COMPONENT VERIFICATION ON ISS (ROKVISS) - FIVE YEARS IN SPACE FINAL EXPERIMENTAL RESULTS ON FRICTION PARAMETER IDENTIFICATION

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ABSTRACT

From January 2005 until November 2010 ROKVISS, the small robot with two torque-controlled joints, was mounted outside at the Russian Service Module of the ISS. After this long term mission, the robot returned to the RMC Institute in Oberpfaffenhofen where it was examined in closer detail.
After a short introduction the main hardware and operational procedures are explained.
The main section of this paper describes the friction identification experiments, the mathematical model and the lessons learned from the results.
At the end all results are discussed physically. The focus is on gearbox as well as the lubricant used for space applications namely „Castrol Braycote 601 EF“.

1. INTRODUCTION

The German space robotic project ROKVISS (german: ”Roboter Komponenten Verifikation auf der ISS”) has just been finished. The system has been returned to earth early 2011 and the hardware was subject to detailed analysis and advanced tests. The final friction analyses results are presented in this paper.

ROKVISS (Fig. 1) aims at the in-flight qualification of DLR’s Light Weight Robot III (LWR III) modules, modified for a space environment. It is a reduced setup of a two degree of freedom (DOF) robot arm. With this experiment DLR could prove the concept to use partly components off the shelf (COTS) within a very tight and highly integrated mechatronic device based on the modular joint concept.
After more than five years of successful operation and without any failure, the innovative mechanical and electronic concept seems very promising for the use in space projects. Those projects are in the wide range of future robonaut applications as well as planetary robotic missions. Indeed what we are still missing in space are fast signal transmissions. One relay satellite could provide signal round trip delays of 0.5 seconds within a coverage times of around 40 minutes. This allows even haptic feedback, which is a major idea of our advanced telerobot control strategy using visual and haptic feedback.
ROKVISS was also a telerobotic demonstrator with real-time stereo-video transmission and tactile feedback. The telerobot success was the second major achievement of ROKVISS, besides the component verification.

Figure 1: ROKVISS photo of the experiment mounted on the ISS

In Figure 1a the overall ROKVISS is shown, while Figure 1b shows the joints as described in the previous section 2. Figure 1c shows ROKVISS in its position outside the ISS at the Zvezda service module.
The ROKVISS experiment consists of a small robot with two torque-controlled joints, mounted on a Universal Workplate (UWP). Each joint module consists of a power supply, a controller board, a power converter, the drive train and a torque sensor. Inside the robot there are 2 joint modules, a stereo camera, an illumination system, an earth observation camera and a power supply is implemented. For verifying the robot functions and performance a mechanical contour device is mounted on the UWP.

Based on our long-term goal to develop “robonauts” for space and the experiences our research department accumulated in space robotics, this article describes recent design and development results at DLR’s Robotics and Mechatronics Center regarding the component verification in real space application. Herein, we focus on lightweight robot arms with highly integrated actuation modules for space applications.

Inside the DLR-RMC light weight robot arm (LWR III), fully sensorized, highly dynamic joint modules with state feedback controllers are implemented. The seven degree of freedom (DOF) torque-controlled robot arms enable innovative cartesian impedance controller.
To provide all this controller possibility’s also at the ROKVISS joints, they consists of the same sensors for motor and drive side measuring of exact positions as well as torque. With these sensors a high quality friction analyses could be performed. For this a multitude number of tests have been done during the mission.
Among other activities, 54 joint friction identifications were performed. It turned out, that joint friction is an important factor in this mechanical system.

2. HARDWARE OF ROKVISS

The ROKVISS Hardware can be best explained regarding Figure 1b, the exploding cad model. In general it consists of the tow joints units and the additional camera, illumination and pointer nose.

Since this paper is focused on the friction identification of the Joint modules this section manly describes the internal structure of one of these actuation units.

The core of the actuation is the ILM motor (German:"Innen-Läufer-Motor"), a brushless DC motor, especially designed for the need of robotics, high dynamic, high efficiency, high torque at low revolution, low weight, small size, and many other advantages for robot actuation. Currently, our motors are becoming state of the art for high performance robotic drives.

As already mentioned, our motors are developed to comply with the ratings of Harmonic Drive gears. Together with those they form the core of our highly integrated actuation units. Aside those core parts, the units include power, data acquisition, motor control and communication electronics in a very dense package.

The amount of wires has been drastically reduced to two power (one for electronics and one for the motors) two communication lines (SERCOS is a ring) and one emergency stop. Due to the large hollow shaft of the motors these lines can be easily guided through a robot joint and thus remain inside the robot. Furthermore, the actuation units comprise a large set of sensors enabling sophisticated impedance and admittance controllers with underlying high performance torque or position control loops. These sensors are motor side position sensors for commutation and relative position measurement as well as link side absolute position and joint torque sensors.

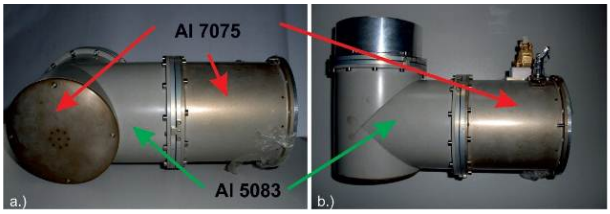

Figure 2: ROKVISS FM modules with colour changes on the surface after return to earth

The second advantage is that the low number of mechanical components reduces the probability of failure. In the following, the key mechanical components of one joint unit are listed:

- Stator
- Rotor with magnets
- Rotor bearing
- Harmonic Drive wave generator (WG)
- Harmonic Drive flex-spline (FS)
- Harmonic Drive circular-spline (CS)
- Output bearing.

Within these components the rotor bearing and the WG bearing are the most crucial elements since the associated friction has to be overcome by the motor torque directly.

In summary, the design of our actuation units allows highly dynamic and powerful operation as well as precise control in fine manipulation tasks. This is a general idea of the DLR-RMC actuation unit concept. The ROKVISS joints are size and performance identical to the LWR III actuation units. Other sizes of actuation units from other Projects like DEXHAND or MASCOT are derivate of the ROKVISS module. The experience with this first launched and returned Hardware after five years of outer space operations makes us believe that the actuation unit concept from us is path-breaking for future robotic space missions. The results from the ROKVISS experiment, also described in this paper, are very important for the future understanding of how our hardware is treated in space.

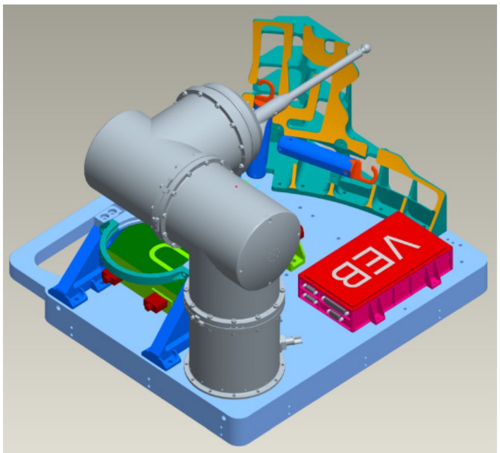

Figure 3: CAD model of the ROKVISS facility

These two robot joints have been extensively tested and the joint parameters have been identified 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 when the ISS passes over the tracking station German Space Operations Center (GSOC). Fig. 3 shows the returned two joint modules. After five years of operation on ISS differences on surface with its anodic treatment (LN9368 I 2101) of the two different aluminium alloys (Al 7075 I Al 5083) are obvious (Fig. 2).

3. FRICTION ANALYSES

Under certain conditions, friction can absorb a large part of the available joint torque. Due to this fact, an accurate knowledge about the total losses is essential especially for space applications.

3.1. Friction Model

The following models were used for the ROKVISS friction identification:

Joint1:

$$\tau_F = (\tau_F + \mu|\tau| + d_1|\dot{q}_1|)\ \mathrm{sign}(\dot{q}_1) \qquad (1)$$

Joint2:

$$\tau_F=(\tau_C+\mu|\tau|+ d_1|\dot{q}_1|+d_1^2|\dot{q}_1|+d_1^3|\dot{q}_1|)\ \mathrm{sign}(\dot{q}_1) \qquad (2)$$

The unknowns in this equation are the coulomb friction $\boldsymbol{\tau_F}$, the load dependent friction $\boldsymbol{\mu}$ and the viscose friction $\mathbf{d_1}$.

3.2. Friction Identification

To identify the joint-friction, the following signals are available:

- motor current, **I**
- motor position, $\mathbf{q_1}$
- joint torque, $\boldsymbol{\tau}$

The motor velocity $\dot{\mathbf{q}}_1$ was determined by differentiation of the motor position $\mathbf{q_1}$.
The identification of these parameters can be formulated as a static, linear optimization problem. Therefore a useful and appropriate trajectory is necessary to excite all parameters. Such a trajectory is given when pulling the springs of the ROKVISS facility, using a saw-tooth trajectory with different constant velocities.
A multivariable optimization algorithm (Matlab®) then is solving this linear optimization problem.
Typical identification plots are shown in Fig. 4 and Fig. 5.

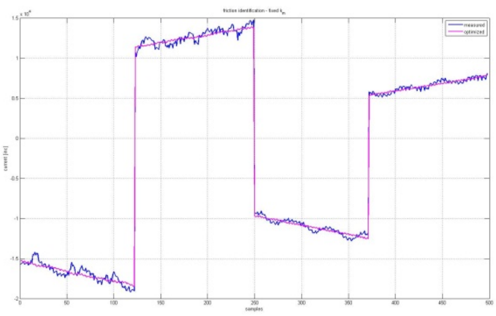

Figure 4: Matlab® Optimization of Joint1

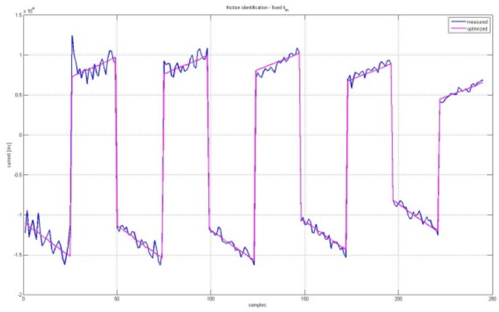

Figure 5: Matlab® Optimization of Joint2

After identifying the first ROKVISS measurements, it became clear that joint1 run into current saturation already at a speed of 10deg/sec. Obviously a strong increase of the joint friction was responsible for this behavior. For the further mission joint 1 only could be identified with the velocities 1deg/sec und 5deg/sec.

3.3. Friction Plots

Due to the large quantity of measured data, a suitable presentation was necessary to show the results in a clear and concise form. The following chapter explains the graphical representation.

The joint friction is divided in coulomb, load dependent and viscose friction. Coulomb friction is shown by the dark grey bars. In light grey the load dependent friction is pictured. The narrow, coloured bars on top, representing the viscose frictions at different, constant joint velocities.
For instance:
The small orange bar (Fig. 6) represents the viscose friction magnitude at a joint velocity of 1 deg/s, the big orange bar the friction at 5 deg/s. The orange colour displays, that the temperature of this joint was somewhere in between +22°C and +28°C. By adding up the bars, one obtains the total output losses in Nm (at the appropriate velocity).
Each color indicates a temperature range. A legend in the figure explains it.

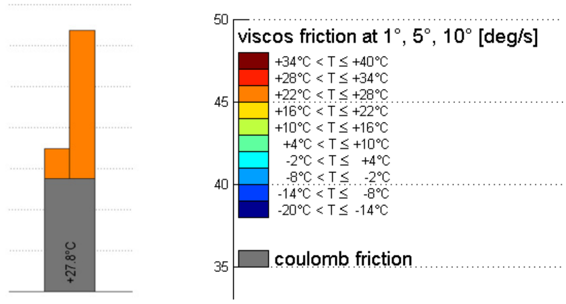

Figure 6: Friction bar and temperature ranges

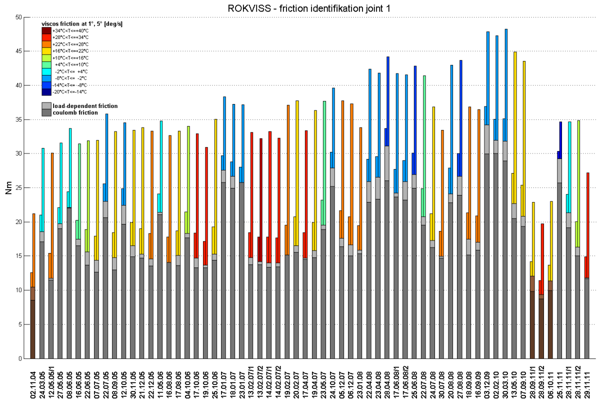

Figure 7: Friction results of joint1

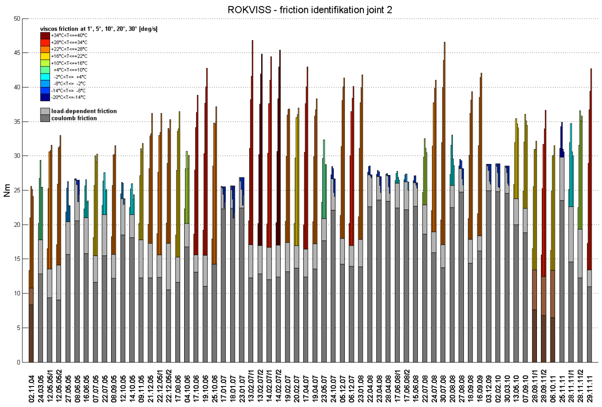

Figure 8: Friction results of joint2

3.4. Results

The results of the whole friction identifications (54 in space) during the ROKVISS mission can be seen in Fig. 7 and Fig. 8. The brown coloured bars are identifications on ground, taken at 20°C under normal atmospheric pressure. The last four bars in each plot, showing results of the post mission inspections (chapter 4).
The preliminary results of the on-orbit identifications showed that the total coulomb friction for the joints in space increased up to 50% compared to the measurements on ground. However, only a small further rising of the friction values has been observed so far. After ROKVISS returned, identifications at 20°C showed again nearly the same values as at the beginning in 2004. This seems to be connected to the vacuum which has an influence on the lubricant.
Another interesting point one can see by looking at cold temperatures. Viscose friction at joint 1 rises while it is decreasing at joint 2. One assumption for this behaviour is that the initial loads of the bearings are so different, that a clamping occurs. But of course a heating system was used to keep the joints between its upper and lower operational qualification temperature (-20°C to +30°C). Since the same lubricant was used for both joints (Braycote 601), further experiments are planned in order to explain these different behaviour.

4. POST MISSION INSPECTIONS

Due to these mysterious effects at chapter 3.4, it was necessary to do more tests with the ROKVISS flight model (FM). Probably the lubricant in the HD gear (Braycote 601) plays an important role.

To achieve the same atmospheric conditions like on the outside of the ISS a thermal vacuum chamber (TVC) was used. Additional heater foils on the reverse side of the joints should simulate the energy of the sun, shining on the robot. The heating of on side generate a temperature gradient within the joints (Fig. 9).

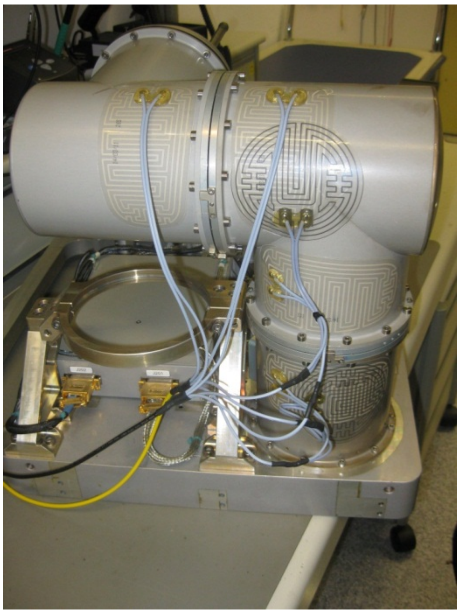
Figure 9: ROKVISS in TVC with external heater foils

4.1. TVC Test 1: Internal Heaters Off

Test Nr. 1 at a temperature range from -17°C to +34°C. The internal and external heaters were switched off. The measurements were started after a thermal equilibrium had been achieved.

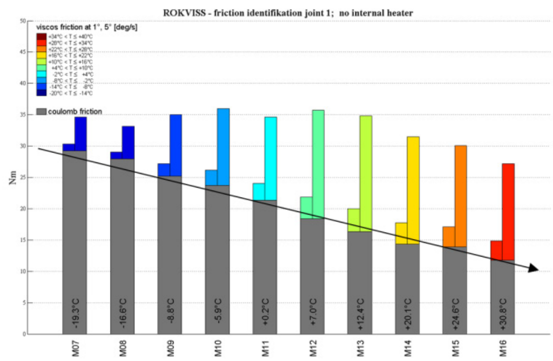

Figure 10: TVC Test 1: no internal heater

While temperature is increasing, coulomb friction is decreasing and the viscose friction is rising in relation to velocity. Especially the quadratic part of the viscose friction indicates a strong rise over temperature.

4.2. TVC Test 2: Drop of Temperature

Measurement without thermal equilibrium.
A temperature gradient within the joints is generated with a drop of temperature. No thermal equilibrium is reached between the friction measurements. The results of these measurements are compared with the results of Measurement 1 at the corresponding temperatures.

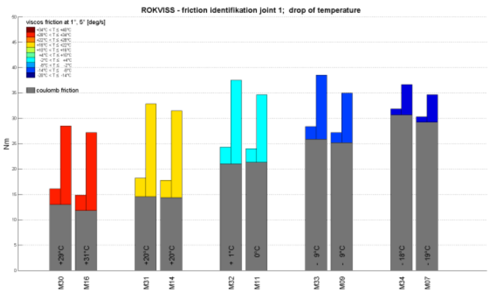

Figure 11: TVC Test 2: drop of temperature

4.3. TVC Test 3: Solar Irradiation

Influence of solar irradiation (represented by heating foils).

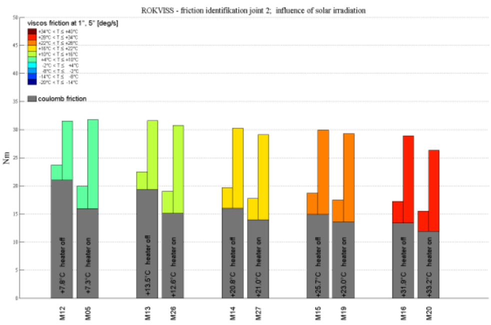

Figure 12: TVC Test 3: influence of solar irradiation

Measurements M13, M14, M15 and M16 are with the thermal equilibrium. For the other measurements the heater foils are switched on to simulate the influence of solar irradiation. The goal is to analyse if the one-sided heating of the joints causes a bracing and therefore a change in the friction

5. CONCLUSION

The ROKVISS mission was planned for one year, already after 8 months of operation the main goals of the mission were achieved. The hardware proved to work reliably under space conditions. The dynamical parameters of the joints, showed a small variation over time and with temperature. The controller structures proved to be robust with respect to these. Within the cooperation with the Russian Institute for Robotics and Cybernetics in St. Petersburg (RTC) the mission of ROKVISS has been extended step by step up to end 2010. Then the collective decision has been taken to bring the main parts of ROKVISS down to earth for further analysis. This analysis has been manly performed until now, and is still continued in some detail parts. The effects of the friction variations with the used lubricant Bracote EF 601 within the different time, temperature, vaccum and non vaccum environmental conditions has been presented in this paper.
With the performed operations, experiences and analysis with ROKVISS further developments of robotic joints elements based on this technology, will improve the robotics over all capability for future space missions.

6. ACKNOWLEDGMENT

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