KONTUR-2 MISSION: THE DLR FORCE FEEDBACK JOYSTICK FOR SPACE TELEMANIPULATION FROM THE ISS

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ABSTRACT

The KONTUR-2 project is a joint venture between the German Aerospace Center (DLR), ROSKOSMOS, the Russian State Scientific Center for Robotics and Technical Cybernetics (RTC) and RSC Energia for the in-flight verification of force feedback and telepresence technologies. The main objectives of the KONTUR-2 project are the development of a space qualified 2 degrees of freedom (DoF) force feedback joystick (developed by DLR), the implementation of telepresence technologies and the investigation of the overall performance when telemanipulating robotic systems on Earth from space with force feedback. The feasibility study of using teleoperation for future planetary explorations with robots on distant planets teleoperated by a human orbiting the planet in a spacecraft (e.g. building habitats on Mars by teleoperated robots) is a desired outcome of the mission.

The force feedback joystick was installed in the Russian module of ISS in August 2015 and shall operate until December 2016. In August 2015 the first experiments were conducted successfully, two cosmonauts telemanipulated robots on ground at DLR and RTC from the ISS.

This paper provides a general overview of the main components of the space qualified 2 DoF joystick where the requirements for a space qualified joystick, the joystick design such as the ergonomics design, the mechanical structure, the electronics and software architecture, the thermal concept and the bilateral control system are described.

1 INTRODUCTION

With the advances in communication and control technologies, it has become possible to communicate *actions* rather than just *words* over large distances by using the concepts of *Telemanipulation* or *Telepresence*. Telemanipulation [1], implies the manipulation of a robot in a distant environment by a human operator while telepresence more specifically refers to the feeling of being present in an environment while being physically situated in another. This enables the extension of human dexterity and other cognitive skills like decision making and problem solving to distances once imagined to be unachievable, including telemanipulation of robots in outer-space from Earth.

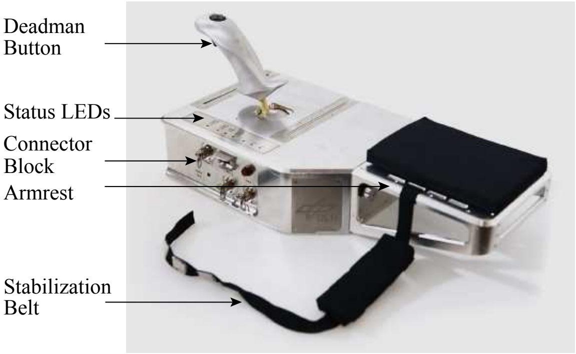

Figure 1. The DLR force feedback Joystick in Operation Mode

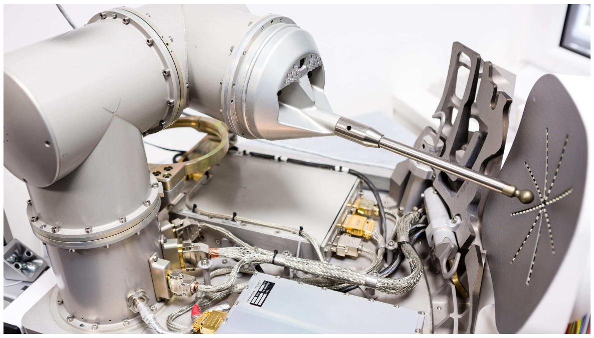

Figure 2. ROKVISS robot at DLR-RM

The ROKVISS (RObotik-Komponenten-Verifikation auf der ISS) project by the Institute of Robotics and Mechatronics of the German Aerospace Center (DLR, Oberpfaffenhofen) and its extension KONTUR-1 (in collaboration with RTC) involved the telepresent control from ground of the 2 DoF ROKVISS robot (shown in

Fig. 2) mounted on the outer wall of the Russian Svesda module of the ISS. The main goals of the ROKVISS experiment were the demonstration and verification of lightweight robotic components under realistic mission conditions in free space, the development of a terrestrial joystick (as the human machine interface, [2]) as well as the verification of direct telemanipulation of the ROKVISS robot using the joystick to show the feasibility of applying telepresence methods for further space-robotic missions [3].

In the recent Haptics-1,2 missions from the European Space Agency (ESA), astronauts from the ISS, using a 1 DoF input device, teleoperated a 1 DoF device on the earth with force feedback [4]. Most of the commercially available force feedback joysticks are used in the gaming domain and so, their specifications are far from the requirements of a space qualified joystick. Devices with high performance in terms of real time and haptic rendering capabilities are found in professional domains such as the sigma.7 from Force Dimension [5], which target minimal invasive surgery applications, and the PHANTOM series [6] from SensAble Technologies.

A major challenge in telemanipulating robots in space arises due to the communication delay of command signals from the human operator to the robot and the force signals back to the operator. In addition to the deterioration of the human perception and performance (due to delayed signals in both directions), large delays can cause the inherent closed loop control system to become unstable [7].

As the signal delay increases with the distance between the operator and the remote robot, a logical method to reduce the delay is by having the operator and the robot closer to one another. One of the possible future exploration scenarios is remote planetary exploration and manipulation with the help of landed robots or rovers at various sites of a planet, controlled by an operator orbiting the celestial body (e.g. planet Mars) in a spacecraft, thereby reducing the signal delays when compared to direct teleoperation from Earth. Note that landing humans on Mars would cost tremendously higher costs, since a return launch vehicle needs to be landed as well. Taking this outlook into account, the KONTUR-2 project was started as a joint venture between DLR (Germany), ROSKOSMOS (Russia), RSC ”Energia” (Moscow, Russia) and RTC (St.Petersburg, Russia) to realistically test the feasibility of planetary exploration and in-contact manipulation using teleoperation having Earth as the planet for the study, the ISS as the manned spacecraft and the ISS crewmember as the operator who controls the robot located on Earth via a real-time telecommunication link. Fig. 3 shows the general mission setup, including the infrastructure used for the cosmonaut training at Gagarin Research and Test Cosmonaut Training Center (GCTC).

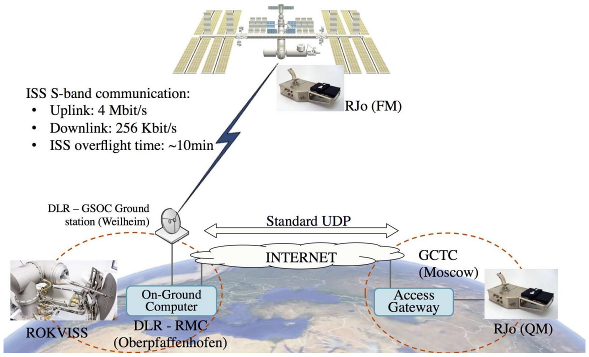

Figure 3. KONTUR-2 communication scenarios

The main goals of the KONTUR-2 project are the design, development, quality analysis and control of a space qualified 2 DoF force feedback joystick (”Raumfahrttauglicher Joystick, RJo”) shown in Fig. 1, the implementation of telepresence technologies and the study of human performance when teleoperating a robot with a force feedback joystick in microgravity.

The sections of the paper are structured as follows: Sec. 2 summarises the requirements that need to be satisfied for a space qualified joystick. Sec. 3 describes the hardware structure including electronics (Sec. 3.1), mechanics (Sec. 3.2), thermal design and safety (Sec. 3.3) followed by software (Sec. 3.4), the bilateral control used for teleoperation (Sec. 3.5) and the ergonomic design (Sec. 3.6). The paper is concluded in Sec. 5 with a quick view of the future work.

2 REQUIREMENTS FOR A SPACE QUALIFIED JOYSTICK

The goal of the Rjo design is to provide the functionality, the necessary computing power and to fulfill the requirements for the Russian segment of the ISS. First, several qualification tests had to be passed with the equipment: Safety (toxicity, flammability), structural tests (vibration and shock loads), environmental tests (humidity and temperature cycles), electromagnetic compatibility tests (EMC) and electrical tests (starting current, working consumption, galvanic isolation).

Secondly, performance related requirements were established. In haptic terms, performance can be described as the range of achievable mechanical impedances displayed by the device. In their lowest limits, the joystick should display zero resistance to the motion, which is equivalent to a free motion case. On one upper limit, the joystick should be able to render an infinitely rigid stiffness, which is equivalent to a hard wall contact case.

3 JOYSTICK DESIGN

This section presents a joystick design that is aimed at meeting mission requirements related to electronics, mechanics (including thermal specifications), software, control and ergonomics.

3.1 ELECTRONICS

3.1.1 Electronic Design

The approach is to use highly reliable components for safety critical parts and military, industrial or automotive electronic components for computing power and motor electronics. Fig. 4 gives an overview of the electronic components of the RJo.

3.1.2 Power Interface

The power circuit of the RJo consists of a power switch, an input EMC filter and a two stage overcurrent protection. A hard wired electronic current limiter and a fuse prevent overloads in the power supply circuit. The soft start functionality of the current limiter also restricts the inrush current when RJo is switched on. The input power range of the RJo is 23-29V and the power supply of the Russian part of the ISS with nominal 28V can directly be connected to RJo. While the motor controllers are powered directly from the input voltage, a highly reliable DC/DC converter is used to generate the supply voltage for the microcontroller and the sensors.

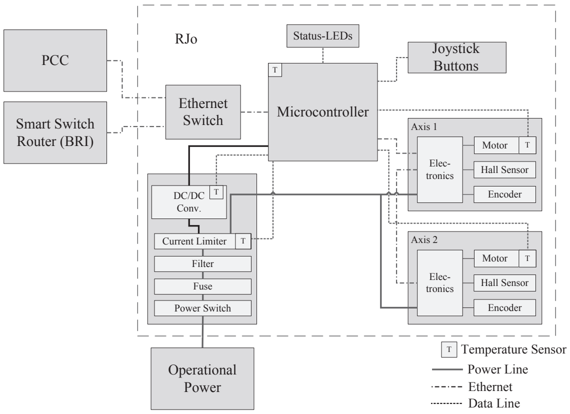

Figure 4. Block Diagram of Electronics

3.1.3 Microcontroller Module

The microcontroller module is a commercial part with a microprocessor and an Ethernet switch. The computing power of this module is sufficient for the force feedback controller, the operational state machine, error handling, I/O processing, temperature supervision and communication with the motor modules and the Portable Control Computer (PCC). Attached to the microcontroller module is an industrial grade microSD card with single-level-cell NAND flash which serves as main memory for program code and log data. For redundancy reasons backup code is stored in the on board flash memory of the microcontroller module. The module also provides an on board EEPROM which is used to store configuration data and checksums.

3.1.4 Motor Modules

The motor modules of the RJo consist of electronics for motor control, a brushless DC motor with a temperature sensor, hall sensors and an encoder. This combination can provide constant forces without position dependent ripple to the RJo handle and abrasive wear of carbon brushes that could pollute the air in the ISS is avoided. The motor control modules communicate over the EtherCAT protocol with the microcontroller module.

3.1.5 Cables, Connectors, Housing and Grounding

All power cables are double insulated, the used materials fulfill the offgassing and flammability requirements for the ISS. Connectors have metallic housings or are additionally protected against flammability. For protection against static electricity, the RJo is completely covered by a metal housing, which is connected to the ISS structural ground. All inner parts of the RJo are galvanicly isolated from case ground. So, as demanded by the requirements for ISS equipment, an accidental short circuit of any part to case ground can not lead to harmful high currents or malfunction of the RJo. All circuit boards including all electronic components are covered with conformal coating material to protect them against humidity and to provide all conductive parts with proper protective isolation against any unforeseen short circuit contact.

3.1.6 User Interface

During normal operation of the RJo a deadman button at the handle ensures that the motors apply forces only when the handle is grabbed by the cosmonaut. This prevents unintentional movements of the handle. During calibration and functional test, where autonomous movements of the handle are commanded intentionally, the deadman button is deactivated by software. Seven LEDs on the top side of the RJo inform the user about the current operational state and possible error conditions (see Fig. 1).

3.2 MECHANICS

3.2.1 Actuation

The core mechanical element of the RJo is a cardan joint that enables the movement of the handle in 2 DoF. The actuation unit for each axis consists of a brushless DC motor and a cable capstan reducer.

3.2.2 Protection cap

While transportation or in non-operation mode of the RJo, a protection cap can be mounted (see Fig. 5) in order to prevent the joystick handle from accidental impacts of the cosmonaut. According to the requirements, impact tests have been conducted with impulses of $F = 556$ N at several testpoints and durations of 0.3 – 1.5 sec.

When the RJo is in operation mode, this protection cap is attached to the rear of the housing and serves as an armrest (see Sec. 3.6.2).

Figure 5. The RJo in Transportation Mode

3.2.3 Materials

All outer metallic parts of the RJo are made out of aluminium and provide an electrically conductive surface (electroless nickel coating). For microbiological cleanliness, the RJo will be disinfected with a 3% water solution of hydrogen peroxide.

All radii of the device are larger than 2 mm as no sharp edges and salient corners are allowed.

3.2.4 Transport bag

The transport bag for the RJo consists of foam material covered with flame-retardant Nomex®.

The bag protects the equipment against shock loads during transportation, launch and on-orbit exploitation as well as against random and sinusoidal vibrations in the range of 20 – 2000 Hz for all three mutually perpendicular directions. Measurements have shown that the bag could reduce peak accelerations with a factor of about 24.

3.3 THERMAL DESIGN AND SAFETY

The thermal design [8] of the RJo is based on a combination of two main purposes. One is the specific requirement to observe the maximum housing temperature of 40 °C at any time to provide a high level of safety for the cosmonaut during interactions with the joystick. The other is to prevent the electronics from overheating.

In order to achieve both goals equally the thermal path of the RJo has been designed in a way that the heat-generating parts have a maximum distance to outer surface areas of the housing which can be touched by the cosmonaut. The electronic components are therefore only thermally connected to the bottom plate of the joystick. Space qualified interface materials such as gap pads or graphit foils improve the thermal conduction to the mechanic structure and prevent hot spots at the electronic components.

During the development of the RJo analysis models based on the finite-element-method have been used to support the optimization of the thermal behavior and heat distribution of the system. As analysis cases the following three different base states have been defined:

3.3.1 Standby state

The standby state is the initial state after switching on and booting of the RJo. It is a passive mode where only communication with the RJo is possible. It is also intended as pause mode when no task is performed.

3.3.2 Idle state

The idle state in which the joystick is calibrated is an intermediate state between the standby and the operation state.

3.3.3 Operational state

The operational state (OpFull) is reached when all hard- and software components are active including force feedback control. Load profiles with the required operational time of 30 min have been assumed for the motors and electronic components.

The evaluation of the analysis cases and measurements from corresponding tests in a thermal chamber have shown that the RJo stays within temperature limits in the standby state and in the operational state.

When the RJo remains in the idle state longer than the required time of 30 min and in unforeseen circumstances, such as incorrect joystick operation time, the temperature limits however may be exceeded. Furthermore in contrast to the analysis cases the real motor load of the RJo is unpredictable. It is a complex combination depending on the specific task, the operating handling of the cosmonaut with the force feedback joystick, etc.

Hence as a safety measure, a temperature control system (TCS) has been developed and implemented in the RJo software (see Fig. 6) which is able to respond to all unforeseen disturbances and accomplishes the two main purposes at any time. Nine calibrated temperature sensors are therefore attached to significant positions of the RJo housing and its components according to Fig. 4.

For the TCS a sampling frequency of 0.1 Hz has been chosen as it provides sufficient measurements for temperature changes of the RJo. The TCS intervenes automatically and also allows the user only to switch to a different state when a certain temperature criterion is fulfilled. When the RJo has already too high temperatures it remains in or switches to the standby state.

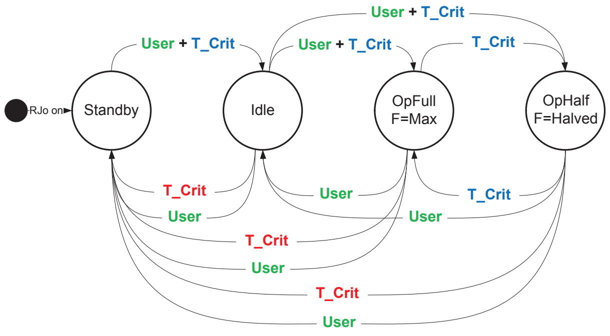

Figure 6. TCS State Machine

In addition to the previously described states, a further state named OpHalf was specified. The difference to the OpFull state is that the commanded force on the RJo handle during the OPHalf state is permanently reduced by the factor 0.5 of the maximum force. The purpose is to enlarge the operational time range of the RJo until the limit temperature of the housing is reached.

3.4 SOFTWARE

This section will briefly describe the software architecture implemented for the RJo.

To cope with the possibility that memory could get corrupted by radiation, two different ways of booting the VxWorks 6.9 operating system [9] have been implemented. By default, the bootloader and then the kernel are started from the first partition of the SD card. If one of these components has been corrupted, the alternative set located on flash is used. Corruption can be detected because CRC32 checksums of the bootloader and the kernel are stored in EEPROM. A similar approach is used for the application software. The joystick is able to start it from three individual locations. The listing is according to the sequence they are used in: SD card, File Transfer Protocol (FTP) folder and flash. The integrity of the application software is checked using the Simple File Verification (SFV) scheme.

The application software consists of three drivers running in the kernel space, a component framework called HIROSCO (HIgh-level RObotic Spacecraft COntroller) [10] managing access to the application software via ECSS PUS [11] and several software components plugged into this framework that implement the behavior of the joystick. The framework and its components are all running in the user space.

Right after the operating system has been started a small driver named ”AppLoader” is called. First, it sets up the network configuration including system clock synchronization via Network Time Protocol (NTP). After that, the available storages of the application software are validated using the CRC32 checksums stored in the SFV files. This validation is continued cyclically every minute until the software is shut down. The results of the validation are provided to the user space for housekeeping. The EEPROM holds a preference which location should be used to start the software in case it is free of errors. If this is not the case, the application software will be started from a different location according to the sequence given above.

Once a location has been chosen, a driver called ”NAND-FlashDriver” is started by the ”AppLoader”. It manages the access of user space applications to the results of the flash checksum test, so that it can be reported to the user. Further, the third driver named ”MicroControllerDriver” is loaded. It provides user space access to the peripherals, such as the motor controllers, LEDs, buttons and temperature sensors. It also enables safety features such as a Cartesian force limit, the deadman button and a temperature supervision. Finally, it provides an algorithm for calibrating the position of the handle after power-on, a position controller to move the handle autonomously and an alive check for its routines.

Finally, the HIROSCO framework is executed. It consists of a supervisor that manages the application specific components and a communication interface that provides a TCP/IP server to which external clients can connect for monitoring and control. HIROSCO is configured by an XML file that specifies available components, their location on the file system and their initial state, e.g. stopped or running.

In the following the components running inside the HIROSCO component framework for Kontur-2 are detailed. The ”OBCMonitor” fetches the current state of the on board computer (OBC), which is responsible for the radio link to ground, and provides this state to the operator as he has no direct interface to the OBC. The ”RJoMonitor” collects the results of check routines contained in the afore mentioned drivers in order to provide this data as housekeeping. The ”EventLib” is used as a plug-in to the HIROSCO supervisor to react on certain events generated by the ”RJoMonitor” in order to implement the temperature control system (see Sec. 3.3). The ”FunctionalTest” component was used during qualification and acceptance tests on ground. It provides a friction test, a workspace test, a virtual spring test and a test of the buttons and LEDs. This functionality can still be used during operation on the ISS to check the correct functionality of the joystick. Finally, a component called ”DLR-TP” implements the master side of the bilateral controller, that is, the real time controller that links the RJo to the slave robot, ROKVISS. The rationale behind this controller is presented in Sec. 3.5.

3.5 CONTROLLER

A sampling frequency of 1000 Hz has been chosen as it provides satisfactory haptic performance, is a standard value in haptics and allows for long enough control cycles to implement sophisticated real time controllers. The lag between a torque command to the RJo and the effect on it, i.e. intrinsic time delay, is 1ms. Given these conditions and together with the encoder resolution, a maximum stable stiffness of $K_0 = 1.57 Nm/rad$ can be reached.

In KONTUR-2, two scenarios had to be considered in the design of the bilateral controller: The operation on board the ISS and the cosmonaut training. The first is the nominal mission case, where the cosmonaut controls the robot from the ISS through a S-band link. The second, is a geographically distributed scenario for cosmonaut training purposes (see Fig. 3). Since the exactly same system needs to operate in both experiments, the requirements for the bilateral controller are clearly strengthened as the two links are characterized by different communication parameters.

The cosmonaut training took place at GCTC, located in Moscow. During the training, the cosmonaut practiced with a RJo qualification model (QM) with identical characteristics as the ISS flight model (FM), and controlled the robot located at DLR, in Germany, through the internet. The nature of the two communication links is quite different in terms of time delay, data losses and jitter. The time delay T 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 and highly oscillating package loss ratio, from 5 to 15% (due to UDP protocol).

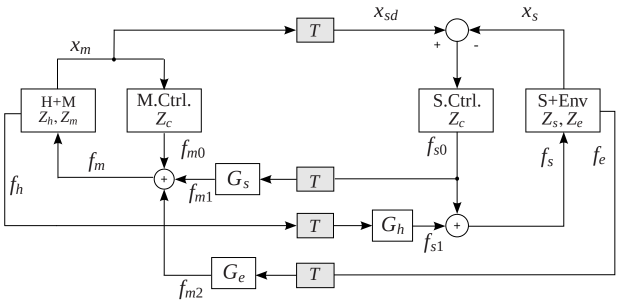

Figure 7. Block diagram of the 4-Channels architecture

The approach for the bilateral controller is based on a 4-Channels architecture (see Fig. 7) whose stability in the presence of time delay, jitter and data losses is addressed through the Time Domain Passivity Control Approach (TDPA) [12], [13]. In this architecture, position and force signals are sent from RJo to the ROKVISS robot, and computed and measured force signals are sent in the other direction. Both systems, RJo and ROKVISS, are impedance controlled, i.e. the commanded signals, f_m and f_s respectively, are forces, and their outputs, x_m and x_s are positions:

$$\begin{aligned} f_s(t) &= G_h f_h(t-T) + K_{ds}(v_m(t-T) - v_s(t)) \\ &\quad + K_{ps}(x_m(t-T) - x_s(t)), \\ f_m(t) &= G_s f_{s0}(t-T) + G_e f_e(t-T) + K_{dm} v_m(t), \end{aligned} \tag{1}$$

where f_h, f_{s0}, f_e are human measured force, computed and measured forces at the ROKVISS side respectively; v_m, v_s are RJo and ROKVISS velocities signals respectively. Furthermore, the controller at the ROKVISS side is a Proportional-Integral with constants K_{ps} and K_{ds} and the RJo has a local damper with value K_{dm}. G_h, G_s and G_e are scaling factors to match both system dynamics.

The 4-Channels architecture is in general higher in complexity than e.g. the more conventional position-force design. The choice is justified in that this architecture can achieve higher performance degrees [14]. One of the main difficulties in designing a control structure based on this architecture is the treatment of time delay and other communication related factors. In KONTUR-2, stability of the 4-Channels is addressed through TDPA and the Time Delay Power Network (TDPN) [12] concept. Thus, stability is guaranteed also in the presence of delay, jitter and package losses. See [15] for details on the implemented bilateral control scheme.

3.6 ERGONOMICS

3.6.1 Joystick Handle

Besides the technical development, ergonomic aspects were also considered when designing the RJo handle. On the one hand, haptic input devices should provide realistic forces and on the other hand the human operator should be able to control these forces safely. Since the RJo generates maximum forces of 15 N and allows a movement range of +/- 20 deg for both axes, the RJo handle was optimized for hand control (in contrast to finger control; [16]). The handle was fitted to the right human hand, since the cosmonauts participating in the KONTUR-2 project are right-handers. The shape of the handle was designed for an optimal form-fit, i.e. the operator does not have to apply high grip forces to stabilize the hand and the forces are transmitted without friction. The operator holds the RJo with a clasping grip and presses the deadman button with the index finger during teleoperation. The handle is inclined by 15 degrees forwards along the longitudinal axis of the RJo, because wrist rotations towards the operator (radial abduction) are more restricted (max. radial abduction: 15 deg; max. ulnar abduction: 30 deg; see [17]). Altogether, the design guarantees a safe and comfortable joystick control and the grip position is standardized for all operators, allowing for a higher comparability of force feedback perception and experimental performance.

3.6.2 Arm Stabilization

In the KONTUR-2 experiments, rapid and precise control movements have to be performed requiring optimal hand/arm stabilization, particularly under the condition of microgravity. Since a position control approach was chosen, the complete RJo workspace (+/- 20 *deg* in each axis) was used, leading to relatively high movement amplitudes. Hence, when designing the armrest for the RJo, the stabilization as well as the reachability requirements were taken into account. Moreover, the armrest has to be comfortable for different operators with individual forearm lengths. A series of usability studies has shown that a plane, padded armrest with an additional stabilization belt meets the requirements best. The padded armrest (20 *cm* x 14 *cm*, see Fig. 1) allows for a sufficient degree of positioning variability for a large anthropometric range (forearm lengths measured from a joystick axis to the elbow: 30 *cm* for the 5th percentile woman and 39 *cm* for the 95th percentile man; see [18]). In the absence of gravity, the hand/arm system has to be stabilized against unintended body movements of the free floating cosmonaut. Thus, a padded stabilization belt can be attached at four individual positions of the armrest, still allowing sufficient arm movability, but also securing against drifting away from the armrest. The usability of the armrest concept was successfully validated in underwater experiments simulating the effects of weightlessness.

Figure 8. Cosmonaut O. Kononenko on board the ISS, Source: ROSKOSMOS

4 EXPERIMENTAL TASKS

In general, there were two types of tasks: 1) Free movement tasks, without contacts between the robot and the task board and 2) contact tasks with different haptic task objectives. During the free movement tasks (like aiming and pursuit tracking, Fig. 9) we investigated the positional accuracy when controlling the telerobotic system from the ISS. Additionally, the accuracy of force regulation was explored during the contact tasks.

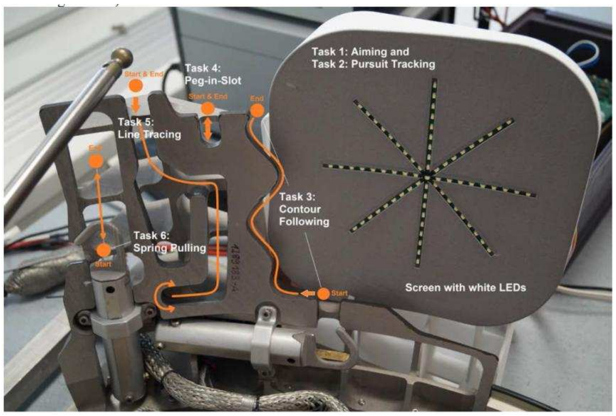

Figure 9. Experimental Task Board

5 RESULTS AND CONCLUSIONS

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 was designed according to a set of performance requirements and space related specifications needed for inflight operation in the ISS. Its materials, thermal design, motors and electronics have been developed to fulfill the required space qualification. 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 (Fig. 8) 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 [15]. 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 better understand the effects of microgravity on sensorimotor performance when controlling a telerobotic system. Preliminary analyses revealed that positional accuracy is degraded in microgravity compared to terrestrial conditions [19]. Yet, these performance losses can partially be compensated by implementing a movement damping at the joystick, allowing a high telemanipulation performance despite microgravity. The KONTUR-2 mission aims at achieving the next milestone in planetary exploration missions, that is, to allow astronauts in orbital stations to work with robots on planet surfaces.

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