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FORCE-FEEDBACK TELEOPERATION OF ON-GROUND ROBOTS FROM THE INTERNATIONAL SPACE STATION IN THE FRAME OF THE "KONTUR-2" EXPERIMENT

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Abstract. The issues on creation and using of the haptic interface for remote control of on-ground robots from the Russian Segment of the International Space Station (ISS RS) in the frame of "KONTUR-2" space experiment are presented. Force-feedback as key technology of this system ensures elements of telepresence of operator in the environment where robot operates using visual and tactile feedback in a closed control loop. Results of space sessions on control of on-ground robots from the ISS RS are presented.

Keywords: space experiment, telepresence, force-feedback, time delay, teleoperation.

Introduction. "KONTUR-2" is a joint space experiment for the in-flight verification of force feedback and telepresence technologies between the German Aerospace Center (DLR), ROSKOSMOS, the Russian State Scientific Center for Robotics and Technical Cybernetics (RTC) and RSC Energia. This mission follows after successful collaboration of these organizations in previous space experiments [1, 2]. The main objectives of "KONTUR-2" are the implementation and evaluation of telerobotics and telepresence technologies for space telemanipulation applications. To that end, a force feedback joystick was built at the DLR and installed in the Russian segment of ISS in August 2015 and a bilateral controller was designed to cope with the communication latencies between ISS and ground station on Earth [4]. Both, DLR and RTC conducted several experiments during 2015 in which two cosmonauts successfully teleoperated the robots on ground at DLR and RTC from the ISS. Figure 1 shows the general mission setup, including the infrastructure used for the cosmonaut training at Gagarin Research and Test Cosmonaut Training Center (GCTC).

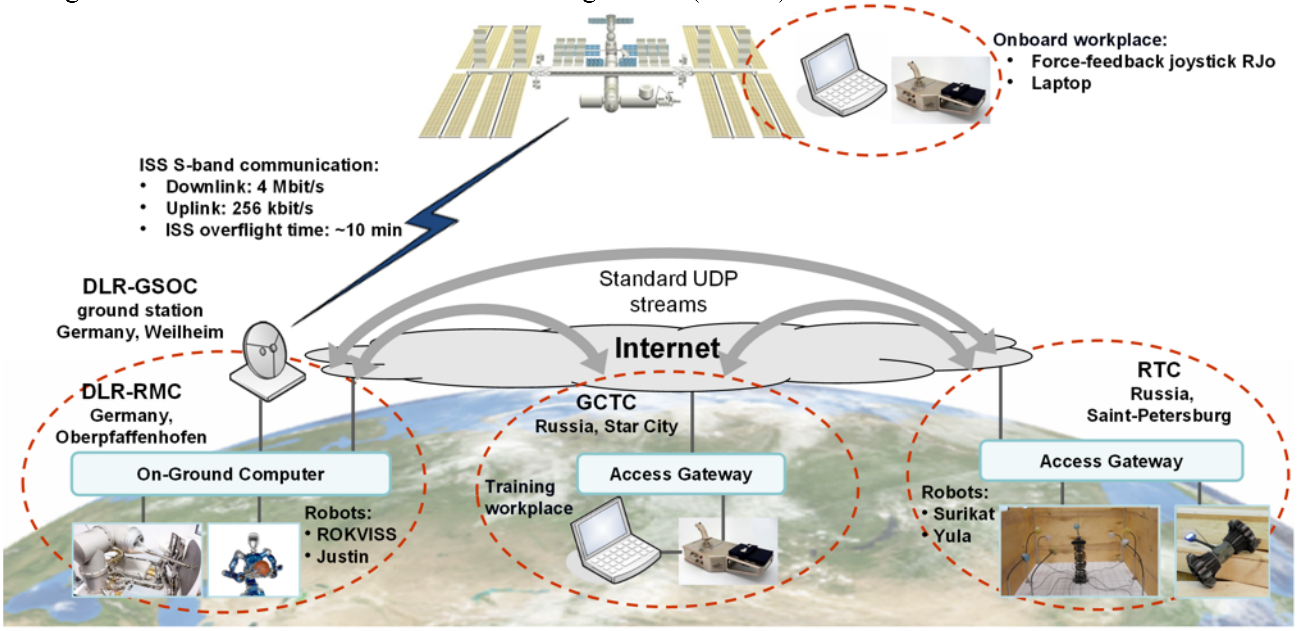

Figure 1. Space experiment setup

The joystick was designed according to a set of performance requirements and space related specifications needed for inflight operation onboard the ISS. Its materials, thermal design, motors and electronics have been developed to fulfill the required space qualification.

The S-Band antenna for real-time communication designed for the ROKVISS experiment [1] was used to communicate both, force-feedback joystick and robots on Earth. The types of data transmitted between both, space operator (cosmonaut) and the robot on Earth are shown in Figure 2. Haptic, visual and voice signals helped the cosmonaut to immerse in the remote Earth environment and to feel tele-present on Earth through the robotic system.

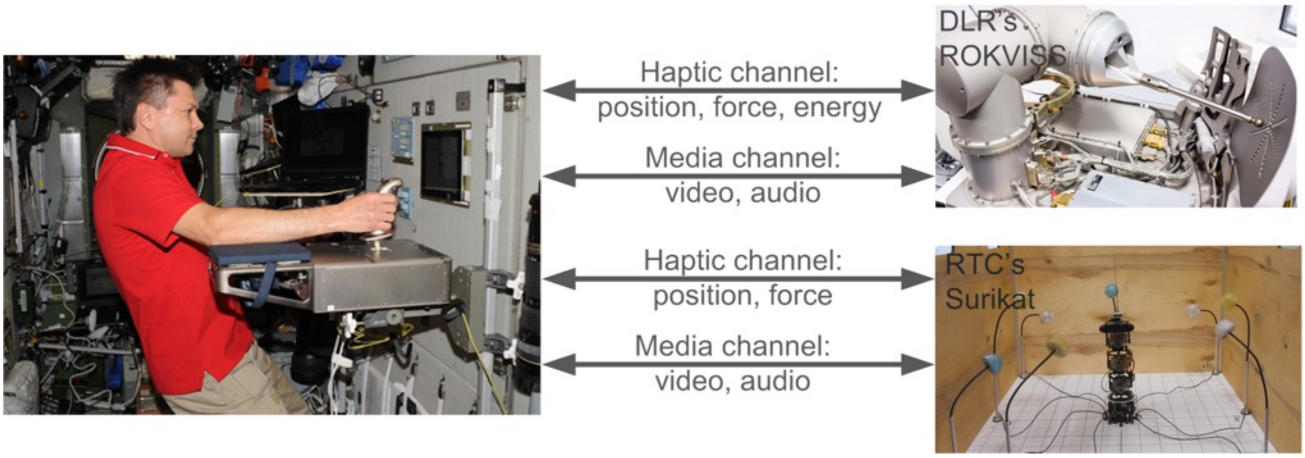

Figure 2. Telepresence data streams

Real time, communication and control requirements. It is well known in robotics, and in particular in the control field, that closed loops systems that include non-negligible time delays can produce negative effects on system stability. This issue is magnified in those closed loop systems that are characterized by tight couplings, that is, where high frequency control actions are required to capture a reasonable spectrum of the dynamics of the controlled system. For instance, in order to capture the interaction of a robot's end-effector while contacting a hard surface, a well established control-loop frequency is 1000Hz. In particular, the control loop frequency of the joystick is as well 1000Hz. However, due to the limitations of the communication link, the transmission frequency through the S-Band link is 500Hz for DLR mission. Arguably, the lower transmission frequency limits the overall control loop bandwidth. Nevertheless, it can be proved that keeping higher local control loop frequencies at the joystick or robot sides has some control and performance benefits. For instance, higher virtual damping values can be achieved or more accurate passivity observers resulting in better bilateral control performance. On the other hand, coping with latencies between master and slave systems can be challenging, especially when delay is non-constant and jitter and data losses are present.

In "KONTUR-2", two scenarios had to be considered in the design of the bilateral controller: ISS and training. The first is the nominal mission case, where the cosmonaut controls the robot from the ISS through the S-band link. The second one is a geographically distributed scenario through the internet for cosmonaut training purposes. Since the exact same system needs to operate in both, the requirements for the bilateral controller are clearly strengthened as both links are characterized by different communication parameters.

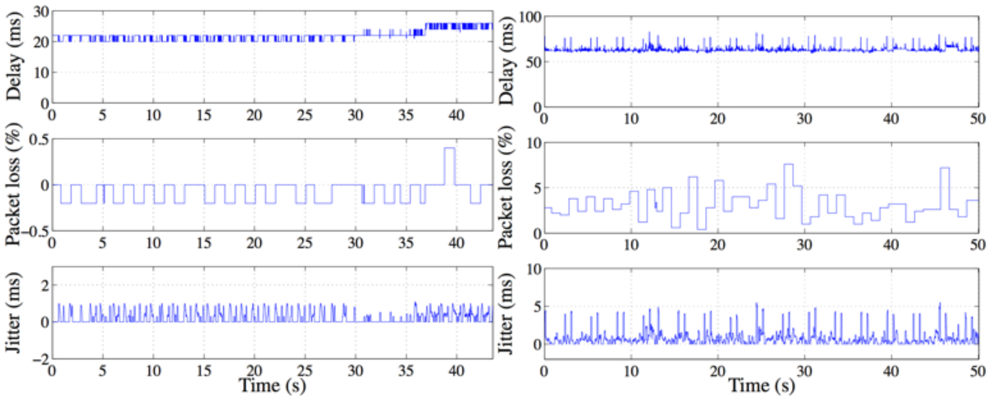

Figure 2. S-band link (left) and training setup (right) round delay measurements (DLR mission)

Figure 3 shows round trip delay measurement in both scenarios. As it can be seen, the nature of these two links is quite different in terms of time delay, data losses and jitter. The time delay for the ISS communication varied from 20 to 30 ms (corresponding to azimuth and horizon points) with mean negligible data losses. The internet training setup introduced a mean delay of 65 ms between Star City and Oberpfaffenhofen (where the DLR is located) and highly oscillating package loss ratio, from 5% to 15%, due to the UDP protocol. Though more limited in bandwidth, the ISS link is higher in performance. However, shadowing can occur resulting in signal attenuation and in turn higher package loss ratios or even communication blackouts. On the other hand, the internet link measurements confirm a typical UDP behavior.

DLR Experiment. The DLR experiment consisted in controlling the ROKVISS arm (see Figure 2. Telepresence data streams
), located in one of the laboratories in Oberpfaffenhofen. Two types of tasks were conducted to evaluate the performance of the teleoperation system: 1) Free movement tasks, without contacts between the robot and the task board and 2) contact tasks with different haptic goals [5, 6]. During the free movement tasks we investigated the positional accuracy when controlling the telerobotic system from the ISS. During contact tasks, the accuracy of the force reflection was evaluated.

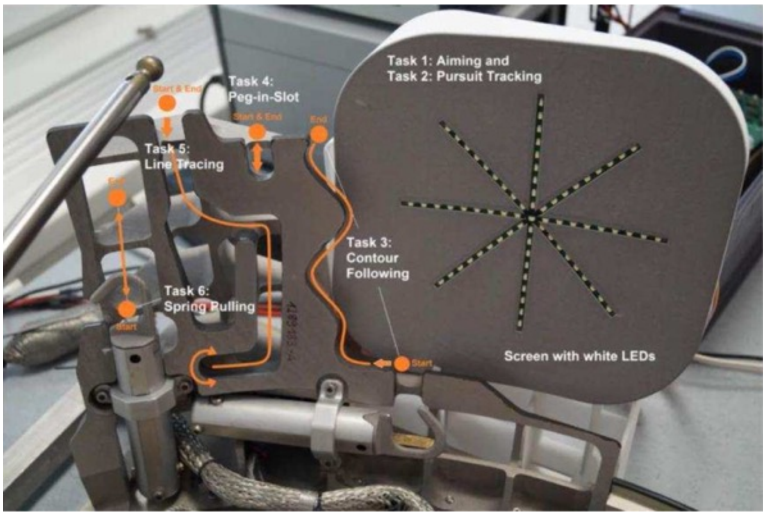

Figure 3: Task board for evaluating the performance of the telerobotics system

To that end, the robot arm interacted with a task board which included several tasks, from pure trajectory following in free space to peg-in-slot, contour following or hard surface contacts with different force controller settings (see Figure 4). At each experimental session, the cosmonaut was asked to perform different tasks. Position and force signals were registered in both, joystick and slave robot systems.

The approach for the bilateral controller is based on a 4-Channels architecture, whose stability in the presence of time delay, jitter and data losses is addressed through the Time Domain Passivity Control Approach (TDPA) [4] and the Time Delay Power Network (TDPN) representation. In this architecture, position and force signals are sent from the joystick to the ROKVISS robot and computed and measured force signals are sent in the other direction. Both systems, the joystick and ROKVISS, are impedance controlled, i.e. the commanded signals to the joystick and to the robot are forces, and their outputs are positions. Interestingly enough, the same controller parameters were used in both described scenarios, that is, mission (ISS S-Band link) and training (internet DLR – GCTC). Indeed, one of the most interesting features of this controller is its adaptability to any communication conditions, including different delay values, jitters and package losses.

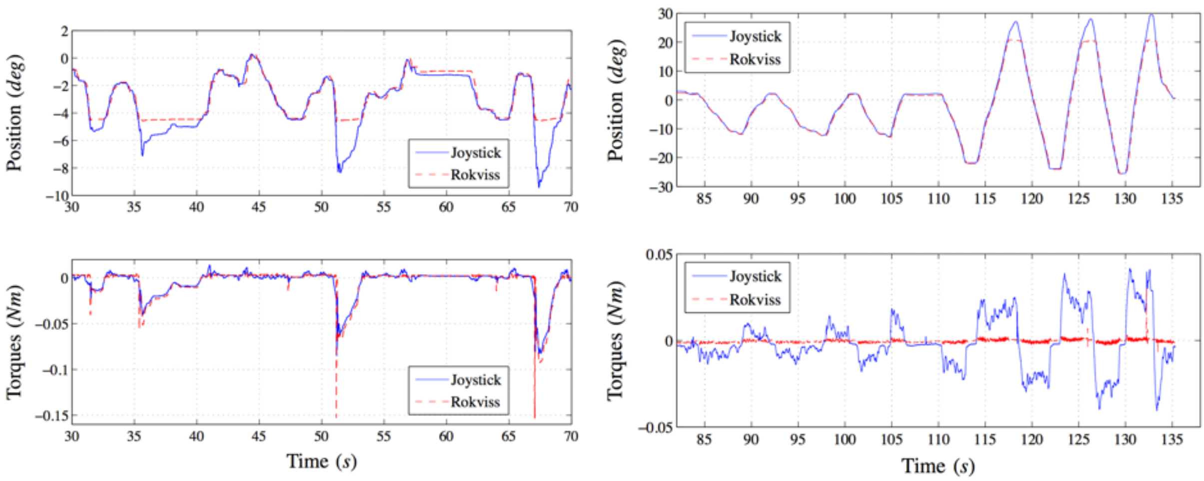

Figure 4. Position and force signals during one experimental session. Left: performance in hard contact situations. Right: performance in free space motion.

Figure 4 shows the results of an experiment session conducted during August 25th 2015 with cosmonaut Mr. Kononenko. These plots show the position tracking and the force feedback performance during rigid contact situations and for free environment respectively. The rigid contact and free environment motion during the cosmonaut training that took place at GCTC in Star City (joystick) and the DLR (ROKVISS robot), are shown in Figure 5.

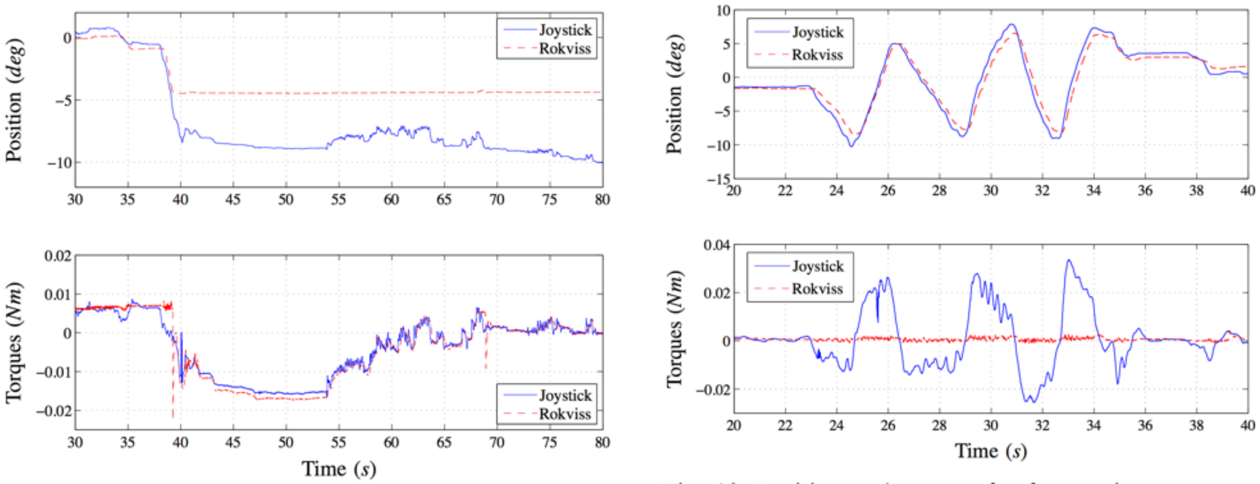

Figure 5. Performance during the training between DLR and GCTC. Left: performance in hard contact situations. Right: Performance in free space motion.

The experiments with the joystick on board the ISS proved that all hard- and software components of joystick as well as the telepresence system are functioning reliably. The joystick is able to provide stable and reliable force feedback performance thanks to its fast real time interface and low intrinsic latencies. These hardware and software components have been validated in the space mission "KONTUR-2". The participating cosmonauts, Oleg Kononenko and Sergey Volkov, were able to perform the experimental tasks with the ROKVISS robot, located in the DLR in Oberpfaffenhofen (Germany) from the Russian Segment of the ISS. Force-feedback and latency compensation technologies for bilateral control were successfully evaluated [3]. The cosmonauts reported that the tasks were easy to perform with the force feedback joystick. Different telepresence approaches were compared in terms of system and operator performance and the results from terrestrial and space sessions were compared to understand better the effects of microgravity on sensorimotor performance while controlling a telerobotic system. Preliminary analyses revealed that positional accuracy is degraded in microgravity compared to terrestrial conditions. Yet, these performance losses can partially be compensated by implementing a movement damping at the joystick. One of the most interesting features of the bilateral control approach based on the Time Domain Passivity Approach is that a system tuned for a setting close to ideal can operate in the ISS communication conditions and the internet training setup with guaranteed stability.

RTC Experiment. During first part of RTC experiment cosmonauts from onboard the RS ISS controlled cinematically redundant manipulator Surikat which equipped stylus and light targets located around (see Figure 2) [7, 8]. Targets lighted up for a short time and the cosmonaut had to extinguish the target, touching it by the stylus. Unlike DLR's robot Surikat didn't have torque sensors so force feedback on the joystick handle reflected the current position of the robot so that operator cannot move the handle faster than the robot has reached already specified position taking into account the delay and inertia of the robot.

Unlike DLR experiment during RTC control sessions connection to the ISS took place not only via S-band link, but also through the Internet (see Figure 1). This imposes additional restrictions on the control system, such as increased delays, a high percentage of packet loss and higher jitter as showed above. Nevertheless established telecommunication infrastructure provides transmission of heterogeneous traffic with an acceptable quality of service for each of the control channels, and feedback. The most critical to latency and bandwidth bi-directional control channel provided total transmission delay for the control and feedback loop (RTT) about 85 ms. Figure 7 shows graphs of RTT for RTC sessions. The graph shows the change of RTT during the sessions which is connected to change in distance between ISS and ground station.

Established control system provided manual teleoperation from the ISS RS of robots located on Earth. Operator onboard the ISS RS receives feedback from the robot through several channels:

− Tactile feedback provided by transfer of information between robot and joystick drives controllers. Minimum delay of this type of feedback is provided by operation of controllers in real time and transmit this information flow via priority channel in S-band link. This type of feedback provided to the operator a tactile information about the inertia of the system in the absence of a torque sensor on the robot;

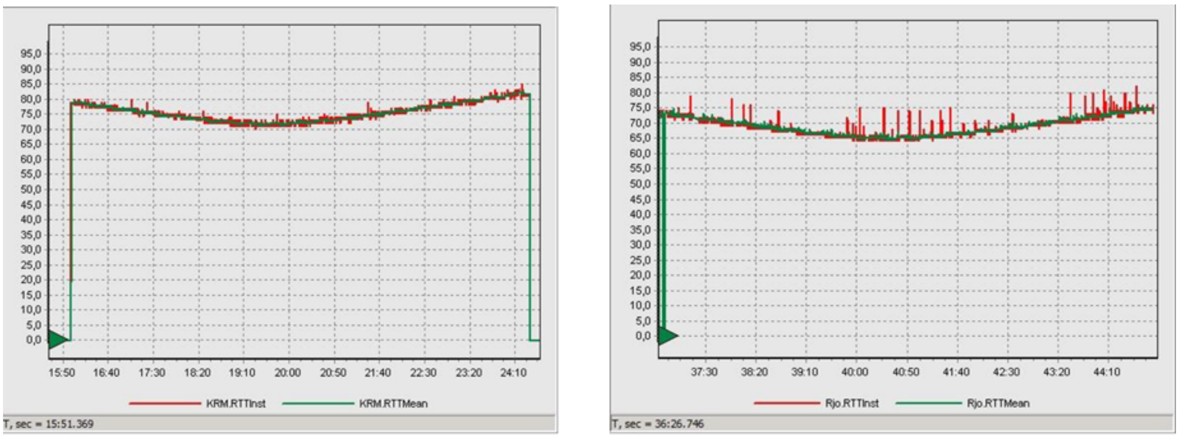

Figure 7. RTT between the ISS and RTC during two different sessions

– Visual feedback, obtained by translation of the video from a camera mounted on the robot, or from the observation camera. For this type of feedback it was defined the balance between the quality of the transmitted image, the frequency of its update and delay in delivery when there are significant limitations on the bandwidth of the communication channel (256 kbit/s for upload). In connection with the need to use data compression algorithms, this kind of feedback provided an appreciable delay due to data processing at the transmitting and receiving sides;

– Visual feedback, obtained by visualization of the robot's 3D-model motion on the laptop. During control of Surikat for animation of 3D-model it was used telemetric information from the robot; this information was delivered in the priority channel, which provided low delays in display. Compactness of transmission data allowed for a low bandwidth to provide higher image refresh rate (compared to video), which significantly improves the dynamic picture representations of the surrounding area.

The effectiveness of combination of several types of feedback – haptic (force in the handle of RJo) and visual (video and 3D-model) – complement each other to provide a virtual "immersion" of operator to the environment of the robot operation, confirmed the successful implementation of manipulation and locomotion tasks carried out during teleoperation sessions.

Force feedback joystick was used in the experiment as part of different teleoperation systems for control heterogeneous robots. Software architecture allowed to choose the controller of RJo depending on the current session (DLR or RTC) and to change dynamically its settings during a session.

For teleoperation of RTC Surikat robot it was used dual-channel architecture with controllers, designed in RTC: the information about current position transmitted between RJo and the robot. RJo controller allowed to implement a virtual spring on the handle, which bind the position of the RJo handle and robot. Furthermore, it provided sensitive of virtual mass and viscosity. The insertion of force feedback to control of the robot which doesn't have force-torque sensors, yielding positive results in the form of increased speed and accuracy of operations. Figure 8 shows the trajectory of RJo and Surikat in the absence and presence of force feedback while performing the same tasks in experiment session.

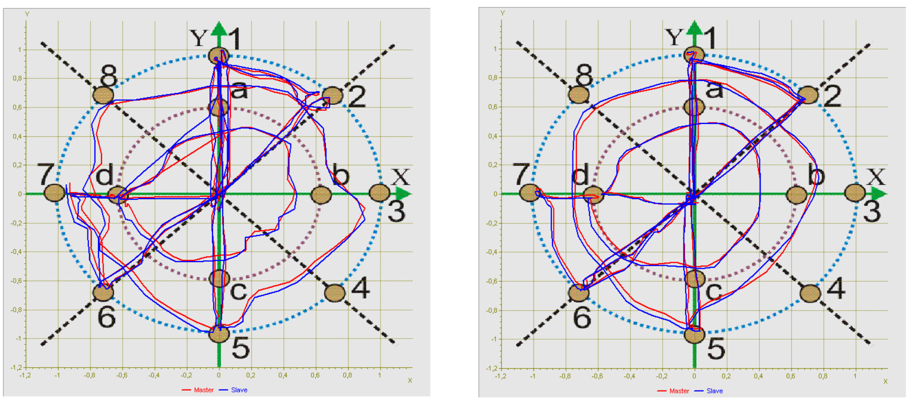

Figure 8. Trajectory of RJo's handle (Master) and Surikat (Slave) in the absence (left) and presence (right) of force feedback

Universal telerobotics system. Teleoperation system with force-feedback joystick originally developed for the two robots (ROKVISS and Surikat) with the corresponding controllers of DLR and RTC, after the success of a series of sessions, was later used to control other robots. Small mobile robot Yula (RTC), in contrast to Surikat required position-speed control: the operator controls the direction of motion, rather than the position of the robot. The Yula robot has not special sensors like radar. The model-based force feedback system was used in this experiment. Cosmonaut saw a 2D-model of the polygon with a robot, obstacles and borders and video from the robot's camera. Force feedback was calculated according the distance from the robot to obstacles. The task for the cosmonaut was to move the robot through the labyrinth. In this case force-feedback of joystick helped cosmonaut did not run into obstacles.

During teleoperation of anthropomorphic robot Justin located in DLR fixed mapping of the two coordinates of RJo onto two joints of robot's arms was used, and the mini-joystick (four-position switch on the handle of RJo) was used to control of the movement of the head with a built-in camera. Two space-separated RJos was used for cooperative control of Justin arms: operator from onboard of the ISS RS controlled right arm, operator in RTC controlled left arm of the robot. Justin controlled simultaneously from the ISS RS and RTC, took the ball by two arms and manipulated them according to the instructions of coordinator stayed in front of the robot (see Figure 9).

Thus, versatility of the developed teleoperation system was demonstrated. This system allows to use the 2-DOF force-feedback joystick for teleoperation of robots which are different in purpose, number of DOF and kinematic schemes.

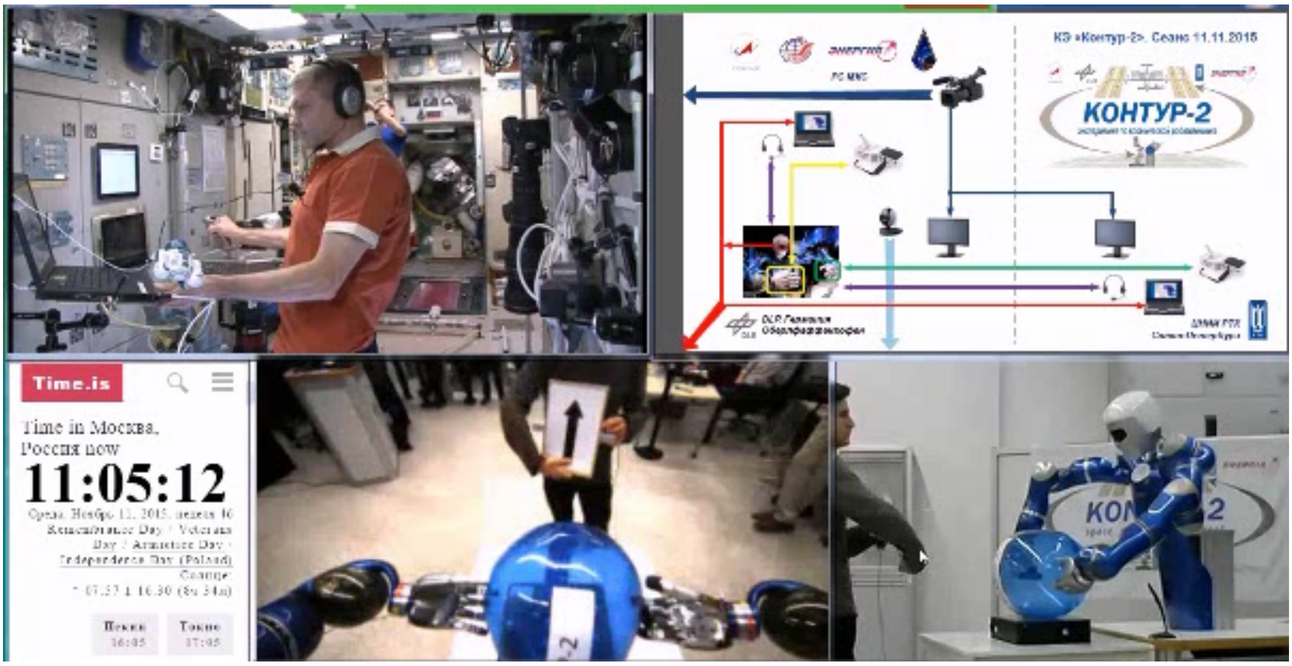

Figure 9. Russian cosmonauts Oleg Kononenko during space sessions of "KONTUR-2" with the robot "Justin" (translated at the he XI International Scientific and Practical Conference "Manned Space Flights")

Main results of "KONTUR-2" experiment. 23 space sessions were held from August to December 2015:
- 9 sessions of teleoperation of DLR robot ROKVISS;
- 4 sessions of teleoperation of RTC robot Surikat;
- 5 sessions of teleoperation of RTC robot Yula;
- 5 sessions of cooperative DLR/RTC teleoperation of anthropomorphic robot Justin.

Figure 10. Russian cosmonauts during space sessions of "KONTUR-2" experiment:
Oleg Kononenko (left), Sergey Volkov (right)

Figure 10 shows photos of Russian cosmonauts onboard the ISS during the performing of tasks in the framework of "KONTUR-2" experiment. Video translation from the ISS and audio dialog with a cosmonaut was established via s-band and internet communications.

During "KONTUR-2" experiment the following world achievements in the field of teleoperation from the ISS RS of terrestrial robots using 2-DOF force-feedback joystick have been established:

− August 2015: high fidelity teleoperation (DLR robot ROKVISS);

− August 2015: teleoperation of manipulator from the ISS via Internet (RTC robot Surikat);

− October 2015: teleoperation of the mobile robot from the ISS via the Internet (RTC robot Yula);

− November 2015: teleoperation of anthropomorphic robot from the ISS (DLR robot Justin);

− November 2015: cooperative teleoperation of anthropomorphic robot from the ISS and from remote workplace via Internet (robot Justin, DLR/RTC).

The main scientific and technical results of sessions are:

− Dual-channel (RTC), and four-channel (DLR) system for teleoperation of on-ground robots from the ISS RS;

− Verified parameters of models of teleoperation systems of DLR and RTC, providing tactile feedback and stability of the system with delays in the control loop up to 85 ms;

− Confirmation of feasibility of using of force-feedback joystick for teleoperation of robotics in microgravity conditions;

− Proof of efficacy of combination of tactile and visual feedback in a control loop, which includes a human operator working in microgravity;

− Confirmation of suitability of a heterogeneous distributed telecommunications system as the infrastructure for remote control of on-ground robotic from onboard the ISS RS;

− Confirmation of suitability of developed system for remote control of robots, which are different in purposes, number of DOFs and kinematic schemes, from 2-DOF RJo.

Conclusion. Scientific and technical tasks of creating of force-feedback teleoperation system for control of on-ground robots from the ISS has been successfully solved within the frame of "KONTUR-2" experiment. The network infrastructure for verification of such a distributed teleoperation systems has been created. For the first time the teleoperation sessions from onboard the ISS of on-ground robots with help of force-feedback joystick were held. Developed technologies are intended for using in space robotic systems during realization of planetary and orbital missions.

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