ROKVISS – ROBOTICS COMPONENT VERIFICATION ON ISS

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ABSTRACT

ROKVISS, Germans new 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 can be 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 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.

GENERAL EXPERIMENT DESCRIPTION

After ROTEX (the first remotely controlled space robot on board of the shuttle COLUMBIA), ROKVISS is the second space robot experiment proposed and realised by DLR's Institute of Robotics and Mechatronics (DLR-RM) in cooperation with the German space companies EADS-ST, Kayser-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 (Fig. 2). Since February 2005 ROKVISS is operated by DLR-RM, close supported by ZUP, the ISS ground station in Moscow.

The ROKVISS experiment consists of a small robot with two torque-controlled joints (Fig. 3), mounted on an Universal Workplate (UWP), a 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 (Fig. 1). 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 German Space Operations Center (GSOC).

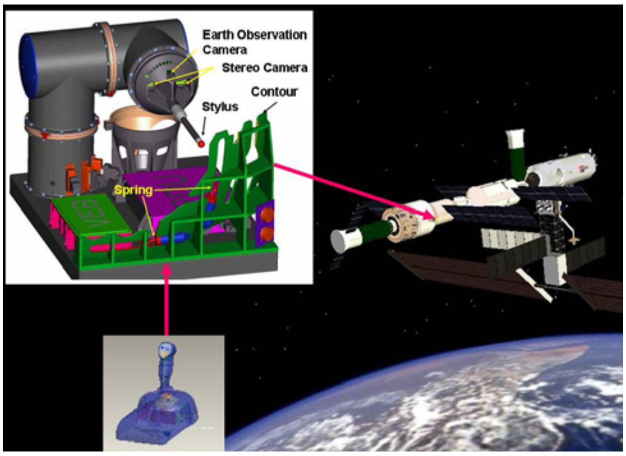

Fig. 1 ROKVISS manipulator with the contour following environment

Fig. 2 At the end of a 5 hours space walk the astronauts succeeded in mounting ROKVISS and connecting the necessary cables

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

- the **verification of DLR's modular light-weight, torque-controlled robotic joints** in outer space, under realistic mission conditions, and the identification of their dynamic and friction behaviour 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 for us is the basis for future "robonauts" (Fig. 3 and Fig. 27).

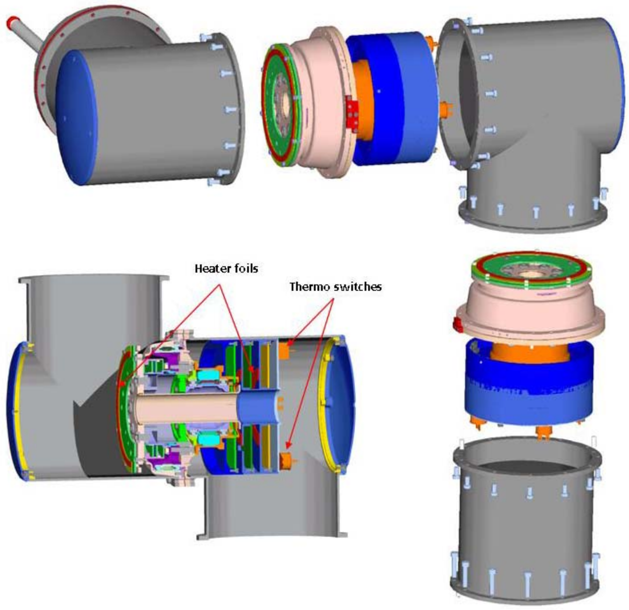

Fig. 3 The two-joint ROKVISS manipulator

- the verification of force-reflecting telemanipulation to show the **feasibility of telepresence methods** [3] [4] for future satellite servicing tasks, as we are convinced that the inclusion of the human ground operator into the control loop is a must in many situations (Fig. 4).

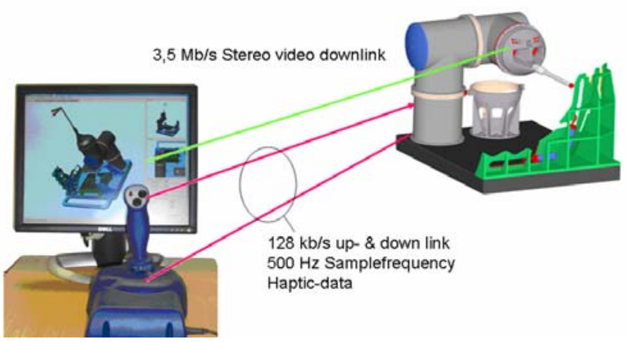

Fig. 4 Telepresence based upon DLR`s high-fidelity force reflecting joystick and stereo visual feedback

THE DLR LIGHT WEIGHT JOINTS CONCEPT

The joint drive requirements in robotics are different from many other applications:

- high torques, not high speed but high dynamics (accelerations),
- a permanent reverse motion around the zero position.

Space robotics (similar to mobile terrestrial robotics) adds additional requirements as low weight, and low power losses.

Thus, an optimised electric motor with respect to the above criteria was developed, using the latest results in concurrent engineering (Fig. 6). It soon became clear that a single-pole coiling concept with an adapted number of pole pairs might be an optimal baseline, and that by "orthocyclicly" winding the single stator poles the available coiling space would be optimally exploited, in addition the loss-inducing iron flow paths would be as short as possible (Fig. 7).

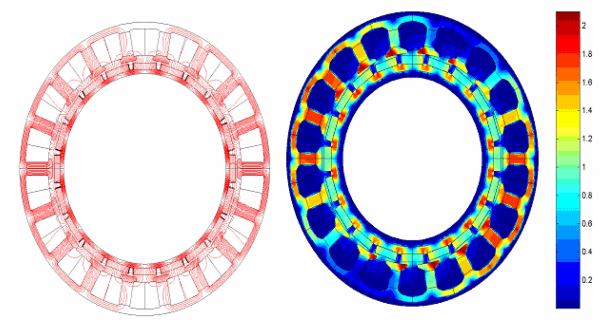

Fig. 5 Simulated magnetic flow in the new ROBODRIVE motor

All (multi-) physical effects and their interactions had to be modelled and simulated "in parallel" (Fig. 5). Finite element technologies were used to model diverse parameter influences on motor performance, such as iron thickness.

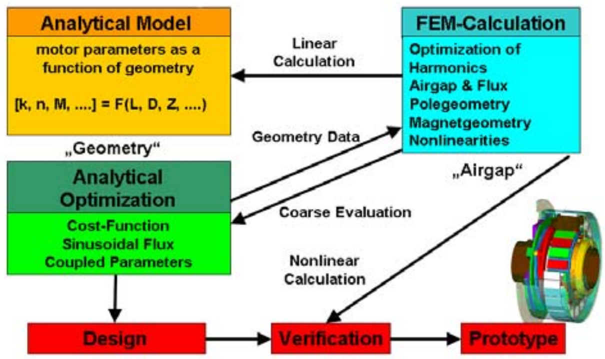

Fig. 6 The Concurrent engineering process

All these dependencies were modelled analytically and verified by hand of prototype realisations. The result was a motor design yielding all relevant characteristics like copper cross section, iron geometry, and a number of coil windings, but in particular a hardly believable 50% reduction in weight and power loss compared to the best commercially available motors we had used so far (Fig. 8).

Fig. 7 Two sizes of ROBODRIVE (ILM 85 with 1.4 Nm torque and ILM 50 with 0.3 Nm torque)

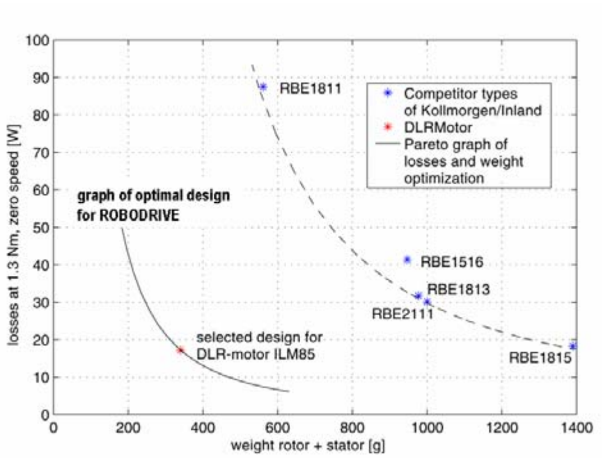

Fig. 8 Comparing ROBODRIVE with the best commercially available motors

Another central component of the DLR light-weight joints is the torque sensor which is based on a strain-gauge technology (Fig. 9).

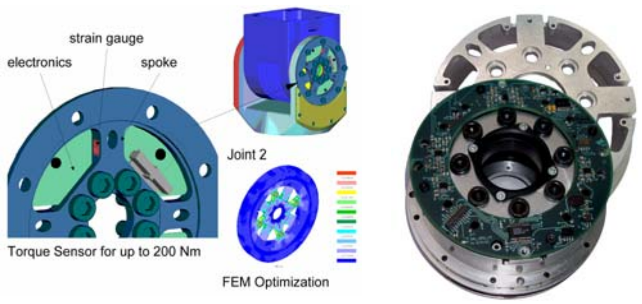

Fig. 9 FEM calculation and real torque sensor

QUALIFICATION CONCEPTS

One basic idea for the ROKVISS project was to get rid of bulky and most expensive radhard components for a space born application in favor of highly integrated circuits used with terrestrial devices. The drawback for using such components is the probability of so called latch-ups due to a CMOS circuit being hit by a heavy ion or proton.

LATCH-UP PROTECTION POWER SUPPLY UNIT

The occurrence of a latch up is characterized by a rapid increase of current in a very short time (a few µsec). As a matter of fact it is set off by the triggering of an SCR to substrate due to a heavy ion, proton impact.

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 a 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 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.

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.

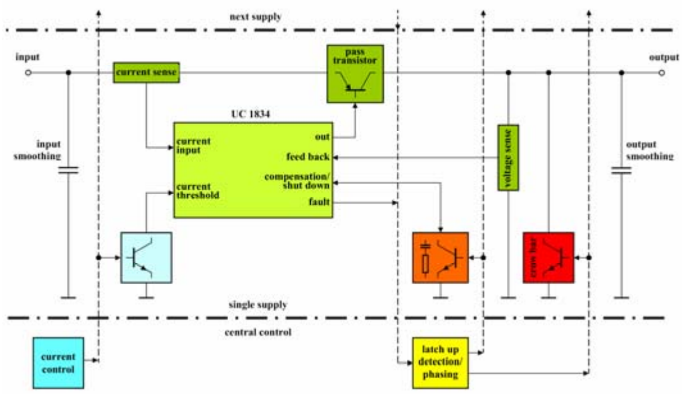

Fig. 10 The new latch-up protection circuit

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.

OVERALL COMMUNICATION

In order to keep the round-trip communication time as low as possible, ROKVISS has its own S-band communication system, including on own 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. The ROKVISS experiments, the data download as well as software uploads are performed via this S-band system.

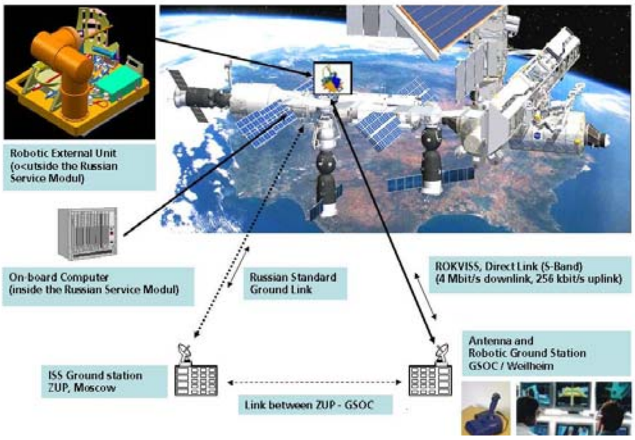

Fig. 11 System overview of ROKVISS

During all ROKVISS operations, even when the system is not in direct contact to the ground station in Weilheim, the housekeeping-data (HK-data) are transferred to the payload server and stored on the server's hard disk. These HK-data are dumped to the Russian ground station and then transferred to the ROKVISS control center via e-mail. The ROKVISS ground control computers are directly coupled to the transceiver system of DLR's tracking station in Weilheim (Fig. 11). The measured round trip times of less than 20 ms are a very good basis to evaluate the telepresence system behaviour

THE COMMUNICATION ARCHITECTURE

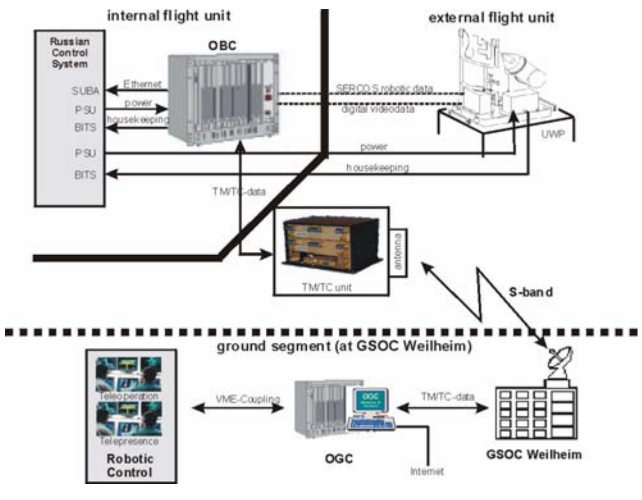

Fig. 12 The communication chain of ROKVISS

A survey of the communication chain within ROKVISS is given in Fig. 12. It shows the data flow between the internal and the external flight unit and the ground segment installed at the GSOC in Weilheim, Germany. As figured out, a combination of a high-speed serial bus RS-485 (SERCOS) and a RS-422 interface connect the ROKVISS manipulator with the internal flight unit (OBC). While real-time robotic control data are exchanged over SERCOS, digital video data uses the RS-422 interface. Additional external connections are the power supply wires for the electronics and the motor.

During operational time ROKVISS provides a set of telemetry parameters for housekeeping and status monitoring to the Russian data management system. An Ethernet interface connects the ROKVISS OBC to the Russian control system. Of major interest for ROKVISS is the payload server (PLS) of the Russian control system. The PLS is responsible for housekeeping and status monitoring. The ROKVISS experiment hardware is switched on or off by the PLS due to a negotiated and prepared timeline. As long as the ROKVISS OBC sends a heartbeat packet each 5 seconds the PLS recognize ROKVISS as nominal. Otherwise the PLS will switch off the ROKVISS experiment hardware assuming a off-nominal situation.

The OBC interfaces the external TM/TC unit. Application data as processed by the OBC is modulated and transferred to the antenna via the TM/TC unit. The antenna is composed to use a S-Band channel for data transmission. A Cortex Data EGSE at the GSOC in Weilheim is used to establish a direct radio link between the ROKVISS flight unit and the on-ground segment. The OGC interfaces the several control stations of the on-ground data handling system. Deviant of other space experiments the ROKVISS communication protocol is served by OBC and OGC. Both are responsible for modulation and demodulation of TM/TC-data which are transferred over the S-Band channel. Additional, the OBC and OGC distribute and collect the application data which are to be transferred.

THE S-BAND COMMUNICATION PROTOCOL

In order to provide real-time data transmission and to keep the round-trip communication time as low as possible, ROKVISS has access to CUP, a dedicated S-Band communication system with an own antenna, pointing to the earth. 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. For this purpose a direct communication radio link between the ground segment and the ROKVISS flight unit must be 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. Thus, for high performance real-time data transmission the transfer frame length is fixed for both directions and can not be dynamically configured during operation as mentioned within the CCSDS standards. In case of ROKVISS the Transfer Frame lengths are set to 450 octets (TM) and 30 octets (TC) to guarantee a maximum jitter of approximately 1 ms.

Of major interest is the usage of a lean protocol which decreases the protocol overhead. 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. Since interleaving is effective only in case of some error detection and correction mechanism, interleaving is not supported within the transfer protocol. 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). 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.

The downlink provides a data rate of 4 Mbps for telemetry data like housekeeping data or video images. 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 fulfilled by supervisor, miscellaneous data (e.g. housekeeping data or logging messages) and at least the CCSDS protocol overhead.

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 1 ms. This is achieved upon a (netto) data rate of maximal 128 kbps in both, up- and downlink.

In summary an overall data rate of 256 kbps is available for telecommands (uplink). But due to the CCSDS protocol overhead approximately only 128 kbps of the uplink are usable for robot control, supervisory and miscellaneous data.

The CCSDS standards provide two different mechanisms for data multiplexing: virtual channels and source application processes. A multiplexing by means of virtual channels is not suitable for ROKVISS, since a Transfer Frame must contain data of one virtual channel only. In order to meet the 500 Hz up-/downlink rate of real-time robot control data very small Transfer Frames are required resulting into a considerable protocol overhead. Thus, the data multiplexing is realized by means of source application processes. Therefore, the ROKVISS experiment distinguishes between small robot data (real-time data of high priority), long video data (low priority) and variable sized TCP/IP data like supervisor or housekeeping information of middle priority. In order to avoid the capture of the TM/TC channels by long and low priority application data (e.g. video data) at the expensive of the shorter and higher priority ones (e.g. robot data) a priority based data multiplexing is required and performed. Every data source is assigned to a unique application data channel with distinguish priorities. The data unit of a one channel is transferred in a single data packet (real-time robot control data) or a sequential group of TM/TC packets (non-real-time data). When a new Transfer Frame is to be generated, the several channels are polled for data in order to the given priority, and the Transfer Frame is filled with the first channel having data available. Afterwards, the polling of the channels is continued until the Transfer Frame is completely filled or no more data is available.

TELEPRESENCE MODE EXPERIMENTS

For the telepresence demonstration a stereo camera is mounted on the 2nd joint: The stereo video images, together with the current robot joint and torque values, are fed back in real-time to an operator at the ground station. The operator controls the slave robot at the remote site via a force-feedback-control device. Force and position commands are generated to drive the robot joints into the desired state. Using high-rate, low latency and jitter-free up- und downlink channels, the operator is “impressively” included in the control loop. A major requirement for this mode is to keep the total data round-trip-delay significantly below 500 milliseconds. Indeed for the ROKVISS direct over-flight situation we have only 10-20ms roundtrip delay, but we will simulate additional time-delays, which occur when a geostationary communication satellite is used.

While large and varying time delay can be compensated by model-based approaches, e.g. using predictive simulation (as was the case in ROTEX), we have a strong signal-based coupling between the ground operator and the space robot in ROKVISS. First the force feedback loop is realised with a common position/force four channel control architecture [5].

To cope with longer and time-varying time-delays, sophisticated bilateral control schemes have to be used. The main requirement is the stability of the master-slave system. On basis of this 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.

For the ROKVISS experiment an approach using wave-variables has been developed [1], in which the time-varying delay due to the orbit of the ISS is simulated and compensated. Alternatively a time domain passivity control scheme has been developed. In Fig. 13 a distributed passivity observer monitors the passivity of the communication channel. In case of activity, which will destabilize the master-slave system, a passivity control acts to maintain stability.

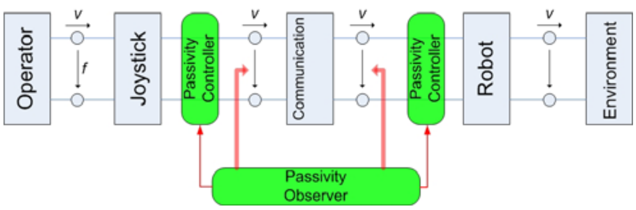

Fig. 13 Control Scheme for Time Domian Passivity Control

Our evaluation contour 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 realises a 3-side-mechanical binding of the touch finger. This represents a typical benchmark for telerobotic applications;

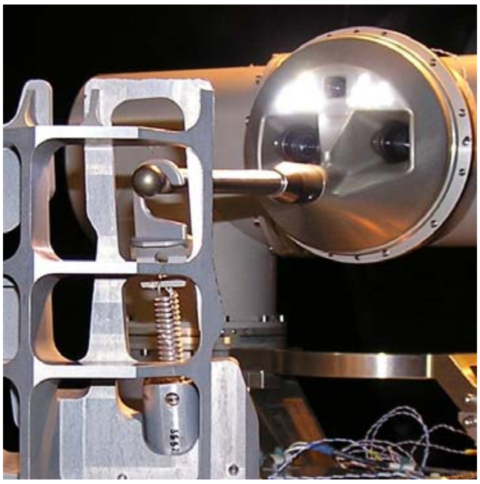

Fig. 14 Spring device for energy storage and friction parameter identification

- mechanical springs simulate an external energy storage, which can add energy to the Master-Slave system (Fig. 14);
- A *virtual spring* is programmed into the robot joints to emulate contour materials of different consistence. The operator has to follow a well-defined virtual path which fades into the video display. The difference between the robot's position and the command position represents the feedback forces.

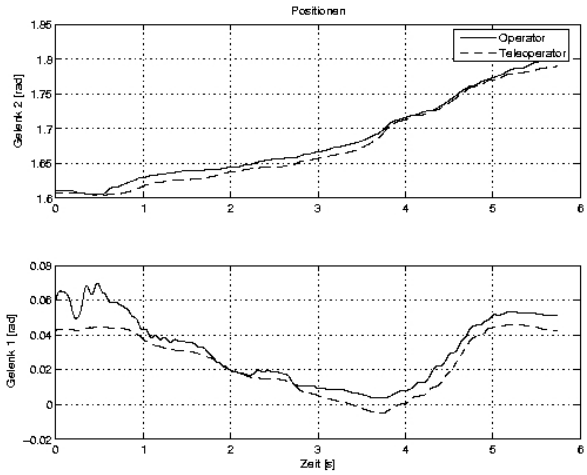

Fig. 15 Recorded positions during telepresent contour following

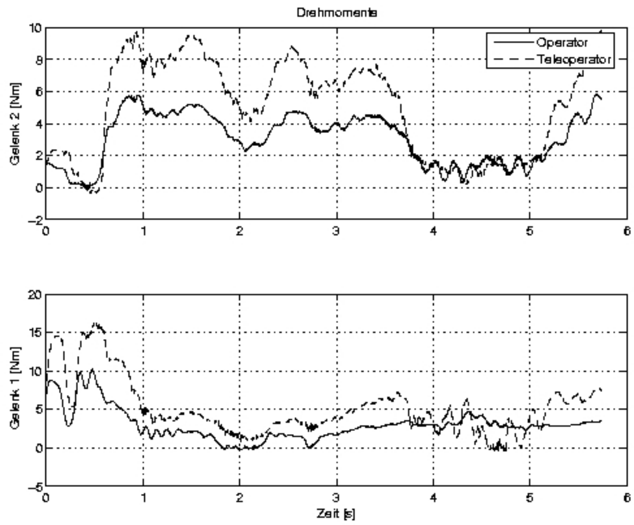

Fig. 16 Recorded torques during telepresent contour following

PRELIMERY RESULTS IN TELEPRESENCE MODE

Already during the first mission contacts also telepresence experiments as described above have been conducted. The stereo video transmission has been given a realistic 3D imagery of the scene, though only as grey image. The presence feeling was improved by the realistic force-feedback provided by the DLR-Joystick.

Fig. 15 and Fig. 16 show the position and force values recorded during a contour-following experiment. A good position-following of the slave system and a scaled but identical force trajectory was felt by the operator. Additional experiments with the different control architectures will follow.

TELEROBOTIC MODE EXPERIMENTS

During direct radio contact the remote robotic system can be commanded by an operator via the supervisory control techniques as realised in the man-machine-interface (MMI) of the MARCO telerobotic ground station. Feedback is provided via the on-board camera system and the telemetry data. All the predefined tasks of ROKVISS can be executed by sending a path or a force trajectory to the on-board system. In contrast to the automatic mode experiments (below), the telerobotic experiments are conducted via direct operator interaction (though he is not "immersively" included in the control loop as in telepresence mode), instead of the activation via the mission timeline. This means that all experiments as described in the following section, which do not exceed the link coverage time, may be performed in telerobotic mode, too.

AUTOMATIC MODE EXPERIMENTS

The following automatic mode experiments (independent of direct RF contact) are conducted:

- Predefined trajectories without force contact;
- Predefined trajectories with force contact, i.e., contour tracking or movement against spring load, as described in the telepresence mode section.
- Predefined trajectories with a change from non-contact to contact condition (contact dynamics experiment).

Fig. 17 shows on top the situation drawing the spring, in the middle the arm pointing at the solar panel, and at the bottom a view of the clouds on earth.

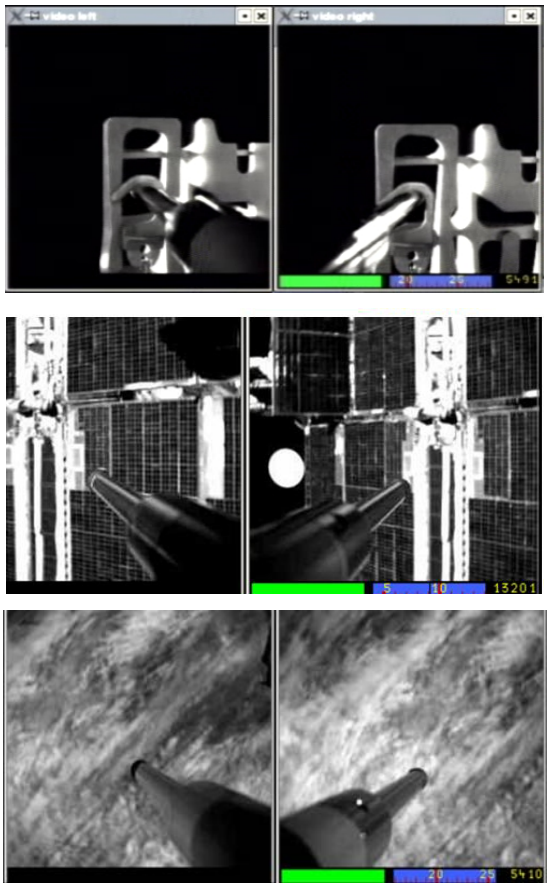

Fig. 17 ROKVISS video images

JOINT CONTROLLER STRUCTURE

The controller structures have initially been developed and verified on the basis of the DLR light-weight robots. In particular a flexible-joint model is assumed. Fast and reliable methods for the identification of the joint model parameters (joint stiffness, damping and friction) were developed, while the rigid body parameters are directly generated from the mechanical CAD programs [6] [7]. This lead to an accurate simulation of the robot dynamics on ground, so that it was possible to develop and test the controller structures in the simulation first.

The basic joint level controller is a joint state feedback controller with compensation of gravity and friction [8]. The state vector contains the motor position, the joint torques, as well as their derivatives. By the appropriate parameterisation 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 Cartesian 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 fulfils the following functionalities:

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

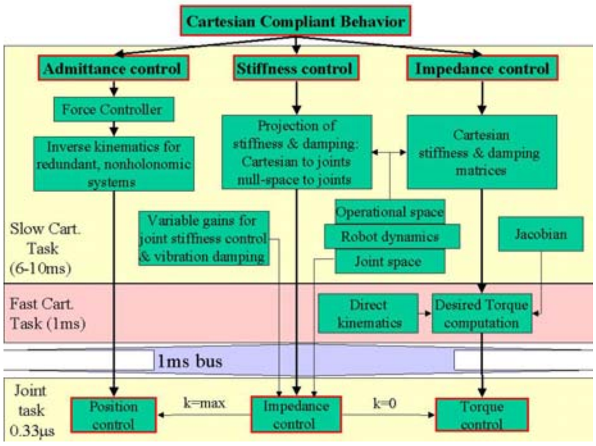

Fig. 18 Controller architecture

Based on this joint control structure, three different strategies for implementing Cartesian compliant motion have been realised (Fig. 18): admittance control, which accesses the joint position interface through the inverse kinematics; impedance control, which is based on the joint torque interface; and Cartesian stiffness control, which accesses the joint impedance controller [9].

The position controller as well as the impedance controller is based on a passivity approach under consideration of the joint flexibilities [10], [11]. A physical interpretation of the joint torque feedback loop has been given as the shaping of the motor's kinetic energy, while the implementation of the desired stiffness can be regarded as shaping of potential energy. Therefore, the Cartesian impedance controller can be designed and analyzed within a passivity based framework in the same manner as the joint state feedback controller. This constitutes a new, unified approach for the torque, impedance and position control on both joint and Cartesian level.

An important advantage of these passivity-based controllers is the robustness with respect to uncertainties of the robot or load parameters, as well as to contact-situations with unknown but passive environments.

Despite of the fact that the Cartesian controllers are of limited practical use for a two DoF robot, the entire control structure of the DLR light-weight robots has been implemented also for the ROKVISS system, in order to validate the software for further missions implying robots with six or seven DoF.

JOINT PARAMETER IDENTIFICATION

Accurate dynamic models were required for both the pre-mission development and testing phase as well as the in-flight operations phase. By using 3D CAD programs for the mechanical design, the problem of determining the parameters of the rigid robot dynamics becomes straightforward, since they can be generated with high accuracy from the design data. This of course requires a detailed modelling of all components, including motors, gears and electronics. The parameters which still have to be identified are the friction parameters, the motor constant and the joint stiffness. The objectives of the technological experiments during the mission are:

- To identify important dynamic non-linear system parameters in micro-gravity environment and validate the underlying multi-body system models,
- To increase modelling fidelity and hence performance quality for future space robotic missions [12].

For the design of the joint controllers (position, torque, and impedance control), recursive least squares methods have been developed, which identify the stiffness and damping, as well as the friction parameters. Starting from the model and the corresponding identification measurements [13], a modified time-efficient, on-line version has been tested on ground and is used during the mission.

To identify the different parameter groups we perform dedicated measurements which enable independent identification for each group [6]. His procedure avoids complex online optimization problems which, in our earlier experiments, always resulted in local minima, very different form the real physical parameters.

Preliminary Joint Friction Identification Results

For the identification of the motor side friction the following signals are available: the commanded motor current, the measured motor position and hence, by differentiation, the motor velocity, as well as the measured joint torque. The identification procedure determines the motor torque constant k_m, the Coulomb friction τ_C, the friction coefficient for the load dependent component μ, and the viscous friction coefficient b_1. The identification of these parameters can be formulated as a static, linear optimization problem. This means that for a properly chosen trajectory, which independently excites all parameters, a fast and reliable parameter convergence can be obtained. Such a trajectory is given when pulling the springs of the test setup using a saw-tooth trajectory with different constant velocities (Fig. 17). Due to the variable load torque, the reversion of the movement direction, and the coverage of the entire velocity range, all parameters are well excited. A typical identification plot is given in (Fig. 19) and the numerical results for the friction values (measured on 22.07.05 during an automatic on-orbit experiment) are given in table 1.

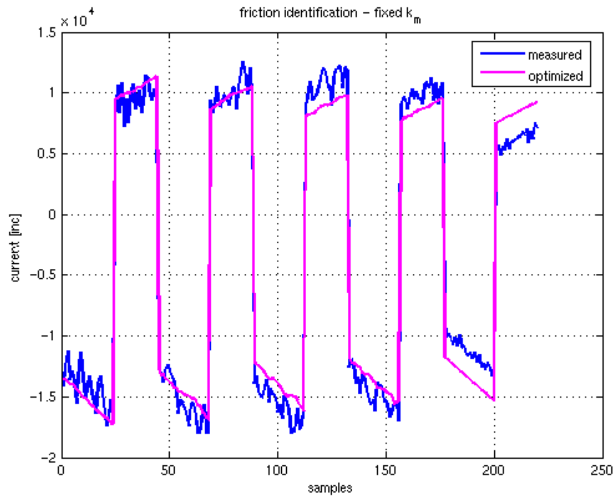

Fig. 19 Commanded current and current estimation after the identification of the friction parameters. The movements are performed with 30.0, 20.0, 10.0, 5.0, and 1.0deg/s.

In order to test the reliability of the identified values, the motor constant km was also identified on a separate motor test-bed and the optimization was performed only for the remaining parameters. Table 1 shows that the results for the two cases are very similar.

Table 1. Friction parameters for joint 1 in space.

	with fixed k_m	with optimized k_m
k_m [Nm/inc]	345.62	337.39
τ_C [Nm]	28.5	29.1
μ []	0.272	0.302
b_1 [Nms/rad]	12.25	12.51

In addition to identifying the parameters of a fixed model, we also try to improve the model itself. For the previously presented triangular trajectory with varying frequency (i.e. velocity amplitude) and undergoing spring load, a nonlinearity of the viscous friction term can be noticed. Fig. 20 compares two further model versions in terms of their degree of complexity and the modelling accuracy on a similar trajectory. Model 1 is a simplified one that accounts only for Coulomb friction and linear viscous damping. Those two damping terms had been identified before in ground experiments to be of dominant influence. The second model, Model 2, is regarded as an improvement of Model 1, and accounts now for more damping terms such as viscous damping of quadratic and cubic velocity dependence, and a term regarding the load dependent effect on Coulomb damping:

$$T_{damp} = (\tau_C + \mu\,|T_{out}|)\operatorname{sign}(\nu) + b_1\nu + b_2\nu\,|\nu| + b_3\nu^3$$

where $|T_{out}|$ is the magnitude of the output torque (e.g. spring load) and ν is the angular velocity. The second model fits the measurements considerably better.

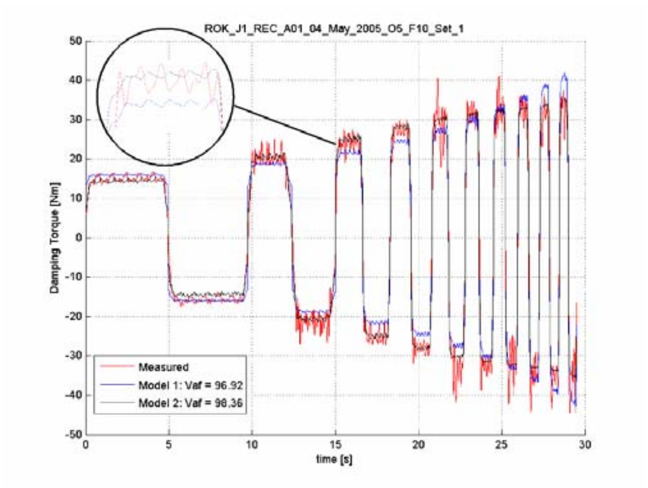

Fig. 20 Two different models for the friction torque are compared. Vaf (= variance accounted for) defines a statistical measure to judge to quality of the identification results and hence the underlying model: The ideal value vaf=100% means that we have total agreement between model and measurement.

Time and Temperature Dependency

The preliminary results of the on-orbit identification show that the total friction in space increased by a factor of about 50% compared to the friction on ground, taken at 20°C, under normal atmospheric pressure. However, no further degradation of the parameters can be observed so far over the first five months of operation (Fig. 21). This suggests the conclusion that the lubricant changed its properties in an early mission stage during the check-out phase and afterwards reached a stable operating condition.

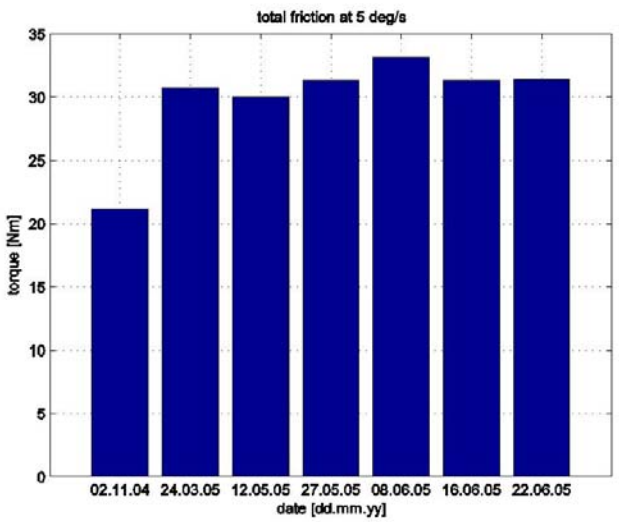

Fig. 21 Time evolution of total friction at a speed of 5deg/s. The first bar corresponds to the reference measurement on ground.

A heating system is used to regulate the operating temperatures on-orbit between -20°C and +30°C. Within this range, the temperature dependence of the parameters is also rather low and lies close to the range of the identification uncertainty (Fig. 22).

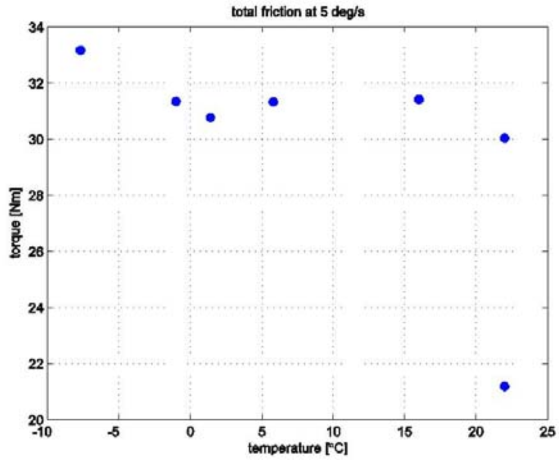

Fig. 22 Total friction at 5deg/s, plotted over the temperature. The isolated value corresponds to the reference measurement on ground.

Stiffness Identification

The main sources of elasticity in the joints are the flex splines of the harmonic drives and the torque sensors. The elasticity is identified by contacting a rigid surface with the tip of the robot and commanding a slowly changing force to the joints. Since the torque is measured after the gear-box, the stiffness can be easily optimized with the available torque and position signal.

A typical identification result can be seen in Fig. 23. The stiffness for both joints has values around 17000 Nn/rad. As expected, the first measurements revealed no significant differences between the stiffness values on ground and in space.

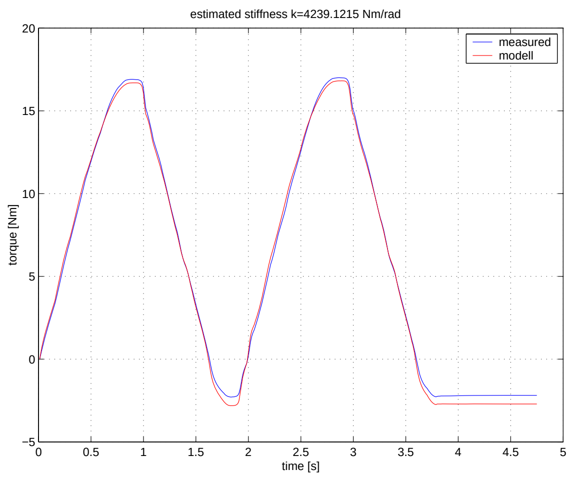

Fig. 23 Result of stiffness optimization.

CONTACT DYNAMICS EXPERIMENTS

The ROKVISS facility is also used to study how the space environment affects the behaviour of bodies interacting together in a contact situation. Compared with joint dynamics changes, strong dependency of temperature variations and space radiation upon surface material properties is far more expected for the impact and contact cases. In impact and contact dynamics, the proper knowledge of both the energy dissipation and the tangential forces (damping, static and dynamic and friction of Coulomb type) is of our primary interest. These experiments are conducted in cooperation with CSA, the Canadian Space Agency. Specifically, the energy dissipation occurring during intermittent impact events (in normal and oblique impact) is measured, as well as the frictional forces acting between two bodies while they are moving w.r.t. each other in a lasting contact situation (Fig. 24).

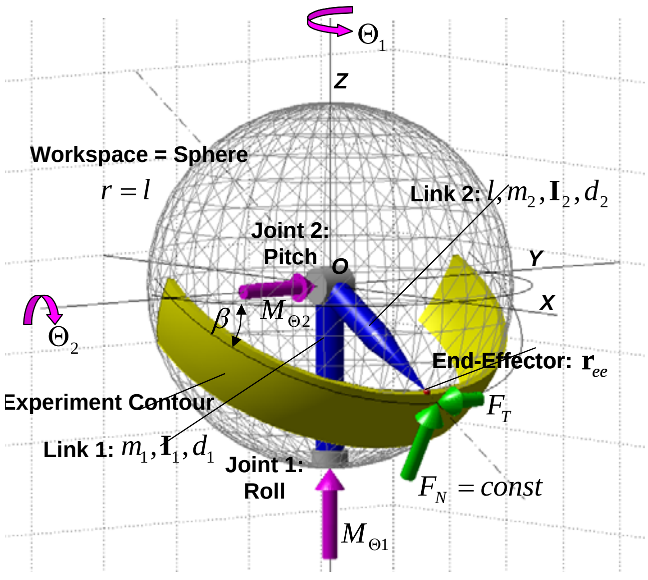

Fig. 24 ROKVISS manipulator: contact case, stylus moving on a given trajectory. This figure is part of an animation: the length of the arrows is varying according with time. The arrows indicate the torques of the two joints exerted during motion and the reaction force at the contact surface.

The stylus is moved back and forth along a straight edge of the contour in a sinusoidal manner (position control), while the contact normal force is kept constant. The contact forces are recorded for various sinusoidal motion frequencies and normal force amplitudes. The experiment studies the friction behaviour over time of aluminum-aluminum contact as well as the contact between the aluminum tip of the pointer and a lubricated section of the contour. Two different types of surface finish on the ROKVISS contour are supplied, such that different contact behaviours can be experimented with. The contact dynamics experiments are performed on an ordinary contour section piece with the nominal surface finish, and on a section of the contour on which a dry-film lubricant has been applied. Dry-film lubricants are commonly used in the space industry to coat parts that will be mating/demating to facilitate the insertion/extraction tasks, as well as to reduce wear on the contacting surfaces.

OUTLOOK

Though ROKVISS operations will be practised at least one year, already now – i.e. after 4 months of operation – we are enthusiastic about its excellent performance and the perfect functioning of the space-qualified, torque-controlled joints based on our new motor ROBODRIVE. The majority of the hardware developed and the results of the experiments will be taken into account for the design of a more complex freeflying robotic system (e.g. 7-axis robot) intended to be used in an On Orbit Servicing (OSS) technology experiment (TECSAS) in which a non cooperative target shall be approached, captured and finally de-orbited. The TECSAS project has already been started, and is the next important step on our roadmap: From our operational terrestrial light-weight arm/hand system (Fig. 25) via ROKVISS and TECSAS (Fig. 26) towards humanoid freeflying or planetary rover based OOS systems (Fig. 27).

Fig. 25 DLR's operational light-weight arm/hand system

Fig. 26 TECSAS - The freeflying Technologie Satellite for Demonstration and Verification of Space Systems

Fig. 27 A humanoid planetary rover concept based on DLR's light-weight arm/hand system

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