The DLR Telepresence Experience in Space and Surgery

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Abstract.
High-fidelity telepresence is considered to be a key subject for the development of advanced robotic applications in space and surgery. The fact that there are only few robots in space and surgery is mainly due to the lack of broadly available sophisticated autonomy and haptic feedback within present robotic systems. Nevertheless, these requirements need to be fulfilled to overcome telepresence barriers, such as (communication) delay, scaling, matter, hazard etc. Besides the technological need for ultralight impedance-controlled robots combined with a high-speed data link the telepresence control strategies including supervisory and bilateral control are essential for high-fidelity telepresence and an immersive impression of the remote side to the human operator. This approach is successfully tested recently within the technology experiment ROKVISS, Germany's present space robotic project. Its aim is the verification and qualification of the DLR's newest lightweight robot joint technologies and provides, for the first time, realistic force feedback in a telepresence space application. The same holds for the new telepresence system for minimally invasive robotic surgery The system will provide realistic 6DoF force/torque feedback of the manipulation wrench as well as of the grasping force. Therefore, a lightweight robot for surgery is built, including a high-speed data link to the haptic master station.

Keywords. *Bilateral Control, Shared Control, Haptic Feedback, Minimally Invasive Robotic Surgery, Telepresent On-Orbit Servicing*

I. INTRODUCTION

The realm of telerobotic is the manipulation of a remote physical environment. Todays telerobotic systems are used in many situations to overcome several kinds of barriers, blocking the human operator from task fulfillment. The barrier which blocks the operator can be among others of distance, scale, material or hazardous matter. While in case of space missions distance and hazardous areas are perceived as the most characteristic barriers, in case of minimally invasive surgery (MIS) cramped spaces and restricted freedom of movement are more likely to cope with. Therefore, the mechatronic manipulator used within a telerobotic system differs between the realm of space and minimally invasive surgery due to the constraints of the specific environment to operate in. But, as will be shown, the basic telepresence-enabling system technology is quite the same, and independent of the realm.

The telerobotic paradigm is coined by *sensing the physical environment, measuring positions, forces, and accelerations, and responding with movements and forces to directly manipulate the physical environment* [5]. Telepresence can be characterized as an advanced concept of telerobotics: the remote robot is directly operated by a human within a closed-loop-control mode using a telerobotic system (so called teleoperator) to perform remote manipulations.

Thus, experiential telepresence systems enable a human operator to manipulate tasks in an inaccessible environment such as a human feels like being present at an event while physically being at some other place (*space-shifting*) or time (*time-shifting*). For high fidelity telepresence the human operator must feel as if he/she is being present at a distant location and interpret the mechatronic manipulator as a natural extension to his/her own body. This suggests that the human operator receives input to (almost) all the human senses (vision, hearing, haptic, sense of smell and degustation) and commands the teleoperator in a nearly natural way by demonstration. The last two senses (smell and degustation) have no practical evidence at present, due to the lack of sensors and actuators to measure and display them.

The absence of numerous robots in space and surgery is explained mainly by the lack of broadly available sophisticated autonomy and tactile feedback within current systems. A high fidelity telepresence concept may overcome these drawbacks and barriers within the field of space and surgery robotics. But telepresence requests high demands to the technologies lying beneath the application. In particular the robot needs sensors compared with the human senses to gather the remote environment, which has to be displayed to the human operator. The exploration and manipulation capabilities need to be similar to the human capabilities, and the communication has to be a broadband communication with low delay to transport the sensorial input and the operator's reac-

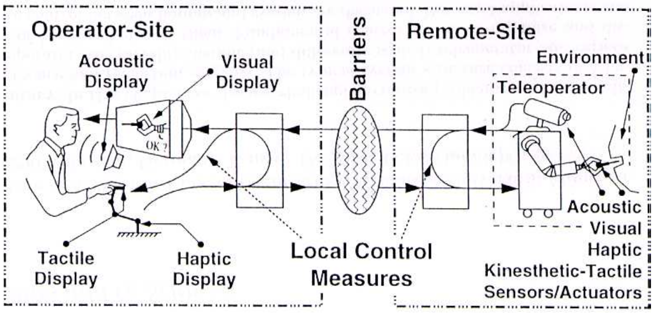

Fig.1: A Multimodal Telepresence and Teleaction System (TPTA) by [4]

tions (commands) almost instantaneously, otherwise the humans feeling of being present at the distant location is disturbed.

After the presentation of the control strategies for telepresence systems, this article focuses on the current telepresence activities of our institute in the field of space and surgical robotics.

II. CONTROL STRATEGIES FOR TELEPRESENCE SYSTEMS

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 [23]: *Human operators are intermittently programming and continually receiving information from a computer that itself closes an autonomous control loop through artificial effectors and sensors.* In case of telepresence the received information about the teleoperator has to be displayed in a sufficiently natural way (hype the human senses).

Supervisory control and telepresence control are not two separate control strategies. In a telerobotic system both control mehtods are used in a mixed mode, in which the weights are adapted according to the task itself and the technological constraints of the system. These constraints are mainly affected by the communication channel (bandwidth, delay, etc.) and the input/output devices on the local and the remote side.

First the telerobotic concepts based on shared control are presented (supervisory control), and the second part outlines the bilateral control concepts used in direct telepresence coupling of the haptic channel. These concepts are basis of the control architectures used in the surgery and space applications described later on.

A. Telerobotic Concepts based on Shared Control

To enable telepresence in space and surgery a sufficient *shared control* concept [5, 7] for the control of the teleoperator is suggested. Herein *shared control* is treated using two different approaches depending on the focus of the control problem.

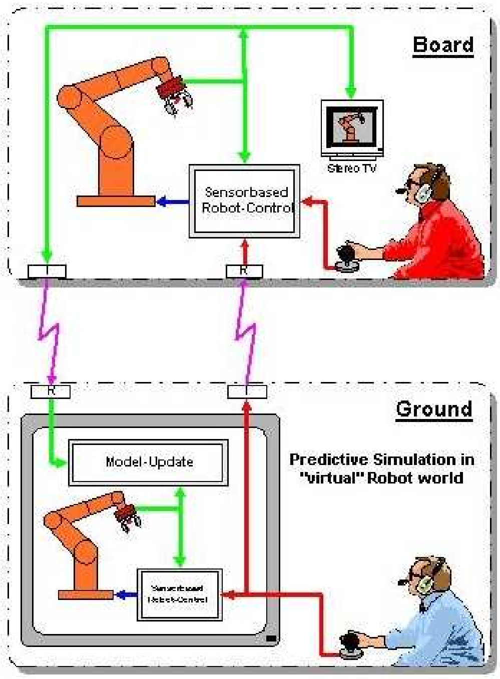

Fig. 2: Concept of Tele-Sensor-Programming as demonstrated during various space missions (e.g. ROTEX or ETS-VII)

In case of a weak coupling of teleoperator and human operator, which can be caused by a "weak" communication channel, the level of intelligence is shared among the human and the machine. This is presented as *Shared Autonomy.* One can also distribute the control based on a certain task, e.g. during a surface following task the force is controlled by the machine and the path by the human operator. This *Shared Task* concept is used in safety relevant applications, like surgery.

B. Shared Autonomy

If the main technological constraint of the telepresence system is the communication delay, like it often occurs in space applications, the shared control is used on an autonomy level basis. That means, gross commands, given by the operator, were refined autonomously by the teleoperator [8]. 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 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 (*tele-sensor-programming*) [3]. The operator expresses his/her commands in a natural way using a virtual reality interface and receives a feedback from a simulation, which is based on the sensory measure-

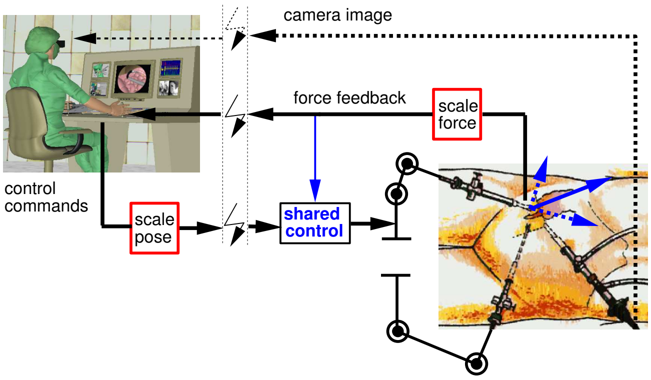

Fig.3: Overview of the Shared Control Concept in Minimally Invasive Surgery.

ments 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 patterns.

C. Shared Task

In the case of a *shared task* control the task is subdivided into two task spaces. One is controlled autonomously by a sensory feedback controller 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 prerequisite for the compensation of the remaining heart motion [13]: 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 [14]. 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 Figure 3).

D. Telepresence Controller

The goal of a telepresence system is, regardless the shared control methods presented before, the direct human in the loop control of the teleoperator. The human should feel like manipulating the remote environment directly, which implies that a sufficient communication link with small delay exist. In the scope of this paper small delay is defined as beeing less than 0.5 seconds.

Providing the human operator with haptic feedback means to include the human into the control loop, i.e. the human arm is energeticly coupled with the teleoperator in the remote environment. This is a source of instability within the telepresence system.The stabilization of this coupled system is additionally complicated due to the presence of time delay within such a system.

At the present space mission ROKVISS[1], which is described later, exist the possibility to evaluate different bilateral control schemes on a real space robot system. The planned bilateral control strategies will be:

D. 1. Direct coupling

For very large communication delays a position-position coupling with virtual dampers is proven to be useful, as Yokokohji demonstrated on ETS-VII [9]. For this strategy the stability of the master-slave system can be obtained regardless the contact situation. But it is a very conservative control approach, which degrades the transparency of the system and so the immersion of the operator evidently. If the communication delays are small, a direct position-force or force-position coupling (depending on the contact situation) is possible. Stability is obtained in each sub-domain (free movement / contact) and in the whole taskspace through a hybrid control state machine. For a detailed description see [18].

D. 2. Wave-Variable Theory

A new approach in space robotics will be the wave variable based control which was introduced by Niemeyer [12]. In this approach a pair of mechanical variables (i.e force/velocity or force/position) will be transformed into wave variables and will be transferred through the communication channel. Thus, the communication channel will be transformed into a loss-less, passive element which will compensate the communication delay and will present robustness to it. The varying delay in the communication link has to be compensated, e.g. using a communication model [2]. The stability is guaranteed by the passiveness of the whole control loop (haptic interface, communication, teleoperator), assuming that the human operator behaves passive too.

D. 3. Time Domain Passivity Control

In the last years the scheme of time domain passivity control has been emerging with the goal to create a

[1]Robot Component Verfication on ISS

less conservative approach to bilateral control. The main idea is use the concept of passivity not only during the design of the controller but in realtime while executing the control (time domain). So a passivity observer estimates the energy flow at the inputs/outputs of a system and activates the passivity controller if the systems becomes active [17]. The concept of reference energy helps here to create a distributed observer, as it is necessary for telepresence systems [21].

III. DLR TELEPRESENCE SYSTEMS

This section presents the current telepresence systems at the DLR. In the field of medical applications a new robot for minimally invasive surgery has been developed. The goal in the space application domain is to realise a telepresent on-orbit servicing by a so-called robonaut.

A. Minimally Invasive Robotic Surgery

The new DLR robot for minimally invasive surgery provides several technological innovations, which enables telepresence control, such as

- a redundant kinematics,
- two degrees of freedom inside the human body,
- compact and light-weight design,
- sensorited instruments and
- advanced control strategies.

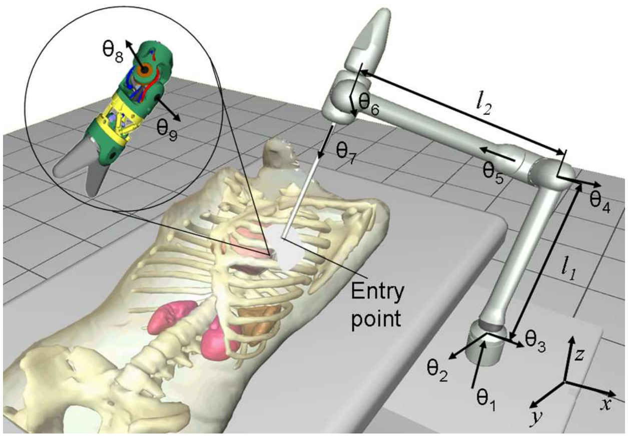

Fig.4: Model of the new DLR MIS robot

As it can be seen in Fig. 4 the compact and redundant design allows an easy access of the teleoperator to the remote environment, while still having full dexterity inside the patient [10]. The sensorized instruments provide force/torque measurements for all DoFs. This allow both an intelligent local sensor control at the teleoperator and a realistic force-feedback to the surgeon. Fig. 5 shows the first prototype of the robot [15].

The operators interface will consist of a force-feedback device being equipped with an additional degree of freedom to display haptic information, e.g. the gripping force

Fig.5: The DLR MIS robot

from the froceps. The control concept is a direct telepresence control combined with a shared task control to compensate organ movements. A typical scenario is beating-heart surgery [16].

B. Telepresent On-Orbit Servicing

On-orbit servicing is an upcoming market for space robotic applications. The concept of telepresence allows to perform complex tasks in a natural way in the hostile space environment. The presented DLR space missions ROKVISS, TECSAS[2] and SLES[3] demonstrate the current steps towards this goal [19].

B.1. ROKVISS

ROKVISS will demonstrate and verify DLR's light-weight robotics components under realistic mission conditions (see Fig. 6)[11]. The most interesting operational mode will be direct haptic telemanipulation, to show the effectiveness of telepresence methods for further satellite servicing tasks.

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. Using high-rate up- und downlink channels, the operator will be 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-

[2]TEChnology SAtellite for Demonstration and Verification ofS pace Systems
[3]Satellite Life Extension System

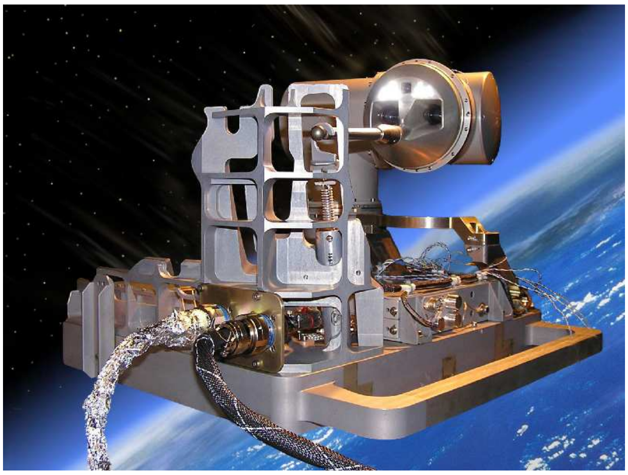

Fig.6: The ROKVISS Manipulator

latency (< 500 ms) and low jitter force/position data, and a reasonable 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) [20].

In Telepresence Mode the following experiments will be executed to verify the various constraints of direct force feedback :

- a typical force-controlled contour-following tasks 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-side 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).

For the long-term verification of the teleoperators light-weight joints during free space operation predefined automatic motion sequences are performed several times during the entire mission. By pulling the spring at different speeds off-line identification methods provide the stiffness and damping, as well as the friction parameters. These identification methods will be used for the parameter estimation of robotics systems under real mission conditions.

B.2. TECSAS

The goal of TECSAS is the on-orbit verification of key robotics hard- and software elements for advanced space maintenance and servicing systems. It is planned to launch a target and a chaser satellite, whereas the chaser is equipped with a seven axis robot arm and a gripper system. For docking and capturing operations, a ROKVISS based robot arm will be used as well as a Modular Automation and Robotic Controller for the overall control system. The mission consists of the following phases: far rendezvous, close approach, inspection fly around, formation flight, capture, stabilization of the compound, compound flight maneuver, active ground control via telepresence, passive ground control during autonomous operations (monitoring), and controlled deorbiting of the compound, see Fig. 7.

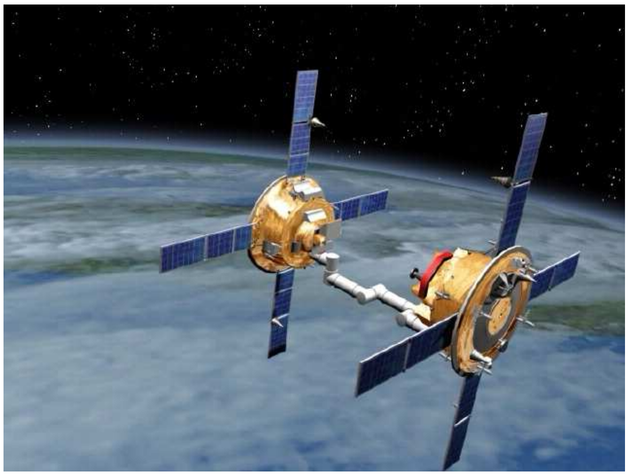

Fig. 7: **TEC**hnology **SA**tellite for Demonstration and Verification of **S**pace Systems

In telepresence mode, the ground operator will position the gripper in front of the structure element by means of stereo video information. After closing the gripper, the compound stabilization takes place. In automatic mode, the ground operator selects the structure element to be tracked by means of image processing and enables the automatic capturing, thereafter.

Dynamic singularities of a free-floating robot are an important issue, too. Whereas they can be easily avoided in automatic mode, for telepresence a supplementary algorithm is necessary to control this subtask using a shared control concept. A workspace analysis can be performed to determine the singularity-free workspace, in which the operator can move safely [6].

B.3. Satellite Live Extension

Orbital Recovery Ltd. [1] has initiated its so-called Spacecraft Life Extension System (SLES), which will significantly prolong the operating lifetimes of valuable telecommunications satellites. The SLES will operate as an orbital tugboat, supplying the propulsion, navigation and guidance to keep a telecommunications satellite in its proper orbital slot for many additional years. Another application of the SLES could be the rescue of a spacecraft that have been placed in a wrong orbit, or which have become stranded in an incorrect orbital location. DLR's capture tool will be used in conjunction with advanced control strategies, to dock the SLES to the telecommunication satellite's apogee kick motor, as proposed within the ESS technology study [22].

IV. CONCLUSIONS

In this paper the control aspect for advanced telepresence systems were presented. The current DLR telepresence scenarios in the scope of minimally invasive robotic surgery and on-orbit servicing demonstrate the applicability of these control strategies to real systems.

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