allowing participants to rate these aspects on a scale and subsequently weighting the scores according to their perceived importance, NASA-TLX provides a comprehensive measure of the overall workload (Human Performance Research Group, 1986). This tool has been extensively utilized in research across diverse fields, including aviation, healthcare, and human-computer interaction, to understand how different tasks impact human performance and workload.

3. **Perceived Usability**: The perceived usability is measured by the System Usability Scale (SUS), which is a tool for assessing the usability of various systems and products. Developed by John Brooke in 1996, this questionnaire consists of 10 items that evaluate user satisfaction and the usability aspect of a system. The SUS provides a global view of subjective assessments of usability, including aspects such as the effectiveness, efficiency, and satisfaction with which specified users can achieve specified goals in particular environments(Brooke, 1996). The simplicity and versatility of the SUS make it a popular choice across different types of user interfaces.

4.1.3. Other obtained data

In addition to the aforementioned independent variables and dependent variables, this user study also collects other data, including participant personal information (age, gender, vision), technical affinity, experience with teleoperation and game controllers, robot movement trajectory, intervention circumstances, and additional feedback. The methods for collecting these data are listed in Table 3. The influence of some of this data on the aforementioned dependent variables will not be discussed in this thesis but could potentially serve as subjects for future research.

Table 3: Data collection methods and measurements

Measurement	**Method**
Personal Data via Demographic Questionnaire	
Personal data: Age, gender, vision	Demographic questionnaire
Technical affinity	Standardized questionnaire: Affinity for Technology Interaction (ATI)
Experience with teleoperation system	Questionnaire
Experience with PS4 controller and similar devices	Questionnaire
Objective Data via Measurements	
Task Completion Time	Measurement from video recording
Grasp and drop attempts	Measurement from video recording
Intervention circumstances	Documented from Video recording
Robot movement trajectory	Accessed through Franka Control Interface
Subjective Data via Questionnaire	
Workload (subjective assessment)	Standardized questionnaire: NASA Task Load Index (NASA TLX)
System usability	Standardized questionnaire: System Usability Scale (SUS)
Subjective Data via Interview	
Additional feedback	Questions by the experimenter

4.2. Hardware Setup

In this user study, two different HMIs were tested, each associated with distinct hardware setups. As shown in Figure 19, HMI1 utilizes a leader-follower configuration, which requires two Franka Emika Panda 7 DoFs robots. Each robot is controlled independently by a laptop, and the two robots communicate via a connected Ethernet local area network. Robot1 is operated by a participant as the leader robot, while Robot2 is the follower robot responsible for completing the experimental tasks. The entire experiment is recorded by two cameras from different angles. Figure 20 shows the setup for HMI2, which is controlled by a PS4 controller linked to a remote robot, with both the robot and the PS4 controller connected to the same laptop. Similarly, the entire experimental process is also recorded by two cameras from different perspectives.

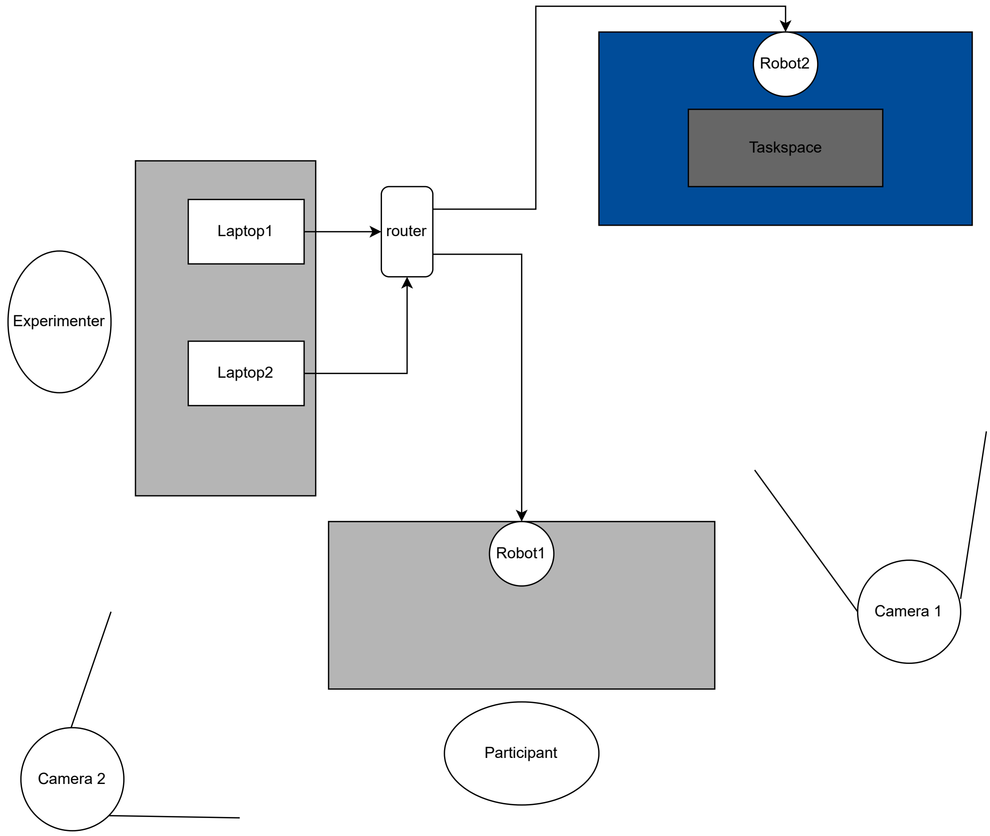

Figure 19: The experiment equipment setup for HMI 1.

4.3. Participants

This user study requires the recruitment of at least 32 participants. The requirement for participants is that they must be at least 18 years old. For safety reasons, pregnant women are not included in the recruitment for this study.

4.4. Ethic Statements and Safety Considerations

This research followed the ethical standards of the Declaration of Helsinki and met local regulatory requirements in Bavaria, Germany. All participants provided written informed consent. The Ethics Committee of the Technical University of Munich reviewed and approved the study involving human subjects, assigning it the reference number 2024-21-NM-KH without any objections, ensuring the study's compliance with ethical and legal standards. The teleoperation system is designed with a strong emphasis on safety, ensuring minimal risks during use. The robots are fixed securely to a table, with a robust mechanism in place to prevent toppling, presenting a very low risk of injury. In terms of interaction, the system involves two scenarios: one where participants use a harmless PS4 controller and another where they interact

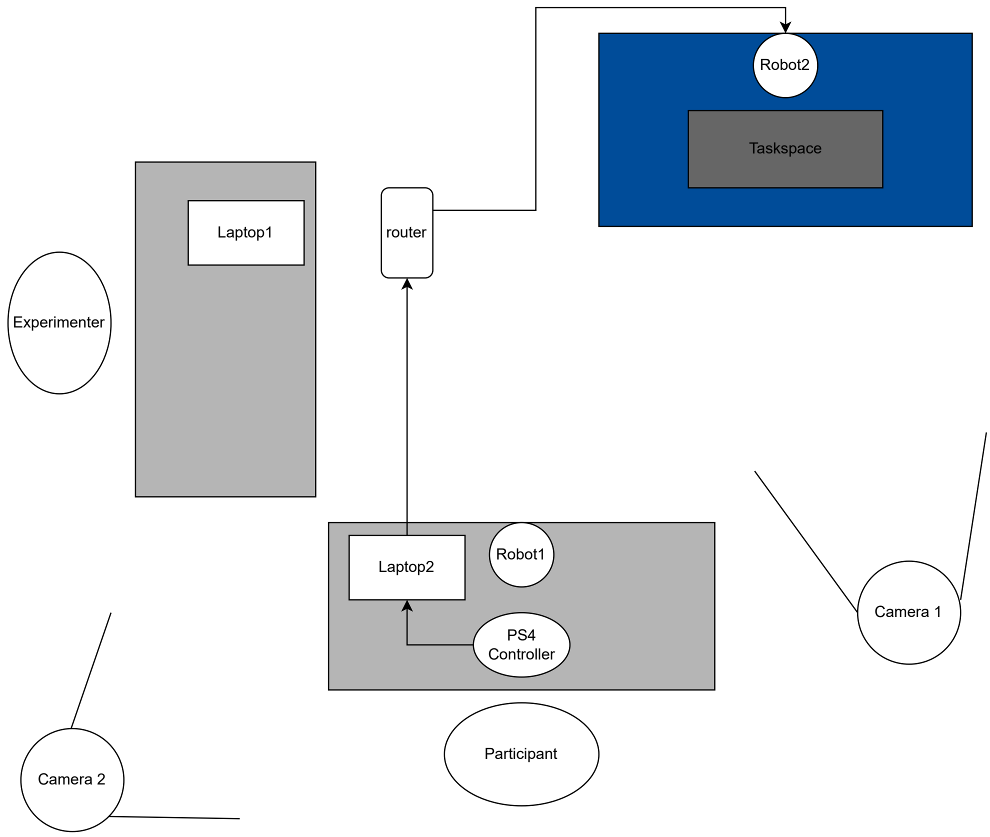

Figure 20: The experiment equipment setup for HMI 2.

with a stationary robot, which only moves to assume its starting position under controlled conditions. The Follower robot, which is the object of control, is positioned in a restricted area far from participants, effectively eliminating the risk of physical contact and accidental collisions. Participants are also informed that they can withdraw at any time without any consequences. During the experiment, the area is secured with barrier tape, and participants are thoroughly trained on the operation of the robots and briefed about the specific conditions under which the robot will move. Movements into the starting position are only initiated after participants have been informed and have moved to a safe distance, with emergency stops readily accessible and constant monitoring by the coordinators to address any issues promptly. These protocols ensure a controlled and safe environment, making the likelihood of injury extremely unlikely.

4.5. Experiment Task

The experiment tasks of this study include a practice task and a main task. The purpose of the practice task is to familiarize the participants with the usage of the HMI, while the main task serves as the primary means of evaluating HMI performance.

4.5.1. Practice Task

The arrangement of the practice task is shown in Figure 21. After learning how to use the HMI, participants have up to five minutes to complete the practice task, which involves using a robot to stack three small cubes. During this process, participants can ask the experimenter questions about HMI operation at any time. If participants feel that they have become familiar with the use of the HMI, they can also choose to end the practice at any time and proceed to the next phase, the main task.

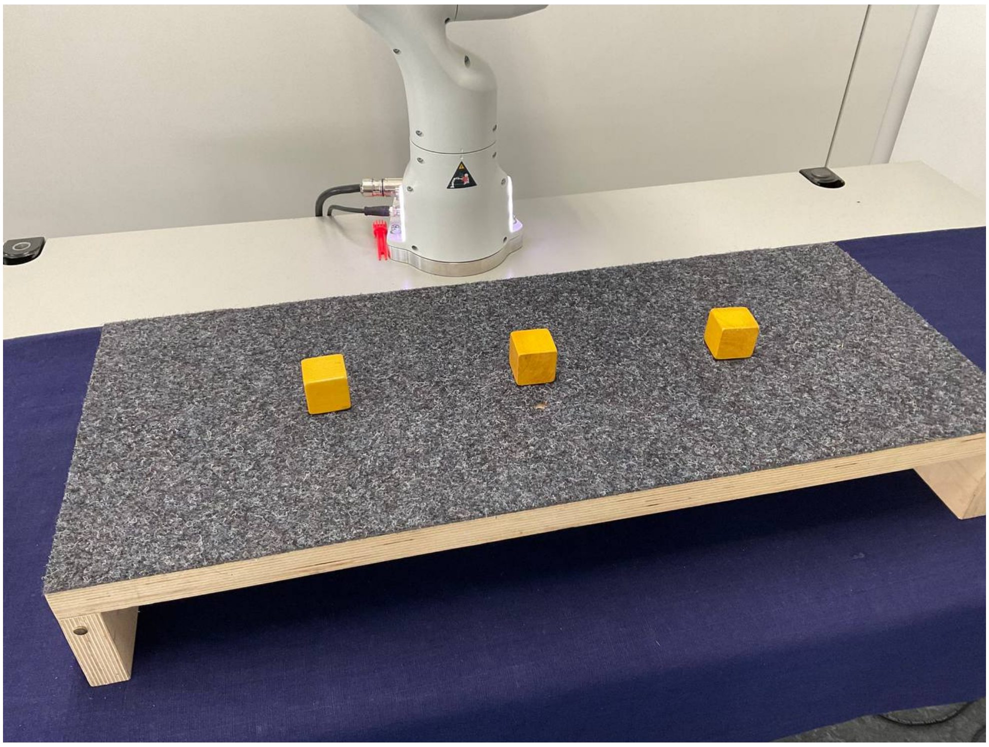

Figure 21: The pratice task

4.5.2. Main Task

To evaluate whether HMI is suitable for assembly tasks in industrial production, a peg-in-hole task is chosen as the main task. Considering the impact of task complexity on the duration of the experiment, the sorting box and 4 different shapes of wooden blocks shown in Figure 22 were selected as the main task. The positions of the 4 blocks and the sorted box on the workspace are shown in Figure 23. Participants control the robot to sequentially pick up wooden blocks and correctly place them in the sorting box. The required order is: first, the left cylinder; second, the left cube; third, the right cylinder; and fourth, the right cube.In principle, participants can use any strategy to complete the task, as long as they succeed in placing the wooden blocks into the sorting box without opening its lid.

4.6. Experiment Procedure

Each experiment is conducted on an individual basis. Before the experiment begins, the experimenter shows the participants a declaration to inform them about the purpose and potential risks of the experiment, along with privacy and security issues. Since the participants are of various nationalities, the experimenter provides translations in English, German, Chinese, and Japanese. The experiment only start after obtaining their consent and signature. During the experiment, they can withdraw at any time as well.

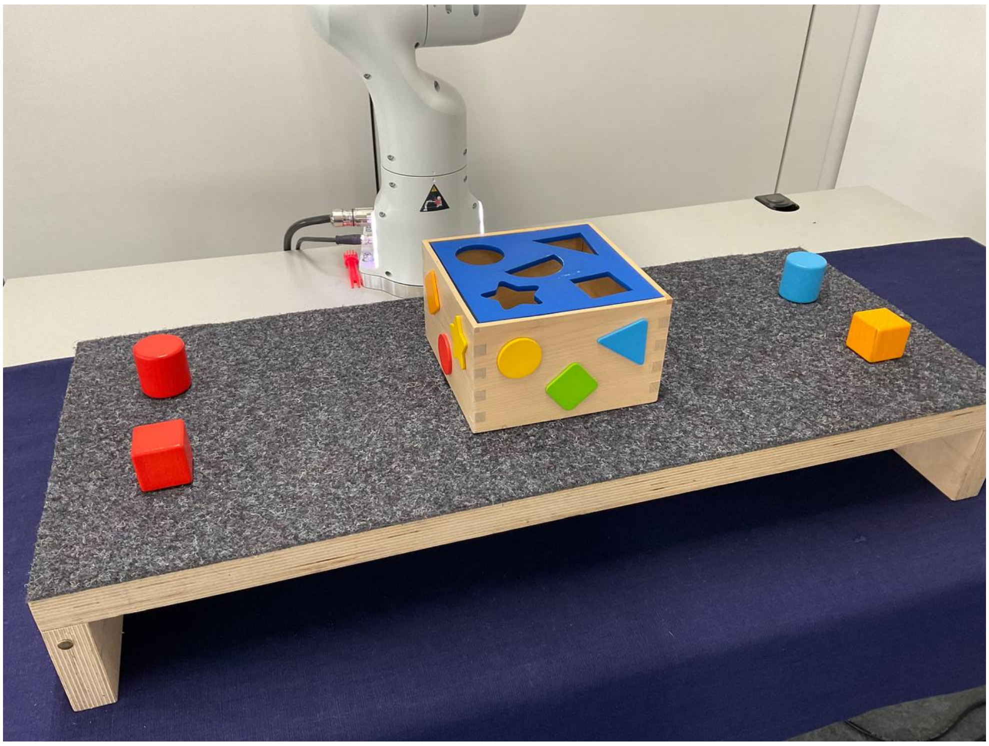

Figure 22: The main task

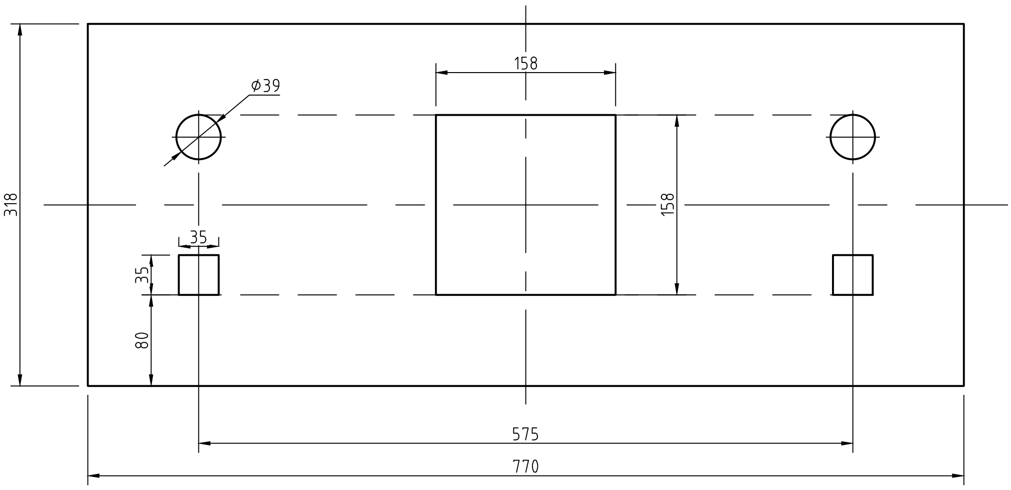

Figure 23: The position of the shapes and the sorted box.

Once they sign, the experimenter has them fill out a survey questionnaire included at the end of the paper. After completing the questionnaire, the formal experiment begins, which is recorded by two cameras:

one capturing both the participant and the experiment workspace, and the other focused solely on the experiment workspace. To ensure the results are not influenced by the language of the experiment, the experimenter communicates solely in English, regardless of the participant's native language.

Participants take turns using two HMIs to complete the same task. To avoid the learning effect influencing the experiment results, half of the participants will use the PS4 Controller HMI first, followed by the Leader-Follower HMI, while the other half will do the opposite. Each participant's usage sequence is recorded in the permutation plan in Appendix G.

Initially, the experimenter introduces the overall procedure of the experiment to the participant, followed by a demonstration of the first HMI usage. They are given five minutes to familiarize themselves with this HMI, during which they can attempt the practice task. If they feel proficient, they can opt to end the practice early and commence the main task.

Subsequently, the experimenter prepares the system by resetting the robot to its initial position and setting up the main task. Once everything is ready, the experimenter allows the participant to start. Throughout the experiment, the experimenter offers no advice on how to complete the tasks, intervening only under special circumstances (detailed in Section 4.7) and deciding whether to restart the experiment based on the specifics of the situation. The experimenter keeps brief records during the experiment. Upon completion, the participant is asked to fill out the SUS and NASA-TLX questionnaire. While they are filling out the questionnaire, the experimenter sets up a new HMI environment.

The same process is then repeated for the second HMI: introducing the HMI, allowing five minutes for familiarization, completing the main task, and filling out the same questionnaires. After the experiment, the experimenter conducts a brief interview with each participant, primarily to gather information not captured by the questionnaires, such as their overall experience with the two HMIs. Lastly, as a token of appreciation for their participation, the experimenter gives each participant gummy bears and a watercolor bookmark that has been personally painted.

The whole procedure is also illustrated in Figure 24.

4.7. Intervention Circumstances

In principle, regardless of how well the main tasks are completed, the experimenter should not interfere with the experiment. Intervention by the experimenter is only allowed when special circumstances arise that prevent the continuation of the experiment. The special circumstances are listed as follows:

- When using the leader-follower interface, if the robot automatically stops because of violation of joints torques and speed limit.
- If a Gripper Error results in the two grippers being unable to synchronize and grasp an object.

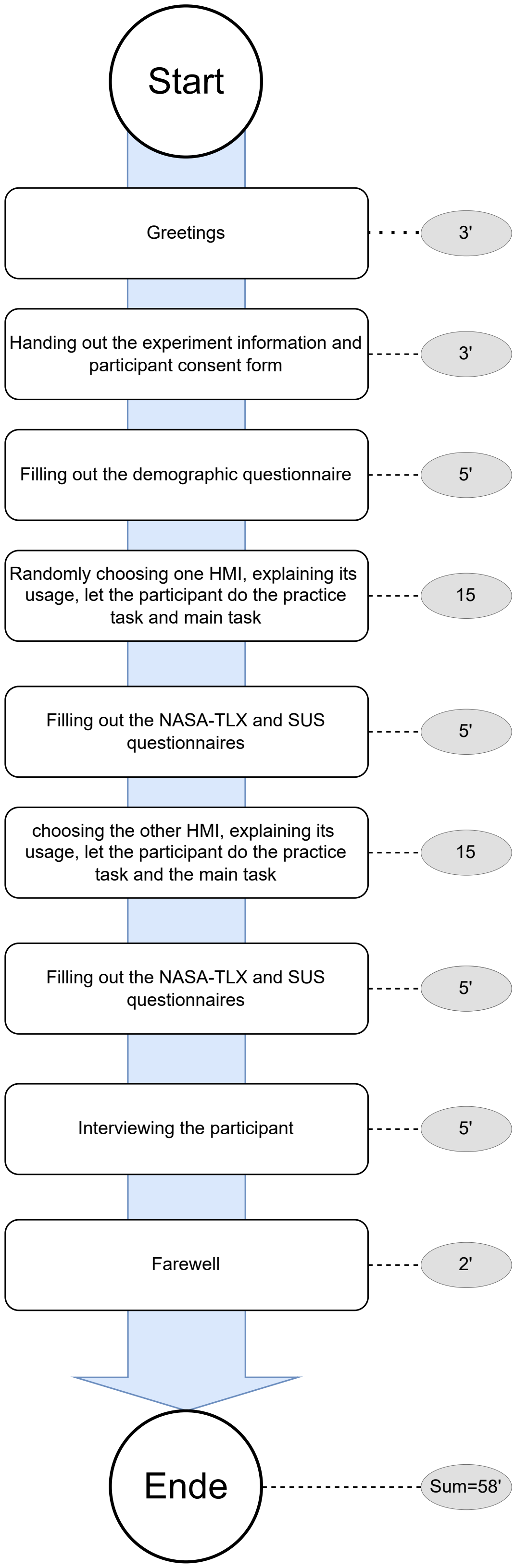

Figure 24: The user study procedure.

- If the grasped object falls off the experimental table. The experimenter will retrieve and replace the object back to its starting position.

- If the sorted box is moved by the robot to an extreme position, making it impossible to complete the task, the experimenter will adjust and straighten the box.
- When using the PS4 HMI, if a cylinder falls over and cannot be righted by the gripper due to the limitations of degrees of freedom, the experimenter will manually reset it to its original position.
- Other technical errors occur that require the support from the experimenter.

5. User Study Result

This chapter outlines the results of the user study aimed at evaluating the performance and workload of the new HMI. Using Matlab for data analysis and visualization, the findings are systematically presented across several Sections.

The chapter begins with the participants' profiles in Section 5.1, detailing demographic and background information. Following this, Section 5.2 examines the core performance metrics—TCT, grasp, and drop attempts—and the statistical methods employed to analyze these data, including both descriptive and inferential statistics.

Subsequent Sections explore subjective assessments through the NASA-TLX and the SUS, providing insights into the participants' perceived effort and interface usability. Finally, qualitative feedback from interviews offers additional perspectives on the HMIs' effectiveness.

The data analysis involves initial descriptive statistics to outline basic data trends and inferential statistics to test the significance of the results between the HMIs. Depending on data distribution, either paired T-tests or bootstrapped T-tests were conducted to ascertain significant differences, ensuring the conclusions are robust and data-driven.

5.1. Participants Profile

This user study recruited 36 participants, including 17 males and 19 females. Their ages ranged from 21 to 37 years, with an average age of 25.6 years, a median age of 26, and a standard deviation of 3.6. The age distribution is shown in Figure 25. The survey also collected additional information about these participants, including their use of visual aids as shown in Figure 26, where a majority (75.00%) require visual aids, and 11.10% of them needed visual aids but did not wear them during the experiment. Regarding the participants' experience with teleoperation and game controllers, this is displayed in Figure 27 and Figure 28, with most participants (72.22%) having no experience operating teleoperations. Similarly, most participants (69.44%) have some level of experience using game controllers.

5.2. Objective Performance

In this user study, all 36 participants successfully completed the main task. The performance metrics used were TCT, grasp attempts, and drop attempts. Lower values for TCT, grasp attempts, and drop attempts indicate higher efficiency of the operator and superior performance of the HMI. To analyze whether the effect of the independent variable on the dependent variable is significant, the data analysis process is as follows:

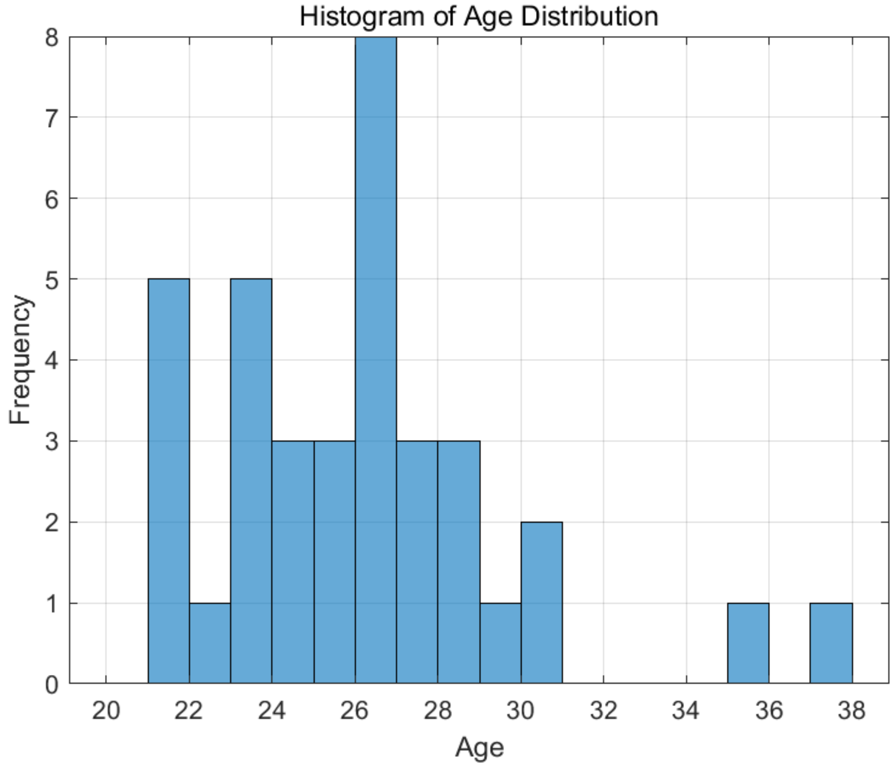

Figure 25: Age distribution of the participants.

1. Firstly, a basic analysis of all dependent variables is performed, calculating the mean (M), median (Md), and standard deviation (SD), and visualizing them using a box graph.

2. Next, the Shapiro-Wilk Test is conducted on the same type of dependent variable to determine if it follows a normal distribution. If the data is normally distributed, a paired T-test is used to verify the significance of the impact on HMI.

3. If the data is normally distributed, a one-tailed paired T-test is used to verify the significance of the impact on HMI. If the data does not follow a normal distribution, the one-tailed bootstrapped T-test is used to verify significance.

5.2.1. Task Completion Time

The main task includes sub-tasks of grasping and placing four shapes: cylinder left, cube left, cylinder right, and cube right. The TCT for each sub-task is calculated as follows:

$$TCT_{\text{shape}} = T_{\text{end}} - T_{\text{start}} - T_{\text{intervention}} \tag{5.1}$$

Here, T_{end} is when the shape fully drops into the sorted box, and T_{start} is the T_{end} of the previous shape. If the current shape is the first one (cylinder left), the starting time is when participants begin moving the robot. $T_{\text{intervention}}$ is calculated from the moment an intervention circumstance occurs until the participants resume operation after the event is cleared.

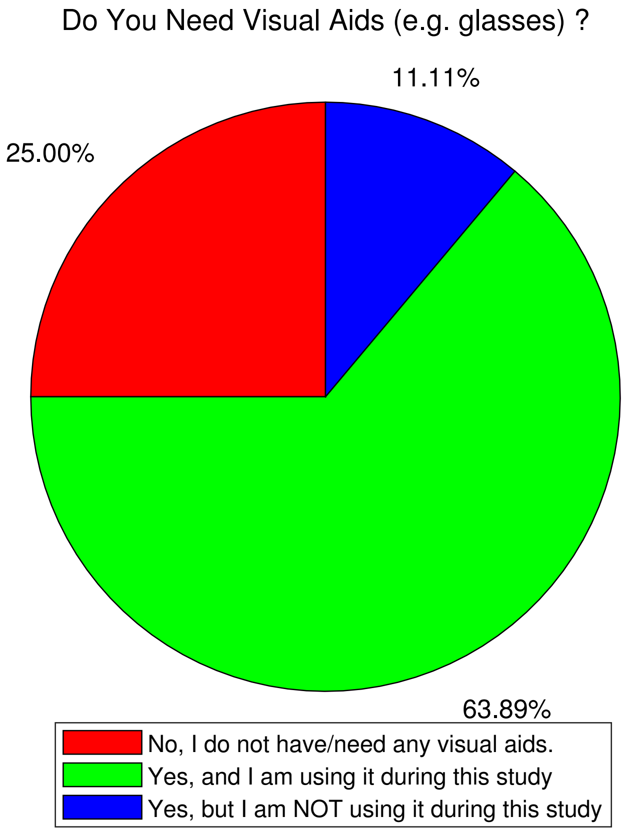

Figure 26: Result of visual-aid usage of the participants.

The TCT_{average} is calculated as:

$$TCT_{\text{average}} = (TCT_{\text{cylinder left}} + TCT_{\text{cube left}} + TCT_{\text{cylinder right}} + TCT_{\text{cube right}})/4. \quad (5.2)$$

The final data is shown in Table 4. Since the Shapiro-Wilk Test indicated that the experimental data does not follow a normal distribution, the one-tailed bootstrapped T-test was used to verify significance. The results show that the TCT using the PS4 controller HMI was significantly greater than that of the leader-follower HMI. On average, completing tasks using the PS4 controller took 3.4 times longer than using the leader-follower HMI. Figure 29 visually displays these results. Specifically, for the same HMI, the TCT for the cube is generally higher than that for the cylinder, and regarding shape, the TCT difference between completing the cube across the two HMIs is also greater than that for the cylinder. This could be because placing the cube into the sorting box requires an additional degree of freedom for rotation, demanding higher precision.

5.2.2. Grasp and Drop Attempts

A grasp attempt is defined as an instance when participants close the robot gripper fingers once. To complete a subtask, at least one grasp attempt is necessary. However, the actual number of grasp attempts typically exceeds one due to potential misjudgments of the shapes' positions, missed targets, or the need to reattempt a grasp after an unsuccessful drop. As demonstrated in Table 5, the Shapiro-Wilk Test results reveal a significant difference in the number of grasp attempts required for tasks when

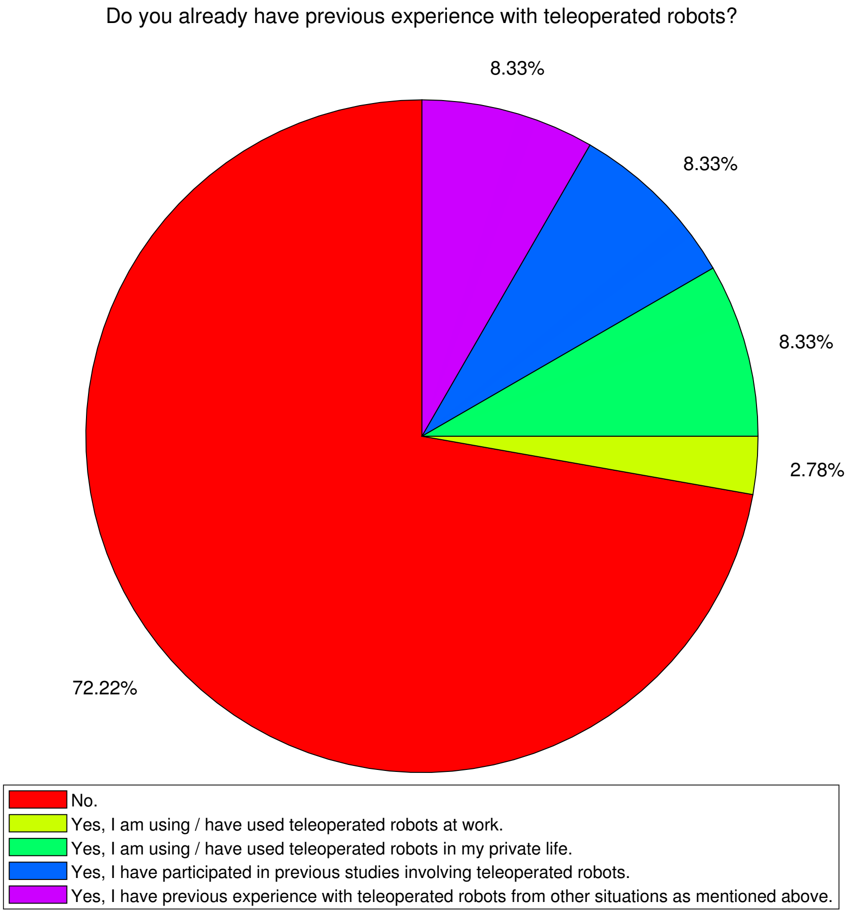

Figure 27: Result of previous familiarity with teleoperation system of the participants.

using the PS4 controller HMI compared to the leader-follower HMI. Specifically, the average number of grasp attempts with the PS4 controller HMI is nearly double that of the leader-follower HMI. This result is depicted in Figure 30.

A drop attempt is defined as an occasion where the gripper is positioned above the hole of the sorted box, and participants release the gripper fingers, attempting to drop the shape into the hole. Placing the shape on the table or the cover of the sorted box for re-adjustment does not qualify as a drop attempt. Completing a subtask requires at least one drop attempt. However, due to frequent misplacements, participants often need to re-grasp the shape—especially cubes—and make multiple drop attempts, resulting in an average number of drop attempts higher than one per subtask. According to the statistics in Table 6, there is a significant difference in the average number of drop attempts between the two HMIs. The PS4 controller HMI generally necessitates more drop attempts than the leader-follower HMI for the cube. However, this pattern does not hold for the cylinder shape; the one-tailed bootstrapped T-test shows there is no enough evidence to reject the assumption that the PS4 controller HMI is equivalent to or better than the leader-follower HMI in terms of performance for dropping cylinders into the box ($p > 0.05$) . Figure 31 illustrates these results.

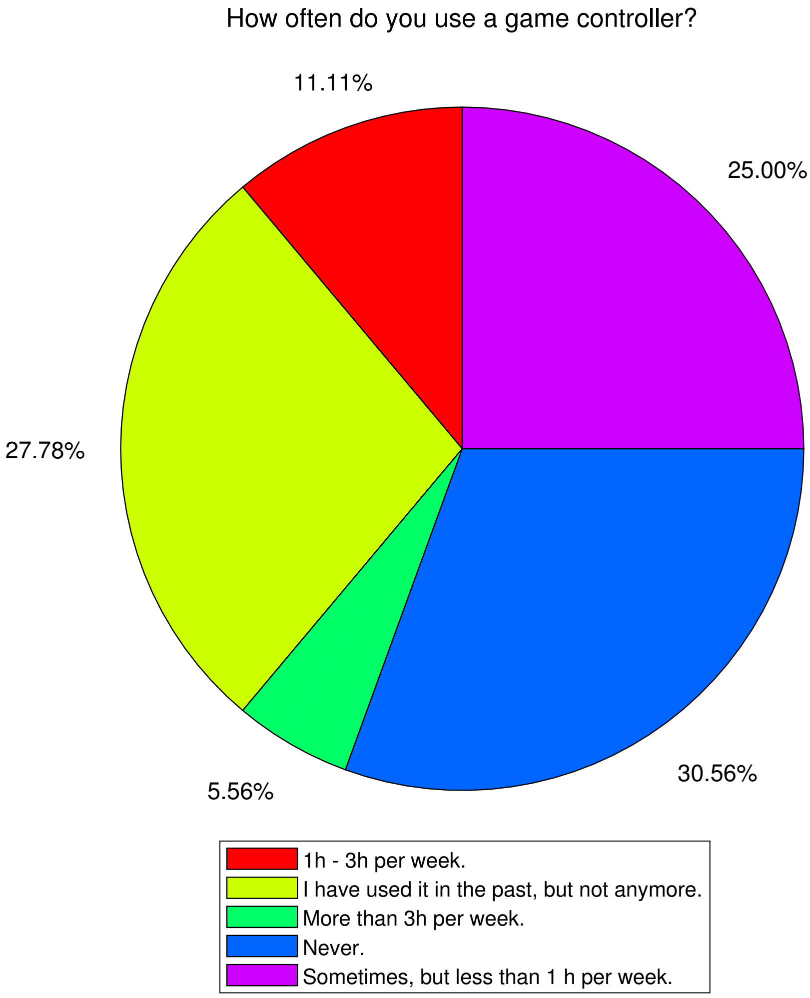

Figure 28: Result of previous familiarity with game controller of the participants.

5.3. Subjective Workload

In this study, 33 valid NASA-TLX questionnaires were analyzed, with results presented in Table 7 and Figure 32. The workload associated with the PS4 controller HMI was found to be significantly higher than that of the leader-follower HMI in five dimensions: mental demand, temporal demand, performance, effort, and frustration. These differences were statistically significant, as confirmed by the one-tailed bootstrapped T-test ($p < 0.05$). In the physical demand dimension, the PS4 controller HMI didn't show significant higher workload than that of the leader-follower HMI($p > 0.05$). Overall, the mean weighted workload scores also showed a significant difference ($p < 0.001$), with the PS4 controller HMI recording a significantly higher score (M=40.883 Md=39.166 SD=17.179) compared to the leader-follower HMI (M=26.136 Md=20.833 SD=17.042).

Table 4: TCT statistics for different shapes.

Shape	TCT(sec) statistics of PS4 Controller HMI	TCT(sec) statistics of Leader-Follower HMI	One-Tailed Boot-strapped T-test
Cylinder left	M=89.278 Md=57.000 SD=103.410 Shapiro-Wilk Test P-Value < 0.001	M=34.250 Md=30.000 SD=16.805 Shapiro-Wilk Test P-Value = 0.001	p<0.001
Cube left	M=161.944 Md=94.000 SD=154.413 Shapiro-Wilk Test P-Value < 0.001	M=46.611 Md=32.000 SD=47.033 Shapiro-Wilk Test P-Value <0.001	p<0.001
Cylinder right	M=69.361 Md=61.000 SD=44.750 Shapiro-Wilk Test P-Value = 0.006	M=26.528 Md=26.000 SD=10.990 Shapiro-Wilk Test P-Value = 0.005	p<0.001
Cube right	M=149.083 Md=88.000 SD=183.585 Shapiro-Wilk Test P-Value < 0.001	M=44.250 Md=30.500 SD=35.428 Shapiro-Wilk Test P-Value <0.001	p<0.001
Average	M=117.417 Md=97.625 SD=76.654 Shapiro-Wilk Test P-Value = 0.002	M=37.9097 Md=34.125 SD=19.678 Shapiro-Wilk Test P-Value <0.001	p<0.0001

5.4. Perceived Usability

In this study, 36 valid SUS questionnaires are collected. The result is shown in Table 8 as well as Figure 33. The one-tailed bootstrapped T-test shows there is a significant difference between the SUS scores of the two HMIs ($p < 0.001$). The usability score of the PS4 controller HMI (M=63.888 Md=63.750 SD=19.461) is significantly lower than that of the leader follower HMI (M=80.416 Md=82.500 SD=15.065), indicating worse usability of the HMI.

5.5. Interview Result and Other Observation

5.5.1. Interview Result

At the end of the user study, the participants were asked for their opinions on the two HMIs and collected both positive and negative feedback about them. This feedback is listed in Table 9. The PS4 controller HMI received more negative feedback, while the leader-follower HMI primarily received positive feedback.

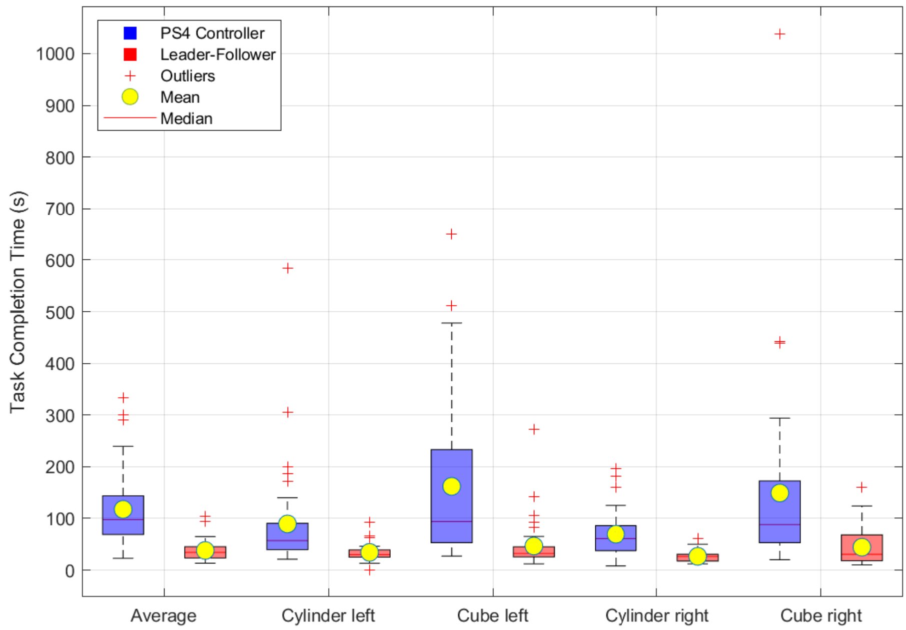

Figure 29: TCT comparison of the two HMIs.

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Table 5: Grasp attempts statistics for different shapes.

Shape	**Grasp Attempts Statistics of PS4 Controller HMI**	**Grasp Attempts Statistics of Leader-Follower HMI**	**One-Tailed Boot-strapped T-test**
Cylinder left	M=2.111 Md=1.500 SD=1.652 Shapiro-Wilk Test P-Value < 0.001	M=1.416 Md=1.000 SD=0.691 Shapiro-Wilk Test P-Value < 0.001	p=0.01
Cube left	M=3.722 Md=2.500 SD=3.684 Shapiro-Wilk Test P-Value < 0.001	M=1.694 Md=1.000 SD=1.305 Shapiro-Wilk Test P-Value < 0.001	p<0.001
Cylinder right	M=1.833 Md=2.000 SD=1.028 Shapiro-Wilk Test P-Value < 0.001	M=1.250 Md=1.000 SD= 0.649 Shapiro-Wilk Test P-Value < 0.001	p=0.004
Cube right	M=3.805 Md=1.000 SD=4.658 Shapiro-Wilk Test P-Value < 0.001	M=1.861 Md= 1.000 SD=1.709 Shapiro-Wilk Test P-Value < 0.001	p=0.001
Average	M=2.868 Md=2.625 SD=1.798 Shapiro-Wilk Test P-Value < 0.001	M=1.555 Md=1.375 SD=0.624 Shapiro-Wilk Test P-Value = 0.003	p<0.001

Table 9: Interview results

Feedback types	PS4 Controller HMI	Leader-Follower HMI
Positive feedbacks	Easy to control with only fingers (3)	Prefer this one better because of easy uasge (15)
	Easy to use (4)	The haptic feedback provides more information (6)
	More precise(1)	More intuitive (4)
	Functions good integrated	More accurate (4)
	Easy to learn (1)	Better feedback (3)
	Easier to move near the workspace limit (1)	Easy to control TCP to the desired position (2)
	Easier to grasp (2)	Suitable for long-term usage(1)
	Easier to restart (1)	Efficient (1)
Negative feedbacks	Inaccuracy and motion shifting (14)	The leader robot is difficult to move (3)
	Robot moves too fast and is too sensitive (7)	Gripper delay (2)
	Motion delay (7)	Inconvenient and clumsy (1)
	It needs more time to learn and practice (3)	The robot movements become less smooth at certain robot poses (1)
	Not enough feedback (2)	
	Not intuitive (2)	
	Left and right joysticks are confusing (1)	
	Need to consider many things when using (1)	
	Not friendly to non-expert users (1)	

	Not perfect for small movements (1) Rotation direction confusing (1) Rotation degree of freedoms not enough (1) The restart function is confusing (1)	

5.5.2. Intervention Documentation

In the user study, a total of 20 intervention situations were recorded. Of these, 16 occurred while participants were using the PS4 controller HMI, and 4 occurred with the leader-follower HMI. These situations are listed in Table 10. The PS4 controller HMI received more negative remarks, primarily concerning its sensitivity and lack of intuitiveness, whereas the leader-follower HMI was generally preferred for its ease of use and intuitive operation. Intervention incidents were notably higher with the PS4 controller HMI, illustrating possible operational challenges.

5.6. Summary

The user study involved 36 participants, ranging in age from 21 to 37, with a majority requiring visual aids. Most participants had limited experience with teleoperation, though a significant number had some familiarity with game controllers. In terms of objective performance, all participants successfully completed the main task. However, the PS4 controller HMI demonstrated longer TCT and required more grasp and drop attempts compared to the leader-follower HMI. Questionnaire results further reflected these differences: the NASA-TLX indicated a higher subjective workload for the PS4 controller, while the SUS showed better perceived usability ratings for the leader-follower HMI. Interviews conducted at the end of the study provided qualitative feedback, with the PS4 controller receiving more negative comments due to its sensitivity and complexity, whereas the leader-follower HMI was generally preferred for its ease of use and intuitive operation. Overall, the leader-follower HMI was found to be more efficient and user-friendly than the PS4 controller HMI, as evidenced by both quantitative and qualitative results.

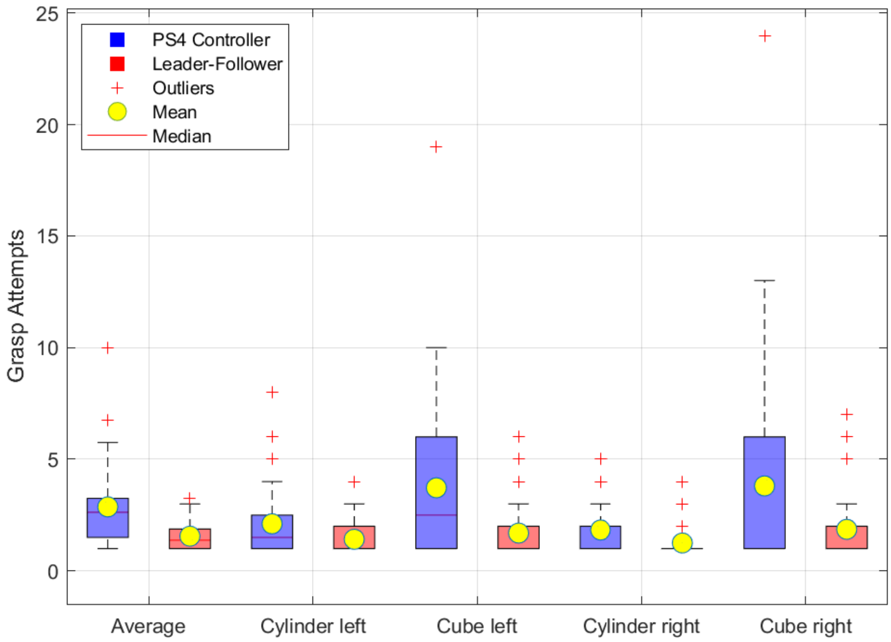

Figure 30: Grasp attempts comparison of two HMIs.

Table 6: Drop attempts statistics for different shapes.

Shape	**Drop Attempts Statistics of PS4 Controller HMI**	**Drop Attempts Statistics of Leader-Follower HMI**	**One-Tailed Bootstrapped T-test**
Cylinder left	M=1.138 Md=1.000 SD=0.487 Shapiro-Wilk Test P-Value < 0.001	M=1.083 Md=1.000 SD=0.280 Shapiro-Wilk Test P-Value < 0.001	p=0.345
Cube left	M=2.194 Md=1.500 SD=1.687 Shapiro-Wilk Test P-Value < 0.001	M=1.333 Md=1.000 SD=0.676 Shapiro-Wilk Test P-Value < 0.001	p<0.001
Cylinder right	M=1.138 Md=1.000 SD=0.350 Shapiro-Wilk Test P-Value < 0.001	M=1.055 Md=1.000 SD=0.333 Shapiro-Wilk Test P-Value < 0.001	p=0.189
Cube right	M=2.166 Md=1.000 SD=2.158 Shapiro-Wilk Test P-Value < 0.001	M=1.444 Md=1.000 SD=1.054 Shapiro-Wilk Test P-Value < 0.001	p=0.010
Average	M=1.659 Md=1.500 SD=0.727 Shapiro-Wilk Test P-Value < 0.001	M=1.229 Md=1.000 SD=0.350 Shapiro-Wilk Test P-Value < 0.001	p<0.001

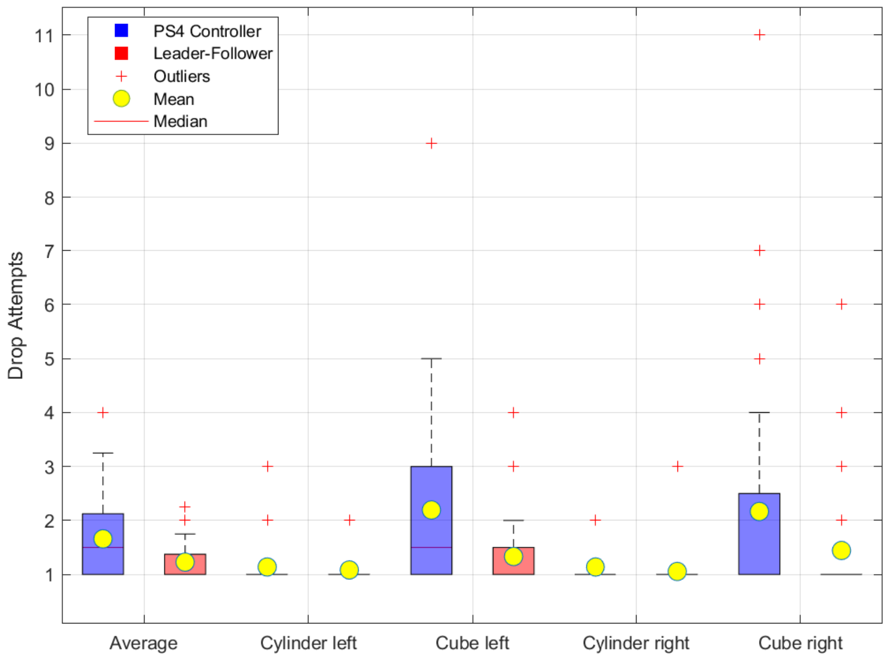

Figure 31: Drop attempts comparison of two HMIs.

Table 7: NASA-TLX scores statistics.

Scale	**Score(0-100) Statistics of PS4 Controller HMI**	**Score(0-100) Statistics of Leader-Follower HMI**	**One-Tailed Bootstrapped T-test**
Mental Demand	M=54.393 Md=55.000 SD=23.971 Shapiro-Wilk Test P-Value =0.515	M=27.272 Md=20.000 SD=25.189 Shapiro-Wilk Test P-Value < 0.001	p<0.001
Physical Demand	M=32.575 Md=20.000 SD=31.177 Shapiro-Wilk Test P-Value = 0.001	M=38.787 Md=30.000 SD=30.078 Shapiro-Wilk Test P-Value = 0.004	p=0.912
Temporal Demand	M=36.515 Md=40.000 SD=22.412 Shapiro-Wilk Test P-Value =0.039	M=27.272 Md=20.000 SD=23.916 Shapiro-Wilk Test P-Value = 0.001	p=0.035
Performance	M=36.666 Md=30.000 SD=24.675 Shapiro-Wilk Test P-Value =0.149	M=20.454 Md=10.000 SD=21.226 Shapiro-Wilk Test P-Value < 0.001	p<0.001
Effort	M=52.272 Md=60.000 SD=28.037 Shapiro-Wilk Test P-Value =0.037	M=24.090 Md=15.000 SD=23.300 Shapiro-Wilk Test P-Value < 0.001	p<0.001
Frustration	M=32.878 Md=30.000 SD=25.587 Shapiro-Wilk Test P-Value =0.041	M=18.939 Md=10.000 SD=24.003 Shapiro-Wilk Test P-Value < 0.001	p=0.003
Mean Weighted	M=40.883 Md=39.166 SD=17.179 Shapiro-Wilk Test P-Value =0.820	M=26.136 Md=20.833 SD=17.042 Shapiro-Wilk Test P-Value = 0.014	p<0.001

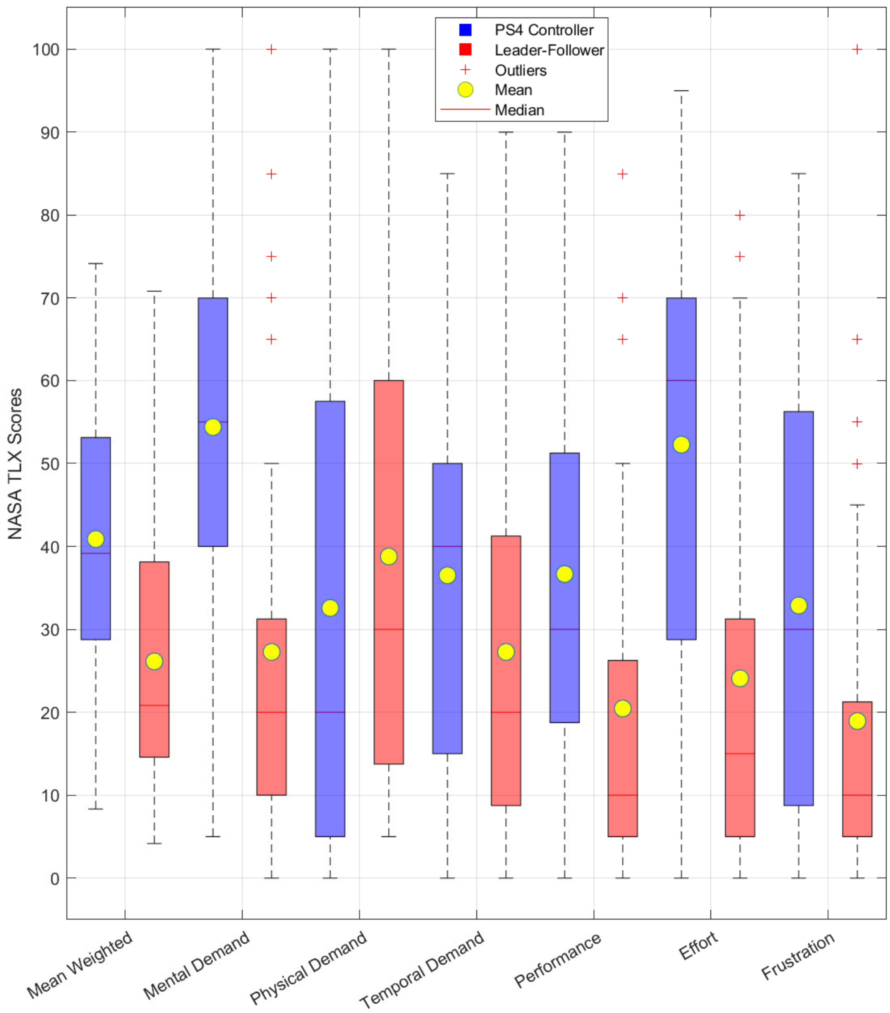

Figure 32: NASA-TLX scores results comparison of the two HMIs. Range from 0 to 100.

Table 8: SUS statisctics of the two HMIs.

HMI	**SUS Scores (0-100) Statistics**	**One-Tailed Bootstrapped T-test**
PS4 Controller	M=63.888 Md=63.750 SD=19.461 Shapiro-Wilk Test P-Value = 0.110	p<0.001
Leader-Follower	M=80.416 Md=82.500 SD=15.065 Shapiro-Wilk Test P-Value = 0.021	

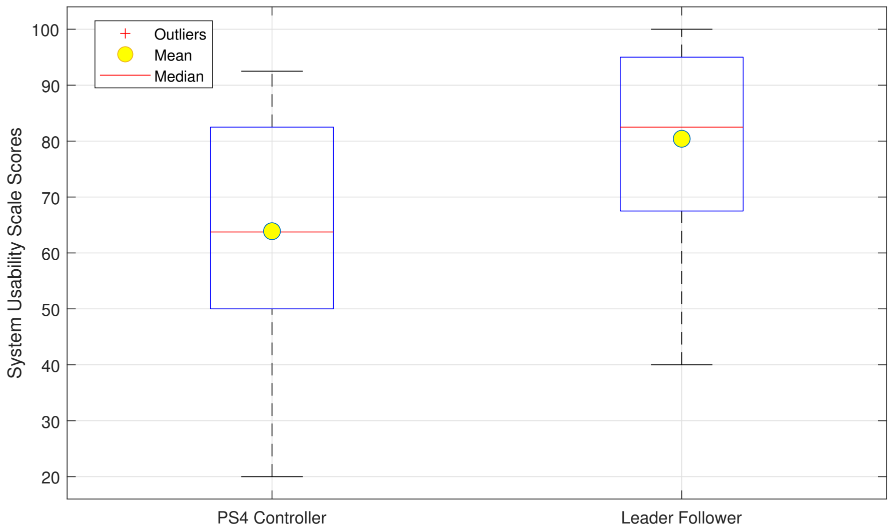

Figure 33: The SUS results comparison of the two HMIs

Table 10: Intervention documentation

Intervention Circumstance	Number of Occurrences when using the PS4 Controller HMI	Number of Occurrences when using the Leader-Follower HMI
The cylinder flipped	7	1
The cylinder fell off the table	3	0
The cube fell off the table	5	0
The sorted box was pushed out of the robot workspace	1	0
The cover of the sorted box fell off	1	0
The robot stopped moving because of joint limits violation or joint toque limits violation.	0	2

6. Discussion

6.1. Hypothesis Evaluation

The user study results in the chapter demonstrated that there are significant difference between the PS4 controller HMI and the was outperformed by the leader-follower HMI in terms of both performance and workload. Based on the results, we evaluate the hypotheses as follows:

- **Null Hypothesis 1:** The PS4 controller HMI is equivalent to or better than the leader-follower HMI in terms of objective performance.
  - **Evaluation:** Rejected. The data showed that the PS4 controller HMI has significantly worse performance compared to the leader-follower HMI, as indicated by longer TCT and higher number of grasp and drop attempts.
- **Alternative Hypothesis 1:** The PS4 controller HMI performs worse than the leader-follower HMI in terms of objective performance.
  - **Evaluation:** Accepted. The results from the user study confirm that the PS4 controller HMI has inferior performance metrics compared to the leader-follower HMI.
- **Null Hypothesis 2:** The subjective workload associated with the PS4 controller HMI is equivalent to or less than that of the leader-follower HMI.
  - **Evaluation:** Rejected. The NASA-TLX results indicated that the workload for the PS4 controller HMI was higher than that for the leader-follower HMI, with significant differences in mental demand, temporal demand, performance, effort, and frustration, as well as the mean-weighted NASA-TLX.
- **Alternative Hypothesis 2:**The subjective workload associated with the PS4 controller HMI is greater than that of the leader-follower HMI.
  - **Evaluation:** Accepted. The user study data showed that participants experienced a higher workload when using the PS4 controller HMI, supporting this hypothesis.
- **Null Hypothesis 3:** The PS4 controller HMI is equivalent to or better than the leader-follower HMI in terms of perceived system usability.
  - **Evaluation:** Rejected. The data showed that the PS4 controller HMI has significantly worse perceived system usability compared to the leader-follower HMI, as indicated by lower SUS scores.
- **Alternative Hypothesis 3:** The PS4 controller HMI performs worse than the leader-follower HMI in terms of perceived system usability.
  - **Evaluation:** Accepted. The results from the user study confirm that the PS4 controller HMI has inferior perceived system usability compared to the leader-follower HMI.

Now the question arise: why does the new designed PS4 controller achieves such performance? Combining the experimental data and user feedback from the previous chapter with other observations, the reasons for these results can be these aspects.

6.2. Disadvantages of the PS4 controller HMI

6.2.1. Inaccurate Motion Control

Many participants reported that the robot's motion was not precise enough. This issue arises partly from the robot's motion algorithms and partly from the design of the HMI parameters.

- **Robot Control Algorithm** The robot control algorithm adopted was impedance control. However, this algorithm has its own limitations. It allows a certain discrepancy between the target pose and the actual pose, which, from a safety perspective, can make the robot more compliant when in contact with the environment. This compliance helps avoid damage to the robot or the surrounding area due to human errors. However, the presence of this discrepancy also leads to reduced operational precision. When the operator commands the robot to move downward, the robot's initial response is slow with a slight delay, and there may be some deviation during movement. For instance, a minor change in the arm's orientation can result in the end-effector not moving in a perfectly vertical line. This error makes it more challenging to accurately place shapes into the corresponding holes of the sorted box, leading to longer TCT and higher drop attempts.
- **Design of Motion Parameters** Many participants noted that the robot moved too quickly or was overly sensitive, which is due to suboptimal optimization of the HMI control function $f(x)$ parameters. Steep response curves of $f(x)$ and excessive maximum speed settings cause the robot to react too quickly, which some users found uncomfortable.

6.2.2. Demand on human reaction capabilities

A significant difference between the PS4 controller HMI and the leader-follower HMI is that the leader robot inputs position signals, while the PS4 controller inputs velocity signals, which require integration over time to derive position information. With the leader-follower HMI, since the input and output devices are identical, operators can directly control the robot's position without considering time. However, when using the PS4 controller, operators actually control the position of the robot's TCP by varying the duration for which the joystick is held in different positions. Managing this time duration, linked to human reaction capabilities, can pose challenges for some users. This could lead to higher workload and worse performance.

6.2.3. Limited Feedback

For tasks such as peg-in-hole, the feedback on the robot's position is crucial. Operators need to know the relative position between the TCP and the sorted box to successfully place the shape into the hole. The PS4 Controller HMI only provides direct visual feedback, forcing operators to rely solely on visual judgment to determine the relative positions of the shape and the sorted box. In contrast, the leader-follower HMI provides haptic feedback. Contact between the follower robot and the environment is conveyed back to the operator through the leader-follower system, allowing the operator to judge by touch whether the shape has been correctly placed into the hole. This enhancement improves the success rate of drop attempts and reduces the task completion time.

6.2.4. Limited Rotation Degrees of Freedom

Compared to the three rotational DoF in the gripper of the leader-follower HMI, the PS4 Controller HMI provides only one rotational degree of freedom. This limitation restricts the robot's operable space. Using the former, if the initial attempt to place a cube into a hole fails and the cube tilts, the operator can adjust the gripper's orientation until the cube is realigned with the hole before attempting to drop again. Such maneuvers are not possible with the PS4 Controller due to its limited DoFs. Operators are forced to adopt different strategies, such as placing the cube down and then re-grasping it, which increases the number of grasp and drop attempts as well as the task completion time.

6.2.5. Complexity of the HMI Interface

Interviews from the user study revealed that a considerable number of participants found the HMI's button layout non-intuitive, particularly with rotation controls that easily confuse directions, and mixing up the left and right joysticks. Observations during the experiments noted that many participants required a significant amount of time to learn, especially to distinguish directions. Compared to the leader-follower HMI, where directly moving the leader robot controls the follower robot, operating a robot with the PS4 controller requires memorizing more information, thus increasing the learning cost. This might impact the participants' performance and workload in assembly tasks.

6.3. Potentials of the the PS4 controller HMI

While the performance of the PS4 Controller HMI was not exemplary in the final experimental data, it displayed potential advantages over the leader-follower HMI in several functions.

6.3.1. Better Release/Grasp Function

In terms of gripper control, the PS4 controller received positive feedback. Several participants reported that controlling the gripper with the PS4 controller buttons was more convenient than directly controlling the Leader robot's gripper, which requires considerable force and could cause slight shifts in the Leader robot's TCP position, affecting the accuracy of the follower robot's grasp. In contrast, the PS4 controller makes grasping more straightforward, needing only the press of a button. However, the advantages of the PS4 controller in grasping did not translate into improved TCT or reduced grasp attempts in the data. This is because successful grasping involves not just control of the gripper fingers but also the precision of robot movement.

6.3.2. Easier Error Recovery

For error recovery, participants found the PS4 Controller's method more convenient. Operators only need to press a button to perform error recovery, whereas the Leader Follower HMI requires the experimenter to manually restart the teleoperation system. However, since manual restarts are considered interventions and are not included in the TCT, this advantage of the PS4 Controller HMI was not reflected in the final results.

6.3.3. More Convenient for Low Precision Movements

For low precision movements, the motion control of the PS4 Controller HMI appears smoother and more convenient compared to the Leader Follower HMI. When controlling the leader robot, users have to consider how to move robot joints to get the TCP to the desired position. Some participants noted that for certain specific poses, such as singular points, the robot's movement could seem awkward and clumsy. The PS4 Controller HMI does not have this problem because the user does not need to think too much—just controlling the direction of the joystick is sufficient, as the robot's internal controller automatically solves the inverse kinematics. Moreover, no matter what pose the robot is in, it does not affect the user's operational experience or result in awkward movements. However, the evaluation task's emphasis on high precision movements had a greater impact on the final TCT, as industrial assembly tasks inherently demand high accuracy. The advantages of the PS4 Controller HMI in handling low precision movements need to be validated in future experiments with new tasks.

7. Conclusion and Future Work

7.1. Conclusion

This thesis embarks on a comprehensive exploration of the design, implementation, and evaluation of a new HMI using a PS4 controller in an industrial teleoperation context. The goal is to determine whether this innovative HMI could match or surpass the traditional leader-follower HMI in terms of performance and workload.

During the design and implementation phases, a teleoperation HMI based on a PS4 controller was developed, allowing users to control a robot to grasp small objects and complete simple peg-in-hole tasks. However, the user study indicated that the efficiency of this HMI is not satisfactory.

The experimental results decisively showed that the PS4 controller HMI did not perform as well as the leader-follower HMI. Specifically, the PS4 controller HMI resulted in longer TCT and higher numbers of grasp and drop attempts. Furthermore, the subjective assessments via the NASA-TLX and SUS questionnaires indicated that the PS4 controller imposed a higher workload on the operators and tended to have lower usability. These outcomes led to the rejection of the null hypotheses stating that the PS4 controller HMI was equivalent to or better than the leader-follower HMI in terms of objective performance, subjective workload and perceived usability.

Analysis of the qualitative and quantitative data suggested that the shortcomings of the PS4 controller HMI were due to several factors:

1. **Inaccurate Motion Control**: The compliance embedded within the robot control algorithm and the high sensitivity of the controller led to reduced precision.
2. **Demanding Human Reaction Capabilities**: The velocity-based input required operators to manage the duration of input more carefully, which was less intuitive than the direct positional control offered by the leader-follower setup.
3. **Limited Feedback Mechanisms**: The lack of haptic feedback in the PS4 controller HMI was a significant disadvantage, especially for tasks requiring precise positioning.
4. **Limited Rotation Degrees of Freedom**: The limited rotation DoF restrict the robot's operable space.
5. **Complex Interface**: The PS4 controller's layout and the need to remember multiple functions for each button increased the cognitive load on the operators.

Despite these challenges, the PS4 controller HMI also demonstrated certain advantages, such as ease of handling the gripper and simplified error recovery processes, suggesting aspects where this HMI might still be effective.

Returning to the original research question:

- **For assembly tasks using a 7 DoF robot, can an HMI using a PS4 controller as input outperform an HMI using a leader-follower configuration in terms of performance, workload and usability?**

According to the results of this study, there is currently insufficient evidence to prove that an HMI based on PS4 controller or similar devices can outperform the leader-follower HMI in assembly tasks. However, it does not rule out the possibility that new design ideas could improve the current PS4 controller HMI, potentially allowing it to surpass the leader-follower HMI in certain specific tasks. To explore this possibility further, the topics in Section 7.2 are available for future research.

7.2. Future Work

This master thesis primarily focused on two aspects: firstly, the design and implementation of a new PS4 controller-based HMI, and secondly, the design of a user study to evaluate the performance of this new HMI. Both aspects have room for improvement in the future:

7.2.1. Future Work on HMI Design

1. **Optimization of HMI Parameters**:For the PS4 controller HMI, both the motion algorithms and the HMI control functions involve a considerable number of empirical parameters, such as the parameter matrix for impedance control and polynomial parameters in the control function $f(x)$. In this thesis, the optimization of these parameters was only tailored to the preferences of the thesis author, without consideration for other users. Future work could involve designing a user study to recruit participants to explore different experimenters' preferences, which would help in better designing these parameters.

2. **Using New Control Algorithms**:As discussed earlier, impedance control suffers from issues of inaccuracy and delay. Parameter optimization may alleviate these issues to some extent but cannot fundamentally resolve them. Future efforts could explore better motion control algorithms, or develop motion control algorithms specifically tailored for teleoperation.

3. **Using New Input Hardware**:Due to the inherent limitations of the PS4 Controller, the design of the HMI and the degrees of freedom for rotation are impacted, and the types of feedback are limited. Using new input hardware could potentially alleviate these issues. For example, joysticks with more DoFs could be employed so that the control of movements in XYZ directions can be executed with a single joystick; additionally, devices with force feedback could enrich the information feedback in the HMI.

7.2.2. Future Work on User Study Design

1. **Task Design Improvements**:Although quantitative data from this user study did not demonstrate the PS4 Controller HMI's superiority in performance or workload compared to the leader-follower HMI, interviews and observations during the experiments indicated that the new HMI has the potential to surpass the leader-follower HMI in certain aspects. These advantages were not reflected in the data primarily because the experiment did not quantify these characteristics. For example, it was noticed that the PS4 controller HMI exhibited advantages in low-precision movements and that its error recovery was more straightforward. Future experiments could attempt to quantify and verify these characteristics using new experiment tasks.

2. **Collecting More Data for Evaluation**:Future experimental designs could explore different assessment forms. As different users have varying habits in handling the joystick to control robots, the next step could involve recording and analyzing how users operate the joystick and comparing this data with the robot's movement data, which might yield some insightful observations.

In conclusion, while the PS4 controller HMI did not meet the expectations set against the traditional leader-follower system in this study, the insights gained point towards potential for improvement. This thesis lays the groundwork for future endeavors in the intersection of teleoperation system and industrial manufacturing.

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Abbreviation

Symbol Directory

Scalar

F

K

Appendix

Appendix A Personal Information and Affinity for Technology Interaction(ATI) Questionnaire

Robot Teleoperation User Experience

There are 13 questions in this survey.

General Information

Please enter the code you receive from the study director for pseudonymization:

Please write your answer here:

Please enter your answer here:

How old are you? *

Please write your answer here:

What is your gender? *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Female
- ◯ Male
- ◯ Diverse

Do you need a visual aid (e.g. glasses, contact lenses)? *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Yes, and I am using it during this study
- ◯ Yes, but I am NOT using it during this study
- ◯ No, I do not have/need any visual aids.

Do you already have previous experience with teleoperated robots? *

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Yes, I am using / have used teleoperated robots at work.
- ◯ Yes, I am using / have used teleoperated robots in my private life.
- ◯ Yes, I have participated in previous studies involving teleoperated robots.
- ◯ Yes, I have previous experience with teleoperated robots from other situations as mentioned above.
- ◯ No.

In the following questionnaire, we will ask you about your interaction with technical systems. The term “technical systems” refers to apps and other software applications, as well as entire digital devices (e.g., mobile phone, computer, TV, car navigation).

Please indicate the degree to which you agree/disagree with the following statements. (1= completely disagree, 5= completely agree)

*

Please choose the appropriate response for each item:

	1	2	3	4	5
I lik e to occupy myself in greater detail with technical systems.	○	○	○	○	○
I lik e testing the functions of new technical systems.	○	○	○	○	○
I predominantly deal with technical systems because I have to.	○	○	○	○	○
Wh en I have a new technical system in front of me, I try it out intensively.	○	○	○	○	○
I enjoy spending time becoming acquainted with a new technical system.	○	○	○	○	○
It is enough for me that a technical system works; I don’t care how or why.	○	○	○	○	○

	1	2	3	4	5
I try to understand how a technical system exactly works.	◯	◯	◯	◯	◯
It is enough for me to know the basic functions of a technical system.	◯	◯	◯	◯	◯
I try to make full use of the capabilities of a technical system.	◯	◯	◯	◯	◯

Have you ever used a PlayStation 4 or Xbox controller before (or similar game controllers)?

If so, how often do you use a PS4/Xbox controller?

*

Choose one of the following answers
Please choose **only one** of the following:

- ◯ Never.
- ◯ I have used it in the past, but not anymore.
- ◯ Sometimes, but less than 1 h per week.
- ◯ 1h - 3h per week.
- ◯ More than 3h per week.

Questionnaire Scenario 1

What kind of teleoperation test have you just done? *

Choose one of the following answers

Please choose **only one** of the following:

- ◯ Using robot to control robot
- ◯ Using PS4 controller to control robot

NASA-TLX

Please give your assessment of the following questions **regarding the control of the teleoperated robot**. (0 = very low, 10 = very high)

*

Please choose the appropriate response for each item:

	1	2	3	4	5	6	7	8	9	10
How mentally demanding was the task?	○	○	○	○	○	○	○	○	○	○
How physically demanding was the task?	○	○	○	○	○	○	○	○	○	○
How hurried or rushed was the pace of the task?	○	○	○	○	○	○	○	○	○	○
How successful were you in accomplishing what you were asked to do (0 = perfect, 10 = failure)	○	○	○	○	○	○	○	○	○	○
How hard did you have to work to accomplish your level of performance?	○	○	○	○	○	○	○	○	○	○
How insecure, discouraged, irritated, stressed, and annoyed wereyou?	○	○	○	○	○	○	○	○	○	○
	○	○	○	○	○	○	○	○	○	○
	○	○	○	○	○	○	○	○	○	○

System Usability Scale

Please give your assessment of the following statements **regarding the control of the teleoperated robot**. (1 = strongly disagree, 5 = strongly agree)

*

Please choose the appropriate response for each item:

	1	2	3	4	5
I think that I would like to use this system frequently.	○	○	○	○	○
I find the system unnecessarily complex.	○	○	○	○	○
I think this system is easy to use.	○	○	○	○	○
I think I would need the support of a technical person to be able to use the system.	○	○	○	○	○
I find the various functions of the system are well integrated.	○	○	○	○	○
I think there is too much inconsistency in the system.	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly.	○	○	○	○	○
I find the system very awkward to use.	○	○	○	○	○

	1	2	3	4	5
I felt very confident using the system.	◯	◯	◯	◯	◯
I needed to learn a lot of things before I could get going with the system.	◯	◯	◯	◯	◯

Questionnaire Scenario 2

What kind of teleoperation test have you just done? *

Choose one of the following answers
Please choose **only one** of the following:

◯ Using robot to control robot
◯ Using PS4 controller to control robot

NASA-TLX

Please give your assessment of the following questions **regarding the control of the teleoperated robot**. (0 = very low, 10 = very high)

Please choose the appropriate response for each item:

	1	2	3	4	5	6	7	8	9	10
How mentally demanding was the task?	○	○	○	○	○	○	○	○	○	○
How physically demanding was the task?	○	○	○	○	○	○	○	○	○	○
How many factors had an impact on the change in your situation during the Trial Execution?	○	○	○	○	○	○	○	○	○	○
How successful were you in accomplishing what you were asked to do? (0 = perfect, 10 = failure)	○	○	○	○	○	○	○	○	○	○
How hard did you have to work to accomplish your level of performance?	○	○	○	○	○	○	○	○	○	○
How insecure, discouraged, irritated, stressed, and annoyed wereyou?	○	○	○	○	○	○	○	○	○	○
	○	○	○	○	○	○	○	○	○	○
	○	○	○	○	○	○	○	○	○	○

System Usability Scale

Please give your assessment of the following statements **regarding the control of the teleoperated robot**. (1 = strongly disagree, 5 = strongly agree)

*

Please choose the appropriate response for each item:

	1	2	3	4	5
I think that I would like to use this system frequently.	○	○	○	○	○
I find the system unnecessarily complex.	○	○	○	○	○
I find the system easy to use.	○	○	○	○	○
I think I would need the support of a technical person to be able to use the system.	○	○	○	○	○
I find the various functions of the system are well integrated.	○	○	○	○	○
I think there is too much inconsistency in the system.	○	○	○	○	○
I imagine that most people would learn to use this system very quickly.	○	○	○	○	○
I find the system very awkward to use.	○	○	○	○	○

	1	2	3	4	5
I felt very confident using the system.	◯	◯	◯	◯	◯
I needed to learn a lot of things before I could get going with the system.	◯	◯	◯	◯	◯

Submit your survey.
Thank you for completing this survey.

Appendix B NASA-TLX Questionnaire

NASA Task Load Index

Please give your assessment of the following questions regarding the control of the teleoperated robot.

Participant	Control robot

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

NASA Task Load Index

Please give your assessment of the following questions regarding the control of the teleoperated robot.

Participant	Control
	PS4

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Appendix C SUS Questionnaire

Participant

System Usability Scale (SUS)

Control

robot

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

Participant

System Usability Scale (SUS)

Control

PS4

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

Appendix D Personal Information and Affinity for Technology Interaction(ATI) Questionnaire Results

Robot Teleoperation User Experience

Survey response 1

General Information

Q00
1

G01Q02
21

G01Q03
Male

G01Q04
No, I do not have/need any visual aids.

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
2

ATI[SQ003]
3

ATI[SQ004]
2

ATI[SQ005]
2

ATI[SQ006]
3

ATI[SQ007]
3

ATI[SQ008]
4

ATI[SQ009]
3

G01Q07
Sometimes, but less than 1 h per week.

Survey response 2

General Information

Q00
2

G01Q02
26

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
5

ATI[SQ002]
5

ATI[SQ003]
5

ATI[SQ004]
5

ATI[SQ005]
5

ATI[SQ006]
1

ATI[SQ007]
5

ATI[SQ008]
5

ATI[SQ009]
5

G01Q07
Never.

Survey response 3

General Information

Q00
3

G01Q02
25

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
5

ATI[SQ003]
5

ATI[SQ004]
5

ATI[SQ005]
5

ATI[SQ006]
3

ATI[SQ007]
4

ATI[SQ008]
2

ATI[SQ009]
5

G01Q07
Sometimes, but less than 1 h per week.

Survey response 4

General Information

Q00
4

G01Q02
23

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
4

ATI[SQ002]
4

ATI[SQ003]
2

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
3

ATI[SQ007]
3

ATI[SQ008]
3

ATI[SQ009]
4

G01Q07
Never.

Survey response 5

General Information

Q00
5

G01Q02
26

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
4

ATI[SQ003]
1

ATI[SQ004]
3

ATI[SQ005]
3

ATI[SQ006]
3

ATI[SQ007]
3

ATI[SQ008]
4

ATI[SQ009]
3

G01Q07
Sometimes, but less than 1 h per week.

Survey response 6

General Information

Q00
6

G01Q02
28

G01Q03
Female

G01Q04
No, I do not have/need any visual aids.

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
5

ATI[SQ003]
2

ATI[SQ004]
2

ATI[SQ005]
3

ATI[SQ006]
5

ATI[SQ007]
1

ATI[SQ008]
5

ATI[SQ009]
1

G01Q07
Never.

Survey response 7

General Information

Q00
7

G01Q02
26

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
Yes, I have previous experience with teleoperated robots from other situations as mentioned above.

ATI[SQ001]
4

ATI[SQ002]
3

ATI[SQ003]
2

ATI[SQ004]
3

ATI[SQ005]
3

ATI[SQ006]
2

ATI[SQ007]
4

ATI[SQ008]
3

ATI[SQ009]
2

G01Q07
Sometimes, but less than 1 h per week.

Survey response 8

General Information

Q00
8

G01Q02
24

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
5

ATI[SQ002]
5

ATI[SQ003]
1

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
1

ATI[SQ007]
5

ATI[SQ008]
2

ATI[SQ009]
5

G01Q07
I have used it in the past, but not anymore.

Survey response 9

General Information

Q00
9

G01Q02
25

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
4

ATI[SQ002]
5

ATI[SQ003]
3

ATI[SQ004]
4

ATI[SQ005]
3

ATI[SQ006]
2

ATI[SQ007]
4

ATI[SQ008]
2

ATI[SQ009]
4

G01Q07
I have used it in the past, but not anymore.

Survey response 10

General Information

Q00
10

G01Q02
35

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
5

ATI[SQ003]
2

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
3

ATI[SQ007]
4

ATI[SQ008]
3

ATI[SQ009]
5

G01Q07
I have used it in the past, but not anymore.

Survey response 11

General Information

Q00
11

G01Q02
37

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
4

ATI[SQ003]
1

ATI[SQ004]
5

ATI[SQ005]
3

ATI[SQ006]
2

ATI[SQ007]
4

ATI[SQ008]
3

ATI[SQ009]
5

G01Q07
Never.

Survey response 12

General Information

Q00
12

G01Q02
30

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
5

ATI[SQ002]
4

ATI[SQ003]
2

ATI[SQ004]
4

ATI[SQ005]
5

ATI[SQ006]
1

ATI[SQ007]
4

ATI[SQ008]
5

ATI[SQ009]
4

G01Q07
Never.

Survey response 13

General Information

Q00
13

G01Q02
26

G01Q03
Male

G01Q04
Yes, but I am NOT using it during this study

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
5

ATI[SQ003]
4

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
4

ATI[SQ007]
2

ATI[SQ008]
3

ATI[SQ009]
5

G01Q07
I have used it in the past, but not anymore.

Survey response 14

General Information

Q00
14

G01Q02
27

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
3

ATI[SQ003]
4

ATI[SQ004]
3

ATI[SQ005]
3

ATI[SQ006]
3

ATI[SQ007]
3

ATI[SQ008]
3

ATI[SQ009]
4

G01Q07
Sometimes, but less than 1 h per week.

Survey response 15

General Information

Q00
15

G01Q02
23

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
5

ATI[SQ002]
3

ATI[SQ003]
3

ATI[SQ004]
2

ATI[SQ005]
3

ATI[SQ006]
3

ATI[SQ007]
4

ATI[SQ008]
4

ATI[SQ009]
3

G01Q07
I have used it in the past, but not anymore.

Survey response 16

General Information

Q00
16

G01Q02
21

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
5

ATI[SQ002]
3

ATI[SQ003]
2

ATI[SQ004]
3

ATI[SQ005]
4

ATI[SQ006]
3

ATI[SQ007]
2

ATI[SQ008]
3

ATI[SQ009]
2

G01Q07
Never.

Survey response 17

General Information

Q00
17

G01Q02
24

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
2

ATI[SQ002]
3

ATI[SQ003]
3

ATI[SQ004]
3

ATI[SQ005]
2

ATI[SQ006]
4

ATI[SQ007]
4

ATI[SQ008]
4

ATI[SQ009]
4

G01Q07
Never.

Survey response 18

General Information

Q00
18

G01Q02
23

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
4

ATI[SQ002]
4

ATI[SQ003]
4

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
2

ATI[SQ007]
3

ATI[SQ008]
4

ATI[SQ009]
3

G01Q07
Sometimes, but less than 1 h per week.

Survey response 19

General Information

Q00
19

G01Q02
27

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
4

ATI[SQ002]
5

ATI[SQ003]
1

ATI[SQ004]
2

ATI[SQ005]
4

ATI[SQ006]
1

ATI[SQ007]
5

ATI[SQ008]
2

ATI[SQ009]
5

G01Q07
1h - 3h per week.

Survey response 20

General Information

Q00
20

G01Q02
28

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
5

ATI[SQ002]
4

ATI[SQ003]
3

ATI[SQ004]
2

ATI[SQ005]
4

ATI[SQ006]
1

ATI[SQ007]
5

ATI[SQ008]
2

ATI[SQ009]
3

G01Q07
Never.

Survey response 21

General Information

Q00
21

G01Q02
21

G01Q03
Male

G01Q04
No, I do not have/need any visual aids.

G01Q05
Yes, I am using / have used teleoperated robots in my private life.

ATI[SQ001]
3

ATI[SQ002]
4

ATI[SQ003]
2

ATI[SQ004]
3

ATI[SQ005]
2

ATI[SQ006]
2

ATI[SQ007]
3

ATI[SQ008]
4

ATI[SQ009]
3

G01Q07
1h - 3h per week.

Survey response 22

General Information

Q00
22

G01Q02
23

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
3

ATI[SQ002]
5

ATI[SQ003]
2

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
1

ATI[SQ007]
5

ATI[SQ008]
2

ATI[SQ009]
4

G01Q07
I have used it in the past, but not anymore.

Survey response 23

General Information

Q00
23

G01Q02
25

G01Q03
Male

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
4

ATI[SQ002]
4

ATI[SQ003]
2

ATI[SQ004]
3

ATI[SQ005]
4

ATI[SQ006]
2

ATI[SQ007]
5

ATI[SQ008]
4

ATI[SQ009]
3

G01Q07
Sometimes, but less than 1 h per week.

Survey response 24

General Information

Q00
24

G01Q02
27

G01Q03
Male

G01Q04
Yes, but I am NOT using it during this study

G01Q05
Yes, I am using / have used teleoperated robots in my private life.

ATI[SQ001]
3

ATI[SQ002]
3

ATI[SQ003]
3

ATI[SQ004]
3

ATI[SQ005]
3

ATI[SQ006]
3

ATI[SQ007]
3

ATI[SQ008]
3

ATI[SQ009]
3

G01Q07
Sometimes, but less than 1 h per week.

Survey response 25

General Information

Q00
25

G01Q02
26

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
5

ATI[SQ002]
5

ATI[SQ003]
5

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
3

ATI[SQ007]
3

ATI[SQ008]
4

ATI[SQ009]
2

G01Q07
Sometimes, but less than 1 h per week.

Survey response 26

General Information

Q00
26

G01Q02
21

G01Q03
Male

G01Q04
No, I do not have/need any visual aids.

G01Q05
Yes, I have previous experience with teleoperated robots from other situations as mentioned above.

ATI[SQ001]
4

ATI[SQ002]
4

ATI[SQ003]
2

ATI[SQ004]
2

ATI[SQ005]
4

ATI[SQ006]
3

ATI[SQ007]
4

ATI[SQ008]
2

ATI[SQ009]
4

G01Q07
I have used it in the past, but not anymore.

Survey response 27

General Information

Q00
27

G01Q02
30

G01Q03
Male

G01Q04
No, I do not have/need any visual aids.

G01Q05
Yes, I have participated in previous studies involving teleoperated robots.

ATI[SQ001]
5

ATI[SQ002]
5

ATI[SQ003]
5

ATI[SQ004]
5

ATI[SQ005]
5

ATI[SQ006]
3

ATI[SQ007]
5

ATI[SQ008]
5

ATI[SQ009]
5

G01Q07
I have used it in the past, but not anymore.

Survey response 28

General Information

Q00
28

G01Q02
21

G01Q03
Male

G01Q04
No, I do not have/need any visual aids.

G01Q05
Yes, I am using / have used teleoperated robots in my private life.

ATI[SQ001]
4

ATI[SQ002]
4

ATI[SQ003]
3

ATI[SQ004]
5

ATI[SQ005]
4

ATI[SQ006]
2

ATI[SQ007]
5

ATI[SQ008]
2

ATI[SQ009]
4

G01Q07
I have used it in the past, but not anymore.

Survey response 29

General Information

Q00
29

G01Q02
23

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
1

ATI[SQ002]
3

ATI[SQ003]
4

ATI[SQ004]
2

ATI[SQ005]
2

ATI[SQ006]
4

ATI[SQ007]
3

ATI[SQ008]
3

ATI[SQ009]
1

G01Q07
More than 3h per week.

Survey response 30

General Information

Q00
30

G01Q02
26

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
Yes, I have previous experience with teleoperated robots from other situations as mentioned above.

ATI[SQ001]
4

ATI[SQ002]
4

ATI[SQ003]
3

ATI[SQ004]
4

ATI[SQ005]
3

ATI[SQ006]
3

ATI[SQ007]
3

ATI[SQ008]
4

ATI[SQ009]
4

G01Q07
I have used it in the past, but not anymore.

Survey response 31

General Information

Q00
31

G01Q02
29

G01Q03
Male

G01Q04
No, I do not have/need any visual aids.

G01Q05
Yes, I am using / have used teleoperated robots at work.

ATI[SQ001]
5

ATI[SQ002]
5

ATI[SQ003]
2

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
3

ATI[SQ007]
3

ATI[SQ008]
4

ATI[SQ009]
4

G01Q07
More than 3h per week.

Survey response 32

General Information

Q00
32

G01Q02
26

G01Q03
Female

G01Q04
No, I do not have/need any visual aids.

G01Q05
Yes, I have participated in previous studies involving teleoperated robots.

ATI[SQ001]
2

ATI[SQ002]
3

ATI[SQ003]
3

ATI[SQ004]
2

ATI[SQ005]
2

ATI[SQ006]
4

ATI[SQ007]
2

ATI[SQ008]
4

ATI[SQ009]
2

G01Q07
Never.

Survey response 33

General Information

Q00
33

G01Q02
28

G01Q03
Male

G01Q04
No, I do not have/need any visual aids.

G01Q05
Yes, I have participated in previous studies involving teleoperated robots.

ATI[SQ001]
5

ATI[SQ002]
5

ATI[SQ003]
1

ATI[SQ004]
5

ATI[SQ005]
5

ATI[SQ006]
1

ATI[SQ007]
4

ATI[SQ008]
2

ATI[SQ009]
5

G01Q07
1h - 3h per week.

Survey response 34

General Information

Q00
34

G01Q02
22

G01Q03
Female

G01Q04
Yes, but I am NOT using it during this study

G01Q05
No.

ATI[SQ001]
4

ATI[SQ002]
3

ATI[SQ003]
4

ATI[SQ004]
3

ATI[SQ005]
3

ATI[SQ006]
4

ATI[SQ007]
3

ATI[SQ008]
4

ATI[SQ009]
2

G01Q07
Never.

Survey response 35

General Information

Q00
35

G01Q02
24

G01Q03
Female

G01Q04
Yes, but I am NOT using it during this study

G01Q05
No.

ATI[SQ001]
4

ATI[SQ002]
5

ATI[SQ003]
3

ATI[SQ004]
4

ATI[SQ005]
4

ATI[SQ006]
2

ATI[SQ007]
4

ATI[SQ008]
2

ATI[SQ009]
5

G01Q07
Never.

Survey response 36

General Information

Q00
36

G01Q02
26

G01Q03
Female

G01Q04
Yes, and I am using it during this study

G01Q05
No.

ATI[SQ001]
5

ATI[SQ002]
5

ATI[SQ003]
5

ATI[SQ004]
5

ATI[SQ005]
5

ATI[SQ006]
2

ATI[SQ007]
5

ATI[SQ008]
3

ATI[SQ009]
3

G01Q07
1h - 3h per week.

Appendix E Independents Results(TCT, grasp and drop attempt, subjective workload and perceived usability)

PS4 HMI	TCT				
Participant	cylinder_l	cube_l	cylinder_r	cube_r	average
1	50.000	229.000	160.000	211.000	162.500
2	92.000	650.000	120.000	96.000	239.500
3	59.000	237.000	93.000	76.000	116.250
4	35.000	107.000	22.000	72.000	59.000
5	55.000	44.000	64.000	29.000	48.000
6	584.000	340.000	107.000	170.000	300.250
7	140.000	64.000	196.000	86.000	121.500
8	21.000	33.000	24.000	41.000	29.750
9	58.000	74.000	80.000	175.000	96.750
10	50.000	246.000	78.000	56.000	107.500
11	199.000	143.000	58.000	90.000	122.500
12	81.000	70.000	181.000	443.000	193.750
13	49.000	511.000	29.000	162.000	187.750
14	56.000	99.000	44.000	129.000	82.000
15	24.000	27.000	16.000	24.000	22.750
16	67.000	211.000	50.000	190.000	129.500
17	65.000	91.000	75.000	80.000	77.750
18	79.000	176.000	74.000	65.000	98.500
19	89.000	411.000	49.000	112.000	165.250
20	187.000	59.000	70.000	177.000	123.250
21	31.000	40.000	41.000	82.000	48.500
22	35.000	46.000	125.000	86.000	73.000
23	42.000	36.000	44.000	439.000	140.250
24	49.000	244.000	36.000	259.000	147.000
25	171.000	55.000	68.000	44.000	84.500
26	29.000	78.000	55.000	126.000	72.000
27	99.000	166.000	8.000	97.000	92.500
28	21.000	97.000	31.000	36.000	46.250
29	37.000	61.000	31.000	36.000	41.250
30	99.000	83.000	86.000	70.000	84.500
31	43.000	39.000	39.000	164.000	71.250
32	58.000	51.000	106.000	50.000	66.250
33	31.000	29.000	22.000	20.000	25.500
34	306.000	478.000	81.000	294.000	289.750
35	72.000	175.000	48.000	1038.000	333.250
36	51.000	330.000	86.000	42.000	127.250

robot HMI	TCT				
Participant	cylinder_l	cube_l	cylinder_r	cube_r	average
1	28.000	22.000	16.000	15.000	20.250
2	38.000	26.000	40.000	124.000	57.000
3	66.000	105.000	29.000	43.000	60.750
4	25.000	24.000	15.000	43.000	26.750
5	25.000	21.000	26.000	22.000	23.500
6	24.000	19.000	19.000	17.000	19.750
7	37.000	28.000	20.000	69.000	38.500
8	13.000	33.000	13.000	15.000	18.500
9	33.000	32.000	28.000	33.000	31.500
10	43.000	32.000	26.000	32.000	33.250
11	0.000	27.000	30.000	67.000	31.000
12	25.000	27.000	16.000	115.000	45.750
13	93.000	39.000	49.000	23.000	51.000
14	38.000	33.000	61.000	71.000	50.750
15	37.000	55.000	12.000	16.000	30.000
16	36.000	40.000	28.000	69.000	43.250
17	40.000	272.000	32.000	69.000	103.250
18	19.000	42.000	13.000	17.000	22.750
19	62.000	47.000	30.000	38.000	44.250
20	36.000	29.000	50.000	27.000	35.500
21	28.000	26.000	17.000	22.000	23.250
22	21.000	30.000	18.000	18.000	21.750
23	66.000	25.000	30.000	19.000	35.000
24	27.000	22.000	31.000	22.000	25.500
25	28.000	47.000	24.000	41.000	35.000
26	46.000	34.000	35.000	72.000	46.750
27	23.000	18.000	16.000	17.000	18.500
28	29.000	31.000	23.000	22.000	26.250
29	29.000	33.000	24.000	29.000	28.750
30	39.000	93.000	26.000	101.000	64.750
31	22.000	22.000	21.000	18.000	20.750
32	42.000	65.000	31.000	41.000	44.750
33	17.000	12.000	14.000	10.000	13.250
34	28.000	82.000	28.000	18.000	39.000
35	31.000	43.000	28.000	58.000	40.000
36	39.000	142.000	36.000	160.000	94.250

PS4 HMI	Grasp Attempt				
Participant	cylinder_l	cube_l	cylinder_r	cube_r	average
1	1	4	2	6	3.25
2	1	10	3	1	3.75
3	1	6	3	1	2.75
4	2	6	1	4	3.25
5	2	1	2	1	1.5
6	8	2	2	1	3.25
7	3	1	3	1	2
8	1	1	1	1	1
9	1	1	3	3	2
10	1	6	2	1	2.5
11	1	3	2	4	2.5
12	2	3	5	13	5.75
13	1	19	1	6	6.75
14	2	3	1	7	3.25
15	1	2	1	1	1.25
16	1	5	1	6	3.25
17	2	1	1	1	1.25
18	2	1	1	1	1.25
19	4	5	1	1	2.75
20	3	1	1	1	1.5
21	1	1	2	2	1.5
22	2	1	4	1	2
23	1	1	1	9	3
24	1	6	1	10	4.5
25	6	1	2	1	2.5
26	1	3	2	7	3.25
27	3	6	2	1	3
28	2	5	1	2	2.5
29	1	1	1	1	1
30	1	1	2	1	1.25
31	3	2	1	6	3
32	1	1	2	3	1.75
33	1	1	1	1	1
34	5	7	1	6	4.75
35	5	7	4	24	10
36	2	9	2	1	3.5

robot HMI	Grasp Attempt				
Participant	cylinder_l	cube_l	cylinder_r	cube_r	average
1	1	1	1	1	1
2	2	1	1	6	2.5
3	1	5	1	1	2
4	1	1	1	2	1.25
5	1	1	2	1	1.25
6	1	1	1	1	1
7	2	1	1	3	1.75
8	1	1	1	1	1
9	2	2	1	1	1.5
10	1	1	1	1	1
11	1	1	2	1	1.25
12	1	1	1	7	2.5
13	3	1	4	1	2.25
14	2	1	3	5	2.75
15	2	4	1	1	2
16	1	1	1	3	1.5
17	1	3	1	1	1.5
18	1	3	1	1	1.5
19	2	1	1	1	1.25
20	1	1	1	1	1
21	1	1	1	1	1
22	2	1	1	1	1.25
23	4	1	1	1	1.75
24	2	1	2	1	1.5
25	1	2	1	2	1.5
26	1	1	1	1	1
27	1	1	1	1	1
28	1	1	1	1	1
29	1	1	1	1	1
30	2	3	1	6	3
31	1	1	1	1	1
32	2	3	1	1	1.75
33	1	1	1	1	1
34	1	4	2	1	2
35	1	1	1	2	1.25
36	1	6	1	5	3.25

ps4 HMI	Drop Attempt				
Participant	cylinder_l	cube_l	cylinder_r	cube_r	average
1	1	3	2	3	2.25
2	1	5	2	1	2.25
3	1	3	2	1	1.75
4	1	4	1	1	1.75
5	1	1	1	1	1
6	3	1	1	1	1.5
7	1	1	1	1	1
8	1	1	1	1	1
9	1	1	1	2	1.25
10	1	4	1	1	1.75
11	1	2	1	2	1.5
12	1	2	2	7	3
13	1	9	1	2	3.25
14	1	2	1	5	2.25
15	1	1	1	1	1
16	1	2	1	2	1.5
17	1	1	1	1	1
18	1	1	1	1	1
19	1	3	1	1	1.5
20	1	1	1	1	1
21	1	1	1	1	1
22	1	1	2	1	1.25
23	1	1	1	6	2.25
24	1	3	1	4	2.25
25	2	1	1	1	1.25
26	1	2	1	3	1.75
27	1	3	1	1	1.5
28	1	3	1	1	1.5
29	1	1	1	1	1
30	1	1	1	1	1
31	1	1	1	3	1.5
32	1	1	1	2	1.25
33	1	1	1	1	1
34	3	3	1	4	2.75
35	1	3	1	11	4
36	1	5	1	1	2

robot HMI	Drop Attempt				
Participant	cylinder_l	cube_l	cylinder_r	cube_r	average
1	1	1	1	1	1
2	1	1	1	4	1.75
3	1	4	1	1	1.75
4	1	1	1	1	1
5	1	1	1	1	1
6	1	1	1	1	1
7	1	1	1	2	1.25
8	1	1	1	1	1
9	1	1	1	1	1
10	1	1	1	1	1
11	1	1	1	1	1
12	1	1	1	6	2.25
13	1	1	1	1	1
14	1	1	3	3	2
15	2	3	1	1	1.75
16	1	1	1	2	1.25
17	1	2	1	1	1.25
18	1	2	1	1	1.25
19	1	1	1	1	1
20	1	1	1	1	1
21	1	1	1	1	1
22	1	1	1	1	1
23	1	1	1	1	1
24	1	1	1	1	1
25	1	2	1	2	1.5
26	1	1	1	1	1
27	1	1	1	1	1
28	1	1	1	1	1
29	1	1	1	1	1
30	2	2	1	2	1.75
31	1	1	1	1	1
32	2	2	1	1	1.5
33	1	1	1	1	1
34	1	2	1	1	1.25
35	1	1	1	1	1
36	1	2	1	3	1.75

ps4 HMI	NASA-TLX						
participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Average
4	55	15	15	40	70	20	35.833
5	5	5	5	10	20	5	8.333
6	100	100	85	50	95	15	74.167
7	75	65	70	45	85	65	67.500
8	70	25	65	25	70	30	47.500
9	25	25	35	25	25	10	24.167
10	75	5	5	30	60	60	39.167
11	50	50	50	0	0	0	25.000
12	40	10	40	30	30	30	30.000
13	55	65	25	70	70	0	47.500
14	45	5	5	45	50	10	26.667
15	20	0	10	10	10	5	9.167
16	40	40	50	45	50	40	44.167
17	80	10	35	25	95	5	41.667
18	40	20	50	55	55	35	42.500
19	70	20	5	60	25	40	36.667
20	55	15	5	80	5	70	38.333
21	20	5	65	20	60	5	29.167
22	80	10	15	90	90	85	61.667
23	20	40	0	25	0	30	19.167
24	55	55	40	60	60	60	55.000
25	65	5	60	5	60	35	38.333
26	50	0	50	25	30	20	29.167
27	70	80	50	20	70	50	56.667
28	40	0	40	15	45	25	27.500
29	95	95	35	0	85	0	51.667
30	60	75	50	50	60	60	59.167
31	70	20	15	10	70	50	39.167
32	70	45	50	85	80	70	66.667
33	15	0	30	15	10	0	11.667
34	70	15	50	45	60	75	52.500
35	30	65	50	30	60	55	48.333
36	85	90	50	70	70	25	65.000

robot HMI	NASA-TLX						
participant	Mental	Physical	Temporal	Performance	Effort	Frustration	Average
4	15	15	15	10	35	5	15.833
5	5	20	5	10	15	5	10.000
6	5	100	5	5	5	5	20.833
7	15	45	15	30	15	5	20.833
8	35	20	70	15	30	15	30.833
9	10	55	40	10	20	10	24.167
10	50	5	5	15	20	5	16.667
11	5	5	5	5	5	5	5.000
12	20	20	20	5	30	5	16.667
13	10	90	90	0	0	50	40.000
14	25	10	5	35	45	20	23.333
15	20	35	10	30	30	20	24.167
16	10	10	10	5	20	0	9.167
17	85	85	70	50	70	65	70.833
18	10	10	10	10	10	10	10.000
19	30	30	15	20	15	15	20.833
20	15	60	20	20	0	45	26.667
21	30	40	20	10	30	15	24.167
22	35	45	60	50	50	65	50.833
23	25	80	0	10	0	0	19.167
24	65	60	30	20	0	100	45.833
25	5	5	15	5	5	5	6.667
26	15	10	50	10	10	0	15.833
27	70	70	70	10	20	20	43.333
28	10	20	20	0	15	0	10.833
29	100	100	30	15	80	0	54.167
30	30	15	15	25	10	10	17.500
31	5	5	5	0	5	5	4.167
32	25	60	45	65	75	55	54.167
33	0	30	5	5	5	0	7.500
34	20	20	40	70	40	35	37.500
35	25	30	35	85	10	5	31.667
36	75	75	50	20	75	25	53.333

ps4 HMI	SUS score									
Participant										Final
1	4	3	2	3	4	2	3	4	4	3	55
2	2	3	2	2	2	3	1	4	3	4	35
3	5	1	4	1	5	2	5	2	4	1	90
4	5	1	3	1	5	1	4	2	3	1	85
5	3	1	5	1	5	1	4	1	5	2	90
6	3	5	3	3	4	5	3	3	3	1	47.5
7	2	2	4	3	4	3	4	3	2	2	57.5
8	4	3	2	2	3	4	3	2	3	1	57.5
9	2	1	5	1	3	3	5	3	5	1	77.5
10	1	3	2	1	3	4	2	4	2	2	40
11	5	1	4	5	3	3	4	1	5	1	75
12	3	2	2	1	4	1	3	2	3	1	70
13	3	4	4	1	4	3	5	4	4	2	65
14	3	2	3	2	5	1	2	2	3	2	67.5
15	4	1	4	1	4	2	5	1	4	3	82.5
16	2	2	3	2	3	1	3	2	3	2	62.5
17	2	1	5	3	2	3	4	2	3	2	62.5
18	3	3	4	2	4	2	3	2	3	2	65
19	3	1	3	1	4	1	5	2	4	1	82.5
20	3	3	2	1	2	4	4	2	2	1	55
21	3	1	4	1	4	1	4	2	4	1	82.5
22	1	3	1	1	2	2	3	4	1	2	40
23	4	1	5	1	5	1	4	1	4	1	92.5
24	3	3	3	3	2	4	3	3	3	4	42.5
25	4	1	5	4	5	1	5	1	5	1	90
26	3	1	3	1	5	3	2	3	3	1	67.5
27	3	4	4	2	3	3	5	3	3	1	62.5
28	2	2	2	3	2	4	3	4	2	3	37.5
29	3	1	5	2	5	1	5	1	5	2	90
30	1	2	2	2	2	3	2	4	2	3	37.5
31	3	3	2	2	5	1	3	1	4	1	72.5
32	1	4	1	4	2	4	1	4	2	3	20
33	5	2	4	1	5	1	3	1	5	1	90
34	2	3	3	3	3	3	2	4	2	4	37.5
35	3	1	3	1	3	4	4	3	2	1	62.5
36	3	2	2	4	4	2	4	2	2	4	52.5

robot HMI	SUS score									
Participant										Final
1	2	4	4	1	3	2	4	2	4	2	65
2	3	1	2	1	4	3	3	2	4	1	70
3	5	1	5	1	5	1	5	1	3	1	95
4	5	1	5	1	5	1	5	1	5	1	100
5	4	1	5	1	5	1	5	2	5	1	95
6	5	1	5	1	4	2	5	1	5	1	95
7	4	1	4	1	5	1	5	5	5	1	85
8	5	1	4	1	5	1	5	2	5	1	95
9	3	1	5	1	3	2	5	4	5	1	80
10	3	2	5	1	4	2	5	3	5	1	82.5
11	4	5	5	4	4	2	5	1	5	1	75
12	4	1	4	1	5	1	5	1	5	1	95
13	4	5	5	1	2	3	5	4	5	1	67.5
14	3	2	4	2	5	2	4	2	3	2	72.5
15	2	3	4	2	5	1	3	3	4	2	67.5
16	2	1	4	2	3	2	4	2	4	1	72.5
17	2	4	3	4	4	1	4	2	4	2	60
18	4	3	4	2	5	1	5	1	4	2	82.5
19	5	1	4	1	5	1	5	1	4	1	95
20	4	1	4	4	4	3	5	2	5	1	77.5
21	2	4	3	1	3	1	4	2	4	1	67.5
22	3	2	3	2	2	4	5	2	4	2	62.5
23	5	1	5	1	4	1	5	1	5	1	97.5
24	1	2	1	2	5	3	2	2	1	5	40
25	4	1	5	1	5	1	5	1	5	1	97.5
26	3	1	5	2	5	1	5	1	4	1	90
27	5	2	5	1	4	3	5	2	5	1	87.5
28	5	2	5	2	5	1	3	1	5	2	87.5
29	4	1	5	2	5	1	5	1	5	1	95
30	3	2	5	5	5	1	5	1	4	1	80
31	5	1	5	1	5	1	5	1	5	1	100
32	2	3	2	2	3	3	4	4	3	1	52.5
33	5	1	5	1	4	1	4	1	5	1	95
34	3	1	4	3	3	3	4	2	3	1	67.5
35	1	1	4	1	5	1	4	1	5	1	85
36	3	1	3	4	4	2	4	1	3	4	62.5

Appendix F Interview Results

Participant	Interview Feedbacks about PS4 controller HMI	Interview Feedbacks about Leader Follower HMI
1	Better grasp function	Haptic feedback is good,feel if the shape is in
2	Inaccurate, shifting	
3	Easy to use , but with time delay	Require strength, but efficient
4	. Ps4 easier, because you only move	robot inconvinient, clumsy
5		robot grippers inconvienient, but movement is
6	easy to use, but motion to fast,	2: easy to control, but inconvient.
7	time demanding, motion delay, easy to control but not accurate enough	much easier, but at certain pose not smooth to move,
8	easier to use, but movement shifting,fun, left/right joystick confusing,	gripper closing move the tcp, provide more DoF for joints movement
9	not accurate	easy to use, get instant feedback, get intuitive
10	need to consider many things when operating, inaccurate, too sensitive,	better, intuitive, easy to move
11	move fast,	easy to use
12	not easy to use, no feedback, need	better, haptic feedback, it will be better to be
13	easy to grasp, but movement is not	haptic feedback is good,feel if the shape is in
14	more precise, movement is more subtle, prefer controller	easy to use, intuitive, does not require strength
15	controller better, easy to use	physical demanding, intuitive
16	cant see clearly, need practice	easy, better, more accurate, faster
17	normal, shifting	
18	need to memorize stuff,	easier
19	not intuitive , movement opposite ,	hard to move(physically)
20	not good enough for none expert, shifting, motion coupling	standard
21	as good as ps4 can do, easy to grasp stuff far away, restart is confusing	more presice, adding a grasp button, figering out robot pose is hard, has more potential, rely less on vision feedback
22	no experice with controller, annoying, rotation DoF lack. Restarting is faster. Personal parameter customization	joint limit unkown is insecure,
23	shifting, delay, release easier	gripper delay
24	hard to controll, time delay	easier, touch the robot make it more intuitive
25	shift , grasp easier	better visualization of the robot movement, more DoF, allows more strategy and
26	delay, shift	
27	hard to place the cube	better. Feel the robot position
28	not perfect for small movements	better sensitivity and accuracy
29	easy to learn because of experience, good integrated, sensitive, shift, best for	interesting, sensitive, easier to control, can use both hands to control, for sugery
30	fast, sensitive,suitable for daily use	precise, better
31	ok to use,	prefer this one for long time use
32	more difficult to use, rotation direction	more convenient to control,
33		better, easier to use, add a button to gripper
34	not familiar with controller, delay,hard to know position, not intuitive	easier
35	shifting, too sensitive	efficient to finish the task
36	move fast	robot has time delay, better and more

Appendix G Permutation Plan

Permutation Plan

Participant Number	Scenario Sequence
1	1.PS4 Controller 2. Leader-Follower
2	1. Leader-Follower 2. PS4 Controller
3	1.PS4 Controller 2. Leader-Follower
4	1. Leader-Follower 2. PS4 Controller
5	1.PS4 Controller 2. Leader-Follower
6	1. Leader-Follower 2. PS4 Controller
7	1.PS4 Controller 2. Leader-Follower
8	1. Leader-Follower 2. PS4 Controller
9	1.PS4 Controller 2. Leader-Follower
10	1. Leader-Follower 2. PS4 Controller
11	1.PS4 Controller 2. Leader-Follower
12	1. Leader-Follower 2. PS4 Controller
13	1.PS4 Controller 2. Leader-Follower
14	1. Leader-Follower 2. PS4 Controller
15	1.PS4 Controller 2. Leader-Follower
16	1. Leader-Follower 2. PS4 Controller
17	1.PS4 Controller 2. Leader-Follower
18	1. Leader-Follower 2. PS4 Controller
19	1.PS4 Controller 2. Leader-Follower
20	1. Leader-Follower 2. PS4 Controller
21	1.PS4 Controller 2. Leader-Follower
22	1. Leader-Follower 2. PS4 Controller
23	1.PS4 Controller 2. Leader-Follower
24	1. Leader-Follower 2. PS4 Controller
25	1.PS4 Controller 2. Leader-Follower
26	1. Leader-Follower 2. PS4 Controller
27	1.PS4 Controller 2. Leader-Follower
28	1. Leader-Follower 2. PS4 Controller
29	1.PS4 Controller 2. Leader-Follower
30	1. Leader-Follower 2. PS4 Controller
31	1.PS4 Controller 2. Leader-Follower
32	1. Leader-Follower 2. PS4 Controller
33	1.PS4 Controller 2. Leader-Follower
34	1. Leader-Follower 2. PS4 Controller
35	1.PS4 Controller 2. Leader-Follower
36	1. Leader-Follower 2. PS4 Controller

Appendix H Ethic Committee Permit

Technische Universität München | Ethikkommission

Herr Jinyang Li, B.Sc.
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Deutschland

Cc.: Theresa Prinz

München, 13.03.2024

Unser Zeichen: **2024-21-NM-KH** (bitte bei Schriftwechsel angeben)

Beratung durch die nicht-medizinische Fachgruppe der Ethikkommission der Technischen Universität München

Studientitel:	Bewertung von HMI für Teleoperation
Antragssteller:	Jinyang Li, B.Sc.
Studienleiter:	Theresa Prinz

Sehr geehrter Herr Li,

die nicht-medizinische Fachgruppe der Ethikkommission hat Ihren Antrag vom 01.03.2024 auf der Basis der vorgelegten Unterlagen geprüft.

Die nicht-medizinische Fachgruppe der Ethikkommission erhebt keine Einwände gegen die Durchführung der Studie.

Die ethische und rechtliche Verantwortung für die Durchführung dieser Studie verbleibt bei Ihnen. Änderungen in Organisation und Ablauf sind der Ethikkommission zur erneuten Prüfung einzureichen.

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Bitte beachten Sie, dass dieses Votum nur für die im Zuständigkeitsbereich der Ethikkommission der TUM tätigen Wissenschaftler gültig ist.

Mit freundlichen Grüßen

Prof. Dr. Alwine Mohnen
Ständige stellvertretende Vorsitzende der nicht-medizinischen Fachgruppe
der Ethikkommission Technische Universität München

Vorgelegte Unterlagen:
1) 2. Formblatt Stellungnahme Einrichtungsleitung-unterschreiben .pdf vom 01.03.2024
2) 0. Antragsformular Sonstige Studien_final.pdf vom 01.03.2024
3) Zuständigkeit 31.10.2023.pdf vom 01.03.2024
4) 1. Versuchsprotokoll_final-unterschrieben.pdf vom 01.03.2024
5) 6. Statement zur Gefährdungsbeurteilung_final.pdf vom 01.03.2024
6) 8.Questionnaire.pdf vom 01.03.2024
7) 3. Probandeninformation_IC_clean_final.pdf vom 01.03.2024
8) 4. Probandeninformation_IC_tracked changes_final.pdf vom 01.03.2024
9) 5. NeuFlyer_final.pdf vom 01.03.2024
10) Lebenslauf Jinyang Li.pdf vom 01.03.2024
11) nicht verfügbar - Verträge.pdf vom 01.03.2024
12) nicht verfügbar - Versicherungsbestätigung.pdf vom 01.03.2024
13) nicht verfügbar - Versicherungsbedingungen.pdf vom 01.03.2024
14) 1. Anschreiben.pdf vom 11.03.2024
15) 1. Versuchsprotokoll_final_v2.0 clean.pdf vom 11.03.2024
16) 1. Versuchsprotokoll_final_v2.0_tracked.pdf vom 11.03.2024

Appendix I