Medical robotics

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Published: 01/01/2003

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Download date: 27. Dec. 2018
Medical Robotics

Design of a master-slave system with force feedback

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Reportnumber: DCT-2003/07

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Abstract

Medical robotic systems are used more and more. They provide physical aid for the surgeon and enlarge his capabilities. The newest developments in medical robotic systems are master-slave systems. The disadvantage of using robotic systems is the lack of haptic feedback for the surgeon. Some haptic feedback can be provided by means of force feedback. In this report the design of a master-slave system with force feedback is described.

First the design of the master and slave is described. Then some basic force feedback control strategies are discussed. The control strategies used in this report are direct force feedback, position error based force feedback with compliance controller and a combination of these two. In direct force feedback the torque applied by the slave on the environment is measured and directly fed back to the master. The surgeon can sense this ‘contact force’ by handling the master manipulator. In the position error based force feedback structure the force fed back to the master is proportional to the position error between the master and the slave. The position error is caused by the interaction of the slave with the environment. These two control structures can also be combined, making the force fed back to the master a linear combination of the torque measured at the slave side and the torque proportional to the position error.

The control structures mentioned above are applied by means of simulations to a 1 DOF master and slave system in which the slave is actuated by a smart memory alloy (SMA). The control systems are analysed with respect to stability for variations in the environment and the dynamics of the human hand. Both the position tracking and the fidelity of the systems are analysed in simulations. From these analyses it turns out that the direct force feedback method gives the best results for this master-slave system.
1. Introduction

In ancient times, man already performed some kind of surgery in order to cure people from their diseases. Two or three thousands years old skeletons are found with holes in them. These holes are perfectly round and point out that even at that time surgery was more common than we might think.

However some things have been changed in surgery during the last thousands of years. Besides the simple scalpel, the surgeon has more advanced tools to do his work properly, but he still has to perform the operations manually. Surgeons are skilled and strong in performing manipulation tasks and they are capable to quick abstract thinking and predicting possible complications. But unfortunately he faces his limits as his hand tremors and limits his positioning accuracy in the sub-millimetres regions.

With the help of robots, these limitations can be conquered. Robotic systems are available, which can help the surgeon in accurately positioning of their surgical tools. Furthermore these medical robot systems provide physical aid for the surgeons in, e.g. cutting, drilling and can scale down the motions from millimetres to micrometers accurately. The newest developments in robotic systems are so-called master-slave systems. By joining the best characteristics of the surgeon and the robot, surgery will gain valuable benefits.

1.1 Minimal Invasive Surgery

In the last decades, the surgeon is trying to reduce the size of the surgical incision. A technique that is used nowadays is called Minimal Invasive Surgery (MIS). In this technique the surgeon operates with specially designed surgical tools through incisions of about 1 cm in diameter. The surgeon puts the instruments through the incisions. In one incision he puts, for example, a small flexible camera and through another incision he puts a tool, for example a grasper like the one shown in figure 1.1. The advantage of this method is that it limits the surgical trauma to tissues, so the patient has less pain and a quicker recovery. The patient can get back to (working) society quicker and there will be a place available in the hospital sooner.

However, there are some disadvantages. During a conventional open surgery the surgeon has a 3D-view of the region he is working in. He also feels whether he is touching soft tissues (like organs) or tissues with more resistance (bones). By examining the structure of the tissue, he gets more insight in the condition of the tissue. Using MIS, the surgeon has to do his work while looking to a 2D video-screen. There is also less space for movement inside the body. Because the surgeon makes less physical contact with the tissue, his diagnostic information of the tissue decreases. The lack of haptic feedback is one of the biggest disadvantages of the tools that are now being used for MIS, especially when MIS is performed with the help of robotic master-slave systems. In the next section, haptic feedback will be explained.
1.2 Haptic perception

A surgeon gets a lot of information about the condition of tissue just by touching and squeezing it by hand, with or without handling surgical tools. This is called palpation information. Two components of palpation information are tactile and kinaesthetic information. Their combined use is referred to as haptic perception. The kinaesthetic sense is a part of the position senses, which are frequently called proprioceptive senses. They can be divided into two subtypes:

The first type is static position sense, which means conscious perception of the orientation of the different parts of the body with respect to one another. Or shortly said, by knowing the position of the different links, the shape of the object to be touched can be reconstructed. The second type is rate of movement sense, also called kinesthesia or dynamic proprioception. Tactile sense tells more about the structure of the object touched. It gives, for example, more information about the resistance and thermal conductivity of the object.

1.3 Master-slave systems

With the incisions getting smaller, the positioning accuracy of the surgeon’s hand has to be increased. Here medical robot systems can have a great benefit. New developments in this field are master-slave systems. These systems consist mostly of two components, a master and a slave. They are not connected mechanically, but linked with electronic devices and a computer. The surgeon handles the master device and these movements are led to the slave that interacts with the environment (body part of the patient). But when using these systems, there is a lack of haptic feedback: This means that using these kinds of robot systems can be dangerous in surgery. The surgeon feels no resistance and can damage, or even cut, for example a blood vessel easily.

However, control strategies have been developed, that feed back the force, performed by the slave on the environment and measured by an appropriate sensor, to the master. By applying a resistance to the movements of the surgeon, the master simulates the force at the slave side and the surgeon senses, until a certain degree, haptic feedback.
This report describes the re-design of the grasper shown in figure 1.1, into a force fed back master-slave system. The master and slave systems have been separately developed by M. Franken [1] and J.M. Peeters [2] respectively and will be discussed first. Then, control strategies for the master-slave system to obtain force feedback will be described. Finally simulations with the different control strategies will be executed and their results will be analysed.
2. The Master Manipulator

In this chapter the master device will be discussed, as developed and already described by M. Franken in [1]. A short overview of the physical design of the master manipulator will be given. In appendix A, the model of the master and the surgeon will be discussed. The simulation of force feedback will be explained in this appendix and the dynamical behaviour of the master will be described.

2.1 Design of the master

The control-objective of the master-slave system is defined as an ideal coupling of master and slave, which implies ‘perfect’ position tracking of the slave with ‘perfect’ force reflection of the master. The reflected force is used to provide the surgeon with contact experiences at the operation area. For the master device the reference ‘force’ to be reflected is the torque measured at the slave side. Keeping this in mind, the following system requirements were made in [1] for the design of the master manipulator:

- a contact area has to be present, where the surgeon can manipulate the master system
- the position displacement has to be measured
- a manipulator is needed for correct delivery of the torque performed at the slave side to the surgeon.

These three requirements were combined into the master device shown in figure 2.1. The link between the master and the surgeon are the handles of scissors. A position sensor is added for position measurement. This position is the reference signal of the slave. A DC-motor is used for a ‘correct’ delivery of torque, such that the surgeon senses the torque measured at the slave side.

![Figure 2.1: Design of the master](image-url)
3. The Slave Device

In this chapter the slave device will be discussed as designed by Peeters [2]. In appendix B a linearised model of the slave will be given and the dynamical behaviour of the slave will be discussed.

3.1 Design of the slave

As mentioned in chapter 2, 'perfect' position tracking of the slave is required for coupling the master and the slave. The design and a schematic outline of the laparoscopic forceps are given in figure 3.1. Minimal invasive techniques of medical master-slave systems require small instruments, i.e. small actuators and mechanisms. Shape Memory Metal Alloy (SMA) actuators pretend to be small and still powerful. An SMA actuator made of a Nitinol wire is chosen to actuate the tip of the slave device. By applying a current, the length of the Nitinol wire will increase or decrease, resulting in a movement of the stiff wire and opening respectively closing of the forceps. The force applied by the tip of the forceps on the environment is measured with a force sensor and fed back to the master.

![Figure 3.1: The laparoscopic forceps](image)

1. Forceps
2. Motion mechanism
3. Drive rod
4. Spring
5. Stiff wire
6. LVDT
7. Nitinol wire
8. Force sensor
4. Master-Slave system

In this chapter the general configuration of a master-slave system with force feedback will be explained. There are different control strategies known to obtain force feedback. A review of some of the most basic strategies is given in this chapter.

4.1 Basic block diagram model

The entire master-slave system can be modelled by five separate components that exchange force and position information. The characteristics of the master, the slave and the surgeon are supposed to be known. The characteristics of the patient are not well known. The communication between master and slave consists of a digital controller equipped with an AD/DA converter.

Figure 4.1 shows a schematic representation of the master-slave system in general. For simplicity a centralised controller is drawn. The vectors \( x \) contain position, velocity and acceleration. The vectors \( f \) contain forces. The figure makes clear there will be a bilateral control structure, which means that communication between the different elements takes place in both directions.

![Figure 4.1: Schematic representation master-slave system](image)

4.2 Control strategies

In literature different control strategies for haptic feedback in master-slave systems have been proposed. Some of the most basic methods are direct force feedback\([6,12,14]\), impedance control \([4,5,6,7,8,9,12,14]\) and a combination of these two methods\([10,12,14]\). In this section these three methods will be discussed.

4.2.1 Direct force feedback

In direct force feedback, also called kinaesthetic force feedback, slave force signals are measured and used for force reflection on the master manipulator. The block diagram of this method is given in figure 4.2. Here \( H(s) \) represents the dynamics of the surgeon, \( M(s) \) represents the master with controller, \( S(s) \) represents the slave with controller and \( E(s) \) resembles the environment/patient. The force applied by the forceps is measured and fed back to the surgeon in order to obtain force reflection. The controller modelled in \( M(s) \), is used to obtain 'perfect' force reflection at the master. The controller modelled in \( S(s) \), is used to obtain 'perfect' position tracking.

The drawback of the direct method is its (in)stability depending on the surgeon's dynamics and the stiffness of the contact environment. They are both directly included in the open loop transfer function of the master-slave system.
4.2.2. Impedance control

With this type of control the system detects the motion commanded by the surgeon and controls the force applied by the slave. One kind of impedance control frequently used for force reflection is position error based force feedback (PERR), in which the position error between the master and the slave is proportional to the reflected forces. A compliance controller is usually added to generate a position error and to improve the performance and stability of the system. With this controller the slave behaves like there were a damped spring between the master and the (otherwise stiff) controlled master. A block diagram of position error based force reflection with compliance control is given in figure 4.3, where $K_F(s)$ and $k_f(s)$ are gains. The figure shows the measured position of the slave $S(s)$ is subtracted from the position of the master $M(s)$. This position error is multiplied by gain $K_F(s)$, resulting in a force that is led to the surgeon $H(s)$. The force obtained at the tip of the forceps is also measured. This signal is led through a low-pass filter to make the measured force smoother and is eventually led through gain $k_f(s)$ resulting in a position that is subtracted from the reference signal of the slave. This leads to a position error between the master and slave necessary to reflect the force performed on the environment by the slave. The loop containing the measured force, the low-pass filter and gain $k_f(s)$ is called the compliance controller. In this report the PERR structure with compliance controller will be discussed and will further on also be referred to as PERR.

The position error based force feedback strategy does not really resemble the impedance of the system. A stricter form of impedance control is based on the difference in velocity between the master and the slave. This velocity error is proportional to the force reflected to the master. However this type of control is most useful in hard contact cases and in big workspaces. This is not the case in our system, so this type of control will not further be explained.
4.2.3. Position and force feedback

This control strategy is a combination of the direct method and the position error based force feedback as already described in the previous sections. The force that is sent back to the surgeon is a linear combination of the force measured at the tip of the slave and the force proportional to the position error between the master and the slave. By adjusting the ratio between the force gain, \( \alpha \), and the position error gain, \( K_F(s) \), the structure varies between a pure position error based force feedback and a direct force feedback.

By plotting the ratio between the force gain and the position error gain against the performance of the system, one can investigate which structure performs best. The block diagram of the position and force feedback is given in figure 4.4.

![Figure 4.4: Block diagram of the position error based force feedback in combination with the direct method](image-url)
5. Simulations

In the previous chapter some of the basic control strategies for force feedback are discussed. In this chapter we will implement these control strategies in simulations on the controlled master and controlled slave as described in chapter 2 and 3 and appendix A and B. For the human operator we will use the model given in appendix B. But before implementing in a simulation environment, we will first mention some points of attention when designing the master-slave system. After this the direct method will be discussed. Then the position error based force reflection strategy with compliance controller will be applied. We will conclude this chapter with the position and direct force feedback method.

5.1 Design criteria

When designing a master-slave system with force feedback, a few requirements of the system should be kept in mind.

Stability

A master-slave system consists of four basic elements, the (controlled) master, the (controlled) slave, the environment and the human operator. The master and slave contain some modelling errors. It is also not very clear how the dynamics of the human hand can vary for different persons and the environment changes much. For doing a proper analysis on the stability of the system, robust stability criteria are developed. Such criteria take into account the fluctuation in dynamics and modelling errors of one of the elements. In this report we will check the robustness of the stability by checking the stability of the open loop system under changing impedance of the environment and for different dynamics of the human operator. The system should stay stable for a wide range of variation of the impedance of the environment and the dynamics of the human hand. It is not very clear how wide this range should be, so no further quantitative specifications will be given about stability.

Tracking

Once the stability criterion is met, the performance of the controller is evaluated. Position tracking and fidelity are the two measures employed to determine the performance of the system. Tracking is a measure of how well the slave can follow the position commanded by the master. The tracking requirement placed on our system is to limit the position error between the master and the slave by choosing the proper gains. Tracking is evaluated for the closed loop system in free space where the slave is not influenced by the environment. The required accuracy of the grasper is 500 μm, resulting in an accuracy of 0.025 rad, for the length of the forceps to be 2 cm. The settling time of the system should be faster than the reaction time of the human operator. So the maximal settling time of the system will be 0.1 seconds.

1 The controllers of master and slave are not changed, because they are already designed to obtain proper tracking of the reference signal.
Fidelity
There is no universal definition for fidelity in teleoperation. Some definitions found in literature [11,13] are that fidelity is the ratio between the transmitted and environmental impedance. With this measure one is able to determine the frequency range in which the system transmits the impedance accurately. Another definition is that the fidelity is a measure for the sensitivity of the system to detect changes in the impedance of the environment. Or in other words, what is the smallest change in impedance of the environment that will be detected by the system. Especially in surgical applications the last definition is very usable. Changes in impedance can tell the surgeon more about the condition of tissue. In this report we will only discuss the ratio between the torque applied at the tip of the forceps and the torque fed back by the master, because in simulations every change in impedance of the environment will be detected because of no disturbances and measurement noise. A bandwidth of 5 Hz is required where the ratio between measured and transmitted torque equals one. Some phenomena that occur in the torque fed back by the master will also be discussed.

5.2 Direct force feedback
When applying this control strategy, we just have to feed back the measured torque signal at the slave side to the master. In this section we will check the dynamical behaviour of the torque fed back master-slave system with Bode plots. The stability of the system will be checked for different values of the impedance of the environment and for different values of the human hand. Afterwards we will look at the performance by showing some simulations and explain the results.

Stability analysis
The stability of the master-slave system depends partly on the environment it is acting on. In appendix C this is discussed in more detail and a model of the environment, a linear spring, is proposed. Now the system can be checked for its robust stability for this type of environment. Different values for the spring constant are taken. Figure 5.1 shows the Bode plots of the system for different spring constants \( k = k_{\text{stiff}} \). The phase does not vary for different impedance. The figure shows the system gets unstable for a stiff environment. More details about what his instability means for the physical system is explained in appendix D.

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1 In this report we assume the force sensor as used in the slave is suitable for our purposes.
2 The SMA wire of the slave has two states: elastic and a transformation state. Because the Bode plots of both states are quite similar, we only show Bode plots of the system with the Nitinol SMA wire in elastic state. With this Bode plots the behaviour of the system in transformation state by varying environment can easily be predicted.
To investigate the performance of the system, the spring constant is chosen to be 100 N/m. Figure 5.1 shows the system is stable for interaction with an environment with this impedance. Now the influence of the human hand on the stability of the system is evaluated. The impedance of the environment is kept at 100 N/m. The human hand is modelled as a mass-spring-damp system, meaning there are three variables (see equation A.2). To check the stability of the master-slave system, we vary one variable and keep the other two variables constant.
Figure 5.2 shows the open loop Bode plots of the master-slave system for changing $m$, $d$, and $k^3$. It shows the closed loop system gets unstable when the spring constant equals zero. In appendix D more details are given about instability caused by the human hand. Variation in the mass and damping constant cannot make the closed loop system unstable. This however is not a surprise, because the DC gain stays constant (because of a constant value of $k$) and under 0 dB. We can also see a decrease of the damping leads to an undesirable resonant peak. An increase of the mass means the magnitude starts to decrease at a lower frequency.

**Simulation**

With the help of Matlab's Simulink we can perform some simulations on the master-slave system. In simulations a non-linear model of the slave is used, combining the two states of the SMA wire. In the design of the master-slave system, the output of the master is the reference input of the slave. In the original design however the output of the master is an angular displacement, while the input of the slave is the translation of the driving rod. Therefore we first have to convert the signal between the master and the slave. This conversion is given in appendix E.

**Tracking**

Now we have defined the proper inputs and outputs, we can do some simulations to investigate the performance of the master-slave system. First consider the tracking performance of the system, by means of the position error between the master and the slave in free space. Figure 5.3 shows that for the position 0.3 rad the position error goes to zero after some settling time for step-input. The figure also shows the system has quite an overshoot and has a large settling time. This is because of the rather slow response of the SMA-wires used for actuation of the slave.

**Fidelity**

The torque measured at the slave side is directly fed back to the master. So in theory the ratio between the torque measured at the slave side and the torque by the master equals one after a settling time with infinite bandwidth. In practice this ratio will not

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3 For the same reason as mentioned in footnote 1 here only Bode plots of the system are given with the Nitinol wire in elastic state.
equal one and the bandwidth will not be infinite, because of noise in the system and the dynamics of the force sensor.

Let us do some simulations of the system in a contact case. Figure 5.4 shows the torque applied by the master for step input and time varying sinusoidal input.

![Figure 5.4: Torque for step input (left) and time varying input (right)](image)

The left figure shows that, after the settling time, there is a time varying force feedback under steady-state conditions. This can be caused by an unstable system. However the linearised system is stable for the environment and human hand used for this plot. Another possible cause is mentioned in literature by Hannaford [8]; use of an I-action will give fluctuations of the output under steady state conditions in force feedback.

Leaving the I-action of the slave controller and only using a proportional action indeed leads to a constant force feedback under steady-state conditions after the settling time. However in this case the I-action is necessary to achieve proper position tracking of the slave. It is beyond the scope of this project to design another controller without I-action, but still having good tracking (zero steady-state error) of the master-slave system. So in this report the original PI-controller will be used and the fluctuations will be seen as an unwanted phenomenon and taken into account in further analyses. However it is recommended that in future research a suitable controller will be designed without containing an I-action.

5.3 Position error based force feedback
In the position error based force feedback control strategy (PERR) the torque fed back to the master is proportional to the position error between the master and the slave. In this section a stability analysis will be given and the system's performance will be evaluated. The control design will be explained in appendix F.

Stability analysis

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4 The Bode plots of the controlled system are low frequent almost similar. The analysis will be discussed for a system with the SMA wires in elastic state. For this state the phase decreases faster for lower frequencies which can give more troubles for stability than the transformation state case. The analysis for the transformation state is similar and results are easily to subtract from the elastic state case.
The stability of the system will be checked with changing impedance of the environment and with changing dynamics of the human hand. Figure 5.5 shows the Bode plot of the closed loop system with varying environment. The figure shows the system is unstable for the spring constant $k = 500$ and $k = 700$. For high values of $k$ the magnitude of the open loop system crosses the zero dB, while the phase of the system is less than zero degrees. The meaning of this instability is already explained in the direct feedback case. See also figure 5.1 for the direct feedback case.

**Bode Diagrams**

![Bode Diagram](image)

Figure 5.5: Bode plot of the open loop system for varying impedance of the environment (*) is unstable system

The stability of the system with varying dynamics of the human hand is shown in figure 5.6. The same methodology is used as in the direct force feedback case. The same kind of behaviour of the system as in the direct feedback case can be seen. For a zero spring constant $k$ the system is unstable. For a decreasing damping the system gets resonance peaks. For an increasing mass, the magnitude decreases for a smaller frequency.
Simulation
In this section the performance of the master-slave system will be discussed. Also for the PERR structure we first check whether the I-action of the slave controller gives fluctuations under steady-state conditions. Figure 5.7 shows, for a reference position of 0.3 rad, the position error between the master and the slave for a free space case with step input. The figure shows there is a fluctuating position error under steady-state conditions when the controller contains an I-action. For the same reasons as explained in the direct force feedback case, leaving the I-action is not an option.

Tracking
From figure 5.7 we can conclude that even in free space the surgeon will have force feedback for step input, although there is no torque applied by the forceps. This is caused by the position error during the settling time of the system and the time varying position error after the settling time.
The PERR structure as discussed in this report is more or less a trade off between the tracking of the torque applied by the slave and the tracking of the rotation of the master. On the one hand proper position tracking of the slave with reference input the output of the master is desired, but on the other hand a position error between the master and the slave is necessary in order to obtain proper transmission of the torque. The position error is already evaluated for the free space case, but it is more interesting to evaluate the position error in comparison with the angle of the master for a contact case. The input of the system is kept sinusoidal with a frequency less than 1 rad/sec to obtain zero error tracking of the torque applied by the slave. The results for some angles are shown in figure 5.8. The figure shows the relative error increases for decreasing angle. For small angles the absolute position error exceeds the required accuracy of 0.025 rad.
Fidelity
The ratio between the torque obtained at the slave side and the torque fed back by the master does not always equal one. Figure F.1 in appendix F shows for which frequencies the ratio will equal (nearly) one. The bandwidth of the system is approximately 1 rad/sec, meaning that for signals with a higher frequency the master will not properly transmit the torque applied by the slave on the environment.

The torque fed back by the master for step-input is proportional to the position error as for example given by figure 5.7 for a free space case and will not further be discussed in this section. We will discuss the behaviour of the system for time-varying input. Figure 5.9 shows the torque fed back by the master in free space and for a contact case for sinusoidal input. The discontinuities shown are caused by the switching points in the model of the slave as explained in appendix B.

In the contact case these discontinuities are amplified. This is because they are present in the position error signal, which will be amplified by a factor 100 because of the force gain. Figure 5.9 also makes clear that disturbances in the position output of master and slave and therefore indirectly also disturbances in the measured force signal of the slave, show up enlarged in the torque fed back by the master.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure5.9_left}
\includegraphics[width=0.4\textwidth]{figure5.9_right}
\caption{Torque fed back by the master for a free space (left) and contact (right) case with sinusoidal input}
\end{figure}

5.4 Position and force feedback
This control strategy is a combination of the two strategies described in the previous sections. The torque fed back by the master is a linear combination of the torque proportional to the position error between the master and the slave and the torque measured at the slave side. In this section we will discuss this control strategy for different ratio between the two torque.

Stability analysis
First we will look at the stability of the system for different ratio. Figure 5.10 gives Bode plots of the open loop system, with the Nitinol wire of the slave in elastic state, with input the additional torque and output the torque fed back by the master for different values of the force gain $\alpha$. Keeping the results of the PERR and direct force feedback structure in mind, this result is not surprising. The system stays between the
boundaries of the PERR and direct method structure. The master-slave system is stable for all values of \( \alpha \) for interaction with a linear spring with constant \( k = 100 \, Nm \).

Fidelity & tracking

The performance of the system for different values of \( \alpha \) will also be evaluated. Figure 5.11 shows the Bode plots for the system with input the torque measured at the forceps and output the torque fed back by the master.

As expected from results discussed in the previous sections, we see that for increasing \( \alpha \) the bandwidth of the system, with respect to proper transmission of the torque, increases.

Another measure of the performance is the position tracking. For a free space case the position error will go to zero error with some fluctuations because of the I-controller.
For sinusoidal input the position error will be zero with some switching points. In a contact case, there will be a position error for $\alpha \neq 1$, because of the compliance controller of the PERR structure. This controller causes a position error and is not influenced by the ratio between the position error gain and $\alpha$.

The system behaves between the boundaries given by the PERR structure and the direct force feedback. We also see this phenomenon in the step response of the system in time domain as shown in figure 5.12. For a decreasing $\alpha$, the settling time and overshoot of the system increases.

**Direct force feedback - Position error based force feedback**

From the results discussed above we can conclude the position and force feedback structure gives some improvements in comparison to the PERR structure. When the position and force feedback structure moves towards the direct force feedback structure there is an increase in the bandwidth where the measured torque is transmitted properly. The settling time of the system is smaller and the overshoot decreases in time domain. With respect to tracking there is no difference with the PERR structure.

In comparison to the direct force feedback the position and force feedback gives no improvements. The direct force feedback structure has a higher bandwidth according to the tracking of the torque at the slave side and is only limited by the bandwidth of the slave (the slave has the smallest bandwidth of all elements of the master-slave system). Direct force feedback gives no position error between the master and the slave for free space and contact case and has a smaller settling time with less overshoot. Discontinuities in the measured force are not amplified in the signal fed back to the master.

When comparing the PERR strategy with the direct method, the system with direct force feedback stays stable for higher values of the impedance of the environment than the position error based system.
Conclusions & Recommendations

In this report the design of a master-slave system with force feedback is described. Three basic control strategies are described, direct force feedback, position error based force feedback and position and force feedback. These three control structures are implemented in simulations on the master-slave system. The system is analysed for three criteria; stability of the system for varying impedance of the environment and the human hand, performance and fidelity.

In this report the robust stability of the system for varying impedance of the environment and human hand is analysed quantitatively. An environment with a wide range of variation in the impedance can be inspected before the system gets unstable. Use of robust stability criteria gives more insight in the boundaries of the usability of the system.

Direct force feedback has theoretically an infinite bandwidth in which the measured torque is transmitted well. The position error does not exceed the required accuracy of 0.025 rad. This in contrast to the PERR method, where the bandwidth is less than the required 5 Hz. For a free space case the position error does not exceed the required accuracy. For a contact case the required accuracy is not achieved. For both methods a time-varying output under steady-state conditions occurs in a contact case. In time domain the settling time of the direct force feedback method is smaller and the system has less overshoot for a step-input. So according to simulations direct force feedback is most preferable.

However only simulations have been discussed in this report. These simulations describe the 'perfect' system with no noise and time delay. Implementation of the control strategies on an experimental set up is required to investigate the influence of noise, disturbances and time delay on the stability, performance and fidelity of the system. According to simulations the combination of direct force feedback and PERR gives no benefits above pure direct force feedback. Experiments have to show if a combination of direct force feedback and PERR will be more preferable according to measurement noise and disturbances, like for example tremors of the human hand. Interesting is the influence of the force sensor on the torque fed back by the master. In the direct method the signal of the force sensor is directly fed back to the master, while for the PERR structure the force sensor is used indirectly for reflecting the force to the surgeon. In this structure the force sensor is only used in the compliance controller to obtain a position error between the master and the slave. Implementation has to make clear if the sensor noise is such that the performance of the PERR structure or the combination of direct force feedback and PERR is preferable above the performance of the direct method.

As can be seen in simulations the system has a slow response. The settling time of the system is more than 1 sec. This is too slow for use in a medical robotic system. The slave is in this case the cause, because of the slow response of the SMA wires. A new set up of the slave has to be designed, that has a higher bandwidth. When designing another set up of the slave one should keep in mind the use of an I-action should be avoided as much as possible because of time-varying output under steady-state conditions.
Bibliography

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Appendix A: The Master

A.1 Model of the master

For deriving a model of the master, the mechanical part as well as the electric part has to be taken into account. The electrical part consists of the differential equations of a rotating DC motor. The mechanical part consists of the equations of motion. Combining these two leads to the following equation:

\[ J_m \ddot{\theta}_m + b_m \dot{\theta}_m = \frac{K_t}{R_a} \left( v_a - L_a \frac{dI_a}{dt} - K_e \dot{\theta}_m \right) + T_{load} \]  

(A.1)

with:

- \( J_m \) = inertia (4.9 e^{-3} km^2)
- \( \theta_m \) = angular displacement [rad]
- \( b_m \) = viscous friction (5 e^{-3} Nm)
- \( K_t \) = motor constant (120)
- \( R_a \) = electric resistance (3.2 \Omega)
- \( v_a \) = voltage input [V]
- \( L_a \) = induction (1 e^{-6} H)
- \( I_a \) = current [A]
- \( K_e \) = back electromotive force (0.69)
- \( T_{load} \) = disturbance torque, i.e. the torque applied by the surgeon [N/m]

The torque obtained at the slave side has to be proportional as the torque performed by the master to the surgeon. In the design of the master, a torque, equal to the torque at the slave side, is considered to be input. A simple PI-controller is applied in order to transfer this signal properly to the surgeon. In practice, a current amplifier replaces this PI-controller.

A.2 Force feedback

When designing a master-slave system with force feedback, also the operator of the master, in this case the surgeon, has to be taken into account. However it is very difficult to give a proper model of haptic sensing of the human hand. Franken [11] proposes a mass-spring-damper model to describe the kinaesthetic feeling. This model will also be used in this report and is given by equation A.2.

\[ F = m \ddot{\theta}_m + b \dot{\theta}_m + k \theta_m \]  

(A.2)

with:

- \( F \) = force applied by the surgeon [N]
- \( \theta_m \) = angular displacement of the master [rad]
- \( m = 0.01 \) N
- \( d = 1 \) Nm
- \( k = 10 \) N/m
The master is designed in such a way that the torque, measured at the slave side, will lead to a rotation of the handles of the scissors. The surgeon however will suppress this rotation, by applying a certain torque to the handles. This torque is the same as the one measured at the slave side. This force feedback scheme of the master manipulator with surgeon is schematically represented in figure A.1. The sensitivity of the human hand contains the model given by equation A.2 with an eventual constant for conversion to torque. The figure also shows an extra input, called additional torque. The total torque the surgeon applies to the master consists of the torque necessary to suppress the rotation of the handles and an (eventual) additional torque to change the position of the handles of the master with respect to the visual feedback of the surgeon.

From the above we can also conclude the surgeon contributes to the stability of the system (in a contact case of the slave). When the surgeon would not be there to suppress the rotation of the handles, the handles would begin to spin around.

![Figure A.1: Force feedback](image)

**A.3 Dynamical behaviour**

Before the master and slave can be coupled some information about the dynamical behaviour of both devices is necessary. As mentioned above the surgeon is necessary for the stability of the force feedback in the master. In this section the master and surgeon will be examined as a whole. With the help of Matlab's Simulink and the Matlab-command `linmod` a state space model of the combined master and surgeon is found. To examine the stability of the system, the eigenvalues of the system matrix are calculated.
The master manipulator with surgeon has two inputs, the additional torque and the torque measured at the slave side, and one output, the angular displacement. The response of the system for both inputs will be discussed. First the behaviour of the system with a change in the additional torque input will be described. The torque obtained by the slave will be kept constant.

![Figure A.2: Bode plot of the master with input additional torque](image)

Figure A.2 shows the Bode plot of the system. The figure shows there is low frequent a 180 degrees phase lead. This means there is a minus sign in the transfer function of the system.

The step response of the system in figure A.3 also shows there is a minus sign in the transfer function of the master with the surgeon. It shows the system gets negative amplitude for a positive input, meaning the bigger the input, the smaller the output and vice versa. This can be explained by the fact the force feedback is designed in such a way that the total torque applied by the surgeon equals the torque obtained at the slave. Meaning:

\[
\tau_{\text{slave}} = \tau_{\text{additional}} + \text{sensitivity human arm} \tag{A.3}
\]

An increase in the additional torque means a decrease in the sensitivity of the human arm for constant \( \tau_{\text{slave}} \). This decrease is a result of a smaller angular displacement.

![Figure A.3: Step response of the master with input additional torque](image)
Figure A.4 shows the Bode plot of the system. The input is the torque measured at the slave side. It shows the system is stable.
Appendix B: The slave

B.1. Linearised model of the slave
The SMA actuators as used in the slave have a highly non-linear behaviour. As proposed in [2], a linear transfer function of the slave is determined by linearisation of the SMA dynamics and the dynamics of the motion mechanism around $x = 0$. This model also includes friction in the slave mechanism. The transfer function from the translation $x$ of the driving rod to the control input $u (=-I^2)$ is described by:

$$H(s) = \frac{X(s)}{U(s)} = \frac{ck_o}{(ns+1)(Ms^2 + bs + k_x + k)}$$

with:
- $c = 120 \, \text{°C}A^2$
- $M = 0.06 \, \text{kg}$
- $n = 2.1 \, \text{s}$
- $b = 20 \, \text{Nsm}^{-1}$
- $k = 2400 \, \text{Nm}^{-1}$
- $k_{x0} = 5.3e-8 \times \pi_e$
- $k_{00} = 5.2e-8 \times \pi_0$

The values of $\pi_e$ and $\pi_0$ are strongly dependent of the state of the Nitinol wire. During elastic elongation large values for $\pi_e (=16.4 \, \text{Gpa})$ and small values for $\pi_0 (=1.5 \, \text{MPa.K}^{-1})$ occur. During transformation opposite values occur, $\pi_e (=2.9 \, \text{Gpa})$ and $\pi_0 (=6.5 \, \text{MPa.K}^{-1})$.

B.1.1 The Controller
A PI-controller in combination with a feedforward controller controls the slave. The feedforward controller takes into account the hysteresis of the Nitinol wire and some other system dynamics. This controller is of most use for a non-linear model of the slave. For analysis of the system the linearised model of the slave will be used without taking into account the feedforward controller. In simulations a non-linear model with feedforward controller will be used. The PI-controller used has a proportional gain $K = 14 \, 000 \, \text{A}m^{-1}$. The zero of the integral action is placed at a frequency of 2 Hz, which results in an integral time $\tau = 0.08 \, \text{sec}$.

B.2 Dynamical behaviour
In this section the dynamical behaviour of the slave and controller will be examined. The Bode plot of the theoretical open loop is given in figure B.2.
The figure shows the theoretical bandwidth of the system is about 5 Hz, meaning the master-slave system will also have a rather low bandwidth. Figure B.2 shows the closed loop Bode plots of the system.

Figure B.3 shows a simulation with the non-linear model of the slave. It shows the angle of the forceps for sinusoidal input. The model shows a remarkable behaviour, the switching points in both directions show some small vibrations. These switching points are caused by a linearisation of the hysteresis loop of the Nitinol wire and are located where an elastic length change of the Nitinol wire changes into a length change due to transformation.
Figure B.4 shows the angle of the forceps for a constant input. It shows the system has a relative large overshoot and large settling time.
Appendix C: Environment

The environment can have a big influence on the stability of the master-slave system. Figure C.1 shows the Bode plot of the open loop system including the (controlled) master, the (controlled) slave and the human hand.

![Bode plot of the open loop master-slave system without environment for transformation (solid) and elastic (dotted) state of the Nitinol wire of theslave](image)

However by including the dynamics of the environment on the open loop, the open loop system can become unstable for certain types of environment. There are no proper models available from the environment where the forceps has to work in, so we choose a simple linear spring as a model for the environment. This spring is given by:

\[
\tau = k_{vee} \cdot d \cdot (\sin(\phi_{max}) - \sin(\phi))
\]

with:
- \(\tau\) = torque applied by slave on the environment [Nm]
- \(k_{vee}\) = spring constant [N/m]
- \(d\) = length of the tip of the forceps [m]
- \(\phi_{max}\) = maximal angle of the tip of the forceps [rad]
- \(\phi\) = angle of the tip of the forceps [rad]
Appendix D: Instability

D.1. Stiff environment
In practice instability of the system caused by a stiff environment means that the torque applied by the slave gets, even for a small angular displacement, that big that the human operator cannot apply this torque. In an attempt to get the maximum torque applied by the human hand, the angular displacement needs to get as large as possible, resulting in a small angle of the handles of the master and a small angle of the forceps. As a result of the decrease of the angle the torque applied by the slave increases. This increase of the torque needs to be compensated by an increase of the angular displacement, which on its turn again leads to an increase of the torque at the slave side. In the end, the angle of the forceps is small, resulting in a large torque that cannot be compensated by the human operator.

D.2. Human hand
The system has unstable behaviour when the spring constant of the human hand equals zero. This can be explained by the fact that when the handles of the master are kept on a constant angle, the rotational speed and acceleration of the master are zero. This results in a zero torque applied by the surgeon while (in a contact case) there is a torque applied by the slave on the environment. Because of the torque measured at the slave side, the handles of the master start to rotate. The surgeon, because of the zero torque, does not suppress the rotation and the handles start to spin around.
Appendix E: Conversion

First a conversion from rotation to translation is given by the next equation:

\[ x = x_0 \left( \frac{\sin(\varphi_{\text{max}}) - \sin(\theta/2)}{\sin(\theta/2) + \sin(\gamma)} \right) \]  

(C.1)

with:

- \( x = \) translation rod [m]
- \( x_0 = \) initial length of the Nitinol wire = \( 2.2 \times 10^{-3} \) m
- \( \varphi_{\text{max}} = \) maximal angle of the forceps = \( 53^\circ = 0.93 \) rad
- \( \theta = \) angle of the master [rad]
- \( \gamma = \) constant angle = \( 33^\circ = 0.58 \) rad

The master gives an angular displacement of the handles, while the conversion given by equation C.1 needs the angle between the handles of the master device. We assume the maximal angular displacement of the master to be the same as the maximal angular displacement of the slave, which is 0.93 radians. The angle between the handles of the master is then given by:

\[ \theta = 0.93 - \psi \]  

(C.2)

with \( \psi \) the angular displacement of the master.
Appendix F: Control design PERR

To design this control strategy there are two transfer functions that have to be taken into account. Namely the transfer from the torque measured at the environment to the torque fed back by the master, that is obtained by multiplying the position error between the master and the slave by gain $K_F(s)$ (see also figure 4.3). And the transfer from the torque performed by the operator ($F_{op}$, see figure 4.3) to the torque fed back to the master. The first transfer function is a measure for the performance of the system, meaning the ratio between the torque measured at the slave side and the torque fed back by the master. The latter transfer function is to check the stability of the system. The first transfer function cannot be used as a measure of the stability, because the open loop system is cut open between the low pass filter and the gain $k_i$ (see figure 4.3) to create the measured torque as the input signal. So the environment is not taken into account in this transfer function. Figure F.1 shows the Bode plot of the system with input the measured torque at the forceps and output the torque fed back by the master. This Bode plot is obtained by taking force gain $k_i$ 1/100 and position error gain $K_F$ 100. These gains give the highest bandwidth. Because we do not have noise in simulation level and we only apply low frequent input signals, the low pass filter has for now a 0-dB magnitude for all frequencies.

![Figure F.1: Bode plot for designing the PERR structure](image-url)