Implementation and Evaluation of a Robot Control Scheme for Teleoperation

Implementierung und Evaluierung eines Robotersteuerungsschemas für die 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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Eingereicht am Garching, den 12.02.2025

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Abstract

The goal of this thesis is the design, implementation and evaluation of a usable control scheme for the gripper of a teleoperated robot arm. The current implementation of the teleoperation system synchronizes the movement of both robot arms (leader-follower). This solution works well for the general positioning of the arms, but does not extend well to the operation of the gripper end effector. The control scheme developed in this thesis is intended to replace the synchronization of the arms' grippers with a more usable solution.

For this purpose, three controller prototypes were designed, each equipped with different input devices: buttons, joystick and slide potentiometer.

A usability study was conducted to investigate which of the controller prototypes is best in terms of performance and preferences of the study participants. Study participants were given a series of simple pick-and-place tasks, which they completed with all controller prototypes. The metrics used to evaluate the participants' performance were TTC (Time to Complete) and success rate. Participants preferences were assessed via a SUS (System Usability Scale) questionnaire.

The results of the study showed no significant difference between the controllers. However, the participants performed slightly better with the buttons controller, and also preferred it over the others. This suggests the buttons controller is a good candidate for future developments of the system.

Kurzfassung

Das Ziel dieser Arbeit ist der Entwurf, Implementierung und Evaluierung eines brauchbaren Steuerungsschemas für den Greifer eines teleoperierten Roboterarms. Die derzeitige Implementierung des Teleoperationssystems synchronisiert die Bewegung beider Roboterarme (Leader-Follower). Diese Lösung eignet sich gut für die allgemeine Positionierung der Arme, aber nicht für die Steuerung des Greifer-Endeffektors. Das in dieser Arbeit entwickelte Steuerungskonzept soll die Synchronisation der Greifer durch eine brauchbarere Lösung ersetzen.

Zu diesem Zweck wurden drei Steuerungsprototypen entworfen, die jeweils mit unterschiedlichen Eingabegeräten ausgestattet sind: Tasten, Joystick und Schiebepotentiometer.

Eine Usability-Studie wurde durchgeführt, um zu untersuchen, welcher der Controller-Prototypen in Bezug auf Leistung und Präferenzen der Studienteilnehmer am besten für die Aufgabe geeignet ist. Den Studienteilnehmern wurde eine Reihe von einfachen Pick-and-Place-Aufgaben gestellt, die sie mit allen Controller-Prototypen lösen mussten. Zur Bewertung der Leistung der Teilnehmer wurden die Kennzahlen TTC (Time to Complete) und Erfolgsquote herangezogen. Die Präferenzen der Teilnehmer wurden anhand eines SUS (System Usability Scale) Fragebogens bewertet.

Die Ergebnisse der Studie zeigten keinen signifikanten Unterschied zwischen den Controllern. Allerdings schnitten die Teilnehmer mit dem Tasten-Controller etwas besser ab und bevorzugten ihn auch gegenüber den anderen Controllern. Dies deutet darauf hin, dass die Tastensteuerung ein guter Kandidat für zukünftige Entwicklungen des Systems ist.

Contents

1. Introduction

Teleoperation allows human operators to remotely control a machine and manipulate objects from a distance. As a consequence, it commonly finds application in fields where distant or hazardous environments need to be reached. Teleoperation systems can accomplish this without exposing the operator to danger.

In recent years, teleoperation has been finding a new application in industrial manufacturing. Collaborative robots, designed to physically interact with human operators, have the potential to combine the advantages of full automation and manual processes (Matheson, Minto, Zampieri, Faccio & Rosati, 2019). This becomes increasingly relevant as manufacturing demand shifts toward increased customization, asking for more flexible production lines and a reduction of lead times (Barbazza, Faccio, Oscari & Rosati, 2017).

One option of realizing a teleoperation system is by using a copy of the teleoperated robot arm as an input device. The operator interacts with one robot arm by moving it into a desired position (leader). The teleoperated robot arm copies the movements of the leader in real time (follower). It is crucial to design such systems with high usability and high reliability as priorities, particularly when they are intended for use by non-expert operators in time-sensitive manufacturing processes (Prinz & Bengler, 2023).

The leader-follower scheme works well for the positioning of the robot arm, but it does not extend well to the operation of the gripper end effector. To grasp objects with the teleoperated gripper, the operator manually pushes/pulls the fingers of the gripper together/apart. This is a sub-optimal solution, since the operator must move their hands to the gripper fingers to grasp an object, and move them back to the robot hand to move the arm to a target position. Therefore, it may be advantageous to use a separate control scheme for the end effector.

The goal of this thesis is the design and implementation of a usable control scheme for the end effector of a robot arm for use in teleoperation. To this end, multiple controllers are to be designed and constructed, each with different input devices. The controllers are to be evaluated in a study according to their usability to the operator.

The research question to be answered by the thesis is:

- **How is a control scheme for the end effector of a teleoperated robot arm for use in assembly best realized?**

To answer the research question, the thesis is divided into two major parts:

1. Design and implementation of three controller prototypes for the gripper of the robot arm.

2. A usability study to compare the controller prototypes to each other on a simple pick-and-place task. The performance and preferences of study participants will be evaluated to determine which controller prototype is best suited to the task.

The thesis begins with an overview of the **state of the art**, where key concepts and existing research is presented. The **outline of the thesis** shows an introduction to the system that will be designed in the thesis, and states objectives of the thesis in each area. The **controller design and implementation** chapter details the mechanical, electrical and software design of the controller prototypes. The chapter **study design** shows the design of the usability study, and defines hypotheses and variables used for the remainder of the thesis. The results are presented in the chapter **study results**, including statistical analyses where applicable. These results are **discussed** in the following chapter, where the hypotheses are also evaluated. Finally, chapter **conclusion and outlook** provides the summary of the thesis, answers the research question and gives an outlook on possible future research.

2. State of the Art

This chapter seeks to introduce key concepts around teleoperation and present an overview of existing research. First, the topic of teleoperation is presented in greater detail, followed by the design and evaluation of controllers. Examples of usability studies on topics similar to this thesis conclude the chapter.

2.1. Teleoperation Systems

Teleoperation is defined by Niemeyer et al. as operation of a robot from a distance, with a barrier separating the operator from the robot (Günter Niemeyer, Carsten Preusche, Gerd Hirzinger, 2008). The human operator is stationed at the local site, using various input and output devices to control the robot. The robot is located at the remote site, where it follows the input from the operator and sends feedback from sensors back to the local site (Günter Niemeyer, Carsten Preusche, Gerd Hirzinger, 2008).

Teleoperation currently finds application in a wide range of fields, from handling of explosives to surgery.

A typical application for teleoperation systems is work in hazardous environments. The disposal of explosive ordnance is one such application. The operator can use a teleoperated robot to inspect, handle and safely transport suspicious objects from a safe distance (Canaza Ccari et al., 2024).

Semi-autonomous teleoperated systems are also used for performing various tasks in space, for example satellite refueling and maintenance (Kazanzides et al., 2021).

Resource extraction industries make use of teleoperated robots, for example in mining (Hainsworth, D., W., 2001) and to assist with tasks on oil platforms (Caiza, Garcia, Naranjo & Garcia, 2020).

Another field of application is medicine, with teleoperated robots being used in surgery (Munawar & Fischer, 2016) and robot-assisted microsurgery (D. Zhang, Si, Fan, Guan & Yang, 2022).

The military also increasingly makes use of unmanned robots, which are often teleoperated (Kot & Novák, 2018). Improvements in visualization and teleoperation techniques are also being made specifically for military purposes (Redden, Elliott, Pettitt & Carstens, 2011).

2.2. Controller Design and Evaluation

The design of devices for interaction with human operators should conform to the standards of human-centered design. The principles of human-centered design are well established, with the international norm ISO 13407 defining the general process of human-centered design (DIN EN ISO 13407, 1999).

The norm ISO 9241-11 provides more detailed information on usability testing (DIN EN ISO 9241-11, 2018). It outlines three components of usability for the purposes of usability testing:

- **Effectiveness:** The rate of tasks successfully completed by users. A task is considered successfully completed, when the user did not produce an error and did not need to ask for assistance.
- **Efficiency:** A measure of how well the user completed the task. The less time, effort, or other resources were expended, the higher the efficiency.
- **Satisfaction:** A measure which includes the user's physical, emotional and cognitive reactions to the interaction, such as discomfort, dissatisfaction with actions taking too long etc.. Ideally, such negative experiences are absent.

The field of controller design for teleoperation seems relatively under-explored. There are some novel approaches, for example experiments with haptic feedback gloves (Z. Zhang & Qian, 2023). Studies about controller design are typically performed with videogame controllers (Brown, Kehoe, Kirakowski & Pitt, 2010), (Young, Kehoe & Murphy, 2016). While these studies are not done in the context of teleoperation, they offer transferable insights into general controller design. They particularly emphasize the importance of usability testing and investigating the relationship between users' performance and subjective experience.

2.3. Related Research

Recent research of topics related to leader-follower teleoperation systems in assembly applications shows some interesting developments.

Manipulators based on augmented reality were developed, intending to replace existing control interfaces with a headset (Solanes et al., 2020).

An improved control scheme for the posture regulation of the robot arms was created, to help the robots better avoid singularities and potential obstacles, while improving the safety of the human operators (Situ, Lu & Yang, 2024).

A compliant teleoperation system was developed, which endowed the follower robot arm with perception abilities, and allowed it to autonomously adjust its own stiffness based on the current task (Li, Cheng & Ding, 2023).

3. Outline of the Thesis

In this chapter, the system that will be used to answer the research question will be described in general terms. Then, the goals of the thesis in each category will be described.

3.1. System Description

To control the end effector of the robot arm with an external controller, a system consisting of four parts is needed, as illustrated in fig. 1:

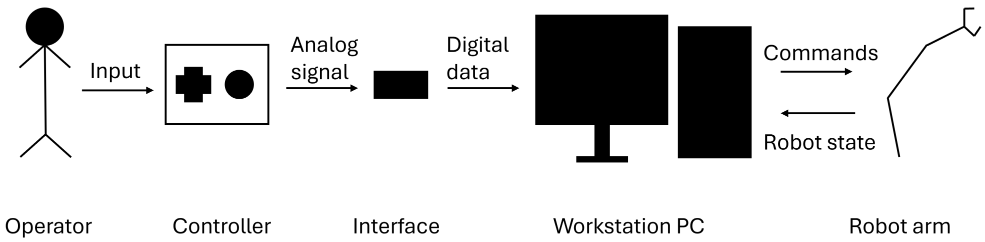

Figure 1: System overview

- External controller
- Interface electronics
- Workstation PC
- Robot arm

3.1.1. External Controller

This part of the system lets the operator give input using an appropriate input device, for example an analog stick, buttons, potentiometer etc. The controller should be made in compliance with the standards of human-centered design, to make it easy to use.

3.1.2. Interface Electronics

The input data from the controller needs to be processed into a form that is recognizable to the Workstation PC. In a pre-made controller, all necessary processing is integrated into the controller's body, and it can be plugged into the Workstation PC directly. For a custom-made controller, the analog electrical signals must first be turned into digital data that can be transferred over USB or other appropriate communication line.

3.1.3. Workstation PC

The Workstation computer is connected both to the robot arm, sending commands and receiving feedback, and to the controller via the interface electronics. The control interface of the robot arm can be accessed using a computer running the *libfranka* c++ package. This allows the workstation PC to send real time and non-realtime commands to the arm, as well as read the robot state, as described in the FCI (Franka Control Interface) documentation (FRANKA EMIKA GmbH, 2022). The realtime commands are used to command a specific motion or define joint torques of the arm, or both. The non-realtime commands control the hand, its movement and grasping action, and are therefore especially relevant. With the collection of packages *franka_ros*, *libfranka* can be used in the ROS (Robot Operating System) environment. The *franka_gripper* package implements pre-made commands that control the end effector. It is also possible to write custom commands to control the robot in more detail.

3.1.4. Robot Arm

A Franka Emika Panda collaborative robot arm with 7 DOF is connected to the workstation PC, from which it receives commands and control values, and sends measurement data back. This data consists of the pose of the robot in joint and Cartesian coordinates, state of the end effector, collision data, and the last command issued.

3.2. Aim of the Thesis

3.2.1. External Controller Objectives

The design of the controllers is the first major part of the thesis. Three different controller prototypes are to be designed, so they can be compared in the usability study. There are two main concerns when designing the controllers: the separation of the position and force controls, and the compatibility with the Franka Hand, which makes up the end effector of the robot arm.

The operation of the end effector consists of the positioning of the gripper fingers around a target object, and the application of force on the object. These functions can be separated to varying degrees on different controllers. Finding how much separation is ideal for operators in terms of their performance and preferences is a vital part of answering the research question of the thesis.

The controllers are not intended to replace the Franka Hand, but rather be installed on it. Care must therefore be taken that the controller prototypes do not inhibit the native functionality of the Franka Hand.

3.2.2. Interface Electronics Objectives

The concrete design of the interface electronics must be decided based on the chosen controller designs. A versatile option could be to make use of a pre-made, programmable interface, like an Arduino board. It can directly receive the raw input signals from the controller and be programmed to send appropriate messages to the workstation PC without needing to be physically modified.

3.2.3. Workstation PC Objectives

As mentioned above, Franka Emika provides freely accessible software equipped with built-in control commands for control of the gripper. These can be used to make custom programs to control the gripper behavior however desired, based on the inputs from the interface electronics and feedback from the robot arm.

3.2.4. Usability Study Objectives

When the controller prototypes are finished, a usability study will be conducted. This is the second major part of the thesis.

Study participants will be tasked with completing a series of simple tasks common in assembly applications, such as pick-and-place tasks, using the system described in this chapter. They will repeat the same tasks while controlling the robot arm with all three different controller prototypes. The participants' performance and preferences will then be evaluated to find the control scheme best suited to carrying out these assembly tasks, thereby answering the research question.

4. Controller Design and Implementation

This chapter is concerned with the design and implementation of prototype controllers which each allow for the operation of the end-effector gripper using different input devices. The chapter is divided into the selection of input elements followed by mechanical, electrical and software design. Each section is introduced with design goals or requirements, after which the chosen implementation is shown in detail.

4.1. Input Element Selection

One major concern in the controller design is the separation of the positioning and force controls. The operation of the end effector consists of two actions: the positioning of the gripper fingers around a target object, and the application of a grasping force on the object. The controller needs to allow the operator to perform both actions in a reliable and straightforward way. Different combinations of input elements can be used to separate the controls of these actions to various degrees, to test which arrangements lead to a better performance of study participants, and whether there is a preference towards some input element combinations over others.

Based on this, three sets of input elements were chosen for three controller prototypes:

- **Buttons Controller:** Two buttons gradually open and close the gripper, a third one attempts to grasp an object
- **Slider Controller:** The gripper follows the position of a slide potentiometer, from a fully open to a fully closed position. A grasp attempt is initiated automatically when the gripper is closed beyond a defined threshold
- **Joystick Controller:** Joystick tilts gradually open and close the gripper, a press of the joystick initiates the grasping of an object

4.2. Mechanical Design

The form of the controller is constrained by two general requirements: It needs to fit on the Franka Hand without obstructing its function, and it should follow principles of human-centered design to make it easy to use.

4.2.1. Franka Hand

The Franka Hand (see fig. 2, source: (FRANKA EMIKA GmbH, 2022)) features three essential parts that may not be obstructed by the controller.

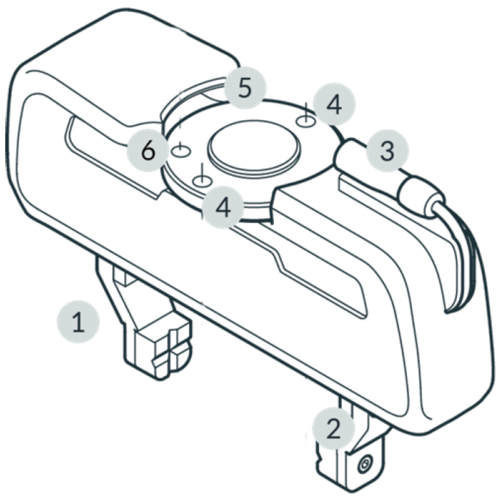

Figure 2: Franka Hand diagram.

- The gripper fingers (parts number 1, 2 in fig. 2) at the bottom of the hand need to be kept free in their full range of motion.
- The plug next to the interface flange (part number 3 in fig. 2) connects the hand to the circuitry of the arm, allowing it to receive commands and send feedback. Even when the hand is turned off, the plug cannot be readily removed without damaging the hand. It needs more room at the top to accommodate the cable leading to the plug as well as the plastic support of the cable and the plug
- The interface flange (see part number 5 in fig. 2) at the top is used to attach the hand to the rest of the arm, and must remain free with sufficient room on all sides to also accommodate the corresponding flange of the arm

4.2.2. Human-Centered Design

The controller is the part of the teleoperation system that operators will manually interact with, so it should conform to the requirements of human-centered design. The norm ///source/// describes overall development of human-centered systems. It outlines four general steps:

1. Defining and understanding the context in which the device will be used
2. Defining the needs of the user
3. Design of the system
4. Evaluating the design of the system

Step 3. is addressed in the remainder of this chapter and step 4. in the remainder of the thesis. With guidance of steps 1. and 2., the following requirements on the controller can be defined:

- The controller is developed in a university lab environment, but it is intended for manipulation of small objects in a generic industrial environment

- Using the controller, the operator must be able to easily and safely operate the robot end-effector: use it to grab, move and set down objects
- The controller should be efficiently usable without requiring any special technical knowledge or skills from the operator

In summary, the controller should be easy to interact with, while being able to fit on the Franka Hand without interfering with its main features.

4.2.3. Controller Form

Based on the requirements and goals listed above, the controller form was made from a preexisting model of a shell of the front part of the Franka Hand (see fig. 3).

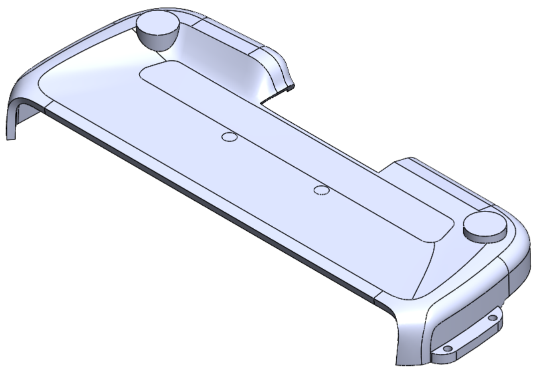

Figure 3: Preexisting 3D model of the shell

Using SolidWorks 2024, this model was scaled by a factor of 1.02 to fit on the Franka Hand, and split into three copies, each of which modified to fit the requisite input elements. The final 3D models can be seen in fig. 4, 5, 7, with a view on the backside of the shell in fig. 6.

The top of the shell was cut (see number 1 in fig. 4) to prevent collision with arm parts surrounding the arm-hand interface flange. The sides of the shell were extended (number 2 in fig. 4) to fit snugly around the Franka Hand and prevent unwanted movement of the shell. The ends of these side extensions were each provided with a slotted hole (number 3 in fig. 4) to allow the shell to be fastened to the Franka Hand. The backside of the model was fitted with several spacers (number 2 in fig. 6) to create sufficient room for electronics between the Franka Hand and the controller shell.

To fit the input elements described in the section 4.3, each shell was modified with suitable features:

- **Buttons Controller:** Panel-mounted buttons were used, which only require a thru-hole of appropriate diameter to be installed. The three holes were positioned so that all buttons are within reach of the operator's thumbs when holding the controller: two buttons on the right side, to gradually open and close the gripper, and one button on the left side to grasp objects (see number 4 in fig. 4).

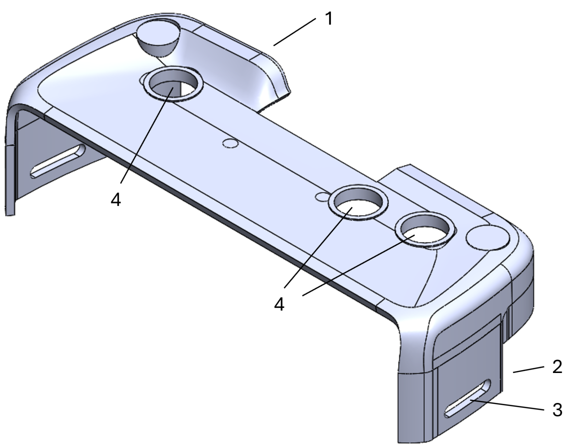

Figure 4: Buttons controller shell. 1 - Cut top. 2 - Extended sides. 3 - Slotted hole. 4 - Holes for buttons.

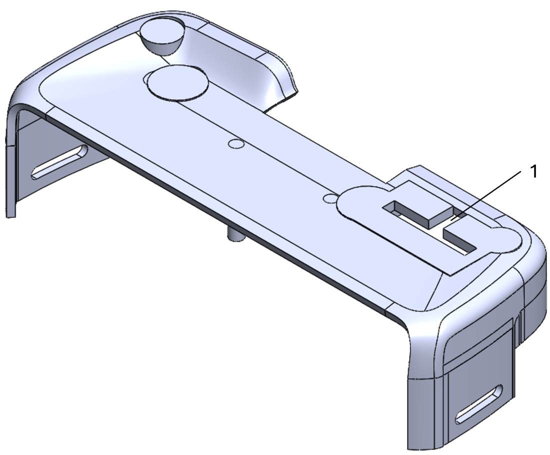

Figure 5: Slider controller shell. 1 - Slot for slide potentiometer.

- **Slider Controller:** The chosen potentiometer does not feature any obvious way to be attached to the shell, so a slot with its precise measurements was made (see number 1 in fig. 5 and 6). To install the potentiometer, it is to be positioned in the middle of its range to fit into the cutout over the top of the slot (also visible in fig. 5), and pushed down. The columns at the back of the slot (see fig. 6) are positioned to not interfere with the potentiometer contacts and other protrusions. The slider is positioned on the right side to be in reach of the right thumb.
- **Joystick Controller:** The joystick does feature four screw-holes for easy installation, however the low thickness of the shell necessary to not block the movement of the joystick makes using screws difficult. Instead, a slot was fashioned based on the side profile of the joystick, where the part can be inserted from the top (see number 1 in fig. 7). The contacts of the joystick remain accessible through the side. The joystick is positioned on the right side to be in reach of the right thumb.

The finished models were sliced using Bambu Studio version 1.9.3.50 and printed from PLA filament with the Bambu Lab X1E 3D printer.

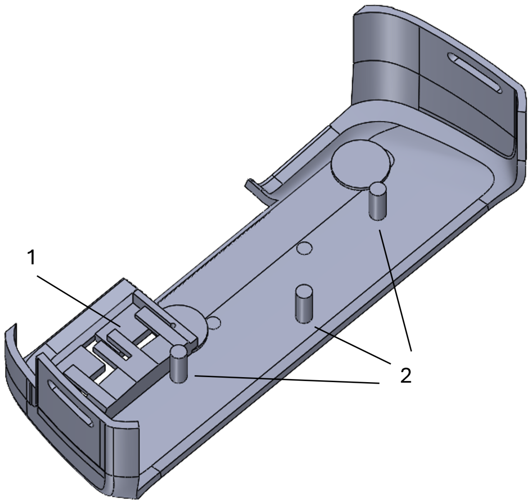

Figure 6: Backside of the slider controller shell. 1 - Slot for slide potentiometer. 2 - Spacers.

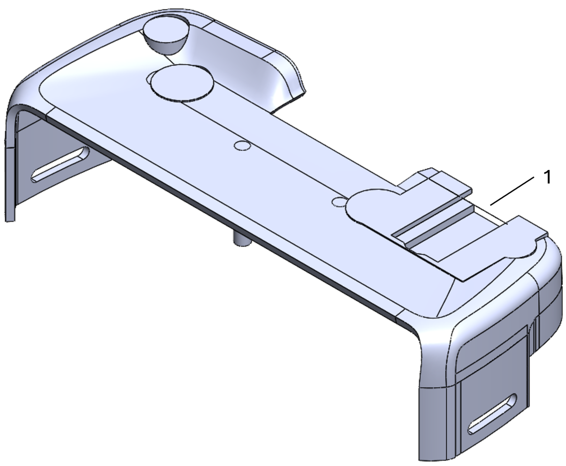

Figure 7: Joystick controller shell. 1 - Slot for joystick.

4.3. Electrical Design

The raw signals from buttons, slider and joystick need to be transformed into a form intelligible to a computer via interface electronics, which can be connected to the PC via USB or a similar communication line.

To fulfill the role of interface electronics, Arduino Nano 33 BLE was chosen. The input elements can be connected directly to its pins. The Arduino is supplied with power via a USB 2.0 Micro-B cable, which can also double as a communication line when connected to a computer.

The chosen input elements are: the buttons Tru Components 701829 GQ16H-10/J/N, the slider potentiometer Tru Components F3031N single type and the joystick Arceli PS2 Joystick 00022 (see fig. 8).

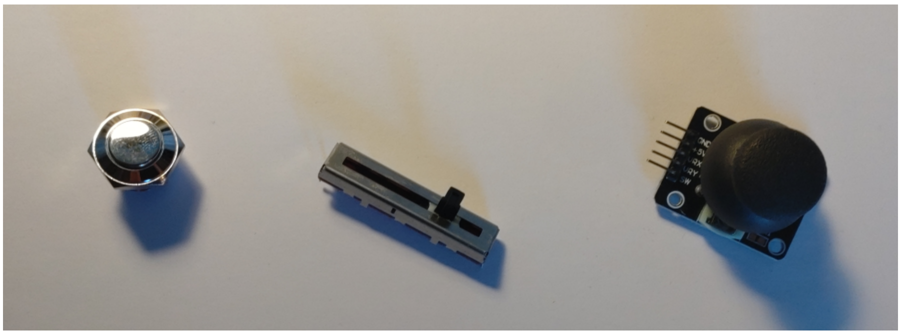

Figure 8: Selected input elements. From left to right: Button, slide potentiometer, joystick.

Each prototype controller is intended to have its own Arduino permanently attached, which results in three simple circuits.

The Arduino offers a wide selection of pins (see fig. 9, source: (*Arduino Nano 33 BLE Pinout*, 16.09.2020)).

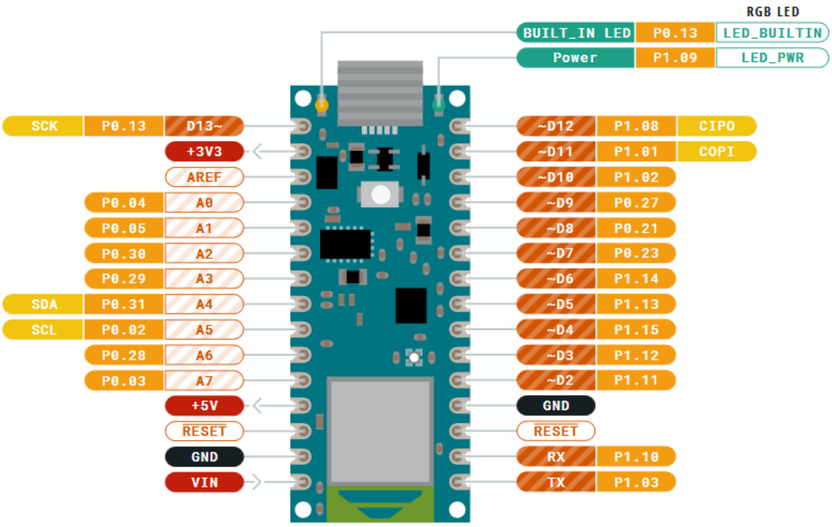

Figure 9: Arduino Nano 33 BLE pinout

Relevant pins for the input element connections are:

- **GND:** Ground
- **+3V3:** Provides 3.3 V power
- **D pins:** Digital input/output
- **A pins:** Analog input/output

The controller prototypes were wired as follows.

The buttons each feature two interchangeable terminals, and the selected parts do not require a pull-up resistor, resulting in simple wiring seen in table 1.

Table 1: Buttons controller wiring

Button Pin	**Arduino Pin**
Button 1 Pin 1	GND
Button 1 Pin 2	D2
Button 2 Pin 1	GND
Button 2 Pin 2	D3
Button 3 Pin 1	GND
Button 3 Pin 2	D4

The slide potentiometer features three numbered terminals: a power input, ground and analog output. The connections are mapped out in table 2.

Table 2: Slider controller wiring

Slide Potentiometer Pin	**Arduino Pin**
Slider Pin 1	GND
Slider Pin 2	A0
Slider Pin 3	+3V3

The joystick features five labeled terminals: a power input, ground, two analog output pins for joystick position and a digital output for the built-in button. The connections are noted in table 3.

Table 3: Joystick controller wiring

Joystick Pin	**Arduino Pin**
GND	GND
+5V	+3V3
VRX	A0
VRY	A1
SW	D2

These circuits were tested on a temporary breadboard setup, before being soldered in place inside the 3D printed shells described in section 4.2.

4.4. Software Design

To enable the controller to move the hand's gripper, it needs to be able to communicate with the control software of the robot arms. The existing teleoperation system uses ROS (Robot Operating System) as a middle-ware suite to relay commands between custom programs and the FCI (Franka Control Interface), which issues control commands to the robot arms.

The prototype controllers therefore need to be able to communicate their input data to the ROS layer of this system, so that the input may be processed by a custom program also in the ROS environment.

4.4.1. Arduino - ROS Communication

The Arduino comes with its own software, the Arduino IDE 2.3.3, and is programmed in its own dialect of c/c++. To enable Arduino to communicate with ROS, the package *ros_lib* is installed in the Arduino IDE, and the libraries *rosserial* and *rosserial_arduino* on the computer running ROS.

With *ros_lib*, Arduino can be programmed to communicate with its environment as a ROS publisher. Its data becomes accessible to the ROS Master when running the *rosserial* client on the USB port the Arduino is connected to.

With this background, each Arduino can be programmed with a publisher to send its input signals to the computer. Each publisher is named differently for reasons explained in the next subsection. The following data is being sent:

- **Buttons Controller:** Publisher *button_press* sends the state of all three buttons from `000` to `111`, each digit representing one button. When a button is pressed the corresponding digit is `0`, and when released it is `1`.
- **Slider Controller:** Publisher *slider_position* sends the position of the slider as a single value from `0` being fully on one side to `99` being fully on the other.
- **Joystick Controller:** Publisher *joystick_move* has to communicate both the tilt of the joystick and the state of its built-in button. To achieve this with a single message, the joystick tilt value is compressed from its original range to `10-99`, to ensure it always occupies two digits. The input from the other direction of joystick tilt is discarded. The state of the built-in button can be communicated with a single `0` or `1`. The published message is then concatenated from the two-digit joystick tilt value and the one-digit button value into a three-digit message in the form `JJB`.

4.4.2. Gripper Control Program

The input element data from Arduino publishers can now be processed by a custom gripper control program.

To receive the messages sent by the Arduino publishers, three corresponding subscribers are programmed. This enables the program to automatically detect which controller is connected, based on which of the three subscribers is receiving messages. This feature is intended to simplify the administration of the user study, since all three prototypes can be controlled by a single program without the need for human input.

As stated in the FCI (Franka Control Interface) documentation ///source///, all commands issued to the Franka Hand are non-realtime TCP/IP-based commands. This significantly limits the functionality of the gripper control program in the context of manual operation, as simple commands in the style of 'keep closing the gripper as long as the button is pressed' are not possible without a realtime control loop. To work around this limitation, the control program will open and close the gripper in steps of defined length.

Since the grasping of an object is a one-time action, it is not affected by the non-realtime nature of the hand controls. However, an issue can arise when the gripper is commanded to close by a given amount, and is blocked by an object in the process. The program is then stuck, and has to wait until the *move* function of the gripper delivers an error after receiving no response for a long time. This delay makes such an implementation unusable. To resolve this, the largest object that will be used in the study is measured, and its longest dimension used as a threshold value. The control program will automatically initiate a grasp attempt instead of closing the gripper, if the closing would bring the gripper fingers closer together than the threshold value.

Based on these considerations, the *gripper_control* program is made to process input as follows:

- **Buttons Controller:** If the 'grasp' button is pressed, initiate a grasp attempt. If the grasp attempt fails, leave the gripper fully closed. If the 'grasp' button is pressed when the gripper is fully closed, fully open it instead.

  If the 'open' button is pressed, open the gripper by a predefined amount. Should the button remain pressed, open by another step without needing another button press.

  If the 'close' button is pressed, close the gripper by a step. Should the button remain pressed, close by another step without needing another button press. If the closing movement would bring the gripper fingers closer together than the threshold value of the biggest object, initiate a grasp attempt instead. Should this grasp attempt fail, reopen the gripper to the position it would be in if the grasp attempt didn't happen.

- **Slider Controller:** When the slider is moved, move the gripper to the corresponding position. Slider fully on the left side corresponds to a fully closed gripper, and the slider fully on the right side corresponds to a fully open gripper etc..

If any closing movement would bring the gripper fingers closer together than the threshold value of the biggest object, initiate a grasp attempt instead. Should this grasp attempt fail, reopen the gripper to the position it would be in if the grasp attempt didn't happen.

- **Joystick Controller:** If the joystick button is pressed, initiate a grasp attempt. If the grasp attempt fails, leave the gripper fully closed. If the button is pressed when the gripper is fully closed, fully open it instead.

  If joystick is tilted right beyond a predefined value, open the gripper by a step.

  If the joystick is tilted left beyond a predefined value, close the gripper by a step. If the closing movement would bring the gripper fingers closer together than the threshold value of the biggest object, initiate a grasp attempt instead. Should this grasp attempt fail, reopen the gripper to the position it would be in if the grasp attempt didn't happen.

This summarizes the input processing as well as the control behavior of the *gripper_control* program.

4.5. Finalized Controllers Overview

The completed controller prototypes as described in this chapter were 3D printed, had electronics soldered in place, and were labeled for the purposes of the user study:

- **Buttons Controller:** Labeled A, seen in figures 10 and 11
- **Slider Controller:** Labeled B, seen in figures 12 and 13
- **Joystick Controller:** Labeled C, seen in figures 14 and 15

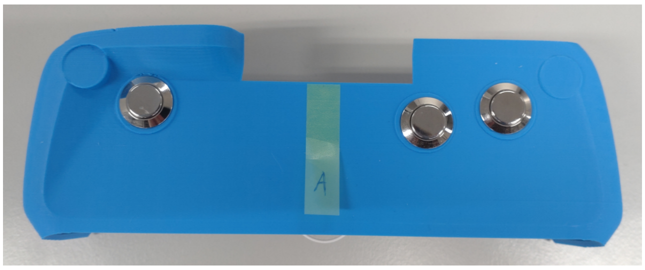

Figure 10: Buttons controller front view

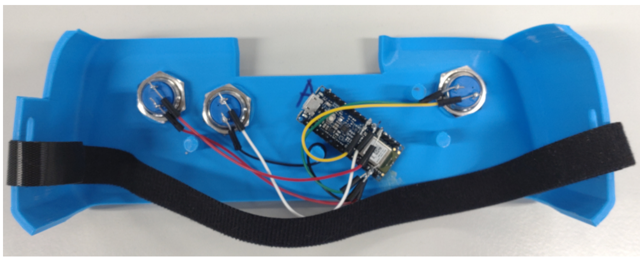

Figure 11: Buttons controller back view

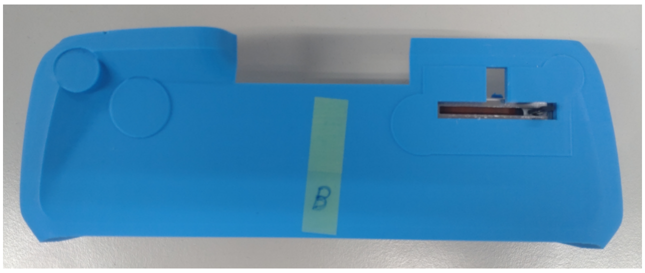

Figure 12: Slider controller front view

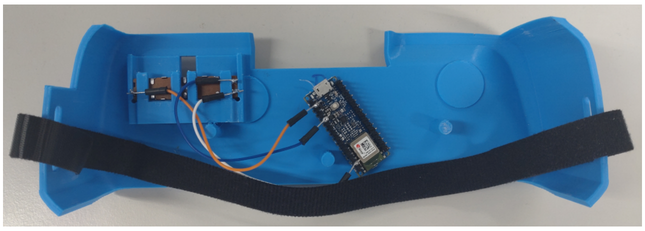

Figure 13: Slider controller back view

In order to fasten the prototypes to the Franka Hand, a hook-and-loop fastener band was used (visible in figures 11, 13, 15). This attaches the prototypes firmly enough that they hold in place when used, but can still be easily taken off and exchanged as will be necessary during the study. Figure 16 shows how the prototypes are fastened to the Franka Hand.

The connection between the Arduino in the prototype and the computer is realized with a long USB cable, which is attached to the robot arm at key points as to not become tangled with the arm (see fig. 17).

To start the teleoperation and gripper control programs, the following procedure is to be observed:

On the follower laptop:

1. Start FCI (Franka Control Interface) in browser

On the leader laptop:

1. Start FCI in browser
2. Start ROS Master in command line: `roscore`
3. Start the teleoperation program
4. Run the *rosserial* client: `rosrun rosserial_python serial_node.py /dev/ttyACM1` The final argument must be changed depending on which USB port the Arduino is connected to (changed to `ttyACM2` or `ttyACM3`).
5. Start the *gripper_control* program

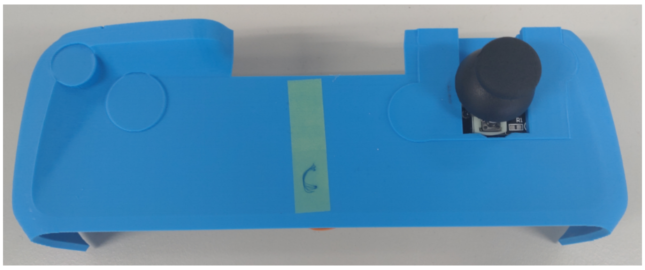

Figure 14: Joystick controller front view

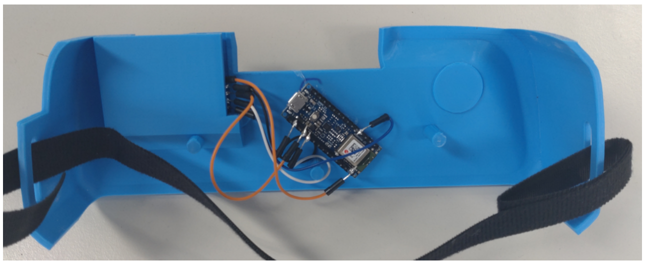

Figure 15: Joystick controller back view

Due to the automatic controller detection described in section 4.4, the prototype controllers can be freely disconnected and exchanged while the *gripper_control* program is running, and the newly connected controller will function immediately. A restart of the control program is not necessary.

Figure 16: Prototype fastened to the Franka Hand

Figure 17: USB cable fastened to the Franka Hand

5. Study Design

This chapter describes the design of a usability study conducted to compare the controller prototypes described in the previous chapter to one another. The controllers will be compared based on the study participants' performance and preferences when using each controller.

5.1. Hypotheses

The following hypotheses are formulated, categorized by which question they're intended to answer:

Question 1: Which input elements should be used on the controller?

- **Hypothesis 1.1:** Users will perform better using a controller with analog input elements (slider and joystick).
- **Hypothesis 1.2:** Users will prefer using a controller with analog input elements (slider and joystick).

Question 2: Does wearing gloves impact the users' performance or preferences?

- **Hypothesis 2.1:** Wearing gloves will have no major effect on users' performance.
- **Hypothesis 2.2:** Wearing gloves will have no major effect on users' preferences.

Question 3: Does the size of the controller impact users' performance?

- **Hypothesis 3:** Users' hand size will have an impact on their performance.

5.2. Variables

To quantify the performance and preferences of study participants, the following variables are introduced.

5.2.1. Independent Variables

The controllers' attributes are the main subject of the study, a secondary concern is the effect of gloves on the participants' performance. Thus, the independent variables for each task are:

1. Number and type of control elements on the controller (buttons, joystick, slide potentiometer)
2. Size of the controller relative to the participant's hand size

3. Participant wearing or not wearing gloves

5.2.2. Dependent Variables

To analyze the difference between the three controllers, the participants' performance and preferences are of interest. To quantify the participants' performance using different controllers, the time to complete each sub-task will be measured, as well as the success rate of task completion. Participants' preferences will be assessed via the standardized SUS (System Usability Scale) questionnaire. The dependent variables are:

1. Time to complete: Time to finish each successfully completed sub-task
2. Success rate: Percentage of successfully completed tasks
3. Usability Score: Score from the SUS questionnaire administered after each task

5.2.3. Other Data

In addition to the independent and dependent variables, additional data will be collected such as personal information, technical affinity, previous experience with teleoperation etc. This data will not be discussed in depth in the thesis, but it may be of use for future research. A summary of all data collected for the study can be found in table 4.

5.3. Setup

The controller prototypes are tested on a preexisting leader-follower teleoperation system consisting of two Franka Emika Panda robot arms with 7 DOF. A simplified diagram of the setup is shown in fig. 18 and a photo from the perspective of a participant in fig. 19. Each arm is controlled by its own laptop running a separate instance of FCI (Franka Control Interface). The laptop can communicate with its assigned arm as well as with the other arm via a local Ethernet network.

Arm 1 is the designated leader, and will be manually operated by the study participant. The hand of the leader arm is also where the controller prototypes will be mounted. A USB cable is prepared on the leader arm, which will connect the controllers to the leader laptop.

Arm 2 is the designated follower, and will copy the movements of the leader. The hand of the follower arm responds to the commands from the *gripper_control* program which processes the inputs from the controller prototypes. The experimental task is located in reach of the follower arm.

A camera is stationed next to the setup, oriented to film both arms, the task, and the participant for subsequent analysis. A third laptop is used to manage the administration of the study, and it does not interact with the technical system in any way. A fourth laptop (not pictured in fig. 18) is used to display the LimeSurvey questionnaire for participants to fill in over the course of the experiment.

Table 4: List of data collected during the study, by category

Data	Description	Collection Method
	Personal Data	
Demographics	Age, sex, occupation	Initial questionnaire
Handedness	Left-handed, right-handed or ambidextrous	Initial questionnaire
Hand size	Hand size measured from the base of the wrist to the tip of the middle finger	Measurement via tape measure
Experience with teleoperation systems	Does the participant have previous experience with teleoperation: no experience - a lot of experience	Initial questionnaire
Affinity for technology	ATI (Affinity for Technology Interaction) Scale	ATI Scale in initial questionnaire
	Objective Data	
Time to complete	Time to finish each successfully completed task	Measurement from video recording
Success rate	Percentage of successfully completed sub-tasks, classified as: successful, successful with corrections or unsuccessful	Observation from video recording
Interventions	Intervention from the study administrator. In case there was an intervention, its duration is measured to be subtracted from task completion time	Observation and measurement from video recording
	Subjective Data	
Usability	SUS (System Usability Scale)	Questionnaire after each task
Final questions	A collection of open-ended questions about the participant's experience and preferences, and ranking of the three controllers	Final interview

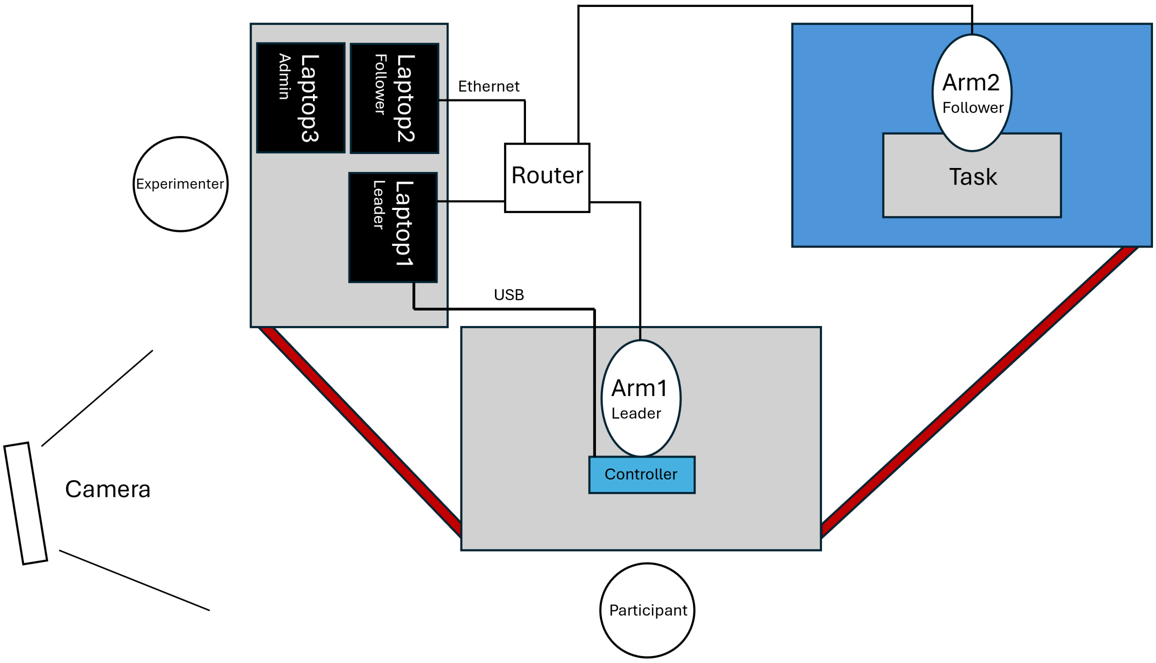

Figure 18: Diagram of the experiment setup

Figure 19: Photo of the experiment setup. The leader arm (left) has no controller currently installed

5.4. Task Description

During the experiment, the participants are presented with a sorting box, and are tasked with inserting six objects (3 cubes and 3 cylinders) into the appropriate openings (see fig. 20). Every participant is asked to begin each task by inserting the cylinder on the upper left, then proceed with the opposing cube and so on, as labeled in fig. 20. Each participant is to complete the task a total of six times: twice with each controller prototype, once without and once with gloves. The task is not altered between these six completions. To ensure the box and the six surrounding objects are placed in their predetermined positions, sticker markers are used (see fig. 21, 22).

This task was chosen since it is a well known game most people are acquainted with from childhood, and therefore requires little explanation. It also has a clear and easily measurable goal: put all objects into

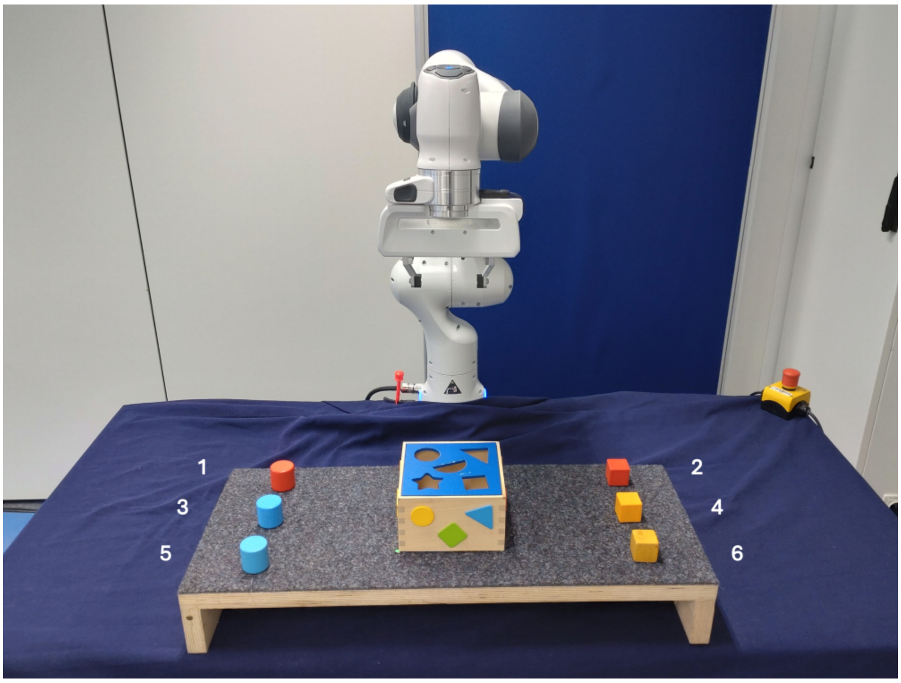

Figure 20: Task prepared under the follower arm. Numbers indicate the order in which the objects are to be inserted into the central box.

the box. At the same time, it is a pick-and-place task comparable to tasks commonly seen in assembly applications, as it requires accuracy in grasping, positioning and rotation of objects. The task is also similar to tasks in previous studies in the research project, making the acquired data more easily comparable with their results.

5.5. Population

The usability study requires at least 32 participants. To take part in the study, each potential participant must fulfill all the following inclusion criteria and must not fulfill any exclusion criteria.

Inclusion Criteria:

- The participant is between 18 and 65 years old
- The participant is able to give consent

Exclusion Criteria:

- The participant is unable to give or did not give their consent
- The participant is pregnant

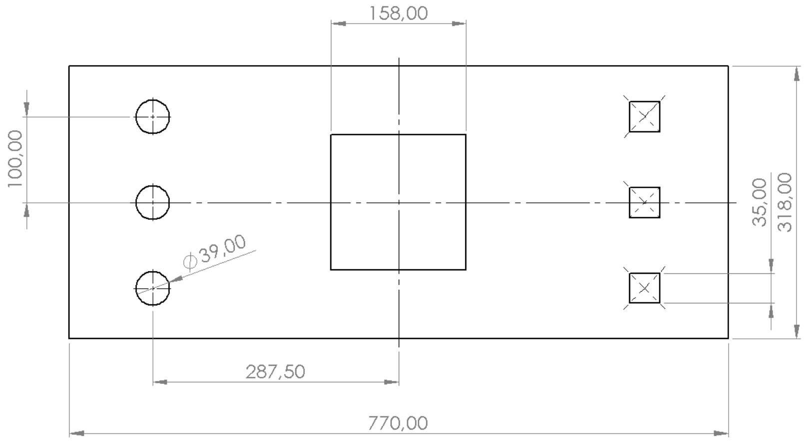

Figure 21: Positions and dimensions of the task

Figure 22: Markers for the positions of task objects

An experiment in progress may be terminated at any point by the participant withdrawing their consent without needing to specify a reason. Severe unforeseen technical issues may also lead to the termination of an ongoing experiment.

5.6. Ethical and Safety Considerations

This study followed the ethical principles of the Declaration of Helsinki and complied with the local statutory requirements of Bavaria, Germany. The Ethics Committee of the Technical University of Munich reviewed the study involving human participants and approved the proposal under reference number 2024-127-NM-BA.

The data of each participant acquired during the study is managed via an ID number not connected to the participant's name. This number is retained for the analysis and reporting of results. All data is stored locally and on the servers of the TUM Leibniz-Rechenzentrum (Sync & Share). Only persons involved with the preparation, execution or evaluation of the study will have access to the saved data. The locally stored copy of the data will be deleted after the completion of the study. The data stored in LRZ will be kept for 10 years in the interest of good scientific practice. Personal data will be kept to a minimum.

The teleoperation system used in the study was designed with emphasis on safety. Both robot arms are attached to a table with a robust connection to prevent toppling. The leader robot arm, which the study participants interact with, performs no autonomous movements, including during startup, and its gripper is turned off for the entirety of the experiment. The follower robot arm moves to align with the pose of the leader at startup, and the gripper closes and opens to initialize. After startup, the follower arm copies the movements of the leader, making it clear how the arm is moving at all times. The follower arm is positioned out of reach of the participants, and this distance is enforced with barrier tape. An emergency stop button is also positioned next to each robot arm, and participants are informed about its location and function before the experiment begins. These measures make for a safe and controlled environment which makes the risk of injury of any kind extremely small.

5.7. Procedure

The experiment is conducted with one participant at a time. Before the start of the experiment, the experimenter, performed by myself, will give the participant a short verbal overview of the purpose, contents and schedule of the study. In this introduction, the participant will be explicitly informed about the proper behavior with and around the teleoperation system, and the potential safety risks. They will also be notified about the data collected during the study, especially the filming of the experiment. After this brief introduction, the participant will be presented with the informed consent form, which they can agree to. Instead of collecting a signature, the informed consent is collected at the beginning of the LimeSurvey questionnaire. The participant is free to withdraw or to not give consent and end their participation at this or any point during the experiment, without needing to specify a reason. If the participant agrees to partake in the study and gives their consent, the experiment can begin. Following the introduction, the participant is encouraged to briefly familiarize themselves with the teleoperation system by operating it when no controller is installed on the hand.

The study begins with a demographic questionnaire, including exclusion criteria. Should any exclusion criteria be fulfilled, the experiment will be aborted. The hand size of the participant is also obtained, via a tape measure. While the participant is filling out the demographics form, the experimenter will set up the task, fasten the first controller to the hand of the leader arm and check that the control software is functioning as intended. When ready, the participant is given an introduction to the first controller, where the experimenter states and demonstrates the function of each input element on the controller. The participant is then free to familiarize themselves with the controller. The experimenter then begins the video recording and the participant is instructed to begin the first completion of the task. When finished, the participant is presented with a SUS (System Usability Scale) questionnaire. While they are filling it out, the experimenter resets the task setup. After finishing the questionnaire, the participant is instructed to put on appropriately sized light working gloves, which are provided in sizes 7 - 11. The participant is then asked to complete the task again, while wearing gloves. After completing the task for a second time, the participant is again presented with a SUS questionnaire. This time, the experimenter resets the task and exchanges the controller with the second controller prototype.

The participant is introduced to the second controller and is instructed to complete the task two more times with it, first without and then with gloves, filling out a SUS questionnaire after each task. After the fourth completion, the experimenter exchanges the controller for the third controller prototype.

The fifth and sixth completions of the task are done using same procedure with the third controller.

To prevent learning effects from distorting the results, the order of the three controllers is changed between participants, in such a way that around a third of the participants will use each controller first. The order of controllers used by each participant is recorded in the study protocol attached in the appendix.

After finishing all six tasks, the experimenter stops the video recording and conducts a final interview with the participant, asking open-ended questions about their experience, and their opinions about the three controller prototypes. Before leaving, the participant is given a small sweet as a token of appreciation.

The procedure is illustrated in fig. 23.

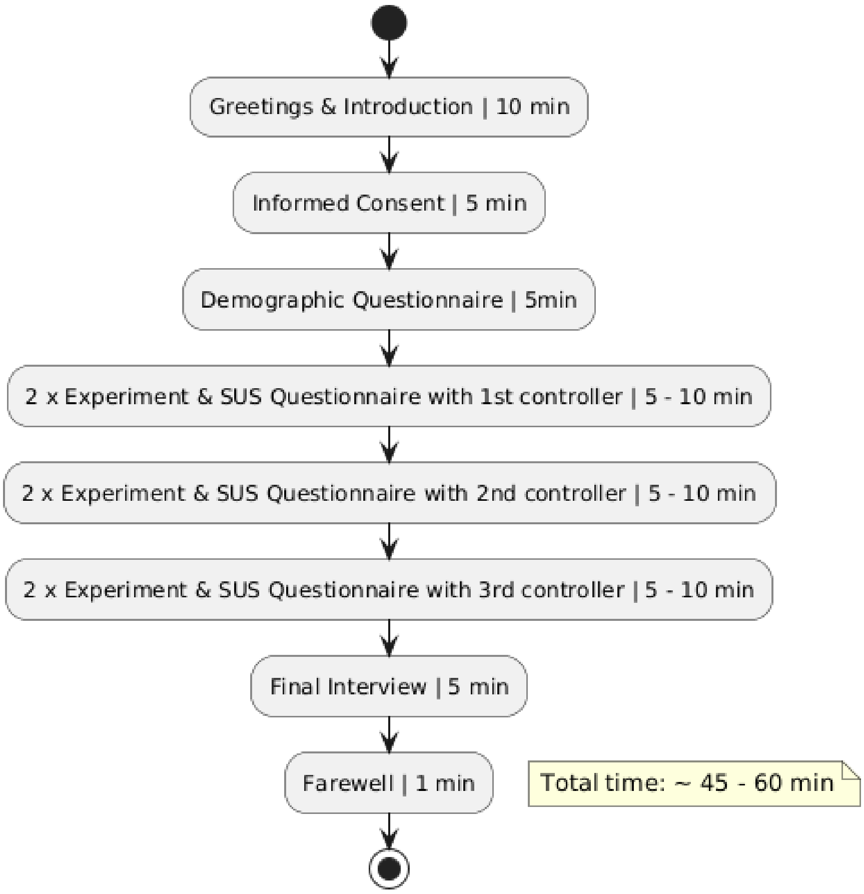

Figure 23: Diagram of the study procedure

During each task, the experimenter should intervene as little as possible, to not affect the results of the experiment. As a result, the experimenter will only intervene in the following special circumstances:

- When an error of the *gripper_control* program occurs, the participant will be instructed to pause, and lift the robot hand where it can't collide with any part of the task. The *gripper_program* is then restarted, and the participant can continue with the task.
- When a task object is dropped on the floor or otherwise made inaccessible to the follower arm, the participant will be instructed to continue the task with the next object. The lost object will be retrieved by the experimenter during the next reset of the task.
- When the teleoperation program stops because its speed or torque limit was exceeded, or the joint limits of the arm have been violated, the experimenter will manually move the arm out of the problematic position, and restart the teleoperation program. The participant will be instructed to continue with the task when the restart is finished.
- When the central sorting box is moved to a position difficult to reach with the follower arm, the experimenter will interrupt the task and move the box back to its starting position.
- Should an unforeseen technical issue occur, the experimenter will attempt to resolve it and resume the experiment.

5.8. Materials

The questions and standardized questionnaires the participants fill out during the experiment are explained in more detail in this section.

5.8.1. Demographics Questionnaire

In the beginning of the experiment, the participants were presented with a demographics questionnaire. It included standard questions about age, sex and gender. In addition, data about handedness and hand size was collected. Hand size was measured from the base of the wrist to the tip of the middle finger. Participants were also questioned on their previous experience with teleoperation systems.

5.8.2. Affinity for Technology Interaction Scale

The ATI (Affinity for Technology Interaction) scale was included immediately after the demographics questionnaire. It is a standardized questionnaire designed to assess a person's tendency to 'engage in intensive technology interaction' (Franke, Attig & Wessel, 2019).

The ATI questionnaire consists of nine questions answered on a 6-point Likert scale from *completely disagree* (coded as 1) to *completely agree* (coded as 6). To obtain the overall score, the responses to three negatively worded question need to be reversed, and a mean over all nine questions is computed. The results is the ATI score ranging from 0 - 6, with a higher score indicating a greater affinity for technology. (Franke et al., 2019)

5.8.3. System Usability Scale

The SUS (System Usability Scale) questionnaire is a standardized test to quickly make reliable assessments of a system's usability (John Brooke, 1996). The questionnaire consists of ten questions answered on a 5-point Likert scale from *strongly disagree* (coded as 0) to *strongly agree* (coded as 4). The responses to the even numbered questions are reversed, then all answers are summed and the result is multiplied by 2.5. The resulting SUS score ranges from 0 to 100. (John Brooke, 1996)

5.8.4. Final Interview

After finishing the experiments, participants were asked several questions about their experience. The form of an interview was chosen to allow the participants to express themselves more freely than through a questionnaire or a text box. The first two questions prompted participants to rank the controller prototypes according to their preferences and their perception of their own performance. After this, open ended questions about their general experience using the controllers and the perceived difficulty of the task followed. The effects of gloves and differences in usability and comfort between the three controllers were also queried from the participants. The final question asked the participants for improvement suggestions.

6. Study Results

This chapter shows the results of the user study conducted as a part of the thesis. First, the profile of study participants is presented. The remainder of the chapter is mainly focused on measures of performance and preference. The results of the interviews with participants and a collection of miscellaneous observations are found at the end of the chapter.

The data presented in this chapter was kept and pre-processed in Microsoft Excel, and statistical analyses were performed using JASP 0.19.3. All graphs were also generated with JASP unless stated otherwise. The data from questionnaires was acquired by exporting the LimeSurvey results into Microsoft Excel. The data about participants' performance in experiments was acquired by watching recordings of the experiments and manually measuring and logging the relevant data into Microsoft Excel.

6.1. Study Participants

A total of 34 participants completed the study, of which 20 were male and 14 female. The participants' ages ranged from 18 to 36, with a mean age of 24.77 and standard deviation of 3.62. All of the participants were recruited from the university environment, with 28 reporting being students and the remaining 6 researchers or academic staff.

Participants' previous experience with teleoperated robots varied, 24 reported having no experience, 4 have experience from having participated in similar studies, 1 participant reported teleoperating robots outside of work and 2 work with teleoperated robots, but do not personally operate them. No one reported working with teleoperated robots and personally operating them. The 3 remaining participants report miscellaneous experiences: witnessing a demonstration of a teleoperated system, having visited a lab with a teleoperation system and a further unspecified experience with Roboy.

The ATI (Affinity for Technology Interaction) questionnaire measured scores ranging from 1.34 to 5.56, with a mean score of 4.34. This represents an above average affinity for technology $(M = 4.34, SD = 1.04, \alpha = 0.91)$.

6.2. Performance: Time to Complete

The TTC (Time to Complete) is used as the main measure of performance for the study. The completion of each task consists of inserting 6 objects into the central box. The time measurement starts when the participant first attempts to grasp the first object, and ends when the final object is successfully inserted. The insertion of each object is measured as a separate sub-task, the TTC of a task is defined as the mean of its 6 composite sub-tasks, and measured in seconds. The successful placement of objects was timed using the distinct sound of the falling object striking the bottom of the box.

When interventions from the experimenter were necessary, usually due to an error of the *gripper_control* program which required its restart, the length of the intervention was recorded and subtracted from the time of the sub-task. The details of how intervention were handled are described later in this chapter.

In 7 sub-tasks, the participants accidentally knocked or dropped the task object on the ground, and have not delivered it into the box. As a consequence, no time could be measured for the sub-task completion. The participants were instructed to continue the task by skipping to the next sub-task. To avoid discarding the data sets associated with these unsuccessful attempts, the missing values were replaced by the mean of available sub-tasks 2-6. Sub-task 1 was excluded, since it's measured from the first grasp attempt, while the other sub-task are measured from the completion of the previous sub-task. This results in substantially shorter completion times for sub-task 1. This substitution was performed after the intervention times were subtracted from the sub-task times, and all 7 instances of it are marked in the study videos data sheet.

Due to an oversight, the camera battery ran out during one participant's first task, and this was not noticed until the task was complete. As a result, all six sub-task times are lost. All five other tasks were recorded normally. The missing times will be left blank for the statistical analysis, as JASP can automatically exclude missing data.

6.2.1. Descriptive Statistics of TTC

Table 5 shows an overview of descriptive statistics of TTC, split by task. The valid and missing data rows are included to show the lost data mentioned above. A visualization of these results can be seen in fig. 24.

Table 5: Overview of descriptive statistics of TTC split by task

	Time to Complete					
Task	**1**	**2**	**3**	**4**	**5**	**6**
Valid Data	33	34	34	34	34	34
Missing Data	1	0	0	0	0	0
Mean TTC	20.743	15.468	16.490	13.795	14.973	12.257
Std. Deviation	9.612	5.483	8.329	5.107	5.825	4.172
Minimum	11.300	7.683	7.167	7.667	7.750	6.500
Maximum	51.533	30.800	42.700	26.017	35.133	23.650

The decreasing TTC suggests a learning effect. The particularly pronounced decrease from task 1 to 2, and only smaller differences between other tasks support this observation. The participants most

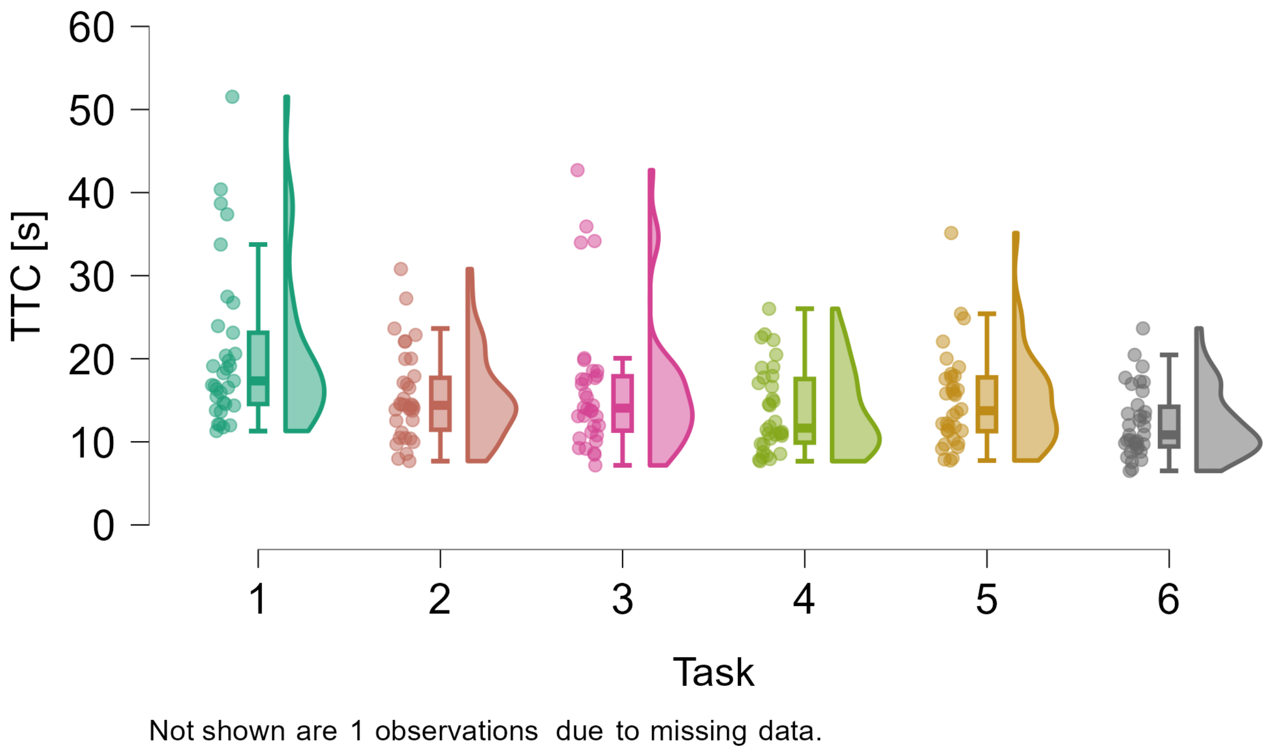

Figure 24: TTC separated by task

likely familiarize themselves with the experimental setup quickly in the beginning, and then make small improvements over the course of the later tasks.

The participants did not wear gloves during tasks 1, 3, 5 and did wear gloves during the tasks 2, 4, 6. The results show that participants perform better in the tasks where they did wear gloves. However, it is unclear to what degree this improvement is caused by the gloves and to what degree it is the result of the learning effect. In addition to the participants getting accustomed to the experimental system in general, in tasks 2, 4, 6, they operated the controller prototypes for a second time, which probably had a positive effect on their performance. In summary, the effect of gloves on the performance of the study participants is unclear.

To investigate the effect of the controller prototypes on participants' performance, the TTC is shown again, split by controller. For this analysis, only the data from tasks 1, 3, 5 (no gloves) will be used, to at least partially circumvent the unclear learning effects. Table 6 shows the results, which are visualized in fig. 25.

Both the mean TTC and the standard deviation with controller A (Buttons controller) are substantially lower than the other controllers, suggesting the participants performed best using it and did so consistently. Controller C (Joystick controller) scores second best and controller B (Slider controller) worst in terms of performance, although the difference between them is minimal.

Table 6: Descriptive statistics of TTC split by controllers. Only data from tasks 1, 3, 5 (no gloves) is included.

Controller	A	B	C
Mean TTC	14.852	18.659	18.523
Std. Deviation	3.754	9.695	9.691
Minimum	7.167	8.633	7.750
Maximum	22.067	51.533	40.383

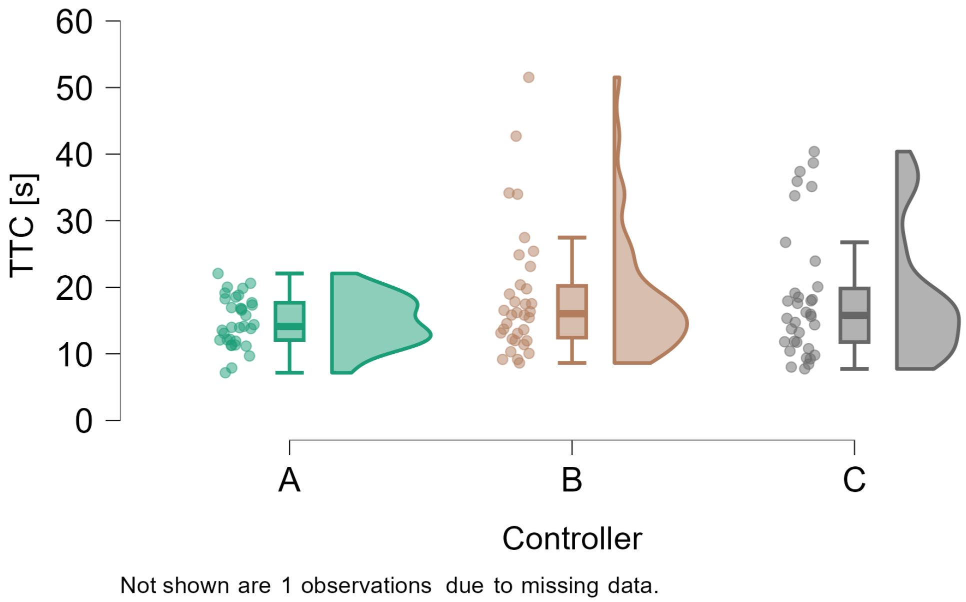

Figure 25: TTC separated by controller. Only data from tasks 1, 3, 5 (no gloves) is included.

6.2.2. Inferential Statistics of TTC

To test if the differences in performance with different controllers are statistically significant, an ANOVA will be conducted. The analysis will only be performed with data from tasks 1, 3, 5, where participants didn't wear gloves.

The assumption for ANOVA are:

1. **Normal Distribution:** A Shapiro-Wilk test is conducted for each of the three controllers. The results are shown in table 7, with deviations marked *. Two of the three groups show significant deviations from a normal distribution. A visual inspection of Q-Q plots (fig. 26) reveals several extreme outliers, confirming the result of the test. The data cannot be considered normally distributed.

2. **Categorical & Continuous Variables:** The independent variable is the controller (A, B or C), which is categorical. The dependent variable is TTC (a time value), which is continuous. The assumption is fulfilled.

3. **Homogeneity of Variances:** Levene's test for equality of variances shows a significant result $(F(2, 98) = 6.126, p = 0.003)$. Therefore, variance homogeneity can't be assumed.

4. **Independence of Groups:** The order of controllers was changed between participants to minimize the impact of learning effects on the resulting data. For this reason, the groups will be considered independent.

Table 7: Results of the Shapiro-Wilk test on the TTC (no gloves) data

Controller	A	B	C
Shapiro-Wilk	0.976	0.810	0.845
P-value of Shapiro-Wilk	0.645	$<$ .001*	$<$ .001*

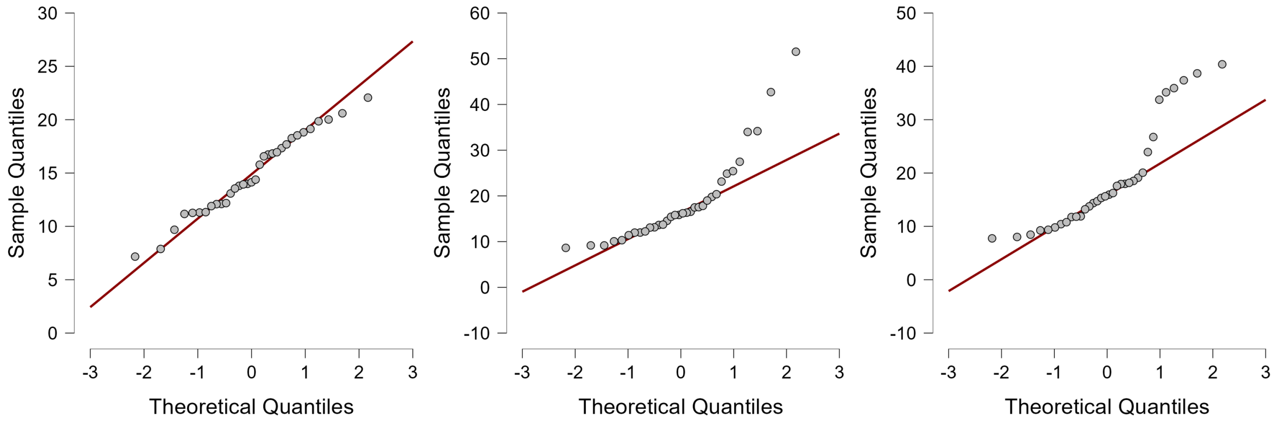

Figure 26: Q-Q plots of the TTC data separated by controller. From left to right, controller A, B, C.

Kruskal-Wallis

Since the assumptions for ANOVA are not fulfilled, a Kruskal-Wallis test is performed instead. The results of the Kruskal-Wallis test show there is no statistically significant difference in TTC between the controllers $(H = 1.250, p = 0.535)$.

6.2.3. Effect of Hand Size

The hand size of participants was collected as an addition to the demographics questionnaire. A Pearson correlation coefficient was computed to asses whether there is a linear relationship between hand size and TTC for each completed task. There is a negative correlation between the two variables $(r(201) = -0.233, p < 0.001)$. The correlation is visualized in fig. 27.

6.3. Performance: Success Rate

The success rate seeks to measure how successfully each sub-task was completed. Each sub-task was classified as on of the following:

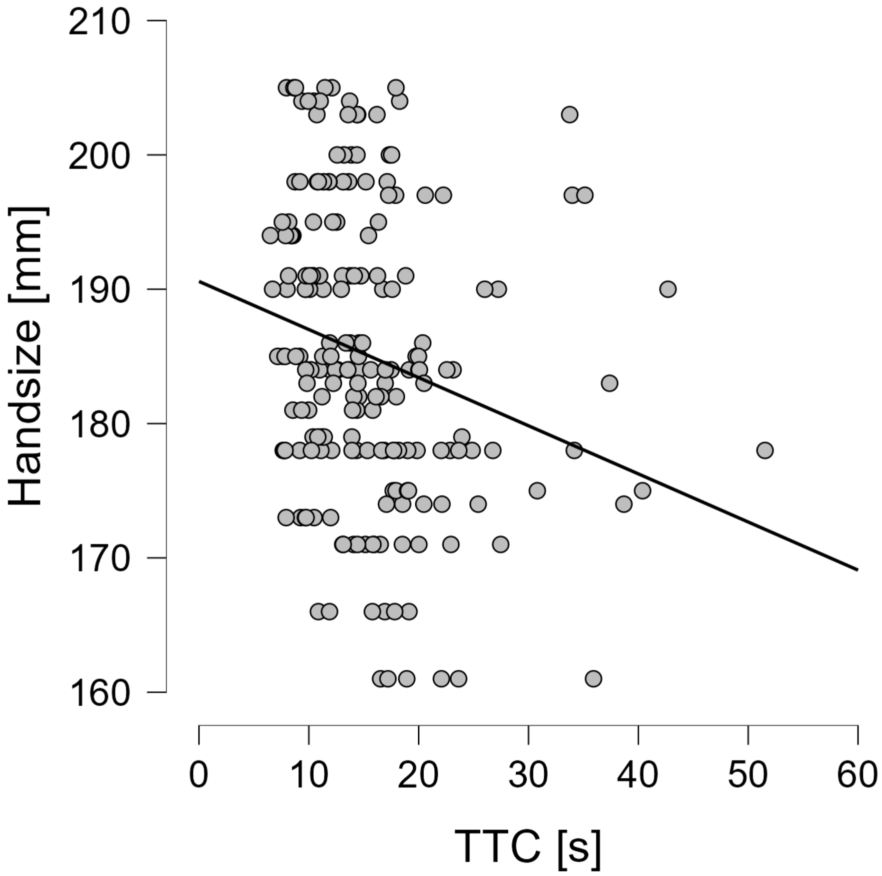

Figure 27: Scatter plot showing the negative correlation between hand size and TTC

- **Successful:** The object was inserted into the box cleanly on the first attempt.
- **Successful with corrections:** The object was inserted into the box, but multiple attempts had to be made, typically because the test object became stuck in its opening instead of falling through.
- **Unsuccessful:** The object was not delivered into the box, usually be cause it was knocked or dropped on the floor.

Sub-tasks were classified into one of these categories by observation from the study recordings.

Participants employed a wide range of correction techniques when the object did not fall into the box on the first attempt. Most common corrections involved grasping the object again, lifting it up and approaching the box again with a new orientation of the gripper, or setting the object back on the table near its original position and trying again. Some participants opted to poke the stuck object with the gripper fingers until it fell into the box, and a few used the gripper to grasp the side of the box and shake it to make the object fall in. The amount of corrections performed during a given sub-task also varied among participants, as some correction attempts resulted in the object becoming stuck in a different way, or at times the same way, instead of falling into the box. As a result, it would be difficult to count the kind and number of corrections in a standardized way. Therefore, it was only counted whether any corrections were made as a Boolean value.

Of the recorded sub-tasks, 7 were classified as unsuccessful, 173 required corrections and the remaining 1038 were successful. Table 8 shows the distribution of corrections and unsuccessful attempts among the six sub-tasks. Cubes seem to require more corrections than cylinders, which is likely explained by the cubes getting stuck in their lid opening more easily due to having more edges than a cylinder.

Table 8: Total numbers of recorded corrections and unsuccessful attempts by sub-task

Sub-task	1 - Cylinder	2 - Cube	3 - Cylinder	4 - Cube	5 - Cylinder	6 - Cube
Corrections	24	35	30	28	23	33
Unsuccessful Attempts	0	0	2	0	4	1

6.4. Interventions

A total of 25 interventions by the experimenter were necessary during the study. The concrete reasons for each intervention were not logged, but a brief overview is possible:

- 2 interventions were caused by the cap of the joystick falling off. It was successfully reattached in both cases.
- 2 interventions were caused by the violation of the speed limits of the arm. A restart of the teleoperation program resolved this.
- 1 intervention was caused by an unidentified communication issue between the controller and the leader laptop. Unplugging and reattaching the controller and a restart of the *gripper_control* program resolved the issue.
- 20 interventions were caused by various errors of the *gripper_control* program. The cause of these errors could not be identified, but all were resolved by restarting the program.

There were no cases where a task had to be abandoned due to a technical issue.

6.5. Preference: Usability Score

In the study, participants were presented with a SUS (System Usability Scale) questionnaire after completing each task. The participants were instructed to evaluate the usability of the system, mainly focusing on the controller prototype they just used. In total, 6 sets of 34 SUS scores were collected, two for each of the three controller prototypes: with and without gloves. The SUS score ranges from 0 to 100, with a higher value indicating a higher perceived usability.

6.5.1. Descriptive Statistics of Usability

A summary of the data is shown in table 9. The SUS scores are split by controller, and split again based on whether the participant wore gloves during the task or not. The data is visualized in fig. 28 (no gloves) and fig. 29 (gloves).

Table 9: Overview of descriptive statistics of SUS scores

	SUS No Gloves			SUS Gloves		
Controller	A	B	C	A	B	C
Mean	81.618	72.426	74.412	81.618	73.382	79.265
Std. Deviation	16.247	13.463	18.279	14.833	14.419	14.309
Minimum	35.000	45.000	22.500	37.500	47.500	40.000
Maximum	100.000	95.000	100.000	100.000	100.000	100.000

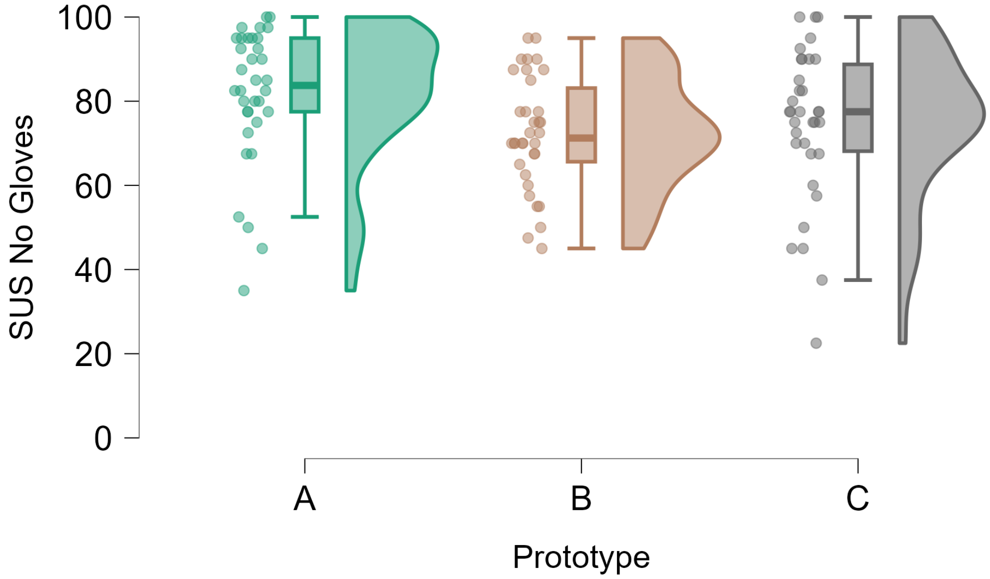

Figure 28: SUS scores when not wearing gloves

Participants assigned the highest score to controller A (Buttons controller), the second highest to controller C (Joystick controller) and the lowest score to controller B (Slider controller). Notably, this order is the same in both the scenarios with and without gloves. The score values are also very similar. These results show that gloves do not have a major impact on the participants' perception of usability of the controller prototypes.

6.5.2. Inferential Statistics of Usability

To test whether the differences between controllers are statistically significant, an ANOVA will be conducted. This analysis will only be conducted with the SUS scores without gloves, as investigating the

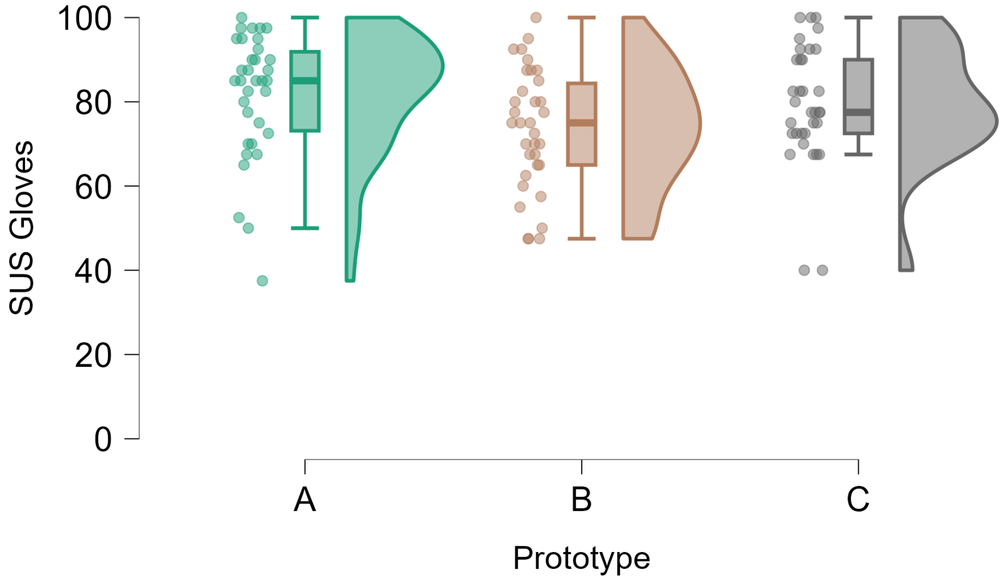

Figure 29: SUS scores when wearing gloves

effect of gloves is only a secondary objective of the study. The primary concern are differences between the controller prototypes.

The assumptions for ANOVA are checked:

1. **Normal Distribution:** A Shapiro-Wilk test is conducted for each of the three controllers. The results are shown in table 10, with deviations marked *. Two of the three groups show significant deviations from a normal distribution. A visual inspection of Q-Q plots (fig. 30) shows some deviation, but no extreme outliers. The data is assumed to be normally distributed.

2. **Categorical & Continuous Variables:** The independent variable is the controller (A, B or C), which is categorical. The dependent variable is the SUS score (range from 0 to 100), which is continuous. The assumption is fulfilled.

3. **Homogeneity of Variances:** Levene's test for equality of variances shows no significant result $(F(2, 99) = 0.648, p = 0.525)$. Therefore, variance homogeneity can be assumed.

4. **Independence of Groups:** The order of controllers was changed between participants to minimize the impact of learning effects on the resulting data. For this reason, the groups will be considered independent.

Table 10: Results of the Shapiro-Wilk test on the SUS (no gloves) data

Controller	A	B	C
Shapiro-Wilk	0.870	0.963	0.927
P-value of Shapiro-Wilk	$<$ .001*	0.294	0.025*

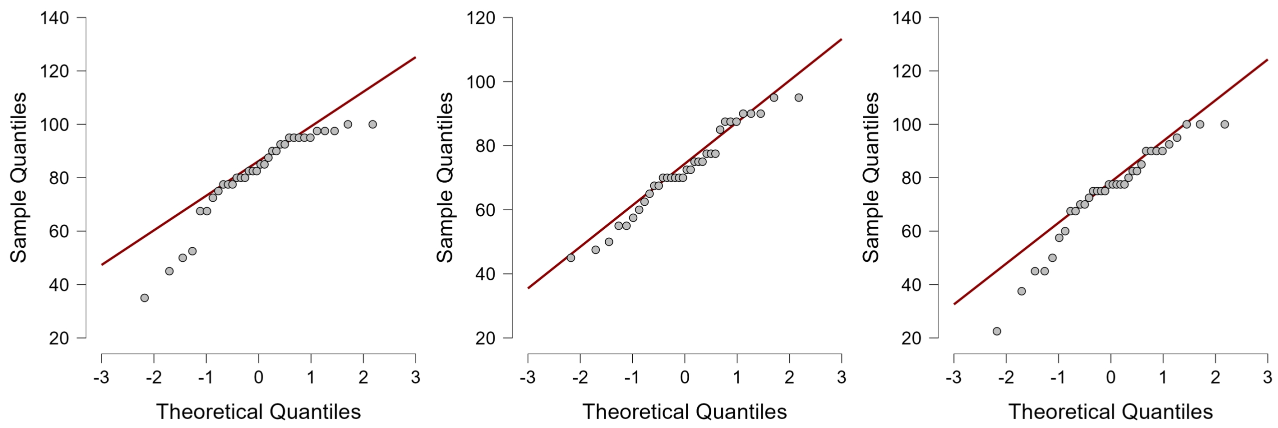

Figure 30: Q-Q plots of the SUS scores separated by controller. From left to right, controller A, B, C.

ANOVA

A one-way ANOVA was performed to compare the effects of the controller prototypes on perceived usability. The analysis shows that there is not a statistically significant difference in SUS scores between the controllers $(F(2, 99) = 3.061, p = 0.051)$.

Post-Hoc Analysis

Since ANOVA showed no significant difference between all three controllers, a series of t-tests was used to investigate differences between pairs of controllers. The results are shown in table 11. The pairwise comparison shows that there is a statistically significant difference in SUS scores between controllers A and B (Buttons and Slider), and no significant differences between other pairs of controllers.

Table 11: Pairwise t-tests of SUS scores (no gloves)

Controller Pair	T-Test Result
A - B	$t = 2.540, p = 0.013$*
A - C	$t = 1.718, p = 0.090$
B - C	$t = -0.510, p = 0.612$

6.6. Interview Results

Participants gave a wide range of feedback to the controller prototypes. A summary of the responses can be seen in table 12.

Table 12: Summary of interview responses

Positive Feedback	**Negative Feedback**	**Other Feedback**
	Buttons Controller (A)	
Grasp button very useful	Age, sex, occupation	Prototypes feel flimsy
No noticeable input delay	Buttons difficult to find by touch wth gloves	Prototypes generally easy to use
Hand size	Buttons difficult to press with longer fingernails	Controllers are a significant improvement over teleoperated gripper
	Slider Controller (B)	
Felt natural to use	Input delay is irritating	
	Slider hard to reach when fully on the left	
	Slider knob uncomfortable	
	Joystick Controller (C)	
Joystick button very useful	Accidentally pressed button	
Usable with one hand	Can't correct inputs due to input delay	

6.7. Other Observations

During the study, some miscellaneous observations were made by the experimenter that are not quantified by the measures above, but may still be of interest.

One participant reported a feeling of mild confusion, expecting the follower arm to mirror the movement of the leader in the depth direction, as in the follower should move forward when the leader is pushed backward. Upon further questioning, the participant did not report a similar expectation for the sideways motion of the arm. The participant also added that this confusion resolved itself as they got used to the system over the course of the experiment, and they completed the study normally. Some other participants mentioned briefly experiencing a similar feeling in the beginning of the experiment, but did not elaborate further.

Several participants who struggled with the task, and consequently had to perform many lengthy corrections, showed visible signs of frustration ranging from sighs to angry exclamations. These were almost universally followed by a reassurance to the experimenter that they intend to continue with the task. No participants accepted the suggestion of a break, and all finished the experiment afterwards.

The participants employed a range of postures and grips of the controller. Most participants opted to hold the controller and the Franka Hand firmly with both hands, and operated the system only moving their hands and arms while standing still and upright. A few participants, particularly those who completed the tasks quickly, instead chose to employ a light squat, and move their entire upper body while keeping their arms relatively still. One participant who used this technique expressed their satisfaction at how comfortable it was compared to the default posture. Some participants also deviated from the common hand grip, at times letting go of the controller with one or both hands and pushing against the joints of the robot arm instead. This usually resulted in a slower completion of the task.

In chapter 5, detailing the design of the study, it was mentioned that participants' handedness would be collected as an addition to the demographics questionnaire. The intention behind this was to investigate whether there is a difference in performance or preference between left- and right-handed participants, since the controller prototypes are built with most of the input elements situated in reach of the right hand. However, out the 34 participants, 33 were right-handed, making such analysis impossible.

7. Discussion

7.1. Hypothesis Evaluation

Based on the study results presented in the previous chapter, the hypotheses are evaluated as follows:

Question 1: Which input elements should be used on the controller?

- **Hypothesis 1.1:** Users will perform better using a controller with analog input elements (slider and joystick).
- **Evaluation:** Rejected. The data showed that the participants' performance as measured by TTC was slightly better with the buttons controller. The analysis found no statistically significant difference between the controllers in terms of performance.
- **Hypothesis 1.2:** Users will prefer using a controller with analog input elements (slider and joystick).
- **Evaluation:** Rejected. The participants assigned the highest usability scores to the buttons controller. The difference between the buttons and slider controllers was statistically significant, the remaining pairs were not.

Question 2: Does wearing gloves impact the users' performance or preferences?

- **Hypothesis 2.1:** Wearing gloves will have no major effect on users' performance.
- **Evaluation:** Accepted. The effect of wearing gloves on the users performance was unclear, suggesting it was only minor.
- **Hypothesis 2.2:** Wearing gloves will have no major effect on users' preferences.
- **Evaluation:** Accepted. The participants assigned very similar usability scores to the controllers in both the scenario with and without gloves.

Question 3: Does the size of the controller impact users' performance?

- **Hypothesis 3:** Users' hand size will have an impact on their performance.
- **Evaluation:** Accepted. There was a negative correlation between TTC and hand size.

With the hypotheses evaluated, the associated questions can be answered:

- **Question 1:** Which input elements should be used on the controller?

- **Answer:** Equipping the controller with push buttons seems preferable to the joystick and slide potentiometer.
- **Question 2:** Does wearing gloves impact the users' performance or preferences?
- **Answer:** No, wearing gloves does not have a major impact on the users' performance or preferences.
- **Question 3:** Does the size of the controller impact users' performance?
- **Answer:** Yes, participants with smaller hands performed worse, suggesting the current controller is too large.

7.2. Controller Design Limitations

The controller prototypes designed for the thesis were limited in three main ways which are discussed in the following.

7.2.1. Asynchronous Gripper Control

Due to the asynchronous nature of the Franka Hand controls, the originally intended functionality of the controller prototypes had to be severely limited. The step-wise opening and closing of the gripper finger was the main limitation. The gripper fingers were initially intended to move smoothly, and react immediately to the input on the controller.

The asynchronous control introduces a clearly noticeable delay between user input and the movement of the gripper. The functionality of the joystick and slider controller was constrained severely by this, as the input delay was most clearly felt there. Many study participants explicitly pointed out the input delay and their dislike of it. It is possible the participants' preferences and performance favored the buttons controller at least in part because it was not affected by the input delay very much.

7.2.2. Limited Feedback

All three controller prototypes do not give the operator any feedback.

In the current implementation, the teleoperation program gives haptic feedback through the leader arm by simulating the forces experienced by the follower, especially due to collisions with the follower arm's surroundings. This principle is not extended to the gripper controllers designed in the thesis. The controllers are input-only devices, and the operator must gather the required feedback to their actions visually. This did not present issues in the user study, since the study was specifically designed to test the controller prototypes, and the participants were given a clear view of the follower arm and the task space. In a more conventional teleoperation scenario, where the operator does not have a direct view of the follower, the lack of feedback may become problematic.

7.2.3. Shell Sturdiness

The shells of the controller prototypes were made with relatively low wall thickness. This was done for two reasons: to speed up the 3D printing of the prototypes, and to provide sufficient room for electronics. A side effect of this was a low sturdiness of the shells, which bent and twisted slightly when pushed against.

The bending did not cause any observable damage to the controller prototypes. It did irritate several participants, who reported having to treat the controllers more carefully and operating them with less force then they would prefer, out of fear of breaking them.

7.3. Study Design Limitations

All participants recruited for the study were affiliated with a university, either as students or as academic staff. Many were in the process of acquiring a technical degree. Participants were also young (ages 18 - 36). This means the population of the study is not representative of the general population, and its results cannot make any statement about the performance of preferences of the general population.

The acquisition of the performance data (TTC, corrections) was performed by manual measurement from the recordings of the study, and was then manually logged into a data sheet. While care was taken to do this accurately, due to the manual and repetitive nature of the process, it is possible that some data may have been accidentally corrupted. The extracted data does not contain any implausible values (unrealistically high or low TTC, duplicates of data points etc.) and the statistical analyses also did not report any implausible results. This suggests that the accidental data corruption either did not occur, or only occurred in very few cases which would not compromise the results of the study.

8. Conclusion and Outlook

The goal of this thesis was to design a usable controller for the gripper end effector of a teleoperated robot arm for use in light industrial assembly applications. Its purpose was to replace the existing solution of a teleoperated gripper, which was deemed unsatisfactory. Multiple controllers were to be designed, so they can be compared in a usability study.

During the design and implementation part of the thesis, three different controller prototypes were created, each allowing the operator to control the gripper using different input elements:

- **Buttons Controller:** Uses three buttons to open and close the gripper and grasp objects
- **Slider Controller:** Uses a slide potentiometer to control the position of gripper fingers
- **Joystick Controller:** Uses a joystick to control the gripper. Tilts open and close the gripper, a press of the joystick grasps an object

A usability study was conducted to compare the controller prototypes to one another. Participants were given a simple pick-and-place task and asked to complete it with all three controllers. The main measures used were TTC (Time to Complete) for performance and SUS score for preference.

The study results showed that participants had the lowest TTC when using the buttons controller, and lso assigned the highest SUS scores to the buttons controller. These results were however not statistically significant.

With the results of the study, the original research question can be answered:

- How is a control scheme for the end effector of a teleoperated robot arm for use in assembly best realized?

The results of the study show that the participants both performed the best and preferred to use the buttons controller the most. While there is insufficient evidence to show that the buttons controller is significantly better than the others, the results suggest that future developments of a usable control scheme may be best focused on a controller using buttons as input elements.

In future work, the possibility of exchanging the Franka Hand for an end effector that supports real time control should be considered. This would eliminate the input delay which currently worsens the usability of the gripper controls. The design of the controller can be improved by increasing the thickness of the shell, and attaching the Arduino in a way to make its USB port more easily accessible. The positioning of the input elements on the controller can also be changed, as several study participants reported having to strain their hands to reach some of the input positions. The spacers which create space for electronics between the controller and the Franka Hand should be made significantly larger to prevent unwanted movements of the controller. A more robust way of attaching the controller to the Franka Hand is also desirable. The gripper control program should be improved to better handle various edge cases and reduce the frequency of errors.

The results of this thesis, combined with the research suggested above, may lead to the development of a gripper controller usable in an industrial setting, potentially increasing the viability of using teleoperation systems in assembly applications, increasing productivity without an increase in workload.

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List of Figures

List of Tables

List of Acronyms

Appendix

The following data is attached digitally:

- This document and the associated LaTeX project.
- All figures from the thesis.
- PDF documents and Citavi project with all used literature.
- The *gripper_control* program (main.cpp), and three Arduino programs for each controller prototype.
- All documents produced for and during the usability study.
- Statistical analysis files in JASP.