Control Design and Performance Analysis of
Force Reflective Teleoperators
- A Passivity Based Approach

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Control Design and Performance Analysis of Force Reflective Teleoperators - A Passivity Based Approach

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Doctoral thesis

Academic thesis, which with the approval of Kungliga Tekniska Högskolan, will be presented for public review in fulfilment of the requirements for a Doctorate of Engineering in Machine Design. The public review is held at Kungliga Tekniska Högskolan, Brinellvägen 64, 100 44 Stockholm in room M3 at 10.00 am on the 10th of June 2004.
**Title**
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**Abstract**

In this thesis, the problem of controlling a surgical master and slave system with force reflection is studied. The problem of stiff contacts between the slave and the environment is given specific attention. The work has been carried out at KTH based on an initial cooperation with Karolinska Sjukhuset. The aim of the overall project is to study the possibilities for introduction of a force reflective teleoperator in neurological skullbase operations for the particular task of bone milling and thereby, hopefully, increase patient safety, decrease surgeon workload and cost for the society.

The main contributions of this thesis are:

Derivation of a dynamical model of the master and operator’s finger system and, experimental identification of ranges on model parameter values. Based on this model, the interaction channel controllers optimized for transparency are derived and modified to avoid the influence of the uncertain model parameters. This results in a three channel structure. To decrease the influence of the uncertain parameters locally at the master, a control loop is designed such that the frequency response of the reflected force is relatively unaffected by the uncertainties, a result also confirmed in a transparency analysis based on the H-matrix. The developed teleoperator control structure is tested in experiments where the operator could alter the contact force without facing any problems as long as the slave is in contact with the environment.

As a result of the severe difficulties for the teleoperator to move from free space motion to in-contact manipulation without oscillative behaviour, a new detection algorithm based on passivity theory is developed. The algorithm is able to detect the non-passive behaviour of the actual teleoperator induced by the discrete change in system dynamics occurring at the contact instant. A stabilization controller to be activated by the detection algorithm is designed and implemented on the master side of the teleoperator. The detection algorithm and the stabilization controller are shown highly effective in real experiments.

All major research results presented in the thesis have been verified experimentally.

**Keywords**
Teleoperator, Force Feedback, Passivity, Stiff Contacts, Control, Robustness, Transparency, Bone Milling, Uncertainty

**Language**
English
Preface

I came to KTH to do my master thesis in mechatronics. When the master thesis was finished, my professor Jan Wikander offered me a position as a PhD student which I still am grateful for. I soon realized that the Mechatronics Lab was a good place to do the PhD degree at. This is due to the positive atmosphere in the department, the freedom that the PhD students have in selection of area in which they put their research focus and the supportive and encouraging supervision that professor Jan Wikander gives. Thank you Jan for providing us with such a good place to work at!

After several years at KTH, the list of people to whom I would like to express my gratitude can be made very long, but I will make a try to mention some of them. Bengt Eriksson has been a good friend and an extremely valuable supervisor for me during the work. He has a view on control theory slightly different from mine and our discussions have provided me with a lot of practical insight to many control problems. My good friend and inspiring colleague Ola Redell whom I have known since we started the university studies together in Uppsala thirteen years ago! Ola is actually one of the reasons why I came to Damek in the first place. The “Ultimate Icelandic” Freyr Harðarson who left Damek last summer for industry in Reykjavik has been a very fun room mate and a good friend. Martin Grimheden for doing a great job at arranging social events at the department and for being a good friend.

Further on, my old room mate Andreas Archenti, and the new ones Fredrik Roos and Magnus Eriksson give our room a good atmosphere to work in. Avo Kask for always saying “Good Afternoon” when I come in at eight o’clock in the morning! The two sys.admin. guys Peter Reuterås and Payam Madjidi - both very helpful guys. Mikael Hellgren for all help with the hardware in the lab and for all the interesting lunch discussions regarding chain saws, saw mills and all other kinds of interesting things!

I would also like to say thanks to all the students in the RIP - course through all these years. They have taught me a lot on how to explain control theory to people with a large variety of prior knowledge.

Finally, special thanks to Lisa and, most of all, Aron for letting me know and feel what really is important in life!

Stockholm, May 2004

Henrik Flemmer
List of appended papers

**Paper A**

**Paper B**

**Paper C**

**Paper D**

In all the papers, the research, the writing and the experiments were carried out by Henrik Flemmer. Bengt Eriksson contributed a lot by providing many ideas for the experiments. Both Bengt and especially Jan Wikander have done a great work in editing the papers.

Some of the published papers have before inclusion in the thesis been subject to minor editorial updates to improve language and clarity.
Other publications that are not appended


# Table of contents

Notation and list of abbreviations 2

1. **Introduction** 3
   1.1. Background and earlier work 4
   1.2. Motivation and aim of research 6
   1.3. Method and delimitation 6
   1.3. Thesis outline 7

2. **Teleoperator control** 8
   2.1 Controller design 8
      2.1.1. Interaction channel controller design 8
      2.1.2. Slave control loops 9
      2.1.3. Master controller 10
   2.2 Transparency analysis 11

3. **Robustness analysis of teleoperator systems** 12
   3.1 Passivity 12
   3.2. Real-time detection of non-passivity of the teleoperator 13
      3.2.1 Network theory 14
      3.2.2 Network theory applied to teleoperators 15

4. **Thesis summary and contributions** 19
   4.1. Paper A: Control Design for Teleoperators with Model Parameter Variation 19
   4.2. Paper B: Transparency and Stability Analysis of a Surgical Teleoperator 20
   4.3. Paper C: Aspects of Using Passivity in Bilateral Telemanipulation 20
   4.4. Paper D: Stabilization of Bouncing Teleoperators - A passivity Based Approach 20
   4.5. Experimental setup and investigated system 21

5. **Conclusions, future work and future additional functionality** 23
   5.1. Future additional equipment and functionality 23
   5.2. Recommended future research 24

6. **References** 26

Paper A 29

Paper B 45

Paper C 63

Paper D 87

Appendix 111
Notation

Upper case indicates frequency domain and lower case indicates time domain.

\( C_1(s) \) Interaction channel controller 1, communicates \( V_m \) to slave side.
\( C_2(s) \) Interaction channel controller 2, communicates \( F_e \) to master side.
\( C_3(s) \) Interaction channel controller 3, communicates \( F_r \) to slave side.
\( C_4(s) \) Interaction channel controller 4, communicates \( V_s \) to master side.
\( C_5(s) \) Local force compensator at the master side.
\( C_6(s) \) Local force compensator at the slave side.
\( C_m(s) \) Master damping and in some cases damping applied by the operator.
\( C_s(s) \) Slave feedback controller
\( E_c(t) \) Energy of the two-port controller.
\( E_m(t) \) Energy on the master port of the two-port controller.
\( E_s(t) \) Energy on the slave port of the two-port controller.
\( F_{am}(s) \) Control signal from master controller, i.e. desired master actuator force.
\( F_{as}(s) \) Control signal from slave’s controller, i.e. desired slave actuator force.
\( F_e(s) \) Contact force as measured by the force sensor on the slave.
\( F_r(s) \) Reflected force, the force the operator senses in the master.
\( G_{fr}(s) \) The gain between measured contact force and reflected force.
\( G_p(s) \) The gain between master position/velocity and desired slave position/vel.
\( h_{11}(s) \) H-matrix element, the reflected force dependency on the master velocity.
\( h_{12}(s) \) H-matrix element, the reflected force dependency on the contact force.
\( h_{21}(s) \) H-matrix element, the slave velocity dependency on the master velocity.
\( h_{22}(s) \) H-matrix element, the slave velocity dependency on the contact force.
\( V_m(s) \) Master velocity as measured by the sensors on the master.
\( V_s(s) \) Slave velocity as measured by the sensors on the slave.
\( Z_m(s) \) Master open loop impedance.
\( Z_s(s) \) Slave open loop impedance.

List of abbreviations

dSPACE\textsuperscript{TM} Manufacturer of the rapid control prototyping card.
FF Force force teleoperator control structure.
FV Force velocity teleoperator control structure.
PD Proportional and derivative controller.
TCP Tool centre point, the tool attachment point on the manipulator.
VV Velocity velocity teleoperator control structure.
1. Introduction

The research work reported in this thesis has been carried out within the Skullbase project at the Mechatronics Lab, the Department of Machine Design, KTH. The aim of the project is to study the possibilities for introduction of a teleoperator system with force reflection in skullbase operations. In a skullbase operation, the surgeon’s task is to remove cancer tumours lying in the brain or in the vicinity of the brain. The surgeon has to remove parts of the skull bone by milling to reach the tumour. Today, these operations are performed by the surgeon holding the milling tool in the hand while bending over the patient in an uncomfortable position. As the milling procedure proceeds into the bone, the mill reaches regions where the bone has a geometrically complicated structure and is surrounding neurons, brain tissue and critical parts of the nervous system. As a consequence, the surgeons often need to pause the milling and use literature and computer tomography images of the actual patient to orient themselves in the bone and to decide where to mill in the next moment. By introduction of a teleoperator system in a skullbase operation, the position, orientation and 3-D representation of the tumour, the skullbone (i.e. the patient’s head) and the mill are synchronized in the same coordinate system based on information provided by the computer tomography images. The mill is mounted in the slave’s tool centre point (TCP) (see Fig. 1) and its position in the bone is visualized to the surgeons in real time in a virtual representation of the patient’s scull. In this future scenario, the surgeon controls the milling process through the master while sitting comfortably in a chair beside the patient with a good overview of the actual working area and the monitors showing the mill’s progress through the bone.

![Diagram of a teleoperator system](image)

**Figure 1. Schematic picture of a teleoperator in operation.**

Besides making the operation more ergonomically adapted to the surgeon, the teleoperator system can make the milling process safer and less time consuming. Today, the milling phase of a skullbase operation can take several hours and is very tiring for the team of surgeons working with the patient. Since these operations are time consuming and require specialist competence, the cost for one operation is high. Reduction of operation time by only a few percent will in the long run save society large expenses.

In such a fine and precise operation as a skullbase operation, the surgeons often need to use their skills to the maximum which imposes high requirements on the teleoperator...
transparency. The term transparency is defined to describe the similarities in terms of “feeling” between performing a task with the teleoperator and performing the same task manually without the teleoperator. If the “feeling” is exactly the same, transparency is said to be one. Although transparency is highly important for a successful teleoperator, robustness of the teleoperator closed loop against all possible variations in operator and environmental dynamics is as important as transparency. Unfortunately, the stability of the teleoperator closed loop is often poor or none at all if the transparency is high and vice versa as mentioned in for instance Hannaford et al. (2002), Ryu et al. (2002) and Yan et al. (1996). As a consequence, a high transparency teleoperator system can often start to oscillate in an uncontrollable way if the slave experiences a contact with a stiff environment. This is not due to the stiff contact in itself, the oscillations are induced by the discrete change of dynamics and the non-linearities involved in at the instant of contact with the stiff environment. This is a highly relevant problem for the actual research application where the slave encounters human bone with a stiffness ranging from high on its surface to less in its interior. Controlling teleoperators when stiff contacts between the slave and the environment are involved has been studied through the years, see for example Hannaford (May 1989), Ryu et al. (2002) and Hannaford et al. (2002). But still, there is no general control solution available with enough robustness, high transparency and applicability when stiff contacts are involved.

This thesis focuses on analysis, design and performance evaluation of control methods for the teleoperator in general and in particular for the case when stiff contacts are involved. Methods ranging from linear analysis to the concept of passivity are utilized to increase the understanding of the phenomena occurring in a teleoperator subject to stiff contacts between the slave and the environment.

1.1. Background and earlier work

The Skullbase project started out as a Mechatronics higher course project. Within the higher course, the master of science students in the fourth year are trained to work in a large team to solve a more complicated task in close cooperation with industry or academia. When the students graduated from the course, they had built a prototype slave manipulator controlled by a joystick not supporting force feedback. The work leading to the Licentiate thesis (Flemmer (2000)) started from there. The licentiate thesis incorporated 4 papers Flemmer et al. (1998), Flemmer (1999), Flemmer et al. (1999) and Flemmer et al. (2001) covering:

- Reconstruction of the slave manipulator to reduce the backlash in the joints. This was done by using Harmonic Drive [20] gears instead of planetary gearheads. Harmonic Drive gears are almost backlash free but they suffer from non-linear friction which was compensated for by using a non-linear friction model resembling the one developed in Tuttle et al. (1996) and feed forward control.
- Construction of a haptic interface. An industrial joystick was bought and equipped with dc motors for torque generation.
- An investigation covering most of the existing control methods for force reflective master and slave systems.
- Equipping the slave manipulator with a force sensor mounted at the final link of the slave.
• Implementation and evaluation of a few of the classical control methods on the experimental setup.

The first paper in the Licentiate thesis is a technical report explaining the basics in control of force reflective master slave systems. The study starts with two classical control structures, the force-velocity (FV) structure (denoted forward flow in Hannaford (August 1989)) and the velocity-velocity (VV) structure. In the first structure, the measured contact forces (measured by the force sensor at the slave) are fed back to the master scaled via the force reflection gain \( G_{fr} \). The positions of the master are sent as references to the slave servo loops scaled via the position gain \( G_p \). In the second structure, the position error between the slave’s requested position and its true position serves as force reference to the actuators at the master. The poor performance of these structures during stiff contacts in terms of allowable force reflection gains and position gains have resulted in structures like shared compliance control from Kim (1992). In shared compliance control, the contact force information from the force sensor is used to alter the references to the slave servo loops to make the slave control loop less stiff when in contact. This structure allows for slightly higher values of \( G_{fr} \) and \( G_p \) but still, performance is not acceptable. The control structure survey ends up with Lawrence’s (1993) four channel control structure by which all other control methods can be described. The survey also includes a few linear models suitable for describing the operator hand/arm and the environment. These models are needed since both operator and environment are included in the teleoperator closed loop and hence affect the robustness of the teleoperator system.

The second paper in the licentiate thesis is a conference paper in which the FV and VV structures are implemented and tested on the experimental setup. The experimental findings in terms of allowable \( G_{fr} \) and \( G_p \) are confirmed by a theoretical stability analysis. The VV structure is found not applicable to the actual research problem since the position error of the slave is related not only to the relatively small cutting forces but also to friction forces and other disturbances. This is likely to cause transparency problems in the actual task.

The third paper in the licentiate thesis is a journal paper in which the influence on teleoperator robustness from the dynamics in the hand grip around the master is examined. The result from the simulations with the identified dynamic model of the coupled master and finger system is that a too compliant and low damped operator grip around the master can cause the teleoperator to start oscillating when contact with a stiff environment is made. It is also shown experimentally in the paper that control methods capable of altering the slave’s stiffness during contact with the environment, like shared compliance control, allow for slightly higher \( G_p \) and \( G_{fr} \) without losing stability.

The fourth paper in the licentiate thesis is a conference paper. A dynamical model of the slave manipulator is identified including non-linear joint friction which is the dominant non-linear phenomenon of the slave dynamics since the coriolis and gravitational contributions are negligible. A model of the contact dynamics is identified from the experimental setup with the mill switched off and in constant contact with the environment. The differences compared to the case when the mill is switched on are discussed. These models together with the model of the coupled master human system from the third paper form a model framework for the total teleoperator system. From the model framework and for a fixed position gain \( G_p \), theoretical upper bounds on \( G_{fr} \) for three differ-
ent control structures are derived for a given stability margin. The control structures are: FV, FV with shared compliance control and Hogan’s (1985) impedance control concept implemented on the slave. Impedance control is here used as if the mill tip of the slave was connected to the base coordinate system with a spring and a damper of designed characteristics. Hogan proposed that the manipulator inertia could be altered to a desired inertia by using actuator power. This is omitted in this version of impedance control and the inertia of the slave is left unchanged. The force reflection is simply the measured contact force fed to the master’s actuators via the force reflection gain as in the FV structure. The theoretical bounds on \( G_{fr} \) are verified experimentally for all three control structures in two steps. First, a \( G_{fr} \) 30% below the theoretical bound was implemented and the user could perform a low velocity contact with the environment, stay in contact, leave the contact and repeat the procedure. Second, a \( G_{fr} \) 30% above the theoretical limit was implemented and the user had serious difficulties to perform a stable task which then confirms the analysis in terms of the critical force reflection gains.

The work presented in the papers in this thesis is a result of a continued research effort motivated by the limited teleoperator performance achievable with the existing and evaluated methods.

1.2. Motivation and aim of research
As indicated above, the aim of the research covered in this thesis has mainly been to increase teleoperator performance when the stiff slave manipulator experiences contacts with a stiff environment. One solution to the stability problem occurring in the contact instant is to reduce the stiffness of the slave servo loop, but that would give unacceptable control performance for small motions and, the slave’s position response would be greatly affected by external forces such as the contact force. As a first step to understand how to increase teleoperator transparency, the four channel structure with interaction channel controllers derived from an optimal transparency point of view as suggested in Hashtrudi-Zaad et al. (1999) is valuable. Regarding the robustness, robustness analysis of any teleoperator structure based on continuous contact between the slave and the environment introduces a coarse simplification and the result of the analysis is often invalid when the slave experiences an impact with the environment above a certain velocity. To cope with the stiff contact induced stability problems and at the same time assure teleoperator transparency, variable structure control approaches as presented in Hannaford et al. (2001), Hannaford et al. (2002) and Ryu et al. (2002) motivate the use of the passivity concept to detect when the teleoperator system turns non-passive and stability is no longer guaranteed.

The physics involved in the contact itself is not treated in the thesis, only its effect on the teleoperator system. This is motivated as follows. If the teleoperator can be kept passive through all times during the operation, stability is guaranteed independent of the properties of the objects involved in the contact.

1.3. Method and delimitation
When the research project first started, the prior knowledge in the area of controlling force reflective master slave systems was limited. To be able to test available control methods, the experimental setup was upgraded with a powerful rapid control prototyping
tool for fast and easy implementation of control structures and data collection. With the upgraded experimental setup in operation, testing and performance evaluation of different available control structures could be done very efficiently. The performance of the tested two-channel control structures was found insufficient in terms of transparency and robustness to varying characteristics of the environment and operator’s grip around the master. Due to the poor performance of the tested structures especially when the stiff slave makes contact with a stiff environment, new approaches for understanding the factors affecting both the transparency and the teleoperator robustness were needed. The focus of the research leading to the papers in this thesis was therefore put on transparency and robustness even though there are many other research issues needing to be addressed before a skull base operation can be performed with a teleoperator in a real situation. This choice was motivated by the importance of these two factors for the success of a future teleoperator. Some of the other research issues are discussed in section 5.2. Another delimitation of the scope of this thesis is that the master lacks a force sensor, extension of the master with a force sensor can provide many interesting possibilities but is left out for the future.

As always when doing control development, new ideas are evaluated in simulations using, in this case, Matlab/Simulink™ before implemented on the experimental setup. These simulations require models of the actual hardware together with parameter values identified on the experimental setup. Identification of parameter values is easily performed on the experimental setup using the rapid control prototyping tool for collection of data and Matlab™ for running the identification process itself.

After testing the new control ideas in simulations, implementation on the experimental setup is easy since the controllers are implemented in the same environment. The only difference is that the hardware models used in the simulation simply are exchanged for hardware interface blocks connected to the experimental implementation. Experimental validation of dynamic models and other ideas has been utilized frequently during the research in this thesis since it gives a direct indication of the usability and validity of the work.

1.4. Thesis outline

This thesis consists of this introductory part, four recent papers that contribute in different ways to the actual research results and an appendix with the complete simulation model of the actual teleoperator system. The four papers Flemmer et al. (2002), Flemmer et al. (March 2003), Flemmer et al. (May 2004) and Flemmer et al. (2004) will in the following be referred to as papers A, B, C and D respectively.

This first part is continued in section 2 which introduces the reader to teleoperator controllers, their structure and control synthesis - how to design different teleoperator controllers. This is followed by a section regarding transparency analysis and section 3 which presents robustness and passivity analysis methods for teleoperators. In section 4 the appended papers are summarized and briefly discussed. Section 5 closes the introductory part with some concluding remarks and some ideas for future work both regarding teleoperator control and regarding the actual research application.
2. Teleoperator control

This chapter is intended to give an overview of the control structures in a teleoperator system as well as a few methods for analysing teleoperator transparency and robustness.

2.1. Controller design

Basically there are three groups of controllers to design in a teleoperator, these are: The interaction channel controllers $C_1$ to $C_4$ (see Fig. 2), the slave control loop and finally the master control loop. These three groups of controllers are discussed in the following.

2.1.1. Interaction channel controller design

In the recent decades, there have been several teleoperator control architectures developed. Usually, they are classified depending on the signals the master and the slave exchange. Basically there are four signals of interest to exchange between the two sides of the teleoperator, these are the velocities for the slave and the master and the corresponding forces. This is used in the four channel structure which is depicted in a simplified version in Fig. 2.

![Figure 2. The four channel structure.](image)

In Fig. 2, $V_s$ is the velocity of the slave, $F_e$ the total environmental force, $F_r$ is the reflected force i.e. the force a force sensor mounted on the master stick would measure and finally, $V_m$ is the velocity of the master as measured by the sensors on the master. The four interaction channel controllers $C_1$ to $C_4$ can be either gains or transfer functions deciding the gain and frequency dependence of each interaction channel.

The FV control structure often leads to instability for the case when the environment is much stiffer than the operator’s grip around the master as mentioned in Hannaford (May 1989). As a consequence, the FV structure is extended with extra damping at the master side at the cost of reduced transparency as discussed in Flemmer et al. (2004). The shared compliance control concept used in Kim et al. (1992) and Kim (1992) also improves the poor stability margins of the FV control structure at the cost of reduced transparency.
In Kazerooni et al. (1993) the force-force (FF) control architecture is proposed. In this structure, the master feeds the reflected force $F_r$ to the slave which returns the measured contact force $F_e$. This structure suffers from poor performance when the stiffness and damping of the environment are small. In this case, a large reference force from the master device can give undesirable large slave motions.

The velocity-velocity (VV) control structure uses the master’s position or velocity as reference to the slave and the position error of the slave as basis for the feedback force to the master. As discussed in Flemmer et al. (1998), the velocity-velocity control structure suffers from poor transparency if the slave’s servo loops and the environment are stiff.

All of these control structures show different performance in different operating cases and they can all be represented by the four channel control structure which is discussed in Lawrence (1993). But, as reported by Hashtrudi-Zaad et al. (2000) and as can be concluded from the above discussion, there is a trade-off which control type should be dominating for each operating case. This is mainly depending on the characteristics of the encountered environment.

As mentioned for example in Hashtrudi-Zaad et al. (2000) and Yokokohji et al. (1992), the four channel teleoperator control structure can be designed such that the transparency is 1 for a linear system being in constant contact with the environment. This is of course depending on actuator power, the actuators need to feed forward forces related to the inertia of both the master and the slave, structural damping and friction completely. This is possible to achieve up to some frequency and with an extensive identification effort performed on the actual hardware. But as actuators always have limited bandwidth, transparency can not be 1 over the complete frequency range. On the other hand, the reference generation at the master performed by the human operator has a limited frequency content since the human hand is incapable of generating high frequency position or force signals.

As said, all control structures can be derived from the four channel structure. Apart from differences in local controllers on the master and slave side, the difference between different control concepts lies in the design of the interaction channel controllers.

2.1.2. Slave control loops
A commonly used control concept on the slave side of the teleoperator is to close position/velocity control loops around each axis of the slave. Hogan’s (1985) impedance control concept is appealing for control of the slave manipulator in teleoperator applications. The advantage with impedance control is that the end effector of the slave appears to be connected to the base coordinate system with a spring and a damper in all three directions. The characteristics of these springs and dampers can then be tuned by the control designer to a desired behaviour. The natural frequency of the slave closed loop is often tuned as high as possible in order to obtain a quick response to reference changes and keep the slave quite unaffected by external forces.
In Fig. 3, $F_{as}$ is the desired slave actuator force going to the slave mechanism, $C_s$ the slave’s feedback controller, $C_5$ is a local force compensator used for stability purposes in Hashtrudi-Zaad et al. (1999) and $Z_s^{-1}$ is the mechanical impedance of the slave. Note that the signal flow going to the master from the slave is left out in Fig. 3 for clarity. The kinematics and the mapping of forces to the slave’s generalized coordinates are also left out for clarity. For the actual slave manipulator, the kinematics, the dynamics and the sensor configuration can be found in the appendix. The most common way of controlling the slave in teleoperator applications is to use a position/velocity loop or a force control loop.

2.1.3. Master controller
In Fig. 4, the master is in focus. $C_m$ represents the structural damping in the master itself and damping applied by the human operator, $F_{am}$ is the desired master actuator force, $Z_m$ is the impedance of the master and $C_6$ is a master force controller used for stabilization purposes.

Figure 3. Teleoperator structure with focus on the slave manipulator. The signals from the slave to the master are left out for clarity.

Figure 4. Teleoperator structure with focus on the master. The signals from the master to the slave are left out for clarity.
Note that the signal flow going from the master to the slave is left out for clarity in Fig. 4. In Hashtrudi-Zaad et al. (2000), the damping in $C_m$ is extended with an extra damping for stabilization purposes. In for instance Bu et al. (1996), the master has no controller. The measured contact force is simply scaled by the force reflection gain and the inverse of the actuator’s torque constant before put out as a control signal to the actuators at the master.

In Chan et al. (1996) the master is controlled such that it behaves as a desired impedance. They discuss guidelines for the selection of the desired impedance for the master. Their solution has similarities to the design in Hannaford (August 1989), where the master control loop is designed to get the master’s impedance equal to the estimated environmental impedance.

### 2.2. Transparency analysis

One way of analysing teleoperator transparency is to study the four transfer functions in the teleoperator’s H-matrix. The H-matrix relates the inputs master velocity $V_m$ and measured contact force $F_e$ to the outputs reflected force $F_r$ and slave velocity $V_s$ as:

$$
\begin{bmatrix}
F_r \\
V_s
\end{bmatrix} =
\begin{bmatrix}
h_{11} & h_{12} \\
h_{21} & h_{22}
\end{bmatrix}
\begin{bmatrix}
V_m \\
F_e
\end{bmatrix}
$$

The elements in the H-matrix are typically linear and hence based on certain simplifications since there are non-linearities in real teleoperators. The result from the transparency analysis using the H-matrix should hence be interpreted with some caution.

A large gain in $h_{11}$ indicates that the velocity of the master affects the reflected force to a great extent which is undesired from a transparency point of view since this can be interpreted as damping in the master. $h_{12}$ describes the reflected force’s dependency on the measured contact force. The gain of $h_{12}$ should for optimal transparency be equal to the user requested force reflection gain and remain unchanged over frequency. $h_{21}$ describes how the velocity of the slave depend on the velocity of the master. For optimal transparency, the gain of $h_{21}$ should be equal to the position gain $G_p$ and like $h_{12}$ remain unchanged over frequency. $h_{22}$ describes to what extent the contact forces affect the slave’s velocity and position. A small gain in $h_{22}$ indicates stiff slave position servos which is desirable from a transparency point of view.

As mentioned by for instance Hannaford (August 1989) and Salcudean (1998) an ideal teleoperator has an H-matrix as

$$H_{ideal} = \begin{bmatrix} 0 & G_{fr} \\ G_p & 0 \end{bmatrix}$$

indicating that the reflected force at the master only should be affected by the contact force $F_e$ scaled via the force reflection gain. And, that the velocity of the slave only should be affected by the master’s velocity scaled via the position gain.
3. Robustness analysis of teleoperator systems

Analysing teleoperator robustness is a difficult task since the dynamics of both the operator holding the master stick and the environment are included in the teleoperator closed loop. A robustness analysis based on the characteristics of the teleoperator closed loop transfer function around the teleoperator, including models of the environment and the human operator, can be found in Bu et al. (1996). Stability of the closed loop can be judged from the pole locations of this transfer function. In Lawrence (1993), the closed loop is divided into two transfer functions and stability is given provided that these two transfer functions are passive. The drawback with the above mentioned methods is that design models covering the environment, the human operator and the complete teleoperator with controllers must be included. These design models are often assumed linear whereas reality can be far from linear and the outcome of the robustness analysis can be misleading.

The LTI restriction of these methods has prompted the usage of other methods for analysing teleoperator robustness covering the linear as well as the non-linear case. The concept of passivity is a promising concept not restricted to linear systems. Introduction of passivity based analysis into teleoperator robustness analysis has provided interesting results such as the approach presented in Ryu et al. (2002) where passivity is used for real-time compensation of non-passive teleoperator behaviour.

3.1. Passivity

As mentioned in Lawrence (1993), if a system can be shown passive, it is thereby stable. Physically, passivity can be interpreted as: For zero initial energy storage, a device is passive if cannot increase the total energy in a system in which it is an element, (Yan et al. (1996)). Since passivity applies to both non-linear systems and linear systems, passivity is promising in teleoperator control.

As a consequence of the fundamental passivity result as presented in Sepulchre (1997) or the “passivity theorem” in Doeser (1975), for the linear system in Fig. 5, the phase lag between the reference \( r \) and the output \( y \) can not be larger than 90 degrees if the manipulator itself and its controller are passive. The fundamental passivity result says that the negative feedback loop of two linear, detectable (all unobservable parts of the system asymptotically stable) and passive systems also is passive since the phase lag of the loop gain never is larger than 180 degrees independent of the feedback gains. This result is also denoted the Nyquist-Bode criterion. In Lawrence (1993), a complete teleoperator control design is done based on the fundamental passivity result. This design is based on linear design models and assure teleoperator stability by designing the loop gain phase lag less than 180 degrees for all frequencies. A loop gain phase lag less than 180 degrees is accomplished by requiring one of the passive blocks in Fig. 5 to be strictly passive. Such a system has then an infinite gain margin since the phase lag of the loop gain never reaches 180 degrees.
In a real teleoperator system, there are non-linear dynamics as well as linear, therefore, the analysis also needs to cover the non-linear case.

For a nonlinear system $NS$ with input $u$ and output $y$, one can define a supply rate function, $w(u,y) = u^Ty$, associated with $NS$ satisfying $\int_{t_0}^{t_1} |w(u(t), y(t))|dt < \infty$ for all $t_0 \leq t_1$, (Sepulchre et al. (1997)). Based on the supply rate function, a storage function, $s(x(t))$, for $NS$ can be defined as

$$s(x(t)) = \int_0^t w(u(t), y(t))dt + s(x(0))$$  \hspace{1cm} (3)

where $s(x(0))$ is the storage function at $t = 0$.

$NS$ is passive if and only if there are no unobservable states in $NS$ and $s(x(t))$ satisfies

$$s(x(t)) \geq 0$$  \hspace{1cm} (4)

From Sepulchre (1997), the negative feedback loop formed by two non-linear and passive systems is also passive.

For the storage function in eqn. (3) to decrease and with time turn negative, the supply rate function must turn negative which occurs if the signs of $u$ and $y$ are different.

### 3.2. Real time detection of non-passivity of the teleoperator

Real time compensation of non-passive states of the teleoperator is a very promising control concept since transparency can be high most of the time and only degraded when necessary for stabilization purposes. Hence, the design of the teleoperator control architecture can mainly be aimed at transparency instead of the traditional trade-off between stability and transparency. Of course stability issues have to be kept in mind during the design phase but to a smaller degree than before since the passivity assuring control portion can stabilize the system if needed. It may even be possible to use an existing control architecture and make it stable for another operational condition if the controller is extended with a passivity assuring control portion, (Ryu et al. (2002)).
Real-time detection of non-passive control system behaviour by monitoring properties of the signals involved in the dynamical interaction between the elements of the control system can be done by using tools from network theory. Therefore, a presentation of network theory and its application to teleoperator control is given in the following section.

3.2.1. Network theory
A general one-port network, $N$, as depicted on the left in Fig. 6 with initial energy storage $E(0)$ is said to be passive if and only if (from Doeser (1975))

$$\int_0^t f(\tau)v(\tau)d\tau + E(0) \geq 0$$

where $f$ is the effort applied across the port and $v$ is the flow flowing through the port. In the context of mechanical systems, when discussing dynamic interaction between network elements, $f$ corresponds typically to the interaction force between two adjacent elements and $v$ typically describes the velocity of the body on which $f$ acts.

Figure 6. Graphic representation of a one-port and an $M$-port networks.

Eqn. (5) states that, for the network $N$ to be passive, the energy supplied through its port via $f$ and $v$ plus the initial energy $E(0)$, must be greater than zero. Eqn. (5) can be extended to cover the $M$-port network, $N_M$, as depicted on the right in Fig. 6 as (from Hannaford et al. (2002))

$$\int_0^t (f_1(\tau)v_1(\tau) + \ldots + f_M(\tau)v_M(\tau))d\tau + E(0) \geq 0$$

The energy is thus the sum of all energies present on all the ports of the network.

For a general network consisting of $P$ arbitrarily connected network elements, the total energy in the complete network for zero initial energy is given by the sum of the energies for each individual element. Passivity for such a network is given if and only if the sum of the energies is larger than or equal to zero.
3.2.2. Network theory applied to teleoperators

Fig. 7 shows a five block representation of the teleoperator where the components of the teleoperator are represented by network elements.

![Diagram of five block network representation of the teleoperator structure.](image)

Figure 7. Five block network representation of the teleoperator structure.

In Fig. 7, energy flows from the operator into the teleoperator (marked by the dashed square) and out from the teleoperator to the environment. $I$ and $U$ represent the current and the voltage to the amplifiers of the actuators respectively. The actuators of the teleoperator are placed in the controller block. Hence, the forces $f_{as}$ and $f_{am}$ are the forces from the actuators to the respective mechanics, i.e. the actuators are regarded as ideal force sources without internal inertia. By doing this, Hannaford et al. (2002) argues that the master and the slave blocks in Fig. 7 can be considered as passive since they are incapable of generating energy. From a phase lag point of view, the requirement of passive mechanics implies that the phase lag from input force to output velocity never is larger than 90 degrees. This can be achieved if there is no flexibility in the mechanics which would result in a second order system with a maximum phase lag as large as 180 degrees from input to output for higher frequencies. All manipulators have at least one flexibility in their structure, but if excitation of the flexible mode never occurs when operating, the manipulator will act as passive.

In Fig. 7, $\dot{Q}_c$, $\dot{Q}_e$, $\dot{Q}_m$ and $\dot{Q}_s$ are the heat flows dissipated from the controller, the environment, the master and the slave respectively. The heat flows $\dot{Q}_c$, $\dot{Q}_m$ and $\dot{Q}_s$ are consequences of friction in the mechanics of the master and the slave and resistance in actuators and amplifiers. $\dot{Q}_e$ is due to heat dissipation to the environment.

In the ideal case, the heat losses in the weightless teleoperator mechanics are zero, the mechanics of the teleoperator is infinitely stiff and the electrical energy injected through the electrical port is equal to the heat dissipation from the controller, $\dot{Q}_c$. For this ideal case, all the mechanical energy that the human inputs at the master is in the controller transformed to electrical energy. This electrical energy is, within the controller, transformed back to mechanical energy and injected into the slave which in turn transfers it to the environment where it is dissipated, see Fig. 8. This is as Handlykken et al. (1980)
described the ideal teleoperator: In the ideal case, the teleoperator acts as an infinitely stiff and weightless mechanical link between the operator and the environment.

Figure 8. The ideal teleoperator, the dashed square represents the teleoperator controller with its ideal two way energy transformers capable of transforming mechanical energy to electrical or vice versa without any losses.

However, all mechanical systems have a moving mass and suffer from friction, hence energy is required to overcome friction and to accelerate the moving mass to the desired velocity. In a teleoperator system, the master is usually designed such that its moving mass and frictional losses are as small as possible, (Buttolo et al. (1995)). Hence, the heat dissipation, the kinetic and potential energy of the master are neglected in this discussion. For the slave manipulator, frictional losses and moving mass can be large depending on teleoperator application. For example, the present slave manipulator in the experimental setup has a moving mass of around a few kilos for one specific axis of motion and a relatively large frictional loss for the same axis. Hence, the mass of the slave and the counteracting forces are larger than those of the milling tool in the current manual operations. Acceleration of the slave manipulator requires thus a certain amount of energy from the controller. In the free space motion case, there is no contact force to reflect to the master, hence, the energy on the master port of the controller is zero. Thus, all the energy required by the slave manipulator to perform the requested motion must originate from the electrical port of the controller.

In the actual teleoperator application, there is a need for amplification and reduction of the motions and forces by the position gain, \( G_p \), and by the force reflection gain, \( G_{fr} \), respectively. Introduction of these gains changes the relation between the amounts of energy present on both sides of the teleoperator controller as can be seen in the following example.

**Example.** Suppose that an ideal teleoperator is operating in steady state motion, with a constant velocity and in contact with a passive environment only consisting of a damper. For this case, the energy dissipated to the environment is the same as the energy that the controller injects into the slave. On the master side of the controller, the same applies, the energy that the operator inputs in the master is equal to the energy that the controller receives from the master. The energies on the master and slave ports of the controller are given by

\[
E_m = \int_0^t f_r v_m \, dt \quad E_s = \int_0^t f_e v_s \, dt
\]

(7)
where $E_m$ is positive, $E_s$ is negative and indices $m$ and $s$ indicate master and slave respectively. When the gains are introduced, the velocity of the slave is given by $v_s = G_p v_m$ and the force to the mechanics of the master from the operator $f_r = -G_{fr} v_e$. Inserting these conditions into eqn. (7) and deriving the energy of the two-port controller, $E_c$, gives

$$E_c = (G_p - G_{fr}) \int_0^t f_e v_m \, dt$$

(8)

The energy described by integration of $f_e v_m$ over time is always negative for the passive environment, thus, eqn. (8) can be written as

$$E_c = -1(G_p - G_{fr}) \int_0^t f_e v_m \, dt = (G_{fr} - G_p) \int_0^t f_e v_m \, dt$$

(9)

The result in eqn. (9) indicates that if $G_p$ is larger than $G_{fr}$, the energy level of the controller grows negative and the controller violates the passivity definition in eqn. (5) unless energy is injected into the controller through the electrical port. If $G_p$ is smaller than $G_{fr}$, the energy level in the controller will increase. However, this is not possible since the controller lacks energy storage capabilities and energy can not be removed from the controller through its electrical port, the energy surplus has to be removed through heat dissipation.

For the ideal teleoperator, the conclusions are.

- For $G_p > G_{fr}$ energy has to be injected into the teleoperator controller through its electrical input.
- For $G_p < G_{fr}$ energy has to be removed from the teleoperator controller by heat dissipation.
- If $G_{fr}$ and $G_p$ are equal, the energies are equal on both sides of the teleoperator controller.

The findings are summarized in Fig 9.

![Figure 9. Energy flows through the ideal teleoperator and their dependence on $G_p$ and $G_{fr}$.]
In Ryu et al. (2002) it is claimed that to assure passivity of the complete teleoperator for all times, it is enough to assure passivity of the two-port teleoperator controller for all times if the slave and the master are passive. Regarding the teleoperator controller as a two-port implies neglecting its heat loss and electrical energy input from the analysis. From the above discussion, it is necessary to require equal $G_p$ and $G_f$, for the success of the method. It is also important to design the mechanics of the slave such that its moving mass and frictional losses are small. This is due to that the position/velocity controller of the slave always tries to fulfill its goal $v_s = G_p v_m$. Hence, the energy amount that the controller must inject into the slave can be large if the frictional losses, mass and desired velocity of the slave are large. The controller receives amounts of energy from its electrical port to cover these energy needs. This energy flow is hence only visible as an energy loss for the controller when regarding the controller as a two-port.

Hence, it is likely that the kinetic energy of the slave and the energy dissipated as heat through friction will cause the detection method presented in Ryu et al. (2002) to falsely detect non-passive behaviour of the teleoperator controller if the mass, and the frictional losses of the slave manipulator are large. Hence, for these circumstances, the detection method is over conservative.

For the assumption of passive teleoperator mechanics to hold, the phase lag between $f_{as}$ and $v_s$ or $f_{am}$ and $v_m$ must not be larger than 90 degrees. As mentioned, if there is a flexibility in one of the mechanical structures, this flexibility will for some frequencies introduce a phase lag larger than 90 degrees between the force and its corresponding velocity. From an energy point of view, a phase lag larger than 90 degrees will cause the mechanics to act as non-passive and hence, indicate that energy is injected into the controller.

Summarizing the discussion, judging passivity of the teleoperator from regarding the teleoperator controller as a two-port is according to the above discussion applicable and accurate only if the following holds. Equal position and force reflection gains, negligible kinetic, potential and frictional energies to the slave from the controller and passive and light-weight master and slave mechanics.
4. Thesis summary and contributions

The four papers included in this thesis contribute in different ways to the aim of understanding the underlying factors affecting teleoperator transparency and how stiff contacts between the slave and the environment affect teleoperator stability. The first paper, A, describes an identified model of the combined master and human system followed by derivation of interaction channel controllers optimized for transparency based on the master human model. In paper B, a three channel teleoperator is analysed with respect to transparency and stability using passivity. In paper C, passivity of the teleoperator controller is analysed for the case when the slave interacts with a stiff environment. Paper D is a follow up on paper C and presents a new method for detecting non-passive teleoperator behaviour. When non-passive teleoperator behaviour is detected, a control signal from a stabilization control portion is appended to the original master control signal and manages to stabilize the teleoperator in a relatively short time after the non-passive behaviour was detected. Hence, the stabilizing control portion temporarily augments the master controller such that a variable structure controller is achieved.

In this section, the four papers are summarized and their contributions are highlighted. Finally, the section ends up with a presentation of the experimental setup and a schematic representation of the investigated system.

4.1. Paper A: Control Design for Teleoperators with Model Parameter Variation

In paper A, a dynamic model of the combined master and human finger system is derived and bounds on its parameter ranges are identified from the experimental setup and the author’s fingers. By using the optimal transparency goals as specified in section 2.2, the governing equations of the four channel teleoperator structure and the master human finger model, the interaction channel controllers are derived. One of the interaction channel controllers is found to contain a parameter uncertainty originating from the master human finger system. This interaction channel controller is set to zero to avoid influence of the parameter uncertainty in the interaction channel. The resulting teleoperator control structure is thus a three channel system. To fulfil the transparency goals as good as possible despite one interaction channel being set to zero, a cascaded control loop around the master is formed and designed using loop shaping techniques from Bailey et al. (1991). The control performance for the master control loop in terms of bandwidth from measured contact force to reflected force was increased and the gain peak present in the non compensated transfer function was significantly reduced. Due to the ranges on the parameters in the master human finger system model, the frequency response of the transfer function from measured contact force to reflected force has a spread in its gain, this spread is significantly reduced by the cascaded loop. The paper ends up with a stability analysis which confirms the experimental results in terms of allowable force reflection gains when operating in constant contact with the environment.
4.2. Paper B: Transparency and Stability Analysis of a Surgical Teleoperator

Paper B builds on the control structure developed in paper A and analyses the transparency of the structure as well as the stability with a method based on passivity. The transparency is analysed by looking at the bandwidths of the four elements in the H-matrix. The stability analysis is taken one step further compared to paper A and is based on passivity and positive real transfer functions. As in paper A, the stability analysis is based on the slave being in constant contact with the environment. It is shown that the design models covering the complete teleoperator structure including the environment describe a passive system. Experimental results verify the theoretical ones in terms of the possibilities to perform a stable operation while in contact with the environment for the actual values of the position gain and of the force reflection gain.

The fact that the stability analysis assumes the slave to be in constant contact with the environment limits the usability of the method, thus prompting development of other methods for analysing stability of the teleoperator system for more realistic scenarios. This fact leads to paper C and its ideas on how to detect non-passive states of the teleoperator in real time.

4.3. Paper C: Aspects of using Passivity in Bilateral Telemanipulation

As the stability problems often occur when the interaction between the slave manipulator and the environment is stiff, the stability analysis needs to cover the contact instant as well as the in-contact phase. A research effort was then needed to take the stability analysis from papers A and B a step further to cover the contact instant itself. The dynamics involved in the contact phase is assumed non-linear, therefore methods capable of handling non-linear phenomena need to be incorporated. The passivity based idea of monitoring the energies flowing in and out of the teleoperator controller is analysed theoretical and in experiments. This is done to test the usability of one existing method for detection of non-passive teleoperator behaviour. The conclusion from the theoretical analysis was that the method has limitations. For instance, the method requires that the slave and master mechanics are passive and that the scalings $G_{fr}$ and $G_{p}$ have the same numerical value. The experimental results showed that the mechanics of the slave contained at least one flexibility which makes it non-passive for certain frequencies, unfortunately, at the frequencies occurring when the instability problems occur. Hence, it is difficult to detect the non-passivity of the actual teleoperator with the tested detection method. Another detection approach is necessary to derive for this case. In the search of new approaches, a simulated DC-motor control example made non-passive on purpose between randomly chosen time instants is studied, and as a result, a few ideas for future work within detection of non-passive behaviour are presented.

4.4. Paper D: Stabilization of Bouncing Teleoperators - A Passivity Based Approach

Paper D continues the work from paper C on how to use passivity theory applied to non-linear systems for detection of non-passive teleoperator behaviour in real time. The results are a detection algorithm based on the concept of passivity as well as a stabiliza-
tion controller. In the detection algorithm, the complete teleoperator closed loop is included in the detection path. The detection algorithm is based on regarding the velocity of the master as the sum of two velocities, one related to the force feedback and one related to the operator’s input. By splitting the velocity of the master into two components, a single loop representation of the teleoperator closed loop can be made with the force feedback induced master velocity as feedback signal. The components of the single loop representation of the teleoperator structure is then grouped into two blocks. One block contains the slave side from master velocity input to slave velocity output and the second block contains the environment, the reverse channel and the combined master and human operator model. If the storage functions defined as in eqn. (3) associated with each of these two blocks never are negative, the single loop representation is passive by eqn. (4) and thereby the complete teleoperator as well. But if one of the storage functions turn negative, passivity of the single loop representation is violated.

If the teleoperator has been operating for a while in a passive manner, positive values can be accumulated in the storage functions and detection of non-passive behaviour will be delayed until one of the accumulated values have been reduced below zero. To handle this problem without having to wait with an oscillating teleoperator until one of the storage functions are reduced below zero, the calculation of those is resetted every time the absolute value of the contact force leaves the zero level, i.e. at the instant of contact. If one of the storage functions turns negative after being resetted, i.e. the slave has experienced a contact and the teleoperator has entered a non-passive mode, the stabilizing controller engages. The stabilizing control portion is implemented on the master side of the teleoperator and is simply a PD controller trying to hold the master in the position it had when non-passive behaviour was detected. The controller structure on the master side is of variable structure in the sense that when engaged, the output from the stabilizing control portion is appended to the master’s original control.

Experimental results show that the developed detection algorithm and stabilizing control portion manages to damp out undesired oscillations induced by stiff contacts between the slave and the environment relatively fast. For comparison, the same contact experiment is performed for the same conditions but with the stabilizing control portion disabled, the result is that the user can not perform a stable contact with the environment, the teleoperator starts to oscillate as soon as the first contact has been established.

4.5. Experimental setup and investigated system

The master (see Fig. 10 left image) is a two degrees of freedom industrial joystick. The joystick is equipped with DC-motors to generate torque to the master stick. For reading the master’s position, the master is equipped with potentiometers.

The slave (see Fig. 10 right image) is a three degrees of freedom manipulator with two rotational degrees of freedom and one translational. To reduce backlash in the joints, the slave manipulator is equipped with Harmonic Drive gears as mentioned earlier.

In the appendix of this thesis, the complete simulation model for the master and the slave is given together with parameter values identified from the experimental setup.
All DC-motors and all sensors are controlled and sampled from a rapid control prototyping PC-board, dSPACE DS1103 [19]. The board has its own CPU on which the control code is running at 1000 Hz. The CPU of the host PC is only logging and monitoring data to the user. The contact forces are measured with a force sensor mounted on the final link of the slave. The force sensor requires an extra PC board in the computer and the force data is output on the data bus of the computer. However, the data bus on the PC is occupied with monitoring data to the user, therefore, the force sensor requires a stand alone PC. This second PC is equipped with an I/O board for communication directly with the digital I/O pins of the dSPACE board. The force data is then imported to the dSPACE board in the beginning of each sample before all other sensors are sampled.

All control development is done in the Matlab/Simulink environment on the host PC. The resulting Simulink block diagram is compiled and down loaded to the dSPACE board. When the control code is running on the dSPACE board the user is able to change parameters and plot signals in real time for analysis and evaluation.

The structure of the investigated system is depicted in Fig. 11. The control structure in papers A and B uses all three interaction channel controllers depicted in Fig. 11. In papers C and D, only $C_1$ and $C_2$ are used. In papers A and B, there is a master controller implemented which is represented by $C_m$ and $C_6$ in Fig. 11. Since the experimental setup lacks a force sensor on the master side an estimator is used. This estimator is not indicated in Fig. 11 but is further presented in the appended papers.
5. Conclusions

5.1. Other potential teleoperator functionality

Skullbase operations are more safety critical than operations in other parts of the human body due to that neurons, in contrast to the cells of many other organs, cannot be replenished in an adult individual. Thus, inadvertent pressure on the brain or stopping of blood flow in important blood vessels may have devastating effects in terms of loss of neurological function. Therefore, if any kind of additional functionality making these operations safer, easier and less time consuming could be developed and added to the future teleoperator system, the surgeons, the patients and society would benefit from it as mentioned in section 1.

In a teleoperator system, the surgeon can scale the motion ranges between the master and the slave and thereby obtain a possibility to adapt the properties of the equipment depending on the task at hand, e.g. to select a smaller $G_p$ when doing the most accurate manipulation. The same possibility is available for the reflected force which can be useful in the following scenario. If the surgeon is milling in an area where the bone is thin, compliant and there is sensitive tissue located behind, the force reflection gain can be enlarged to make it possible for the surgeon to get a better feeling of the small contact forces from the bone. This is particularly important since the event of bone break through is one very critical moment of an operation. Further, if the teleoperator system can be equipped with software notifying the surgeon when bone break through is close at hand, an extra safety feature is obtained. The above mentioned teleoperator functionality contribute to make these operations less time consuming, safer for the patient and to decreasing the work load for the surgeons.

Regarding the visual feedback, it is clear that the surgeons performing these operations today extensively use the eye contact with the mill progressing through the bone for fine control and for planning of the next phase of the operation. This direct visual feedback is therefore important not only to keep, but to improve. The same applies to the auditorial cue, the surgeons trained ear catches vital information of the bone from generated sound.
and from the variation in the mill’s rotational speed. As a future extension to the visual feedback, a visual system showing the position of the mill in the computer tomography images in real time can be added to the system. This visual system would give the surgeon highly valuable information for determination of remaining distance before bone break through and distance to sensitive areas in the skull. For increasing the resemblance with reality of this visual system, bone removal performed should also be visualized. This would require real-time updating of the geometric bone model.

Further, based on information provided by the computer tomography images, the surgeons could in advance define prohibited areas for the mill to enter. The control software must then stop the slave from moving into the prohibited area and also generate a force at the master notifying the surgeon that an attempt to enter one of the prohibited areas was made and that the slave was stopped.

Another future extension would be to provide a virtual representation of the slave, the milling tool and the skull. This representation must include geometric models, dynamic models of the tool-to-bone contact and models of bone removal. By connecting the master to this representation, an operation simulator with force reflection is obtained giving the surgeon a possibility to plan and perform the operation in advance before proceeding with the real operation. Such a system could also be used on a regular basis in education of surgeons. Hence, when the operation simulator is used on-line in real operations, the dynamics in the interaction between the mill and the bone is inactive since the reflected force is originating from the real slave manipulator. The simulator is in this case only receiving joint coordinates of the slave such that the motion of the slave and the progress of the milling is monitored.

Possibly, preparation time can be reduced if the surgeon in advance, in some way, can input an approximate specification of the operation into the virtual representation of the skull. By doing so, a planning tool could potentially be developed to inform the surgeon of distance to sensitive areas along the planned milling path, evaluate different milling paths and give an estimate on the required time for the planned operation.

In order to reduce milling time for the surgeons even more, a future extension to the teleoperator functionality could be to define a bone volume to be milled away using the computer tomography images and let the teleoperator mill away the defined volume automatically. The accuracy in the computer tomography images determines to which extent the automatic milling mode can be used. This automatic mode could also be used for free space motion in the sense that the teleoperator could move the mill from a position away from the skull to a predefined position where the mill is close to contact with the bone. This functionality could be useful if the surgeon for some reason temporarily interrupts the operation, moves the mill away from the skull and after a while continues the operation at the previous location.

5.2. Recommended future research

In Flemmer et al. (2001), there is a contact model derived describing the dynamics of the final link of the slave, the mill and the encountered piece of wood for the case when the mill is switched off and in contact with the environment. Incorporating this in-contact
model with a dynamic model describing the dynamics of the contact making phase can reveal interesting details regarding the build up of contact forces and its dependence on impact velocity and mill rotational speed. This information can in future control synthesis work be used for designing a stabilization control portion for faster recovery from a non-passive state caused by an impact and for less transparency deterioration when the control portion is active. The model describing the dynamics in the contact making phase is not only useful for control synthesis purposes, it is also necessary for the success of the operation simulator described in section 5.1.

For the future operation simulator, apart from the dynamics involved in the interaction between the mill and the bone, geometrical considerations must be included to get a realistic impression of the milling process. For instance, the angle between the mill and the normal to the surface of the bone is assumed to play some role in the dynamics of the interaction between the mill and the bone. In certain specific situations, the surgeons mill a path through the bone to reach a certain location, not to destroy vital parts of the skull bone or to affect the brain itself more than necessary. This path implies that geometrical models describing the constraints induced on the tool by the walls in the path must be included in the training simulator. Further on, for a realistic impression when milling, bone removal performed by the mill must be visualized such that the user experiences that parts of the bone are milled away and turned into a mix of dust and cooling liquid. The removal of bone parts implies in turn that the mentioned geometrical constraints of the bone must be updated continuously to reflect the actual situation.

The detection algorithm for non-passive teleoperator behaviour presented in paper D will be paid research attention in the future. The reason being that there is a large uncertainty in the amount of damping that is provided by the operator. If this damping in reality is larger than the damping present in the model, the detection algorithm will be over conservative and vice versa.

The bone protecting the brain in the skullbase is geometrically very complicated and surrounds in some parts neurons. Hence, milling at certain locations in the bone requires a high level of precision and a master and slave system with enough degrees of freedom to obtain a teleoperator with a usability not limited by its work- and configuration space. As today’s master only has two degrees of freedom, a new master is of great interest to install both for increasing the teleoperator’s working volume and for adaptation of its kinematics such that the surgeons can move it and hold it in an optimal way. Also, the present master lacks a force sensor for measuring the reflected force. A force sensor on the master would give possibilities to further investigate the quality of the reflected force without having to include a force estimate and also further investigate the dynamics of the operator’s fingers holding the master. When force measurements are available on both sides of the teleoperator, on line identification of dynamical parameters for adaptation of control parameters is also easier than with only position and velocity sensing.

Regarding the kinematics of the slave, a slave manipulator with reconfigurable kinematics would be ideal since the surgeons could adapt such a slave manipulator to better fit the kinematic constraints of the actual operation. Reconfigurable slave kinematics requires adaptation of the control software before usage of the system. This could be solved by building the slave manipulator with blocks or modules whose kinematic and
dynamical parameters are known by the software. When the surgeon has configured the slave and is satisfied with its kinematics, the used slave modules and their relative order are specified into the control software and the necessary software updates can automatically be performed.

As mentioned, in certain situations, the surgeon mills a path through the bone to reach a specific location. This scenario implies that parts of the slave manipulator are located within this relatively narrow path. The surgeon, however, should only need to control position/orientation of the end point of the tool. An additional joint coordinate trajectory planner/controller would hence be needed to resolve singularities and potential redundancy while making sure that the slave does no violate the geometrical constraints. Clearly, this planner/controller must continuously be updated with changes in the geometrical constraints. Presumably, parts of the trajectory planning can be performed in advance based on an approximate specification of the operation from the surgeon.

For a teleoperator system to be implemented in real operations, a lot of additional engineering and medical issues need to be addressed. All the software and hardware must be trustworthy and the teleoperator controller must be robust to variations in the dynamics of the operator grip and environmental characteristics. The teleoperator must be constructed such that it does not disturb the function of other medical equipment. Further, in all operations inside a human body, the equipment performing the task needs to be sterile and easy to clean after the operation.

6. References


Aspects of Using Passivity in Bilateral Telemanipulation

by

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Technical report
TRITA-MMK 2004:16, ISSN 1400-1179
ISRN KTH/MMK/R-04/16-SE, May 2004
Aspects of Using Passivity in Bilateral Telemanipulation

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Abstract. In control design for bilateral telemanipulation, there is a trade-off between high transparency and sufficient robustness against variations in dynamics of the encountered environment and the operator’s grip around the master stick. Stability problems can occur when the stiff slave manipulator encounters a stiff environment and large contact forces are fed back to the badly damped master giving oscillative behaviour in the teleoperator. This is the case for the research project presented in this paper where the environment is human bone which has a high stiffness. Variable structure control methods which add extra damping in the teleoperator control loop when it is needed for stabilization purposes is a promising concept. An existing method for compensation of non-passive teleoperator behaviour is analysed theoretically and tested in stiff contact experiments and found difficult to apply to the actual research application. Based on the concept of passivity, ideas on how to detect a non-passive state of a general control system are discussed.

Keywords: Bilateral Teleoperation, Passivity, Stability, Phase lag, Transparency

1. Introduction

A teleoperator system consists of a master device or haptic device and a slave manipulator. Through the master, the operator controls the motions of the slave manipulator which is performing the actual task. In bilateral telemanipulation, the contact forces affecting the slave are fed back to the master to give the operator a feeling of the actual operation. The term transparency is used to describe how close this feeling is to the feeling when performing the same task manually without the teleoperator. It is desirable to build and control the teleoperator such that the transparency is as high as possible. However, there is a trade off between transparency and stability of bilateral teleoperators. The stability problems are in this case related to variations in dynamical properties of the encountered environment and dynamical variations in the operators grip around the master. This is due to the fact that the dynamics of the operator and the environment are integral parts of the teleoperator closed loop, (Hannaford (May 1989)). High transparency often comes
hand in hand with small stability margins or none at all, see for instance (Hannaford et al. (2002)), (Ryu et al. (2002)) and (Yan et al. (1996)).

As mentioned by for instance Hannaford et al. (2002), Yan et al. (1996) and Zhu et al. (2000), the operator and the environment must be included in the analysis since these parts significantly alter closed loop dynamics when interacting with the teleoperator. The environment and operator can typically be characterised as highly nonlinear dynamic processes, (Kazerooni (1990)), which for simplicity often are modelled by Linear Time Invariant (LTI) differential equations to enable the usage of well known linear theory both for analysis and synthesis purposes.

Teleoperation is sometimes associated with manipulation of environments or spaces inaccessible to man, but there are also many applications for teleoperators in the medical area. Introducing teleoperators in medicine may hopefully improve surgical performances in terms of less operation time, less risk of damaging the patient, less invasive operations and more comfortable positions for the surgeons to work in. The actual research project, *Skullbase*, fits into this category since the goal with the project is to develop a teleoperator system to be used in sensitive operations for cancer removal in a human head.

This paper is organized as follows: In section 1, a detailed description of the research project is given together with a description of the experimental setup. Section 2 presents the basics of teleoperator modelling and control followed by section 3 which gives an overview of a few of the existing methods for analysing stability of teleoperator systems. Section 3 discusses also stability issues of teleoperators when using the concept of passivity. Section 4 presents the concept of network theory and its application to teleoperators in theory as well as in experiments. Section 5 contains a control example which is made non-passive on purpose to show the effectiveness of using passivity for detection of unstable behaviour. Finally, in section 6, conclusions and ideas for future work are given.

1.1. The *Skullbase* research project, specifications

The research project *Skullbase* focus on developing a force reflecting teleoperator system to be used in skull base surgery. The project is based on an initial cooperation with the Department of Clinical Neuroscience, Section of Neurosurgery at the Karolinska Sjukhuset in Stockholm Sweden, which is one of the major hospitals in Sweden.

In skull base surgery, the task is to remove one or several cancer tumours lying under the skull bone in a human head. To reach the cancer tumours, the surgeon has to remove parts of the skull bone by milling. The milling itself is a critical phase in an operation of this kind due to the risk of damaging the brain tissue or neurons lying in the vicinity of the skull bone. Today, the surgeons perform the milling with a hand held mill while bending over the patient in an uncomfortable position. When introducing a teleoperator, the mill is instead mounted in the slave’s tool centre point (TCP) and the surgeon controls the milling process via a master, while sitting comfortably in a chair beside the patient. And, the important direct visual contact with the operation area is kept. Today, the manually performed operations can take up to 20 hours and are very tiering for the
team of surgeons working with the patient. A long term vision of this project is to minimize the risk of human (i.e. surgeon) errors and to reduce the operation time. Human errors can be reduced by defining allowed regions for the slave’s TCP to operate in, based on information provided by Magnetic Resonance and Computer Tomography images in a virtual representation of the actual patient’s skull. These allowed milling regions would then prevent the mill from damaging sensitive tissue or neurons lying in the vicinity of the actual working area. Real-time visualization of the position of the mill in the virtual representation of the skull would enhance the abilities of the surgeon to plan and carry through with an operation.

Force feedback needs to be provided to the surgeon as a complement to the visual feedback in an application of this kind since task performance in terms of precision and task completion time are improved with force feedback, (Bu et al. (1996)), (Lazeroms et al. (1996)). Further, high quality force feedback is very important since the surgeon often switches the mill off and pushes the mill carefully against a bone area of particular interest to estimate the remaining thickness of bone before break through. This requires a high transparency teleoperator with high resolution for small contact forces, preferably with a goal as suggested in Handlykken et al. (1980). The teleoperator acting as a virtual infinitely stiff and weightless mechanical link between the mill housing and the surgeons hand.

1.2. Experimental setup
The developed teleoperator system prototype consists of a master device and a slave manipulator as depicted in Fig. 1. Bone structures are supposed to be milled away by a mill mounted at the slave’s TCP. The contact forces between the mill and the bone are measured by a force sensor mounted on the slave’s last link, see Fig 1. The last link of the slave is made fairly long to make it possible for the surgeon to have a good visual contact with the working area.

![Figure 1: System hardware, left: Master, right: Slave.](image)

2. Teleoperator modelling
Modelling the teleoperator by five blocks as in Fig. 2 is commonly in the teleoperator research community, see for instance Adams et al. (1999), Hannaford (August 1989), Hashtrudi-Zaad et al. (2000) and (Lawrence (1993)). The components of the complete teleoperator setup is divided into five separate subsystems: The operator, the master, the
controller, the slave and the environment. The teleoperator system in terms of hardware and software, is represented by the dashed block.

**Figure 2: The Force-Velocity teleoperator control structure.**

The signals in Fig. 2 are: The reflected force $F_r$, which is the interaction force between the operator and the master. The master and slave velocities $V_m$ and $V_s$ respectively are modelled such that 1: The operator’s intentions enter the teleoperator as forces and 2: The environment is modelled as an impedance as done in Colgate (1993), Flemmer et al. (2003) and Lawrence (1993). $F_{am}$ and $F_{as}$ are the requested actuator forces to the master and the slave mechanics respectively.

The scalar gains $G_{fr}$ and $G_p$ are the force reflection gain and the motion gain respectively. The output from the velocity and position controller of the slave, the requested actuator force $F_{as}$ expressed in the base coordinate system $CS_0$ is mapped to requested actuator torques $\tau_{as}$ expressed in the slave generalized coordinates $q$ via the slave’s Jacobian transpose as:

$$\tau_{as} = J^T(q)F_{as}$$  \hspace{1cm} (1)

Thus, the position and velocity feedbacks can be interpreted as if the tool was connected to the base coordinate system with springs (denoted $P$) and dampers (denoted $D$). This is basically the impedance control concept presented in Hogan (1985) without altering the inertia of the manipulator with actuator power as Hogan proposed.

All the classical control structures for bilateral teleoperators can be derived from the so called four channel structure, (Lawrence (1993)). The different control structures are usually classified depending on which signals the master and the slave send to each other and they have different performance depending on the operating case, (Hashtrudi-Zaad et al. (2000)). In Fig. 2, the force-velocity structure is depicted (denoted Forward Flow in Hannaford (August 1989)) in which the master provides velocity/position references for the position servos of the slave to follow and, the slave sends back the measured contact force to the master. This is the control structure used in this paper.
3. Stability of teleoperator systems

3.1. Introduction

In this section, a few methods for analysing stability of teleoperator systems will be discussed, starting out with methods limited to LTI teleoperator models. The LTI restriction of these methods has prompted the usage of other methods, for instance the concept of passivity. Passivity has its roots in network theory and has been shown promising within teleoperator control, (Ryu et al. (2002)).

3.2. Stability analysis of teleoperators using design models

A stability analysis based on the characteristics of a closed loop transfer function around the teleoperator including models of the environment and the human operator can be found in Bu et al. (1996) and Flemmer et al. (2002). Stability of the closed loop can be determined from the pole locations of this transfer function. The drawback with this method is that design models covering the environment and the operator must be included, (Hannaford et al. (2002)), (Zhu et al. (2000)) and (Yan et al. (1996)). The drawback with all design model based stability analysis methods is that the quality of the design model (i.e. discrepancies between reality and the design model) determines the outcome of the stability analysis. The assumptions in the design models are all possible sources of unpredictable system behaviour and stability can not be guaranteed for the real teleoperator.

3.3. Passivity

As mentioned in Lawrence (1993), if a system can be shown passive, it is also stable. And, since passivity applies to both non-linear and linear systems, passivity is promising for improving teleoperator control.

3.3.1. The fundamental passivity result

For a linear system, passivity can be interpreted as a phase property. The phase lag through a linear and passive system can not be larger than 90 degrees. In Fig. 3, let us assume a control system in which both the manipulator and the controller are linear and passive. The control system is fed with reference $r$ and has an output $y$. As a consequence of the fundamental passivity result (Sepulchre et al. (1997)) or the Nyquist Bode criterion, the phase lag between $r$ and $y$ can not be larger than 90 degrees if the manipulator itself and its controller are passive. The fundamental passivity result says that the negative feedback loop of two linear and passive systems also is passive since the phase lag of the loop gain never is larger than 180 degrees.

![Figure 3: Block diagram for illustrating the fundamental passivity result](image-url)
In Lawrence (1993) and in Flemmer et al. (2003), a complete teleoperator control design is done based on this. These designs assure a loop gain phase lag less than 180 degrees by requiring one of the passive blocks in Fig. 3 to be strictly passive. Such a system has an “infinite gain margin”. From this, passivity can be interpreted as a “phase property” for linear systems.

3.3.2. Supply rate and storage functions
As said, the phase lag between the input \( u \) and the output \( y \) of a linear and passive SISO system, \( LPS \), is never larger than 90 degrees. Let us define the two functions \( w(t) \) and \( s(t) \) associated with \( LPS \) as

\[
    w(t) = u(t)y(t) \quad s(t) = \int_0^t w(t) \, dt
\]

(2)

where \( s(0) \) is set to 0. For \( LPS \), \( s(t) \) can never grow negative since the phase lag between \( u \) and \( y \) never is larger than 90 degrees. Hence, the requirement for passivity is

\[
    s(t) \geq 0
\]

(3)

for all times. Further, we must require that all unobservable states of \( LPS \) are asymptotically stable, (Sepulchre et al. (1997)). \( w(t) \) will clearly take on both positive and negative values, but integrated over time to form \( s(t) \), a positive value is achieved. In Sepulchre et al. (1997), \( w(t) \) is denoted supply rate function and \( s(t) \) is denoted storage function and eqn. (3) is stated to be valid also for non-linear systems if \( w(t) \) is integrable and if there are no unobservable states in the monitored system.

3.4. Real-time stability analysis of teleoperators
Real-time compensation of non-passive states of the teleoperator is a very promising control concept since transparency can be high most of the time and only degraded when necessary for stabilization purposes. Hence, the design of the teleoperator control architecture can be aimed mainly at transparency instead of the traditional trade-off between stability and transparency. Of course stability issues have to be kept in mind during the design phase but to a smaller degree than before since the passivity assuring control portion can stabilize the system when needed. It may even be possible to use an existing control architecture and make it stable for another operational condition if the controller is extended with a passivity assuring control portion, (Ryu et al. (2002)).

Real-time detection of non-passive control system behaviour by monitoring properties of the signals involved in the dynamical interaction between the elements in the control system can be done by using tools from network theory. Therefore, a presentation of network theory and its application to teleoperator control is given in the following section.
4. Network theory

A general one-port network, \( N \), as depicted to the left in Fig. 4 with initial energy storage \( E(0) \) is said to be passive if and only if (from Doeser (1975))

\[
\int_0^t f(\tau) v(\tau) d\tau + E(0) \geq 0
\]  

(4)

where \( f \) is the effort applied across the port and \( v \) is the flow flowing through the port. Originally, \( f \) and \( v \) describe voltage and current respectively. In the context of mechanical systems, when discussing dynamic interaction between network elements, \( f \) corresponds typically to the interaction force between two adjacent elements and \( v \) typically describes the velocity of the body on which \( f \) acts.

Eqn. (4) states that, for the network \( N \) to be passive, the energy supplied through its port via \( f \) and \( v \) plus the initial energy \( E(0) \), must be greater than zero.

Eqn. (4) can be extended to cover the M-port network, \( N_M \), as depicted to the right in Fig. 4 as (from Hannaford et al. (2002))

\[
\int_0^t (f_1(\tau)v_1(\tau) + \ldots + f_M(\tau)v_M(\tau)) d\tau + E(0) \geq 0
\]  

(5)

For a general network consisting of one open connection and \( P \) arbitrarily connected network elements as depicted in Fig. 5, the total energy in the complete network for zero initial energy is given by the sum of the energies for each individual element as

\[
E_{tot}(t) = \sum_{i=1}^{P} E_i(t)
\]  

(6)

and passivity of the network is given if and only if \( E_{tot}(t) \geq 0 \).

The energies present on each element in Fig. 5 are given by
Summarizing the total energy from all the energies in eqn. (7) gives $E_{\text{tot}} = \int f_1 v_1 dt$. The energy present in the network depends hence solely on the open end, port 1. This is due to the fact that none of the network elements in the network has an energy source or an energy leak where energy can be generated or dissipated.

$$
E_1 = \int (f_1 v_1 + f_2 v_2 - f_3 v_3) dt \\
E_2 = -\int f_2 v_2 dt \\
E_3 = \int (f_3 v_3 - f_4 v_4 - f_P v_P) dt \\
E_4 = \int f_4 v_4 dt \\
E_P = \int f_P v_P dt
$$

Figure 5: A general network consisting of $P$ arbitrarily connected network elements.

4.1. Network theory applied to teleoperators

Fig. 6 shows a five block representation of the teleoperator where the components of the teleoperator are represented by network elements.

Figure 6: Five-block network representation of the teleoperator structure.
In Fig. 6, the muscle power contribution from the operator is described by \( fhv_h \), where \( v_h \) is the velocity of the operator’s hand and \( fh \) is the muscle force. \( \dot{Q}_c, \dot{Q}_e, \dot{Q}_m \) and \( \dot{Q}_s \) are the heat flows dissipated from the controller, the environment, the master and the slave respectively. The heat flows \( \dot{Q}_c, \dot{Q}_m \) and \( \dot{Q}_s \) are consequences of friction in the mechanics of the master and the slave and resistance in actuators and amplifiers. \( \dot{Q}_e \) is a consequence of heat dissipation to the environment. Further, energy flows from the operator into the teleoperator (marked by the dashed square) and out from the teleoperator to the environment. \( I \) and \( U \) represent the current and the voltage to the amplifiers of the actuators respectively. The actuators of the teleoperator are placed in the controller block. Hence, the forces \( f_{as} \) and \( f_{am} \) are the forces from the actuators to the respective mechanisms, i.e. the actuators are regarded as ideal force sources without internal inertia. By doing this, Hannaford et al. (2002) argues that the master and the slave blocks in Fig. 6 can be considered as passive since they are incapable of generating energy. From a phase lag point of view, the requirement of passive mechanics implies that the phase lag from input force to output velocity never is larger than 90 degrees. This can be achieved if there is no flexibility in the mechanics which would result in a second order system with a maximum phase lag as large as 180 degrees from input to output for higher frequencies. All manipulators have at least one flexibility in their structure, but if excitation of the flexible mode never occurs when operating, the manipulator will act as passive.

In the context of teleoperators, the physical signals of interest to monitor are typically the forces and the velocities which result from the dynamical interaction between the involved elements. All motions in the following analysis are for simplicity assumed to be in one axis. When defining the directions of the forces and velocities and hence the direction of the energy flow, the following is assumed.

- For the master and the slave, equal directions within the pairs \((v_m, f_r)\) and \((v_s, f_e)\) indicate that energy is received from the operator and the environment respectively.
- For the controller, equal directions within the pairs \((f_{am}, v_m)\) and \((f_{as}, v_s)\) indicate that energy is extracted from the controller to the master and the slave units respectively.

Hence, the energies for each block are given by

\[
E_{op} = \int_{\tau} (fhv_h - frv_m) d\tau \\
E_m = \int_{\tau} (frv_m + famv_m - \dot{Q}_m) d\tau \\
E_{cntrl} = -\int_{\tau} (famv_m + fasv_s - \dot{Q}_c + P_{el}) d\tau \\
E_s = \int_{\tau} (fasv_s + fev_s - \dot{Q}_s) d\tau \\
E_{env} = -\int_{\tau} (fev_s + \dot{Q}_e) d\tau
\]  

(8)
if the initial energies are set to zero. In eqn (8), $P_{el}$ is the power injected into the controller through its electrical port. In the ideal case, the heat losses in the weightless teleoperator mechanics are zero, the mechanics is infinitely stiff, the motion is in a plane perpendicular to the direction of gravity and the electrical energy is equal to the heat dissipation from the controller, $Q_c$. For this ideal case, the total energy in the teleoperator system is

$$E_{tot} = E_{op} + E_m + E_{ctrl} + E_s + E_{env} = \int (f_h v_h - \dot{Q}_c) d\tau$$

(9)

which indicates that all the energy that the operator injects in the system is dissipated to the environment as heat where the environment is assumed to be of pure damping characteristics.

In Ryu et al. (2002) it is claimed that to assure passivity of the complete teleoperator for all times, it is enough to assure passivity of the two-port teleoperator controller for all times if the slave and the master are passive. In their analysis, the electrical port and the heat dissipation of the controller are excluded, hence, the controller has only two ports, one connected to the master and one connected to the slave.

In the following, passivity of the teleoperator controller when the gains $G_p$ and $G_{fr}$ are varied is discussed since this functionality is vital in the actual context. When the gains are introduced, the controller is designed to achieve

$$f_r = -G_{fr} f_e \quad v_s = G_p v_m$$

(10)

In the general case, the equations of motion for the master and the slave respectively are given by

$$m_m \ddot{v}_m + g_m + f_m^f + c_m = f_{am} + f_r$$

$$m_s \ddot{v}_s + g_s + f_s^f + c_s = f_{as} + f_e$$

(11)

Where index $m$ indicates master and index $s$ indicates slave. $m$ describes the mass, $g$ the gravitational force, $f^f$ the frictional force and $c$ the coriolis contribution. Since the motion is assumed to be in one axis, the coriolis contribution is zero.

For the subsequent analysis, there are two operating cases of interest. First, when the operator inputs energy in the teleoperator, i.e. the direction of $v_m$ is opposite compared to $f_{am}$. Second, when $v_m$ has the same direction as $f_{am}$, for this case the controller injects energy into the master and into the slave.

For the first case, by using eqn. (11), the energy of the controller can be calculated as
where it is assumed that \( m_s \) is constant. In the following discussion, the integrals in the bottom row of eqn. (12) are discussed. The first integral is in this case the energy input on the master port of the controller since the directions of \( f_{am} \) and \( v_m \) are opposite. Assuming that the environment is passive, hence, the environment is incapable of generating energy, the directions of \( f_e \) and \( v_s \) are opposite and this integral describes an energy loss for the controller. The third integral is the kinetic energy of the slave, i.e. \( m_s v_s^2/2 \). The fourth integral describes the potential energy of the slave, i.e. \( m_s g v_s \) where \( g \) is the gravitational constant. Assuming that the motion is performed in a plane perpendicular to the direction of \( g \) makes this integral zero. The last integral is the frictional loss for the slave. This integral always describes an energy loss since this energy is transformed into heat. The energy calculated by the sum of the frictional loss integral and the integral describing the kinetic energy must be injected into the slave from the controller such that the slave can fulfil \( v_s = G_p v_m \). For the moment, let us assume that these contributions are small. Since the master runs in open loop, i.e. there is no local control loop at the master, \( f_{am} \) is generated as \( f_{am} = G_{fr} f_e \). By using eqn. (10), eqn. (12) can be written as

\[
E_{cntrl} = -(f_{am} v_m + f_{as} v_s) d\tau =
\]

\[
-\int_{\tau} f_{am} v_m d\tau + \int_{\tau} f_e v_m d\tau - m_s \int_{\tau} \dot{v}_s v_s d\tau - g_s \int_{\tau} v_s d\tau - \int_{\tau} f_{fr} v_s d\tau
\]

The energy described by integration of \( f_e v_m \) over time is always negative for the passive environment, thus, eqn. (13) can be written as

\[
E_{cntrl} = (G_p - G_{fr}) \int_{\tau} f_e v_m d\tau
\]

The result in eqn. (14) indicates that if \( G_p \) is larger than \( G_{fr} \), the energy level of the controller grows negative and the controller violates the passivity definition in eqn. (4) unless energy is injected into the controller through the electrical port. If \( G_p \) is smaller than \( G_{fr} \), the energy level in the controller will increase. However, this is not possible since the controller lacks energy storage capabilities and energy can not be removed from the controller through its electrical port, the energy surplus has to be removed through heat dissipation.

Given the stated assumptions, the conclusions are.

- For \( G_p > G_{fr} \) energy has to be injected into the teleoperator controller through its electrical input.
- For \( G_p < G_{fr} \) energy has to be removed from the teleoperator controller by heat dissipation.
- If \( G_{fr} \) and \( G_p \) are equal, non-passive behaviour of the teleoperator controller can be detected by using the method proposed in Ryu et al. (2002).
The findings are summarized in Fig 7.

\[ G_p > G_{fr} \Rightarrow E_{electrical} = \int UId\tau > 0 \]

\[ G_p < G_{fr} \Rightarrow E_{heat} > 0 \]

Figure 7: Energy flows through the teleoperator and their dependence on \( G_p \) and \( G_{fr} \).

The position/velocity controller of the slave always tries to fulfil its goal \( v_s = G_p v_m \). Hence, the energy amount that the controller must inject into the slave can be large if the frictional losses, mass and desired velocity of the slave are large. The controller receives amounts of energy from its electrical port to cover these energy needs. This energy flow is hence only visible as an energy loss for the controller when regarding the controller as a two-port as in Ryu et al. (2002).

Hence, it is likely that the kinetic energy of the slave and the energy dissipated as heat through friction will cause the detection method presented in Ryu et al. (2002) to be over conservative.

For the second case, the direction of \( f_{am} \) and \( v_m \) are the same and the controller loses energy on both its master and slave port. This second case can occur when the slave moves from free space motion to in contact motion as follows. When the slave is moving with a constant speed in free space motion, \( f_e \) and \( f_{am} \) are zero. When the slave moves into contact with the environment, a contact force, \( f_c \), with opposite direction as \( v_s \) and \( v_m \) arises. This contact force gives rise to a force to the mechanics of the master, \( f_{am} \), with opposite direction as \( v_m \). If this \( f_{am} \) is large, \( v_m \) can change direction and take on the same direction as \( f_{am} \) and the controller loses energy on both its ports. For this case, \( f_{am} \) is larger than \( f_e \) and the controller injects energy into the master which there partly is transformed to kinetic energy and heat through friction. However for transparency purposes, the master is designed to have small frictional losses and a small moving mass, therefore, these contributions are assumed negligible.

For the assumption of passive slave mechanics to hold, the phase lag between \( f_{as} \) and \( v_s \) must not be larger than 90 degrees and likewise for the master. As said, if the mechanical structure of the slave contains a flexibility, this flexibility will for some frequencies introduce a phase lag larger than 90 degrees between \( f_{as} \) and \( v_s \). From an energy point of view, this flexibility would result in non-passive slave behaviour in that the slave appears to inject energy into the controller. From earlier research presented in Flemmer et al. (2000), it is known that the dynamics of the slave contains at least one flexibility. It is
likely that this flexibility will cause the slave to act as non-passive and hence violate the passivity requirement. The flexibility in the slave manipulator originates mainly from two rubber pieces located between the mill housing and the final link of the slave. These two rubber pieces are used for reduction of vibrations induced in the mechanical structure by the rotating mill not to get too much noise in the force data. For the next generation slave manipulator, a design goal is hence to build it such that it is passive for the frequencies present in the teleoperator control loop. Regarding the master, it is assumed that there is no flexibility in the master mechanics.

Summarizing the discussion, judging passivity of the teleoperator from regarding the teleoperator controller as a two-port and using \( E_{cntrl} = -\int (f_{am}v_m + f_{as}v_s)d\tau \) for detection of non-passive states is only applicable and accurate if the following holds. The position gain, \( G_p \), the force reflection gain \( G_{fr} \), are equal, the energy required to overcome friction and the kinetic energy to the slave from the controller are negligible and master and slave mechanics are passive. If the kinetic and frictional related energies to the slave from the controller are substantial, over conservatism of the detection method is likely.

4.2. Monitoring the energies of the teleoperator controller

From now on in section 4, the method for detection of non-passive teleoperator behaviour presented in Ryu et al. (2002) is discussed and tested on the experimental setup. Hence, the energy and power flows in and out of the master and slave ports of the teleoperator controller are in focus.

As said, \( f_{as} \) and \( f_{am} \) are the actuator forces acting on the respective mechanics. In the experiments in this paper, \( f_{as} \) and \( f_{am} \) are the requested actuator forces to be supplied by the actuators. It is here assumed that the requested actuator forces are the same as the true actuator forces.

The sign convention used in the experiments is as defined earlier, energy is extracted from the controller when the directions within the pairs \( f_{as},v_s \) and \( f_{am},v_m \) are equal where all forces and velocities are defined in the same cartesian coordinate system. The energy of the controller is given by \( E_{cntrl} \) which is the sum of the energies on the ports of the controller. \( e_{cm} \) is the energy on the master port and \( e_{cs} \) is the energy on the slave port. \( p_{cm} \) and \( p_{cs} \) are the respective powers on the master and slave port of the controller.

\[
E_{cntrl} = e_{cm} + e_{cs} \quad e_{cm} = \int_{\tau} p_{cm}d\tau \quad e_{cs} = \int_{\tau} p_{cs}d\tau \quad p_{cm} = -f_{am}v_m \quad p_{cs} = -f_{as}v_s
\] (15)

This section presents two experiments where the amount of energy extracted from the controller to the slave mechanics are analysed. In the first experiment, the force reflection to the master is turned off, the slave is moving in free space and the master is moved slowly back and forth by the operator in order to generate a motion reference for the slave. For this case, energy from the electrical port of the controller is injected into the slave and there converted into kinetic energy and heat due to friction. In the second
experiment, the conditions are the same except that the slave moves faster than in the previous experiment.

Fig. 8 presents plots from the first experiment. The left plot shows the velocity of the slave, \( v_s \) (dashed line) and the control force, \( f_{as} \) (solid line) to the slave. As can be seen in the plot, \( f_{as} \) and \( v_s \) have the same sign almost all the time. Hence, the controller only loses power and energy on its slave port as shown in the right plot where the power, \( p_{cs} \), is represented by a solid line and the energy, \( e_{cs} \), is represented by a dashed line.

In the second experiment, as said, the conditions are the same but the master moves quickly back and forth, thus, generating a higher rate of change in \( f_{as} \). As can be seen in Fig. 9, left plot, \( v_s \) (dashed line) and \( f_{as} \) (solid line) have different signs temporarily and the teleoperator controller occasionally gains power (solid line) on its slave port as shown in the right plot. The energy flow from the controller to the slave is also displayed to the right in Fig. 9. Due to that the power occasionally is positive, the energy injected to the slave from the controller is less compared to the previous experiment.
Hence, one conclusion from these two experiments is that if there are quick sign changes
in the reference command, $f_{as}$, to the slave, the power signal will indicate that the slave
occasionally is injecting power into the controller. This is a consequence of the limited
mechanical bandwidth of the slave, i.e. for the slave motion there is a frequency limit
over which the assumption of a passive slave is no longer appropriate. If the frequency
limit is violated, a positive $e_{cs}$ will indicate that the slave starts to inject energy into the
controller.

4.3. Experimental results, energies on the teleoperator controller ports
during oscillation

This experiment is carried out to study the energy levels of the master and slave ports of
the teleoperator controller when the force reflection is active and the complete teleopera-
tor is oscillating. During these oscillations, the slave manipulator is bouncing against an
environment consisting of a piece of wood. Fig. 10 presents results from this experiment.
The force reflection gain $G_{fr}$ is set to 0.3 and the position gain $G_p$ is set to 0.5 during the
experiment. Hence, $G_{fr} \neq G_p$ and as mentioned earlier, there is presumably an energy
flow through the non monitored ports of the controller, but, the intention with the experi-
ment is solely to monitor the energy flows in and out of the controller, no attempt is
made to detect any non-passive behaviour of the teleoperator.

The experiment is performed under the following conditions: The motion is done in one
cartesian axis only and contact is established for $x_s < 0.2$, impact velocity is approxi-
mately 25 - 40 mm/s, the combined stiffness of the slave-environment system is approxi-
mately 25 kN/m, this value comes from a model of the interaction between the slave and

![Figure 9: Experimental results, slave in free space motion, force feedback turned off and
high rate of change in the slave’s control input $f_{as}$. The left plot shows the slave velocity
$v_s$ (dashed line) and slave input $f_{as}$ (solid line), the right plot shows the energy, $e_{cs}$,
dashed line and the power, $p_{cs}$, (solid line) over the slave port of the teleoperator
controller.](image)
the encountered environment identified in Flemmer et al. (2000). The sampling frequency is 1000 Hz and the control structure is as depicted in Fig. 2.

Figure 10: Experimental results. Plot A: The positions of the master and slave. Plot B: The energies present on the controllers master and slave port. Plot C: The contact force. Plot D: The total energy on the controller.

In Fig. 10, plot A shows the master and slave positions during the experiment, plot B shows the energy levels present on the master and slave ports of the teleoperator controller. Plot C shows the contact force, plot D shows the energy of the teleoperator controller which is the sum of the two signals in plot B. There are time intervals marked with letters from a to g in all the plots. In plot D, during time interval a, the slave is bouncing against the environment as can be seen from the positions in plot A and from the contact force in plot C. During the same time interval, the energy on the controller in plot D has negative peaks but the average energy level only decreases by small amounts due to the energy gain from slave port and the energy loss on the master port as can be seen in plot B. The energy gain on the slave port during the oscillative behaviour indicates that for these frequencies, the slave is non-passive due to a phase lag between \( f_{as} \) and \( v_s \) larger than 90 degrees. A phase lag larger than 90 degrees between force input to velocity output for a manipulator indicates, as said, that there is at least one flexibility in its mechanical structure. Hence, this result confirms the existence of a flexibility in the slave mechanics from
Flemmer et al. (2000). In the free space motion time interval b, the energy level decreases fast due to energy loss on the slave port and constant energy level on the master port. The energy loss on the slave port during the interval is assumed caused by friction compensation energy and kinetic energy injected to the slave from the controller. Kinetic energy here refers to the energy injected to the slave mechanics corresponding to its kinetic energy. This pattern repeats itself during the whole experiment, during the free space motion time intervals b, d and g, there are relatively large energy losses on the slave port of the controller. During time intervals a, c and e of oscillative behaviour, the average energy losses are relatively small. During time interval f, the teleoperator is operating with zero velocity, in contact with the environment, in a stable manner and with an almost constant controller energy level. From the plot, the energy level seems to grow by very small amounts, this is assumed to be the result of sensor noise since the velocities are zero.

Hence, the relatively large energy losses during free space motion and the relatively, on average, small energy losses during oscillative behaviour of the teleoperator makes it difficult to detect the oscillative behaviour of the experimental setup with the method proposed in Ryu et al. (2002). The energy required by the slave manipulator in the free space motion time intervals is presumably injected into the teleoperator controller through its electrical port. Since this energy flow is absent in the detection method, the monitored energy decreases fast even though the teleoperator is stable and operating as desired.

5. Simulation case study, passivity as a phase property

In order to get new ideas on how to detect non-passive states of a control system, this section presents simulations of a simple control system made non-passive on purpose during randomly chosen time intervals. This is done to study the properties of the supply rate function and the storage function defined in eqn. (2), during the non-passive time intervals. In Fig. 11, a DC-motor Maxon RE-035 118777 ([22]) is modelled as a first order system by \( G_1 = \frac{342.5}{s + 10.67} \) (i.e. from voltage input to velocity output) where the rotor inertia is multiplied by 20 to represent a load. The slave manipulator in the experimental setup is equipped with DC-motors of this type. The motor’s angular velocity is controlled by a P-controller and the velocity sensor has a time constant of 1 ms. The time constant and the P-controller are combined into one linear system denoted \( G_2 = \frac{P}{s/(2*1000*\pi) + 1} \), where \( P = 1 \). Both systems are passive and the feedback system with the input \( r \) and output \( y \) is also passive according to the fundamental passivity result. A pure time delay of 5 ms is introduced in the loop just after \( G_2 \) to destroy passivity when the time delay is activated for \( t \in [1; 1.8] \).

Figure 11: System for the case study. Both systems \( G_1 \) and \( G_2 \) are passive and thereby also the feedback loop. Passivity is violated when the time delay is activated.
The phase margin of the system without the time delay is 88.7 degrees at 341.7 rad/s. With the time delay activated the phase margin drops down to -9.2 degrees and the system is then non-passive and unstable. The reference $r$ is a square wave of frequency 1 Hz.

As can be seen in the left plot in Fig. 12, the output $y$ oscillates totally out of control when the delay is activated. The right plot in Fig. 12 shows $w(t)$ and $s(t)$. The $s(t)$ plot reveals passive behaviour up to $t = 1.45$ s i.e. $s(t)$ is positive up to this instant. But, by studying the plot it can be concluded that $w(t)$ goes negative already at $t = 1.0$ s and, since $s(t)$ is $w(t)$ integrated over time, $s(t)$ will decrease if $w(t)$ goes negative. Hence, by studying the sign and behaviour of $w(t)$, it can be detected at an early stage if $s(t)$ is about to decrease and passivity is about to be violated.

Let us from now on assume that the storage function, $s(t)$, describes the energy in the system and that the supply rate function, $w(t)$, describes the power in the system. Hence, for a general passive system, the energy level of the system is positive when the system is passive (i.e. eqn. (3)). In any passive system, the power can turn negative occasionally when the input changes, for a linear system, this is a result of the phase lag through the system being larger than 0 degrees. These occasional power losses implies that the energy will decrease by small amounts but not turn negative depending on earlier accumulated energy. From the case study, when the time delay is activated at $t = 1.0$ s, there is a positive energy accumulated. Due to the accumulated energy, detection of the non-passive behaviour from a negative energy will occur at $t = 1.45$ s. This problem is also discussed in Hannaford et al. (2001), where accumulated energy delays the detection of undesired teleoperator behaviour. One possible solution to explore for detection of undesired behaviour (i.e. triggering of a stabilization controller portion) is to study the power to get information regarding the future behaviour of the energy. However, triggering of a stabilization controller portion as soon as one negative power sample is detected would...

\[ r \text{ and } y \]

\[ s(t) \text{ and } w(t) \]

*Figure 12: Simulation results, left: Reference (grey) overlapping the motor angular velocity (black) and right: The $s(t)$ (black) and the $w(t)$ (grey) of the system.*
be over conservative in the general case, this can occur as soon as the reference (i.e. input) changes sign. One idea is to study the behaviour of the power over a specific period of time and take control action based on that. In a general sampled control system, several negative samples in a row of the power signal can be an indication of that non-passive behaviour might be close at hand and that the system can start to behave in an undesired manner. The length of the time period for which the power signal should be studied is a design parameter and differs between different control systems and their operating cases. Another idea is simply to reset the integration of the energy calculation if an indication of future non-passive behaviour is given and engage a stabilization controller portion if the energy turns negative after being resetted. The indication of future non-passive behaviour does not necessarily have to come from the power signal, other sources might be of interest depending on control system and application. Evaluation of these ideas is left out for future work.

6. Conclusions and Future Work

Stability of the teleoperator system is poor when the slave manipulator makes contact with a stiff environment. To improve the poor stability of the teleoperator during these stiff contacts, more damping is often required in the teleoperator control loop. However, this extra damping affect transparency of the teleoperator negatively, therefore, the extra damping portion cannot always be active. A variable structure control approach capable of engaging the stabilization controller portion when it is necessary is a very attractive solution since transparency in that case only is affected when the stabilizing control portion is active. An existing method for detection of non-passive teleoperator behaviour is tested on the experimental setup and found difficult to apply to the actual research application. This statement is based on experimental results showing that the average energy loss of the teleoperator controller was larger in stable free space motion than in unstable oscillative behaviour. The relatively large energy amount injected into the slave during free space motion was the energy required for friction compensation and the energy required by the slave as kinetic energy. The on average smaller energy loss during unstable oscillative behaviour was mainly caused by a flexibility in the mechanical structure of the slave - environment system. For high frequencies, this flexibility induces a phase lag larger than 90 degrees between the control force to the slave and its measured velocity and, hence, causing an energy input to the controller instead of an energy extraction.

Instead of the existing detection method for non-passive teleoperator behaviour, an idea on how to detect when to engage a stabilization controller of a general control system is presented based on the concept of passivity.

The major research contribution of this paper is the clarification of the energy flows present on the system ports in a control system modelled as network elements. For the specific task of teleoperator control, a clarification of this kind has not been found elsewhere in literature. The moving mass and the frictional losses of the slave are found to play an important role and the energy flows induced by these phenomena can not be neglected in a general energy analysis of the teleoperator system. Further, amplification/reduction of forces and motions between the master and slave sides of the teleoperator controller are required in many teleoperator applications. These gains introduce a rela-
tion between the energy flows on the master and the slave sides of the controller. Hence, this relation needs also to be considered in the energy analysis.

Future research within the project will be aimed at development of a new detection algorithm for non-passive teleoperator behaviour together with a stabilizing controller portion. Desirable is to design the detection algorithm such that it detects undesired control system behaviour independent of the force and motion scalings and the physical phenomena mentioned earlier.

7. References


