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Robotics Component Verification on ISS ROKVISS – Preliminary Results for Telepresence

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Abstract— **ROKVISS, Germany's newest space robotics technology experiment, was successfully installed outside at the Russian Service Module of the International Space Station (ISS) during an extravehicular space walk at the end of January 2005. Since February 2005 a two joint manipulator is operated from ground via a direct radio link. The aim of ROKVISS is the in flight verification of highly integrated modular robotic joints as well as the demonstration of different control modes, reaching from high system autonomy to force feedback teleoperation (telepresence mode). The experiment will be operated for at least one year in free space to evaluate and qualify intelligent light weight robotics components under realistic circumstances for maintenance and repair tasks as foreseen in upcoming manned and unmanned space applications in near future. This paper focuses in the telepresence control mode, its technology and first results from the space experiment ROKVISS.**

I. INTRODUCTION

After ROTEX (the first remotely controlled space robot on board of the shuttle COLUMBIA), ROKVISS is the second space robotics experiment proposed and realised by DLRs Institute of Robotics and Mechatronics (DLR-RM) in cooperation with the German space companies EADS-ST, Kaiser-Threde, and vHS (von Hörner & Sulger) with close collaboration of the Russian Federal Space Agency ROSKOSMOS and RKK Energia. While the project was started in 2002, the ROKVISS hardware was mounted outside at the Russian Service Module of the ISS in January 2005. Since February 2005 ROKVISS is operated by DLR-RM, close supported by ZUP, the ISS ground control station in Moscow.

The ROKVISS experiment (Fig. 1) consists of a small robot with two torque-controlled joints, mounted on an Universal Workplate (UWP), an experiment controller, a stereo camera, an illumination system, an earth observation camera, a power supply, and a mechanical contour device for verifying the robot's functions and performance. These two robot joints are extensively tested and identified (dynamics, joint parameters) by repetitively performing predefined robot tasks in an automatic mode, or based on direct operator interaction. The automatic mode is necessary due to the fact that communication constraints limit the direct link experiment time to windows of only up to seven minutes length, when the ISS passes over the tracking station in Weilheim. For a more detailed description of the ROKVISS experimental setup see [1].

The main goals of the ROKVISS [2] mission are:

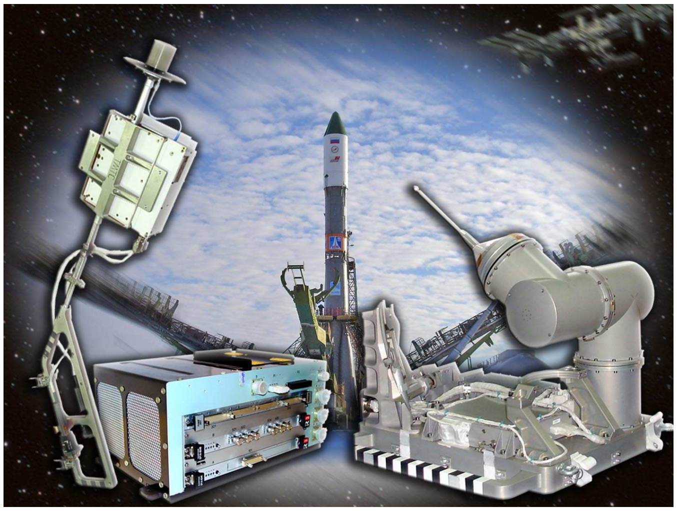

Fig. 1. Components of the ROKVISS Experiment

- the verification of DLRs modular light-weight, torque-controlled robotic joints in outer space, under realistic mission conditions, and the identification of their dynamic and friction behavior over time; The joints are based on DLRs new high energy motor ROBODRIVE, which are identical to those used in DLRs current seven joint light weight robot [3].
- the verification of force-reflecting telemanipulation to show the feasibility of telepresence methods [4], [5] for future satellite servicing tasks (Fig. 2).

In the next section the ROKVISS technology components are presented, followed by a description of the bilateral control strategies. The section "Experimental Setup" explains the layout of the experiments. Then preliminary results of the telepresence experiments are shown. Finally some conclusions are drawn and an outlook of the ongoing ROKVISS mission is given.

II. ROKVISS TECHNOLOGY FOR TELEPRESENCE

High-fidelity Telepresence implies a number of technological challenges, which nowadays space robotic system do not meet [6]. The telepresence system has to consist of

- a highly dynamic teleoperator equipped with sensors and local intelligence,

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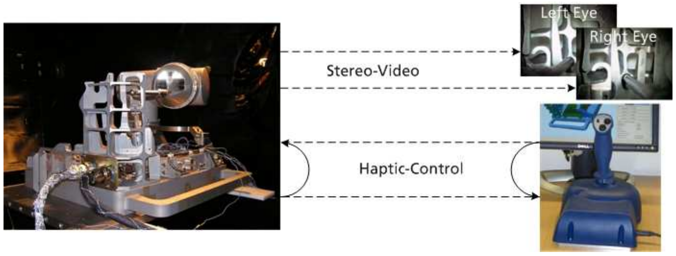

Fig. 2. ROKVISS Telepresence mode data flow

- a high-bandwidth realtime communication channel and
- an immersive multimodal man-machine interface.

These components have to be connected by an advanced control concept, which combines shared autonomy and bilateral control of the teleoperator and guarantees a synchronicity between the visual and haptic information. ROKVISS is a testbed to evaluate DLRs developments towards a high-fidelity telepresence system for upcoming On-Orbit Servicing space experiments. For a detailed description of the robotic components and the other experiments conducted please see [7]. In the following a short presentation of the experiment with focus on the telepresence needs is given.

A. The DLR Light-Weight Teleoperator

The ROKVISS space manipulator is based on the latest DLR light weight robotics developments [3]. The main part is the modular, intelligent joint, designed by mechatronic principles.

The joint actuation in robotics demand electrical drives with high torques and high dynamics (accelerations). Thereby a permanent reverse motion around the zero position is executed. Space robotics extends the requirements as low weight, and low power losses. Thus, an optimized electric motor with respect to the above criteria was developed, using the latest results in concurrent engineering.

Besides the actuation the sensors play an important role for the achievement of an "optimal" teleoperator. In the DLR light-weight joint the complete state of the flexible joint can be acquired by measuring the motor and the off-drive position, the current and the joint torque.

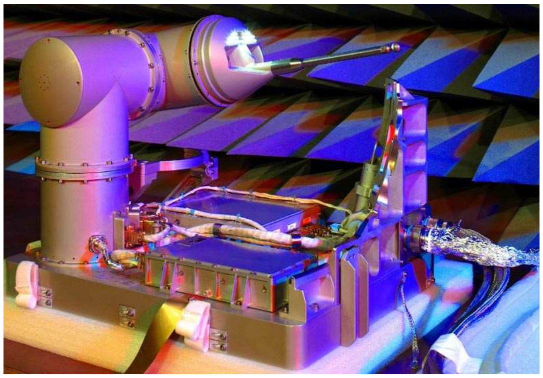

Fig. 3. The two-joints ROKVISS manipulator

Based on this drive and sensor technology an intelligent joint is built. The local decentralized controller is designed using a passivity approach as a state-feedback controller with compensation of gravity, friction [8] and the joint flexibility [9], [10]. By the appropriate parameterization of the feedback gains, the controller structure can be used to implement position, torque or impedance control. The gains of the controller can be computed in every control cycle, based on the desired joint stiffness and damping, as well as depending on the actual value of the inertia matrix. Hence, this controller structure fulfills the following functionalities:

- It provides active vibration damping of the flexible joint structure;
- It maximizes the bandwidth of the joint control for the given instantaneous values of the inertia matrix;
- It implements variable joint stiffness and damping.

The ROKVISS teleoperator is constructed of two light-weight joints (Fig. 3). At the endeffector a stylus is mounted for interaction with the experimental contour. Three cameras plus an illumination system are integrated in the last joint of the manipulator. The cameras consist of a stereo video camera pair and an earth observation camera for high-resolution still images.

B. The Realtime S-Band Communication

In order to keep the round-trip communication time as low as possible, ROKVISS owns a S-band communication system, including a separate antenna, pointing to the earth. The overall uplink channel-data rate is 256 kbit/s whilst the downlink data rate is 4 Mbit/s, including 3,5 Mbit/s video-data. Via this S-band radio link the ROKVISS experiments like telepresence, data downloads as well as software and configuration uploads are operated online from ground.

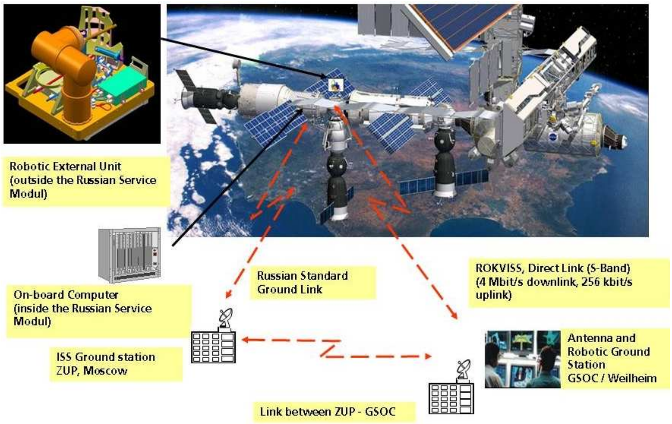

Fig. 4. System overview of ROKVISS operations

The ROKVISS ground control computers are directly coupled to the transceiver system of DLRs tracking station of the German Space Operation Center (GSOC), see Fig. 4. The round trip times are expected to be less than 20 ms and are a very good basis to evaluate the telepresence system behavior.

A direct communication radio link between the ground segment and the ROKVISS flight unit is established, compliant to the CCSDS telemetry and telecommand standards. To meet the specific real-time requirements of the telepresence mode the S-Band communication protocol is tailored.

Of major interest is the usage of a lean protocol which decreases the computational overhead within the lower communication layers. Due to the large protocol overhead within the CCSDS standards no error detection and correction mechanism like Reed-Solomon or Viterbi approaches are implemented within ROKVISS. Only a simple Cyclic Redundancy Check (CRC) mechanism is processed for error purposes on transfer frame level. Thus, the S-Band communication protocol provides an unreliable data transmission to the ROKVISS application as required by the real-time robot control (telepresence mode), to guarantee a maximum jitter of approximately $1ms$. Reliable data transmission between the ground segment and the flight unit is built upon the high level Transport Control Protocol (TCP), using a combination of the Serial Line IP (SLIP) and Point-to-Point (PPP) protocol as Internet Protocol implementation.

Within the downlink channel the video data can optionally be a pair of images, produced by two stereo cameras each with 15-20 frames/s and a resolution of 256x256 pixel, or a single still image as processed by the earth observation camera with 1 frame/s and a resolution of 1024x1024 pixel. In case of the telepresence control mode the robot control data requires a sample rate for transfer of 500 Hz and a jitter of at most $1ms$. This is achieved upon a (netto) data rate of maximal 128 kbit/s in both, up- and downlink, see [1].

C. Man-Machine Interface at Ground Station

The man-machine interface (MMI) plays a major role for immersive telepresence. The operator should feel like being at the remote location, so as many senses as possible have to be stimulated by the MMI. Due to the fact that audio (smell or taste) is not common in outer-space environments, ROKVISS concentrates here on the visual and the haptic modality. The stereo video images transmitted from the cameras of the ROKVISS manipulator can be displayed using passive stereo, such that the operator perceives a 3D-image of the remote workspace as the experimental contour.

A new version of the DLR USB Force-Feedback Joystick is used for the haptic feedback. Its actuated two degrees-of-freedom correspond to the two link manipulator at the space station. The design of the joystick is done to achieve high-fidelity force feedback to the human operator. The result enables a very precise force feedback with forces up to $15N$ over a moving range of $\pm 20°$. Fig. 5 shows the mechanics and electronics of the joystick without the housing. The additional control elements in the handle are also visible.

Like in the case of the intelligent joint a strict mechatronic approach is used. A Freescale DSP is the heart of the electronic design, see Fig. 6. It performs a current control of the motors and a high level control, which includes a force and an impedance controller. Furthermore some simple simulations like virtual walls, etc. can be computed here. As high-speed communication to the PC a USB interface is implemented, which has a $1ms$ cycle time. For a detailed description of the DLR Force-Feedback Joystick see [11].

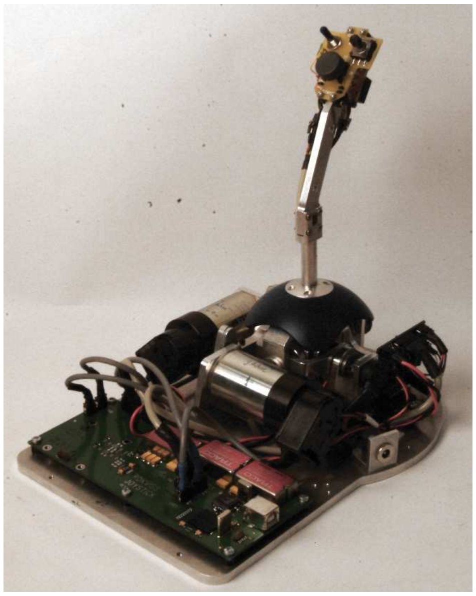

Fig. 5. DLR Force-Feedback Joystick (open)

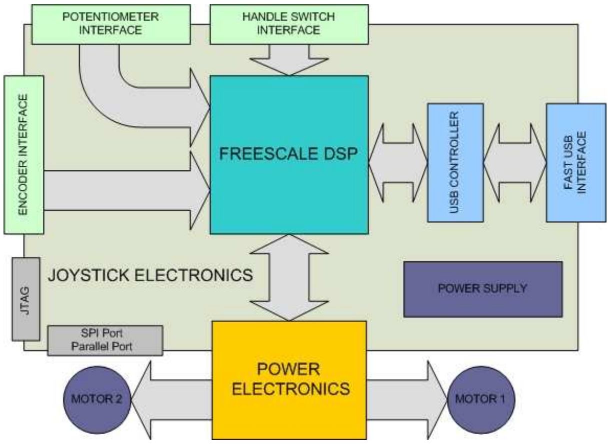

Fig. 6. Electronic Design of DLR Force-Feedback Joystick

III. Bilateral Control Approach

Beside the real stereo image the haptic feedback is one major component to achieve realistic feedback from the remote system, allowing an intuitive exploration and manipulation of the remote environment. 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 slave manipulator at the ISS. The stabilization of this coupled master slave system is additionally complicated due to the presence of time delay in the system [12], [13]. The time delay in telepresence systems with haptic feedback is an often addressed problem in the literature [14], [15] and many solutions are given [16]–[19]. An advantage of the ROKVISS space application is, that the communication delay is relatively small (only 10-20 milliseconds shortest) and predictable. This allows to simulate additional time delay to test different control schemes and communication systems within a real space experiment.

In the following the basic theory of the control strategies, which have been or are about to be verified, are presented. The bilateral control schemes are evaluated with increasing complexity and novelty.

A. Position-Position Coupling with Virtual Dampers

For very large communication delays a position-position coupling with virtual dampers is proven to be useful, as Yokokohji demonstrated on ETS-VII [20]. For this strategy the stability of the master-slave system can be obtained regardless the contact situation. So this control strategy is used for the first experiments.

But it is a very conservative control approach, which degrades the transparency of the system and so the immersion of the operator evidently. This control strategy should be verified in comparison to the experimental data obtained by Yokokohji, but also with shorter time delays.

B. Adding Direct Force Feedback

If the communication delays are small, an additional direct force 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. The joystick on-ground is in force control mode and the robot in space in position control mode, while the robot is in free motion. If the robot is contacting the contour, the space robot switches to force control mode and expects force commands, while the master control switches to position control displaying the space robots position to the user. For a detailed description see [21]

C. Wave-Variable Theory

A new approach in space robotics will be the wave variable based control which was introduced by Niemeyer [17]. 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.The theory itself presents an extension to the theory of passivity, and the global control scheme uses methods taken from the network theory. 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.

Each wave transformer will encode a wave towards the communication channel, and will decode a desired motion towards the Joystick/robot, 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 too.

The varying time delay is compensated by a time delay model and an appropriate compensator [22]. This method can be used with ROKVISS, due to the fact, that a dedicated radio link is used. So the exact time delay can be precalculated using a quite simple model.

D. Time Domain Passivity Control

A new approach in bilateral control in the last years represents the *Time Domain Passivity Control* [13]. 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 and to damp any generated energy by a dedicated controller, such that the system remains passive. This has successfully applied to haptic interfaces [23], [24].

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 [25], [26] and will also be verified in ROKVISS.

IV. EXPERIMENTAL SETUP

Based upon a guaranteed stability the bilateral control scheme has the goal to achieve "transparency", i.e. the operator should feel as directly operating in the remote (space) environment. The technical master-slave system appears transparent.

Fig. 7. ROKVISS Experimental Contour

Our evaluation contour (see Fig. 7) provides several experiments to verify our new control schemes under realistic space conditions:

- the contour itself represents a hard surface, which can be contacted with a finger
- different geometric forms are included for contour following tasks
- a 2-DoF "Peg-in-Hole" part in the contour realizes a 3-side-mechanical binding of the touch finger. This represents a typical benchmark for telerobotic applications

- mechanical springs simulate an external energy storage, which can add energy to the master-slave system

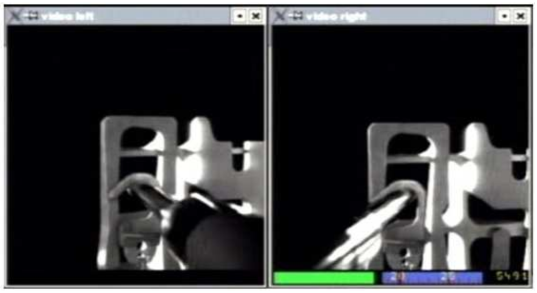

Fig. 8. ROKVISS video images, while pulling the spring

V. PRELIMINARY EXPERIMENTAL RESULTS FOR TELEPRESENCE

A. Realtime Communication

The measured round trip delay is given in Fig. 9. In this plot can be verified, that the round trip delay for this specific orbit lies between $12-17ms$ and the jitter is less than $1ms$. So the realtime communication link satisfies the requirements formulated for the telepresence experiments. The variation of the delay over time also can be seen in the figure. This variation corresponds to the changing distance between the ground antenna and the space station during the overfly.

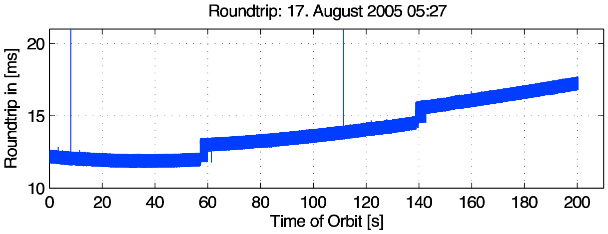

Fig. 9. Roundtrip Delay measured on Orbit 2527 (17.Aug. 2005)

B. Telepresence Control

In the following the results from two experiments conducted with the controller described in section III-A are presented. This control strategy was also used during the “Check-out” of the telepresence mode on the 25th of March 2005. The presented results have been recorded at the 15th of December 2005. It was planned to perform and present more detailed results here, but a necessary update of russian power supply element could not be realized yet.

The first experiment is the “Peg-in-Hole”-Task, which can be seen in Fig. 10 showing the path in the Joint1-Joint2 plane. The position and force values recorded during this experiment are presented in Fig. 11 and Fig. 12. A good position tracking of the slave system and a scaled but identical force trajectory was felt by the operator. It can be seen that the peg is inserted into the hole at $1.9s$, since we have a position offset between master and slave and the torques in joint 2 increase. This situation keeps stable until $3.5s$, while the operator is pushing against the right and the left wall of the hole. After this the peg is withdrawn.

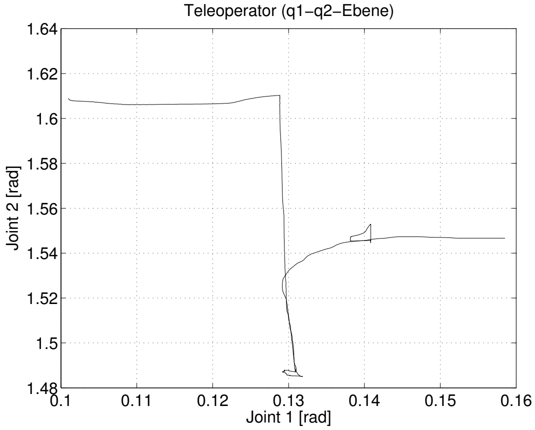

Fig. 10. Cartesian track of the “Peg-in-Hole” experiment

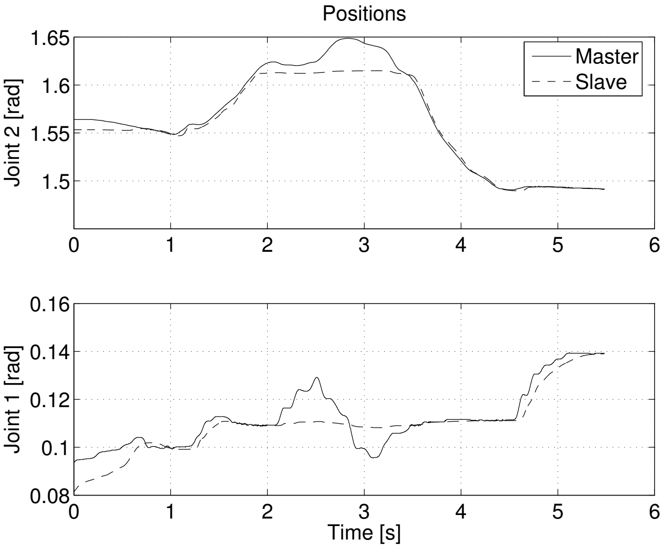

Fig. 11. Recorded positions during telepresent “Peg-in-Hole” experiment

The second experiment shown in Fig. 13 and Fig. 14 is the spring experiment. Here the operator telepresently pulls the vertical spring, such that the spring acts on joint 2 of the manipulator. The system was moved with different speeds, which had no differences on the results. Again position tracking is good and only disturbed by the delay of the system. In the torque recordings an oscillation occurs between $6-7.5S$ and $14-15S$ (plus smaller ones later). The reason for this is a very slight slip-stick effect in the manipulator joint, which is amplified by the controller on the master side.

VI. CONCLUSIONS AND OUTLOOK

In this paper the technical system for the telepresence mode in the ROKVISS space mission and the preliminary results of experiments are presented. These results indicate, that space

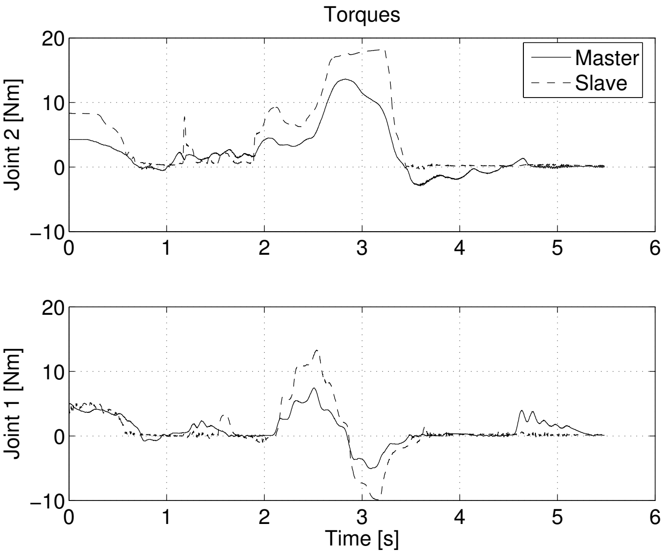

Fig. 12. Recorded torques during telepresent “Peg-in-Hole” experiment

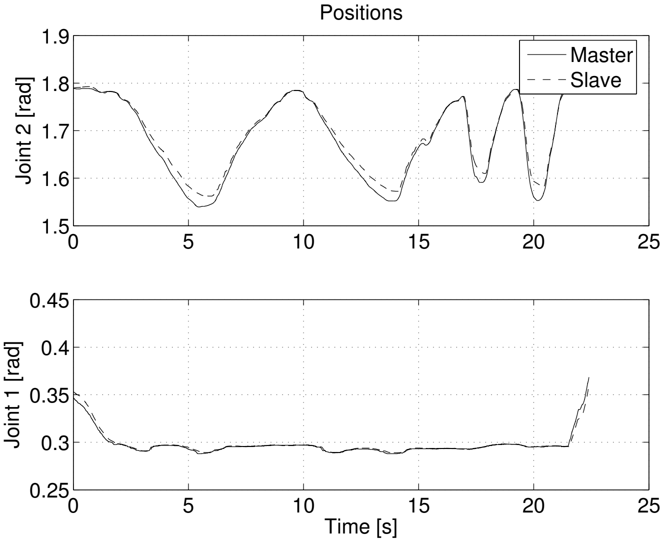

Fig. 13. Recorded positions during telepresent spring experiment

telerobotic systems can be extended to telepresence system including high-fidelity force-feedback to the operator. This requires a realtime communication, which is not standard in nowadays space communication. The ROKVISS-solution inherits the drawback of a very short communication period, which could be overcome by using one relay-satellite.

In the upcoming months the ROKVISS mission continues and further evaluation with the presented control concepts are done. Actually a testbed for using one relay-satellite to enlarge the period of contact is prepared with partners. An overview of the current DLR activities in On-Orbit Servicing is given in [7].

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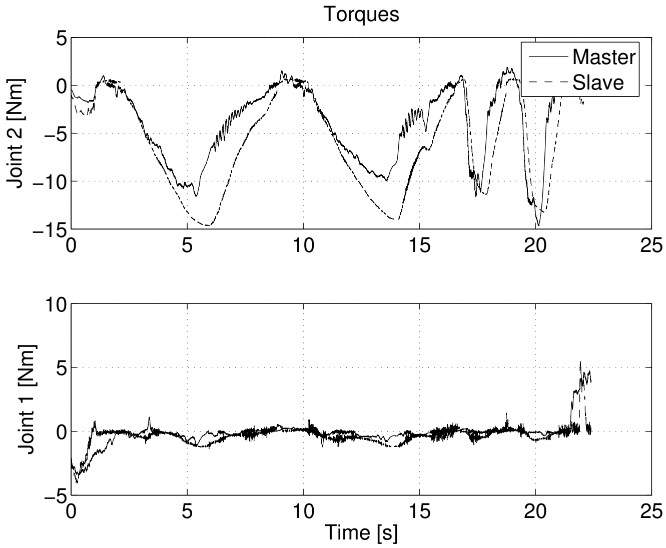

Fig. 14. Recorded torques during telepresent spring experiment

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