# Passivity Issues in Bilateral Teleoperation - a Phase Property

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**Abstract.** In control design for bilateral telemanipulation there is a trade-off between high transparency and sufficient stability margins. 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. Adaptive control methods which adds extra damping in the teleoperator control loop when it is needed is a promising concept. This paper presents an idea on how to detect when to engage such an adaptive controller. The idea is based on the fundamental passivity result where passivity is regarded as a phase property and experimental results which show that during certain stiff contacts and oscillative behaviour, the teleoperator controller has a slightly positive net energy as a result of power gain on the master port and power loss on the controller's slave port. The power loss on the slave port can then be used to engage a future stabilizing control portion.

**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, [11]. High transparency often comes hand in hand with small stability margins or none at all, see for instance [14], [21], [23].

As mentioned by for instance Hannaford and Ryu [14], Yan and Salcudean [23] and Zhu and Salcudean [25], the operator and the environment must be included in the analysis since these blocks significantly alter closed loop dynamics when interacting with the teleoperator. However, the environment and operator can be characterised as highly nonlinear dynamic processes, [17]. 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 2, a detailed description of the research project is given together with a description of the experimental setup. Section 3 presents the basics of teleoperator modelling and control followed by section 4 which gives an overview of a few of the existing methods for analysing stability of teleoperator systems. Section 5 discusses stability issues of teleoperators using passivity regarded as a signal phase property. The section starts out with a control example which is made non-passive on purpose to show the effectiveness of passivity for detection of unstable behaviour. Finally, in section 6, conclusions and future work are given.

## 2 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 runs in 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 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.

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 is improved with force feedback, [3], [19]. 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's and Turner's paper [10]: The teleoperator acting as an infinitely stiff and weightless mechanical link between the mill housing and the surgeons hand.

### 2.1 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.

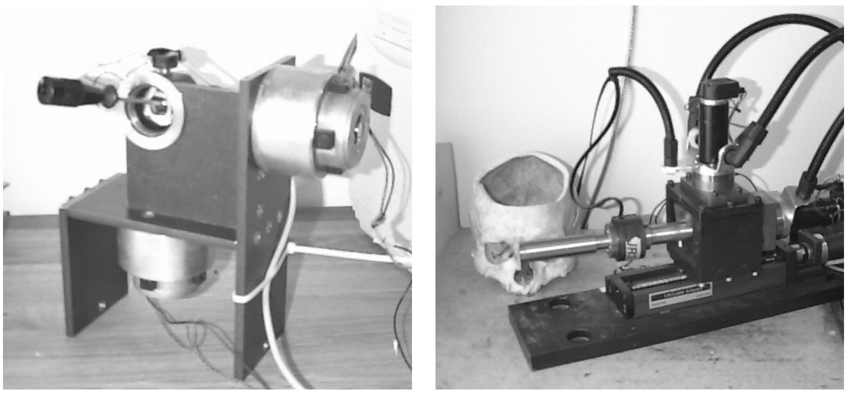

**Fig. 1.** System hardware, left: Master, right: Slave.

## Teleoperator Modelling

Fig. 2 shows a commonly used model for representing the teleoperator, a model for instance used in: [1], [2], [12], [15], [18]. 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 which typically is modelled as a LTI two-port network

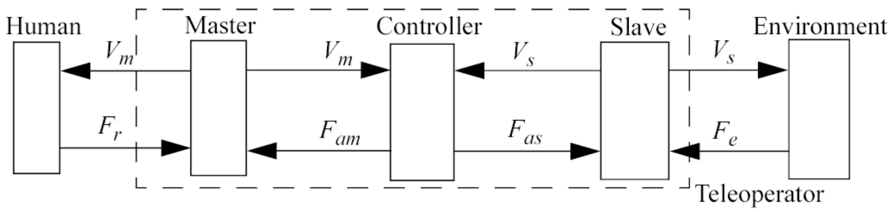


**Fig. 2.** General teleoperator model

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 [6], [9] and [18]. $F_{am}$ and $F_{as}$ are the requested actuator forces to the master and the slave mechanics respectively.

All the classical control structures for bilateral teleoperators can be derived from Lawrence's [18] four channel structure. 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, [15]. In this paper, the force-velocity structure is used (denoted Forward Flow in [12]) in which the master provides velocity/position references for the slave's position servos to follow and, the slave sends back the measured contact force to the master, see fig. 3

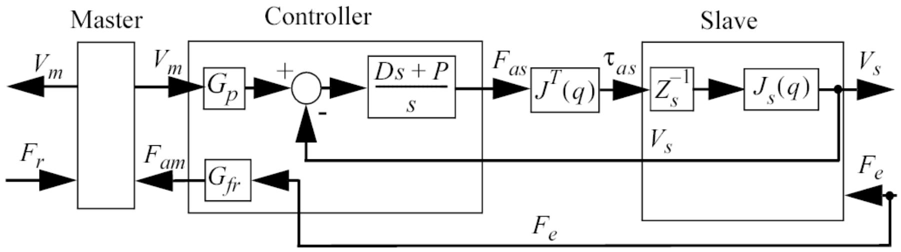


**Fig. 3.** The Force-Velocity teleoperator control structure.

In fig. 3, the scalar gains $G_{fr}$ and $G_p$ are the force reflection gain and the motion gain respectively. The slave's velocity and position controller output, the desired actuator force $F_{as}$ expressed in the base coordinate system $CS_0$ is mapped to desired actuator torques $\tau_{as}$ expressed in the slave generalized coordinates $q$ via the slave's Jacobian transpose as:

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

Then, 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 Hogan's [16] impedance control concept without altering the inertia of the manipulator as Hogan proposed.

# 4 Stability of Teleoperator Systems

## 4.1 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, i.e. energy based analysis. Passivity has its roots in network theory and has been shown to be a promising concept for teleoperator control, [21].

## 4.2 Stability Analysis of Teleoperators Using Design Models of Operator and Environment

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 [3] and [8]. 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, [14], [25], [23].

## 4.3 Passivity and Energy

Colgate and Hogan in [5] and Colgate in [4] showed that a necessary and sufficient condition to guarantee stability of a LTI two-port coupled to an *arbitrary* passive network is that the LTI two-port itself is passive. Hence, as mentioned in [1], [20] and [24], the control designer only needs to ensure passivity of the teleoperator (the dashed square in fig. 2) itself to guarantee teleoperator stability if the environment and the operator are passive.

The well known mathematical definition of passivity for a two port with the injected flows $v_1$ and $v_2$ and with the applied efforts $f_1$ and $f_2$ is: (from [7])

$$\left( \int_0^t (f_1 v_1 + f_2 v_2)dt + E(0) \right) \geq 0 \qquad \forall t \geq 0 \tag{2}$$

where $E(0)$ is the energy stored at $t = 0$.

A physical interpretation of passivity is that a device is passive if it cannot increase the total energy in a system of which it is an element, [23]. Passivity as defined in eqn. (2) can also be interpreted as a phase property, which is best explained by an example.

In fig. 4, let us assume a manipulator with a reference *r* and represented as a one port network. From eqn. (2), energy is extracted from the network if the two signals *r* and *y* have opposite signs (i.e. there is a considerable phase lag between *r* and *y*). As a consequence of the fundamental passivity result [22], 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. In Lawrence's paper [18] and in [9], 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. 4 to be strictly passive, i.e. strictly positive real. Such a system has an "infinite gain margin". From this, passivity can be interpreted as a "phase property" which is valid for linear as well as nonlinear systems [22].

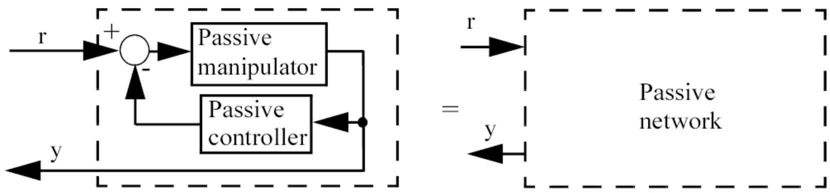


**Fig. 4.** Block diagram for illustrating the fundamental passivity result

## 4.4 Adaptive Methods

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 model are all possible sources of unpredictable system behaviour and stability can not be guaranteed. Instead, using methods capable of detecting and compensating for non-passive behaviour on-line have several advantages:

- 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 adaptive passivity assuring portion of the controller can add damping when needed if the passivity requirement is violated (if the actuators do not saturate).
- It may be possible to use an existing control architecture and to make it stable for an higher environmental stiffness if the controller is extended with an adaptive passivity assuring portion, [21].

Lately, Ryu and Hannaford published a series of papers [13], [14] and [21] describing a method for *real time* detection and compensation of non-passive behaviour of a teleoperator system. The basic idea is to monitor the energy flows on both sides of the controller, see fig. 3. If more energy is flowing out than flowing in, the controller is about to violate the passivity definition and the net energy in the controller needs to be increased. This is done by two passivity controllers, one placed at each port of the controller. Practically, more damping is added when eqn (2) is violated.

Another adaptive approach is presented in Zhu's and Salcudean's paper [25], the parameters in combined human-master and slave-environment dynamics are adapted depending on the environmental and operator characteristics. The parameters are adapted within specified ranges and the control architecture is $L_2$ and $L_\infty$ stable under the modelling assumptions in both free space motion and in rigidly constrained motion.

# 5 Passivity Properties of Teleoperator Systems

## 5.1 Introduction

The phase lag between signals over a network port provides information on when power and energy are extracted from the network port and when there is a risk that the network violates the passivity definition, eqn (2). If the power over a port of a network is negative, i.e. there is a phase lag between the signals larger than 90 degrees, energy is about to be extracted from the network and passivity assuring control is necessary.

## 5.2 Simulation Case Study, Passivity as a Phase Property

In fig. 5, a DC-motor Maxon RE-035 118777 [26] is modelled as a first order system by $G_1 = 342{,}5/(s + 10{,}67)$ (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 $G_2 = P/(s/(2*1000*\pi) +1)$, where $P = 1$. Both systems are passive and the feedback system with the input $r$ and output $\omega$ is also passive by 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 $t \in [1; 18]$.

The phase margin of the system without the time delay is 88.7 degrees at 341.7 rad/ sec. 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. The sampling frequency for the control loop is 10 kHz.

As can be seen in the left plot in fig. 6, the output $\omega$ oscillates totally out of control when the delay is activated. The right plot in fig. 6 shows the power and the energy

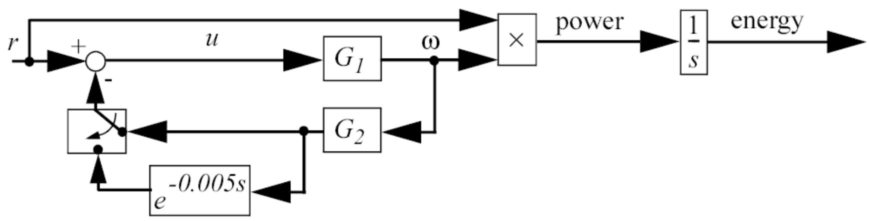


**Fig. 5.** System for the case study. Both systems $G_1$ and $G_2$ are passive and thereby also the feedback loop. Passivity is violated when the time delay is activated.

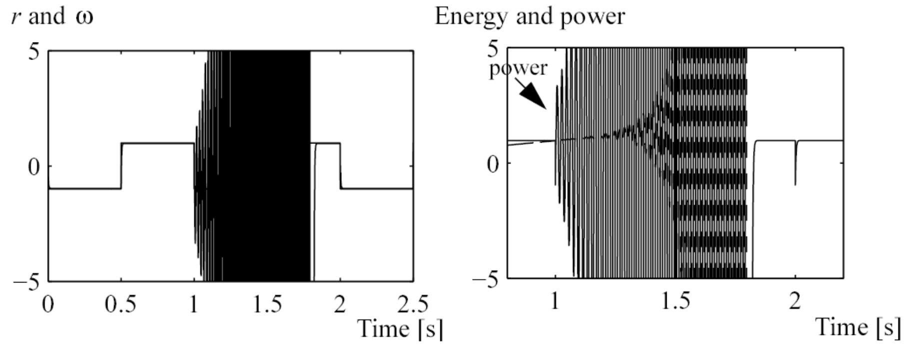


**Fig. 6.** Simulation results, left: Reference (solid line) overlapping the motor angular velocity (dashed line) and right: The energy (dashed line) and the power (solid line) of the system.

levels in the system. The energy plot reveals passive behaviour up to $t = 1.45$ sec. since the energy is positive up to this instance. But, by studying the power plot it can be concluded that the power in the system goes negative already at $t = 1.0$ sec. and, since energy is the power integrated over time energy will decrease if the power goes negative. By studying the sign of the power in the system, it can be detected at an early stage if the energy in the system is about to decrease and the passivity requirement is about to be violated.

The problem with detecting unstable behaviour from the energy signal discussed in Hannaford's and Ryu's paper [13] is obvious in this example when positive energy has been accumulated before the system turns unstable at $t = 1.0$. One possible solution to explore is to take stabilizing action if several samples of the power signal in a row are negative. The reason for not take action if one power sample is negative is due to the risk of over conservatism. For instance, the power is negative for a short time when the reference changes sign since the feedback system in practical is a low pass filter.

Implementing a "power controller" (running at 1 kHz sampling frequency) which simply turns off the control signal $u$ if three samples in a row of the power are negative would then keep the energy from growing negative and keep the feedback system from $r$ to $\omega$ stable even though the time delay causes the phase margin to be negative. The left plot in fig. 7 shows the reference and the output and, the right plot shows the energy and power levels in the system when the power controller is implemented.

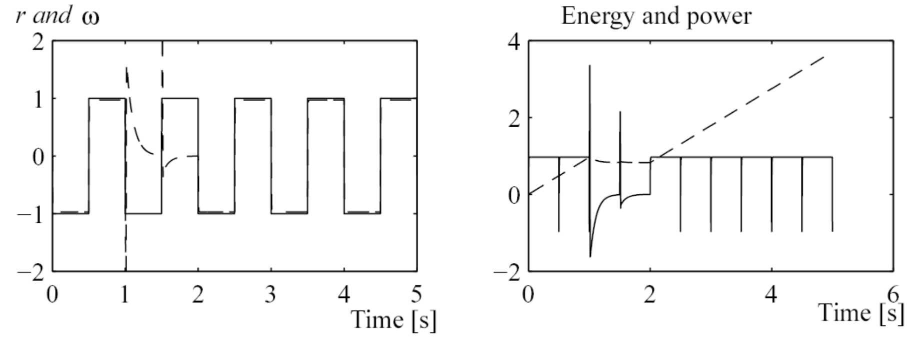


**Fig. 7.** Simulation results for the system in fig. 5 when the power controller is implemented. Left plot: The output (dashed line) and the reference (solid line). Right plot: The energy (dashed line) and the power (solid line).

As can be seen in the plots of fig. 7, as soon as the power goes negative, the power controller turns off the control signal and the output approaches zero resulting in a strictly positive energy and thereby a system which act as a passive system.

The units for the reference signal can be chosen to be Volts or rad/sec. Depending on the unit on the reference, the energy takes the unit Nm or ($rad^2$/sec). This is of less concern since the phase difference between r and ω plays the most important role when regarding passivity as a phase property.

To conclude this example: The key issues when using passivity as a phase property and the power signal to detect when a passive system is about to turn non-passive are:

- The phase lag through a passive system is never larger than 90 degrees.
- In order for a system to turn non-passive, the power must turn negative which occurs before the energy level in the same system turns negative.
- The power can temporarily be negative when the reference changes sign rapidly. To reduce over conservatism in this case, the detection must compare several samples of the power signal. This solution to reduce over conservatism is just an idea, more research will be spent on this issue in the future.

Remark: A smaller *P* gain can be found for which the phase margin is positive for $t \in [1; 18]$. But with this smaller *P* gain, the control performance during $t \in [1; 18]$ is much more oscillative compared to setting $u = 0$. This is due to that during $t \in [1; 18]$ the system starts to switch between the two P controllers and the result is oscillative behaviour.

### 5.3 Phase Properties of Signals in Bilateral Teleoperator Systems

In this paper, only the energy and power flows in and out of the teleoperator controller are monitored, as done in [21]. This is due to the following observations:

**Phase Properties on the Slave Side of the Teleoperator, Experimental Results**. The interaction between the environment and the slave manipulator is considered as passive if the mill is turned off. It is not obvious what happens if the mill is switched on. Can the motions induced by the rotating mill in the slave mechanics cause the interaction to be active? Clearly, it is not sufficient to model the contact force with $F_e = Z_s V_s$, an additional term $F_e$* must be included $F_e = Z_s V_s + F_e$*, as done in [18]. Further investigation of this topic is left out for future research.

The slave mechanics i.e. the linkage and the actuators, is connected to the teleoperator controller's slave port, see fig. 3, with input $F_{as}$ and output $V_s$. The dissipative nature of the actuators and linkages makes them passive by default, but if the slave's input changes sign to fast for the actuators to follow, the output can temporarily have a different sign than the input, then the teleoperator controller will loose small amounts of energy on its slave port as in the case study. This is r elated to the slave's limited mechanical bandwidth, the actuators can not follow motion commands infinitely fast.

These observations are tested experimentally in two experiments. In the first experiment, the force reflection is turned off, the master moves slowly and the slave moves in free space. As can be seen in fig. 8, left plot, $V_s$ (dashed line) has the same sign as $F_{as}$ (solid line) and the teleoperator controller does not loose energy (dashed line) or power (solid line) over the slave port as shown in the right plot.

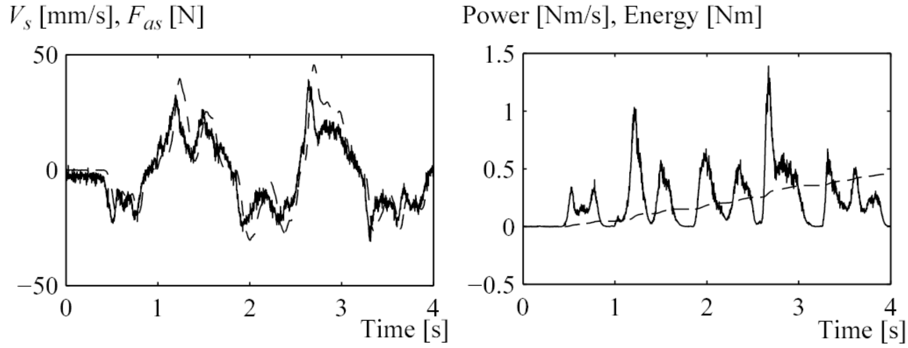


**Fig. 8.** Experimental results, slave in free space motion, force feedback turned off and low rate of change in the slave's control input $F_{as}$. The left plot shows the slave velocity $V_s$ (dashed line) and slave input $F_{as}$ (solid line), the right plot shows the energy (dashed line) and power (solid line) over the teleoperator controller's slave port

In the second experiment, the conditions are the same but the master moves quickly 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) has different signs temporarily and the teleoperator controller loose power (solid line) on its slave port as shown in the right plot

**Phase Properties on the Master Side of the Teleoperator** The mechanics of the master is considered passive. This assumption is supported by earlier research presented in [8], where a passive model of the combined master and human finger system is derived with lower and upper bounds on the model parameters are identified. Further, the interaction between the human operator and the master hardware is considered as passive, as assumed also in Adams and Hannaford [2] and references therein.

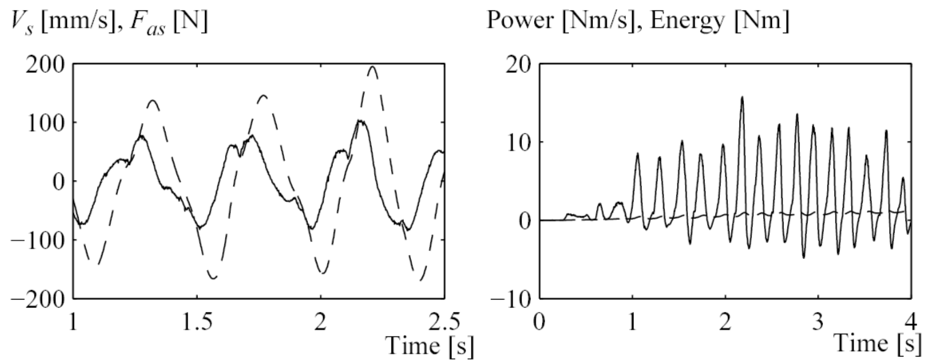


**Fig. 9.** Experimental results, slave in free space motion, force feedback turned off and high rate of change in the slave's control input $F_{as}$. The left plot shows the slave velocity $V_s$ (dashed line) and slave input $F_{as}$ (solid line), the right plot shows the energy (dashed line) and the power (solid line) over the teleoperator controller's slave port

### 5.4 Experimental Results, Phase Properties in Bilateral Teleoperators During Oscillation

From the energy and power flows on both sides of the teleoperator controller, i.e. eqn (2), it is possible to decide where and when passivity assuring control action is necessary for stabilizing an oscillating teleoperator. In the following experiment, the force reflection gain $G_{fr}$ is set to 0.3 and the position gain $G_p$ is set to 0.5.

In fig. 10, plot A shows the master and slave position during the experiment, plot B shows the energies on the teleoperator controller's master and slave port. The energies are calculated by integration over time of $F_{as}$*$V_s$ and $F_{am}$*$V_m$. Plot C shows the contact force, plot D shows the teleoperator controller's energy which is the sum of the two signals in plot B, and plots E and F show the power over the teleoperator controller's master and slave port respectively. As can be seen in plot D, the teleoperator controller is passive during the experiment since the energy is positive. But, as can be seen in plots A and C the teleoperator bounces against the environment between $t \in [0; 0.5]$ , $t \in [0.8; 1.5]$ and between $t \in [1.8; 2]$. Then, this bouncing behaviour could not be detected by monitoring the controller's energy as done in [21]. From the plots E, F and B it can be seen that the teleoperator controller *only* loses energy on its slave port in this experiment.

In this case, stability assuring control action is only necessary on the teleoperator controller's slave port. As in the study case, section 5.2, the power on the teleoperator controller's slave port turns negative before the energy does. Hence the stability assuring control action should be engaged on the negative power over the teleoperator controller's slave port. Future work within the project will be aimed at development of such a controller.

The experiment is performed under the following conditions: Contact is established for $X_s < 0$, impact velocity is approximately 25 - 40 mm/s, the environmental stiffness

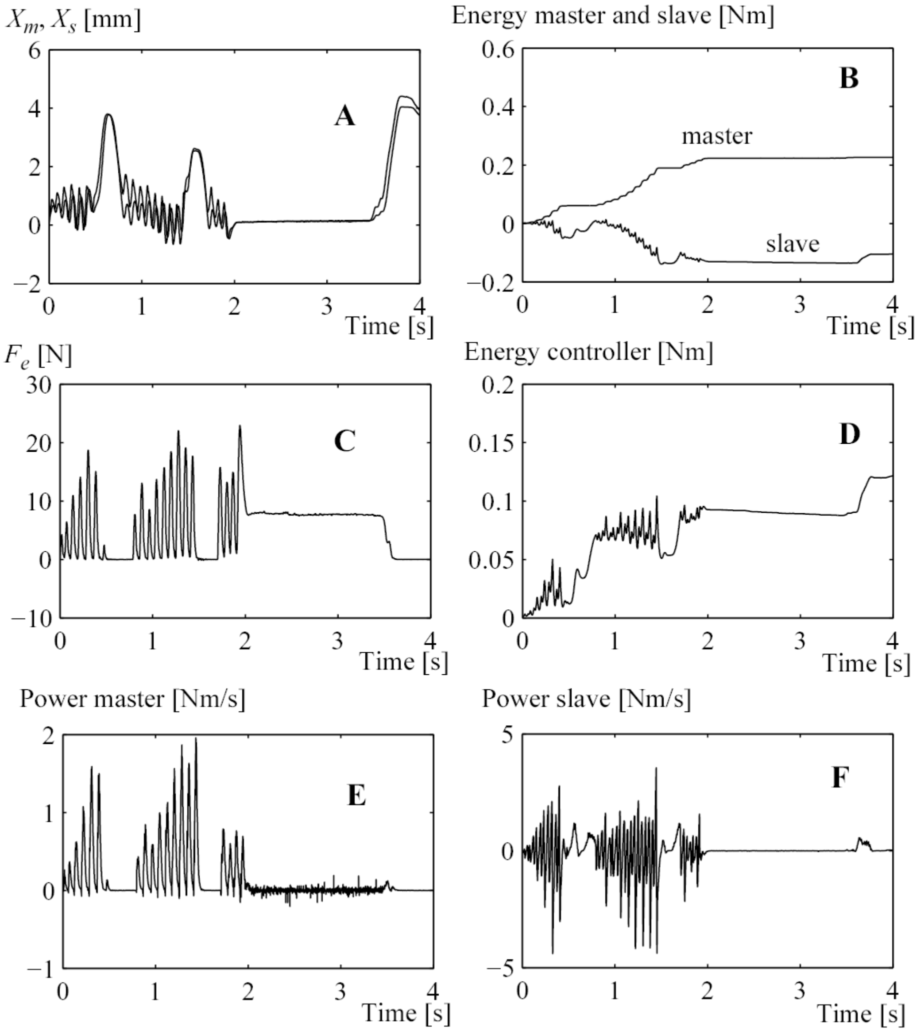


**Fig. 10.** Experimental results. Plot A: The positions of the master and slave. Plot B: The energies present on the controllers master and slave port. Plot C: The contact force. Plot D: The total energy on the controller. Plot E and F: The power on the controller's master and slave port respectively.

is approximately 25 kN/m. The master and slave is controlled as depicted in fig. 3 and the slave control loop's bandwidth from $X_m$ to $X_s$ is around 4 Hz.

## Conclusions and Future Work

Passivity of the teleoperator controller is often violated or almost violated when the stiff slave manipulator makes contact with a stiff environment. To improve the poor stability margins 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 engaged. An adaptive approach is necessary. This paper presents an idea of when to engage a stabilizing control portion of the teleoperator controller. The idea is based on the fundamental passivity result, [22], where passivity is regarded as a phase property. Experimental results show that the teleoperator can start to oscillate during stiff contacts even though the controller's net energy is positive. During these oscillations, the teleoperator controller is found to loose power on its slave port and gain power on its master port. For this case, the teleoperator controller need to be equipped with a "power" controller able to always keep the power over the slave port positive and thereby the complete teleoperator stable during all times. Future research within the project will be aimed at development of such a power controller.

## References

1. Anderson R. J., Spong M. W., *Bilateral Control of Teleoperators with Time Delay*, IEEE Transactions on Automatic Control, Vol. 34, No. 5., May 1989.
2. Adams R. J., Hannaford B., *Stable Haptic Interaction with Virtual Environments*, IEEE Transactions on robotics and Automation, June 1999, vol. 15, No. 3, pp. 465 - 474.
3. Bu Y., Daniel R. W., McAree P. R., *Stability analysis of force reflecting telerobotic systems*, IEEE International Conference on Intelligent Robotic System, 1996. Vol.3, pp 1374-1379.
4. Colgate J. E., *Coupled stability of multiport systems-theory and experiments.* Transactions ASME Journal of Dynamical Systems Measurements and control vol. 116, no 3, pp 419-428, 1994.
5. Colgate J. E., Hogan N., *Robust Control of Dynamically Interacting Systems*, International Journal of Control, vol 48, no. 1, pp. 65 - 88, 1988.
6. Colgate J. E, *Robust Impedance Shaping Telemanipulation*, IEEE Transactions on Robotics and Automation, Vol. 9, No. 4, pp. 374 - 384, August 1993.
7. Doeser C.A., Vidyasagar M., *Feedback Systems: Input-Output properties*, New York: Academic 1975.
8. Flemmer H., Eriksson B. and Wikander J., *Control Design for Transparent Teleoperators with Model Parameter Variation*, Proceedings of the IEEE International conference on Robotics and Automation, Washington DC, May 2002, pp.
9. Flemmer H. and Wikander J., *Transparency and Stability Analysis of a Surgical Teleoperator System*, Proceedings of the 11:th Haptics symposium, Los Angeles, March 2003.
10. Handlykken M., Turner T., *Control Systems Analysis and Synthesis for a Six Degree-of-freedom Universal Force-Reflecting Hand Controller*, Proceedings of the IEEE conference on decision and control, 1980, vol 2, pp 1197 - 1205.
11. Hannaford B., Stability and Performance Trade-offs in Bi-lateral Telemanipulation, Proceedings ICRA May 1989, Scottsdale AZ, Usa, Vol 3, pp. 1764 - 1767.
12. Hannaford B., *A design framework for Teleoperators with kinesthetic feedback*, IEEE transactions on robotics and automation, vol 5, no 4, pp 426-434, August 1989.
13. Hannaford B., Ryu J.-H., *Time Domain Passivity Control of Haptic Interfaces*, Proceedings ICRA-2001, Seuol, Korea, pp. 1863 - 1869.
14. Hannaford B., Ryu J.-H., *Time Domain Passivity Control of Haptic Interfaces*, IEEE Transactions on Robotics and Automation, vol. 18, no. 1, February 2002
15. Hashtrudi-Zaad K. and Salcudean S. E., *Analysis and Evaluation of Stability and Performance Robustness for Teleoperation Control Architectures*, Proceedings IEEE ICRA-2000, San Francisco, USA, pp. 3107-3113.
16. Hogan N., *Impedance Control: An approach to manipulation, Part II - Implementation*, Transactions of the ASME Journal of Dynamic Systems Measurement and Control, March 1985, Vol. 107.

17. Kazerooni H., Contact instability of the direct drive robot when constrained by a rigid environment, IEEE Transactions on Automation and Control, Vol. 35 Issue 6, Jun. 1990 pp. 710 -714.
18. Lawrence D., A., *Stability and Transparency in Bilateral Teleoperation*,. IEEE Transactions on robotics and automation, October 1993, vol. 9, no. 5, pp. 624 - 637.
19. Lazeroms M., Van Der Ham A., Jongkind W., Honderd G., *Force-feedback for Minimal Invasive Instruments*, Symposium on Robotics and Cybernetics, CESA '96 IMACS Multi conference, Computational Engineering in Systems Applications, Lille, France 1996, pp 228 - 231.
20. Raju G. J., Verghese G. C., Sheridan T. B., Design Issues in Two-port network models of Bilateral Remote Manipulation, Proceedings of the 1989 IEEE International Conference on Robotics and Automation, pp. 1316 – 1321
21. Ryu J.-H., Kwon D.-S. and Hannaford B., *Stable Teleoperation with Time Domain Passivity Control*, Proceedings ICRA-2002, Washington DC, USA, pp. 3260 - 3265.
22. Sepulchre R., Jankovic M., Kokotovic P., *Constructive Nonlinear Control*, Springer-Verlag London 1997, ISBN 3540761276.
23. Yan J., Salcudean S. E., *Teleoperation Controller Design Using - Optimization with Application to Motion Scaling*, IEEE Transactions on control systems technology, May 1996, Vol. 4, No. 3, pp. 244 - 258.
24. Yokokohji Y., Yoshikawa, *Bilateral Controller of Master-slave Manipulators for Ideal Kinesthetic Coupling*, Proceedings of the 1992 International Conference on Robotics and Automation, Nice, France, pp. 849 - 858.
25. Zhu W.-H., Salcudean S. E., *Stability Guaranteed Teleoperation: An Adaptive Motion/Force Control Approach*, IEEE Transactions on automatic control, November 2000, vol. 45, no. 11, pp. 1951 - 1969.
26. ftp://ftp.maxonmotor.com/Public/Download/catalog_2002/Pdf/02_076_e.pdf