ROKVISS
Verification of Advanced Light Weight Robotic Joints and Tele-Presence Concepts for Future Space Missions

K. Landzettel, A. Albu-Schäffer, B. Brunner, A. Beyer, R. Gruber, E. Krämer, C. Preusche, D. Reintsema,
J. Schott, B.-M. Steinmetz, H.-J. Sedlmayr, G. Hirzinger

DLR Oberpfaffenhofen
Insitute of Robotics and Mechatronics
D-82234 Wessling
Email: Klaus.Landzettel@dlr.de

ABSTRACT

ROKVISS, Germany’s new space robotics technology experiment, was successfully installed outside at the Russian Service Module of the International Space Station (ISS) at the end of January 2005, Fig. 1 (Courtesy NASA). Since February 2005 the two joint ROKVISS manipulator can be operated from ground via a direct radio link. The aim of ROKVISS is the in flight verification of highly integrated modular light weight robotic joints as well as the demonstration of different control modes, reaching from high system autonomy to force feedback tele-operation (tele-presence mode). Meanwhile the experiment was operated for more than one year in free space, delivering lots of interesting data concerning the joints reliability and the tele-presence mode performance. ROKVISS is a further step forward to provide space robotics hardware and powerful control concepts for on orbit servicing and for planetary exploration as required in upcoming manned and unmanned space missions.

This paper describes the modifications which were necessary to prepare DLR’s light weight robotic joints for free space operation, the performance of the joints over a longer period of time, the results and experiences gained from tele-presence mode experiments, as well as some operational aspects concerning the S-band communication system.

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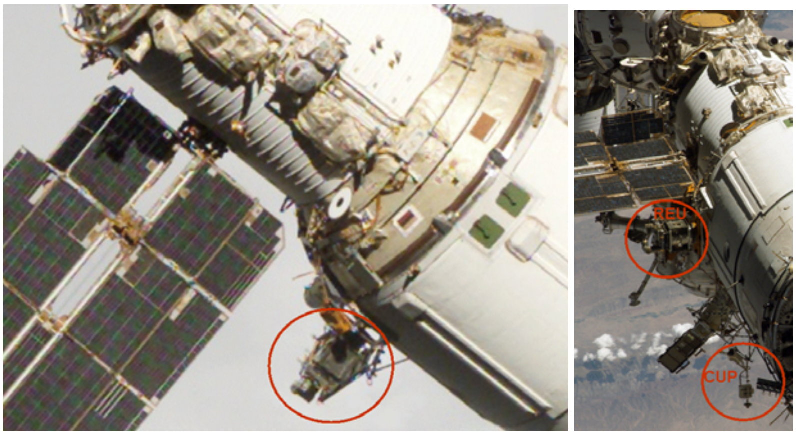


Fig. 1 ROKVISS REU and CUP with antenna

EXPERIMENT GOALS

The main goals of ROKVISS are:

- the verification of DLR’s modular light-weight, torque-controlled robotic joints in free space, under realistic mission conditions, and the identification of their dynamic and friction behavior over time; The joints are based on DLR’s new high energy motor ROBODRIVE and they are identical to those used in DLR’s seven joint light weight robot, which is the basis for future “robonauts”.
- the verification of force-reflecting telemanipulation to verify the applicability of telepresence methods for future satellite servicing tasks. For many space repair and maintenance situations the high-fidelity inclusion of the human operator into the control loop is inevitable.

EXPERIMENT SETUP

ROKVISS comprises a ground section and an internal and external space section. The external section REU (ROKVISS External Unit, Fig. 2) consists of a two joint robot, a stereo camera system, an earth observation camera, the power distribution unit and an experiment contour including spring elements for joint friction evaluation. These elements are mounted to the external surface of the Russian ISS module Svezda, while the ROKVISS onboard computer (OBC, Fig. 3) is installed inside the module but connected to the REU by external supply lines and data links (Fig. 6).

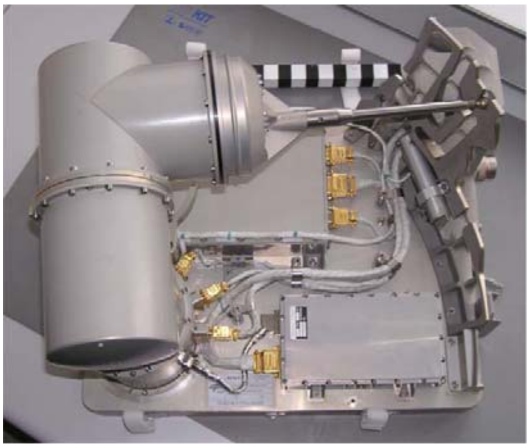


Fig. 2 External unit REU

Fig. 3 Onboard Computer OBC

The robot receives its motion commands from the ground station in real-time via an S-band communications link. During direct radio contact phases, when the ISS passes over the tracking station in Germany (German Space Operation Center, GSOC), the telepresence mode can be activated for up to seven minutes for a high-fidelity force feedback closed loop control. Thus, one major requirement for this mode is to keep the total data round-trip-time significantly below 500 milliseconds.

In automatic mode, the system goes through selected, predefined motion sequences. The measured joint data will be stored on-board and transmitted to ground during one of the next possible radio contact phases.

The experiment contour of ROKVISS contains different shapes, different surface treatments, as well as spring elements which are used for tele-presence experiments and friction parameter identification.

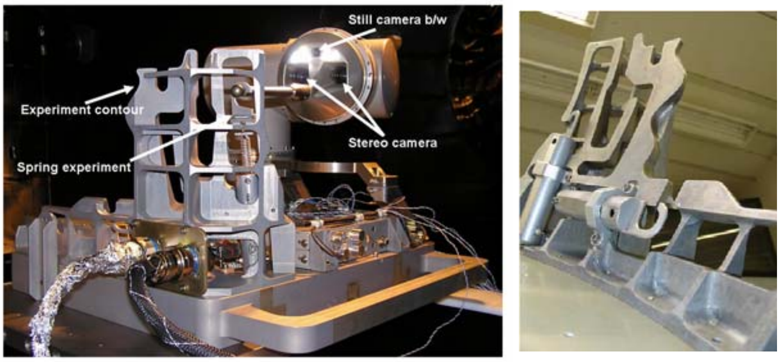


Fig. 4 ROKVISS elements and contour

COMMUNICATION SYSTEM

In order to keep the round-trip communication time as low as possible, ROKVISS has its own S-band communication system, including an own antenna (Communication Unit for Payloads CUP). 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.

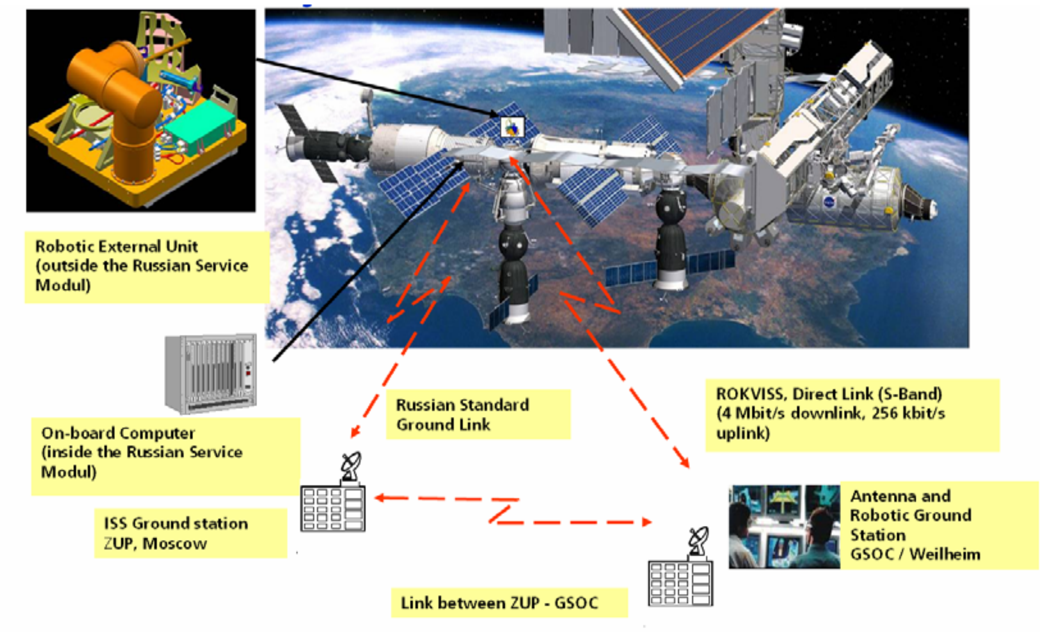


Fig. 5 System overview of ROKVISS

The ROKVISS ground control computers are directly connected to the transceiver system of DLR's tracking station in Weilheim. Measured round trip times of less than 20 ms are a very good basis for the evaluation of the telepresence system behavior. Depending on the performed operation the downlink data rate sums up approximately by 128 kbps for robot control data and 3,5 Mbps for digital video data, remaining resources are filled by supervisor, miscellaneous data (e.g. housekeeping data or logging messages) and at least the CCSDS protocol overhead.

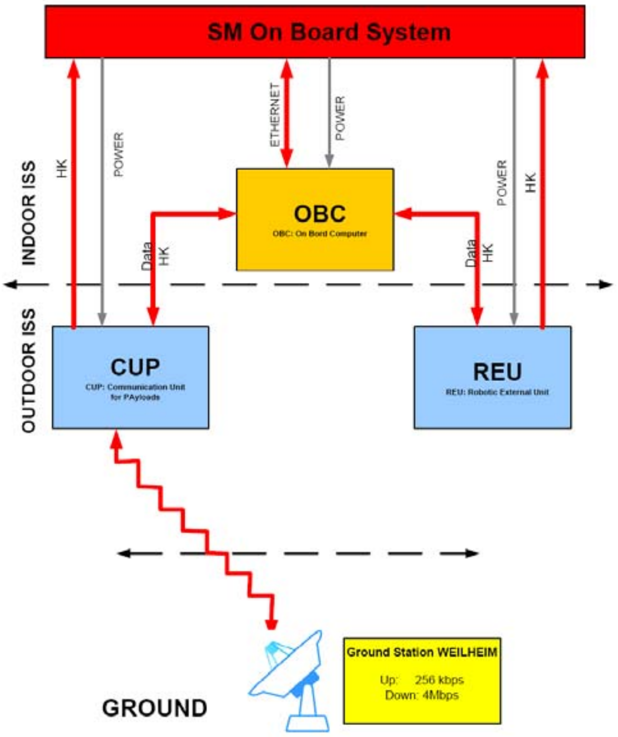


Fig. 6 ROKVISS Dataflow

Fig. 6 shows, amongst others, the dataflow between the on-board computer of ROKVISS and the so called payload computer (PLS) inside the Russian service module Svezda. The power on and off sequences for ROKVISS are triggered by the mission timeline which is executed on the PLS. After power on, the ROKVISS OBC will boot and commence the operation according to a previously loaded command file. During normal operation the OBC sends house keeping data, collected from the ROKVISS subsystems, to the PLS each second. If the PLS does not receive house keeping data for more than five seconds, the ROKVISS power will be switched off.

The protocol stack of ROKVISS (Fig. 7) is designed to meet the telepresence experiment requirements on the communication link in order to achieve high-fidelity force feedback control. In general, a single telepresence control packet should be sent within one transfer frame to avoid time consuming data collection, recovery and retransmission. Due to requirements of closed loop control an unreliable data connection is typically used to minimize the time delay. Data losses are compensated by suitable interpolation schemes.
Due to guidelines for space missions and the limited uplink data rate the transfer frame of ROKVISS is based on a lean CCSDS compliant protocol to cover the TM/TC data stream between the flight unit of ROKVISS on the ISS and the ground control station. Error detection and correction mechanism as Reed-Solomon or Viterbi as well as

interleaving techniques are not supported to reduce protocol overhead. Only a cyclic redundancy check (CRC) on transfer frame level provides basic error detection.

The lean CCSDS compliant TM/TC protocol minimizes the protocol overhead due to requirements of the closed loop force feedback control results in an unreliable connection on transfer frame level which meets originally the needs of telepresence applications. A priority-based TM/TC DEMUX is responsible to (de-)multiplex different logical data channels into a transfer frame:

- The teleoperation application channel provides general access to the ROKVISS flight unit. Flight unit monitoring and control, mission configuration, as well as data up-/download (FTP) error detection and correction are provided by the higher layer standard protocol TCP/IP. Serial line protocols (CSLIP, SLIP) are used to encapsulate IP packets to minimize the protocol overhead for IP-based services.
- The telepresence application channel is a bidirectional data connection. A dedicated telepresence control protocol is used to provide a high-performance access to the ROKVISS manipulator for high-fidelity closed loop control. The telepresence control protocol encapsulates the force feedback control packets. The telepresence control protocol is a dedicated protocol which combines TCP and UDP like properties within one implementation. State changes are handled by a TCP like handshake protocol while real-time control data are transferred via UDP data-grams.
- The video data channel is a unidirectional connection. Stereo video images captured by the camera system of the flight unit are fit into the transfer frame directly without any additional protocol overhead. Commands for the video system are transferred over the IP-based teleoperation channel.

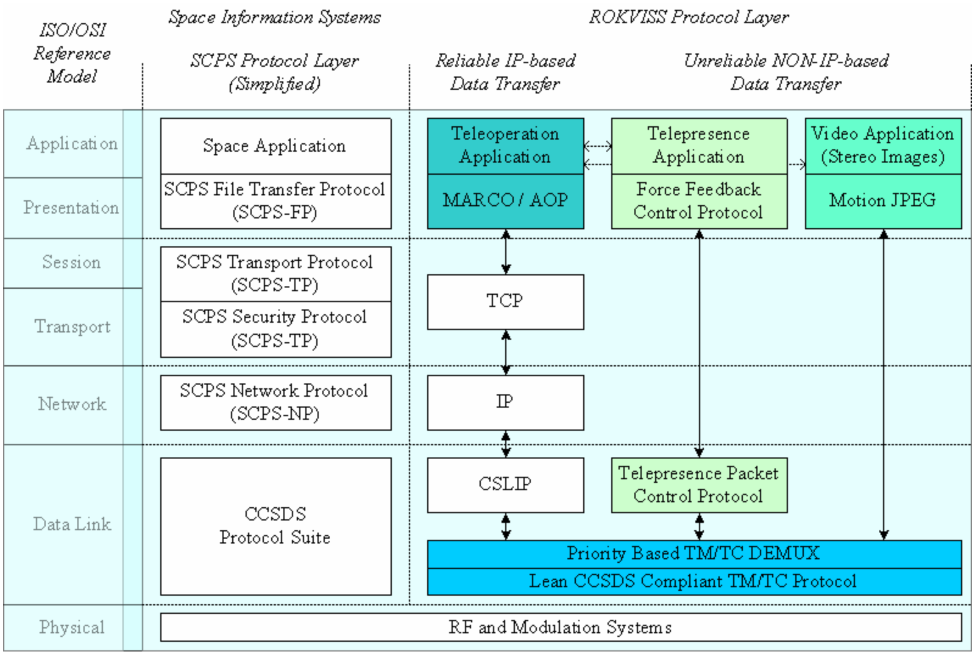


Fig. 7 The protocol stack of ROKVISS compared to the SCPS protocol suite

QUALIFICATION APPROACH

As mentioned above, the ROKVISS joint development is based on DLR’s light weight intelligent joints. One basic idea for the ROKVISS project was to get rid of bulky and expensive radhard components for a space born application in favor of highly integrated circuits used with terrestrial devices. To come to a first assessment of the applicability of the joint mechatronics for free space, we performed a radiation, an EMC and a thermal test with one of the existing joints, Fig. 8. The results of all these tests were very convincingly, no problem in principle could be identified.

Despite these encouraging test results, it was clear that some kind of redesign had to be done:

- Exchange cross roller bearing against two angular roller bearings
- Exchange all electrolytic capacitors against tantalum types
- The gear output position sensor from the Netzer company was not available, therefore a potentiometer based position measurement system was developed

- All heat producing electronic parts need to be thermally coupled to the robot’s structure to allow for heat dissipation
- The optical SERCOS bus ring topology was modified into a point to point connection via copper wires. Each joint is coupled via SERCOS with the main computer (OBC). The advantage of the point to point structure is that even if one joint electronic fails the remaining joint is still operable.
- A latch-up protected power supply circuit had to be implemented
- Electronic parts with extended temperature range (-45 C to +85 C) are used.
- The holding brake is not part of the ROKVISS joint (to avoid cold welding problems!)

All these modifications led to the joint design as shown in Fig. 9.

The drawback for using components off the shelf is the probability of latch-ups, which may destroy a CMOS circuit when hit by a heavy ion or proton. Based on the fact, that neither a hot nor a cold redundant configuration for the joint electronics was intended, a latch-up protected power supply circuit had to be implemented. The task of the latch up protection circuit is to prevent burn out of the device hit and hence to protect it. It is self-evident that the power supply itself must be latch up immune and able to handle latch up situations. Therefore it must be built with radiation tolerant parts (with the temp. range: -55 C to + 125 C) in order to guarantee the correct functionality during the whole mission.
To prevent burn out of the device being hit it is surely not sufficient to switch off the power, because the charge stored in the smoothing capacitors will permanently damage the device. So additionally to switching off the supply one must short the output by use of a so called crow bar circuit.

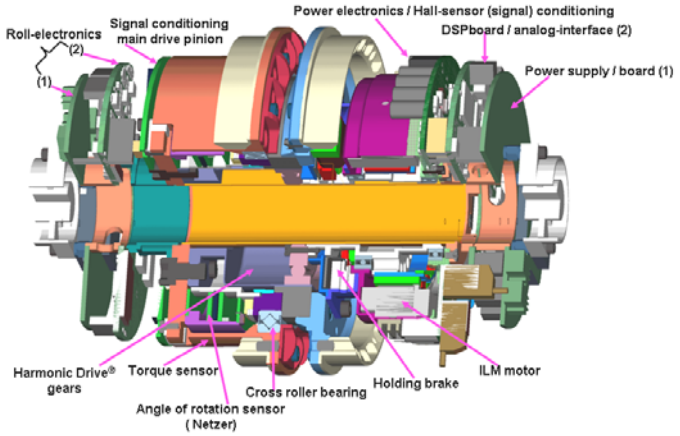


Fig. 8 DLR’s light weight intelligent joint

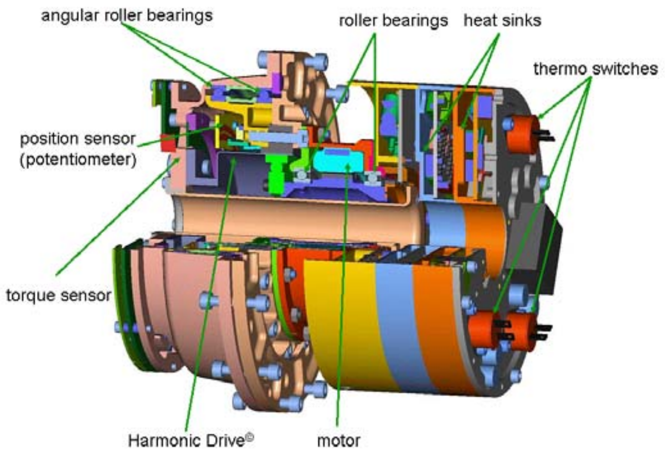


Fig. 9 ROKVISS joint unit

Our latch-up protection circuit is based on a linear voltage controller, featuring besides the voltage control loop also a current control loop (Fig. 10). Moreover the latter is level adjustable to take care of increased supply currents due to derating along the mission.
A latch up in the protected circuit causes the current controller to pull down the output voltage. Reaching the voltage trippoint activates the fault signal triggering the latch up protection sequence. The fault signal is used to serve two tasks: The voltage/current controller is switched off by shorting the compensation/shut down input. In parallel the output is shorted by the so called crow bar to discharge all smoothing capacitors rapidly. When using several latch-up protection equipped power supplies, switching off and on again must be done for all supplies with a central control circuit.
During power up the latch up protection is suppressed. Meanwhile, within approx. two years of operation we noticed one latchup in joint electronic II without any influence on the electronic components.

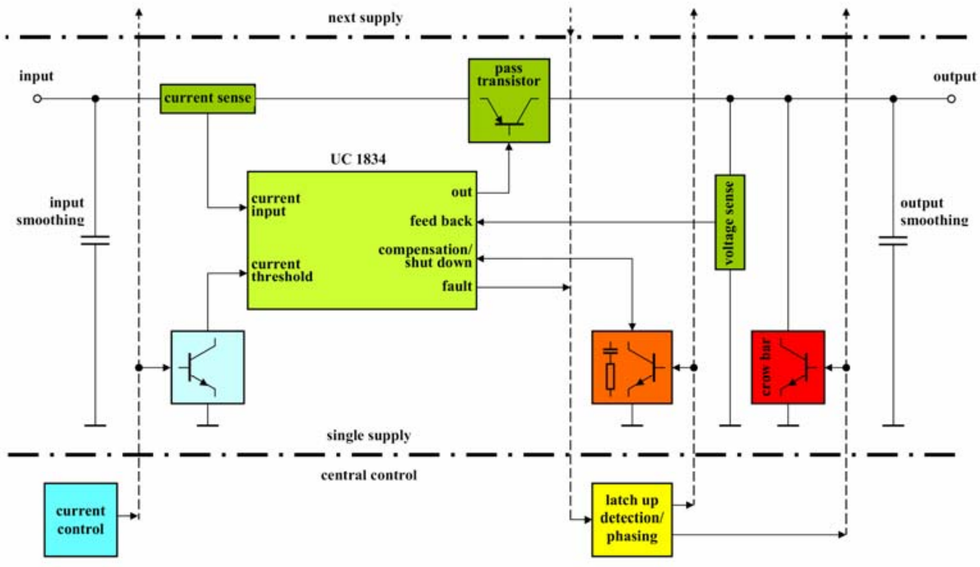
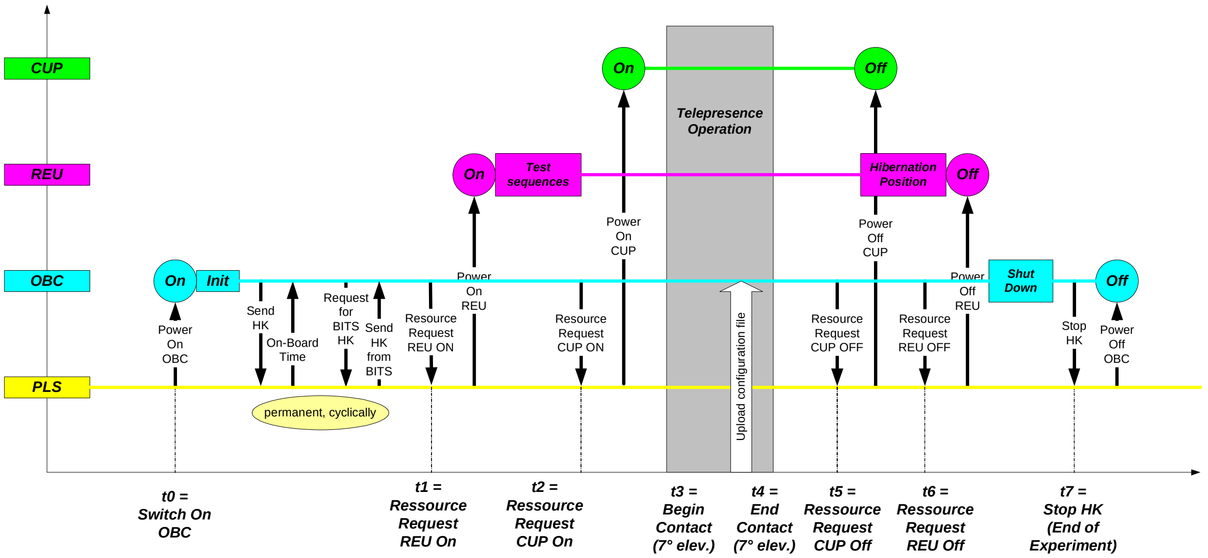


Fig. 10 Latch-up protection circuit (patent pending)

OPERATION

As mentioned above, ROKVISS operation is handled via the mission timeline on the Russian payload server. Therefore we have to submit our planning data to the Russian flight control center in Moscow beforehand. A typical planning diagram is shown in Fig. 11. The respective values for t3 (acquisition of signal, AOS) and t4 (loss of signal, LOS) are excerpted from the ISS orbit data prediction. These time values are the basis for the ROKVISS subsystem activation and de-activation planning.



Date: 12.08.2005 (224)
Orbit: 2449 (4), Station WHM
Purpose: Tele-presence operation.
Experiment duration: 00:09:12

t0	t1	t2	t3	t4	t5	t6	t7
04:02:58	04:06:58	04:09:58	04:13:08	04:22:20	04:25:20	04:29:20	04:33:30

Fig. 11 ROKVISS operation planning diagram

Since January 2005, when ROKVISS was installed on the outer surface of the ISS, we performed more than 160 experiments in different operational modes, as shown in Fig. 12.

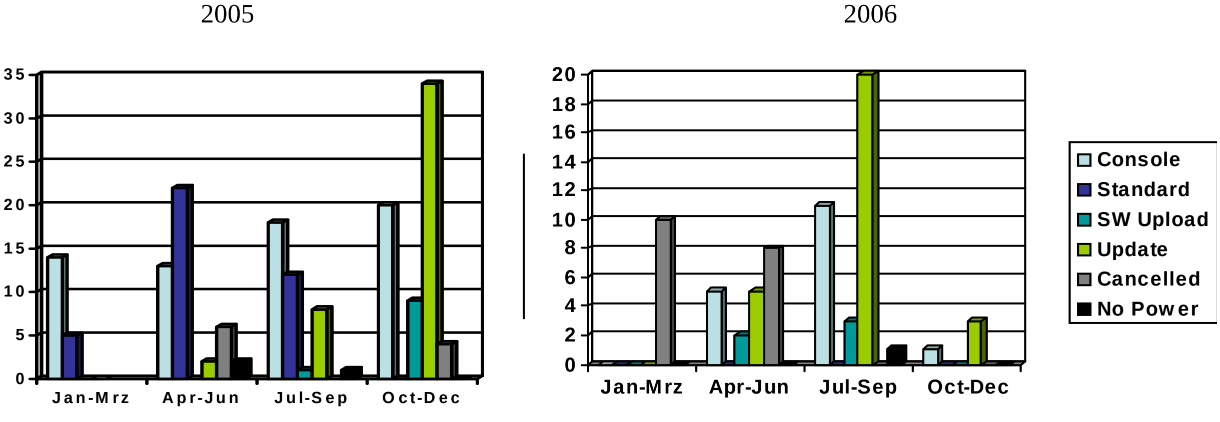


Fig. 12 ROKVISS experiments in 2005 and 2006

At the beginning of the mission we struggled with some operational problems such as:

- Imprecise ground antenna (15m dish) pointing position, due to problems with the conversion of the state vector prediction from our Russian colleagues into 2-line elements, as required for the antenna. This is important when the ISS changed its orbit height shortly before the next ROKVISS experiment takes place.
- The required power for the joint motors (Fig. 13) was not available due to a typo in the interface control document (3 Amps instead of 5 Amps for the REU).
- Many data transfer errors occur when the elevation angle of the antenna is below ~4 degree due to signal phase shifts. This is leading to communication problems via the network stacks. At the time being we overcome this problem by operational measures (transmit un-modulated carrier below 4 degree elevation on the uplink channel).

RESULTS

The on-orbit identification shows that the total friction for joint 1 in space increased by a factor of about 50% compared to the friction on ground, taken at 20°C, under normal atmospheric pressure. However, only a small further continuous change of the parameters can be observed so far (Fig. 14). This suggests the conclusion that the lubricant changed its properties when exposed to outer space conditions at the beginning of the mission and afterwards reached an operating state with slow parameter variation.

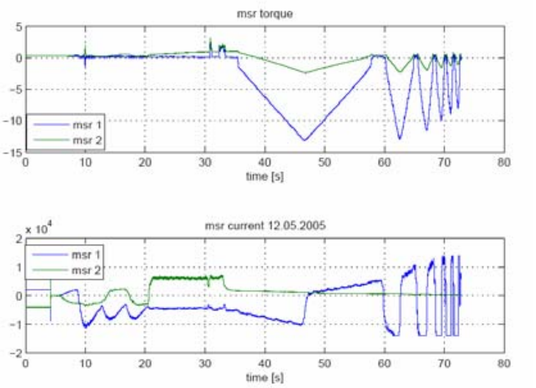


Fig. 13 Torque and current measurements during spring experiment. (Current limited to ~1.5 A)

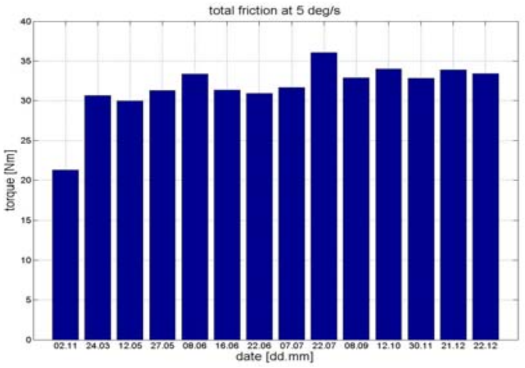


Fig. 14 Time evolution of total friction at a speed of 5deg/s. The first bar corresponds to the reference measurement on ground

Detailed information about the joint parameter identification results are given in [1] and [2].

After an operational gap of more than 3 month we recognized a strange behavior on the measured gear position values of the potentiometer system. Due to measurement errors the joint's motion was stopped by the joint's internal surveillance system because the difference between motor- and gear position violated its limit. The analysis of the potentiometer values revealed the source of this problem, the surface of the potentiometer was contaminated or the potentiometer slider was defective. We performed a few motions over the defective angle range of the joint and noticed a rapid decrease of the measurement noise. This result assured the assumption that the surface of the potentiometer is contaminated by some off-gassed material (lubrication, glue etc.).

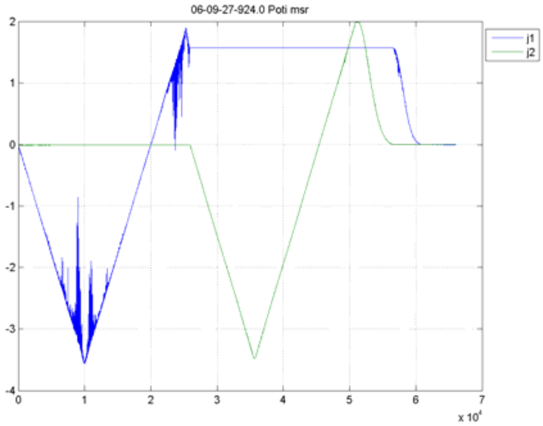


Fig. 15 Gear position, first measurement

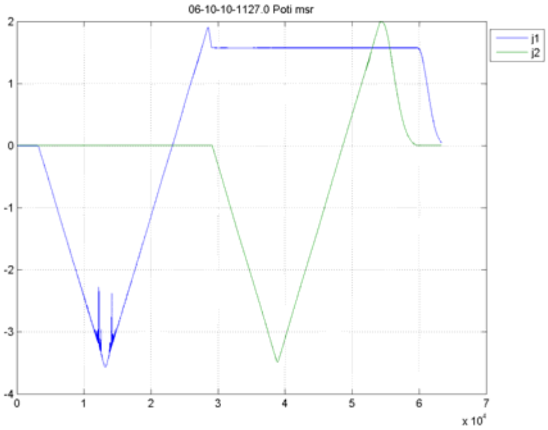


Fig. 16 Gear position, second measurement

Tele-presence operations with force feedback require low round trip delay and low jitter. Both requirements could be satisfied and the excellent performance of tele-presence (Fig. 18) successfully demonstrated in a realistic space mission. The measured round trip delay lies between approx. 12 and 20 ms, depending on the orbit (Fig. 17). The variation of the delay corresponds to the distance between ground station and ISS. During the next planned experiments we will artificially increase the round trip time delay in order to simulate tele-presence operations in GEO (~250 ms), or on a spacecraft in LEO via a relay satellite in GEO (~500 ms). Detailed results concerning the tele-presence operation are given in [3].

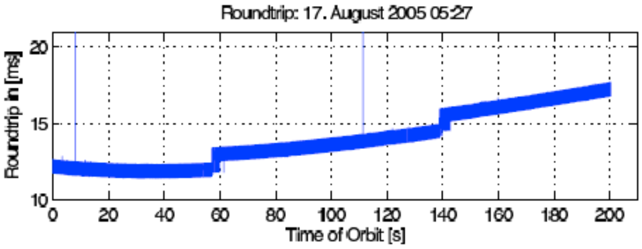


Fig. 17 Signal round trip delay

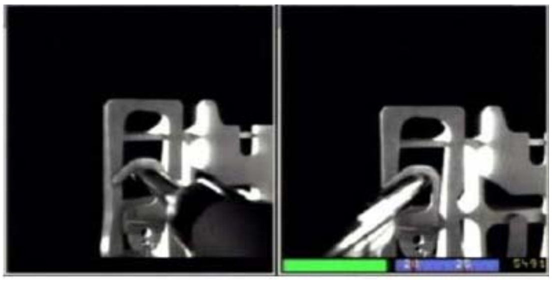


Fig. 18 Spring experiment

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[2]	A. Albu-Schaeffer et al, „ROKVISS – Robotics Component Verification on ISS, Current Experimental Results on Parameter Identification", Orlando, Florida, May 15 to May 19, 2006

[3]	A. Albu-Schaeffer et al, „ROKVISS – Robotics Component Verification on ISS, Preliminary Results for Telepresence", Beijing, China, October 9 to 15, 2006