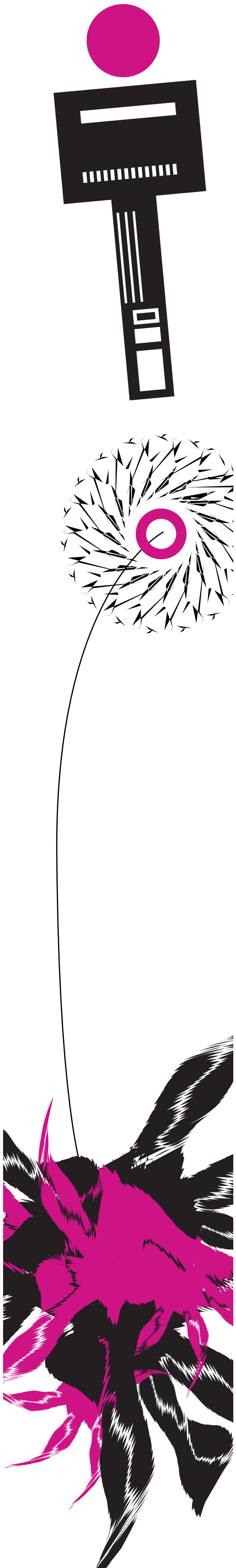

RAM ROBOTICS AND MECHATRONICS

Bi-directional impedance reflection for Cartesian space telemanipulation control to reduce the effect of time delay

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Summary

In the field of telerobotics, the primary goal is to use robotic systems to execute tasks in a remote environment while being controlled by a human operator. To increase the effectiveness in execution of these tasks, the robot must feel like a natural extension of the human body. This can be achieved by providing the operator with force feedback. Ideally, the operator will feel the dynamics of the remote environment undisturbed, achieving perfect transparency. However, time delays in the communication channel reduce transparency and can cause instabilities, reducing the sense of embodiment and user experience, thus the effectiveness of the system. Many research has been done to compensate for this effect of time delay. In this research, a bi-directional impedance reflection controller has been designed to overcome the negative effects of time delay. In this method, the impedance of the operator and the environment is estimated and reflected. A trajectory predictor is added to compensate for the delayed motion. Different techniques of impedance reflection and trajectory prediction have been analyzed and the best methods are used or altered. This system is implemented on a real telemanipulation setup, where the environment is reflected using the measured external forces and the operator is reflected using EMG signals. A simple linear trajectory estimator is added. Due to COVID-19 the slave device is changed to a simulation. A tracking performance is done to evaluate the performance of the system. This showed that the system worked until a time delay of 50 ms seconds. Higher time delays resulted in instabilities in the system, caused by the simplicity of the trajectory predictor. The task effectiveness of the designed system is evaluated by performing a user study. Here, three controllers are compared: classical bilateral impedance control, classical bilateral impedance control with passivity layers and the new designed bi-directional impedance reflection technique. Here 15 people are separated into three groups, each group experienced a different time delay. All these groups had to perform 4 tasks where quantitative and qualitative results are measured. This study showed that, under time delays, the user experience is better with the newly designed controller. Without time delay the classical impedance controller with the passivity layers is better. The study also showed that the effectiveness of the operator reflection could be improved. Overall the system showed promising results when dealing with time delays. However, the trajectory predictor could be improved to deal with higher time delays and the implementation of the operator reflection using EMG signals could be improved.

Bi-directional impedance reflection for Cartesian space telemanipulation control to reduce the effect of time delay

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***Abstract*— To increase the effectiveness in the field of telerobotics, the robot must feel like a natural extension of the human body. This can be achieved by providing the operator with force feedback. However, due to time delays, the system becomes less transparent or even unstable. In this research, a bi-directional impedance reflection controller has been designed to overcome the negative effects of time delay. In this method, the impedance of the operator and the environment is estimated and reflected. A trajectory predictor is added to compensate for the delayed motion. The task effectiveness of the designed system is evaluated by performing a user study. Here, three controllers are compared: classical bilateral impedance control, classical bilateral impedance control with passivity layers and the new designed bi-directional impedance reflection technique. This study showed that, under time delays, the user experience is better with the newly designed controller.**

I. Introduction

In the field of telerobotics, the primary goal is to use robotic systems to execute tasks in a remote environment while being controlled by a human operator. To increase the effectiveness in execution of these tasks, the robot must feel like a natural extension of the human body. This can be achieved by providing the operator with force feedback [1], [2], which projects the forces from the environment of the robot back to the operator, increasing the sense of embodiment.

Ideally, the operator will feel the dynamics of the remote environment undisturbed, achieving perfect transparency. However, time delays in the communication channel reduce transparency and can cause instabilities, reducing the sense of embodiment and user experience, thus the effectiveness of the system.

Significant effort has been concentrated to compensate for the effect of time delays in the communication channel [3], [4]. Different techniques are used to keep the system stable or reduce the effect of this time delay. Well known examples are guaranteeing the passivity in a system by monitoring the total energy flow of the system [5] or by continuous online estimation of the remote environment's impedance, used for a local model at the master site [6]–[8]. Other methods focus on the prediction of the master state to control the robot [3] or on modulating the robot's impedance based on the co-contraction levels of the operator [1].

Some methods, such as [5] maintain stability when the time delay increases but lowers the transparency toward the operator. This can be improved by using impedance reflective methods. Most of these methods show good results for estimating the environment's and operator's impedance, however, the effectiveness of such systems is not well tested or applied in practical situations and the full scheme as proposed in [2] has not been implemented so far.

In this paper, the goal is to achieve a telemanipulation system that can be effectively used in the presence of time delays through combining current state of the art ideas in impedance reflection and operator state prediction. Master and slave reflection techniques are combined as originally proposed in [2]. The impedance parameters of the environment will be estimated and reflected toward the user via a model. In addition, the impedance of the master will be estimated and reflected toward the slave device following [1]. All in combination with a trajectory predictor, which compensates for the delayed motion. A user study is used to show the effectiveness of this system for Cartesian space telemanipulation control compared to current systems.

This paper is structured as follows, In section II the related work is discussed. In section III the controller design is explained and in Section IV the user studies. The analysis, results, and discussion of the designed system and the user studies can be seen in Sections V and VI and the conclusion in Section VII.

II. Related Work

Different methods have been applied to solve the effects of time delay. The goal of this paper is the use of impedance reflecting teleoperation control, also called model-mediated teleoperation or model predictive/prediction based teleoperation. This idea is not new and has been implemented in different ways [9]. In existing literature, the proposed framework of Hannaford [2] is generally split into two. Where commonly the environment of the slave robot is modeled in different ways based on different estimation methods [6]–[8], [10]–[13].

[6] shows that it is possible to render the impedance of the slave side in an unknown environment, using an impedance adaption law, which is designed using Lyapunov

to maintain stability. This is done by using on-line estimation of the stiffness and contact position. Their experiments are done in 1 degree of freedom (DOF) in simulation and show a fast and stable impedance adaptation of the simulated environment characteristics. Under variable time delay the approach shows superior performance compared to classical position-force teleoperation.

In [12] impedance rendering of the environment is extended to 6-DOF tasks, where the translational impedance is estimated and send to an admittance controller. This estimated impedance is done based on the Kelvin-Voight model for stiff objects and the Hunt-Crossley model for soft objects. These models are estimated using a self-perturbing recursive least-squares method. The results show that these models are applicable to model-mediated teleoperation. However, sufficient human input force is required and the stiffness of the robot limits the rendered impedance of the virtual environment.

As mentioned in [9] the human behaviour in model-mediated approaches has not been studied intensively. Approaches are found that predict the master state to control the robots [3], [14] or by position assistance [15], which improves the impact stability but decreases the realism toward the user. In [1] the impedance of the slave device is modulated based on the muscle activation of the user using electromyography (EMG). This is done to improve the effectiveness for a variety of tasks: for position tracking a higher impedance results in higher performance and for impact tasks, low impedance is preferred. The experiments show that this method improves effectiveness for these tasks significantly, thanks to the ability to change the impedance. This method can also be used to reflect the impedance of the human towards the slave robot.

Although all these publications show that impedance reflection is a useful addition to maintain stability and transparency, none of the methods apply both impedance reflection of the master and slave in multiple degrees of freedom, which should increase the transparency towards both the operator and the environment. Furthermore, no comprehensive study on system transparency or effectiveness of impedance reflective teleoperation is available in literature yet [9].

III. Controller design

In the previous section, several impedance reflective control structures are discussed. In this section, a new proposed control structure is introduced based on this discussion.
In the classical position-force architecture, an impedance controller is used to calculate the forces applied on both the master and slave devices. This results in a physical connection between the master and slave. However, when latencies are present in the system, the dynamic properties of both sides are not equal anymore, resulting in lower transparency and instabilities [5], [6].

In the proposed bi-directional impedance reflection technique, both the operator and robot are provided with model-based predictions on the reaction of the environment and operator, respectively. The prediction is done by a combination of an impedance estimate and trajectory prediction. A schematic overview of the controller design is visible in Figure 1. It can be seen that both the master and slave have a local model in which impedance is modulated based on the estimation done on the other side, both the trajectory of the master and slave is predicted.

The generated force F_m on the master side is based on the master position X_m and the predicted slave position $\tilde{X}_{p,s,d}$. The generated forces F_s on the master side are based on the slave position and the predicted master position $\tilde{X}_{m,s,d}$

$$F_m = \hat{K}_m(X_m - \tilde{X}_{p,s,d}) \tag{1}$$

$$F_s = \hat{K}_s(\eta)(X_s - \tilde{X}_{p,m,d}) \tag{2}$$

The resulting scheme has similarities with the position-position architecture, with modifications that predicted position are send supplemental with an impedance estimate.

In the following subsections, the three main components of the proposed impedance reflection technique are discussed, namely; environment impedance estimation, operator impedance estimation and trajectory prediction.

A. Environment impedance estimation

As shown in Equation 1, the force applied on the master device is based on a modulated spring stiffness. To estimate the spring stiffness, the environment will be modeled as a simple spring, as shown in the following equation:

$$F_e = K_e(X_s - \tilde{X}_{p,m,d}) \tag{3}$$

Where F_e is the force applied on the environment by the robotic end-effector and K_e is the stiffness of the environment. In some cases the contact position is used to determine the stiffness of the environment. This contact position can be determined using the external force sensing or by modeling it [6], [11]. However, this approach introduces a limitation to static objects. When moving objects, the absolute contact position changes, this cannot be measured or modeled using the methods found in literature. Also, backdrivability is not ensured because this contact position is then used in combination with the master position to calculate the applied force on the master. Meaning that the operator on the master side cannot feel the external forces of the slave device.

In this work, the predicted master position is used to estimate this impedance, in combination with the current slave position and measured external force, using linear regression. This means that not only the stiffness of the environment is taken into account, but the kinematics between master and slave as well. As the master and slave

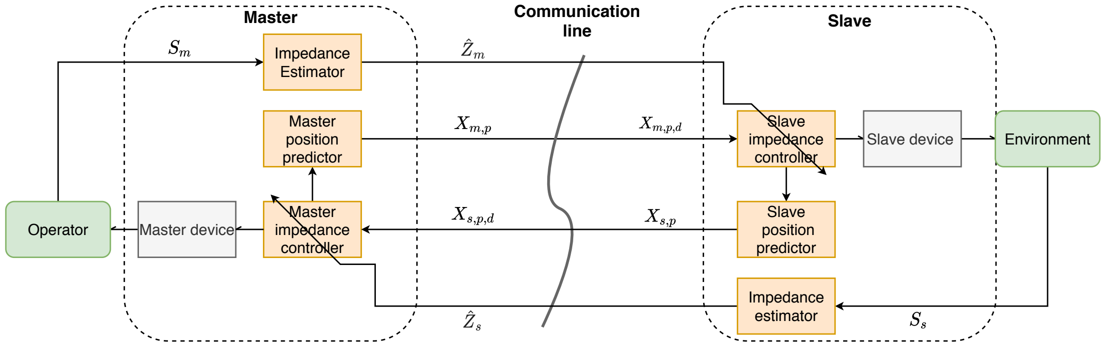


Figure 1: General overview of the bi-directional impedance controller. At both the master and slave side, the impedance is estimated and the trajectory is predicted, both are sent to the other side.

positions are influenced by the impedance of the controllers and dynamics of the hardware. This has the advantage that the mentioned shifting contact points (moving objects, lifting masses) are possible and backdrivability is ensured in combination with Equation 1.

Using linear regression with the recursive least squares algorithm the impedance is estimated as proposed by Simpkins [16]. A forgetting factor λ is added to deal with changes in the impedance of the environment. The force is the dependent variable y and the position difference is the independent variable φ. The estimated parameter $\hat{\theta}$ can be found using the following set of equations, which is done for every degree of freedom: [16]

$$\hat{\theta}(t) = \hat{\theta}(t-1) + L(t)\left[y(t) - \varphi^T(t)\hat{\theta}(t-1)\right] \tag{4}$$

$$L(t) = \frac{P(t-1)\varphi(t)}{\lambda(t) + \varphi^T(t)P(t-1)\varphi(t)} \tag{5}$$

$$P(t) = \frac{1}{\lambda(t)}\left[P(t-1) - \frac{P(t-1)\varphi(t)\varphi^T(t)P(t-1)}{\lambda(t) + \varphi^T(t)P(t-1)\varphi(t)}\right] \tag{6}$$

Here $\hat{\theta}$ is in this case $\hat{K}_e$.

As the position and torque sensors will never be ideal, the estimated parameter $\hat{\theta}$ can go to infinity when the manipulator is moving in free space and perfect tracking behaviour is achieved. As the position error noise is relatively low compared to the force sensor noise. To overcome this problem, a force threshold F_{thres} is used to check if an object is touched, after that the system start estimating. If the external measured force (F_{ext}) is below this threshold the system uses a low impedance (K_{low}), this has the additional advantage that the operator does not perceive the dynamics of the manipulator when moving in free space. The variation law for the impedance controller at the master side is then as follows:

$$\hat{K}_m = \begin{cases} K_{low}, & \text{for } |F_{ext}| \leq |F_{thres}| \\ \hat{K}_e, & \text{for } |F_{ext}| > |F_{thres}| \end{cases} \tag{7}$$

To have some perception of the inertia of the manipulator and to reduce the jumping effect of sudden forces, it is chosen to make K_{low} non-zero in free-space.

B. Operator impedance estimation

To estimate the impedance of the operator, the method proposed in [1] will be adapted. The impedance of the operator is estimated based on the co-contraction level of certain muscle pairs in the arm. Co-contraction of muscle pairs is used to change the impedance level of, for example, the human arm without changing the configuration of the limbs or the exerted force.

The co-contraction levels are estimated by the activation level(α) of an antagonistic muscle pair obtained using EMG signals. Using a calibration test the maximum level(α_{max}) and minimum level(α_{min}) can be obtained. These values are then used to normalize the activation level values by:

$$\hat{\alpha} = \max\left(0, \frac{\alpha - \alpha_{\min}}{\alpha_{\max} - \alpha_{\min}}\right) \tag{8}$$

The normalized contraction levels are restricted to be positive. The co-contraction level is determined by taking the commonality of flexor(α_{flexor}) and extensor($\alpha_{extensor}$) muscles. Using the following equation the normalized co-contraction level η can be determined:

$$\eta = \min\left(1, \hat{\alpha}_{\text{flexor}}, \hat{\alpha}_{\text{extensor}}\right) \tag{9}$$

To avoid an impedance level above the maximum level, the value is restricted to be lower than or equal to 1. A higher value can occur when the maximum level is incorrectly determined during the calibration.

Finally, the normalized co-contraction level(η) is low-pass filtered with a cut-off frequency of 5Hz to reduce the effect of high-frequency behaviour.

The variation law for the impedance controller at the slave side is then given by:

$$\hat{K}_s(\tilde{\eta}) = K_{\min} + \tilde{\eta} \cdot (K_{\max} - K_{\min}) \tag{10}$$

Here $\tilde{\eta}$ is the normalized estimation of the co-contraction levels delayed in time. K_{min} and K_{max} are empirically tested and are hardware dependent. When K_{min} is too low, the arm does not have sufficient force to execute a task, and when K_{max} is too large, the robot is prone to show more oscillation behaviour, both these effects lower the transparency.

C. Trajectory prediction

Due to time delay, the slave and master positions are send delayed in time. Equation 1 shows that the position difference between master and slave can be bigger or smaller than in reality due to the latency in the communication channel. This results in a dragging effect, where the operator feels more dragging or exerted force when the delay increases.

That is solved by using a trajectory predictor that predicts the trajectory of the operator and the slave device. The amount of time it will predict its trajectory will be based on the delay in the communication channel. In this method, an estimation of the slave and master position is used to compensate for the delay. A simple linear trajectory predictor is designed based on velocity(v) and delay(t_{delay}):

$$X_p = X_{current} + (v \cdot t_{delay}) \tag{11}$$

Where X_p is the predicted position and $X_{current}$ is the current position of the end-effector. This is done in both directions for both the master and slave devices.

IV. User Study

In this section, the design and setup of the user study are presented. The user study aimed to show the effectiveness of the impedance reflection technique under different time delays. Where the effectiveness will be expressed in: the quantitative results, sense of embodiment(SoE) and, user experience(UEQ). An increase in one of these dimensions without the loss of another is considered as higher effectiveness. A user study was designed in which the following three systems are compared:

- Classical bilateral impedance control(BIC): An impedance controller which couples the master and slave device.
- Classical bilateral impedance control with passivity(BICP): Using the BIC scheme with the addition of the passivity layer of [5].
- Bi-directional impedance reflection technique(BIR): The newly proposed system of this paper.

A. Hypothesis

In this paper, the following hypotheses are developed to compare the effectiveness of the BIR control with the BIC and BICP control under different time delay conditions:

1) The BIC and BICP controllers have better effectiveness compared to the BIR controller when no time delay is present, as the forces are directly fed back, and no estimation method is in the middle.
2) The effectiveness of the BIR controller is higher when time delays are present in the communication line. As it is expected that instabilities occur in the BIC controller and energy limits are applied in the BICP controller.
3) When the time delay increases, the effectiveness of every controller will decrease, as the time delay has more influence on the performance.

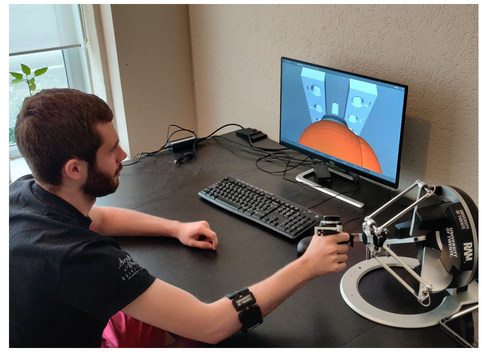


Figure 2: Experimental setup of the user study. The Omega 7, Myo Armband and simulation can be seen.

To measure the effectiveness of these controllers a user experiment is set up, which measures the quantitative results. A questionnaire is designed to measure the sense of embodiment and user experience. More explanations can be found in the following sections.

B. Experimental setup

The experimental setup can be seen in Figure 2. At the master side, an omega is present which can measure the position of the operator and apply force feedback. To measure the EMG signal of the user a Myo gesture control armband [17] was used to measure the unit-less activation levels(α) of the forearm. At the slave side, the telemanipulated environment is simulated, using Gazebo[1] and visualized on a computer screen. The simulated manipulator is modeled after a KUKA LWR4+, by Research Center E. Piaggio at the University of Pisa, Italy[2]. As the external torques cannot be measured in Gazebo, the internal dynamics of the robotic arm are made negligible, such that it can be assumed that the commanded torques are the external torques, above the threshold(F_{thres}) of 4N.

C. Experimental design and protocol

15 healthy volunteers without previous issues to nerves or muscles participated (8 males and 7 females, between 18 and 27 years old). This group was split in 3. Each group performed a calibration task for the BIR controller, then 3 tasks are performed with each of the 3 controls. Each group

[1]Open Source Robotics Foundation, Mountain View, CA, USA

[2]This model is available on the Centro E. Piaggio GitHub: https://github.com/CentroEPiaggio/kuka-lwr

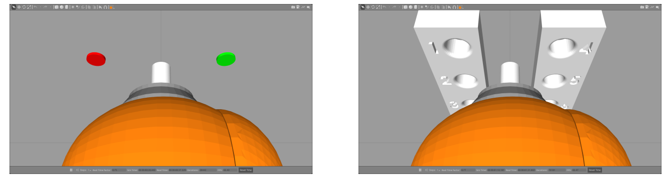
experienced a different time delay condition as can be seen in Table I. The BIC controller is not designed to handle time delays and does not work for 10 ms delays or higher, thus lower time delays are chosen.

Table I: Delays of each group and controller

	Controllers	
Group	**BIC**	**BICP and BIR**
1	0 [ms]	0 [ms]
2	2 [ms]	10 [ms]
3	5 [ms]	20 [ms]

Following, the protocol, different tasks, and their measurements are explained:

- **Task 0: EMG calibration task:**
  - *Goal*: Calibrate the minimum and maximum contraction levels of the muscle of each user;
  - *Method*: A changing random sine wave motion was applied to the master controller;
  - *User instruction*: First: act compliant to the behaviour (minimum co-contraction). Then try to keep the controller at the same place (Maximum co-contraction);
  - *Repetition*: This is done one time;
  - *Measurements*: Minimum and maximum contraction levels of the muscle.
- **TASK 1: Proprioceptive Calibration task:**
  - *Goal*: For participants to experience the environment and to get used to the embodiment;
  - *User instruction*: Move the arm from point A to point B;
  - *Repetition*: 6 trial for each controller (18 times);
  - *Measurements*: Proprioceptive drift, accomplishment time, sense of embodiment and user experience.
- **TASK 2: Stop and go:**
  - *Goal*: Test how the users reacted to unexpected instructions and how they could deal with them considering the control and the time delay;
  - *User instruction*: Move the arm from point A to point B and touch it. For half of the trials, the user must come back to the starting point while they are moving to the target point;
  - *Repetition*: 6 trial for each controller (18 times).
  - *measurements*: Reaction time, sense of embodiment, and user experience.
- **TASK 4: Peg in hole:**
  - *Goal*: Test how easily the users could move through the environment, their perception of the space and distances, and finally their ability and experience in teleoperating the system with different controls in different time delay conditions;
  - *User instruction*: Move the arm from one hole on a wall, to another hole on another wall. There were 6 holes;
  - *Repetition*: 6 trial for each controller (18 times);
  - *measurements*: Accomplishment time, sense of embodiment, and user experience.



(a) Screenshot of task 1 and 2 of the user study

(b) Screenshot of task 3 of the user study

Figure 3: View of the operator on the simulation during the user study.

The display of the simulation and the different tasks can be seen in Figure 3.

D. Questionnaire

A questionnaire was filled in online on the *SurveyMonkey* platform, and aimed to collect three types of information:

1) Proprioceptive information profile: The participants are asked to provide information related to their level of proprioceptive information, namely age, gender, if they practised a sport, which sport, at which level (amateur or professional), and if they had previous problems to the upper body nerves or muscles.

2) The Sense of Embodiment (SoE): Is described by three sub-components [18]: i) the sense of ownership, which is defined as the feeling of self-attribution of an external object or device. For example, if the user is teleoperating a robotic arm, we will talk about the sense of ownership if the user will experience to own that robotic arm [19]; ii) the sense of agency, namely the feeling of being able to interact with the environment with the manipulated device. Therefore, the sense of agency is characterized by the trust that users put in the fact that their intended actions are mirrored by the controlled device. [20]; and iii) the sense of self-location, which is defined as the volume of space where one feels located. Therefore, the users should be aware of the space in which they teleoperate, they should feel confident about the distance, position, and stiffness of objects, and, if possible, in moving around in the remote environment [21]. To evaluate the level of SoE, we adopted the questionnaire from [22]. Participants had to evaluate 10 items, using a Likert scale from 1 to 7. Questions 1-3 measured the sense of ownership, questions 4-6 measures the sense of agency, and questions 7-10 measures the sense of self-location.

3) The User Experience (UE): To measure the subjective impression of participants towards the user experience of each control, we adopted the UEQ from [23]. The UEQ is a semantic differential with 26 items, divided into 6 subscales: i) attractiveness: the overall impression of the control (do users like or dislike it? Is it attractive, enjoyable or pleasing?); ii) perspicuity: the easiness of use (is it easy to get familiar with the control? Is it easy to learn? Is the control

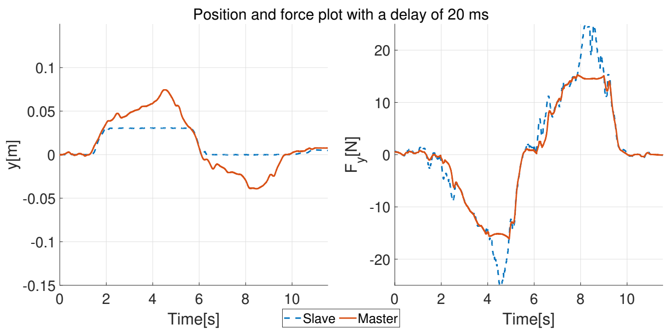


Figure 4: A plot of the BIR tracking performance while moving against a rigid object. On the left side, the position of the master and slave side in the y-direction is visible. On the right side, the force in the y-direction of both is visible.

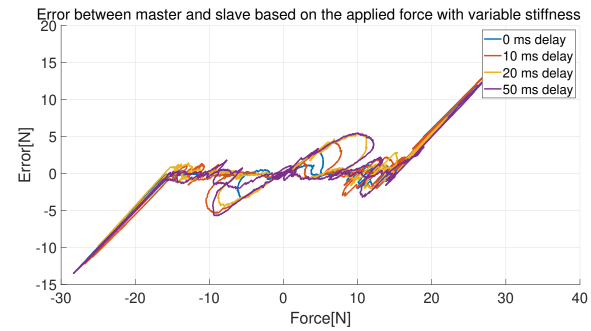


Figure 5: An error force plot of the y-direction of the BIR controller while moving against a rigid object under different time delays.

easy to understand and unambiguous?); iii) efficiency: the perceived quality of the control (can users solve their tasks without unnecessary effort? Is the interaction efficient and fast? Does the control react to user input quickly?); iv) dependability: related to the sense of agency and control of the device (does the user feel in control of the interaction? Can he or she predict the system's behavior? Does the user feel confident when working with the product?); v) novelty: since we were comparing three different controls, this set of items helped us in understanding the perceived difference (Is the control innovative and creative? Does it capture the user's attention?); vi) stimulation: how much the participants liked to use the control and the experience in general (is it exciting and motivating to use the product? Is it enjoyable to use?). Participants had to evaluate each item using a Likert scale from 1 to 7.

The participants had to fill this questionnaire after the use of each control; therefore, each participant had to fill the questionnaire three times during the experiment;

V. Results

In this section, the design and results of the tracking performance of the system and the user study are presented.

A. Tracking performance

In Figure 4, the tracking performance of the BIR controller under a time delay of 20 ms is shown. In this experiment, a motion against a rigid body in the y-direction is executed. Note that when the slave hits the rigid body, the master can go beyond this point, but feeling more force. There is accurate force tracking between 4N and 15N. The 4N bound is caused by the threshold of the estimator and the 15N bound by the maximum activation force of the haptic device. In Figure 5, the error plot of reflected forces against a rigid body can be seen under different time delays. It can be seen that the tracking error increases when the time delay increases; particularly, above 15N the error increases linearly. These results are discussed in Section VI.

B. User study

For the user study, only the significant results are shown. The p-value threshold is set at 0.05. A one-way ANOVA test is applied to test if responses were significantly different between groups and repeated measure ANOVA within group. These results can be seen in Table II and III. These tables are shown in Figures 6-10 for more clarity. The most significant results concern the user experience, while the sense of embodiment showed little significance. The quantitative measurements did not show significant results.

Table II: Values detected by the ANOVA test within group. Where the Agency and Ownership are part of the SoE and the others of the UEQ

					mean sq
Scale	**Gr**	**p-value**	**df**	**f-value**	**BIC|BICP|BIR**
Agency	1	.0244	2, 12	5.141	3.86|1.60|2.40
Ownership	3	.0411	2, 12	4.214	5.05|5.05|3.45
Attractiveness	1	.0260	2, 12	5.002	3.35|5.30|4.75
Dependability	1	.0310	2, 12	4.731	4.50|5.55|4.85
Novelty	1	.001	2, 12	13.220	3.30|5.40|3.75
Perspicuity	1	.008	2, 12	7.356	3.90|5.50|3.95
Stimulation	1	.0002	2, 12	18.680	3.40|4.55|4.30
Attractiveness	2	.0160	2, 12	6.003	3.85|4.95|6.30
Attractiveness	3	.009	2, 12	7.102	2.40|3.40|5.50
Dependability	3	.008	2, 12	7.282	4.05|4.00|5.40
Efficiency	3	.006	2, 12	7.903	4.30|4.00|5.40
Novelty	3	.003	2, 12	9.706	2.70|3.30|5.40
Perspicuity	3	.039	2, 12	4.287	3.30|4.00|5.65
Stimulation	3	.0140	2, 12	6.226	3.32|3.45|4.60

It is shown that within-group, the user experience overall the sub-scales is higher for the BICP control when no time delay is present as can be seen in Figure 6. Figure 7 shows that in group two only the attractiveness showed a significant difference in UEQ, which was higher for the BIR controller, and in Figure 8 that in group three all the sub-scales show significantly better results for the BIR controller. In Figures 9 and 10, it can be seen that between-group the UEQ decreases when the time delay increases. The same could be observed for the BIR controller, except for group 1.

Table III: Values detected by the ANOVA test between groups. All scales are part of the UEQ

					mean sq
Scale	**Control**	**p-value**	**df**	**f-value**	**Gr1|Gr2|Gr3**
Attractiveness	BICP	.045	2, 12	4.043	5.30|4.95|3.40
Dependability	BICP	.0310	2, 12	5.379	5.55|5.30|4.00
Novelty	BICP	.001	2, 12	5.594	5.400|4.80|3.30
Perspicuity	BICP	.008	2, 12	5.733	5.50|5.75|4.00
Stimulation	BICP	.0002	2, 12	4.791	5.50|4.55|4.30
Attractiveness	BIR	.0160	2, 12	4.622	4.55|4.35|3.45
Efficiency	BIR	.009	2, 12	5.866	4.15|5.15|5.40
Novelty	BIR	.008	2, 12	23.050	3.75|5.65|5.40
Perspicuity	BIR	.006	2, 12	12.200	3.95|6.10|5.65

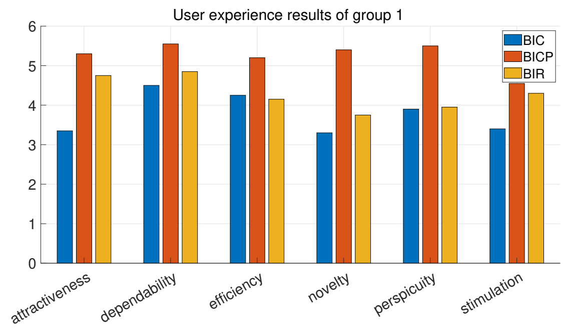


Figure 6: Bar graph of the user experience within group 1, without time delay

VI. Discussion

In this section, the results of the tracking performance, the user study and the overall system are discussed.

A. Tracking performance

Figures 4 and 5 showed that the forces are reflected properly when using the BIR. The error increases linearly above the limit of 15N, as this is the maximum activation force of the master device, and a linear model is applied. Figure 5 shows that without time delay, the force applied at the slave side is tracked by the force applied at the master side between the threshold of 4N and the haptic device limit of 15N. When time delay increases, the error increases. This is caused by the combination of the time in which the impedance needs to converge and the impedance lag. The impedance convergence time is caused by the estimator, resulting in a force error, this is always the same. However, the impedance lag increases with the latency, resulting in a higher force error.

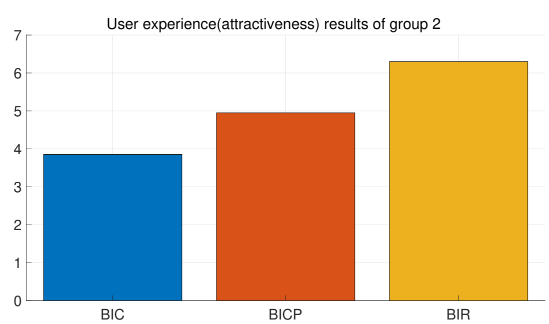


Figure 7: Bar graph of the user experience within group 2, only the attractiveness is shown as this is the only significant result, with 2 ms delay for the BIC and 10 ms for the BICP and BIR

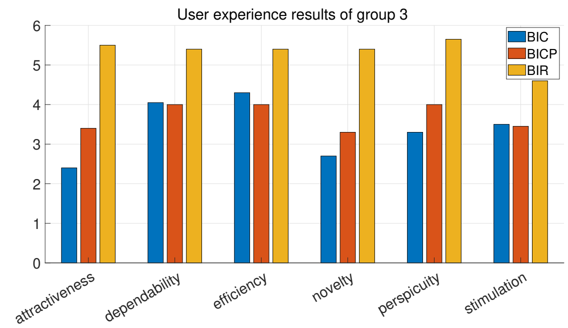


Figure 8: Bar graph of the user experience within group 3, with 5 ms delay for the BIC and 20 ms for the BICP and BIR

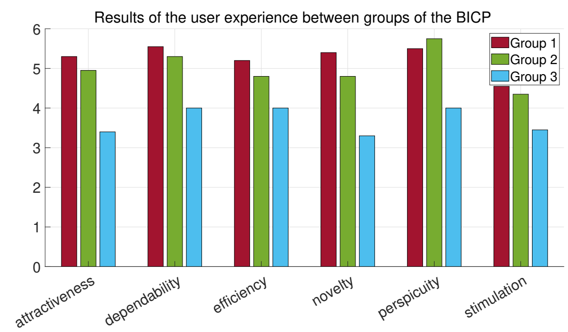


Figure 9: Bar graph of the user experience between groups of the BICP controller, where group 1 has no delay, group 2 has 10 ms delay and group 3 has 20 ms delay

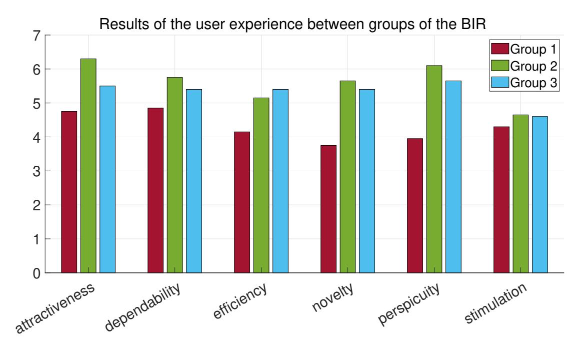


Figure 10: Bar graph of the user experience between groups of the BIR controller, where group 1 has no delay, group 2 has 10 ms delay and group 3 has 20 ms delay

B. User study

It can be noted that mainly the UEQ showed a significant difference. This showed that the participants were able to deal with the tasks quantitatively speaking, but qualitatively a difference was noticed. Based on this observation the aforementioned hypotheses are accepted or rejected.

The first hypothesis stated that the BICP and BIC controller without time delay would show higher effectiveness than the BIR controller. The hypothesis is partially accepted as the BICP controller has higher UEQ scores compared to the BIR controller but the BIC controller not in this case. This can be explained by the passivity bounds of the passivity layer. The BIC controller tended to behave unstable even when there is no delay present. This is caused by the realtimeness of the simulation, which was not always sufficient. The passivity layer reacted to the unstable behaviour where the BIC did not.

The second hypothesis was accepted. It states that the BIR controller results in higher effectiveness when time delays are present in the system, and the results from the UEQ confirm it.

The third hypothesis is that the effectiveness of every controller decreases when the time delay increases. This hypothesis is partially accepted. The BIC controller's performance is consistently lower than the BICP and BIR and in this case did not show a significant difference between groups for the UEQ, meaning that the user experience was the same for all delays. For the BICP controller, the UEQ scores decreased when the time delay increased. For the BIR controller, the UEQ is significantly lower than the BICP controller in group 1. As the BICP behaved better when no time delay was present. However, the UEQ scores decrease when time delays increase, which is expected due to the increased influence of the time delay in the system.

C. Overall discussion BIR controller

The goal of this paper was to design a stable teleoperation system that can be effectively used in the presence of time delay. The tracking performance shows that, indeed, a stable and transparent system is created. The user study results show that the effectiveness of this system is better experienced compared to the other controllers in the presence of time delays. However, some remarks on the implementation have to be made, to further improve the system in later stages.

The impedance modulation of the operator and its model can be improved. Particularly, it was noticed that the calibration method can be improved as the normalized measured impedance was low compared to the maximum measured EMG. This resulted in a low impedance at the slave side, resulting in little force feedback towards the user and hard to control end-effector, due to overshoot. An additional damper could be added to the system at the slave side to compensate for this effect.

VII. Conclusion

The goal of this paper was to design a stable telemanipulation system that can be effectively used in the presence of time delay. This is done by combining impedance reflection of both the operator and the environment. A trajectory predictor is added to compensate for the delay in motions. The tracking performance showed that a stable and transparent system is created and the user study showed that the effectiveness is improved regarding user experience when time delays are present.

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Technical attachment:
Bi-directional impedance reflection for Cartesian space telemanipulation control to reduce the effect of time delay

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Wednesday 15th July, 2020

i-BOTICS
an initiative of TNO and University of Twente

Contents

1 Introduction

In the i-Botics centre, founded by TNO and the University of Twente, a project is carried out focused on telerobotics. With telerobotics a robot is able to perform tasks on remote locations. For some of these tasks, human expertise is needed for assessing and responding to unpredictable situations. To increase the effectiveness of these tasks, the robot must feel like a natural extension of the human body. This can be done using different forms of feedback such as audio, vision and haptics. The latter can be done by the means of force feedback or vibrations, which projects the forces from the environment of the robot back to the operator, increasing the sense of embodiment. In classical teleoperation, an operator directly controls a slave device by the use of a haptic interface or master device. Between these subsystems, control signals are sent back and forward via a communication line.

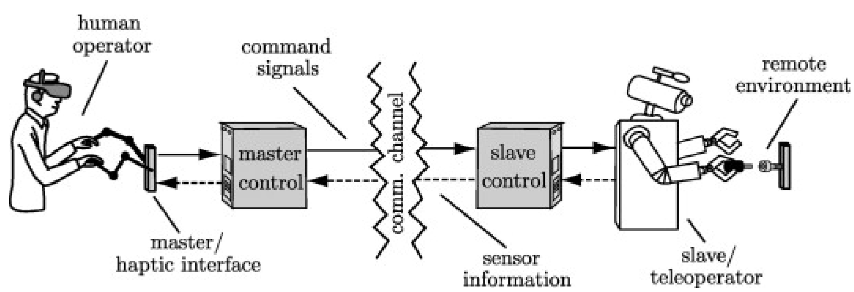


Figure 1.1: Classical teleoperation setup [1]

The main goals when designing such a system are the transparency, stability and task effectiveness of such a system. However, time delays are present in the communication channel, as well as discretization effects, sensor noise and packet loss. These factors can cause instabilities in the system and reduces the task effectiveness, so they need to be taken into account when designing such a system. Significant effort has been concentrated to compensate or reduce the effect of this time delay[2, 3]. Different methods are described which deal with these instabilities, such as guaranteeing the passivity in the system by monitoring the energy flow[4] or by continuous online estimation of the remote environment's impedance, used for a local model at the master site [5, 6, 7]. Other methods focus on the prediction of the master state to control the robot[2] or on modulating the robots impedance based on the co-contraction levels of the operator [8]. Most of these methods show good results, but have a trade-off between stability and transparency or are not well applied in practical situations.

1.1 Scope of this Thesis

The goal of this thesis is to achieve a telemanipulation system that can be effectively used in the presence of time delays through combining current state of the art ideas in impedance reflection and operator state prediction. This new control scheme will be based on the proposed work of Hannaford [9], where the impedances of the environment and operator are reflected, shown in Figure 1.2. Hannaford uses this impedance reflection to compensate for the effect of time delay, by using two simplified models of the master and slave device. Where the master will directly interact with a model of the slave device and the other way around. Instead of sending forces over the communication lines, impedances/-model parameters and positions are send back and forward. The parameters are estimated based on different sensory information of both sides. This has the advantage that the time delay does not directly influence the system, as the master and slave are decoupled and the force feedback is calculated locally. This all should increase the transparency while maintaining a stable system. To compensate for the delayed position send over the line, a trajectory predictor is added.

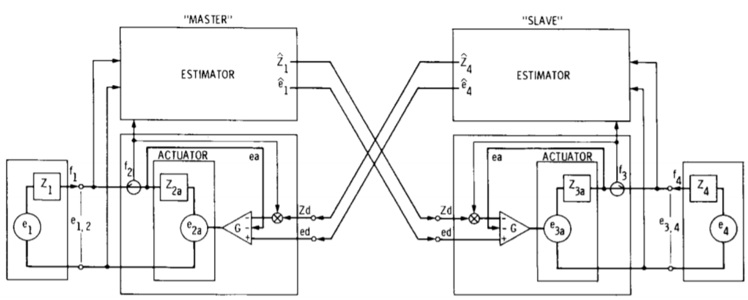


Figure 1.2: Bilateral impedance control proposed by Hannaford [9]

Many controllers have been designed to compensate for latency's in the communication line. However, the effectiveness of such systems is not well tested or applied in practical situations and the full scheme as proposed in [9] has not been implemented so far.
To check the user effectiveness a user study is performed. The task effectiveness, sense of embodiment and user experience will be tested and compared with different control strategies.

1.2 Research questions

Based on the scope of this thesis the main research question of this thesis is as follows:

- *How can bi-directional impedance reflection techniques be generalized to a Cartesian-space telemanipulation control to reduce the effect of time delays on the operator experience?*

Which is divided into the following 2 sub-questions:

- *Which impedance reflection techniques can be found in literature and how can they be used in Cartesian-space telemanipulation control?*
- *What are the effects of time delay on the operator experience and how can they be evaluated?*

These questions will be answered in the following document.

1.3 Document Outline

This document is the technical attachment of the paper, here the paper is explained in more detail. The technical attachment outline will be as follows:

- *Chapter 2 Analysis:* Different methods of environment estimation, operator estimation and trajectory prediction will be explored for the design of the system and answer the first sub question
- *Chapter 3 Feasibility studies:* As some approaches are not well tested yet, some feasibility studies are done.
- *Chapter 4 Conceptual design:* Design of the system.
- *Chapter 5 implementation:* Implementation of the system.
- *Chapter 6 Performance evaluation:* Technical performance of the system.
- *Chapter 7 User study:* Testing the user effectiveness, sense of embodiment and user experience of different controllers commonly used.

2 Analysis

In this section, the analysis of the impedance reflection technique is done in bullet points style. In these subsections multiple methods are analyzed based on literature, this will answer the first research sub-question. These methods are discussed and the best methods will be used for the conceptual design.

2.1 General overview

Figure 1.2 shows the general overview of impedance reflection technique proposed by Hannaford. An addition to this system is the trajectory predictor, this predictor compensates for the effect of time delay of the motion of the master and slave, which also results in a faster estimation of the environment.
As been explained and shown in the figure the impedance of the environment is send back(reflected) towards the local model of the master and vica versa. This is done by online estimating the impedances of the environment and operator, based on the parameters of the environment and the master. The predictor will predict the path of the master and slave based on previous inputs. in [9] the proposed technique is designed to overcome the instabilities caused by the delayed information send through the communication channel. The time delay has no influence as the force applied force is calculated locally, meaning it is not delayed in time. Figure 2.1 shows a general overview of this system.

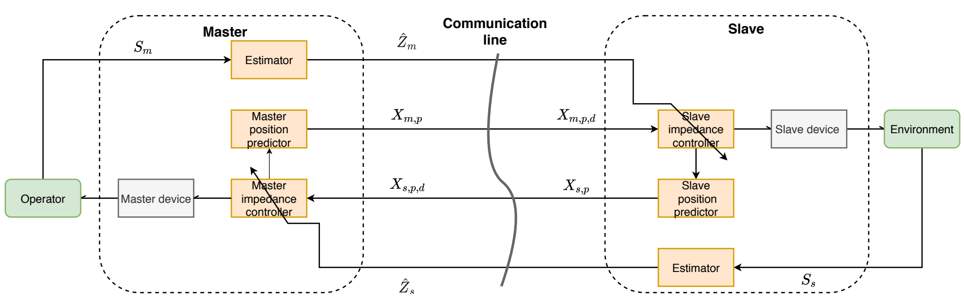


Figure 2.1: General overview of the bi-directional impedance controller. At both the master and slave side the impedance is estimated and the trajectory is predicted, both are sent to the other side.

Where S_m, S_e and $\hat{Z}_m$, $\hat{Z}_e$ are the states and the impedance's of the master and the environment, respectively. The information shared between the blocks and the needed information for the estimation and trajectory prediction are still unknown and is based on the method used.

In the next subsections, the different methods of impedance reflection and trajectory prediction are analyzed. These sections will answer the first sub research question. Based on this analysis an appropriate method will be chosen and designed.

2.2 Environment impedance estimation

- in [5] the environment's impedance is reflected towards the user using an impedance adaptation law. This is done by:
  - Online estimating the stiffness and the assumed contact position, this environment is kept stable using Lyapunov.
  - Two experiments are performed to assess the performance of the system. The environment is a simulation with a wall, where the time delay in the communication line is increased during the experiments. Both experiments are performed with and without the impedance adaptation law and a measure for transparency is made to further evaluate the system:
    * The first experiment uses a linear motion, with a linearized model for the human-arm impedance. The transparency and the force reflection towards the master in a time delayed system is checked. The system shows a higher transparency and a better force reflection compared to an ideal system without adaptation law.
    * The second experiment uses the Phantom omni coupled to a human to validate the simulated results above. The validation is done by showing the time to complete a task and the force error between the master and slave. The completion time was faster and the force error was less with the adaptation law under different time delays(0 - 2 seconds).
- In [10] the impedance of the environment is estimated in an unknown and unstructured environment. This is done by:
  - Considering point contact and using the non-linear Hunt-Crossley model, This model can better estimate soft materials compared to the classical Kelvin-Voight model, due to the non-linear behaviour of soft materials.
  - Linear regression is used to estimate the parameters. The point of contact is measured based on the force sensor, this point of contact is needed to know the insertion depth of the material. Two recursive

least squares algorithms are made and applied in two stages. These algorithms have a forgetting factor to detect material changes.

  - The experiments are done in 1 DOF using a load cell as a force sensor. This is done to validate the parameters of different known materials(stiff and soft) and check the convergence time.
    * The results show that the estimated parameters of soft materials is better with the Hunt-Crossley model compared to the Kelvin-Voight model. However, with stiff objects the Kelvin-Voight models show better results.
    * This method is complicated for the system and due to the complicated two stage least squares algorithms the convergence time is long. This method is only used to parameterize materials.

- In [11] the impedance of the environment is reflected towards the master to compensate for the friction in the slave robot. This is done by estimating the environment using an external force sensor, neglecting the internal forces of the robotic device. No time delay is taken into account but a little was created due to the estimation lag. This research is done by:
  - Estimating a spring which is non-linear. It is expected that the human does relatively slow motions, so no damping is taken into account. The estimation is done by:
    * Measured position of the slave.
    * Measuring forces at the end of the rod, meaning that only at the sensor contact estimations can be done.
    * The spring is estimated using a local Kallman filter, which online estimates the stiffness of the spring, further explained in [12]
  - The experiments are performed in 1 DOF and 3 DOF, both experiments are performed with direct force feedback and the environment reflection.
    * The 1 DOF shows that when the position is reversed the direct force feedback still increases in forces where it should decrease, when using the reflection technique this is compensated. Also the hysteresis significantly less.
    * The 3DOF case show better performance compared to classical force feedback scheme, the master has no effect of phase lag due to the simulated model. The friction is also compensated using this approach.
  - The system is explained in detail in [12]. However, the system designed does not allow backdrivability. The force feedback is induced based on the master position, when an external force is moving the

slave end-effector this is not taken into account in the simulated master environment, meaning that the master will not feel this effect.

- In [7] the environment is reflected toward the user using visual, force and position feedback, this is done by:
  - Making a visual image of the environment. The object is detected and touched by the robotic arm to generate a virtual environment. Then the operator gets the task to touch the object. The real arm is delayed in time due to the time delay, and due to the delayed images it looks like the arm is following the direct trajectory.
  - The experiments are done in 1 DOF, a mass and spring are placed in the environment which the robotic manipulator needs to touch, the results are as follows:
    * The system shows that the master directly feels the block on the right position, which is desired. the system gives stable and accurate behaviour at long time delays, such as 10 second or 15 seconds. The time of contact is very accurate.
    * However, the forces are not equal. This is due to sensor noise.
  - This not really the method for this thesis, because the objects are detected by a virtual algorithm. Then the objects are touched and then the human can control the robot. This heavily depends on a static environment, where everything needs to be touched at forehand.
- In [13] the environment is reflected toward the user using two different models with a 6DOF robotic manipulator.
  - This is done using the kelvin-Voight models for stiff objects and the Hunt-Crossley model for soft objects, which are changed based on the estimations of the spring.
  - Some assumptions are made in this paper:
    * No grasping tool is present
    * The objects are static
    * The geometry is not estimated
    * The objects are not coupled, damping can only occur when pushing an object
  - A self-perturbing recursive least squares algorithm is used for the estimation of the Kelvin-Voight model. Where the stiffness and damping parameter is estimated based on the penetration and velocities.
  - No time delay is added and stability analysis is missing
  - The system gave a good parameter estimation of the environment.

- In [14] the environment is reflected towards the user and the master is reflected towards the slave controller. An extra focus is applied on the jumping effect when suddenly touching high forces. This paper is build up as follows:
  - Different models are analysed such as a spring model, Kelvin-Voight and the Hunt-Crossley model. It is chosen to use a spring model because the Hunt-Crossley is too complex and computational heavy and the damper in the Kelvin-Voight model will not change the feeling towards the user, because the environment is usually stationary or quasi-static.
  - In this paper, the self disturbing recursive least squares will be used. Where the penetration depth is used to estimate the spring constant. The rest position is determined by the contact force change.
  - Next up the paper the jumping effect is analysed carefully and a method is designed to overcome this. This is done by predicting forces which the user can handle. The forces can not be higher than those to avoid sudden large forces towards the user.
  - The impedance controller of the slave robot is made adaptive, this is done based on the force and position input of the user. These parameters will change the stiffness of this controller, which in this case is the master reflection
  - The experiments are done in 1DOF with a 3DOF device.
    * These results showed good behaviour with large time delays. This paper is close to my proposed system. The only downside is that backdrivability is not possible, because the slave position is not used at the master side. This approach can be of influence in this thesis.

2.3 Master impedance estimation

- As mentioned above in [14] the master is reflected towards the slave to show its compliant behaviour by using not only the position input but also the force input. Based on this the impedance parameters are changed for the slave controller

- In [8] the master's impedance is reflected toward the slave model using EMG signals. This approach here is developed at the University of Twente. This method works as follows:
  - The slave controller is adaptive. The spring constant of this slave

    controller can be changed.
  - The adaptive slave controller reflects the dynamics of the human arm to the slave arm. These dynamics are lost due to the time delay in the channel
  - The passivity layer is used to keep the system stable under time delay.
  - The experiment is a use case study done in 3DOF with multiple different users.
    * A position task is done which shows the accuracy of position
    * An impact task is done to check the perception of the environment.
    * The results are compared with classical impedance control. With both tasks, the new designed system showed better position accuracy and impact perception.
  - This research has a high chance to be used due to the knowledge and the implementation already done here at the University of Twente.

2.4 Master and slave trajectory prediction

In this subsection, the different methods of master state prediction and their references are addressed in a bullet point style.

- In [2] a method of predicting the master state is addressed:
  - The following methods are used to realise this master state prediction
    * Using polynomial interpolation of lower order(which order is not specified), which is then extrapolated
    * Using spline interpolation which is then extrapolated. the extrapolation method is not explained in this paper.
    * Using a stark model based on EMG and ENG inputs, which is undesirable due to the added hardware for this thesis due to the extra addition of hardware.
  - The results are based on simulations done in Matlab in 1DOF, the results are as followed, visible in Figure 2.2.

Type	T.d.margin	Complexity	Robustness
Polynomial	$\leq 1/15\ f_i$	low	poor
Spline	$\leq 1/10\ f_i$	medium	adequate
Model	≤ 500 msec	high	good

Figure 2.2: Result of the master state prediction[2]

- In [15] the trajectory of the master is predicted by a 5th degree polynomial in every dimension. This is done using the minimum jerk model and using Kallman filters to track it. The results show very good results in 100 ms delayed 3DOF motions. However, the tests are only done for free motions, where also the start and end positions need to be known in the jerk model.
- In [16] the minimum jerk model is used to predict a trajectory of the master. This prediction needs an end and start point. Looking at the paper it can not be used for continuous movements.

2.5 Discussion

The above sections show the different possibilities of every block shown in the general overview of Figure 2.1. In this section, the different methods will be discussed and the best fitting method will be chosen and/or altered.

2.5.1 Environment estimation/reflection

The papers showed that there are many ways to reflect the environment towards the user. As this thesis will be partially done for the Xprize some objectives need to be set to achieve the desired results in the system. These are as follows:

- Backdrivability
- handle time delay

The definition of backdrivability, in this case, is that the master can feel the external forces of the slave and vica versa. Meaning that both the master and slave can be controlled from the opposite side. Handle time delay is the main goal of this thesis. As the current setup of the passivity layer can handle a time delay of 10 ms[17], a higher time delay than this is required.

Looking at the papers, all the methods do not have the option of both estimating the environment and have the system to be backdrivable. In all the literature the contact position and the slave position are used to determine the environment characteristics. A simplified method in one degree of freedom(DOF) of these cases can be seen in Equations 2.1 and 2.2.

$$\hat{K}_e = \frac{F_e}{(x_c - x_s)} \tag{2.1}$$

$$F_m = \hat{K}_e(x_c - x_m) \tag{2.2}$$

Where $\hat{K}_e$ is the estimated environment stiffness, x_c is the contact position and x_m and x_s are the master and slave positions. These equations show that the estimation and the force feedback(F_m) is calculated based on the contact position. These equations shows that when external forces are exerted on the robotic device the master will not feel this, because the position change of the slave position does not influence the forces of the master.
This means that the approaches used in literature will be adapted to ensure this backdrivability. This can be done by sending back the slaves position towards the master. This is not done before in impedance reflection, to test this approach a small feasibility study is done. The applied method will be further explained in the feasibility section.

2.5.2 Master reflection

For the master reflection, the work of [8] will be used as explained in the analysis section. It can be seen that the master reflection section is rather short. This is because not many work has been done in the reflection of the human impedance towards a slave device. Because the work of [8] has been done at this university and lots of knowledge is available this approach is chosen as implementation.

2.5.3 Trajectory prediction

In this thesis, the impedance of the environment will be reflected towards the user. When the user moves to an object the slave will touch this object delayed in time. This means that the impedance of the environment will be sent back to the master delayed in time. This result in a delayed feeling of the user of an object, resulting in higher forces against such an object. To compensate for this effect a trajectory predictor is added to the system. The prediction will be done both at the master and slave side this is done for the following reasons:

- Reduce impedance lag: As explained above, the master position is lagged in time due to the communication line. This result in a delayed estimation of the impedance of the environment. When a future path is generated towards the slave device, the object will be touched earlier. When the exact time delay is compensated, the estimation will be delayed by half the round trip time instead of the whole round trip time.
- Reduce forces due to position lag: To ensure backdrivability the slave position needs to be known by the master device. Due to the time delay in

the line the slave position will be delayed in time resulting in a bigger position difference between the master and slave then there actually is. This results in a higher force feedback to the master, this is compensated by such a trajectory predictor.

The analysis above did not show a good method which can be used in this thesis. The reason for this is that the higher-order polynomial and spline methods induce oscillations between points, where other methods are too complicated for this time period, such as the stark method mentioned in [2]. When assuming that a human will move linearly towards an object, simpler methods are used such as a 1st order polynomial will be used. A feasibility study will be done to check if this method is sufficient.

2.6 Effect time delay

As already been mentioned, time delay has a significant influence on the transparancy and stability of the system. In this section the effect of this delay in classic bilateral teleoperation is mentioned and what the expected influences are in the proposed system with this delay.

2.6.1 Time delay in classic bilateral teleoperation

Classic bilateral teleoperation is the standard structure of teleoperation shown in Figure 2.3.

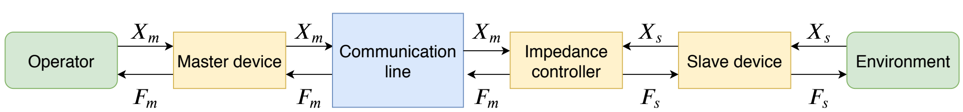


Figure 2.3: Classical impedance control

Latencies are predominant and occur in the communication channel. This element will behave as an active element and the system may lose passivity properties. This causes the system to behave active and create unstable behaviour. This can be shown using the associated power variables. An ideal system without time delays can be seen in Equation 2.3 and 2.4 and with a time delay can be seen in Equation 2.5 and 2.6[18].

$$\dot{q}_s(t) = \dot{q}_m(t) \tag{2.3}$$

$$\tau_s(t) = \tau_m(t) \tag{2.4}$$

$$\dot{q}_s(t+T) = \dot{q}_m(t) \tag{2.5}$$

$$\tau_s(t+T) = \tau_m(t) \tag{2.6}$$

Where $\dot{q}_s$ and $\dot{q}_m$ are the according velocities, τ_s and τ_m are the corresponding forces and T is the time delay. It is visible in Equation 2.3 and 2.4 that the velocity and force reflect on each other in the same moment of time. This shows that the energy level is the same thus passive, but Equation 2.5 and 2.6 shows otherwise. Due to the time delays, the power variables are not the same anymore and the power at the two ports of the communication channel may be different, resulting in either active of dissipative behaviour.

As been mentioned by [19], delays in bilateral control with force reflection an order of a tenth of a second already destabilizes the system.[20] states that force reflecting can not be used with delays above 0.5 seconds. However, in this method, an extra damper is added to stabilize the system.

2.6.2 Expected influence time delay

In this part the expected influences of time delay of the proposed scheme will be elaborated, this can be taken into account with the decision choice at the design:

- Synchronization delay: due to the delayed input of the user the slave touches the environment delayed and the change of the virtual environment will be delayed by the round trip time[21]. This will be partly solved by the trajectory predictors but still the estimation is delayed by half the round trip time.
- Predicted path: Due to the delay and the prediction of the master, the slave will move further than when the master has stopped. This will induce higher forces against the object and will result in instabilities, damages of the object and higher impedance's reflected towards the user. However, the time delays are relatively small, so these effects are minimal.
- Jumping effect: However this is not a direct consequence of time delay, this latency makes the effect larger. The operator can suddenly feel large forces when a sudden change of impedance happens. When the operator

can not handle these forces, the system will react unstable.

The points mentioned above mention the expected negative influences are mentioned, below the positive influences will be mentioned:

- Increased transparency with higher time delays: The transparency decreases drastically with higher time delays(10 ms), due to instabilities or by limiting the energy in the system in case of the passivity layers[4]. In this new proposed system the forces are decoupled. This latency will not affect on the force reflection but will be induced locally. This results in higher transparency when dealing with larger time delays.

- Partial friction compensation: The forces induced by the internal friction of the joints will be neglected, when the external forces will be used in the system to reflect the impedance of the environment towards the user. This will have an increased effect of transparency toward the user.

2.7 Proposed feasibility studies

As can be seen in this section many options are possible and the time delay can have many influences. As explained above some of the methods will be altered compared to literature, the following feasibility studies are done to check if the methods are viable:

- Estimation of the environment: In literature, it was visible that backdrivability was not ensured in the systems. In our case backdrivability is needed for the Xprize. To ensure this the position of the slave is also send back to the master.
- Trajectory algorithm: A simple trajectory predictor to overcome the time delays will be used.

3 Feasibility studies

As been mentioned above, two feasibility studies are done, existing out of the environment estimation and the trajectory predictor. This studies showed if the new and altered methods are viable.

3.1 Environment estimation

As visible in Figure 2.1 the estimation of the environment will be done based on different sensor readings of the manipulator. These readings will be used to online estimate the impedance of the environment. To test this concept a simplified system will be taken into account visible in Equation 3.1. Here the sensor readings are the external forces on the slave manipulator F_{ext} and the position of the master X_m and slave X_s.

$$F_m = \hat{K}_e(X_m - X_s) \tag{3.1}$$

$$\hat{K}_e = \frac{F_{ext}}{(X_m - X_s)} \tag{3.2}$$

Where F_m is the force applied on the master and $\hat{K}_e$ is the estimated impedance of the environment. This method is a simple estimation of the impedance and is prone to different errors such as sensor noise and jumping effects. A moving average filter was added to compensate for the jumping effects, this however caused a large estimation lag. The system used for this study can be seen in Figure 3.1

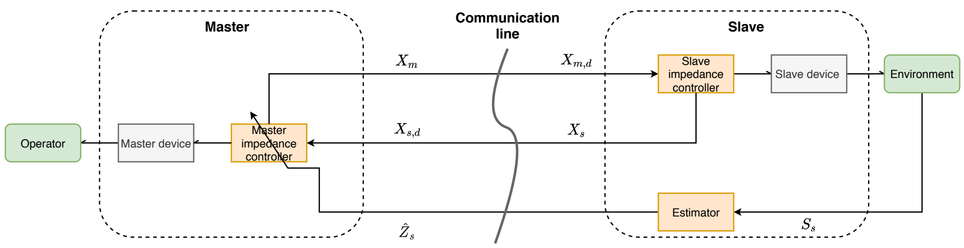


Figure 3.1: Block scheme of the feasibility study, where the environment is estimated and reflected towards the operator

The test is applied to a non-delayed line and a delay line of 20 ms. This study showed that the estimation method worked and a stable backdrivable system was created. However, it is prone to noise and has a large estimation lag. An improved method can be seen in Section 4.

3.2 Trajectory prediction

A feasibility study of the trajectory predictor is also performed. It is chosen to add 2 trajectory predictors, one at each side.

This study shows that the path of the slave device deviates less than without a trajectory predictor. A simple prediction based on velocity(v) and the delay(τ) step will be applied as shown in Equation 3.3

$$X_p = v_X \cdot \tau \tag{3.3}$$

Where x_p is the predicted position. This simple algorithm uses the velocity and the delay to calculate the predicted path. As this method showed to be viable, this is used in the final design visible in Section 4. A detailed performance evaluation of this method can be seen in Section 6

4 Conceptual design

Based on the analysis and the feasibility studies a conceptual design is made. First, a detailed overview of the system can be seen, which is followed by the explanations of the blocks of this overview

4.1 Detailed overview of the system

In the analysis section a proposed overview is given of the system. In Figure 4.1 a more detailed scheme is provided. This scheme has similarities with the position-position architecture, with modifications that predicted position are send supplemental with an impedance estimate.

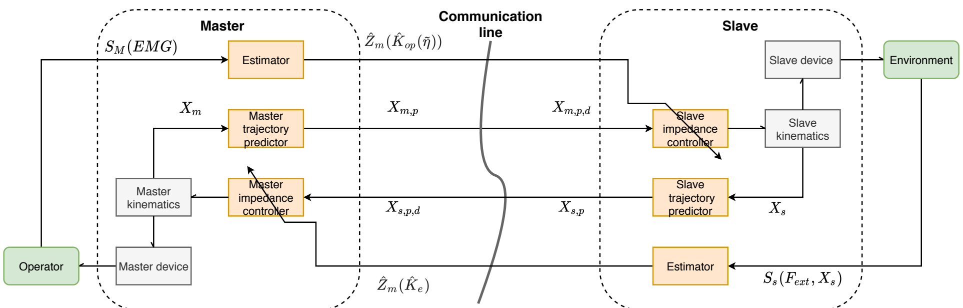


Figure 4.1: General overview of the bi-directional impedance controller. At both the master and slave side, the impedance is estimated and the trajectory is predicted, both are sent to the other side. Where the impedance is a spring constant, which are estimated based on the EMG signals of the operator at the master side and external forces and position measurements at the slave side

4.2 Trajectory prediction

The trajectory prediction has been described in detail in the feasibility study above.

However, the delay in the communication line must be determined roughly to know how far in the future the trajectory needs to be predicted. It is assumed that this is known in the system or can be derived using software.

4.3 Environment estimation

In the feasibility study, a simple implementation of the environment estimation can be seen. This feasibility study showed that the backdrivability is possible when estimating the environment. A new method is designed in this section, as the simple method was prone to noise and had a large lag in the impedance estimation.

As the environment will be estimated, a correct model must be chosen which will be estimated. Multiple models can be taken into account, Linear models such as the model of Hooke or Kelvin-Voight, or non-linear models such as Hertz or Hunt-Crossley, which are all shown below:

$$F_e(t) = F_{\text{Hooke}}(x) = kx \tag{4.1}$$

$$F_e(t) = F_{KV}(x, \dot{x}) = kx(t) + d\dot{x}(t) \tag{4.2}$$

$$F_e(t) = F_{\text{Hertz}}(x, n) = kx(t)^n \tag{4.3}$$

$$F_e(t) = F_{HC}(x, \dot{x}, n) = kx(t)^n + d\dot{x}(t)^q x(t)^p \tag{4.4}$$

As can be read in [13] the non-linear models such as the Hunt-Crossley model are good for soft surfaces and the linear models such as Kelvin-Voight can be used better for rigid objects. For simplicity, it will be assumed in this thesis that the environment will be mostly rigid and no soft tissues will be touched, this because rigid objects are more common and time constraints in this thesis.

Both [13] and [10] show that the linear models are better for rigid bodies and are less computational heavy. [14] states that the damper in the Kelvin-Voight model does not change the feeling toward the user as the environment is usually stationary or quasi-static. Resulting in the decision that the Hertz model will be used as can be seen in Equation 4.3 used.

To estimate the parameters of the spring constant of the Hertz model, an estimator algorithm must be chosen. Literature showed that linear regression is a common solution for the estimation of such parameters[10, 13, 21]. However, there are multiple methods to do this linear regression, such as the least squares method or the recursive least squares(RLS)[21]. The RLS method has the advantage that it has a faster convergence time than the least squares method and can be used efficiently in real-time. The computational load is heavier that the least square method, but as only one parameter is estimated this is sufficient. As the impedance changes real time, a forgetting factor(λ) is added.

To compute the impedance of the environment, the same parameters as the method proposed in the feasibility study will be used in the RLS algorithm. The measured force is the dependent variable $y(t)$ and the position difference is the independent variable $\varphi(t)$. The estimated parameter $\hat{\theta}(t)$ can be found using the following set of equations[22]:

$$\hat{\theta}(t) = \hat{\theta}(t)(t-1) + L(t)\left[y(t) - \varphi^T(t)\hat{\theta}(t)(t-1)\right] \tag{4.5}$$

$$L(t) = \frac{P(t-1)\varphi(t)}{\lambda(t) + \varphi^T(t)P(t-1)\varphi(t)} \tag{4.6}$$

$$P(t) = \frac{1}{\lambda(t)}\left[P(t-1) - \frac{P(t-1)\varphi(t)\varphi^T(t)P(t-1)}{\lambda(t) + \varphi^T(t)P(t-1)\varphi(t)}\right] \tag{4.7}$$

This will be done for every degree of freedom giving:

$$\hat{K}_e(t) = \begin{bmatrix} \hat{K}_{F,x} \\ \hat{K}_{F,y} \\ \hat{K}_{F,z} \\ \hat{K}_{\tau,x} \\ \hat{K}_{\tau,y} \\ \hat{K}_{\tau,z} \end{bmatrix} = \hat{\theta}(t) \tag{4.8}$$

Now $\hat{K}(t)_e$ is dependent on both the slave position and master position. Meaning that not only the impedance of the environment has influence on the estimation, but also the dynamics between the master and slave device. It can be derived that with rigid objects the estimated impedance is the impedance of the slave controller. With semi-rigid objects the impedance will be dependent on the impedance of this slave controller but will be lower.

4.4 Master estimation

The master state needs to be estimated as well. This can be done using EMG signals, these signals can give a sense of the impedance of the operator's arm. Fortunately, this work has already been done at the University of Twente by Kees van Teefffelen [8] but will be summarized below.

The impedance of the operator is estimated based on the co-contraction level of certain muscle pairs in the arm. During co-contraction of muscle pairs, the

impedance level of the human arm can change without changing the configuration of the limbs or the exerted force.
The co-contraction levels are estimated by the activation level(α) of an antagonistic muscle pair obtained using EMG signals. Using a calibration test the maximum level (α_{max}) and minimum level(α_{min}) can be obtained. These values are then used to normalize the activation level values by:

$$\hat{\alpha} = \max\left(0, \frac{\alpha - \alpha_{\text{min}}}{\alpha_{\text{max}} - \alpha_{\text{min}}}\right) \tag{4.9}$$

The normalized contraction levels are restricted to be positive. The co-contraction level is determined by taking the commonality of flexor(α_{flexor}) and extensor($\alpha_{extensor}$) muscles. Using the following equation the normalized co-contraction level η can be determined:

$$\eta = \min\left(1, \hat{\alpha}_{\text{flexor}}, \hat{\alpha}_{\text{extensor}}\right) \tag{4.10}$$

To avoid impedance levels above the maximum level, the value is restricted to be lower or equal to 1. A higher value can occur when during the calibration the maximum level is incorrectly determined.
Finally, the normalized co-contraction level(η) is low-pass filtered using a second-order Butterworth filter with a cut-off frequency of 5Hz to reduce the effect of high-frequency behaviour:

$$f_{\text{low-pass}} = \frac{\omega_{c,lp}^2}{s^2 + \sqrt{2}\omega_{c,lp} s + \omega_{c,lp}^2} \tag{4.11}$$

The variation law for the impedance controller at the slave side is then given by:

$$\hat{K}_{op}(\tilde{\eta}) = K_{\text{min}} + \tilde{\eta} \cdot \left(K_{\text{min}} - K_{\text{max}}\right) \tag{4.12}$$

Here $\tilde{\eta}$ is the normalized estimation of the co-contraction levels delayed in time and $\hat{K}_{op}(\tilde{\eta})$ is the estimated impedance of the operator. K_{min} and K_{max} are empirically tested and are hardware dependent. When K_{min} is too low the arm does not have sufficient force to execute a task and when K_{max} is too large the robot is prone to show more oscillation behaviour, both these effects lower the transparency.

5 Implementation

The previous section shows the conceptual design. In this section, the implementation of this design is explained. First, the chosen hardware is explained and further an overview of the software framework is given.

5.1 Hardware

To realize the system, hardware must be chosen which is compatible with the proposed system. For the EMG signals, the MYO Armband will be used, which can measure the muscle activity. The master and slave device, however, need to have the following requirements.

- Requirements master device:
  - Control in 6 DOF
  - Render force feedback in 6 DOF
  - Position, velocity and force data
- Requirements slave device:
  - 6 DOF end effector movement
  - Joint force control
  - Position, velocity and force data

The decisions are made based on available hardware a the RaM chair at the University of Twente. For the master device the omega device is the best option. This device is able to meet the requirements, except for the force feedback rendering in 6 DOF. The omega 7 device can only render force feedback in 3 DOF, which is in the translational directions. However, in later stages the Virtuose of Haption will be available. This device has a larger workspace can induce a higher amount of force feedback and in 6 DOF.
For the slave device, two options are open. At the RaM lab, the KUKA lwr 4+ and the Franka Emika are available. Both devices are 7 DOF manipulators and meet all the requirements. The difference between the devices are the interfaces. The Franka Emika has a better interface with ROS, the KUKA can handle a larger payload. As the interface of the Franka Emika is better and no large payload is needed, this one will be used.

5.2 Change to simulation due to COVID-19

As during this thesis COVID-19 occurred, the hardware of the lab was not accessible anymore. Due to these sudden changes, a shift in hardware decisions are made which can be facilitated at home. It is chosen to use the omega 7 device, as this device can be transported and used at home. Unfortunately, a slave manipulator cannot be used at home. For this reason it is chosen to use a simulation of the slave manipulator.

For the simulation the gazebo environment will be used. Gazebo(Open Source Robotics Foundation, Mountain View, CA,USA) is a commonly used simulator in ROS. For the simulation a KUKA LWR4+ 7 DOF manipulator will be used, both for the technical performance and user study. However, the simulation has some limitations and extras which needs to be taken into account stated below:

- Ideal behaviour
- No sensor noise
- joint friction can be altered
- No external force measurements
- Bodies are always rigid

This will result in different behaviour compared to reality. As the system estimates the impedance of a surface, the rigid bodies will always estimate the same impedance, which in this system will be the impedance of the slave controller. This will not influence the user study but will have an influence on the technical performance as semi-rigid bodies can not be tested, because gazebo does not support this natively.

The other thing which will be severely different compared to reality are the external force measurements. These are needed to estimate the impedance of the environment. As the external forces cannot be measured, the known internal torques generated in the joints of the KUKA will be used. When the friction of this robotic device is made negligible the internal torques applied on the robotic device is roughly the same as the external forces when rigid bodies are assumed. This is in case of this gazebo simulation.

5.3 Software implementation

The software is implemented in ROS(Robotic Operating System), this platform is commonly used at the robotics and mechatronics chair at the University of Twente. This platform allows for fast development of software and takes care of the communication between the different platforms. The software is implemented in different nodes using standalone libraries. These standalone libraries can be reused easily on different platforms. As the implementation is done on a simulation the whole software runs on 1 PC. The different methods as explained above are implemented in separate nodes in C++. Blocks which have more functionality than shown in their design section are explained below:

5.3.1 Environment estimator

The design of the environment estimator is shown in Section 4. The estimation method as described will be used in this node. However, some minor alterations are made to compensate for the noise in the force measurements, due to the minor friction of the slave model in Gazebo. The force is made negligible but when moving in free space still some forces are needed. This force ranges between -4 Newton and 4 Newton. This was also the case with the real manipulator. This means that a threshold is made where the estimator starts estimating, following Equation 5.1

$$\hat{K}_m = \begin{cases} K_{low}, & \text{for } |F_{ext}| \leq |F_{thres}| \\ \hat{K}_e(t), & \text{for } |F_{ext}| > |F_{thres}| \end{cases} \tag{5.1}$$

This means that above the threshold the estimated parameter of the environment will be used and below the threshold, a low impedance will be used. A non zero impedance is chosen, to reduce the jumping effect and give the user a feeling of moving a manipulator, as the friction is not feelable in this method.

5.3.2 Slave controller

The slave controller handles multiple tasks, such as the conversion from Cartesian space to joint torque space and the communication between ROS and the gazebo simulation using the ROS controller manager. This controller runs at 1KHz. As the omega can only induce force feedback in the translational directions, only translation is done in this study. The input of this slave controller is the predicted position of the master device $X_{p,m}$. The translational force $F_{s,t}$ applied on the end-effector will be calculated using this position as shown in Equation 5.2.

$$F_{s,t} = \hat{K}_{op}(\tilde{\eta})(X_{p,m} - X_s) \tag{5.2}$$

Where $\hat{K}_{op}(\tilde{\eta})$ is the estimated impedance of the human operator and X_s is the position of the slave device. The rotational forces are applied according to Equation 5.3, this is done to keep the peg straight.

$$F_{s,r} = K_r(X_r - X_{r,s}) \tag{5.3}$$

Where $F_{s,r}$ are the rotational forces and X_r is the desired straight orientation of the peg of slave manipulator and $X_{r,s}$ is the current orientation of the peg. The applied forces in Cartesian space must be converted to joint space using Equation 5.4.

$$\tau_m = J^T(F_{s,t} + F_{s,r}) \tag{5.4}$$

Where τ_s is a vector with joint torques which is 7 in the case of the 7 DOF robotic manipulator and J is the jacobian of the slave manipulator.

5.3.3 Master controller

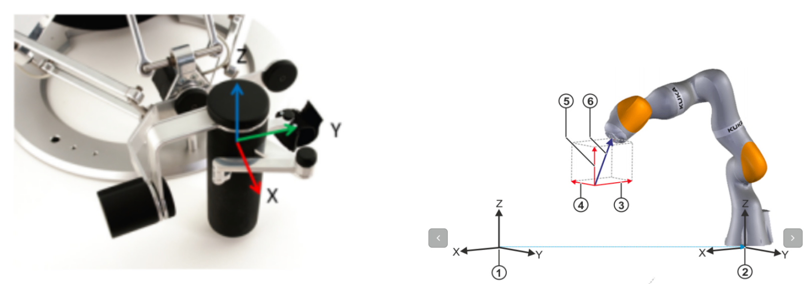
The master controller handles the communication between the master device and calculates the forces applied on the operator. The same applies for the master controller, only translational forces are taken into account. The force law for the operator is given by Equation 5.5.

$$F_m = \hat{K}_m(X_{p,s} - X_m) \tag{5.5}$$

Here F_m is the force applied on the master and $X_{p,s}$ is the predicted slave position.

5.3.4 Frame converter

As the omega frame is not the same as the frame of the KUKA robot, this frame needs to be converted. Not only for the position but for the full state and force feedback of the omega. This converter is used to convert the whole state and the force feedback. In this case, this is a 180 degrees turn along the z-axis, the different coordinate frames are visible in Figure 5.1



(a) Coordinate frame of the omega 7 (b) Coordinate frame of the KUKA arm

Figure 5.1: Coordinates frame of the master and the slave

5.3.5 Delay node

Normally delay is present in the system, due to the effect of long distances between the master and slave platform. This current setup runs on a single PC, meaning that this delay must be simulated. This is done by adding a delay node, which delays both the master and slave position and the estimated impedance's. This means that the messages sent to the other side are delayed by the given delay time, so packet loss is not taken into account.

5.3.6 Controllers user study

For the user study, 3 controller will be tested, further explanation can be seen in the next Section. However, the other 2 controllers are also implemented on the teleoperation system. The two other controllers implemented are the Classical bi-lateral impedance controller, as can be seen in Figure 2.3 and the same controller in addition with the passivity layer as can be seen in [18]. The system parameters can be seen in the next subsection

5.3.7 System parameters

For the user study, 3 controllers are implemented with all their parameters, which will be mentioned here. The parameters for the impedance reflection technique can be seen in Table 1. The parameters for the bi-lateral impedance control with the passivity layers can be seen in Table 2[8]. For the impedance controller without a passivity layer, parameter K_{max} will be used.

Table 1: Parameters of bi-directional impedance reflection

Parameter	**Value**	**Unit**
K_{low}	100	N/m
K_{min}	100	N/m
K_{max}	600	N/m
K_r	100	$\frac{N/M}{Rad}$
$\omega_{c,lp}$	5	Hz

Table 2: Parameters of the bi-lateral impedance control with the passivity layers[8]

Parameter	value	unit
β	0.01	-
H_D	0.1	J
γ_m	200	$\mathrm{N} \cdot \mathrm{s} \cdot \mathrm{m}^{-1} \cdot \mathrm{J}^{-1}$
γ_s	0	$\mathrm{N} \cdot \mathrm{s} \cdot \mathrm{m}^{-1} \cdot \mathrm{J}^{-1}$
K_t	600	N / M
K_r	100	$\frac{N/M}{Rad}$

6 Performance evaluation

This section provides a performance evaluation for the new impedance reflection technique. The goal of this evaluation is testing the technical performance of the system.

6.1 Approach

For the technical performance, the separate parts will be tested as well as the full system. The different parts tested are shown below:

- Environment force reflection
- Trajectory prediction
- Full system test

At every experiment the results are shown and discussed, in the end an overall performance discussion is done to verify the system.

6.2 Environment reflection

For perfect transparency the operator should exactly feel what the robot is feeling. This means that the measured force at the slave side must be equal to the force measured/applied at the master side. This results in the first experiment.

Experiment 1

- *Goal:* Test the difference between the reflected force towards the master and the force measured at the slave side and see how much influence the time delay has.
- *Assumption:* Rigid bodies, due to simulation.
- *Setup:* A simulation in gazebo with the omega as master device. Only the impedance of the environment is reflected which is shown in Figure 6.1. No time delay and 20 ms time delay have been chosen, as the passivity layer has a good behaviour until 10 ms, 20 ms is tested to check if this has good behaviour.
- *input:* Motion of a human operator against a rigid object
- *Measurements:* ROS topics of the forces measured at the master and slave side.
- *Question:* Does the estimator minimize the error as it should? Is the force error higher when higher time delays are present?

- *Expected results:* It is expected that with higher time delays the force error is higher, because the impedance is send delayed over the line. As the impedance estimation is only done above a certain threshold(4N), it is expected that the force error below this value is high.

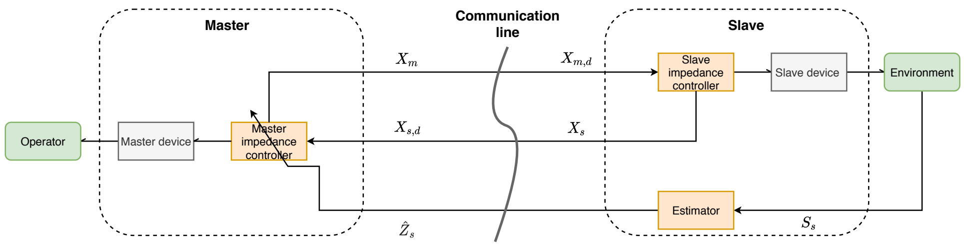


Figure 6.1: Block scheme of the system in experiment one. Here the environment estimation is done.

Results

The results of the experiment described above can be seen in Figure 6.2. It shows the applied force on the master device and the end-effector of the slave manipulator. The error between these two platforms can be seen in the plot below it. These results show some expected but also unexpected behaviour. Starting off with the tracking behaviour of forces around 4N, it is visible that the error between the forces of the master and slave is high. This was expected because the estimation process starts at 4 Newton as a threshold. Below this threshold the impedance of the master controller is made relatively low compared to the slave controller, this gives the operator the feeling that it is moving in free space. This means that the slave controller applies high force to move the manipulator while the operator does not feel this, this results in the force difference shown. Also, a force difference can be seen around 15 Newton and higher, which was not expected. However, this can be explained, as the maximum activation force of the omega is 15 Newton. Between these ranges the estimator shows good tracking behaviour of both forces.

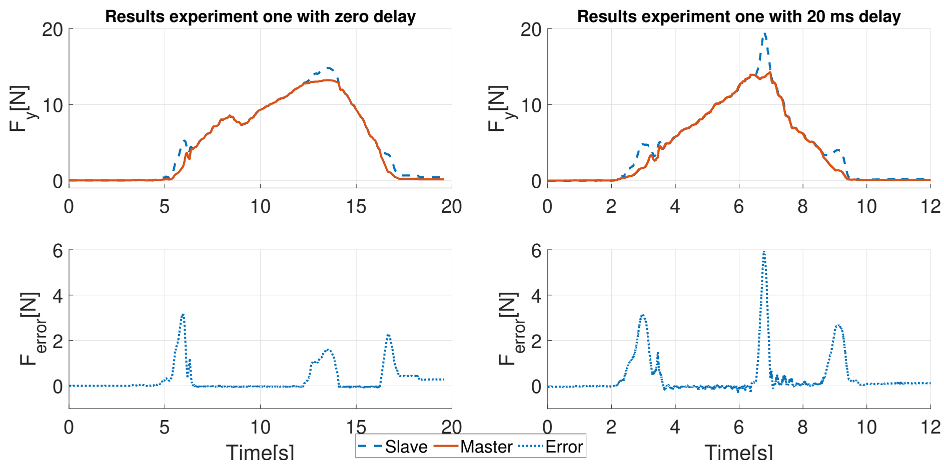


Figure 6.2: The results of experiment one. In the left column, the result of the experiment with zero time delay is shown, the right column is the experiment with 20 ms of delay.

To have a better understanding of the differences between the forces of the master and slave device under different time delays Figure 6.3 is made. This plot shows the force error dependent on the applied force. This figure shows that large errors occur above 15 Newton and below 4 Newton, which are caused by the effects described above. Between these values it is visible that without time delay the tracking of force is almost perfect and with 20 ms time delay, this tracking is worse but still minimal as the force differences are below half a Newton. This effect should be less when the trajectory predictor is added, which allows for faster impedance tracking, due to earlier contact with the surface.

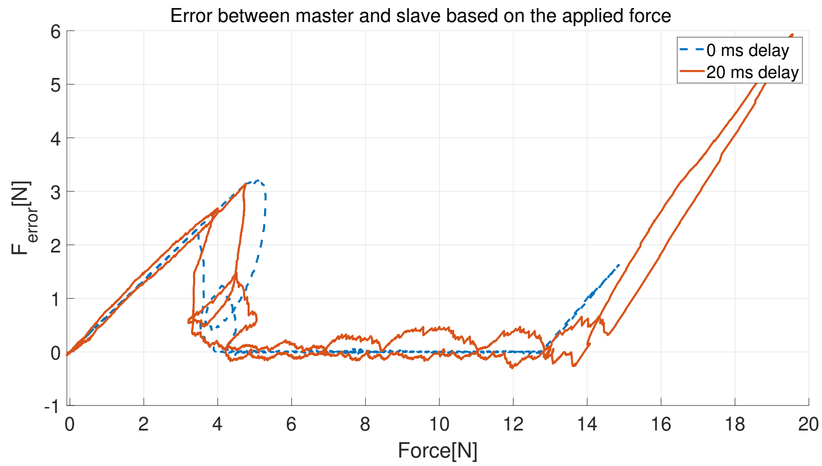


Figure 6.3: Error force plot experiment one while moving against a rigid object under different time delays.

6.3 Trajectory prediction

The trajectory predictor should compensate for the delayed trajectory due to the communication lines. Meaning that the trajectory is predicted exactly the amount of time as there is a delay in the channel. This can be tested as follows:

Experiment 2

- *Goal:* Test if the predicted trajectory over the delay line is the same as the input trajectory or within a certain margin.
- Assumption: It is assumed that the delay in the communication line is known or can be derived from data(ROS topics).
- Setup: A simulation of the KUKA arm in gazebo with the omega as master device. The system applied in ROS is shown in Figure 6.4 with a time delay of 20 ms.
- *input:* Motion pattern by the operator in free space.
- *Measurements:* ROS topics of the motion of the master, and the delayed motion of the master and the predicted motion of the master.
- *Question:* Is the delayed predicted trajectory of the master the same as the trajectory of the master or at least within a certain margin(5%).;
- *Expected result:* It is expected that the trajectory during motion will be within the margins. With velocity changes it is expected that the trajectory error will be bigger.

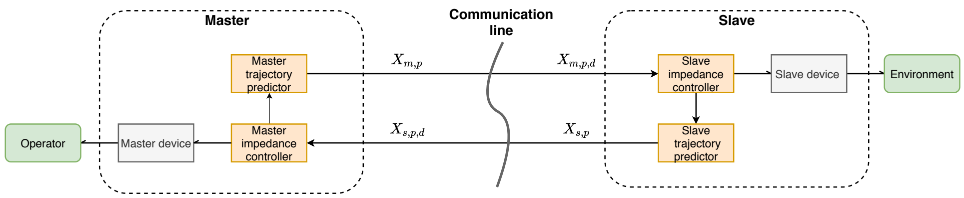


Figure 6.4: Block scheme of the system in experiment two. Here the trajectory prediction is done at both sides.

Results

Figure 6.5 shows the behaviour of the trajectory predictor. A motion in the y-direction can be seen, based on this motion a trajectory is predicted. The delayed trajectory is the predicted trajectory out of the delay node. Meaning that the slave receives this trajectory at the same moment of time. The figure shows clear results that the trajectory predictor works. The trajectory of the master device and the trajectory received at the slave side is almost equal. The maximum error between these trajectories is a maximum of 0.8 mm with a mean error of 0.002 mm, which is well within the desired margin. Next to the trajectories, the motion of the slave device can be seen, which is almost equal to the trajectory of the master, due to the low friction in the simulation.

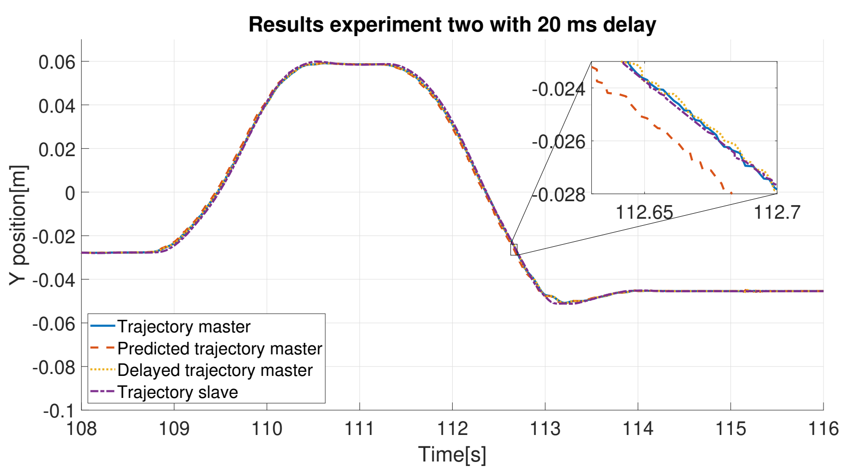


Figure 6.5: Result of experiment two with a delay of 20 ms

6.4 Full system test

Finally, a full system test needs to be done. This system is developed to handle higher time delays than a regular impedance controller or passivity layer, while maintaining stability and still have a sense of transparency. The full system test will be checking these factors. The full system test will be split into two experiments shown below. The first experiment will be based on stability and the second one on transparency. The system as shown in Figure 6.6 will be used.

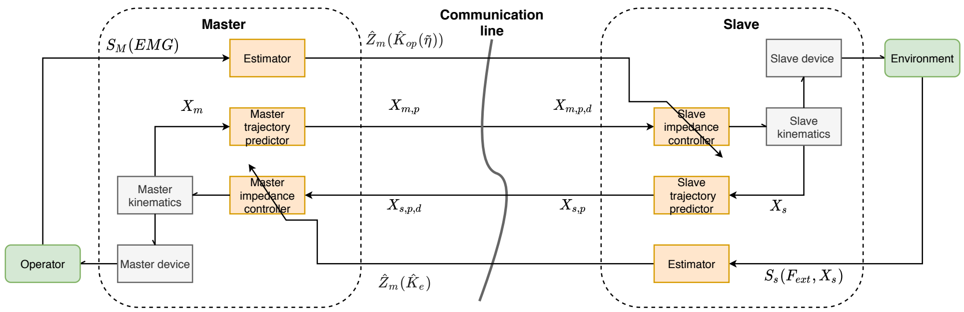


Figure 6.6: Block scheme of the system in experiments four and five.

Experiment 4

- *Goal:* Check the stability of the full system, by showing active behaviour of the system(oscillations of the master device with a loose grip of the operator(undamped)).
- Assumption: Rigid bodies
- Setup: Full system as shown in Figure 6.6, with the omega as master device and a simulation in gazebo of the KUKA arm.
- *input:* Operator motion pattern in free space
- *Measurements:* ROS topics of the master and slave controllers forces and positions.
- *Question:* Does the time delay affect the stability of the system and until which delay is this system usable?
- *Expected result:* It is expected that the system will perform better than the passivity layer in this case. This passivity layer is usable until 10 ms. It is expected this system can handle larger time delays, but when the delay becomes bigger damping needs to be added because the predictor will not be precise enough to predict much time in the future(above 50ms)

Results

In Figures 6.7 and 6.8 the results of the test can be seen. The motion of the operator was a sideways motion in the y-direction in free space. The following figures show that the controller has good behaviour up to 50 ms and that there are no other movements/oscillations visible due to an unstable system. There

are however two things visible in this graph, an overshoot of the position and some peaks in the force plots. Starting with the peaks in the force plots, these sudden changes are caused due to the change of impedance, as the impedance changes in time continuously. As the estimator creates an estimation lag in combination with the delayed impedance sent back, this creates an error when the impedance changes.
The overshoot in the trajectories are caused by the low impedance. This is caused by low co-contraction levels of the operator. The lower forces applied on the slave device are prone to overshoot as no damper is added to the system.
The effect of simulation can also be seen, on a real manipulator the external forces are sensed and used to estimate the impedance, now the internal torques are used. Due to lower impedance's at the slave side the forces applied in the system are higher, which is counter-intuitive(further explained below). This results in an estimation of the environment even if the manipulator moves in free space.

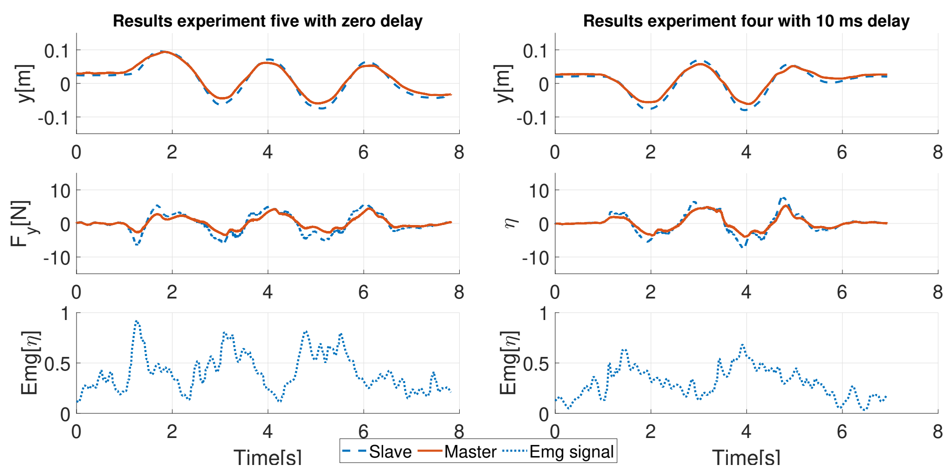


Figure 6.7: Results of experiment four with variable stiffness in the left column zero time delay is present in the right column 10 ms of time delay is present

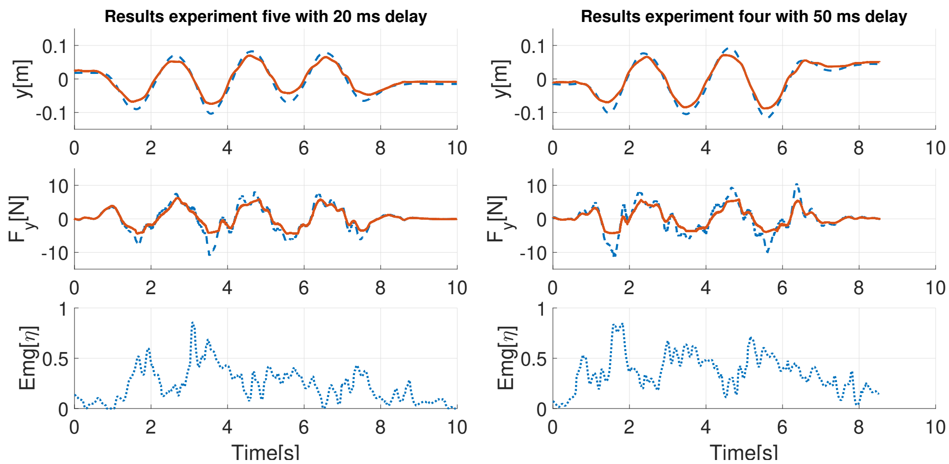


Figure 6.8: Results of experiment four with variable stiffness in the left column 20 time delay is present in the right column 50 ms of time delay is present

Due to the low and varying EMG signals overshoot and peaks in the forces at the slave side occurs. Another experiment is done where the full system is used but the impedance controller of the slave device is made high and constant, meaning that the EMG signals are not taken into account. This can be seen in Figures 6.9 and 6.10.

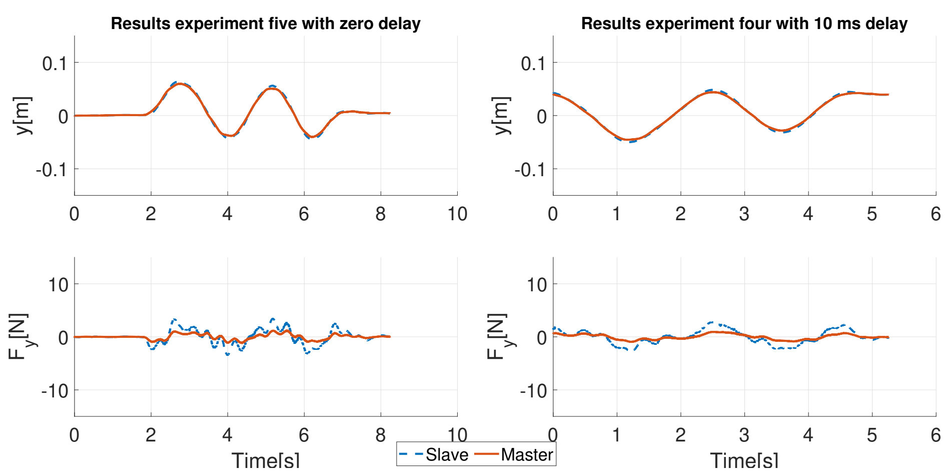


Figure 6.9: Results of experiment four with high stiffness in the left column zero time delay is present in the right column 10 ms of time delay is present

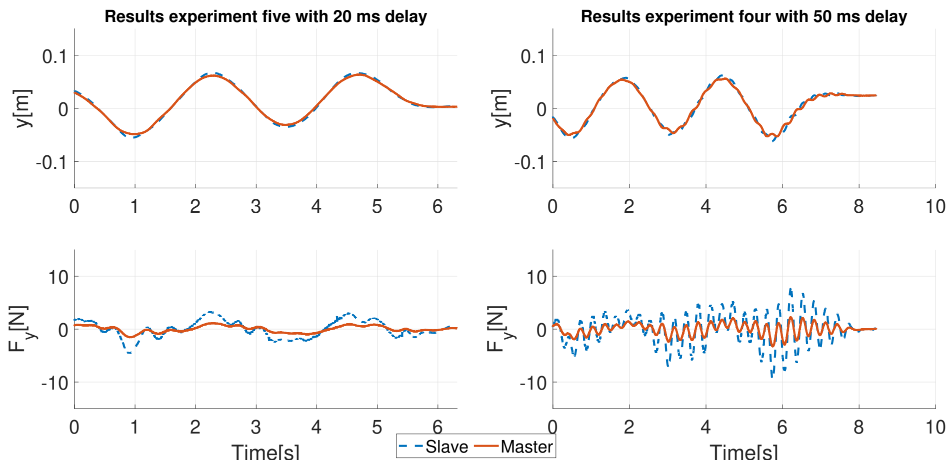


Figure 6.10: Results of experiment four with high stiffness in the left column 20 time delay is present in the right column 50 ms of time delay is present

These figures show very different behaviour. It can be seen that there is less overshoot, caused by the high impedance of the controller. This has another significant effect on the system, namely much less forces are applied. The reason for this is the difference of impedance's applied on both sides, in this case the impedance of the slave device is high but the impedance of the master side is low(free space). Due to the higher impedance at the slave controller the stick and slip of the joints of the manipulator have less influence as a higher force is applied to overcome this. Causing a better tracking of the trajectory, less overshoot and faster reaction of the system. This results in less applied forces at both sides.
However, in the high impedance case oscillations can be seen in the forces with a latency of 50 ms. This is caused by the trajectory predictor. As the predictor is fairly simple large velocities at large time delays results in relatively large position predictions into the future, this causes the oscillatory behaviour. This is the case due to the high impedance of the slave controller, resulting in faster displacements. This can be improved by adding damping to the system, or by making a better trajectory predictor, this will be more elaborated in the Recommendation section 8.2.3.

Experiment 5

- *Goal:* Check the transparency of the system, by looking at the reflected force versus the measured force at the slave side
- Assumption: Rigid bodies

- Setup: Full system as shown in Figure 6.6, with the omega as master device and a simulation in gazebo of the KUKA lwr
- *input:* Operator motion pattern against a rigid body
- *Measurements:* ROS topics of the measured forces and applied forces
- *Question:* Is the reflected force within a margin of the measured external force with different time delays(0ms ... 50ms)
- *Expected result:* It is expected that the reflected force will be better than without trajectory prediction. This predictor decreases the position lag of both the master and slave device, resulting in a better force reflection

Results

Figures 6.11 and 6.12 show the results of the motion of the manipulator against a rigid object. Some phenomena can be seen which are already explained above, such as force peaks caused by the changing EMG signals and maximum force of 15 newton due to the omega. The results below show that the impedance method works and that the reflected forces are almost equal as the measured forces. A big difference which can be seen here is that the EMG contraction levels are higher, as the operator needs a lot of force to apply the motion against the rigid body, to apply this force higher co-contraction levels are needed. Another test with only high impedance is done and can be seen in Appendix in Figures 8.1 and 8.2.

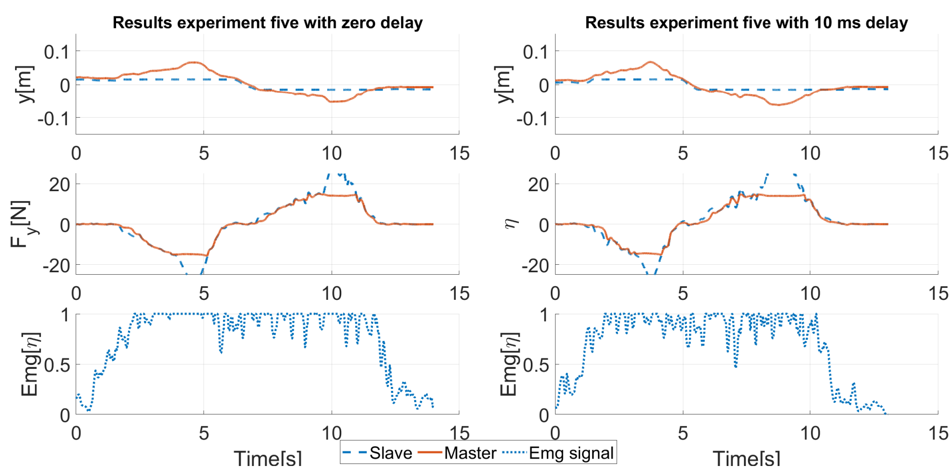


Figure 6.11: Results of experiment five with variable stiffness in the left column zero time delay is present in the right column 10 ms of time delay is present

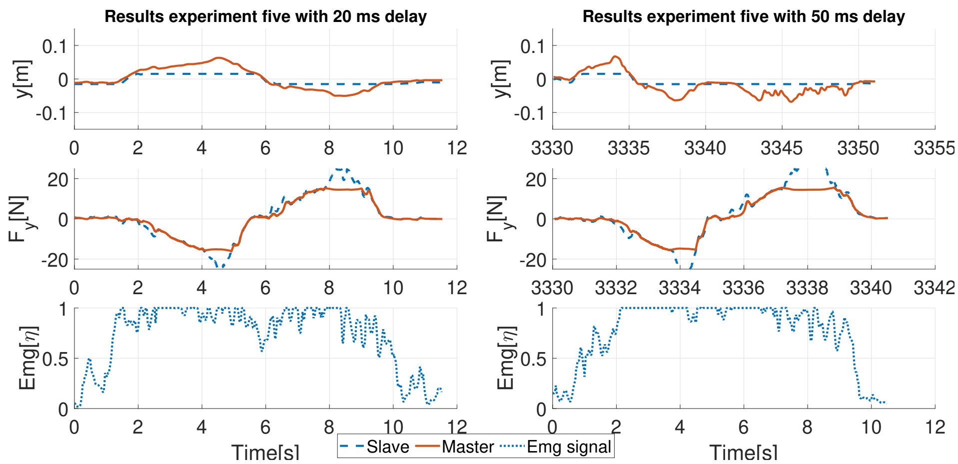


Figure 6.12: Results of experiment five with variable stiffness in the left column 20 time delay is present in the right column 50 ms of time delay is present

To show the error of the forces applied at both sides the error plot of the variable stiffness can be seen in the Appendix 8.3, because this is more unclear because of the varying impedance. However, to show the difference in the forces applied at both sides the error plot of the high stiffness case of the slave controller is shown in Figure 6.13. The error plot shows that when the time delay increases the error increases, especially at the force threshold. This is caused by the estimation lag, it takes a small time to convergence to the right impedance estimation, this can be seen in the half circles. When the delay increases these half circles increases, because of the time lag. As expected the error at 20 ms is lower in the full system compared to experiment one due to the trajectory predictor.

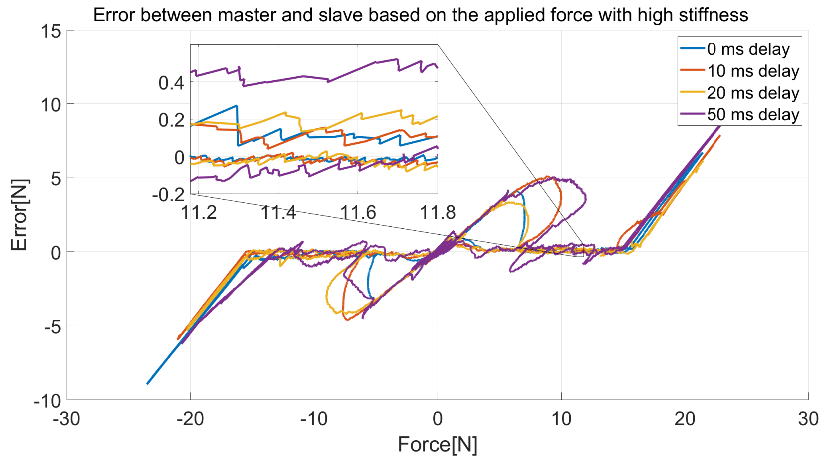


Figure 6.13: Error plot between the forces of the master and slave of experiment five with high stiffness

6.5 Overall performance discussion

During the results all the phenomenon in the figures were described and discussed. An overall discussion for the performance is not done yet and will be done here. This new technique will be compared to the classical impedance control and the impedance control with passivity layer as this will also be done during the user study and being the first controllers applied at the Xprize.

The new impedance reflection technique used the position-position architecture opposite of the position force architecture of the other controllers. This has the disadvantage that the forces calculated on both platforms are calculated separately. Where with the position force architecture the calculated force is applied on both platforms. To compensate for this problem the impedance estimator of the environment estimate the impedance based on the measured force and counteract for any deviation in the reflected impedance and the measured impedance. The figures show that the reflected force between the threshold of 4 and 15 newton are indeed tracked carefully, except around the threshold, due to the estimation lag. In combination with the trajectory predictor the lag of delayed positions is solved as well.

Where the classical impedance technique can not handle time delay and the passivity layer can only handle time delay until 10 ms [8], the new impedance reflection technique has no problems handling time delays up to 50 ms. It is visible that with the varying impedance no oscillations occur in the system. However, the time delay does affect the error between the reflected and measured force. It has been shown that with higher time delays the force error is higher. This is caused by the delayed impedance send to the other side, this however is minimal.

The goal of the thesis was designing an impedance reflection technique which can handle larger time delays than the currently used system of the passivity layers and still have a large transparency. The overall performance showed that indeed the system can handle 5 times larger time delays and that the reflected force error is small. Another advantage of this system is that the friction can be neglected when using external force sensing or by the use of a model to remove the commanded torques which can be done on a real manipulator. However, the predictor can be improved as this can make the system unstable with higher time delays and velocity (explained further in the recommendations section). To verify if the users have a better effectiveness using this system, a user study is performed.

7 User study

In this section, the user study is explained. The user study is done to show the user effectiveness of the system. It was realized in collaboration with Sara Falcone, who helped setting up the experiments, as well as designing, analyzing and discussing the results. First, the design of the user study is explained (aim, participants, set-up, and tasks), followed by the results, and finally the discussion.

7.1 System effectiveness

This user study aimed to show the effectiveness of the impedance reflection technique under different time delays. Where the effectiveness will be expressed in: the quantitative results, sense of embodiment(SoE) and user experience(UEQ). An increase in one of these dimensions without the loss of another is considered as higher effectiveness. A user study was designed in which the following three systems are compared:

- Classical bilateral impedance control(BIC): one impedance controller which couples the master and slave device.
- Classical bilateral impedance control with passivity(BICP): Using the BIC scheme with the addition of the passivity layer of [4].
- Bi-directional impedance reflection technique(BIR): The newly proposed system of this paper.

We realized a between-group design, in which each group tested all the 3 controls but each group under a different time delay condition, following Table 3. The BIC controller is not designed to handle time delays and does not work for 10 ms delays or higher, thus lower time delays are chosen.

Table 3: Delays of each group and controller

	Controllers	
Group	**BIC**	**BICP and BIR**
1	0 [ms]	0 [ms]
2	2 [ms]	10 [ms]
3	5 [ms]	20 [ms]

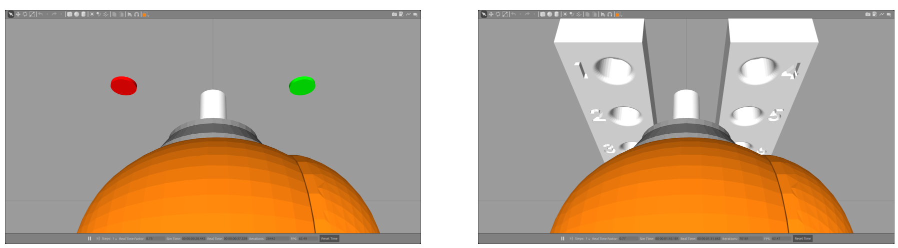
7.1.1 User study design

15 healthy volunteers without previous issues to nerves or muscles participated (8 males and 7 females, between 18 and 27 years old). This group was split in 3. Each group performed a calibration task for the BIR controller, then 3 tasks are performed with each of the 3 controls. Each group experienced a different time delay condition as can be seen in Table 3. Following, we explain the different tasks and their desired results:

- **Task 0: EMG calibration task:**
  - *Goal*: Calibrate the minimum and maximum contraction level of the muscle of each user.
  - *Method*: A changing random sine wave motion was applied to the master controller;
  - *User instruction*: First: act compliant to the behaviour (minimum co-contraction). Then try to keep the controller at the same place (Maximum co-contraction);
  - *Repetition*: This is done one time;
  - *Measurements*: Minimum and maximum contraction levels of the muscle.
- **TASK 1: Proprioceptive Calibration task:**
  - *Goal*: For participants to experience the environment and to get used to the embodiment.
  - *User instruction*: Move the arm from point A to point B;
  - *Repetition*: 6 trial for each controller (18 times);
  - *Measurements*: Proprioceptive drift, the time needed to accomplish the action. Sense of embodiment and user experience;
- **TASK 2: Stop and go:**
  - *Goal*: Test how the users reacted to unexpected instructions and how they could deal with them considering the control and the time delay.
  - *User instruction*: Move the arm from point A to point B and touch it. For half of the trials, the user must come back to the starting point while they are moving to the target point.
  - *Repetition*: 6 trial for each controller (18 times).
  - *measurements*: Reaction time, sense of embodiment, and user experience.

- **TASK 4: Peg in hole:**
  - *Goal*: Test how easily the users could move through the environment, their perception of the space and distances, and finally their ability and experience in teleoperating the system with different controls in different time delay conditions;
  - *User instruction*: Move the arm from one hole on a wall, to another hole on another wall. There were 6 holes.
  - *Repetition*: 6 trial for each controller (18 times).
  - *measurements*: Accomplishment time, sense of embodiment, and user experience.

The display of the simulation and the different tasks can be seen in Figure 7.1, the gui used can be seen in the Appendix in Figure 8.4.



(a) Task 1 and 2 of the user study (b) Task 3 of the user study

Figure 7.1: Simulation for the user study

7.1.2 Hypotheses

3 hypotheses are developed to compare the effectiveness of the BIR control with the BIC and BICP control under different time delay conditions:

1) The BIC and BICP controller have a better effectiveness compared to the BIR controller when no time delay is present, as the forces are directly fed back and no estimation method is in the middle.

2) The effectiveness of the BIR control is higher when time delays are present in the communication line. As it is expected that instabilities occur in the BIC controller and energy limits are applied in the BICP controller.

3) When the time delay increases the effectiveness of every controller will decrease, as the time delay has more influence on the performance.

To measure the effectiveness of these controllers a user experiment is set up explained in Section 5, which measures the quantitative results. A questionnaire is designed to measure the sense of embodiment and user experience. This is further explained in the following sections.

7.1.3 Questionnaire

A questionnaire was filled in online on the *SurveyMonkey* platform, and aimed to collect three types of information:

- Proprioceptive information profile: The participants are asked to provide information related to their level of proprioceptive information, namely age, gender, if they practised a sport, which sport, at which level (amateur or professional), if they had previous problems to the upper body nerves or muscles;
- The Sense of Embodiment (SoE): Is described by three sub-components [23]: i) the sense of ownership, which is defined as the feeling of self-attribution of an external object or device. For example, if the user is teleoperating a robotic arm, we will talk about the sense of ownership if the user will experience to own that robotic arm [24]; ii) the sense of agency, namely the feeling of being able to interact with the environment with the manipulated device. Therefore, the sense of agency is characterized by the trust that users put in the fact that their intended actions are mirrored by the controlled device. [25]; and iii) the sense of self-location, which is defined as the volume of space where one feels located. Therefore, the users should be aware of the space in which they teleoperate, they should feel confident of the distance, position and stiffness of objects, and, if possible, in moving around in the remote environment [26]. To evaluate the level of SoE, we adopted the questionnaire from [27]. Participants had to evaluate 10 items, using a Likert scale from 1 to 7. Questions 1-3 measured the sense of ownership, questions 4-6 measures the sense of agency, and questions 7-10 measures the sense of self-location.
- The User Experience (UE): To measure the subjective impression of participants towards the user experience of each control, we adopted the UEQ from [28]. The UEQ is a semantic differential with 26 items, divided in 6 subscales: i) attractiveness: the overall impression of the control (do users like or dislike it? Is it attractive, enjoyable or pleasing?); ii) perspicuity: the easiness of use (is it easy to get familiar with the control? Is it easy to learn? Is the control easy to understand and unambiguous?); iii) efficiency: the perceived quality of the control (can users solve their tasks without unnec-

essary effort? Is the interaction efficient and fast? Does the control react to user input quickly?); iv) dependability: related to the sense of agency and control of the device (does the user feel in control of the interaction? Can he or she predict the system's behavior? Does the user feel confident when working with the product?); v) novelty: since we were comparing three different controls, this set of items helped us in understanding the perceived difference (Is the control innovative and creative? Does it capture the user's attention?); vi) stimulation: how much the participants liked to use the control and the experience in general (is it exciting and motivating to use the product? Is it enjoyable to use?).

Participants had to evaluate each item using a Likert scale from 1 to 7.
The participants had to fill this questionnaire after the use of each control; therefore, each participant had to fill the questionnaire three times during the experiment;

7.2 Results

For the user study, only the significant results are shown. The p-value threshold is set at 0.05. We applied a one-way ANOVA test to test if responses were significantly different between conditions and repeated measure ANOVA within-group; then, we used a post hoc t-test to look more closely at the data, as to do statistics within subjects in the same condition or between subjects comparing just two conditions. Moreover, we applied a Pearson's correlation to verify if there was a correlation between the embodiment components and the user experience questionnaire scales. We applied the Pearson's correlation also to look for a correlation between the user experience scales and the accomplishment time of task 1 and 3. Table 4, 5, and Figures 7.2-7.7 resume the ANOVA test results.
Following, we report the results more in detail. For what concerns the sense of embodiment within-group, we compared separately the sense of ownership, the sense of agency and the sense of self location, for the same time delay with different controls. We did not find significant results, apart from a significant difference in the group 1 (delay 1) for the sense of agency ($F(2, 12) = 5.141$, $p = .0244$) in which the BIC control received the highest scores. Indeed, the post-hoc revealed significant results for the difference between BIC and BICP ($t = 3.3181$, $df = 4.9201$, $p = .02157$, $r = 2.098552$), and in the group 3 (delay 3) for the sense of ownership ($F(2, 12) = 4.214$, $p = .0411$), in which the BIC and the BICP scored equally higher than the BIR. Indeed, we found a significant differences in the post-hoc for the sense of ownership between BIC - BIR ($t = 2.6393$, $df = 7.9631$,

Table 4: Values detected by the ANOVA test within group.

						mean sq
Questionnaire	**Scale**	**Condition**	**p-value**	**df**	**f-value**	**BIC|BICP|BIR**
SoE	Agency	1	.0244	2, 12	5.141	3.86|1.60|2.40
SoE	Ownership	3	.0411	2, 12	4.214	5.05|5.05|3.45
UEQ	Attractiveness	1	.0260	2, 12	5.002	3.35|5.30|4.75
UEQ	Dependability	1	.0310	2, 12	4.731	4.50|5.55|4.85
UEQ	Novelty	1	.001	2, 12	13.220	3.30|5.40|3.75
UEQ	Perspicuity	1	.008	2, 12	7.356	3.90|5.50|3.95
UEQ	Stimulation	1	.0002	2, 12	18.680	3.40|4.55|4.30
UEQ	Attractiveness	2	.0160	2, 12	6.003	3.85|4.95|6.30
UEQ	Attractiveness	3	.009	2, 12	7.102	2.40|3.40|5.50
UEQ	Dependability	3	.008	2, 12	7.282	4.05|4.00|5.40
UEQ	Efficiency	3	.006	2, 12	7.903	4.30|4.00|5.40
UEQ	Novelty	3	.003	2, 12	9.706	2.70|3.30|5.40
UEQ	Perspicuity	3	.039	2, 12	4.287	3.30|4.00|5.65
UEQ	Stimulation	3	.0140	2, 12	6.226	3.32|3.45|4.60

Table 5: Values detected by the ANOVA test between groups.

						mean sq
Questionnaire	**Scale**	**Control**	**p-value**	**df**	**f-value**	**Group1|Group2|Group3**
UEQ	Attractiveness	BICP		2, 12	4.043	5.30|4.95|3.40
UEQ	Dependability	BICP	.0310	2, 12	5.379	5.55|5.30|4.00
UEQ	Novelty	BICP	.001	2, 12	5.594	5.400|4.80|3.30
UEQ	Perspicuity	BICP	.008	2, 12	5.733	5.50|5.75|4.00
UEQ	Stimulation	BICP	.0002	2, 12	4.791	5.50|4.55|4.30
UEQ	Attractiveness	BIR	.0160	2, 12	4.622	4.55|4.35|3.45
UEQ	Efficiency	BIR	.009	2, 12	5.866	4.15|5.15|5.40
UEQ	Novelty	BIR	.008	2, 12	23.050	3.75|5.65|5.40
UEQ	Perspicuity	BIR	.006	2, 12	12.200	3.95|6.10|5.65

p = .02986, r = 1.66925) and BICP - BIR (t = 2.495, df = 7.7825, p = .03802, r = 1.577964).

For what concerns the sense of embodiment between groups, we compared separately the sense of ownership, the sense of agency and the sense of self location,

for the same control dealing with different time delays. We did not find significant results.
For what concerns the User Experience within-group, we compared separately the six scales (Attractiveness, Dependability, Efficiency, Novelty, Perspicuity, and Stimulation), for each of the three controls dealing with the same time delay. In order from group 1 (delay 1) to group 3 (delay 3): i) in the group 1, we found significant differences for all the scales, with the only exception of the Efficiency (F(2, 12) = 3.224, p =.0758), in which the BCIP scored the best and the BIR the worst, indeed we found significant difference with a post-hoc (t = -2.6563, df = 5.3088, p = .04248, r= -1.68). Particularly, for the Attractiveness (F(2, 12) = 5.002, p= .0263), from the post-hoc: BIC - BICP (t = -4.7469, df = 4.1203, p = .008357, r= -3.002221), BIC - BIR (t = -2.8141, df = 7.156, p = .02541, r= -1.779797), BICP - BIR (no significant difference); Dependability (F(2, 12) = 4.731, p= .0306), from the post-hoc: BIC - BICP (t = 2.6888, df = 5.2622, p-value = 0.04116, r= 1.70053), BIC - BIR (no significant difference), BICP - BIR (t = -3.1305, df = 7.824, p = .0144, r= -1.979899); Novelty (F(2, 12) = 13.22, p= .000926), from the post-hoc: BIC - BICP (t = -8.4, df = 7.9491, p = 3.187e-05, r = -5.312626), BIC - BIR (no significant difference), BICP - BIR (t = 5.6595, df = 7.242, p =.0006801, r= -3.579353); Perspicuity (F(2, 12) = 7.356, p= .00822), from the post-hoc: BIC - BICP (t = -2.8174, df = 5.2254, p-value = 0.03544, r= 1.781907), BIC - BIR (no significant difference), BICP - BIR (t = 6.3948, df = 6.4543, p-value = 0.0005144, r= 4.044434); and Stimulation (F(2, 12) = 18.68, p= .000206), from the post-hoc: BIC - BICP (t = -5.9386, df = 6.5693, p = .0007307, r= -3.755884), BIC - BIR (t = -5.0912, df = 7.0822, p = .001364, r= -3.219938), BICP - BIR (no significant difference); to sum up, the BICP got the highest scores, immediately followed by the BIR and finally the BIC. ii) in the group 2, we found significant results just for the Attractiveness scale (F(2, 12) = 6.003, p= .0156), in which the BIR control received the highest score, with detachment; indeed from the post-hoc: BIC - BICP (no significant difference), BIC - BIR (t = -3.6779, df = 4.2795, p-value = 0.01887, r= -2.326092), BICP - BIR (t = 2.3726, df = 4.3877, p = .0709, r= -1.500579). iii) Finally in group 3, we found significant difference for all the scales, particularly, for Attractiveness (F(2, 12) = 7.102, p= .00922), from the post-hoc: BIC - BICP (no significant difference), BIC - BIR (t = -3.9691, df = 7.9891, p = .004135, r= -2.510307), BICP - BIR (t = -2.4391, df = 7.67, p = .04187, r= -1.542648); Dependability (F(2, 12) = 7.282, p= .0085), from the post-hoc: BIC - BICP (no significant difference), BIC - BIR (t = -2.6041, df = 6.5537, p = .03733, r= -1.646985), BICP - BIR (no significant difference); Efficiency (F(2, 12) = 7.903, p= .00646), from the post-hoc: BIC - BICP (no significant difference), BIC - BIR (t = -2.9665, df = 6.4465, p = .02302, r= -1.876166), BICP - BIR (t = -4.3464, df = 7.2344, p = .003117, r= -2.748932); Novelty (F(2, 12) = 9.706, p= .00311), from the post-hoc: BIC - BICP (no significatn differ-

ence), BIC - BIR (t = -4.7361, df = 4.9517, p = .005299, r= -2.995381), BICP - BIR (t = -3.6487, df = 4.9321, p-value = 0.01513, r= -2.307657); Perspicuity (F(2, 12) = 4.287, p= 0.0394), from the post-hoc: BIC - BICP (no significant difference), BIC - BIR (t = -2.7364, df = 7.2909, p = .02794, r= -1.73068), BICP - BIR (no significant difference); and Stimulation (F(2, 12) = 6.226, p= .014), from the post-hoc: BIC - BICP (no significant difference), BIC - BIR (t = -3.4626, df = 7.9926, p-value = 0.008547, r= -2.189955), BICP - BIR (t = -2.7995, df = 7.6471, p-value = 0.02428, r= -1.770541). The BIR control scored always as the highest, followed by the BICP and as last the BIC, with the only exception of the Dependability and Efficiency scales in which the BICP scores the worst.
For what concerns the User Experience between groups, we compared separetely the six scales, for the same control dealing with different time delays. We report, in order, the results for the BIC, BICP and BIR. i) We did not find significant results for the BIC dealing with the 3 different time delays. ii) For what concerns the BICP, we found significant results for all the scales with the only exception of the Efficiency (F(2, 12) = 3.048, p =.0851). Particularly, Attractiveness (F(2, 12) = 4.043, p= .0455), from the post-hoc: BICP1 - BICP2 (no significant difference), BICP1 - BICP3 (t = 2.8324, df = 4.0447, p = .04663, r= 1.791337), BICP2 - BICP3 (no significant difference); Dependability (F(2, 12) = 5.379, p= .0215), from the post-hoc: BICP1 - BICP2 (no significant difference), BICP1 - BICP3 (t = 3.1639, df = 4.7699, p = .02667, r= 2.001041), BICP2 - BICP3 (no significant difference); Novelty (F(2, 12) = 5.594, p= .0192), from the post-hoc: BICP1 - BICP2 (no significant difference), BICP1 - BICP3 (t = 3.6836, df = 4.7691, p = .01549, r= 2.329741), BICP2 - BICP3 (no significant difference); Perspicuity (F(2, 12) = 5.733, p= .0179), from the post-hoc: BICP1 - BICP2 (no significant difference), BICP1 - BICP3 (t = 2.6312, df = 5.215, p = .04459, r= 1.664101), BICP2 - BICP3 (t = 2.6844, df = 7.242, p-value = 0.03036, r= 1.697749); and Stimulation (F(2, 12) = 4.791, p= .0296), from the post-hoc: BICP1 - BICP2 (no significant difference), BICP1 - BICP3 (t = 3.0509, df = 6.0022, p = .02248, r= 1.929528), BICP2 - BICP3 (no significant difference). To sum up, for all the scales the first condition, therefore the one with the lowest delay, was the one in which the scores are higher, with the only exception of the Perspicuity for which the highest scores were collected in the delay 2 condition. iii) Finally, for what concerns the BIR, we did not find significant results for what concerns the Dependability and Stimulation scales, but we found significant results for all the other scales. Indeed, the Attractiveness (F(2, 12) = 4.622, p= .0325), from the post-hoc: BIR1 - BIR2 (t = -4.9961, df = 5.4282, p = .003274, r= -3.159813), BIR1 - BIR3 (no significant difference), BIR2 - BIR3 (, no significant difference); the Efficiency (F(2, 12) = 5.866, p= .0167), from the post-hoc: BIR1 - BIR2 (no significant difference), BIR1 - BIR3 (t = -5.2129, df = 7.639, p-value = 0.0009378, r= -3.296902), BIR2 - BIR3 (no significant differ-

ence); the Novelty (F(2, 12) = 23.05, p= 7.77e-05), from the post-hoc: BIR1 - BIR2 (t = -5.8987, df = 7.9435, p = .0003722, r= -3.730693), BIR1 - BIR3 (t = -5.4622, df = 7.5885, p = .0007185, r= -3.454598), BIR2 - BIR3 (no significant difference); and the Perspicuity (F(2, 12) = 12.2, p= .00128), from the post-hoc: BIR1 - BIR2 (t = -8.6, df = 6.2972, p = .0001043, r= -5.439118), BIR1 - BIR3 (t = -3.2793, df = 4.4713, p = .0259, r= -2.073981), BIR2 - BIR3 (no significant difference). To sum up, the BIR control got the highest scores in the second condition, followed by the third and finally the first.

We also looked for a correlation between the embodiment components and the user experience scales. In group 1 for the BIC control we found a negative correlation between the sense of agency and i) the attractiveness scale (r(3)= -.90, p<.05) and ii) the perspicuity scale (r(3) = -.89, p<.05). For the BICP control, instead, we found a negative correlation between the sense of ownership and the stimulation scale (r(3)= -.92, p<.05). Finally, for the BIR we found a negative correlation between the sense of agency and i) the attractiveness scale (r(3)= -.92, p<.05); and also a positive correlation between the sense of self-location and the perspicuity scale (r(3) = .88, p<.05). In group 2, starting with the BIC control, we found a negative correlation between the sense of ownership and the dependability scale (r(3) = -.95, p<.05); and between the sense of agency and i) the novelty scale (r(3) = -.90, p<.05), the perspicuity scale (r(3) = -.92, p<.05), and the stimulation scale (r(3) = -.87, p<.05). For the BICP control, we found a negative correlation between the sense of agency and i) the attractiveness scale (r(3) = -.89, p<.05) and ii) the novelty scale (r(3) = -.93, p<.05). For the BIR control, we found a positive correlation between the sense of self-location and the perspicuity scale (r(3) = .98, p<.05). Eventually, concerning the group 3, for the BIC control we found a negative correlation between the sense of agency and i) the attractiveness scale (r(3) = -.90, p<.05), and ii) the novelty scale (r(3) = -.91, p<.05). For the BICP, we found a negative correlation between the sense of agency and i) the dependability scale (r(3) = -.91, p<.05), and ii) the efficiency scale (r(3) = -.89, p<.05). Moreover, we found a negative correlation between the sense of self location and i) the attractiveness scale (r(3) = -.87, p<.05), and ii) the dependability scale (r(3) = -.91, p<.05). To conclude, for the BIR we found a negative correlation between i) the dependability scale (r(3) = -.99, p<.05), ii) the efficiency scale (r(3) = -.92, p<.05), iii) the novelty scale (r(3) = -.99, p<.05), and iv) the stimulation scale (r(3) = -.94, p<.05).

Finally, concerning the quantitative data, we did not find significant results, apart from the accomplishment time of the task 1, in the between group condition with the BICP control (F(2, 12) = 7.395, p= .00314), from the post-hoc: BICP1 - BICP2 (no significant difference), BICP1 - BICP3 (t = -3.8973, df = 5.7354, p = .008749, r =-2.464885), BICP2 - BICP3 (t = -2.7573, df = 6.3442, p = .03114, r= -

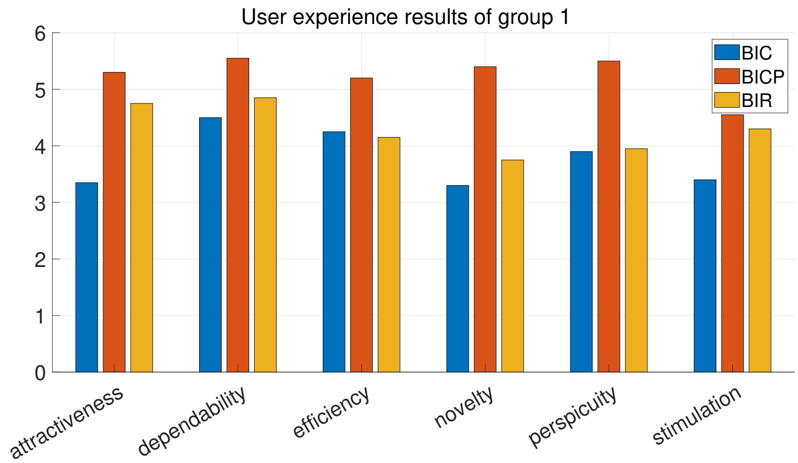


Figure 7.2: Bar graph of the user experience within group 1, with no time delay

1.743865); and for the accomplishment time of the task 3, both in the between group condition for the control BICP (F(2, 12) = 111.7, p= .0084), from the post-hoc: BICP1 - BICP2 (no significant difference), BICP1 - BICP3 (t = -3.4512, df = 4.0463, p = .02555, r= -2.182716), BICP2 - BICP3 (t = -2.8984, df = 4.4993, p = .03837, r= -1.833101); and within-group with the delay 3 (F(2, 12) = 146.8, p= .0029), from the post-hoc BIC - BICP (t = 2.7134, df = 4.3735, p = .04849, r= -1.71608), BIC - BIR (no significant difference), BICP - BIR (t = 2.817, df = 4.4276, p-value = 0.04271, r= 1.781635).

7.3 Discussion

In this subsection the results are discussed, first, the hypotheses are accepted or rejected based, then an overall discussion is done based on all the results.

7.3.1 Hypotheses

The first hypothesis stated that the BICP and BIC controller under zero time delay would show a higher effectiveness than the BIR controller. The hypothesis is partially accepted as the BICP controller has higher UEQ scores compared to the BIR controller but the BIC controller not in this case. This can be explained by the passivity bounds of the passivity layer. The BIC controller tended to behave unstable even when there is no delay present, this is caused by the realtimeness of the simulation, which was not always sufficient. The passivity layer reacted to the unstable behaviour where the BIC did not.

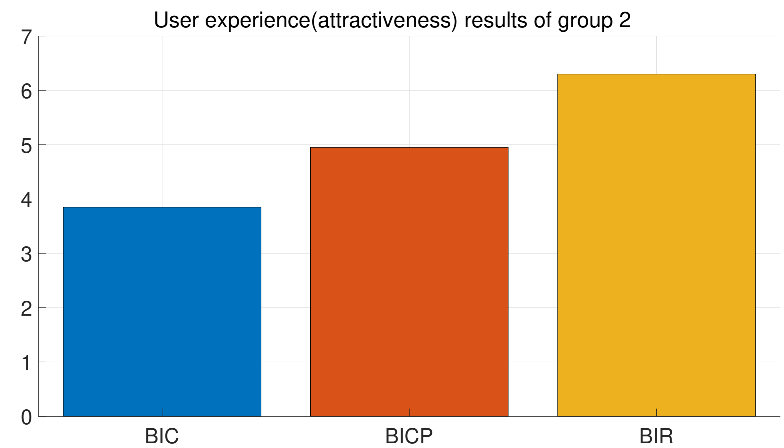


Figure 7.3: Bar graph of the user experience within group 2, only the attractiveness is shown as this is the only significant result, with 2 ms delay for the BIC and 10 ms for the BICP and BIR

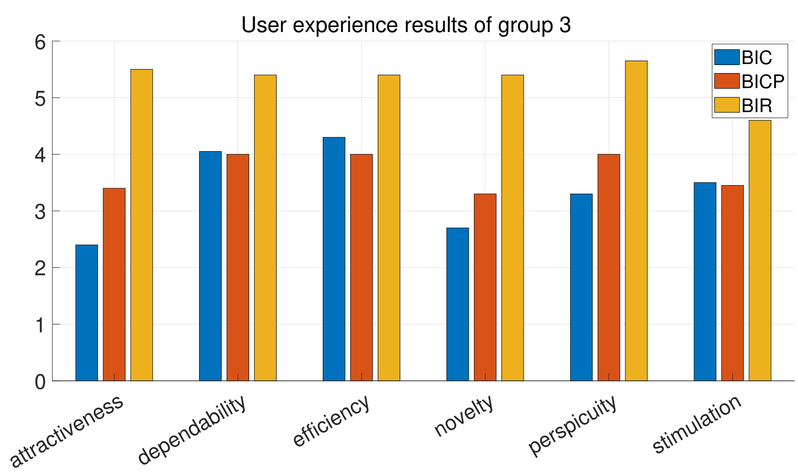


Figure 7.4: Bar graph of the user experience within group 3, with 5 ms delay for the BIC and 20 ms for the BICP and BIR

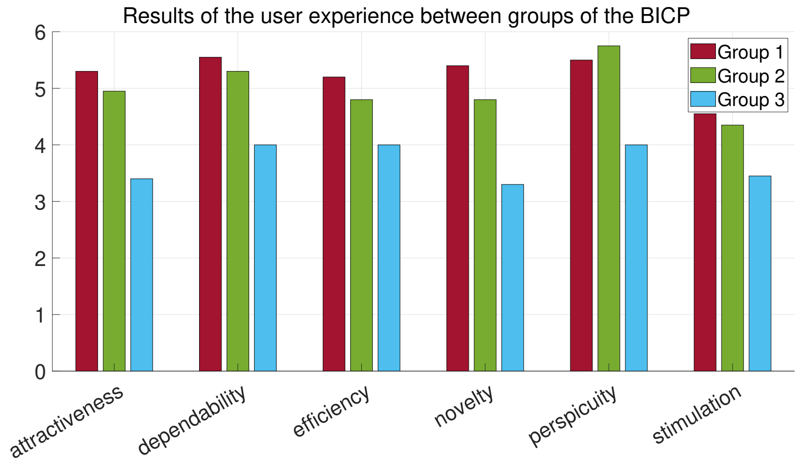


Figure 7.5: Bar graph of the user experience between groups of the BICP controller, where group 1 has no delay, group 2 has 10 ms delay and group 3 has 20 ms delay

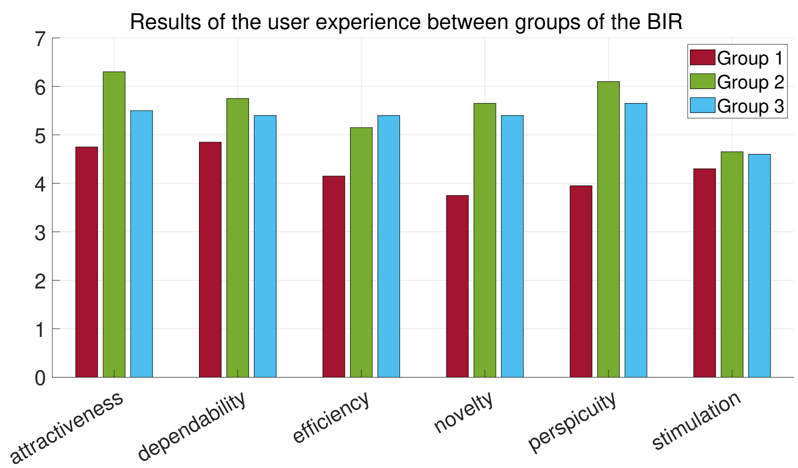


Figure 7.6: Bar graph of the user experience between groups of the BIR controller, where group 1 has no delay, group 2 has 10 ms delay and group 3 has 20 ms delay

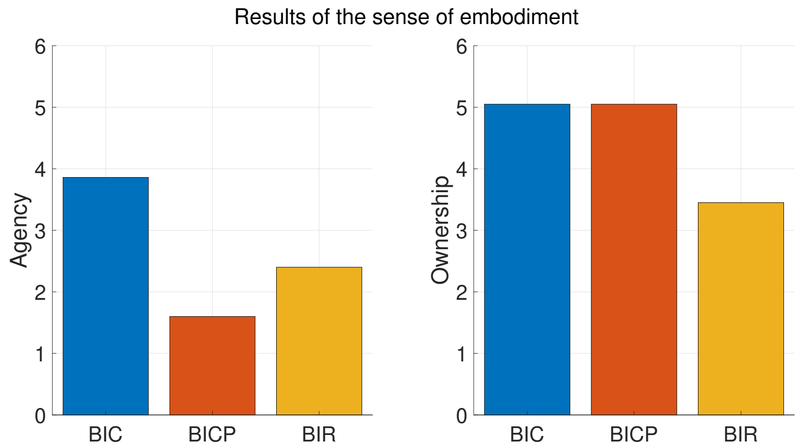


Figure 7.7: Bar graphs of the sense of embodiment, the left plot is of group 1, the right plot is of group 3

The second hypotheses was accepted. It states that the BIR controller results in a higher effectiveness when time delays are present in the system and the results from the UEQ confirm it.
The third hypothesis is that the effectiveness of every controller decreases when the time delay increases. This hypothesis is partially accepted. The BIC controller's performance is consistently lower than the BICP and BIR and in this case did not show significant difference between groups for the UEQ, meaning that the user experience was the same for all delays. For the BICP controller, the UEQ scores decreased when the time delay increased. For the BIR controller, the UEQ is significantly lower than the BICP controller in group 1. As the BICP behaved better when no time delay was present. However, when time delays are present, the UEQ scores decrease when this delay increases, which is expected due to the increased influence of the time delay in the system.

7.3.2 Overall discussion user study

Considering the condition in which the experiment sessions were realized, we reduced our expectations about the evidence that we would have found for the Sense of Embodiment. This is due to two main reasons: 1) instead of manipulating the physical KUKA arm as originally planned, the participants had to telemanipulate in simulation without VR, therefore just looking at a screen; 2) the set-up did not contribute to create an immersive experience, since the participant were accomplishing the tasks in a house, instead of a more formal environment, such as a lab.

Starting from the SoE evaluation within-group, we did not find many significant results, apart from the observation that BIR got the lowest scores in all condition, especially for the sense of ownership and agency. This result was expected since, due to simulation, the friction in the internal joint of the robotic manipulator of the KUKA arm was low. It was noticed that the EMG signals were overall relatively low. Therefore, with these low EMG signals, the impedance of the slave controller is relatively low, resulting in spring like behaviour, causing overshoot. This feels less transparent for the operator. Between groups, instead, we did not find significant results. Probably because different participants experienced the same control in different time delays, but the same participant had to compare it with the other controls, therefore this within-group comparison overlapped the between group ones.
For what concerns the User Experience, it was interesting to observe that the participants perceived a difference both among controls with the same time delay and with the same control among different time delays. Particularly within-group, i) in group 1, the BICP was the best evaluated control in all the scales, this is probably due to the fact that it was considered more stable with respect to the BIC and it gave more sense of agency with respect to the BIR, indeed we also found a negative correlation between the sense of agency and the BIR control in the first condition. This can be explained, again, by the low friction in the model in combination with the low EMG signals. ii) In group two, the BIR scored significantly higher in attractiveness scale. Therefore, the participants found it more pleasant to use, probably because they started to feel the instability with the other two controls. iii) This was more evident in the results from group 3, where the BIR got the highest scores, with significant difference, for all the scales. Between group, i) we did not find significant results for the BIC control, probably because it did not get high score in all of the conditions, since the other controls were always better experienced. ii) The BICP control got the highest scores in the first group, and then the scores started to be lower with the increment of the delay. Indeed, iii) the BIR got the highest scores in the second condition, followed by the third and finally the first. The reason why it did not get the highest scores in the third condition, can be explained by the fact that in the group 3 was the one who dealt with the worst delay condition, so all the controls got lowest scores with respect to the other two groups conditions.
We also looked for correlations between the SoE components and the control in the different delay conditions. i) Starting from the first condition, the BIC control resulted in a negative correlation between the sense of agency and the attractiveness and perspicuity scale, therefore the participants could perceive

more freedom in the movement but at the same time they experienced the control as less pleasant and easy to use. The BICP control got a negative correlation between the sense of ownership and the stimulation scale, this means that, even if the participants could not really experience the sense of ownership, they appreciated the task performance of the control, they found it motivating and valuable. For the BIR control, we found a negative correlation between the sense of agency and the attractiveness, for the reasons already explained before. We also found a positive correlation between the sense of self-location and the perspicuity, probably because they found that the tasks, especially because they required precision, were easier to accomplish with this control, since the control is easy to use and less complex to understand how to deal with it. ii) In the second delay condition, the BIC control resulted in a negative correlation between the sense of ownership and the dependability scale, this is because even if they felt more in involved in the control of the arm, they felt it as unstable, unpredictable and less secure. We also found a negative correlation between the sense of agency and three UE scales: the novelty, the perspicuity and the stimulation. The reason behind these results are the same explained before. Indeed, more and more we increase the delay, the quality of the BIC control experience get worse. Concerning the BICP control, we found a negative correlation between the sense of agency and two UE scales: the attractiveness and the novelty. Indeed, as explained before, the participants felt a highest sense of agency but the experience got worse with the increased delay. For the BIR we just found a positive correlation, again, between the sense of self-location and the perspicuity scale, for the reason explained before. Eventually, iii) in the third and highest delay condition, for the BIC control we found a negative correlation between the sense of agency and the attractiveness, and novelty scale. Eventually, concerning group 3, the negative correlation starts to increase for all the controls both quantitative and qualitative. But, if for the BIC and BICP control the SoE gets higher while the UE gets lower, for the BIR the relation is the opposite.

We did not find significant results for what concerns the accomplishment time, the reaction time and the proprioceptive drift. Even if, the accomplishment time of the tasks 1 and 3 were on average always better with the BIR control. Therefore, since we found significant results for what concerns the user experience, we can deduce that the cognitive workload was high for the participants. This means that they were able to deal with the tasks quantitative speaking, but qualitative speaking they noticed the difference.

8 Conclusion and recommendations

8.1 Conclusion

At the I-botics centre, founded by TNO and the University of Twente a project is carried out focused on telerobotics. By the use of haptic feedback the operator can exactly feel what it is doing and can respond to unpredictable situations. However, due to the physical distances between the master and slave device, time delays occur in the system. These time delays cause instabilities in the system, which lowers the transparency. Numerous controllers are designed to compensate for this behaviour, but mostly this is a trade-off between transparency and stability or no backdrivability is insured. Further, literature showed us that no comprehensive user study is done of the effectiveness of different controllers

In this thesis, a new impedance reflection technique is designed based on the work of Hannaford. A comprehensive analysis is done of the estimation methods of the environment and operator as well as a trajectory predictor. Based on the analysis a new system is designed and implemented on a simulation. A technical performance is done to check if the system works as desired.

It was desired that the system behaves transparent and stable above 10 milliseconds, as this was the case with the passivity layers. The performance evaluation showed that the system works up to a delay of 50 milliseconds. With almost no position and force error between the master and slave.

A comprehensive user study is done to test the user effectiveness. This showed us that with the sense of embodiment en quantitative results no significant result could be found. However, looking at the user experience the study showed that the classical impedance control with passivity layers is better when no time delays are present. With higher time delays are present in the system, the newly proposed scheme showed better results on all scales of the user experience.

Overall it can be shown that the bi-directional impedance reflection technique has a better performance and user experience when dealing with time delays.

8.2 Recommendations

Based on the technical performance and the user study some recommendations are made to improve the current system.

8.2.1 Reliability EMG signals

During the user studies, it was noticed that the reliability of the EMG signal was different depending on each person. On the start of an experiment, an EMG calibration task was performed to measure the maximum and minimum EMG signal of a person. During the experiment itself, it could be seen that the EMG signal rarely reached the maximum signals measured. Meaning that overall the impedance of the slave controller was relatively low. This results in less sense of rigid objects, as less forces are felt by the user when touching objects. Also due to a low spring constant, overshoot occurred.

It is recommended to change the way the EMG signals are measured. This can be done by changing the calibration method, which gives a more accurate maximum and minimum EMG signal when controlling the robotic device. Another method could be to change the hardware, as the myo does not give the exact EMG signal, but a unit less estimation of the human co-contraction levels. Or a new improved method of human impedance estimation can be done.

8.2.2 Improved operator models

As the controller was designed for a real manipulator, a simple spring constant was used to model the operator at the slave side. This was done as the joint friction was high, so another addition of joint damping was not necessary. As in the simulation the friction is minimized to measure the external forces. Damping should be added to overcome the problems of overshoot in the system. This is a partial solution for the problem described in the section above.

8.2.3 Improved trajectory predictor

The trajectory predictor showed with high impedance's that oscillation occurred when dealing with time delays of 50 ms or higher. This could be solved by adding extra damping to the system. As adding unnecessary damping is undesired in teleoperation, a more complicated trajectory predictor could be designed.

8.2.4 Performance and user study on a real telemanipulation setup

The main goal of this thesis was the design of the newly proposed impedance reflection technique in combination with a user study. Where the performance evaluation and the user study would be done on a real robotic device in a teleoperation cockpit. Due to COVID-19, this was unfortunately not possible. It is expected that the results of the newly proposed system are much better on the

real manipulator.
The main reason is the friction in the slave manipulator. A big advantage of the impedance reflection technique, aside from the time delay problem, was that the friction in the system will not be felt by the operator, as only the external forces are measured.
In the simulation this friction was totally removed to solve the problem of the external force measurement. This reduces the difference between the controllers significantly.

Extra: Accurate force sensing(more for information, not really results visible of this in this attachment)

This recommendation is done based on the real setup of the telemanipulation setup. The external force measurement was done by using the internal joint torque sensors of the Franka Emika robot. Internally the Franka software filtered these torques, which resulted in the external forces applied on the robotic device. These had an offset of 4 newton, meaning that estimation of low impedance's could not be done. It is proposed to add a torque sensor at the end-effector in combination with the internal torque sensors to measure the external exerted force on the system. This has the advantage that precise impedance reflection can be done, but also external forces on different parts of the robotic manipulator can be felt by the operator.

Appendix

A Extra results performance evaluation

This section shows the extra results of the performance evaluation.

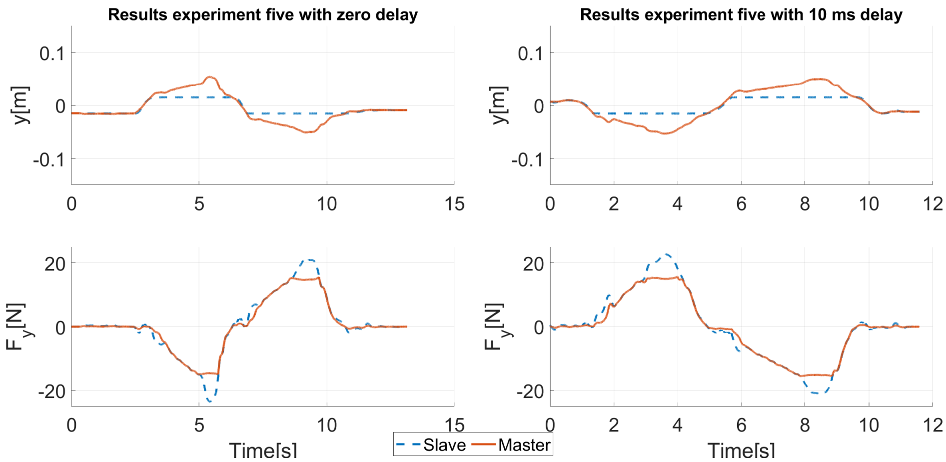


Figure 8.1: Results of experiment five with high stiffness in the left column zero time delay is present in the right column 10 ms of time delay is present

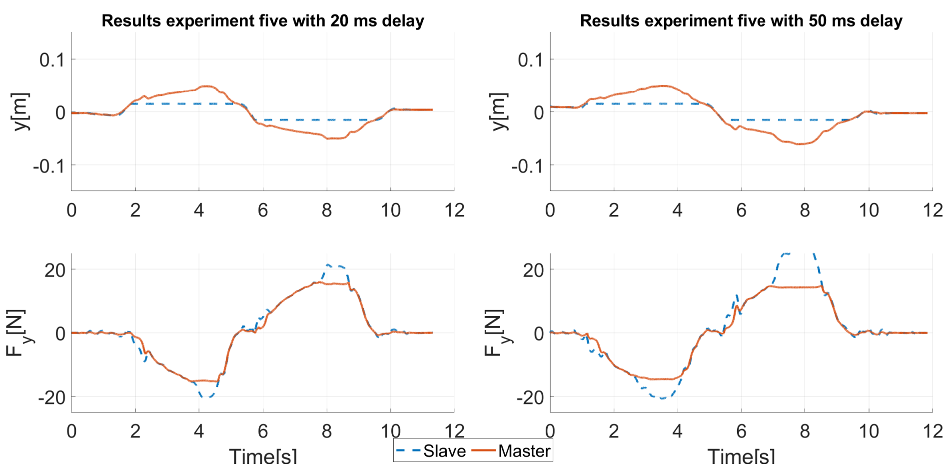


Figure 8.2: Results of experiment five with high stiffness in the left column 20 time delay is present in the right column 50 ms of time delay is present

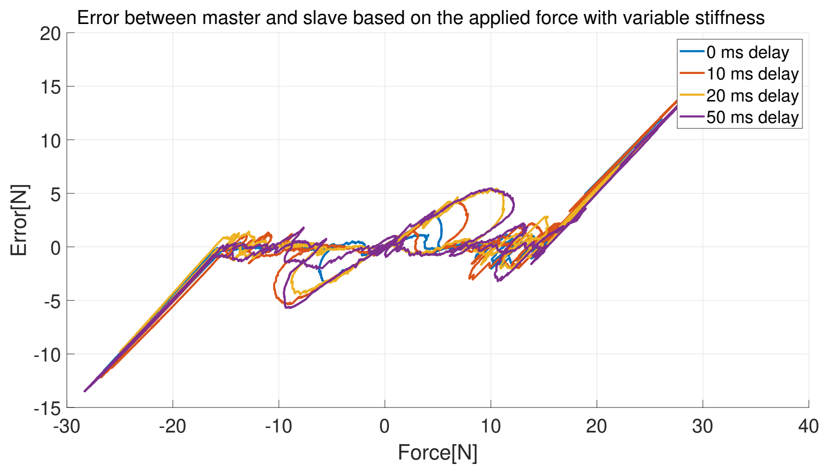


Figure 8.3: Error plot between the forces of the master and slave of experiment five with variable stiffness

B Extra figures user study

This section shows the extra figures of the user study

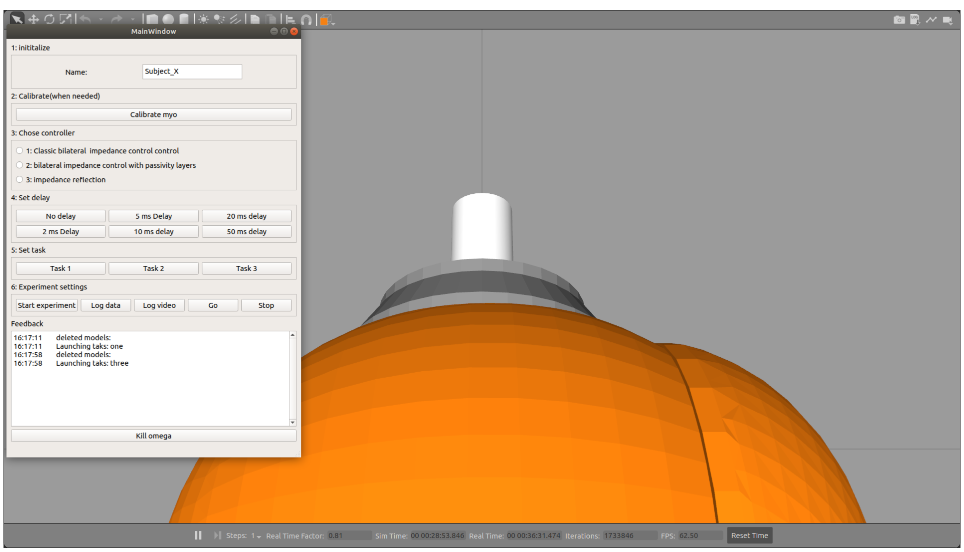


Figure 8.4: User study in combination with the GUI

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