Reduced-complexity Teleimpedance Command Interface Enabling Single-handed Control of 3D Stiffness for Unstructured Tasks

MSc: Thesis

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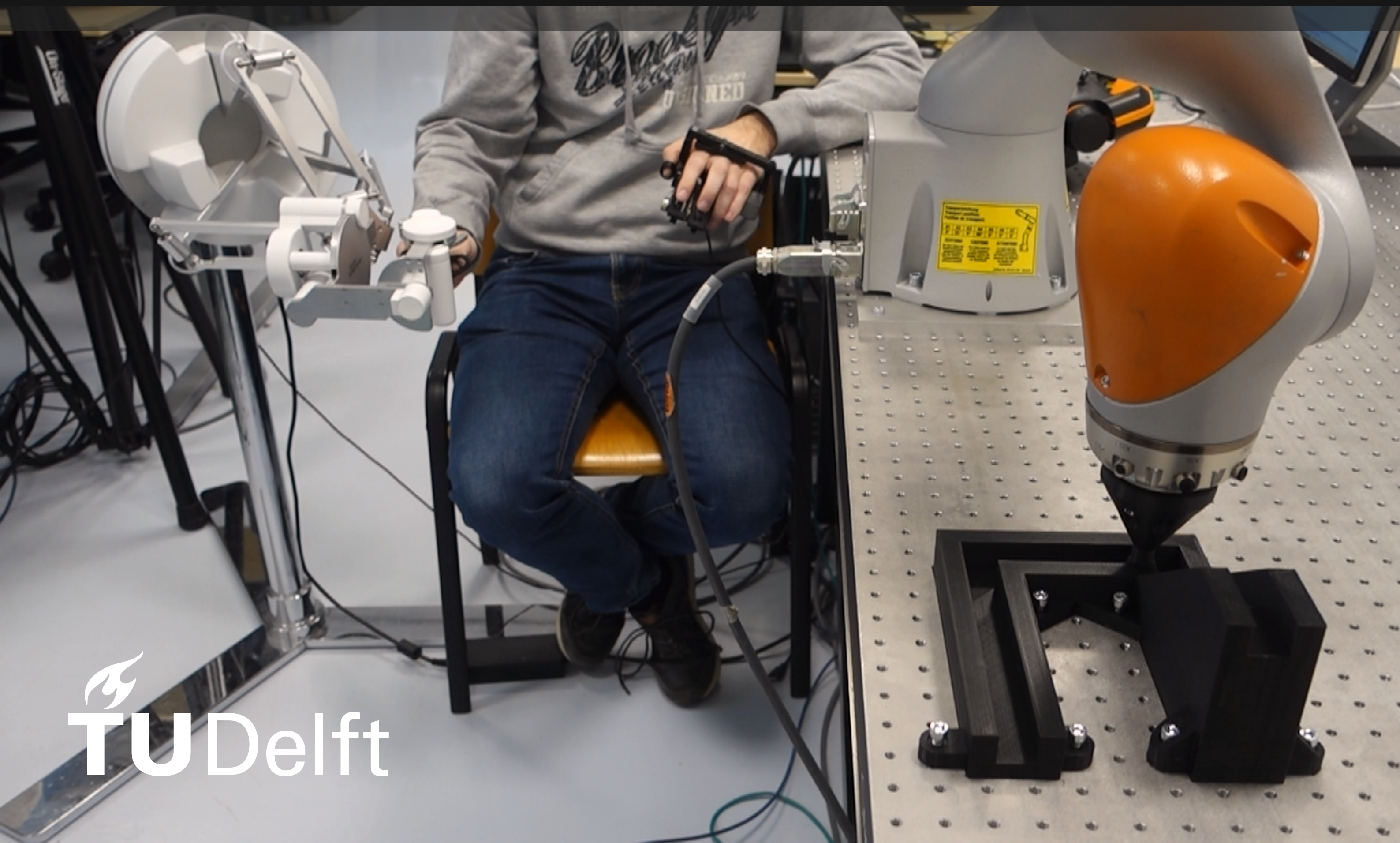

Reduced-complexity Teleimpedance Command Interface Enabling Single-handed Control of 3D Stiffness for Unstructured Tasks

by

F.M.C.Kraakman

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TU Delft

Preface

This thesis marks the end of my master's in Biorobotics at the TU Delft. For this research project, I have developed a novel teleimpedance command interface that enables the operator to configure 3D robot stiffness configurations single-handedly.

I want to thank Luka Peternel for sharing a tremendous amount of knowledge with me on this subject and for his advice, guidance, and support during my literature study and thesis. The weekly meetings were always a pleasant experience, with constructive discussions on many of the subjects of my literature study and thesis. They were also there during more trying times and made me leave the weekly meeting with a positive view and new goals. I would also like to thank Michaël Wiertlewski for taking the time to review my thesis as a committee member.

I especially would like to thank my parents, who have given me the best support I could have ever wished for throughout my life and in everything I do. I want to thank Floortje Lycklama for being a fantastic friend with whom I have always had a great time throughout our student time and for always being there for me when I had questions or needed support in times of need. Further, I feel grateful for everyone I have encountered and interacted with who has contributed to my personal growth, formed me into who I am today, and helped me graduate from the TU Delft with fond memories to look back on.

F.M.C.Kraakman
Delft, April 2024

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Master thesis paper

Reduced-complexity Teleimpedance Command Interface Enabling Single-handed Control of 3D Stiffness for Unstructured Tasks

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***Abstract*—The state-of-the-art teleimpedance command interfaces used to command the robot stiffness configuration are either too complex to set up, such as those that use physiological signals and other tracking methods or cannot configure the stiffness appropriately for 3d environments. To mitigate these issues, a novel teleimpedance interface is proposed. The proposed interface can independently control the stiffness configuration's shape, orientation, and size with single-hand operations while allowing the operator to use that hand to command the robot's position. The teleimpedance interface is attached to the operator's hand and uses two scroll wheels, a joystick, and a force sensor to configure the robot's stiffness and has two different modes of operation. Compared to the state-of-the-art methods, the main advantage of the proposed teleimpedance command interface is that it does not require additional hardware with force feedback or complex setup calibrations while allowing for control of the robot's 3D stiffness configuration with single-handed operation. An experiment with human subjects was performed to demonstrate the proposed interface's acceptance and functionality. To demonstrate the teleimpedance command interface's ability to adjust 3D stiffness configurations a teleoperation was performed, utilizing a Kuka robotic arm and a Force Dimension Sigma7 position input interface. The teleimpedance interface functioned as intended during teleoperation in a 3D environment to configure and adjust the 3D stiffness configuration for the task in real-time. The results from the human subject trials indicate that the participants can successfully operate the interface to complete the alignment tasks in both modes for 3D stiffness configurations.**

Keywords: Teleimpedance, teleoperation, real-time impedance adjustment, control, robotics.

I. Introduction

With robotics becoming more integrated into society, the need to complete more elaborate and force-sensitive tasks increases. These force-sensitive tasks can be both close by and far away. When the robot is controlled remotely, it is called a teleoperation. Teleoperations offer a solution for tasks in hazardous or remote environments where human involvement is undesirable.

With remote tasks, it can also be assumed that there are cases when the environment is not fully known. This type of unknown environment is called an unstructured environment. Unstructured environments are complicated to operate in as the tasks and environment's locations and dimensions are not fully defined. Controlling the robot becomes a physically complex interaction without knowing the exact locations and properties of that task. The task is physically complex because the robot applies forces by controlling its position relative to the target surface. To exert a force, the reference position has an offset into the object's surface. Hence, the dimensions and stiffness values must be known to control the exerted force effectively.

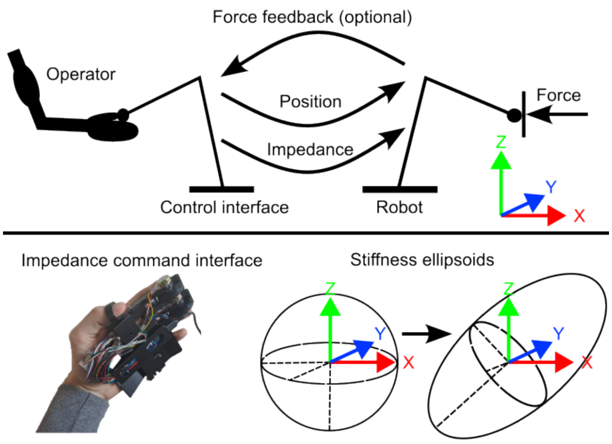

Fig. 1. Schematic example of a teleoperation where the teleimpedance command interface adjusts the stiffness configuration.

Due to the limited or incorrect information that an unstructured environment has provided, this method is not directly a viable option in an unstructured environment. With the lack of information about the environment, the reaction forces can quickly exceed the desired values due to the inability to predict material properties and reaction time. Changing the environment's properties is often impossible, so making the robot more stiff or compliant on demand can be preferable. A variable impedance controller can be used to make the robot stiff or compliant, as seen in figure 1.

The variable impedance controller allows the robot's stiffness to be changed depending on the given task and objective. The change in impedance affects the

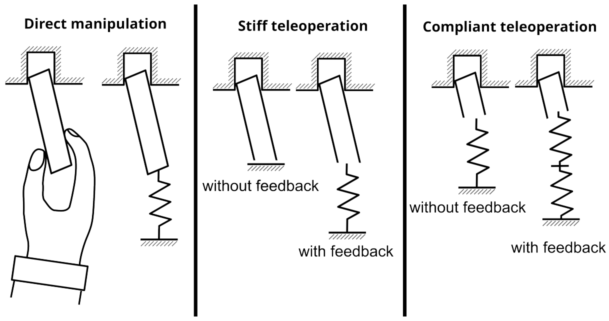

Fig. 2. Different teleoperation configurations for a peg in the hole task with illustrative stiffness comparisons.

robot's stiffness and dampening for both static and dynamic interactions. This adjustment for high and lower stiffness values depends on the given task. An example of this would be picking up an egg. The egg will shatter if the robot grasps too tightly with a high stiffness setting. If the robot does not exert enough force due to a too-low stiffness setting, the gripper will not be able to hold it, and the egg will drop. Another typical example of a task where adjusting the robot impedance benefits the success rate is the peg-in-a-hole task [1], [2]. The peg-in-the-hole task is commonly used to test the functionality of teleoperation features. For the peg-in-the-hole task, lowering the stiffness in the plane with the hole allows the peg to self-align with the hole without binding up, as it would with a stiffer configuration. This self-centring behaviour with low stiffness helps to increase the success rate in the presence of slight deviations. Examples of peg-in-the-hole tasks with different telerobotic configurations can be seen in figure 2. The left section illustrates how the operator directly manipulates a peg-in-hole task, where the operator's hand is metaphorically viewed as a spring. The remaining four scenarios involve remote actuation of pegs using stiff and compliant telerobotic configurations with and without feedback. In the presence of feedback, the setup becomes less rigid because the operator adjusts the position based on the feedback. The operator decreases the setup's stiffness while the robot remains stiff. In the last two scenarios, compliant teleoperation is introduced to both setups with and without feedback. This means that the robots can have adjustable stiffness configurations without the operator needing feedback from the robot to be compliant. Consequently, the robot can exhibit both stiff and soft characteristics.

For the operator to adjust the robot stiffness configuration, he must have an interface that allows him to change the configuration. The stiffness configuration of a robot is not a single value but rather a $n \times n$ matrix. Each position in the matrix represents a different dimension of the robot's endpoint stiffness configuration. These separate values can be represented as a virtual stiffness ellipsoid, which helps to visualize

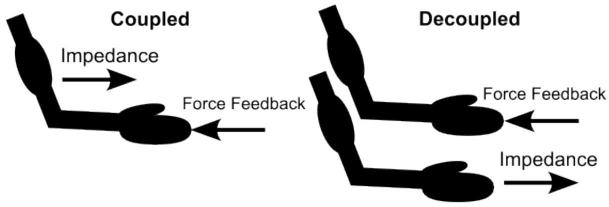

Fig. 3. Difference between coupled and decoupled impedance command interfaces.

the stiffness configuration to the operator. There exist several teleimpedance command interfaces in literature; examples of teleimpedance command interfaces are a linear slider button to change the value of the configuration [3], methods utilizing Electromyography (EMG) [4] where muscle activity is measured, with force feedback through the position command interface [5] and the touchscreen tablet interface [6]. The different teleimpedance command interfaces each have their advantages and disadvantages. While force depended tasks are more straightforward to complete where the operator has access to force feedback from the robot, others can become more challenging. A reason for this is the coupling effect between the force feedback and the input devices. It was found that the subjects tracked the position better with a coupled force feedback interface [7], whereas the force tracking tasks were done better with decoupled force feedback [7]. A visual representation of coupled and decoupled stiffness command interfaces can be seen in figure 3. An input interface is considered coupled when the robot's feedback can be fed back into the input interface for said robot. Decoupled interfaces do have feedback, but it's fed back in a manner that does not influence the correlated input.

The teleimpedance command interfaces that use this coupling effect are some of the muscle activation and force-based methods. While the muscle activity-based methods are intuitive to use, they suffer from complex installation and calibration processes. The coupling effect can also negatively impact the operator's performance. These muscle activation-based teleimpedance command interfaces require the use of EMG stickers. These EMG stickers can be problematic for long-term use due to adhesives, but the conductivity changes due to fluctuations in moisture and temperature, reducing the robustness. EMG is also sensitive to various kinds of noise: ambient noise, motion artefacts, cross-talk and various others [8]. Among the limitations of the present EMG technique are the local validity of calibration data and the need for recalibration in different poses and for other subjects [9]. It is also suggested in [9] that the participant has more control over the overall size rather than the actual shape of the stiffness ellipsoid. Consequently, EMG-based teleimpedance command interfaces would likely not benefit from higher channel interfaces over a single channel interface. The lack of degrees of freedom (DOF) in stiffness commandment interfaces is not exclusive to the muscle activation type interfaces. In literature, most teleimpedance interfaces were tested in a way that only modified the robot stiffness configuration only in size or 2D to either reduce complexity or it was a limitation of the interface. Since the telerobotic tasks generally are in a 3D unstructured environment, the tasks could also present different orientations in 3D space that are not parallel or perpendicular to the limited DOF that current teleimpedance command interfaces offer. This introduces the requirement for higher DOF teleimpedance command interfaces. Two example teleimpedance command interfaces are the following: a tablet with touchscreen interface [6] and a foot-based interface [10]. The tablet's touchscreen interface [6] allows the operator to command the stiffness ellipse in 2 planes, resulting in a 3D stiffness ellipsoid. While the touchscreen interface works for configuring and visualizing the stiffness ellipses, using a tablet to configure them introduces problems. One of these problems is that it is hard to determine the orientation of the stiffness ellipsoid compared to the robot. It also forces the operator to divide his attention between the task and the tablet interface, as the operator has to look and interact with the tablet screen to command the stiffness ellipses. This makes it impossible to look at the robot and the screen simultaneously, making it very hard, if not impossible, to command both the stiffness and the position, forcing the operator to alternate his attention. This decreases the interaction speed between the robot and the operator while increasing the risk of accidents.

The foot-based interface [10] consists of a base plate rotated by the operator's foot to set the angle. The same foot is connected to a force sensor, which is used to command the size of the stiffness ellipsoid. This partially defines a stiffness ellipsoid. To fully define a 3D ellipsoid, the operator needs to push a button and set the other angle and size as well. While it is possible with the foot-operated interface to keep their eyes on the task, it is challenging to make quick adjustments due to the requirement to set the interface to the correct setting before making any adjustments.

Existing teleimpedance command interfaces have the following problems: setup complexity, limited degrees of freedom and dividing the operator's attention. To resolve these issues, a new teleimpedance interface was developed. The proposed teleimpedance interface is designed with a set of requirements and assumptions. An experimental setup was created to test the viability of the interface. The experimental setup consists of the novel teleimpedance command interface and a display that shows two ellipses as a 2D representation of the 3D stiffness ellipsoid. The participants were trained on the teleimpedance command interface on both control modes using a familiarisation process. For the familiarisation process, the device's functionality was gradually introduced in two stages using training tasks. For the tasks, the participants had to match the controlled ellipsoid to a reference ellipsoid. A second experiment was done to demonstrate the interface functionality to adjust a 3D stiffness configuration for various actions. For the second experiment, the task is to insert the peg into a slot and trace the U-shaped slot with a ramp on the end. For each direction of motion, a different 3D stiffness configuration was used to prevent binding and excessive forces from happening.

The report structure is as follows: in chapter II, the research method is discussed in the sections interface design requirements, assumptions and the interface design. Chapter III contains the experiment setup, data analysis method and experimental protocol. Chapter IV presents the results obtained by the experiment and questionnaires. The obtained results are discussed in chapter V. The conclusion, recommendations and further study suggestions are in chapter VI.

II. METHOD

For this work, a novel teleimpedance command interface was designed. This teleimpedance command interface enables the operator to change the orientation and shape of the 3D stiffness ellipsoid in real-time with single-handed operation. The block diagram in Figure 4 provides a schematic representation of teleoperation utilizing the teleimpedance command interface. Teleoperation consists of two locations: the local site, where the controls are commanded by the operator, and the remote site, where the task is executed. On the local site, the operator can access a position command interface, which acts as a translation layer for position commands and potentially delivers force feedback between the robot and the operator. Meanwhile, the novel impedance command interface acts as a translation layer between the operator's desired stiffness configuration and the robotic stiffness controller.

This chapter continues by explaining the interface design requirements and comparing the state-of-the-art interface to these requirements in section II-A. Some interface design assumptions were made when designing the impedance command interface, these are discussed in section II-B. The design of the novel impedance command interface is elaborated on in section II-C, with the physical design, electronic components and interface configuration modes in subsections II-C1, II-C2 and II-C3. This chapter concludes with the remote robot impedance controller design in section II-D

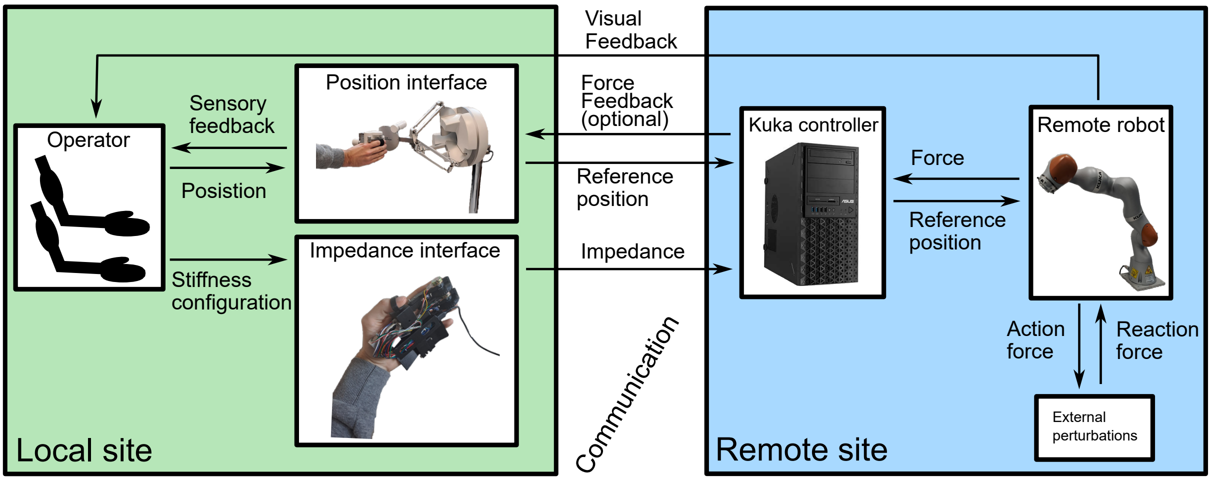

Fig. 4. Block diagram illustrating teleoperation with force feedback. The operator utilizes a position command interface and an impedance command interface to control the remote robot. The operator can command the robotic arm's position and stiffness configuration with these interfaces. Additionally, the operator can receive sensory feedback when desired, enhancing the perception of the configuration and task execution.

A. *Interface design requirements*

Several teleimpedance command interfaces were briefly discussed in the introduction, and some of their shortcomings were highlighted. With this information and other interfaces found in literature, such as listed in table I, a set of requirements was formulated to guide the design of a novel teleimpedance command interface, aimed at remedying the aforementioned shortcomings. Below is a list of design requirements(R1-R5), followed by an explanation of why they were chosen.

- R1: The stiffness command interface must not interfere with the operator's arm range of motion.
- R2: The stiffness command interface must have the option of being used with the same arm that is being used for position commands.
- R3: The stiffness ellipsoid must be commanded in 3D.
- R4: The design does not involve long calibration procedures and knowledge of human anatomy.
- R5: The stiffness command interface does not introduce a coupling effect between force feedback and the stiffness command interface.

The requirement in question will be referred to as R(number) from here on out. This set of requirements comes from the following reasoning:

The stiffness command interface should not hinder the operator's range of motion. Thus, the operator can interact with the position command interfaces with limited interference from the impedance interface (R1) and utilize the operator's maximum range of motion.

In specific environments, it can also be desirable that the operator can use two robotic arms to interact with the environment while still being able to manipulate the stiffness configuration (R2). With the ability to control two robotic arms, more physically complex tasks can be successfully executed, such as rotating and balancing objects [11]. The impedance command interface should be usable in all sorts of environments. Considering different environments, the operator should not lose the ability to change locations by walking or using a foot interface to control the operator's location or other functions, thus excluding leg-based impedance command interfaces.

Outside of the lab and in the real world, most of the positioning and executing of the tasks are done in 3D space. While rotational degrees of freedom are not taken into account for now, a 3D stiffness configuration is still required (R3).

For an interface to be viable in most environments, it should also be relatively easy to set up without any complex requirements like, for example, external sensors or extensive calibration requirements (R4). This requirement is due to the potential inability to do these properly due to a lack of available time in critical situations or environmental influences that can throw the sensors off.

While force feedback can enhance task execution and transparency by providing information regarding the exerted forces, it can also introduce undesirable coupling and feedback effects into the position and impedance command interface. This force information can also be presented to the operator in other ways to not interfere with the interfaces (R5).

The impedance command interfaces found in the state-of-the-art interfaces have different working principles. These interfaces can be categorized into the following categories: muscle activation, mechanical controller, force, haptic, algorithm, and voice. The different working principles from the state-of-the-art

Category	Interface method	DOF	Violates requirement nr.	Reference
Muscle activation	EMG	1-3	R3, R4, R5	[11]–[16]
	EIT	1-3	R3, R4, R5	[17]
	Air pressure band	1-3	R3, R4, R5	[18]
Mechanical controller	Slider trigger	1	R2, R3	[3]
	Rotating foot plate	2	R2, R3	[10]
	Tablet	3	R2	[6]
Force	Force sensor	3 or 6	R5	[5], [19], [20]
	Perturbation	3 or 6	R5	[21], [22]
Haptic	Vibration	3 or 6	R5	[23]
Algorithm	Semi-autonomous	1-3	R3	[24]
	Posture based	3-6	R4	[14], [25]
	Fractal impedance	3-6	R3	[26]
Voice	Vocal frequency	1	R2, R3	[24]
proposed	scroll wheel + joystick +force sensor	3	-	-

TABLE I: Different teleimpedance command interface categories with interface methods as found in the literature. The state-of-the-art interface designs are compared to the design requirements for the proposed interface, the requirements that were not met are listed.

interfaces were compared against the five design requirements and found lacking. The state-of-the-art teleimpedance command interfaces did not pass the five design requirements in one or multiple ways, as explained below and listed in table I.

The interface types that are based on muscle activity, such as EMG [11]–[16] and posture [14], [25] based interfaces violate R4 due to the extensive calibration requirements which also tend to drift over time. Interfaces that use EMG also do not satisfy R3 and R5 as they are generally limited to a single DOF or only work in a local range. Given the operational mechanism of EMG, force feedback becomes mandatory for such interfaces to function as it relies on the coupling effect. The voice-based control [24] and slider/trigger [3] interfaces are mostly limited to 1 or 2 DOF, so R3 is not met. Whereas the tablet [6] and rotating foot interface [10] do meet most requirements, they do not pass R2. For the force and perturbation-based [5], [19]–[23] stiffness command interfaces, a device with force feedback is required, this violates R5 as this can make the system unwieldy and introduces a coupling effect. A more in-depth survey for teleimpedance interfaces from the last decade can be found in [27].

B. Interface design assumptions

Some design assumptions were to be made for the interface design. For tasks in a 3D environment, a 3D stiffness configuration is required to have full control over the robot stiffness configuration. This stiffness configuration can be represented as a 3D ellipsoid shape. To fully define a 3D stiffness ellipsoid, 6 variables are needed. These 6 variables fully determine the shape and orientation of the stiffness ellipsoid. The 6 variables consist of 3 eigenvalues for the shape of the ellipsoid and 3 angles for the orientation around the centre point. The rotational stiffness will be a fixed value for this project and is not considered a part of it but would follow similar constraints. The three eigenvalues are denoted as e_1, e_2 and e_3 for defining the ellipsoid's shape as seen in figure 5. The actual sizes and ratios between the eigenvectors depend on the task and its requirements. The three eigenvalues would be the same value for general motion tasks without specific directional constraints, resulting in a spherical geometry for the impedance ellipsoid and the robot having the same stiffness in all directions.

When a task requires a different stiffness configuration, it is assumed that the stiffness requirements between the orthogonal vectors on a particular plane will be reasonably similar for many tasks, resulting in a round cross-section. This observation allows two independent eigenvalue variables to be reduced to a single value for both directions. With this, the assumption $e_1 = e_2$ is made. With this simplification, the ellipsoid shape can be either a sphere, oblate or prolate as a configuration shape. Examples of the shapes can be seen in figure 5. Two examples of tasks where the impedance configurations are not spherical and vastly different are the peg-in-the-hole task and a surface polishing task. The peg-in-the-hole task is a prime example where a prolate-shaped stiffness ellipsoid would be used. With the prolate shape as the stiffness configuration, the peg can align better with the hole due to the lower stiffness in the surface plane while still being able to exert a force to insert the peg into the hole direction without binding due to friction. On the other hand, the surface polishing task is a prime example of where an oblate-shaped stiffness ellipsoid would be used. With the oblate shape as the stiffness configuration, the tool will be compliant perpendicular to the surface, preventing surface damage while still being stiff enough in the plane to overcome rough spots with increased friction and thus not losing positional accuracy.

With the earlier assumption that $e_1 = e_2$, the operator is no longer required to have individual control over these two variables and can be reduced to one single input. This reduces the number of required configuration inputs from 6 to 5.

For specific tasks, just changing the shape of the

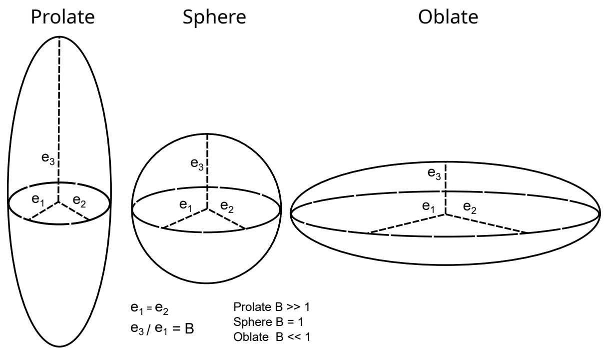

Fig. 5. Visual illustration of the prolate, sphere and oblate shapes.

stiffness ellipsoid is not enough. In these cases, the ellipsoid must be orientated to align with the task objective. When the stiffness ellipsoid is rotated, this rotation is done around the origin of the stiffness ellipsoid x,y and z-axis. To orient the stiffness ellipsoid in any orientation, only 2 rotations about different axes are required. The 3rd rotation won't be required due to the available shapes not changing the stiffness configuration when rotating about e_3. With this, one rotational direction can be omitted.

With this final simplification, the number of variables required to be configured with the teleimpedance command interface has been reduced from 6 to 4. The four variables remaining are two orientation angles and two eigenvector scalars.

C. Stiffness-command interface design

For the design of the novel impedance command interface, the requirements from section II-A and the assumptions from section II-B were taken into account together with what was learned from the literature.

Given the current requirements, utilizing anything other than the operator's hand or arm to control the impedance command interface is not feasible, as R2 states that the impedance must be commanded using the same hand or arm that interacts with the position command interface. R4 eliminates the use of muscle activation and EMG methods for impedance control. These are excluded and not viable due to the lengthy and intricate calibration procedures and their diminishing accuracy over time.

Incorporating force feedback can enhance the transparency of the robot's operation. Additionally, this technology has the potential to partially offset the challenges associated with network time delays [28]. But in some situations, force feedback is not practical or desired as this can fatigue the operator. It was observed that the operators had better results with a median force feedback of 50% from the real world [29]. Force feedback has its set of advantages and complexities. Still, it also has the potential problem of introducing a significant coupling effect on both the stiffness and the position command interfaces depending on the input methods used [7]. Considering these advantages and disadvantages, R5 still excludes all methods that require force or haptic feedback as a central component to controlling the impedance. This decision aims to broaden the situational cases where the impedance command interface can be used, enabling its use in operations with or without force feedback. Given the constraints, the decision was made to attach the impedance command interface to the operator's hand. While the operator's hand is typically used for manipulating a position command interface, the fingers are generally not used for position tasks, leaving them available for additional functions, such as controlling the impedance interface.

Reliable and cost-effective sensors are preferred to evaluate the operator's input. Examples of commonly used, affordable, and reliable input methods for electronics that can be used to manipulate the size and orientation of the stiffness ellipsoid are click buttons, distance meters, linear/rotational potential meters, and load cells. Various configurations can be used to interpret the operator's input and adjust the orientation and size of the stiffness ellipsoid. There are three possible approaches to use the inputs from the interface to manipulate the stiffness configuration: position (0th-order), velocity (1st-order) and acceleration (2nd order)control [30]. In the 0th-order method, the operator has direct control over the value, meaning the set value remains constant over time. The 1st-order method involves the operator controlling the amount of change per time step rather than having direct control over the values themselves. With the 2nd-order control method, the rate of change is changed per time step. but that one was proven to be hard for human operators to have accurate and reliable position control with 2nd-order [31].

1) Physical design: With the assumption made in section II-B, it was defined that the configuration of the stiffness ellipsoid depends on 4 variables for a complete configuration. With 4 dependent variables, the impedance command interface will need at least 4 different input methods to make the necessary adjustments. The 4 variables fall into two groups: shape and orientation.

To ensure the transparency of the interface and make it user-friendly, the choice was made to use commonly used input methods such as scroll wheels, a joystick, and a force sensor. The scroll wheel and joystick are chosen because they are often used in everyday items like computer mice and gaming consoles, so the operators will be familiar with these input methods. A force sensor is used to change the overall size.

Figure 6 shows the impedance command interface

	Scroll wheel 1 (index finger)	Scroll wheel 2 (middle finger)	Joystick (thumb)	Force sensor (thumb)
Mode 1	Angle 1	Angle 2	Eigenvalues 1 & 2	Size
Mode 2	Eigenvalue 1	Eigenvalue 2	Angles 1 & 2	Size
Control order	0th	0th	1st	1st

TABLE II: Proposed teleimpedance command interface input functionality for modes 1 and 2.

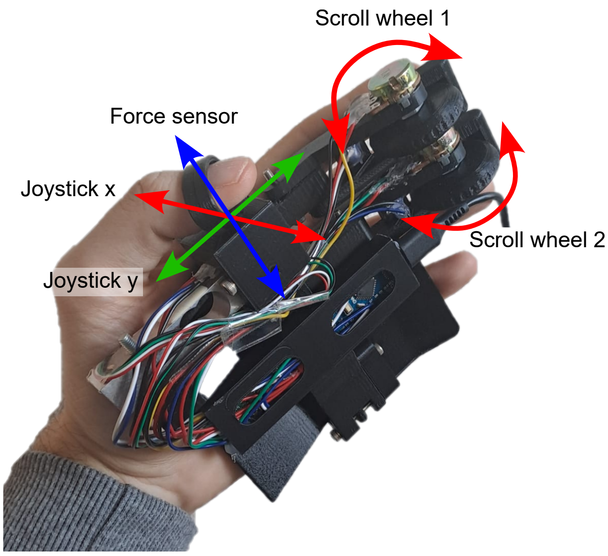

Fig. 6. Overview of the novel impedance command interface. The input sensors' locations and directions are indicated, and the input sensors' functionalities are found in table II.

design and consists of the following features. Two scroll wheels, linked to rotational potentiometers, are situated along the index and middle fingers. These wheels are arranged similarly to those found on a standard computer mouse, with an adjustable distance to the palm to accommodate operators with different hand sizes. A joystick is mounted to the side of the interface on top of a force sensor and located close to the thumb's resting position. This allows the operator to move the joystick to the front or backwards and left to right. The ring on the joystick that encloses the operator's thumb can be used to exert push and pull forces with their thumb. The physical design can be seen in more detail on the schematical drawings in Appendix C.1.2.

The joystick's input directions will never be fully parallel with the direction of motion from the operator's thumb, resulting in unintended inputs. The problem of a significant misalignment is easily solved by setting up a simple initial calibration with the participant. During the calibration phase the operator is asked to move the joystick to the front and back several times, the same process is done from left to right. With this information, a static transformation matrix can be made so that the operator's forward motion results in the intended input.

The teleimpedance command interface is meant to be used in conjunction with a position command interface. Ideally, the two interfaces should be combined into a single device. This would enable the operator to control both the position and impedance configuration of 2 robotic arms at nearly the same time. For this experiment, the impedance command interface is clamped onto the hand with a spring-loaded bar for ease of use. This should be exchanged for more rigid mounting options in future experiments with force feedback. The Sigma 7 interface will serve as the position command interface for this study.

2) Electronic components: The electronic components are powered through a USB data cable, and an Arduino Nano was used as the central signal-processing unit for the interface. The Arduino Nano features a 10-bit analog-to-digital converter, which processes signals from the rotational potentiometers, joystick, and push buttons and communicates them to the computer. The joystick is sourced from a Nintendo 3DS, chosen for its unique characteristic of sliding within a plane without altering its angle perpendicular to that plane. The absence of canting in the joystick allows the operator to slide the joystick freely while exerting push/pull forces, minimizing cross-correlation. The force sensor used is a generic 2 kg load cell selected for its adequate resolution and range suitable for this application. However, the Arduino lacks the necessary resolution to measure the variations in resistance from the load cell directly. To address this limitation, a SparkFun HX711 24-bit ADC load cell amplifier is used between the load cell and Arduino. Click buttons are positioned adjacent to the scroll wheels and can alter the mode of operation or be reprogrammed for alternative functions. The full wiring diagram can be found in Appendix C.1.1. While the current interface does not require additional inputs, there is still the option to incorporate additional input sources and configurations if necessary.

3) Configuration modes: The impedance command interface currently offers two configurations for the control schemes: mode 1 and mode 2. For the operator's convenience, the following inputs have been selected: two scroll wheels, which are configured as 0th-order inputs, and a joystick and a force sensor, which are configured to be 1st-order inputs. These inputs and configurations are selected with the participant's convenience in mind. A 1st-order scroll wheel, as it stands, would not make sense as it does not automatically reset to a 0 position, making the 0th-order a more user-friendly choice. On the other hand, using a 0th-order input for the joystick and force sensor would unnecessarily strain the operator by requiring them to maintain a constant position or force, which is considered impossible and exhausting. With the joystick and force sensor as 1st-order inputs, the control input must be 0 when not commanded by the operator. Hence, a dead zone is implemented. The dead zone effectively removes undesired drift, and the stiffness configuration changes only occur when the operator's input commands surpass the set dead zone threshold.

As modes 1 and 2 have different functions mapped to the controls, the functions per button with configuration modes 1 and 2 can be seen in table II. In mode 1, the orientation of the stiffness ellipsoid is adjusted using the scroll wheels, while the length of the stiffness ellipsoid vectors is adjusted using the joystick. In mode 2, the scroll wheels adjust the length of the stiffness ellipsoid vectors, and the joystick alters the orientation angles around the x and z axes. In modes 1 and 2, the force sensor changes the size without changing the aspect ratio or orientation of the stiffness ellipsoid with a 1st-order configuration. Applying pressure increases the stiffness ellipsoid size while pulling decreases the overall size of the stiffness ellipsoid.

D. Remote robot impedance controller

With the novel teleimpedance command interface configured, configuration values for the stiffness ellipsoid can be obtained for the shape e_{1-3} in N/m and the orientations θ and ϕ in degrees. With these values, a positive definite stiffness matrix $\boldsymbol{E} \in \mathbb{R}^3$ can be made using the following equation.

$$\boldsymbol{E} = \boldsymbol{R}_{xz}\boldsymbol{S}\boldsymbol{R}_{xz}^T \tag{1}$$

With $\boldsymbol{S} \in \mathbb{R}^3$ containing the stiffness values and is constructed from stiffness values $e_{1-3} \in \mathbb{R}$ for the x, y and z direction set by the interface on the diagonal.

$$\boldsymbol{S} = \begin{bmatrix} e_1 & 0 & 0 \\ 0 & e_2 & 0 \\ 0 & 0 & e_3 \end{bmatrix} \tag{2}$$

In mode 1, e_1 & e_2 are adjusted using the scroll wheel near the index finger, and e_3 is adjusted using the scroll wheel near the middle finger. In mode 2, e_1 & e_2 are configured by moving the joystick to the left or right, and e_3 is moving with the joystick to the front or back.

The ellipsoid configuration can be set to the desired orientation using the teleimpedance interface with the inputs that control θ and ϕ used in rotation matrix $\boldsymbol{R} \in \mathbb{R}^3$. With these inputs, the configuration can be rotated about two axes with desired angles θ and ϕ for the respective direction. In mode 1, θ and ϕ are set using the joystick; mode 2 uses the two scroll wheels.

$$\boldsymbol{R}_{xz} = \begin{bmatrix} \cos(\theta) & -\sin(\theta)\cos(\phi) & \sin(\theta)\sin(\phi) \\ \sin(\theta) & \cos(\theta)\cos(\phi) & -\cos(\theta)\sin(\phi) \\ 0 & \sin(\phi) & \cos(\phi) \end{bmatrix} \tag{3}$$

The current setup requires no conversion factor between the interface output and robot translational stiffness input. Thus, the conversion factor $\boldsymbol{C} \in \mathbb{R}^3$ is an identity matrix.

$$\boldsymbol{K}_{translational} = \boldsymbol{E}\boldsymbol{C} \tag{4}$$

The full robot stiffness matrix is defined as $\boldsymbol{K_{robot}} \in \mathbb{R}^{\boldsymbol{6}}$ with $\boldsymbol{K}_{translational} \in \mathbb{R}^3$ and $\boldsymbol{K}_{rotation} \in \mathbb{R}^3$ on the diagonal.

$$\boldsymbol{K}_{robot} = \begin{bmatrix} \boldsymbol{K}_{translational} & 0 \\ 0 & \boldsymbol{K}_{rotation} \end{bmatrix} \tag{5}$$

Rotational stiffness matrix $\boldsymbol{K}_{rotation}$ is constructed using the eigenvectors obtained from $\boldsymbol{E} \in \mathbb{R}^3$ using eigen decomposition.

$$\boldsymbol{E} = \boldsymbol{V}\boldsymbol{\lambda}\boldsymbol{V}^T \tag{6}$$

With the eigenvectors in $\boldsymbol{V} \in \mathbb{R}^3$ and eigenvalues on the diagonal in $\boldsymbol{\lambda} \in \mathbb{R}^3$. The rotational stiffness matrix is defined as $\boldsymbol{K}_{rotation} = \boldsymbol{V}\boldsymbol{K_r}\boldsymbol{V}^T$, with $\boldsymbol{K_r} \in \mathbb{R}^3$, the predefined rotational stiffness values of 50Nm on the diagonal.

When telerobotic tasks are performed, the robot is locally controlled by its impedance controller, which regulates the endpoint stiffness. This impedance controller is defined as:

$$\boldsymbol{F} = \boldsymbol{K_{robot}}(\boldsymbol{x}_d - \boldsymbol{x}_a) + \boldsymbol{D}(\dot{\boldsymbol{x}}_d - \dot{\boldsymbol{x}}_a), \tag{7}$$

In the given expression, $\boldsymbol{x}_a$ represents the actual pose, $\boldsymbol{x}_d$ signifies the reference pose of the robot end-effector, and $\boldsymbol{K} \in \mathbb{R}^6$ and $\boldsymbol{D} \in \mathbb{R}^6$ denote the virtual stiffness and damping matrices of the robot in Cartesian space. The stiffness matrix is adjustable with the novel impedance command interface. The damping matrix is obtained by double diagonalization design [32].

The control [33] of the endpoint force was implemented at the robot joint-torque level using the equation:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{J}^T(\boldsymbol{q})\boldsymbol{F} = \boldsymbol{\tau}, \tag{8}$$

where $\boldsymbol{F}$ represents the interaction force/torque exerted by the robot on the environment and consists of interaction forces from the task $\boldsymbol{F}_{task}$ and force from the impedance controller $\boldsymbol{F}_{imp}$, $\boldsymbol{q}$ denotes joint angles, $\boldsymbol{\tau}$ corresponds to joint torques, $\boldsymbol{J}$ is the robot Jacobian matrix, $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{C}$ is the centrifugal and Coriolis matrix, and $\boldsymbol{g}$ is the gravity vector.

III. Experiments

Fifteen participants took part in the experiment, 4 females and 11 males between the ages 20 and 57 years (Mean = 28.8±9.9) participated in the experiment. Participation in this study was voluntary, and the participant's efforts were not compensated. The interface design and experiment protocols were approved by the Human Research Ethics Committee of TU-Delft, and the research was performed in accordance with relevant guidelines and regulations. All subjects gave written informed consent before their participation.

This chapter is divided into several sections. Section III-A outlines the overall experimental setup The section III-B presents the methods used for data analysis. This chapter concludes with section III-C detailing the interaction with the participant.

A. Experimental setup

For the first experiment, the participants were presented with an alignment task to test the viability and effectiveness of the new impedance command interface in the hand of a human operator. The alignment tasks were displayed on a computer screen and were commanded using the impedance command interface. The task consisted of 2 reference circular/ellipsoidal shapes in red, to which the participant had to match the black shape configured with the impedance command interface. For a successful match to occur, the controlled shape and the reference must match within 5% of the reference for the following values: ϕ, θ, e_1 and e_3. When a successful match is made, the time to completion is recorded, and a new task will be presented. The recorded completion times contain two separate values: the time it took the participant to align both angles with the reference and the time it took to complete the task.

The impedance command interface has two modes/control schemes as defined in section II-C3. The different modes will be presented to the participants in an alternating manner; the odd-numbered participants will begin in mode 1, and the even-numbered participant numbers will begin with mode 2. For both modes, the experiment has three blocks. The first two blocks are used to familiarize the participants with the impedance command interface. These blocks are limited to a maximum of 30 tasks and a time limit of 5 minutes. The third block is used to generate the data points. There is no time limit for the third block, and it is limited to 15 tasks. So blocks 1, 2, 4 and 5 are used for training purposes and blocks 3 and 6 are used for the experimental data set.

The experiments are concluded with two questionnaires for the subjective perspective of the participants: the ”Likert questionnaire” and a ”Van der Laan questionnaire” [34]. The questionnaire presented to the participants can be seen in Appendix C.3. The ”Van der Laan” questionnaire [34] is used to find the acceptance scale of the interface and its modes for the participants. The ”Van der Laan” questionnaire presents the participants with questions from which subjective values were obtained, indicating how useful or useless and satisfying or unsatisfying the interface mode was perceived. The objective of the ”Likert questionnaire” is to obtain a subjective comparison between the different interface input methods. The participants were presented with four statements (S1-S4) and asked to what extent they agreed with them on the scale: strongly agree, agree, neutral, disagree, and strongly disagree.

- S1: ”The Shape/size of the ellipsoid was easier to manipulate with the joystick in comparison to the scroll wheel”.
- S2: ”The orientation of the ellipsoid was easier to manipulate with the joystick in comparison to the scroll wheel”.
- S3: ”The mental workload was higher for mode 1 in comparison to mode 2”.
- S4: ”The physical workload was higher for mode 1 in comparison to mode 2”.

The second experiment is to demonstrate the functionality of the impedance command interface in a 3D environment. To demonstrate the functionality, a U-shaped slot with a ramp on the end was used, as seen in figure 7. To manoeuvre the peg through the slot, a Kuka7 robotic arm is used. The peg is mounted to the robotic arm as the end effector. The position is controlled using a Sigma7 position command interface from Force Dimension, and the proposed teleimpedance command interface is used to control the robot's stiffness ellipsoid.

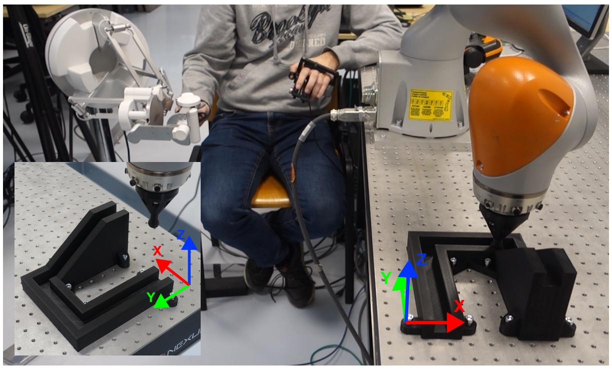

Fig. 7. Telerobotic setup with impedance command interface. The u-shaped slot mounted to the table is used to demonstrate the functionality of the impedance command interface.

B. Data analyses method

The participants who took part in the experiment worked with both interface modes. To reduce the learning bias, the order in which the modes were presented was in an alternating pattern throughout the participants. Still, a learning curve is assumed to be present, as the participants did not have enough time to fully master the interface in the short period they were exposed to the interface. Since the participants cannot fully master the interface and its controls, the task completion time is unlikely to follow a normal distribution. Another factor contributing to the deviation from a normal distribution in the results is the higher likelihood of participants being somewhat slower due to user error than achieving the same degree of improvement due to such errors. The obtained data is tested using Python's Shapiro function to prove whether the dataset was normally distributed. The results from the Shapiro test can be seen in Appendix A.3. Since the data does not follow a normal distributed data set, the normal t-test will be invalid for this data set. For these cases, the Wilcoxon signed-rank [35] test was created and will thus be used here for observing the significance of the difference between the completion times of different modes.

The "Likert scale questionnaire" results are plotted as a box plot with median, upper and lower quartiles and whiskers. The "van der Laan" has a fixed processing methodology [34] to obtain a data point depending on the answers given by the participants. The data points obtained with the "van der Laan" questionnaire are averaged to a median and standard deviation for both modes.

C. Experimental protocol

Before the experiments started, the participants were familiarized with the experiment and the interface. The familiarisation process started with an introduction to the concept of telerobotics and its problems. After the participants were introduced to the concept of impedance commandment for telerobotics in unstructured environments, the impedance command interface was introduced. With the participants slightly more informed about the topic, they were introduced to the interface. A short demonstration was given of how the interface is fitted to the hand and its base functionality. The familiarisation process becomes more hands-on after the initial introduction and moments to let the participant ask questions. The teleimpedance command interface was then fitted to the participant's hand. The participant was then allowed to manipulate the ellipsoids on the screen freely without any tasks for a short while.

The participant starts with two blocks of familiarisation tasks to train with the interface. These familiarization blocks are completed after surpassing the time limit of 10 minutes or successfully completing 30 alignment tasks per block. The first block consists of only circular alignment tasks with varying angle orientations and sizes. The goal is to simplify the interface so the participant can focus on adjusting the angles and the overall size and to familiarize the participant with the control scheme for these functions. The second block presents the participant with alignment tasks with different non-round shapes with different orientations and sizes. After this block, the participant should be somewhat familiar with the complete control scheme of the particular impedance command interface mode and utilize the full functionality of the impedance command interface. In the 3rd block, the experimental data is obtained. This block is virtually the same as the 2nd block but with different tasks. The number of tasks is limited to 15 alignment tasks. There is no time limit for this part of the experiment. The participant repeats this process for the other mode as well.

After completing the experiments for both modes, the participant is asked to fill out the "Likert" questionnaire first, followed by the "Van der Laan" questionnaire [34] for both mode 1 and mode 2.

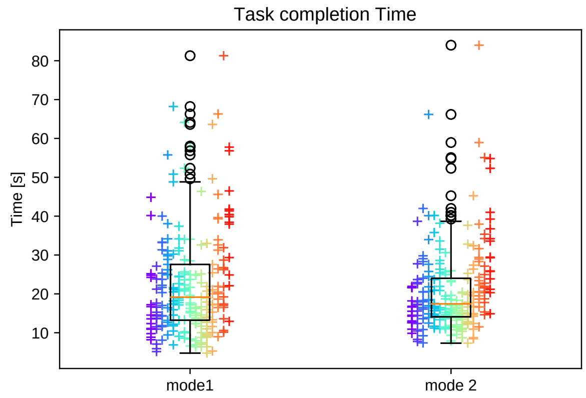

Fig. 8. Time it took for participants to complete an alignment task, where the y-axis represents task completion time in seconds, and the x-axis denotes the mode of the impedance command interface.

IV. Results

The results of the first experiment are displayed in several graphs, figure 8 the task completion times for all tasks and participants are plotted on the y-axis together with the box plot. Figures 9 and 10 similarly represent the time required by the participants to align the orientation or adjust the shape and size. The participant's task completion times per task are found in Appendix A.1 for the familiarization phase and A.2 for the trial.

The median time to complete a task is 22.53±13.32s for mode 1 and 20.51±10.51s for mode 2. The median time it took the participants to align the angles is 6.85±3.38s for mode 1 and 9.44±4.58s for mode 2. The median time it took the participants to adjust the shape to the correct size is 15.68±12.44s for mode 1 and 11.07±8.96s for mode 2.

The Wilcoxon signed-rank test comparing modes 1 and 2 produces the following p-values: 0.30 for task completion time, 0.0033 for angle alignment time, and 0.0011 for shape completion time.

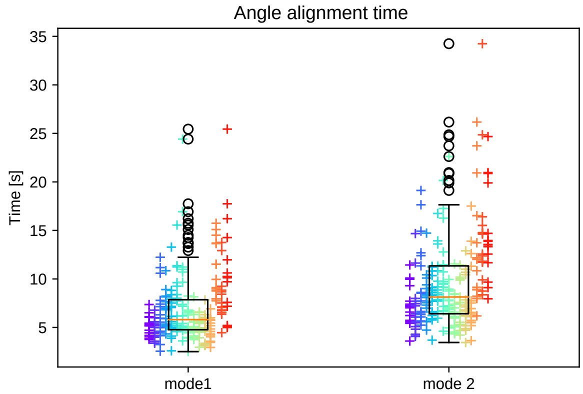

Fig. 9. The time duration participants took to align the angles of the stiffness ellipsoid in seconds.

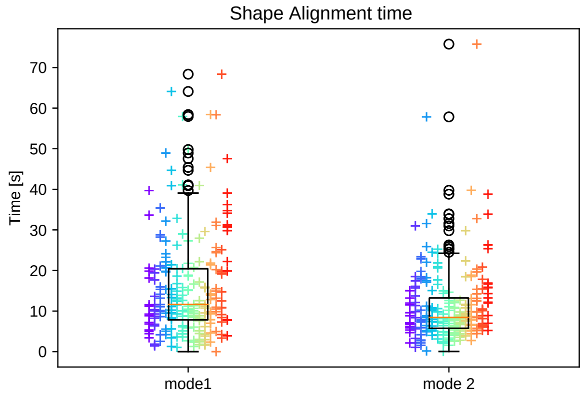

Fig. 10. The time duration participants took to adjust the shape of the stiffness ellipsoid in seconds.

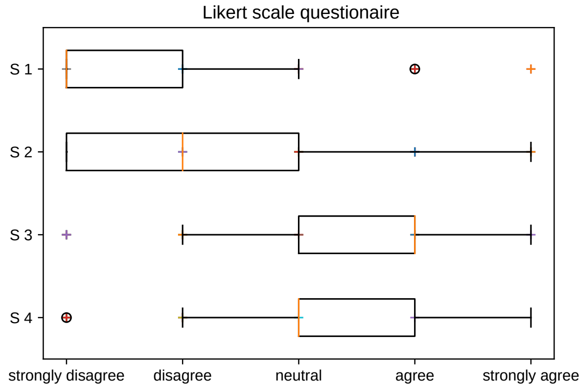

Fig. 11. Likert questionnaire results regarding participant preferences between the two different interface modes. Does the participant prefer the joystick over the scroll wheels to adjust shape/orientation? (S1 / S2) Do the participant's experience mode 1 to have a higher mental/physical workload than mode 2? (S3 / S4)

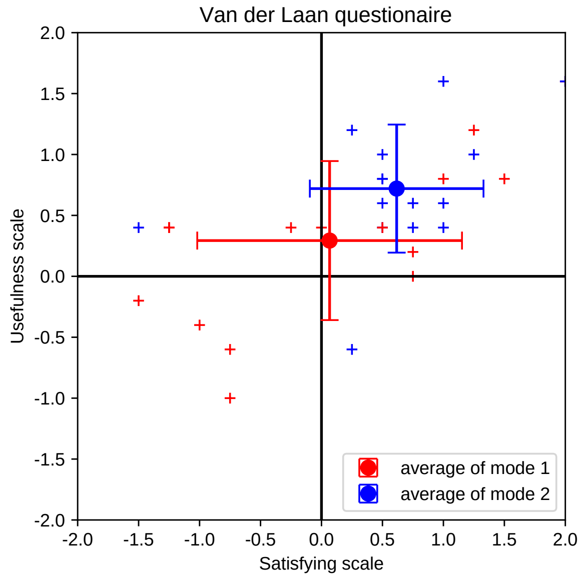

Fig. 12. "Van der Laan" questionnaire [34] results for the acceptance scale. The y-axis is the perceived use fullness. The x-axis is the perceived satisfying scale. Markers positioned to the right or the top on the positive scale indicate a higher perception in the respective area.

The subjective results for the "Likert" and the "Van der Laan" questionnaires [34] are displayed in figure 11 and 12 For the "Likert" questionnaire, the participants could agree or disagree with the statements and had the following results: Most participants did not agree with S1, with the median being between "disagree" and "strongly disagree." The participants found the scroll wheel easier to use for adjusting the shape of the stiffness ellipsoids than a joystick. Though there is a large spread on S2, most participants did not agree with S2, resulting in the median being "disagree". The participants thus preferred the scroll wheel over the joystick to set the angles of the stiffness ellipsoid. The median of the participants agreed with S3, and the mental workload was perceived to be higher for mode 1 than for mode 2. For S4, the median of the participants was neutral about the statement, and the physical workload was perceived to be similar between mode 1 and mode 2.

The "Van der Laan" questionnaire [34] results are displayed in figure 12. The red + symbols represent mode 1, and the blue + symbols are for mode 2. These represent a single participant for the indicated mode. The circle represents the average for the respective mode, with error bars denoting the standard deviation. The higher a symbol is on the graph, the more perceived utility the interface mode has. Similarly, the further to the right a symbol is on the graph, the higher the perceived satisfaction with the interface mode. Participants experienced mode 2, on average, to be more useful and satisfying to use than mode 1. The mode 2 satisfying scale is 0.62±0.71, and the usefulness scale is 0.72±0.52, for mode 1 satisfying scale is 0.07±1.09, and the usefulness scale is 0.29±0.65. The p-values obtained from a T-test for comparing mode 1 with

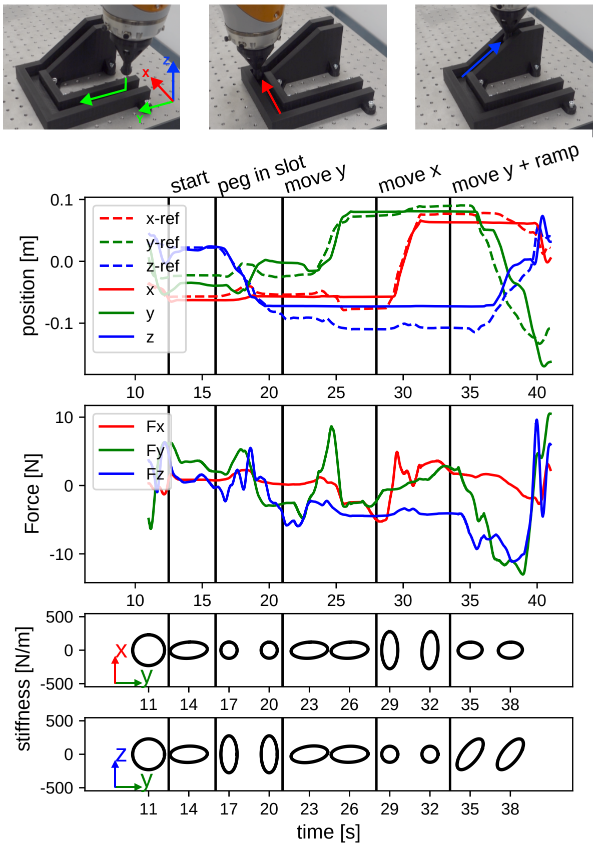

Fig. 13. Position and force graphs with 2D representations of the stiffness ellipsoids in the xy-plane and zy-plane from the second experiment.

mode 2 are 0.11 for the satisfaction scale and 0.05 for the usefulness scale.

For the second experiment, a U-shaped slot with a ramp at the end was traced with a peg during a teleoperation. The direction of motion can be seen in the three images on top in figure 13, where the top graph represents the position where the solid line is the robot position, the dashed line is the commanded reference position, the position on the y-axis is in meters, the time on the x-axis is in seconds. The second graph displays the forces [N] exerted by the robotic arm, and the third and fourth graphs display the stiffness ellipsoid[N/m] configuration in the xy- and zy-planes. A 3d representation of the stiffness configurations can be found in Appendix B.

V. Discussion

With the results presented in chapter IV, several observations can be made concerning the time completion graphs. From the resulting total task completion times in graph 8, a clear conclusion about which mode is better regarding the total task completion times can not be made. It is observed that the overall spread in completion times in mode 2 is smaller compared to mode 1, and the participants are performing more consistently. Yet a decision cannot be made with these results as they have a p-value of 0.30. It does seem to correlate with the slightly lower perceived subjective mental and physical workload for mode 2 in the Likert questionnaire S3 and S4 in figure 11.

While no significant difference was observed in the task completion time as shown in figure 8, there is a noteworthy difference in the angle alignment time and shape adjustment time graphs figures 9 & 10. These differences were found to be statistically significant, with p-values of 0.0033 between modes 1 and 2 for the time it took participants to align the angles and 0.0011 for the time it took to adjust the shape to the required size. These results showed that the participants aligned the angle of the stiffness ellipsoids faster in mode 1 with fewer errors than in mode 2 compared to mode 1. For the adjustment of the shape, it was found that the participants were faster and less prone to making errors in mode 2 compared to mode 1. These observations raise the question of whether the interface and adjustment should be 0th-order inputs as the participants are more proficient with this mode. The significant disadvantage of using the 0th-order scroll wheel input is the limited adjustment range, which is very coarse and lacks resolution, or it will take a relatively long time to make significant adjustments. The 1st order joystick input seemed to lack the granularity for fine adjustments, as some participants had a hard time making small adjustments. These participants also seemed to have a hard time adjusting to this type of input, and this is observable for both mode 1 and mode 2 in figures 9 and 10, where the spread is significantly larger for 1st order joystick inputs. In contrast, the fastest completion times are relatively similar between the scroll wheel and the joystick. While both input methods have advantages and disadvantages, both input methods work as intended and are operable by the participants.

With both interface modes making use of 0th and 1st order input methods, the participants seem to prefer control mode 2 over mode 1 as seen in figures 11 & 12. With the ”van der Laan” questionnaire in figure 12, it does stand out that participants have divided opinions on mode 1. One group gave mode 1 nearly the same usefulness and satisfying ratings as mode 2, while others perceived it as unsatisfying and useless. A comparison between this new interface and the push button and touchscreen interface [6] can be made with the ”van der Laan” questionnaire, as this is standardized and was also used for some of the interfaces in literature, and a comparison can be made. The ”van der Laan” results for the push button were perceived to be a bit less useful & satisfactory than the touch interface. It is observable that there is quite a large spread for both of these interfaces. When comparing the average "van der Laan" results from this new interface to the two existing interfaces, the average results from the different interfaces are around the 0.5 mark for both the satisfying and usefulness scale for all three interface designs. From the interfaces, which could be compared with the "van der Laan" questionnaire results, mode 2 from the new interface was perceived to be the most satisfying but with the same perceived usefulness. Even though the "van der Laan" questionnaire is standardized, the group of participants is not the same. The group of participants was relatively small, so a conclusion could not be made with certainty.

After the experiment and from the results, it became clear that the participants generally preferred the 0th-order scroll wheel inputs over the 1st-order joystick inputs. Hypothetically, a combination of 0th-order inputs could yield an interface with better task completion times. This combination would use the angle completion time of mode 1 and the shape completion time of mode 2. The median values are 6.85 seconds and 11.07 seconds, resulting in a total of 17.92 seconds. Thus, the theoretical completion time would be significantly faster, roughly 18 seconds, compared to the 23 and 22 seconds of mode 1 and mode 2.

While the task completion times of this project can not be directly compared to completion times from [6], a similar ellipsoid alignment task was given to the participants. The main difference is that the alignment task used for the tablet and push button [6] were a single 2D alignment task instead of a 3D task. With this simplification, the participants have more oversight and are less prone to making errors. The average completion time for the push button was roughly 7 seconds, and the touch interface was around 4 seconds. This is significantly faster than with the proposed interface. However, I expect the completion times of 7 and 4 seconds to roughly double to 14 and 8 seconds if the participants would have had to do the task for a 3D environment. These results are closer to the task completion times obtained in this experiment.

During the experiment, it was observed that the participants tended to adjust a single value at a time. With an extended familiarization phase, the participants could learn to adjust multiple values at the same time or in more rapid succession. This would significantly reduce the task completion times. It was observed with several participants who commented that they expected some of the interface inputs to work differently and had a hard time getting used to them. For example, pulling on the force sensor decreased the stiffness ellipsoid's size instead of increasing it. Similar comments were made by a few participants regarding the joystick to change the stiffness ellipsoid's orientation in mode 2. To make the interface more intuitive for a larger audience, individual components of the control scheme should be invertible to the operator's liking.

Another thing that left things to be desired is the interface ergonomics and the component chosen for the scroll wheels. A rotary potentiometer was chosen for the scroll wheels for its ease of obtaining and implementing them. In hindsight, a better option would have been to use an optical rotary encoder to determine the scroll direction and distance. The reason is that complete rotations can be made while a rotational potential meter is limited to roughly 300°of a full rotation. This could have helped to prevent edge cases where a participant maxed out the adjustment range on the scroll wheels. These edge cases could also have been prevented by not giving the participants 2 ways to change the same value for the stiffness ellipsoid configuration. This could have been done by removing a function, such as disabling the force sensor or changing the function of the input that adjusted e_1 and e_2 to be a static value. Another, and potentially better, option would have been to remove the definition made in section II-B that $e_1 = e_2$ so that there is an adjustable ratio between the sizes e_1 and e_2.

With this adjustment, there are no longer two input options to adjust the same value. This will also help prevent cases where one input is preferred to increase the size, while another is preferred to decrease the size, effectively preventing edge cases where participants get slightly stuck while increasing the device's functionality to make more complex stiffness configurations. While the overall size of the interface is adjustable, it is still either too small or too large for specific participants. A wider range of adjustments would significantly benefit the overall ergonomics.

The second experiment demonstrated the functionality by inserting and moving a peg through a slot, as seen in figure 7 with the position force and stiffness configurations in figure13. Initially, the stiffness configuration was spherical, which was then adjusted to be prolate in shape and rotated so the peg could be inserted into the slot while allowing lateral movement. Subsequent translations occur along the y and x axes within the slot, which is concluded with an incline in the yz-plane. To enhance smooth translations in a specific direction, the stiffness ellipsoid shape was made prolate and rotated in the direction of desired travel. This ensured the robot's stiffness aligned with the direction of movement to reduce the perturbations caused by wall contact or other sources.

VI. CONCLUSION

With The proposed teleimpedance command interface, the operator can adjust the robot's 3D impedance configuration depending on the task requirements during real-time teleoperation without making it complex to set up or dependent on external systems. The functionality of the impedance command interface was successfully tested with the virtual impedance alignment tasks, using two different interface configurations and a 3D test environment during teleoperation.

In the first experiment, the participants were tasked to align the stiffness ellipsoid with a reference shape. While no direct conclusion could be drawn from the total task completion times between interface mode 1 and mode 2, it was observed that the participants were faster and more consistent with the 0th-order scroll wheel input than the 1st-order joystick when configuring the orientation and shape of the stiffness ellipsoids. The participants strongly preferred the 0th-order input from the scroll wheel inputs, the joystick with 1st-order inputs is still viable. However, a more extended familiarization phase seems to be required to have a similar performance.

While the experiment was successful, some recommendations and suggestions were made. It was observed that there were a few participants who struggled to adapt to the interface configuration. An example of this was the force sensor used to increase and decrease the shape in size. While the participants had been familiarized with the interface in the same configuration, it always felt like some of the controls should have been inverted for some participants. For operators who have experienced this problem, a selective invertible control scheme could be a solution.

For future research, it is suggested that the operator's performance using this interface in conjunction with augmented reality during teleoperation be explored.

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A

Data points first experiment

Task completion times from all participants for blocks 1-3 from experiment 1, for interface modes 1 and 2. The block numbering 'xy' is interpreted as x being the mode of the interface and y being the block number. The solid line with + symbol is for mode 1, and the dashed line with × is for mode 2. While the tasks seem random for the participants, all three blocks have their own data set. For blocks 1 and 2, there were constraints in place: a time limit of 5 minutes and only a data set of 29 tasks to align For the 3rd block, there was no time limit, and 15 alignment tasks were presented.

A.1. Data points learning phase, blocks 1 and 2

In the first training phase of the experiment, the participants were presented with circular shapes of varying sizes. The task was to align the controllable shape to the reference shape as fast as possible, first doing orientation and then size. A few participants could complete the full set of alignments within the allotted time, while the majority could not. The participants who take relatively long to complete the alignment tasks do not progress as far into the number of tasks available. This also explains the decrease in maximum task completion time, this seems to hold true for both the 1st and 2nd training block

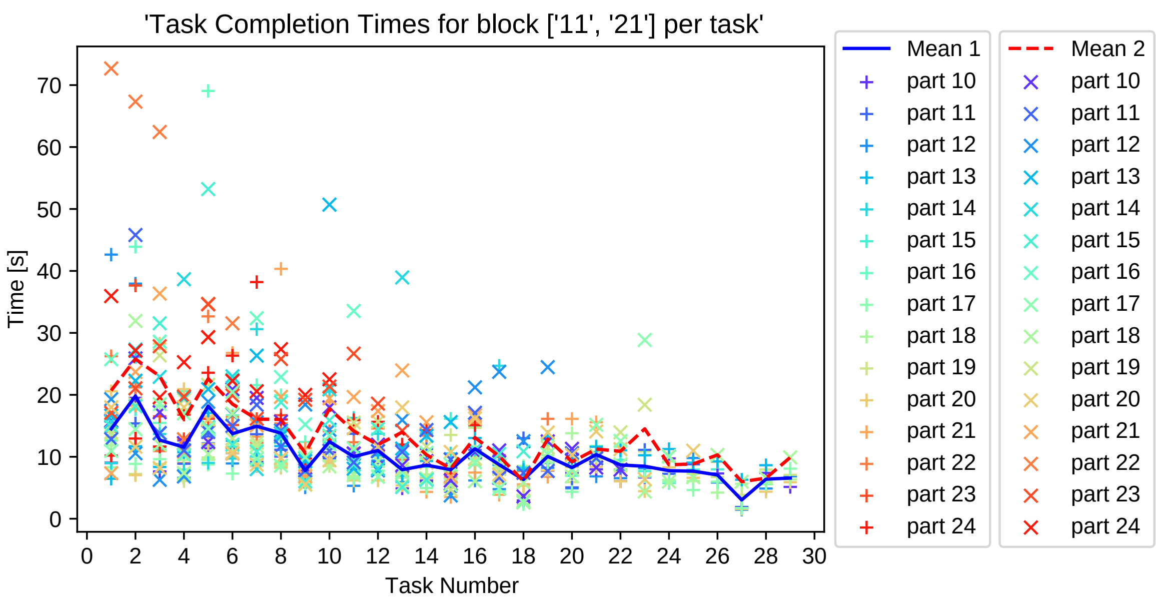


Figure A.1: all data points block 1

For the second block, the reference shapes were no longer only round, there are also ellipsoidal shapes requiring full utilisation of the proposed teleimpedance command interface. The participants require significantly more time to complete these tasks and, therefore, can not complete as many as in the first block.

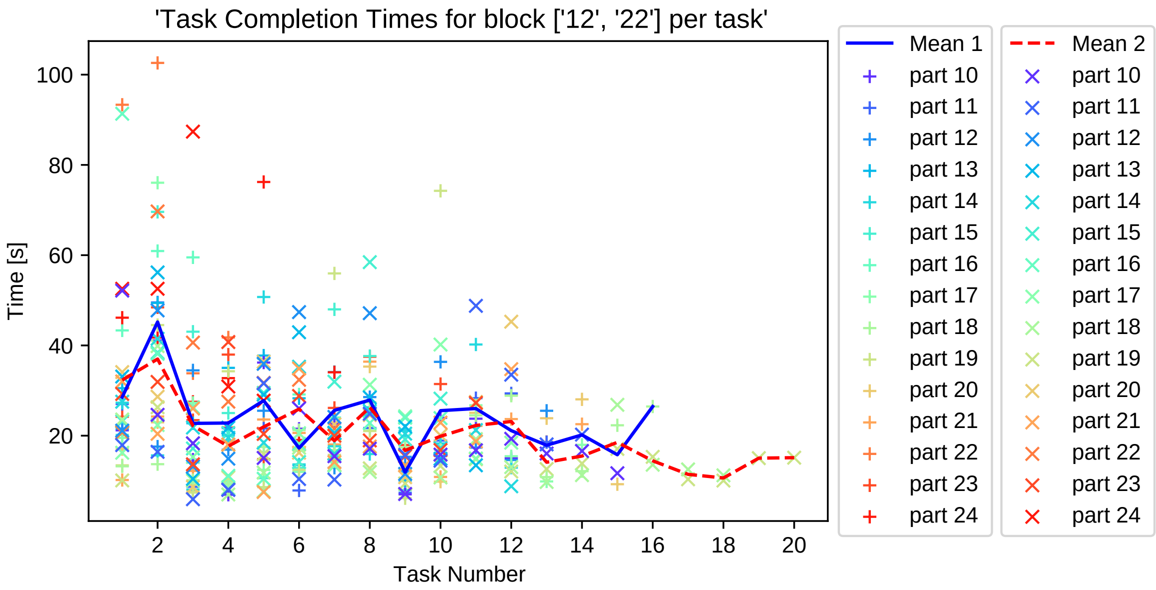


Figure A.2: all data points block 2

A.2. Data points 3rd block

The participants had no time limit for the third block, 15 alignment tasks were presented. The objectives and methods of successfully completing the tasks remained the same while presented with a different data set than block 2.

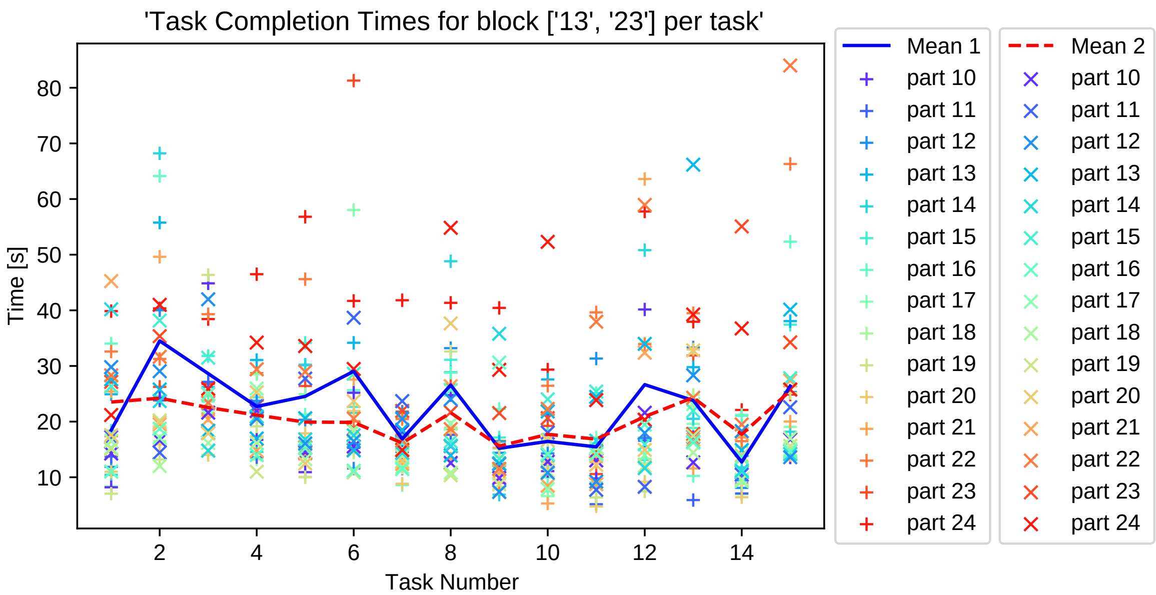


Figure A.3: all data points block 3

A.3. Distribution data points 3rd block

For the t-test to be useful, the data should represent a normally distributed set; this was tested using the Shapiro test function in the Scipy Python library. A p-value below 0.05 would indicate that the data set could sufficiently seen as normally distributed. With the results in Table A.1, the conclusion can be made that the data is not normally distributed and a t-test cannot be used; instead, the Wilcoxon signed-rank[2] test was used.

p-values for:	Task completion time	Angle alignment time	Shape alignment time
Mode 1	0.2811	0.02691	0.3227
Mode 2	0.1361	0.01719	0.1775

Table A.1: Shapiro p-value test results.

B

3D representation of stiffness configuration second experiment.

Stiffness ellipsoid configuration for the second experiment to demonstrate the correct functionality of the tele-impedance command interface in 3d space using a u-shaped slot with a ramp at the end. The 3D ellipsoid configurations are plotted overtime with the same scale of stiffness for all the directions in the graph.

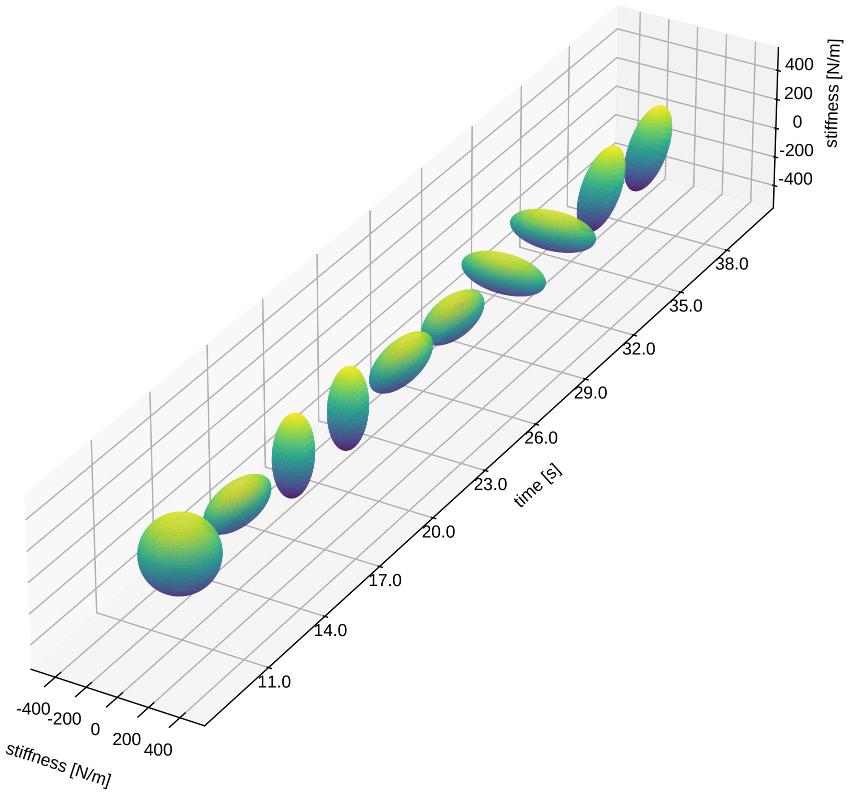


Figure B.1: 3D representation of the telerobotic stiffness configuration from the second experiment teleoperation demonstration with a 3D task.

C

Experiment methods

C.1. Interface design and required documentation

C.1.1. Electrical diagram impedance command interface

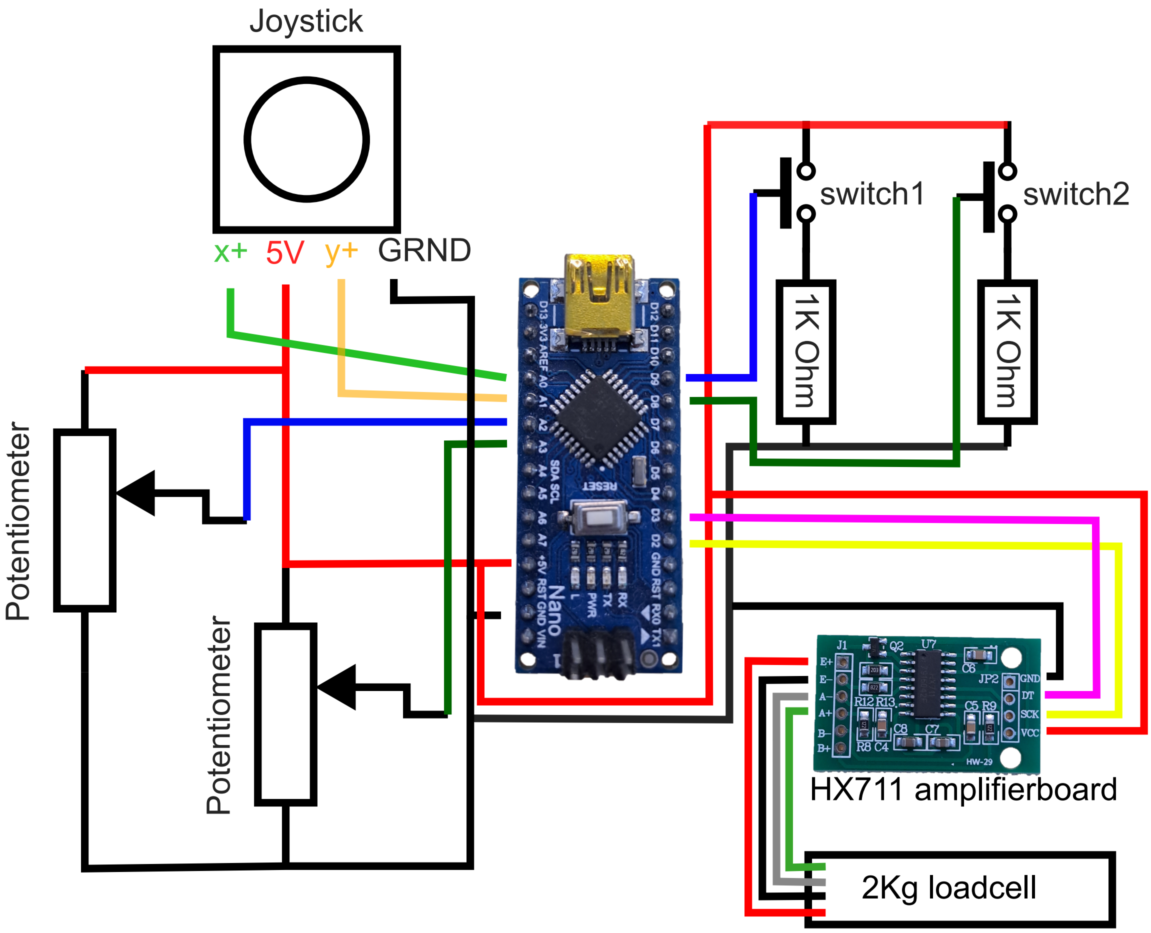
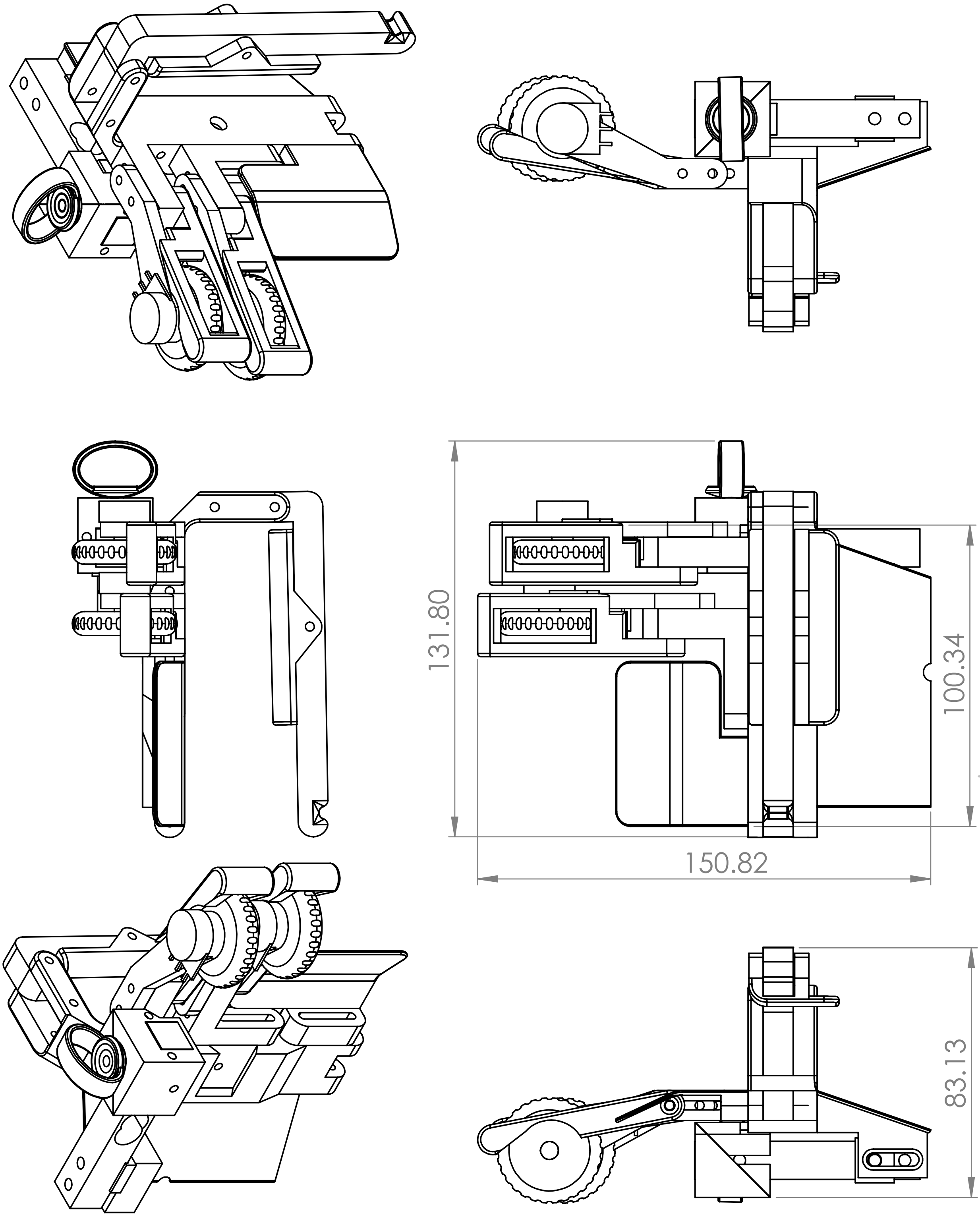


Figure C.1: Electronic Wiring diagram and pinout for the proposed teleimpedance command interface the Arduino board and other components are powered through the USB-data cable.

C.1.2. Schematical drawing teleimpedance command interface



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH: 3D printed surfaces with 20% infill.	DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION: 1

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Teleimpedance command interface

MATERIAL: PLA

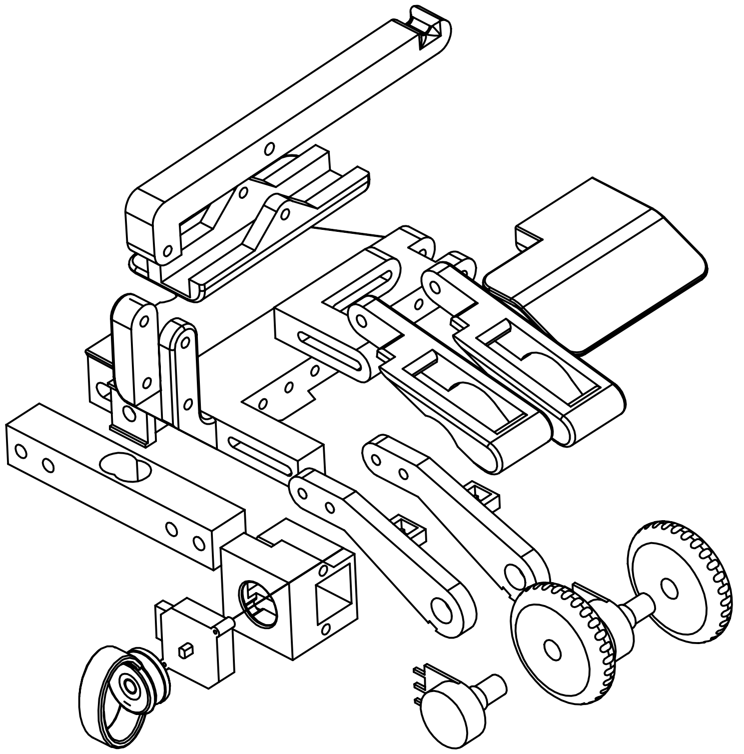
DWG NO.

A4

WEIGHT:

SCALE: 1 :2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES

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REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Teleimpedance command interface

DWG NO.

A4

SCALE: 1:2

SHEET 1 OF 1

C.1.3. HREC Device inspection report

Delft University of Technology
INSPECTION REPORT FOR DEVICES TO BE USED IN CONNECTION WITH HUMAN SUBJECT RESEARCH

This report should be completed for every experimental device that is to be used in interaction with humans and that is not CE certified or used in a setting where the CE certification no longer applies[1].

The first part of the report has to be completed by the researcher and/or a responsible technician.

Then, the safety officer (Heath, Security and Environment advisor) of the faculty responsible for the device has to inspect the device and fill in the second part of this form. An actual list of safety-officers is provided on this webpage.

Note that in addition to this, all experiments that involve human subjects have to be approved by the Human Research Ethics Committee of TU Delft. Information on ethics topics, including the application process, is provided on the HREC website.

Device identification (name, location): novel impedance command interface

Configurations inspected[2]: NA

Type of experiment to be carried out on the device:[3] Controlling and orientation 2 ellipsoids on computer screen

Name(s) of applicants(s): Frank M.C.Kraakman 4399854

Luka Peternel (supervisor)

Job title(s) of applicants(s): MSC

TU Delft employee

(Please note that the inspection report should be filled in by a TU Delft employee. In case of a BSc/MSc thesis project, the responsible supervisor has to fill in and sign the inspection report.)

Date:

Signature(s):

[1] Modified, altered, used for a purpose not reasonably foreseen in the CE certification

[2] If the devices can be used in multiple configurations, otherwise insert NA

[3] e.g. driving, flying, VR navigation, physical exercise, ...

Setup summary

The device will be held onto the hand with velco or an elastic band. The operator will have access to 2 10k Ohm resistance potentiometers, a joystick and a force sensor. With these low powered sensors the operator is able to turn and align ellipsoids on the screen.
With the 2 scroll wheels the operator can change the aspect ratio of the ellipsoid, with the force sensor the size can be increased and decreased. With the joy stick the angles are controlled.
It well be powered from a 5Volt usb port though a usb cable which is used for the serial connection.
No other external connections are present.

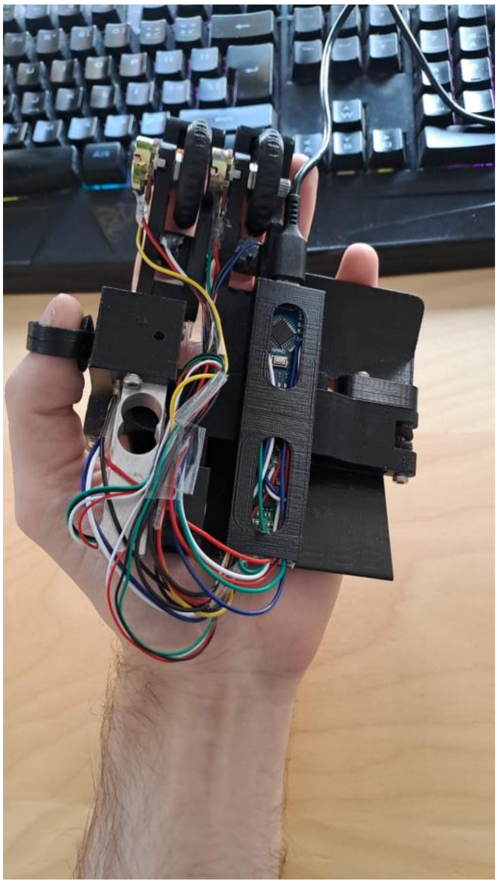
Risk checklist

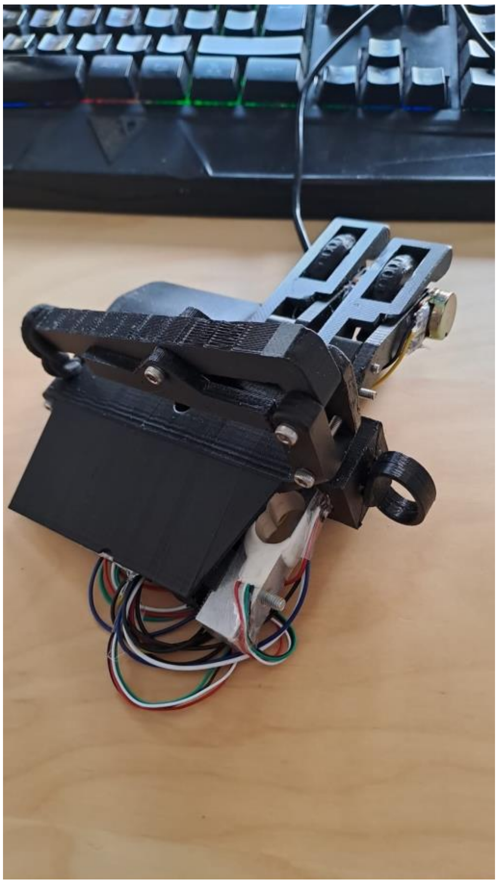
Please fill in the following checklist and consider these hazards that are typically present in many research setups. If a hazard is present, please describe how it is dealt with.

Also, mention any other hazards that are present.

Hazard type	**Present**	**Hazard source**	**Mitigation measures**
Mechanical (sharp edges, moving equipment, etc.)	yes	Edges of 3d printed material	Use rounded corners and mostly plastic (PLA) assembly.
Electrical	yes	Arduino and HX711 aplification board	These 2 boards run off the 5 volt source of a computer which is also current limited
Structural failure	yes	Structure breaking	No large forces are applied during normal opertion. The device is passive
Touch Temperature	no		
Electromagnetic radiation	no		
Ionizing radiation	no		
(Near-)optical radiation (lasers, IR-, UV-, bright visible light sources)	no		
Noise exposure	no		
Materials (flammability, offgassing, etc.)	no		
Chemical processes	no		
Fall risk	no		
Other:			
Other:			
Other:			

Appendices





Device inspection

(to be filled in by the AMA advisor of the corresponding faculty)

Name: Peter Kohne

Faculty: 3mE/IO

The device and its surroundings described above have been inspected. During this inspection I could not detect any extraordinary risks.

(Briefly describe what components have been inspected and to what extent (i.e. visually, mechanical testing, measurements for electrical safety etc.)

Date: 28-03-2023

Signature:

Inspection valid until[4]:

Note: changes to the device or set-up, or use of the device for an experiment type that it was not inspected for require a renewed inspection

---

[4] Indicate validity of the inspection, with a maximum of 3 years

C.2. Informed consent form

Informed consent form:

You are being invited to participate in a research study titled: “Novel impedance command interface for 3d environments”. This study is being done by Frank Kraakman from the TU Delft.

The purpose of this research study is to validate the effectiveness of the novel impedance command interface, and will take you **approximately 50** minutes to complete. The data will be used for MSC graduation thesis and the potential publishing of a scientific research paper. You will be asking to train on the novel impedance command interface with 2 different control schemes. Both methods will consist of 2 training blocks and one test block, each block lasting around 5 minutes. After completion of the last block there will be a survey with the “Likert” style and a “Van der Laan” questionnaire.

To the best of our ability your answers in this study will remain confidential. We will minimize any risks by completing and processing the questionnaires and data anonymously on local storage only.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Data can be removed when decided to withdraw before fully completing all tasks and surveys, after completion the data will be linked to a number for 2 weeks. If requested data can still be removed within that time period by supplying said number per request.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information above, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: the operation of a novel impedance command interface from which the inputs are recorded followed by a digital survey questionnaire after completing the tasks.	☐	☐
4. I understand that I will NOT be compensated for my participation by Frank Kraakman after completion of the experiment.	☐	☐
5. I understand that the study will end “when sufficient participants have participated for the study to yield results or the end of the MSC thesis is reached which is expected to be completed this year.”	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks “mild discomfort” with the hand using the interface. I understand that these will be mitigated by [occasional breaks of desired length]	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) [“age and gender”] and associated personally identifiable research data (PIRD) [-] with the potential risk of my identity being revealed [-]	☐	☐
8. I understand that some of this PIRD is considered as sensitive data within GDPR legislation, specifically [age, gender]	☐	☐

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
9. I understand that the following steps will be taken to minimize the threat of a data breach, and protect my identity in the event of such a breach [data will be gathered and stored locally in an anonymous way]	☐	☐
10. I understand that personal information collected about me that can identify me, such as [*name and age*], will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed when this research reaches completion.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that after the research study the de-identified information I provide will be used for [*graphs and tables in: report, paper and presentation*]	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
13. I give permission for the de-identified [*Age, gender, experimental data*] that I provide to be archived in [4TU.ResearchData & repository.tudelf.nl] repository so it can be used for future research and learning.	☐	☐
14. I understand that access to this repository is [*unrestricted*]	☐	☐

Signatures

____ ________________________________ ______________

Name of participant Signature Date

____

Participant number

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Frank Kraakman ______________________________ ______________

Researcher name [printed] Signature Date

Study contact details for further information:

Frank Kraakman

+31-6-xxxxxxxx

fkraakman@tudelft.nl

C.3. Survey used for the first experiment

The surveys objective was to obtain subjective information regarding the interface and its different modes. To do this two methods were used, a likert questionaire and the ”van der Laan” questionaire [1]. The objective of the likert questionaire is to compare specific methods for adjust the 3D stiffness configuration between mode 1 and mode 2. The objective of the ”van der Laan” questionaire is to obtain the perceived usefullness and how satisfying the teleimpedance command interface is being perceived by the operator.

Participant number: Date:

Gender:

Age:

left / right handed:

Do you have any previous experience with joystick control (example's being: PlayStation, Xbox, Nintendo, RC-equipment, etc.) and how experienced/proficient would you rate your self on those interfaces on a scale of 1 to 5 with 5 being proficient:

Below is a list of statements about the interface and its mode's of operation. Please indicate to what extend you agree or disagree with the statements by checking the corresponding box next to the statement.

PS:
- Mode 1: the scroll wheels changes the orientation, the joystick changes shape.
- Mode 2: the joy stick changes the orientation, the scroll wheels changes the shape

Statement:	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1: The **Shape/size** of the ellipsoid was **easier** to manipulate with the joystick in comparison to the scroll wheel					
2: The **orientation** of the ellipsoid was **easier** to manipulate with the joystick in comparison to the scroll wheel					
3: The **mental workload was higher** for mode 1 in comparison to mode 2					
4: The **physical workload was higher** for mode 1 in comparison to mode 2					

The “Van der Laan” questionnaire, a simple scale to asses the acceptance:
This is not a comparison between the different modes but an overall experience assessment.

Please tick a box on every line:

For mode 1 where the scroll wheels are used to change the orientation:

1 Useful |__|__|__|__|__| Useless
2 Pleasant |__|__|__|__|__| Unpleasant
3 Bad |__|__|__|__|__| Good
4 Nice |__|__|__|__|__| Annoying
5 Effective |__|__|__|__|__| Superfluous
6 Irritating |__|__|__|__|__| Likeable
7 Assisting |__|__|__|__|__| Worthless
8 Undesirable |__|__|__|__|__| Desirable
9 Raising Alertness |__|__|__|__|__| Sleep-inducing

For mode 2 where the scroll wheels are used to change the shape:

1 Useful |__|__|__|__|__| Useless
2 Pleasant |__|__|__|__|__| Unpleasant
3 Bad |__|__|__|__|__| Good
4 Nice |__|__|__|__|__| Annoying
5 Effective |__|__|__|__|__| Superfluous
6 Irritating |__|__|__|__|__| Likeable
7 Assisting |__|__|__|__|__| Worthless
8 Undesirable |__|__|__|__|__| Desirable
9 Raising Alertness |__|__|__|__|__| Sleep-inducing

Van der Laan, J.D., Heino, A., & De Waard, D. (1997). A simple procedure for the assessment of acceptance of advanced transport telematics. Transportation Research - Part C: Emerging Technologies, 5, 1-10.
https://www.hfes-europe.org/accept/accept.htm

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[1] Jinke D Van Der Laan, Adriaan Heino, and Dick De Waard. “A simple procedure for the assessment of acceptance of advanced transport telematics”. In: *Transportation Research Part C: Emerging Technologies* 5.1 (1997), pp. 1–10.

[2] Frank Wilcoxon. “Individual comparisons by ranking methods”. In: *Breakthroughs in statistics: Methodology and distribution*. Springer, 1992, pp. 196–202.