Application of the IMPACT structure on bilateral teleoperation

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DC 2010.053

Bachelor Final Project

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September 16, 2010
Abstract

Teleoperation systems are expected to play an important role in daily healthcare and wellness applications. Time-delays typically cause stability and performance problems in these systems. As a remedy for such problems in position-error based bilateral teleoperations, a control algorithm is proposed which is derived as a robust modification of a Smith predictor structure for time-delay compensation. The considered modification is based on an application of the Internal model principle an control together (IMPACT). The resulting algorithm allows rejection of disturbances from a known class that act at the output of the slave side of the teleoperated system. To build this structure for a certain teleoperation system, the dynamics of both master and slave manipulator need to be known. The mass moments of inertia en viscous friction coefficients of both master and slave manipulators are required to build this structure for a certain teleoperation system.

The parameters of the master and slave manipulators, i.e. the mass moments of inertia and viscous friction coefficients, which are required to design suitable local controllers are obtained by means of frequency response function measurements.

Simulations have been performed on the test-setup. The outcome of the simulations was that the reference can be followed reasonably well and most of the disturbance is absorbed fast. Besides that, the steady-state value of the output remains the same with and without the disturbances applied. In all cases, smaller values for the controller parameters $n$, $T_0$ and $\varepsilon$ can be selected to improve the control performance, however at the cost of decreasing the robustness property.

Eventually, some experiments are done on the real-time test-setup. These experiments are done for both a control structure with and without the IMPACT structure and disturbance absorber. For the control structure with the IMPACT structure and disturbance absorber, the steady-state output remains the same as the reference, in contrary to the structure without the IMPACT structure and disturbance absorber. Furthermore, the offset in the error is removed.

To improve the experiments, better tracking is needed. This can partly be obtained by adding a Coulomb-friction compensator, which is also investigated in experiments and has positive effect on the error. Besides that, different disturbance estimators can have a positive effect on the tracking as well by absorbing the noise better.
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Chapter 1

Introduction

Bilateral teleoperation is becoming more important nowadays. Therefore the research field of it improved a lot the past five decades [1]. The rising popularity of bilateral teleoperations lies in the accuracy and possibility to control it from everywhere. Human operators are not able to perform specific tasks with high accuracy, which is often required like in minimally invasive surgery (see figure 1.1), nuclear waste disposal, explosive devices detonation and manipulation of an object. A controlled manipulator on the other hand, can be able to accomplish such tasks.

In teleoperations, a manipulator located at a remote environment performs an intended task. This manipulator is controlled by a human operator who is at some remote location [2]. The operator’s commands are sent to the manipulator through a communication channel. In the case of bilateral teleoperations, sensor data from the controlled manipulator (the slave) are sent back to the operator through the same or another communication channel.

In teleoperated systems, it is common to encounter time-delayed responses of the slave manipulator to the operator commands due to their communication at a distance. The slave may respond with delays to the operator’s commands; besides that, sensory information from the slave can also be delayed, which can lead to delayed corrective actions of the operator with respect to the actual state of the slave. In both situations, delays can either be constant or time-varying, depending on the type of communication protocol, and they can drastically reduce the performance of teleoperations or even destabilize the whole system [3]. A popular strategy to time-delay compensation is the application of Smith predictors in the control structure [4]. The main purpose of the Smith predictor is to render the control system dead-time free.

There are some issues related to the Smith predictor type control architectures, like limited robustness and disturbance rejection capabilities [5]. Due to these issues, a new control architecture is proposed to improve robustness and performance of disturbance rejection of systems with Smith predictors. This architecture utilizes the internal model principle and control together (IMPACT) approach [7], as a way to combine the internal model principle (IMP) and internal model control (IMC). The former IMP is used to cope with the disturbances that affect the plant, and is known as the absorption principle. The later IMC includes a nominal model of the plant in the controller structure in order to incorporate modeling un-
certainty into the control system. The IMPACT structure provides a systematic and intuitive way to separate the problems of predictor design and the disturbance rejection.

There exist different types of control architectures in bilateral teleoperation systems. These can be categorized based on the exchanged sensory information between the master and slave manipulators. Among these, the most common are position error (PERR) based, force error based and 4-channel control architectures.

In this report, a Smith predictor type control architecture, suitable for PERR based bilateral teleoperations [8] is analyzed and experimentally evaluated. This architecture encompasses advantages of the IMPACT approach where the slave manipulator performs free motion.

The report proceeds as follows. Bilateral teleoperation, the theory of the Smith predictor and the IMPACT structure are introduced in Chapter 2. In Chapter 3, the proposed time-delay compensation for the PERR based teleoperations using the Smith predictor structure and an application of the IMPACT approach [8] are described. The test-base is described in Chapter 4, followed by the frequency response function in Chapter 5. Illustrative simulation on the Pizza-Robot are given in Chapter 6 and the experiments and their outcomes in Chapter 7. Conclusion and possible future research directions are discussed in Chapter 8.
Chapter 2

Theoretical background

2.1 Bilateral teleoperation

Teleoperated systems are becoming a popular technique for certain procedures. Teleoperation extends the human capability to manipulating objects remotely by providing the operator with similar conditions as those at the remote location (see figure [2.1]). This is achieved via installing a similar manipulator joystick, called the master, at the human’s side that provides motion commands to the slave which is performing the actual task.

In a general setting, the human imposes a force on the master manipulator which in turn results in a displacement that is transmitted to the slave that mimics that movement [1]. If the slave possess force sensors, then it can transmit or reflect back to the master reaction forces from the task being performed, which enters into the input torque of the master, and the teleoperator is said to be controlled bilateral. Although reflecting the encountered forces back to the human operator enables the human to rely on tactile senses along with visual senses, it may cause instability in the system if delays are present in the communication channel. Another problem when designing a controller for master-slave systems, is the enormous change in the environmental properties [9]. This means that the controller should be robust against changes in the remote environment system.

Figure 2.1: Bilateral teleoperation
2.2 Smith predictor for time-delayed teleoperations

The problem of constructing control algorithms that are capable of handling time-delay is a key issue in process control, due to the large number of processes which possess time-delay. A control methodology for time delayed plants is motivated by the pioneer work of O.J.M. Smith (1957), who developed the Smith predictor. In this methodology the plant model is utilized to predict the non-delayed output of the plant and move the delay out of the control loop.

The classical Smith predictor is shown in figure 2.2 with transfer function $G_m(s)e^{-T_ds}$. The Smith predictor simulates the difference between the deadtime-free part of the process model and the (delayed) process model. This corrective signal is added to the measured output signal to predict what the output would have been if there were no time-delays [4]. The prediction $q^*$ is fed to the controller $K_m(s)$. A straightforward calculation gives the closed-loop transfer function

$$\frac{Q_s(s)}{Q_{ref}(s)} = \frac{K_m(s)G_m(s)}{1 + K_m(s)G_m(s)}e^{-T_ds}$$

The form of the closed-loop transfer function as well as the interpretation of the feedback signal $q^*$ indicate that the parametrization of the controller should be chosen in accordance with the deadtime-free part of the model $G_m(s)$.

Figure 2.2: Classical Smith predictor structure

The Smith predictor control concept was originally designed for a single-input/output (SISO) controlled plant, input disturbances and a controller that receives the delayed plant output, as shown in figure 2.3.

In order to use the Smith predictor concept in teleoperations, as shown in figure 2.4, the notation needs to be modified to include the master robot, slave robot and the environment. Here $V_h$, $V_e$, $F_h$ and $F_e$ are the Laplace transforms of velocity and forces of the master and slave, respectively. Restructuring the teloperation system of figure 2.3 to fit the block diagram design of the SISO system in figure 2.5 requires that the operator provides the input for the system. The master robot acts as the controller, which sends information through the communication channel. The slave robot and the environment are then considered as the "plant", whose combined dynamics are used in the Smith predictor. This results in the same system without delay in the control loop, see figure 2.6.
Figure 2.3: General SISO control system scheme

Figure 2.4: Teleoperation scheme

Figure 2.5: SISO control system with a Smith predictor in the control loop scheme

Figure 2.6: The resulting SISO system scheme using a Smith predictor with $\tilde{G}_m = G_m$
2.3 The IMPACT structure

Delays cause systems to destabilize or degrade their feedback performance. The Smith predictor is a solution to this problem and is used to improve this performance. Nevertheless, it is pointed out that the Smith predictor is very sensitive to modeling errors. The most sensitive parameters are the time delay and the steady-state gain of the process. Although the Smith predictor has the capability of transforming a time-delay control design to a delay-free problem, three principal problems of the Smith predictor structure occurs: (1) the robustness; (2) the disturbance rejection characteristics, and (3) the extension of the idea of the Smith predictor to the case of systems with integrators. An effective answer to these issues is based on the Internal model principle and control together (IMPACT) structure. The proposed structure can be interpreted as a new structure of the modified Smith predictor for processes that can be described by an integrator, a velocity gain, and a long effective transport lag. The structure enables absorption of the arbitrary class of deterministic disturbances and can easily be tuned to achieve the desired set-point response to maintain the preferred system robustness with respect to interval changes and/or uncertainties of plant parameters [5].

The IMPACT structure constructively achieves both the robust stability and absorption of external disturbances. In the structure design (see figure 2.7), the absorption principle is applied to enable the rejection of arbitrary class of deterministic disturbances and/or to suppress the effects of low frequency stochastic external signals on the system output [6]. The structure enables absorption of general class of disturbances and can easily be tuned to achieve the desired speed of set-point response and to maintain the preferred system robustness with respect to interval changes and/or uncertainties of plant parameters.

Figure 2.7: IMPACT structure of the modified Smith predictor with one-input internal nominal plant model
Chapter 3

Application of IMPACT structure on bilateral teleoperation

3.1 Position error based teleoperations

In the simplest bilateral teleoperation architecture, shown in figure 3.1, only the position information is exchanged between the master and slave manipulator [2]. In the given figure, $G_m(s)$ and $G_s(s)$ denote the master and slave manipulators, respectively. The local controls to the master and slave manipulators are given by

\[
U_m(s) = K_m(s)(Q_{\text{ref}}(s) - Q_m(s)) + K_m(s)(Q_s(s)e^{-T_d s} - Q_m(s)) 
\]

\[
U_s(s) = K_s(s)(Q_m(s)e^{-T_d s} - Q_s(s))
\]

where $K_m(s)$ and $K_s(s)$ are the local controllers for the master and slave manipulators, $Q_m(s)$ is the position of the master, $Q_s(s)$ is the slave position, and $T_d$ represents the time delay in the communication channel.

Figure 3.1: Position error based teleoperation scheme

The master manipulator is commanded to track the position reference $Q_{\text{ref}}(s)$ given by a human operator. The slave manipulator is also commanded to track the same reference...
trajectory, since the master and slave are coupled. An equivalent representation of the scheme shown in figure 3.1 is given in figure 3.2. In that figure, \( G_{d}^{scl}(s) \) denotes equivalent plant, where 'd' refers to delayed and 'scl' refers to closed-loop at the slave side of the telemanipulation system.

Figure 3.2: Position error based teleoperation scheme redrawn

In this work, single degree-of-freedom manipulators are considered at the master and slave sides. The dynamics of these manipulators in time domain, that apply as they conduct free motions, are given by

\[
\begin{align*}
J_m \ddot{q}_m + B_m \dot{q}_m &= u_m \\
J_s \ddot{q}_s + B_s \dot{q}_s &= u_s
\end{align*}
\]

where \( J_m, B_m \) and \( J_s, B_s \) are the mass moments of inertia and the viscous friction coefficients of the master and slave manipulators respectively, while \( u_m \) and \( u_s \) are the input torques. From (3.3) and (3.4), the transfer functions of the two manipulators can be determined as:

\[
\begin{align*}
G_m(s) &= \frac{Q_m(s)}{U_m(s)} = \frac{1}{J_m s^2 + B_m s} \\
G_s(s) &= \frac{Q_s(s)}{U_s(s)} = \frac{1}{J_s s^2 + B_s s}
\end{align*}
\]

3.2 Control structure

The proposed IMPACT structure which is suitable for the considered PERR teleoperation problem is shown in figure 3.3. Here, \( D \) denotes a disturbance at the slave side of the telemanipulation system, such as undesired vibrations acting at the output of the slave manipulator. This structure implements a Smith predictor at the master side, while the slave side \( \tilde{G}_{d}^{scl} \) is the internal nominal plant model and \( A(s)/C(s) \) is a transfer function representing an internal model of disturbance. The difference between the outputs of the actual and nominal plants are filtered by the transfer function \((1/R(s))(A(s)/C(s))\). The resulting signal \( \hat{D} \) is the disturbance estimator [8]. The nominal plant model is given by

\[
\hat{G}_{d}^{scl}(s) = \frac{K_s(s)\hat{G}_s(s)}{1 + K_s(s)\hat{G}_s(s)} e^{-2Ls}
\]

where \( \hat{G}_s(s) \) is the nominal plant model of the slave manipulator and \( L \) is the nominal time-delay in a single direction of the communication channel. In reality, this delay may be time-varying.
In the proposed control design, the nominal time-delay is considered to be constant, known and the same for both forward and backward directions; it can be determined by practical measurements, as an average of the actual time-delays. The actual plant is given by

\[ G_{\text{act}}(s) = \frac{K_s(s)G_s(s)}{1 + K_s(s)G_s(s)} e^{-T_d s} \]  

where \( G_s(s) \) represents the actual transfer function of the slave manipulator.

### 3.3 Controller design

The local feedback controllers \( K_m(s) \) and \( K_s(s) \) for the master and slave manipulators, respectively, are designed based on the inverse plant model [4]

\[ K_m(s) = \frac{1}{W(s) - 1} \frac{1}{G_m(s)} \]  

\[ K_s(s) = \frac{1}{W(s) - 1} \frac{1}{G_s(s)} \]

where \( G_m(s) \) and \( G_s(s) \) are the nominal models of the master and slave manipulators and \( W(s) \) is a characteristic polynomial describing the desired location of the closed-loop poles for the local feedback loops at the master and slave sides

\[ W(s) = (\varepsilon s + 1)^r. \]

Here, \( \varepsilon > 0 \) and \( r \) is the relative order of the nominal models of the master and slave manipulators. This polynomial is selected in order to keep the number of tuning parameters as low as possible. The dynamics of the master and slave manipulators are assumed to be known and given by

\[ \tilde{G}_m(s) = \frac{1}{J_{mn}s^2 + B_{mn}s} \]  

\[ \tilde{G}_s(s) = \frac{1}{J_{sn}s^2 + B_{sn}s} \]
where $J_{mn}$, $J_{sn}$, $B_{mn}$, and $B_{sn}$ are the nominal model parameters that are determined, for instance, using system identification. For the manipulator dynamics of the second order, $r$ equals to 2 in (3.11). In addition to the feedback controllers (3.9) and (3.10), the tracking performance can be improved by adding of the feedforward terms related to the velocity and acceleration profiles of the reference trajectory for the master manipulator. From (3.7), (3.10) and (3.11), the nominal plant model is given by

$$\tilde{G}_{scl}(s) = \frac{1}{(\varepsilon s + 1)^2 e^{-2Ls}}.$$  \hspace{1cm} (3.14)

The closed-loop transfer function, based on the nominal plant, between inputs $Q_{d \text{ref}}(s)$ and $D(s)$ and the output $Q_s(s)$ is:

$$\frac{Q_s(s)}{Q_{d \text{ref}}(s)} = \frac{K_m \tilde{G}_m K_s \tilde{G}_s}{1 + K_s \tilde{G}_s + K_m \tilde{G}_m K_s \tilde{G}_s + 2K_m \tilde{G}_m},$$  \hspace{1cm} (3.15)

$$\frac{Q_s(s)}{D(s)} = \left(1 + \frac{K_m \tilde{G}_m K_s \tilde{G}_s e^{-2Ls}}{1 + K_s \tilde{G}_s + K_m \tilde{G}_m K_s \tilde{G}_s + 2K_m \tilde{G}_m} \right) \left(\frac{1}{1 + K_s \tilde{G}_s} \right) \left(1 - \frac{A}{R C} \frac{K_s \tilde{G}_s}{1 + K_s \tilde{G}_s} e^{-2Ls} \right).$$  \hspace{1cm} (3.16)

where $Q_{d \text{ref}}(s) = Q_{\text{ref}}(s) e^{-Ls}$ represents the delayed reference signal. The Laplace variable is omitted for brevity. The nominal master and slave models are given by (3.12) and (3.13). When (3.9), (3.10) and (3.11) are substituted into (3.15) and (3.16), the following is obtained

$$\frac{Q_s(s)}{Q_{d \text{ref}}(s)} = \frac{1}{\varepsilon s^4 + 4\varepsilon^3 s^3 + 7\varepsilon^2 s^2 + 6\varepsilon s + 1}$$  \hspace{1cm} (3.17)

and

$$\frac{Q_s(s)}{D(s)} = \left(1 + \frac{e^{-2Ls}}{\varepsilon s^4 + 4\varepsilon^3 s^3 + 7\varepsilon^2 s^2 + 6\varepsilon s + 1} \right) \left(\frac{\varepsilon s (\varepsilon s + 2)}{(\varepsilon s + 1)^2} \right) \left(1 - \frac{A(s)}{R(s) C(s) (\varepsilon s + 1)^2} \right).$$  \hspace{1cm} (3.18)

The stability of the closed-loop system described by the transfer function (3.17) can be evaluated using the Routh’s stability criterion [10]. The first column in the table below gives a tabular overview of conditions that have to be satisfied in order to guarantee stability. Since

| $s^4$ | $\varepsilon^4$ | $7\varepsilon^2$ | 1 |
| $s^3$ | $4\varepsilon^3$ | 6$\varepsilon$ | 0 |
| $s^2$ | $12\varepsilon^2$ | $7\varepsilon$ | 1 |
| $s^1$ | $\frac{11\varepsilon^2}{11\varepsilon}$ | \frac{7\varepsilon}{11\varepsilon} | 1 |
| $s^0$ | 1 | 1 | 1 |

Table 3.1: Routh-Hurwitz Table
by definition $\varepsilon > 0$, all the elements in the first column are positive, which according to the Routh criterion implies that the poles of the closed-loop are all in the left half of the complex plane.

By applying the final value theorem\footnote{The final value theorem allows the evaluation of the steady-state value of a time function from its Laplace transform: $\lim_{t \to \infty} x(t) = \lim_{s \to 0} sX(s)$} to equation (3.18), it can be shown that the effect of the disturbance $D$ on the steady-state motion of the slave manipulator diminishes if

$$
\lim_{s \to 0} s \left( 1 + \frac{\varepsilon^{-2Ls}}{\varepsilon^4s^4 + 4\varepsilon^3s^3 + 7\varepsilon^2s^2 + 6\varepsilon s + 1} \right) s \left( \varepsilon s(\varepsilon s + 2) \right) \left( 1 - \frac{A(s)}{R(s)C(s)(\varepsilon s + 1)^2} \right) D(s) = 0.
$$

(3.19)

Since

$$
\lim_{s \to 0} \left( 1 + \frac{\varepsilon^{-2Ls}}{\varepsilon^4s^4 + 4\varepsilon^3s^3 + 7\varepsilon^2s^2 + 6\varepsilon s + 1} \right) = 2,
$$

(3.20)

and

$$
\lim_{s \to 0} \frac{\varepsilon s(\varepsilon s + 2)}{(\varepsilon s + 1)^2} = 2\varepsilon,
$$

(3.21)

to have (3.19) achieved, the following should hold:

$$
\lim_{s \to 0} s^2 \left( 1 - \frac{A(s)}{R(s)C(s)(\varepsilon s + 1)^2} \right) D(s) = 0.
$$

(3.22)

The polynomial $A(s)$ can be selected as any stable polynomial. Here it is selected as

$$
A(s) = (\varepsilon s + 1)^2 A_0(s),
$$

(3.23)

where $A_0(s)$ is a polynomial which is determined based on disturbance. To guarantee stability of the disturbance estimator, polynomials $R(s)$ and $C(s)$ should have stable roots. A simple way to select $R(s)$ and $C(s)$, which decreases the number adjustable parameters, is proposed in [6]:

$$
R(s) = 1,
$$

(3.24)

$$
C(s) = (T_0 s + 1)^n,
$$

(3.25)

where $T_0$ is a time constant and $n$ is an order of the filter. The design parameters $T_0$ and $n$ determine the speed of the disturbance absorption process. The disturbance is absorbed more quickly if lower values are selected for $T_0$ and $n$. For the particular choice of (3.23), (3.24) and (3.25), condition (3.22) can be rewritten as:

$$
\lim_{s \to 0} s^2 (C(s) - A_0(s)e^{-2Ls}) D(s) = 0.
$$

(3.26)

It can be realized from (3.26) that the absorption of a step disturbance (i.e. $D(s) = 1/s$) can be achieved for any $A_0(s)$ and $C(s)$. For a class of polynomial disturbances $d(t) = \sum_{i=0}^{m} d_i t^i$, after application of the L’Hôpital rule, we can uniquely determine the polynomial $A_0(s)$ using the following expression,

$$
\lim_{s \to 0} \frac{d^k}{ds^k} (C(s) - A_0(s)e^{-2Ls}) = 0, \quad 0 \leq k \leq m.
$$

(3.27)
As an example, for a ramp disturbance (i.e. $D(s) = 1/s^2$) by using (3.25) en (3.27) we obtain

$$A_0(0) = 1, \quad \text{for } k = 0$$

(3.28)

In the case of a parabolic disturbance (i.e. $D(s) = 1/s^3$), we determine

$$A_0(0) = 1, \quad \text{for } k = 0$$

(3.29)

$$A_0(s) = (nT_0 + 2L)s + A_0(0), \quad \text{for } k = 1$$

(3.30)

For an arbitrary disturbance described by Laplace transform $D(s) = \frac{N_d(s)}{D_d(s)}$, such as a sinusoid function (i.e. $D(s) = \frac{1}{s^2 + \omega^2}$ for $d(t) = \sin \omega t$), the following condition is induced from (3.27):

$$C(s) - A_0(s)e^{-2Ls} = \Phi(s)B(s),$$

(3.31)

where $\Phi(s)$ represents the absorption polynomial determined by $\Phi(s) \equiv D_d(s)$. In order to solve equation (3.31) for $A_0(s)$, which is used in the design of the disturbance estimator, the exponential term $e^{-2Ls}$ can be approximated by the Taylor series expansion as

$$e^{-2Ls} = \sum_{k=0}^{N} \frac{(-2Ls)^k}{k!},$$

(3.32)

and then substituted into (3.31) which leads to the Diophantine equation given by

$$A_0(s) \sum_{k=0}^{N} \frac{(-2Ls)^k}{k!} + B(s)\Phi(s) = C(s).$$

(3.33)

The obtained relation does not have a single solution in terms of $A_0(s)$. A solution procedure for the Diophantine equation is given in [11]. The only constraints is due to causality, i.e.

$$\text{deg}(A(s)) = 2 + \text{deg}(A_0(s)) \leq \text{deg}(C(s)).$$

(3.34)

The solution procedure roughly works as follow. First select $C(s)$, $N$ and the degree of the polynomial $A_0(s)$ and $B(s)$, and then substitute the corresponding absorption polynomial $\Phi(s)$ for disturbance. After that, (3.33) can be solved for the polynomials $A_0(s)$ and $B(s)$, by equating the coefficients of the terms of the equal order on both sides.
Chapter 4

Test-setup

4.1 iARM

The iArm from Exact Dynamics is used for the TSR (Tele Service Robot) project. The goal of this project is to build a remotely controlled robot to assist disabled and elderly people in their daily life. The robot should help people at home by being controlled by a home-care operator or by a local remote control. The care receiver will be much more independent and will also receive a higher quality of care. The robot will eventually be able to perform autonomous tasks. However the human operator will always stay in the loop.

In their project, the initial experimental test-bed were the two iArms, that played a role as the master and slave robots. For the one-degree-of-freedom measurement, joint “Kolom” (see figure 4.1) is used to be able to neglect gravity.

First, a PD-control structure was programmed in C++, with direct control of the actuators. Afterwards a frequency response measurement took place (see chapter 5.1). The result, displayed in figure 4.2, shows that no proper transfer function as in (3.12) and (3.13) can be
determined from this frequency response function. Therefore, the iArm test-base turned out to be useless for this type of experiments.

![Frequency response function of the iArm](image)

Figure 4.2: Frequency response function of the iArm

### 4.2 Pizza-Robot

The Pizza-Robot is an industrial robot coming from Philips, where it was used for moving LCD-displays. Due to migration of the Philips division responsible for the LCD-displays, these robots became obsolete. Therefore, they are now used for a test-base at the DCT-lab. In figure 4.3(a) and figure 4.3(b) is a picture and a schematic view respectively of the robot shown. In the schematic view, the horizontal degree of freedom displayed with the black arrows, is used for this experiment.

![Pizza-Robot](image)

Figure 4.3: Pizza-Robot
The Pizza-Robots are controlled from a Simulink environment, which is displayed in figure 4.4. The pizza-interface block is responsible for communication between the robot and the model. The required model can be designed around this block in Simulink. Position measurements are obtained with the help of encoders, these are mounted at the axes of the motors.

For designing a decent controller, it is necessary to gain knowledge about the system. Identification of the dynamics of this system is needed. This is achieved with a frequency response measurement, which will be discussed in the next chapter.

Figure 4.4: Pizza-Robot Simulink model
Chapter 5

Frequency response function

5.1 Frequency response measurement

The frequency response technique is often used for the identification of a system. For measuring frequency response in a closed loop system, different methods are available. Normally the sensitivity is measured [12]. The usual way to perform a frequency response function (FRF) measurement is to make use of cross- and autopowerspectra.

Here we are dealing with a linear system in closed loop (see figure 5.1). Where $C$ and $P$ are the system controller and manipulator. The signals $r$, $y$, $e$ and $n$ describes the reference trajectory, the system output, the error and the noise, respectively. There are two common methods to measure the FRF if a system. First one is by exciting it using a zero-mean shite noise where the reference is zero ($r(t) = 0$) and the second one is by exciting it using a multisine reference where $n = 0$.

![Figure 5.1: Closed loop scheme](image)

The system equations for different locations in the loop are written down below:

\[
\begin{align*}
y &= Pu \\
e &= r - y = r - Pu = r - P(Ce + n) \\
u &= Ce + n = C(r - Pu) + n = Cr - CPu + n \\
(1 + CP)u &= Cr + n
\end{align*}
\]
For $r = 0$ and input $n$, it applies:

\[
\begin{align*}
\frac{u}{n} &= \frac{1}{1 + CP} = S \\
\frac{y}{n} &= \frac{P}{1 + CP} = P_s \\
\frac{P_s}{S} &= P
\end{align*}
\]

where $S$ and $P_s$ are the sensitivity and the process-sensitivity functions, respectively. Another method is to generate an identification signal as the reference trajectory. This method is used for this project. Now $n = 0$ and the reference is a multisine, so it applies:

\[
\begin{align*}
\frac{e}{r} &= \frac{1}{1 + CP} = S \\
\frac{y}{u} &= \frac{Pu}{u} = P
\end{align*}
\]

This method is also called the direct method, because of the direct measurement of the system. Using this method, undesired noise causes distortion at the estimated FRF.

### 5.2 FRF Pizza-Robot

For the frequency response measurement, the sensitivity approach is used. Therefore decent controllers were designed in advance. By applying a generated identification signal as reference trajectory the FRF is determined. The used signal is a multisine and is shown in figure 5.2. This measurement has been taken out with a sampling frequency of 500 Hz and a total measurement time of 100 s. The measurement is done at both robots, because Pizza-Robot2 is not that good in trajectory tracking as Pizza-Robot1. PD-controller are used with gains of $K_p = 100$, $K_d = 30$ and $K_p = 60$, $K_d = 5$ for Pizza-Robot1 and Pizza-Robot2 respectively. The results of these frequency response measurements are shown in figures 5.3 and 5.4.

![Identification Signal](image-url)
Figure 5.3: FRF and coherence of a direct measurement of the master Pizza-Robot

Figure 5.4: FRF and coherence of a direct measurement of the slave Pizza-Robot
Out of these frequency response measurements, the transfer functions of the master and slave robots are gathered with the Matlab function 'frfit'. The Matlab command $\text{[num, den]} = \text{frfit}(H, f, [a, b, c], W_f)$ is used to start the function fit, where $H$, $f$, $a$, $b$, $c$ and $W_f$ are the frequency response data, the vector of frequencies, the order of denominator, the order of numerator, the number of integrators and an optional weighting function. To construct a transfer function as (3.12) and (3.13) for both master and slave manipulator, $a = 2$, $b = 0$ and $c = 1$ are used. For a proper fit, frequencies in the domain $[0.5 : 100] \text{Hz}$ are used, because lower and higher frequencies did not contain useful information. The transfer resulting functions are:

$$\tilde{G}_m(s) = \frac{0.0641}{s^2 + 1.005s}$$

(5.4)

$$\tilde{G}_s(s) = \frac{0.1013}{s^2 + 0.2325s}$$

(5.5)

Out of these transfer functions, the mass moments of inertia and the viscous friction coefficients (see (3.5) and (3.6)) can be estimated; which results in $J_m = 15.6$, $B_m = 18.6$, $J_s = 9.87$ and $B_s = 2.30$. Now the transfer functions of the master and slave robots are known, proper controllers can be designed out of (3.9) and (3.10), resulting in:

$$K_m(s) = \frac{1}{W(s) - 1} \frac{s^2 + 1.005s}{0.001282s}$$

(5.6)

$$K_s(s) = \frac{1}{W(s) - 1} \frac{s^2 + 0.2325s}{0.002026s}$$

(5.7)
Chapter 6

Simulations

The following simulations will illustrate the application of the IMPACT structure to the PERR based bilateral teleoperation problem on the Pizza-Robot test-setup. The absorption of two types of disturbances are considered and the reference is a third order polynomial. The parameters of the master and slave manipulator are estimated from the FRF measurement (see chapter 5.2). In both simulations, the time-delay is 0.25 seconds and the predicted time-delay is 5% larger.

The first simulation is related to absorption of a parabolic disturbance. The disturbance absorption polynomial is given by (3.30), with $n = 3$ and $T_0 = 2$. The main controller parameter is selected as $\varepsilon = 0.045$. The corresponding results are shown in figure 6.1. It can be observed from this figure that the influence of the disturbance is absorbed reasonably fast and that the steady-state value of the output remains the same as before the disturbance has been applied.

In the second simulation a multisine is applied, which can represent undesired vibrations acting on the slave side. The following periodic disturbance function is considered:

$$d(t) = \sin(0.1(t - 50))h(t - 50) + 0.5\sin(0.25(t - 50))h(t - 50).$$  (6.1)

The disturbance absorption polynomial in this case is obtained by solving the Diophantine equation given by (3.33). The resulting absorption polynomial is:

$$\Phi(s) = (s^2 + 0.1^2)(s^2 + 0.25^2).$$  (6.2)

Polynomial $A_0(s)$ which solves (3.33) is obtained using (6.2) and selecting $N = 4$, $n = 5$ and $T_0 = 2$. The obtained result is

$$A_0(s) = 96.2s^3 + 36.3s^2 + 10.5s + 0.9.$$  (6.3)

As in the first simulation, the main controller parameter is selected as $\varepsilon = 0.045$. The results are shown in figure 6.2. It can be observed that the influence of the disturbance is fully absorbed; besides that, the steady-state value of the output remains the same as before the disturbance is applied.

For both case-studies it can be observed that the master-manipulator is also affected by the disturbances, however their influences disappear after the applied reference. In both cases,
smaller values for $n$ and $T_0$ can be selected to improve the control performance, however at the cost of decreasing the robustness property [8]. Another observation is that selecting a lower value for $\varepsilon$, in order to increase speed of the setpoint tracking, reduces the robustness of the system. Therefore, there exist a tradeoff between performance and robustness of the control system.
Figure 6.2: Results for disturbance absorption of a sinusoidal disturbance
Chapter 7

Experiments

7.1 Tracking

After implementing the controllers, the tracking of both Pizza-Robots is examined without the presence of time delay. They are both tested in a separate feedback-loop. The measurements are done with applying a repetitive third order reference signal as shown in figure 7.1.

Figure 7.1: Third order reference trajectory

The results of this measurements are shown in figure 7.2. It can be observed that the error for the master is around 5% and for the slave about 20% of the reference signal. This means the tracking of the slave is not that good and might be improved for further experiments.
The time in the graph does not start from zero, this is because of the initializing time of the robots. After initializing, the robot is at its home-position at 0.2m. This holds for all the following experiments.

Figure 7.2: Results for the tracking of the master and slave manipulator with the designed controllers
7.2 Implementation of the Smith predictor

To analyze the control-structure proposed in [8], the structure is first build with only the Smith predictor and the main controller parameter is selected as \( \varepsilon = 0.045 \). Therefore, the disturbance absorber is left out. The time-delay is 0.25 seconds and the predicted time-delay is 5\% larger. The results of this measurement are shown in figure 7.3. It can be seen that the steady-state output does not remain the same as the reference state. Besides that, the error is fluctuating around a certain offset.

Figure 7.3: Results for the control structure with a Smith predictor with 0.25s time-delay
7.3 Implementation of the IMPACT control structure

The structure is now completely embedded, with Smith predictor and disturbance absorber. The disturbance estimator and main controller parameter used in this structure are $A_0 = 1$ and $\varepsilon = 0.045$. The results of this measurement are shown in figure 7.4.

![Figure 7.4: Results for the control structure with a Smith predictor, IMPACT model and disturbance absorber with 0.25s time-delay](image)

It can be observed from this figure that the steady-state output does remain the same as the reference, in contrary to the previous experiment. The error is now pushed down reason-
ably fast and fluctuating around zero. This result means that the IMPACT structure and disturbance absorber clearly have a positive influence on the tracking of both master and slave. The experiment is also done for a time-delay of 0.5 seconds and the results are displayed in figure 7.5. The results look almost the same for a time-delay of 0.25 seconds, but in this case the error is fluctuating very much. This might happen because of noise and can probably be removed with an other disturbance absorber in future experiments.

Figure 7.5: Results for the control structure with a Smith predictor, IMPACT model and disturbance absorber with 0.5s time-delay
7.4 Tracking with a Coulomb-friction compensator

A cause of the error could be the friction. Because friction is non-linear dependent on the velocity, that is shown in figure 7.6.

For the friction applies

\[ F_f = \begin{cases} 
F_f(\dot{x}, F_v), & x \neq 0 \\
F_f(-F_c \ldots F_c), & x = 0 
\end{cases} \quad (7.1) \]

where \( F_c, F_v \) are the Coulomb friction and the viscous friction respectively.

Because of this Coulomb friction, a Coulomb-friction compensator is applied. This friction applied to (3.3) and (3.4) results in:

\[ J_m \ddot{q}_m + B_m \dot{q}_m + T_{fm} sgn(\dot{q}_m) = \hat{T}_{fm} sgn(\dot{q}_m) + u_m \quad (7.2) \]

\[ J_s \ddot{q}_s + B_s \dot{q}_s + T_{fs} sgn(\dot{q}_s) = \hat{T}_{fs} sgn(\dot{q}_s) + u_s \quad (7.3) \]

On the left-hand side, \( T_{fm} \) and \( T_{fs} \) are the Coulomb-friction coefficients of the master and slave manipulators and on the right-hand side, \( \hat{T}_{fm} \) and \( \hat{T}_{fs} \) are the Coulomb-friction compensation coefficients and \( u_m \) and \( u_s \) are the new control inputs.

\( T_{fm} = 0.8 \) and \( T_{fs} = 0.55 \) are estimated empirically in experiments. In these experiments a third order reference trajectory was applied on both robots. Increasing and decreasing the Coulomb-friction compensation coefficients until the error reached a minimum, resulted in the estimated coefficients.

The results of the experiment with Coulomb-friction compensators are shown in figure 7.7. It can be observed that the Coulomb-friction compensator has a positive effect on the tracking of the reference signal. The tracking-error reduces to 2% and 10% for master and slave respectively. Therefore, the error is reduced approximately two times in comparison with the experiments in chapter 7.1. Because of this positive effect, the Coulomb-friction compensator can be added in the control loop to improve its performance.
Figure 7.7: Results for the tracking of the master and slave manipulator with a Coulomb-friction compensator
Chapter 8

Conclusion and future works

In this report, the application of IMPACT structure on the position error based bilateral tele-operation problem is investigated and tested in real-time experiments. The structure contains a Smith predictor and a disturbance estimator. Furthermore, local controllers are designed for master and slave sides.

The experiments on the IMPACT structure are done on the Pizza-Robot test-setup. First the frequency response functions of both Pizza-Robots are measured; whereafter decent controllers are designed. With these results, simulations are done with two different type of disturbances, polynomial and sinusoid. The outcome of the simulations was that the reference is followed reasonably well and the most of the influence of the disturbance is absorbed fast. Besides that, the master-manipulator is also effected by the disturbances.

Finally, experiments are done on the real test-setup. The experiments are done for both a control structure with and without the IMPACT structure and disturbance absorber. The outcome of these experiments is that with the IMPACT structure and disturbance absorber the steady-state output remains the same as the reference, in contrary to the structure without the IMPACT structure and disturbance absorber. Besides that, the offset of the error was removed.

For normal tracking, the errors are 5% and 20% for master and slave manipulator, respectively. With a Coulomb-friction compensator imbedded, these errors reduce to 2% and 10%. For future experiments, different disturbance estimators should be used to absorb the noise better and decrease the errors even further.

In the future, the approach should be extended to teleoperated systems featuring manipulators of nonlinear dynamics with multiple degrees-of-freedom. For this purpose, nonlinear internal model control and different type of disturbance observers can further be investigated. Furthermore, the robustness and disturbance rejection capabilities of the IMPACT approach can be investigated in other bilateral teleoperation architectures such as force error based and 4-channel control architectures.
References