Visual Comput (2007) 23: 273–284
DOI 10.1007/s00371-007-0101-3

ORIGINAL ARTICLE

Carsten Preusche
Gerd Hirzinger

Haptics in telerobotics

Current and future research and applications

Published online: 2 March 2007

C. Preusche (✉) · G. Hirzinger
Institute of Robotics and Mechatronics
German Aerospace Center (DLR)
Oberpfaffenhofen, D-82234 Wessling
Carsten.Preusche@dlr.de

Abstract For telerobotic systems the ultimate goal is transparency, meaning the human operator cannot distinguish between operating in a local or a distant environment. To achieve this, the human operator is coupled with the telerobotic system with all necessary senses: visual, auditory and haptic modality. For the haptic modality this implies research in the following fields: robotic hardware, both handcontroller and teleoperators, and control aspects with time delay. The latter include both supervisory and bilateral control. In this paper the current and future aspects of haptics in telerobotics are shown focusing on the control research. With the evolving technology in these research areas telerobotic systems can now be found in a variety of different application fields, e.g. microassembly, surgery or space.

Keywords Haptics · Telerobotics · Bilateral control · Haptic display · Transparency

1 Introduction

In this paper an overview of the current and future research in telerobotics concerning haptics are given. These developments are inspiring new applications or improving existing ones towards everyday use.

The introduction will clarify the basic terms: telerobotics, haptics, telepresence and transparency. In the next section the current state of the research is given. This will cover mechatronic design of handcontrollers and teleoperators and control aspects in supervisory and bilateral control. Afterwards an overview of modern applications for telerobotic systems is given. Lastly, some research problems are derived and open questions are formulated.

1.1 What is telerobotics?

Literally meaning robotics at a distance, telerobotics is generally understood to refer to robotics with a human operator in control or human-in-the-loop. Any high-level, planning, or cognitive decisions are made by the human user, while the robot is responsible for their mechanical implementation. In essence, the *brain* is removed or distant from the *body*.

The separation of brain and body requires a sufficient bidirectional information flow between the human operator (brain) and the robot (body). The operator needs sensory input to perceive the situation at the remote environment, on which he/she can decide what to do and how to act. This means changing the remote environment. The robot on the other side needs control input to know what to do and how to act. Depending on the control strategy this control input can be gross commands or fine motor input.

Herein the term *tele*, which is derived from the Greek and means distant, is generalized in the sense, that a barrier is located between the user and the robot and has to be overcome by the telerobotic system (see Fig. 1). There exist several kinds of barriers under which the most common is distance. But other barriers also play an important role for telerobotics, which are danger, matter or scaling. Table 1 gives some typical examples for the different barriers, which are overcome by telerobotic systems. All barriers have in common that the user cannot (or will not) reach the remote environment physically by himself.

Summarizing it can be stated that *telerobotics* means to overcome a *barrier* between a human and a remote environment to *manipulate* it.

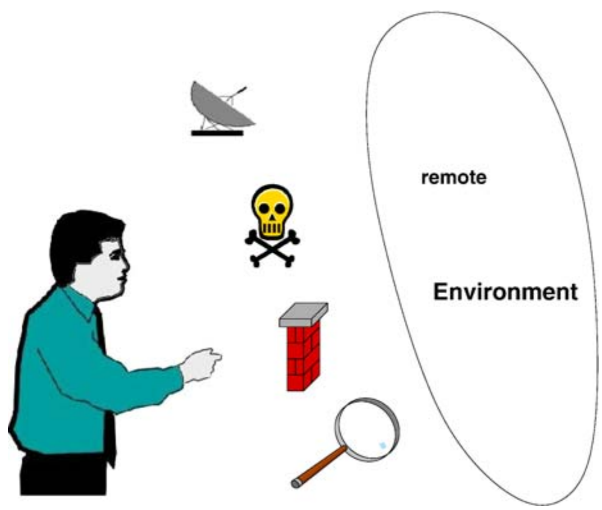

Fig. 1. Telerobotics overcome barriers: distance, danger, matter and scaling

Table 1. Some examples for barriers in telerobotics

Example	Barriers involved
Handling of nuclear material	Danger, matter
Space robotics	Distance, danger
Micro-/nanomanipulation	Scaling
Minimally invasive surgery	Matter, scaling

1.2 Haptics in telerobotics

In telerobotic systems haptics have played an important part from the very beginning in the early 1950s, though it has been evident that the human is widely using his/her haptic modalities when manipulating objects.

In exploration tasks the human uses mainly his/her visual feedback, though it provides a lot of information about a scene. From his/her experience the human heavily relies on the vision. This becomes obvious, if in virtual reality simulations the different feedbacks are inconsistent. In this case, the operator treats the visual feedback as true, until the other modalities provide sufficient information to overrule this assumption.

Although geometrical information in 3D can be obtained by looking at an object and moving around, only pre-knowledge leads the operator to a suggestion about the structure or material of the surface. This information can only be obtained by touching the surface, i.e. the haptic modality. So for a complete exploration of a remote scene and the extraction of information about the structure of the object haptic feedback is needed.

The need for haptics becomes more obvious, if the operator wants to change the remote scene, i.e. interact with the remote objects. Interaction or manipulation requires arms and hands and also the feedback acquired by these means. When directly interacting with an object sensor-motor, feedbacks in the arm and hands are closed, especially if fine manipulation is required to fulfil a certain task.

This situation is the same for telerobotic systems: the sensor-motor feedback loop needs to be closed both for the human operator and for the remote robot. The human receives through the haptic feedback sensed by the remote robot contact and stiffness information, which al-

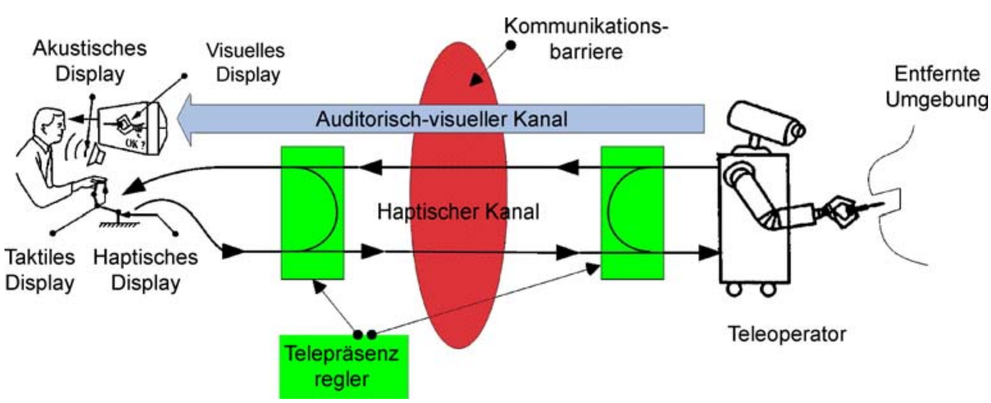

Fig. 2. Telepresence scheme

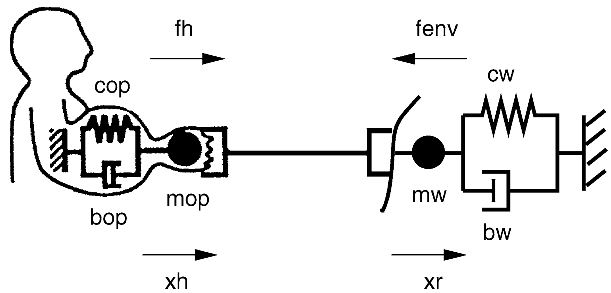

Fig. 3. Ideal response

lows him/her to smoothly interact with the remote scene by commanding the robot.

Figure 2 shows a schematic overview of a telerobotic system. While the visual and the audio channel is mainly uni-directional the haptic channel is bilateral and includes local control loops. In the next section a focus is set on the haptic modality within a telerobotic system.

1.3 Telepresence

Telepresence is somewhat the ultimate goal for telerobotic systems and can be defined as follows:

Definition 1 (Telepresence). *The human operator feels present at the remote location with all his/her sensor-actor modalities.*

Of course this does not only include the telerobotic part (haptic) focused on in this paper, but also other feedback modalities connected with the human senses like vision, hearing or even smell and taste.

As a performance indicator for telepresence systems the term transparency is often used. This describes how *visible* the technical system is:

Definition 2 (Transparency). *The human operator cannot distinguish between operating in the local or distant environment.*

A more mathematic description of transparency is given in [42], in which Yokokohji defines the ideal response for a haptic telerobotic system. It is achieved, if the telerobotic system behaves like a zero mass, infinite stiff bar (see Fig. 3).

This could not be reached by real telerobotic systems, but serves as a measure of performance for the haptics in telerobotics.

2 Research issues

Current research on mechanics, electronics and control theory for telerobotic systems is driven by these demands for ideal transparency and telepresence. In this section recent results are given in three categories:

– Teleoperators
– Haptic interfaces
– Control (with time delay)

2.1 Systems

The first two categories include mechatronic systems, which improve the state-of-the-art in teleoperator and man-machine interfaces. Here the integrated design of mechanics, electronics and information technology leads to high-performance, light-weight and dexterous robotic systems. For telerobotics these systems are the basis for a progress in terms of agility and transparency.

2.1.1 Teleoperators

Teleoperators have to mimic or copy the human abilities on the remote side. This includes both the sensoring possibilities and the manipulation skills of a human arm and hand. So not only the shape and kinematics of the human arm have to be taken into account, but also the dynamics and the low-level sensor-motor skills. The sensor-motor control loop requires robotic joints with torque sensors and local impedance control, as realized with the DLR light-weight robot [16].

Besides the robotic arm at the remote side, dexterous robotic hands are needed to mimic human fine manipulation skills. Also the hands require a high integration of sensors and powerful actuation. The DLR dexterous 4-finger hand represents such a class of manipulators (see Fig. 4). It has 12 torque controlled DoF[1] and a reconfigurable palm, which allows different types of grasps, e.g. fine or powerful [7, 9]. Miniaturized 6 DoF force-torque sensors in each fingertip generate sensor feedback to the human operator for his/her manipulation tasks.

To improve the feeling of being telepresent at the remote location the teleoperator not only needs human-like behavior, but also human-like shape. The teleoperator is the embodiment of the human operator, who more easily identifies himself/herself with the extended body, if this body has a similar shape. Also a human-like kinematic and dynamic system can be more intuitively controlled by a human, as the movements are similar to his/her own.

The DLR human-like two-arm system JUSTIN is such a humanoid teleoperator (see Fig. 5). The upper body consists of 43 torque-controlled joints, which are kinematically copied from a human [27]. Besides the robotic system, it has a multi-sensor head with a stereo camera and additional sensors [40], from which not only a stereo feedback is presented to human operator, but also a world

[1] DoF = degree of freedom

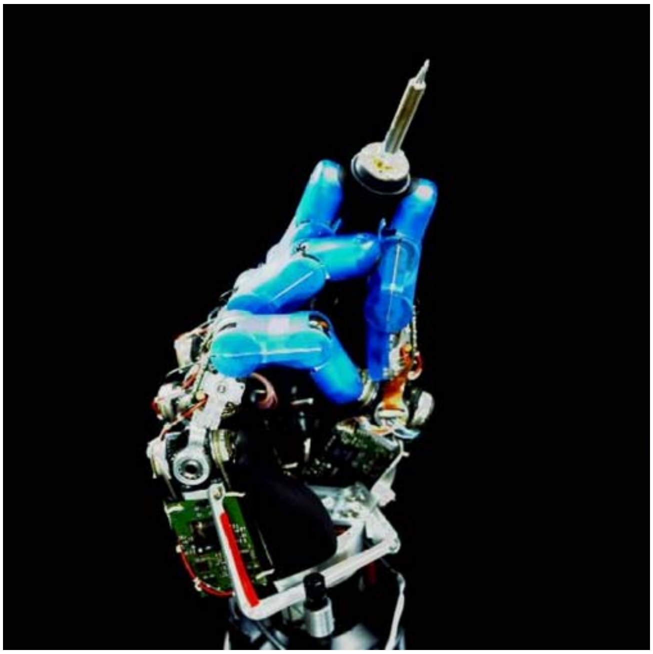

Fig. 4. DLR dexterous robotic hand

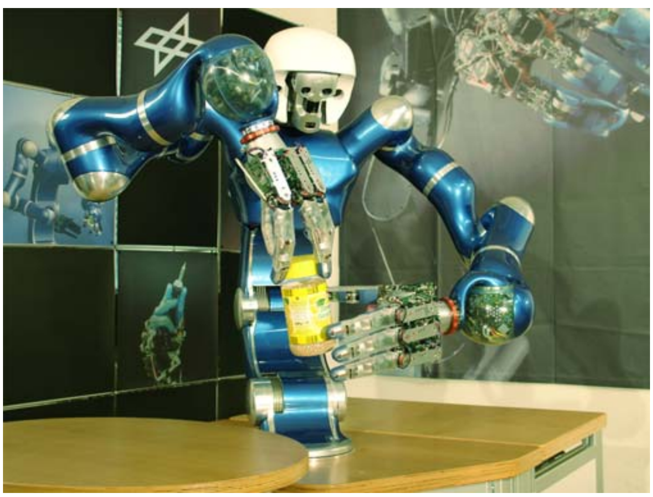

Fig. 5. DLR human-like two-arm system: JUSTIN

model update for supervisory control strategies can be generated.

2.1.2 Haptic interfaces

Identical mechatronic design philosophy must also be applied to the haptic man-machine interface on the master side of the telerobotic system. A force feedback handcontroller needs to have high resolution sensors and fast dynamics, to provide a high bandwidth to the human operator. There exist two types of haptic interfaces which are

Fig. 6. DLR handcontroller on basis of the DLR LWR3

currently developed independently: kinesthetic *arm* and *hand* feedback devices.

In fact the DLR light-weight robot provides a good basis for a haptic handcontroller (see Fig. 6). With its low weight compared to the actuation power and a sophisticated control it presents a haptic interface with a large workspace, which is comparable to the human arm workspace, and applicable force (torques) up to 100 N (20 Nm) [29]. Due to its opposite configuration it is easy to use und no time-consuming attachment of the device is necessary. This configuration allows an unscaled teleoperation in a typical setup.

Due to complexity and mobility of the human hand a high-fidelity haptic feedback for the hand manipulation is still a challenging problem. Therefore only reduced solutions for haptic hand feedback exist. These limitations can be a reduced number of DoF with haptic feedback or a substitution of haptic feedback by, e.g. vibration stimuli.

An example for a hand exoskeleton is the HFF (Hand Force Feedback) device. The HFF provides three DoF force feedbacks at each fingertip (see [5]), so detailed grasping feedback can be provided. These hand-exoskeleton devices promise a higher level of intuitive tactile feedback for telerobotic systems.

For special uses, which require only a certain type of feedback, dedicated devices can be developed, which provide the desired force feedback. At DLR a gripping force master device for minimally invasive robotic surgery is under development, which can easily be attached to a force feedback device (see Fig. 7). The forceps used in surgery provide only one DoF, so the desired master haptic interface can also be reduced to one DoF, without restriction in the use.

Often force feedback, especially for finger devices, is substituted by vibro-tactile stimuli. These devices are de-

Fig. 7. Prototype of one DoF gripping force master device

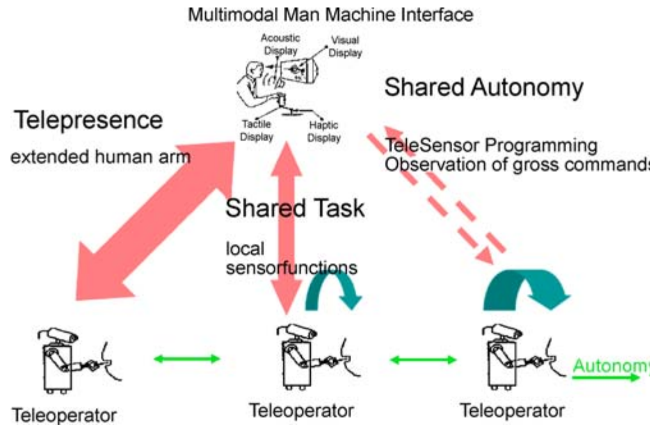

Fig. 8. Telerobotic control concepts

signed to be more compact and more actuators can be assigned. Though the stimuli is not realistic because one can penetrate objects, the vibration at the contact point helps the operator to perceive an object. A study for the use and design of vibro-tactile feedback for the arm is given by [38]. In [10] the stimuli substitution by thermal and vibro-tactile actuation for the human hand is studied.

The next developments have to move towards the integration of arm kinesthetic and finger tactile feedback. This should also include the stimuli not mentioned here, like temperature, pressure, etc.

2.2 Control

The fundamental control concept of telerobotics is human supervisory control. Sheridan characterizes human supervisory control related between the two extremes of automatic control and manual control [39]: *Human operators are intermittently programming and continually receiving information from a computer that itself closes an autonomous control loop through artificial effectors and sensors.* Today the autonomous control loops can also be closed on the remote side and only the state and model information is transmitted to the operator side. The operator supervises the telerobotic system and decides how to act and what to do.

There exist several approaches for the control of telerobotic systems covering the two extremes of automatic and manual control. This division is not strict and the transitions between the control strategies are soft. A catalog can be made in terms of connection between master and slave system (see Fig. 8).

A very strong connection characterizes bilateral control, i.e. nearly no intelligence is located at the slave side and all motion is controlled by the master. If the task is shared among local sensory functions and operator commands, a shared control strategy is applied to the telerobotic system, which is then controlled on task-level. Supervisory control is given if master and slave are connected loosely with strong local autonomy, i.e. the operator is giving gross commands, which are refined and executed by the teleoperator. This control architecture tends towards autonomous systems. In the following these approaches are explained (see also [35]).

2.2.1 Shared autonomy control

If the main technological constraint of the telepresence system is the communication delay, like often occurs in space applications, the shared autonomy control type is often used on an autonomy level basis. That means, gross commands, given by the operator, were refined autonomously by the teleoperator (see Fig. 9) [13]. The teleoperator acts like an intelligent system using its local sensory feedback loops. On the other side the human operator originates gross path commands by using a kinesthetic feedback device, which are "fine-tuned" by the teleoperator himself. In this situation the operator receives haptic feedback from a world model simulation, which is built from pre-knowledge and refined and kept up-to-date by remote sensor information.

In telerobotic systems with large time delays this shared autonomy concept distributes intelligence between the operator and the teleoperator in the sense of a task-directed approach (telesensor programming) [14]. The operator expresses his/her commands in a natural way using a virtual reality interface and receives a feedback from a pre-simulation, which is based on the sensory measurements of the remote environment. Based on this input an autonomy level generates general sensory patterns. A local sensor controller at the teleoperator performs the refined task using this sensory pattern.

2.2.2 Shared task control

In the case of a shared task control the task is subdivided into two task spaces. One is controlled autonomously by

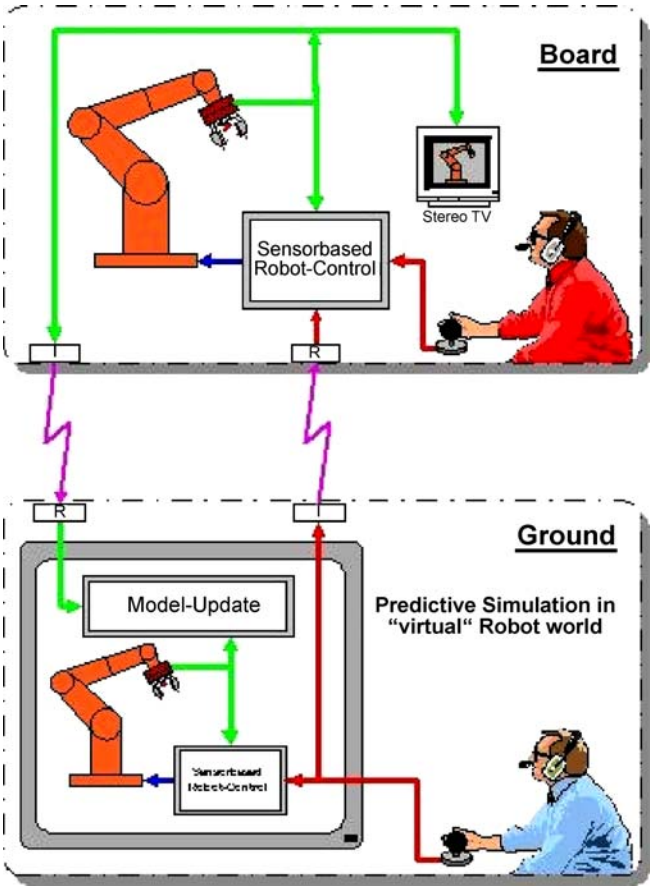

Fig. 9. Shared autonomy in space application

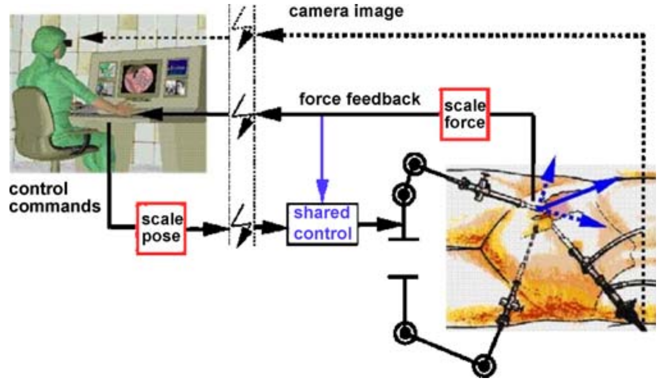

Fig. 10. Shared task in surgery application

a sensory feedback controller at the remote robot and the other is performed by a telepresent human operator. This strategy is designed to ease the task for the operator, such that he/she can concentrate on the main problem of the application. The autonomous controlled subtask can be the compensation of a relative movement between the teleoperator and the remote environment, e.g. during a space servicing mission.

In the field of surgery robot assistance the shared control approach can be used to compensate organ movements. The teleoperator compensates the disturbing organ motion, such that the relative pose between the target area and the surgical instrument remains constant. The surgeon can then work on a virtually stabilized organ. This is especially the case in beating heart bypass grafts. Mechanical stabilizers (e.g. Octopus by Medtronic) are utilized in these operations to reduce the motion of the beating heart. The reliable measurement and prediction of the motion is a prerequisite for the compensation of the remaining heart motion [24]: In case of contact between a surgical instrument and the heart surface, the motion of the heart at this contact point can be estimated indirectly via force sensors integrated into the instrument [25]. If there is no contact between instruments and heart surface, contactless sensors are applied, such as the laparoscope. Therefore, prominent image structures on the heart surface are used as natural landmarks. The motion of the landmark is approximated by an affine motion model. The obtained near-future positions of the landmarks are used to command the robot such that both heart and instrument move synchronously (see Fig. 10).

2.2.3 Bilateral control

Providing the human operator with direct haptic feedback means to include the human in the control loop, i.e. the human arm is energetically coupled with the slave manipulator at the distant location. This is a source of instability within the coupled master-slave system [12, 42].

The stabilization of this coupled system is additionally complicated due to the presence of time delay in the system. So the time delay (often varying) is the main problem for the stability of a telerobotic system. The time delay in these systems with haptic feedback is an often addressed problem in the literature [8, 20] and many solutions are given [1, 6, 21, 41].

The main concept for stabilization of bilaterally controlled telerobotic systems is that of passivity. It means that a system is stable, if it is passive, i.e. it is not producing energy. And a complex system is passive, if it is built only from passive subsystems.

A telerobotic system can be described like a connected network for the analysis. Figure 11 shows the relevant subsystems in a telerobotic network, which are

– Operator
– Haptic handcontroller
– Communication
– Teleoperator
– Remote environment

If it can be proven that all subsystems are passive, the telerobotic system itself is passive and stable. As mentioned

Fig. 11. Network presentation of a telerobotic system

before the communication, which includes the time delay, is the major source of activity in the system and is therefore addressed by the bilateral controllers presented below.

Wave variables. A common approach for stabilizing bilateral controllers is the wave variable based control, which was introduced by Niemeyer [21]. In this approach a pair of conjugate mechanical variables (i.e. force/velocity or force/position) will be transformed into wave variables and will be transferred through the communication channel. Such transformation is a mathematical tool which will make the whole loop behave like a system of wave nature. The theory itself presents an extension to the theory of passivity, and the global control scheme uses methods taken from the network theory (see Fig. 12). Thus, the communication channel will be transformed into a lossless passive element which will compensate for the communication delay. Each wave transformer will encode a wave towards the communication channel, and will decode a desired motion towards the handcontroller/teleoperator, which in turn will be computed by the local controller on each side. The stability is guaranteed by the passiveness of the whole control loop (joystick, communication, robot), assuming that the human operator behaves passive as well.

The varying time delay is compensated by a time delay model and an appropriate compensator [3]. This method can be used if the time delay is know a priori or models exist to predict it. In case of space telerobotic systems this is often the case, due to the fact, that a dedicated radio link is used. So the exact time delay can be pre-calculated using a quite simple model.

Time domain passivity control. A new approach in bilateral control in the last years represents the *time domain passivity control* [12]. It is also based on the concept of passivity and the main idea of this control strategy is to observe the actual energy of a certain part of the telepresence system (passivity observer) and to dampen any generated energy by a dedicated controller (passivity controller), such that the system remains passive. This has been successfully applied to haptic interfaces [28, 36]. Recently some approaches have been done to extend the time domain passivity control to telepresence systems, which are distributed and the observation of the subsystems cannot be done at the same time step. One solution for this is presented in [4, 37], in which a telerobotic system is separated into different subsystems. These subsystems are observed and controlled separately such that the

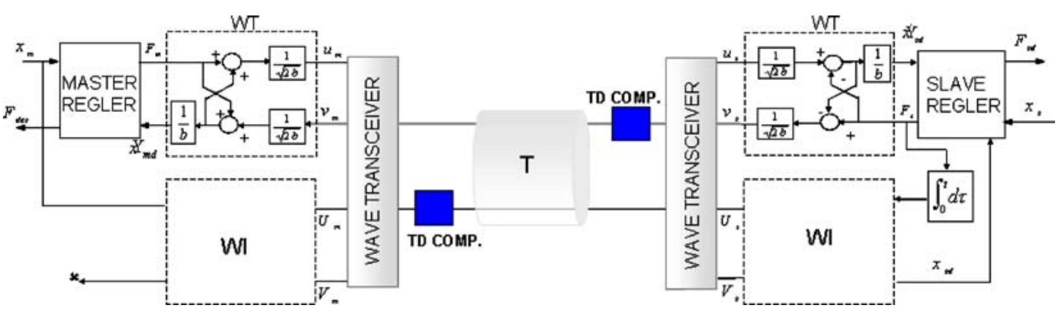

Fig. 12. Improved wave variables scheme

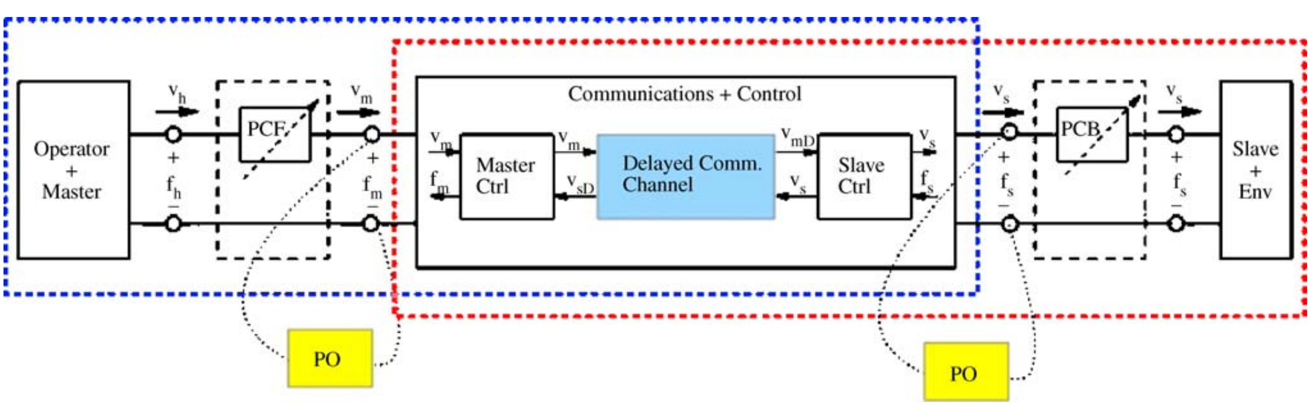

Fig. 13. Time domain passivity control scheme for time delayed telerobotic systems

total passivity of the bilateral control can be guaranteed (see Fig. 13).

3 Applications

This section will give a rough overview of modern applications, which are in use or under research. It gives a selection of possible tasks, which are related to the work at DLR [34].

As mentioned above, the handling of dangerous material in nuclear or chemical engineering plants was and still is a driving application for telerobotic systems, to overcome the barrier of danger. In addition de-mining of explosives is an upcoming field for telerobotic systems, also because the teleoperators are becoming mobile. Therefore telerobotics, to avoid danger for the human, is an application, which is of high interest for various disciplines.

In the field of industrial applications for telerobotic systems there arise two typical scenarios: assembly of micro- or even nanostructures and telemaintenance of plants. The assembly of microstructures is often limited to a reduced quantity, such that the programming of robots is ineffective compared to direct manual handling by a telerobotic system [43]. Regarding the telemaintenance of plants, there exist already numerous solutions based on videoconferencing tools. This means that the remote human partner acts as a teleoperator commanded by a supervisory or shared autonomy control concept. In the future this human teleoperator can be replaced by a humanoid robotic teleoperator, such that the control can change towards bilateral control and telepresence.

DLR work on two other application scenarios: minimally invasive robotic surgery and space robotics. These two domains will be presented in more detail in the following section.

3.1 Surgery

Minimal invasive surgery (MIS) is one of the fields where telerobotics enlarges the human possibilities [26]. In this application the telerobotic system has to overcome at least the barrier of the human's body. Using MIS – instead of open surgery (i.e. removing the barrier) – leads to several advantages for the patient. These are among others:

- Small incisions reduce pain and trauma
- Shorter residence at hospital and shorter rehabilitation time
- Cosmetic advantages due to small incisions

On the contrary, for the surgeons, MIS has several disadvantages:

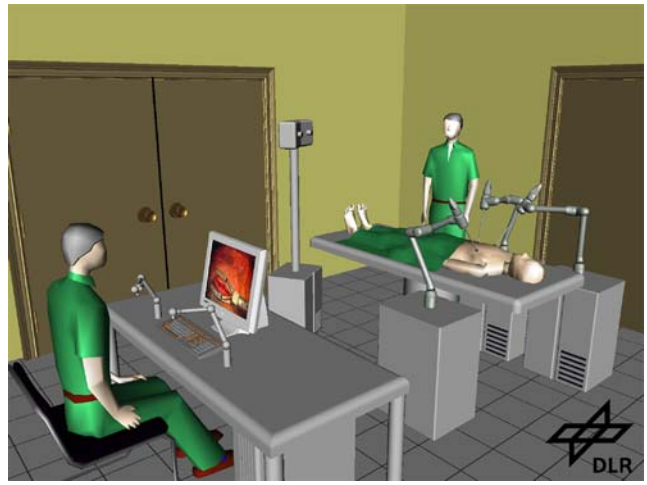

Fig. 14. DLR: telesurgery vision

- Reduced sight
- Restricted motion because of pivot point (trocar kinematic)
- Reduced tactile and force feedback because of long instruments
- Amplification of the tremor because of the large lever arm

The above-mentioned disadvantages are the main reasons why MIS is – despite its advantages for the patient – restricted to a small number of applications. To overcome those handicaps and to establish new fields of applications, new surgical robots, e.g. the da Vinci System from Intuitive Surgical or the "Kinemedic" designed by DLR [11], play an important role, as they provide a teleoperator system.

In addition to these surgical robots new instruments that are able to measure the contact forces at the instrument tip are under development [17]. This enables force control as well as haptic feedback, through appropriate master devices. These new instruments are giving a realistic impression of the actual contact situation during surgery.

For the telerobotic minimally invasive surgery a matching haptic interface [17] and suitable control methods are required, as introduced before [23, 30]. In Fig. 14 the vision of future telerobotic surgery is depicted, in which the surgeon is acting intuitively through two haptic handcontrollers, while the organ movement is compensated by the robots.

3.2 Space

The concept of telerobotics allows to perform complex tasks in the hostile and distant space environment. Hereby the space environment is divided into two domains: foreign planet and earth orbit.

Robotic exploration missions to other planets of the solar system has become quite popular in recent years. The two Mars rovers from NASA, Spirit and Opportunity, provided new finding from the Martian surface. The rovers have been teleoperated from earth with a communication delay of about eight minutes [22]. For this long communication delay only supervisory control is possible.

In the earth orbit domain the topic of *on-orbit servicing* is an upcoming market for space robotic applications. Robotic "astronauts", which are designed for the free space environment, can capture, maintain, repair or de-orbit other satellites. Due to the shorter communication delays telepresence systems with bilateral control and direct force feedback can be designed. This allows the robonaut systems to become as agile and "intelligent" as the human operator on ground. DLR is performing research and space missions towards this goal [15, 31]. The latest space research experiment is ROKVISS, Robotic Component Verification on ISS.

ROKVISS demonstrates and verifies DLR's lightweight robotics components under realistic mission conditions (see Fig. 15)[19]. The most interesting operational mode is the direct haptic telemanipulation, to show the effectiveness of telepresence methods for further satellite servicing tasks [32]. For telepresence mode demonstration and verification, stereo video images in conjunction with the current robot joint and torque values are fed back as the current situation to the ground operator. The operator controls the slave robot at the remote site via a force feedback control device (Fig. 15). Using high-rate up und downlink channels, the operator is directly involved into the control loop.

Crucial factors in gaining a high quality immersion of the operator into the remote scenery are high-rate, low-latency (< 500 ms) and low jitter force/position data, and a reasonably good and up-to-date stereoscopic video transmission. The telepresence mode can only be used for several minutes during the phase of direct radio contact, when the system passes over the tracking station in Germany (German Space Operation Center) [18].

In telepresence mode the following experiments are executed to verify the various constraints of direct force feedback:

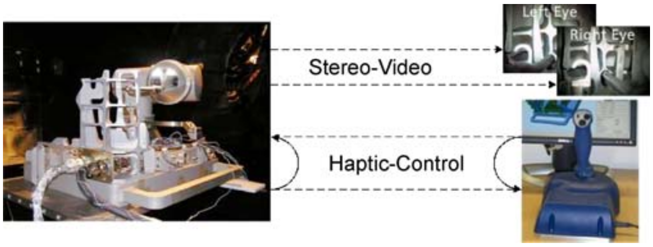

Fig. 15. ROKVISS

– A typical force-controlled contour-following task at the different parts of the contour
– A 2 DoF peg-in-hole experiment, in which the operator has to move the stylus into a narrow hole in the contour, such that a three-sided constraint is given
– To verify the impact of external energy storage within the closed-loop control link, the operator drives the stylus within one of the open ended spanners, which are connected to a real spring.
– To verify the impact of time delay, some experiments will be performed with varying simulated time delays, whereas a round trip time up to 500 ms is simulated (representative for the use of a data relay satellite in GEO).

ROKVISS was launched in December 2004 and has been mounted outside the Russian service module since January 2005. The robotic joints have worked successfully since then and various experiments in telepresence mode have been carried out [33]. Based on these experiences a testbed for future more complex on-orbit servicing missions has been developed and implemented at DLR [2].

4 Summary and outlook

In this paper the importance of haptics for immersive telerobotics systems has been refined, presenting current research efforts and application domain. The research on telerobotics can be divided into two sections: technical systems and control theory. Other than the results achieved in the last year there are still some open questions.

In the field of the telerobotic hardware, i.e. handcontrollers, teleoperators and communication networks there are the following goals. There is a need of human-like teleoperators in terms of shape and sensor-actor abilities. Locomotion and integration are still efforts to be done. Concerning the handcontroller there exist various solutions for different stimuli, which of course can be improved, but there is a lack of integration into a single preferable handheld device. Regarding the communication network, the development in the Internet is also helping the use of telerobotic systems over this medium, but, especially for the haptic feedback, the reliability, bandwidth, and transfer rates need to be increased.

The research in control theory for bilateral control in the future should and will include the following topics. Passivity as a method for analysis of the stability of the system is conservative, while direct stability analysis is very complex. To increase the transparency of the control the controller had to become less conservative and methods for stability analysis has to be found. The measurement of the transparency (performance) of the system should be unified and an objective index should be found by cooperation between psychophysics and control engineers. The Internet will stay an unreliable communication medium, so the efforts to adapt the bilateral control to this type of communication need to continue and be intensified.

For the applications there exist numerous examples, but two domains were described in detail: surgery and space. In general there is an increasing interest in telerobotic systems for different applications. The wide use of a telerobotic system to overcome the barrier of danger especially is a driving task.

Acknowledgement This paper presents research on mechatronics, telerobotics and haptics carried out at the Institute of Robotics and Mechatronics at DLR.

References

1. Anderson, R.J., Spong, M.: Bilateral control of operators with time delay. IEEE Trans. Autom. Control **34**, 494–501 (1989)
2. Artigas, J., Kremer, P., Preusche, C., Hirzinger, G.: Testbed for Telepresent On-Orbit Satellite Servicing. In: Proceedings of the International Workshop on Human Centered Robotics Systems. Munich, Germany (2006)
3. Artigas, J., Preusche, C., Hirzinger, G.: Wave variables based bilateral control with time delay model for space robot applications. In: ROBOTIK 2004, pp. 101–108. Munich, Germany (2004)
4. Artigas, J., Preusche, C., Hirzinger, G.: Time Domain Passivity-based Telepresence with Time Delay. In: Proceedings of the International Conference on Intelligent Robots and Systems (IROS). Peking, China (2006)
5. Avizzano, C., Bargagli, F., Frisoli, A., Bergamasco, M.: The hand force feedback: analysis and control of a haptic devicefor the human-hand. In: IEEE International Conference on Systems, Man, and Cybernetics, vol. 2, pp. 989–994. Nashville, TN (2000)
6. Baier, H., Buss, M., Freyberger, F., Schmidt, G.: Benefits of combined active stereo vision and haptic telepresence. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems. Takamatsu, Japan (2000)
7. Borst, C., Fischer, M., Haidacher, S., Liu, H., Hirzinge, G.: DLR Hand II: Experiments and experiences with an anthropomorphic hand. In: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA). Taipei, Taiwan (2003)
8. Buss, M., Schmidt, G.: Control Problems in Multi-Modal Telepresence Systems. In: P.M. Frank (ed.) Advances in Control, Highlights of ECC'99, pp. 65–101. Springer, Berlin Heidelberg New York (1999)
9. Butterfaß, J., Grebenstein, M., Liu, H., Hirzinger, G.: DLR-Hand II: Next Generation of Dextrous Robot Hand. In: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), pp. 109–114. Seoul, Korea (2001)
10. Deml, B., Kron, A., Kuschel, M., Buss, M.: Actuating a Data-Glove with Thermal and Tactile Feedback – Human Factors Consideration. In: Joint International Workshop on Human Adaptive Mechatronics and High-Fidelity Telepresence. Tokyo Denki University, Japan (2005)
11. DLR – Institute of Robotics and Mechatronics: Kinemedic – A Robot for Medical Applications. http://www.robotic.dlr.de/kinemedic
12. Hannaford, B., Ryu, J.H.: Time domain passivity control of haptic interfaces. IEEE Trans. Robot. Autom. **18**(1), 1–10 (2002)
13. Hirzinger, G., Brunner, B., Dietrich, J., Heindl, J.: Sensor-based space robotics – rotex and its telerobotic features. IEEE Trans. Robot. Autom. **9**(5), 649–663 (1993)
14. Hirzinger, G., Brunner, B., Dietrich, J., Heindl, J.: Rotex – the first remotely controlled robot in space. In: IEEE International Conference on Robotics and Automation. San Diego, CA (1994)
15. Hirzinger, G., Landzettel, K., Brunner, B., Fischer, M., Preusche, C., Reintsema, D., Albu-Schäffer, A., Schreiber, G., Steinmetz, M.: DLR's robotics technologies for on-orbit servicing. Adv. Robot. (Special Issue Service Robots in Space) **18**(2), 139–174 (2004)
16. Koeppe, R., Albu-Schäffer, A., Preusche, C., Schreiber, G., Hirzinger, G.: A New Generation of Compliance Controlled Manipulators with Human Arm Like Properties. In: Proceedings of the 10th International Symposium of Robotics Research, ISRR'01, pp. 125–135. Lorne, Victoria, Australia (2001)
17. Kübler, B., Seibold, U., Hirzinger, G.: Development of actuated and sensor integrated forceps for minimally invasive robotic surgery. Intl. J. Med. Robot. Comput. Assist. Surgery **1**(3), 96–107 (2005)
18. Landzettel, K., Brunner, B., Beyer, A., Krämer, E., Preusche, C., Steinmetz, M., Hirzinger, G.: ROKVISS Verification of Advanced Tele-Presence Concepts for Future Space Missions. In: Proceedings of Advanced Space Technologies for Robotics and Automation. Netherlands (2002)
19. Landzettel, K., Preusche, C., Albu-Schäffer, A., Reintsema, D., Rebele, B., Hirzinger, G.: Robotic On-Orbit Servicing – DLR's Experience and Perspective. In: Proceedings of the International Conference on Intelligent Robots and Systems (IROS). Peking, China (2006)
20. Niemeyer, G., Slotine, J.: Stable adaptive teleoperation. IEEE J. Oceanographic Eng. **16**(1), 152–162 (1991)
21. Niemeyer, G., Slotine, J.: Towards Force-Reflecting Teleoperation over the Internet. In: Proceedings of the IEEE International Conference on Robotics and Automation, pp. 1909–1915 (1998)
22. Norris, J., Powell, M., Vona, M., Backes, P.G., Wick, J.: Mars exploration rover operations with the science activity planner. In: Proceedings of the 2005 IEEE International Conference on Robotics and Automation (ICRA), pp. 4618–4623 (2005)
23. Ortmaier, T.: Motion Compensation in Minimally Invasive Robotic Surgery. Dissertation, TU M"unchen (2003)
24. Ortmaier, T., Gröger, M., Hirzinger, G.: Robust motion estimation in robotic surgery on the beating heart. In: Proceedings of Computer Assisted Radiology and Surgery – CARS, pp. 206–211. Paris, France (2002)
25. Ortmaier, T., Hirzinger, G.: Cartesian control of robots with working-position dependent dynamics. In: 6th International IFAC Symposium on Robot Control – Syroco (2000)
26. Ortmaier, T., Weiss, H., Hirzinger, G.: Minimally invasive robotic surgery: Foundations and perspectives. In: ICRA-IEEE International Conference on Robotics and Automation, Workshop on Recent Advances in Medical Robotics. Taipei, Taiwan (2003)
27. Ott, C., Eiberger, O., Friedl, W., Bäuml, B., Hillenbrand, U., Borst, C., Albu-Schäffer, A., Brunner, B., Hirschmüller, H., Kielhöfer, S., Konietschke, R., Suppa, M., Wimböck, T., Zacharias, F., Hirzinger, G.: A humanoid two-arm system for dexterous manipulation. In: HUMANOIDS'06. Genoa, Italy (2006)
28. Preusche, C., Hirzinger, G., Ryu, J.H., Hannaford, B.: Time Domain Passivity Control for 6 Degrees of Freedom Haptic Displays. In: Proceedings of the International Conference on Intelligent Robots and Systems, pp. 2944–2949. Las Vegas, NV (2003)
29. Preusche, C., Koeppe, R., Albu-Schäffer, A., Hähnle, M., Sporer, N., Hirzinger, G.: Design and Haptic Control of a 6 DoF Force-Feedback Device. In: Workshop on Advances in Interactive Multimodal Telepresence Systems. Munich, Germany (2001)
30. Preusche, C., Ortmaier, T., Hirzinger, G.: Teleoperation Concepts in Minimal Invasive Surgery. Control Eng. Pract. **10**(11), 1245–1250 (2002)

31. Preusche, C., Reintsema, D., Landzettel, K., Fischer, M., Hirzinger, G.: DLR on the way towards Telepresent On-Orbit Servicing. In: Proccedings of the International Conference in Mechatronics and Robotics. IEEE Industrial Electronics Society APS, Aachen, Germany (2004)
32. Preusche, C., Reintsema, D., Landzettel, K., Hirzinger, G.: ROKVISS – Towards Telepresence Control in Advanced Space Missions. In: Proceedings of 3rd International Conference on Humanoid Robots. Munich and Karlsruhe, Germany (2003)
33. Preusche, C., Reintsema, D., Landzettel, K., Hirzinger, G.: ROKVISS – Preliminary Results for Telepresence Mode. In: Proceedings of the International Conference on Intelligent Robots and Systems (IROS). Peking, China (2006)
34. Preusche, C., Reintsema, D., Ortmaier, T., Hirzinger, G.: The DLR Telepresence Experience in Space and Surgery. In: Proceedings of Joint International COE/HAM-SFB453 Workshop on Human Adaptive Mechatronics and High Fidelity Telepresence, pp. 35–40. Tokyo, Japan (2005)
35. Reintsema, D., Preusche, C., Ortmaier, T., Hirzinger, G.: Towards High-Fidelity Telepresence in Space and Surgery Robotics. PRESENCE – Teleoper. Virt. Environ. **13**(1), 77–98 (2004)
36. Ryu, J., Kim, Y., Hannaford, B.: Sampled and Continuous Time Passivity and Stability of Virtual Environments. In: IEEE International Conference on Robotics and Automation. Taipei, Taiwan (2003)
37. Ryu, J.H., Preusche, C., Hannaford, B., Hirzinger, G.: Time Domain Passivity Control with Reference Energy Following. IEEE Trans. Control Syst. Technol. **13**(5), 737–742 (2005)
38. Schätzle, S., Hulin, T., Preusche, C., Hirziner, G.: Evaluation of Vibrotactile Feedback to the Human Arm. In: Proceedings of Eutohaptics 2006, pp. 557–560. Paris (1006)
39. Sheridan, T.B.: Telerobotics, Automation and Human Supervisory Control. MIT Press, Cambridge (1992)
40. Suppa, M., Kielhöfer, S., Langwald, J., Hacker, F., Strobl, K.H., Hirzinger, G.: The 3d-modeller: a multi-purpose vision platform. In: International Conference on Robotics and Automation (ICRA). Rome, Italy (2007, in press)
41. Yokokohji, Y., Imaida, T., Yoshikawa, T.: Bilateral Teleoperation under Time-Varying Communication Delay. In: Proceedings. 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 3, pp. 1854–1859. Kyongju, South Korea (1999)
42. Yokokohji, Y., Yoshikawa, T.: Bilateral control of master-slave manipulators for ideal kinesthetic coupling. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 355–362 (1990)
43. Zaeh, M., Clarke, S., Petzold, B., Schilp, J.: Achieving flexible micro-assembly systems through telepresence. In: Proccedings of the International Conference in Mechatronics and Robotics. IEEE Industrial Electronics Society APS, Aachen, Germany (2004)

CARSTEN PREUSCHE received his Dipl.-Ing. degree in electrical engineering from the Technical University of Munich in 1998 after studies at RWTH Aachen, Centro Polytechnico Superior (Zaragoza,Spain) and TU München. In 1999 he joined the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR) as a research engineer. He is now head of the Multimodal Telepresence and Virtual Reality group at the Institute of Robotics and Mechatronics, coordinating projects in the fields of fundamental research in telepresence, space and surgery applications and virtual reality. His main research topics include immersive man-machine interaction, supervisory and bilateral control, haptic rendering and design of haptic interfaces.

GERD HIRZINGER received his Dipl.-Ing. degree and the Ph.D. degree from the Technical University of Munich, in 1969 and 1974, respectively. In 1991 he received a joint professorship from the Technical University of Munich, and in 2003 a honorary professorship at the Harbin Institute of Technology in China. Since 1992 he has been director at the DLR Institute for Robotics and Mechatronics, which is one of the most acknowledged institutes in the field worldwide, including not only robot development for space and terrestrial applications, but also aircraft control and optimization, vehicle technology (x by wire components and systems) and medical technology (artificial hearts and surgical robots).

He has published more than 300 papers in robotics, mainly on robot sensing, sensory feedback, mechatronics, man-machine interfaces, telerobotics and space robotics. He was prime investigator of the space robot technology experiment ROTEX, the first remotely controlled robot in space, which flew onboard the shuttle COLUMBIA in April 1993. In a number of international (especially IEEE) conferences he was an invited plenary speaker, program committee member or conference chair.

He has received numerous national and international awards, e.g. in 1995 the Leibniz-Award, the highest scientific award in Germany and in 1997 the IEEE-Fellow Award. He is now a member of the IEEE fellow award committee. In 2004 he received the order of merit of the Federal Republic of Germany and became member of the "wall of fame" of the Heinz Nixdorf Computer Museum. In 2005 and 2006 he received the IEEE Pioneer Award and IEEE Field Award of the Robotics and Automation Society, respectively.