The Success of the ROTEX Spacelab D2 Experiment.

„[The Chinese company] Midea has [acquired] three-quarters majority [of KUKA]!“ – these stunning news were announced by the Bavaria’s public broadcasting service (BR-online) on 18th July 2016.

“The Chinese appliances and air conditioning equipment manufacturers Midea has now acquired over 75 percent of KUKA shares. Thus the Chinese have exceeded their own target by more than 40 percent. Originally they wanted to settle for a 30 percent share of the Augsburg based robot manufacturer KUKA. Midea has the sole say in KUKA now. Upon reaching the three-quarters majority the Chinese may take all important decisions without participation of third parties at the general meeting and the supervisory board. Against this background, is of great interest, how the end of June concluded investment agreement will be implemented. In a control- and profit agreement Midea renounced any interference until 2023, i.e., all German locations and employees will remain as is and all patents are the property of KUKA.” [1]

The first light-weight robot (LWR) was DLR’s Light-Weight Robot-I (LWR I) of the Institute of Robotics and Mechatronics and was completed in 1995. Both the LWR I and its successor LWR II (presented in 2000) were mere research systems. The experiences from these two generations of light-weight robots were taken into account for the development of the LWR III (presented in 2003).
In 2004 the DLR LWR III was licensed to KUKA Roboter GmbH. KUKA refined the technology in its KUKA LBR 4 (2008) followed by KUKA LBR 4+ (2010) and finally the KUKA LBR iiwa (intelligent industrial work assistant - 2013). [2]

Just to remember how this successful technology transfer started and to point out the substantial role of DLR and the spacelab D2 ROTEX technology-experiment played in the development, the following article was compiled from original sources:

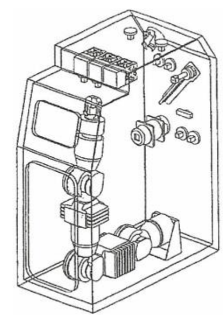
ROTEX-was the first remotely controlled space robot, flying with the space shuttle Columbia in April 1993 to test teleoperation, shared autonomy and fully autonomous operations for the first time in space.

The success or ROTEX was essentially based on the sophisticated multisensory gripper technologies, the local autonomy approach using intelligent sensory feedback capabilities and the predictive graphics simulation concept, compensating the 5-7 seconds communication time delay.
The most applauded experiment was the autonomous catching of a free-floating object. It was performed to show the capabilities of local feedback loops to remotely control a space robot under communication constraints. This experiment was the first precursor mission with respect to the goal to finally capture a tumbling satellite in free space for on orbit servicing activities.

The main features of the experiment were: a small, six-axis robot was mounted inside a space-lab rack. Its gripper, probably the most complex multisensory gripper that has been built so far, was provided with a number of sensors: two 6-axis force-torque wrist sensors (one stiff strain-gauge-based sensor and a more compliant optical one), tactile arrays, grasping force control, an array of 9 laser-range finders, and a small pair of stereo cameras to provide a stereo image of the robot’s working area as seen from the gripper’s integrated cameras (see also Fig. 7).

The verified operational modes were *automatic* (pre-programming on ground, re-programming from ground), *tele-operated onboard* (astronaut controlled robot using a stereo-TV-monitor), *tele-operated from ground* (using predictive computer graphics) via human operators and machine intelligence, and *tele-sensor-programmed* (learning by displaying a completely simulated environment on ground including sensory perception with sensor-based time-delayed execution on-board).[3]

The ROTEX experiment was accommodated in a standard spacelab rack. The gripper can be seen through a viewing port and the lower portion of the robot's "arm" can be seen behind a specially prepared glass opening displayed at the "Deutsches Museum" (Munich).
The whole system was enclosed in the rack only accessible through a little door for the astronauts.



◄ Schematic view of the ROTEX arm and the various objects (tools) which could be used for manipulations by the multisensory gripper and the 6 deg. of freedom robot arm during the flight.

Figure 2 below summarizes the various modes of operation

◄ **Fig. 1** Part of the ROTEX rack housing the robot arm (Deutsches Museum, Munich)

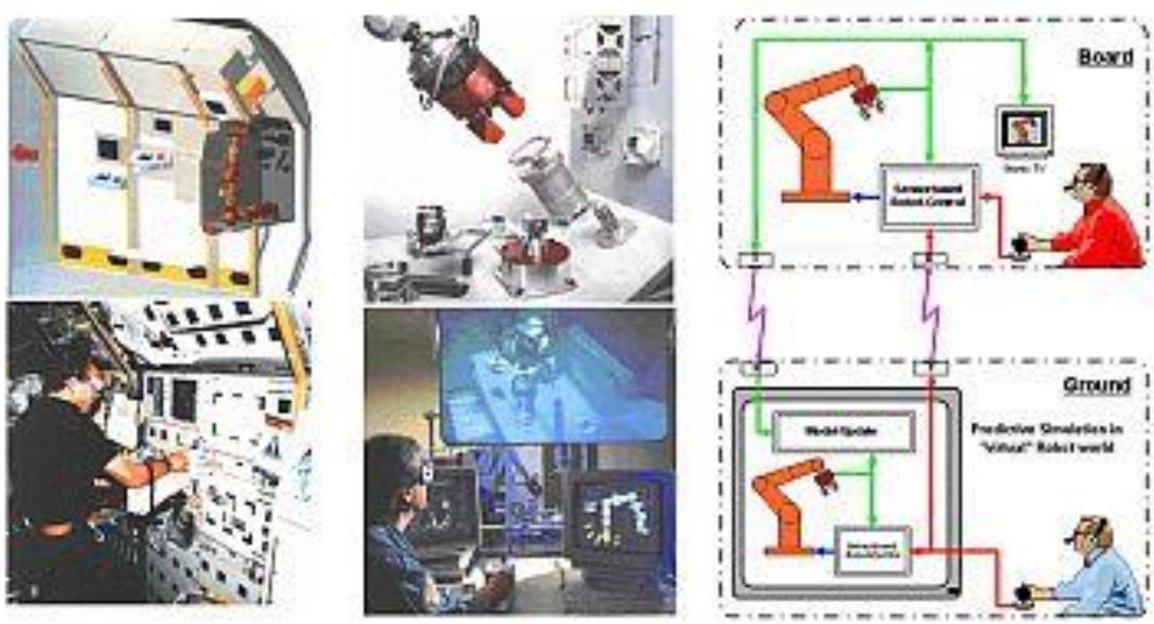


Fig. 2 ROTEX various modes of operation

In order to illustrate the achievement of "catching a free flying object" autonomously in space, the setup, constraints and control mechanisms are described in more detail.

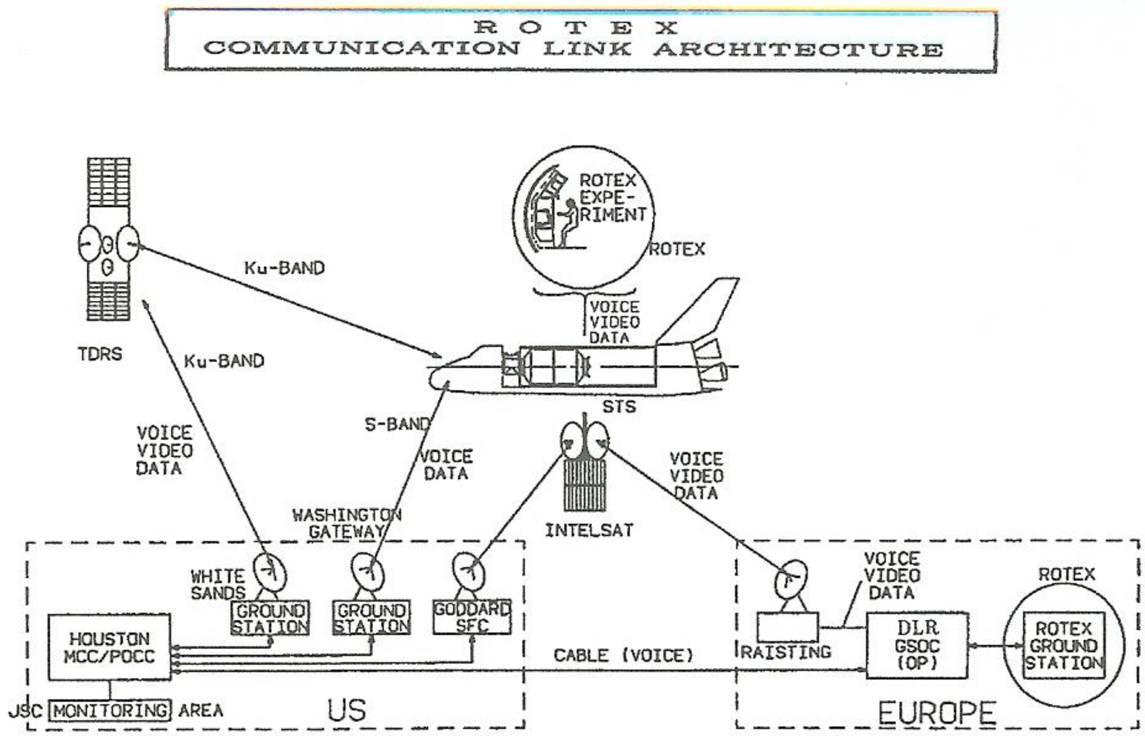


Fig. 3 Communications links for Spacelab D2 during flight for real-time control of ROTEX

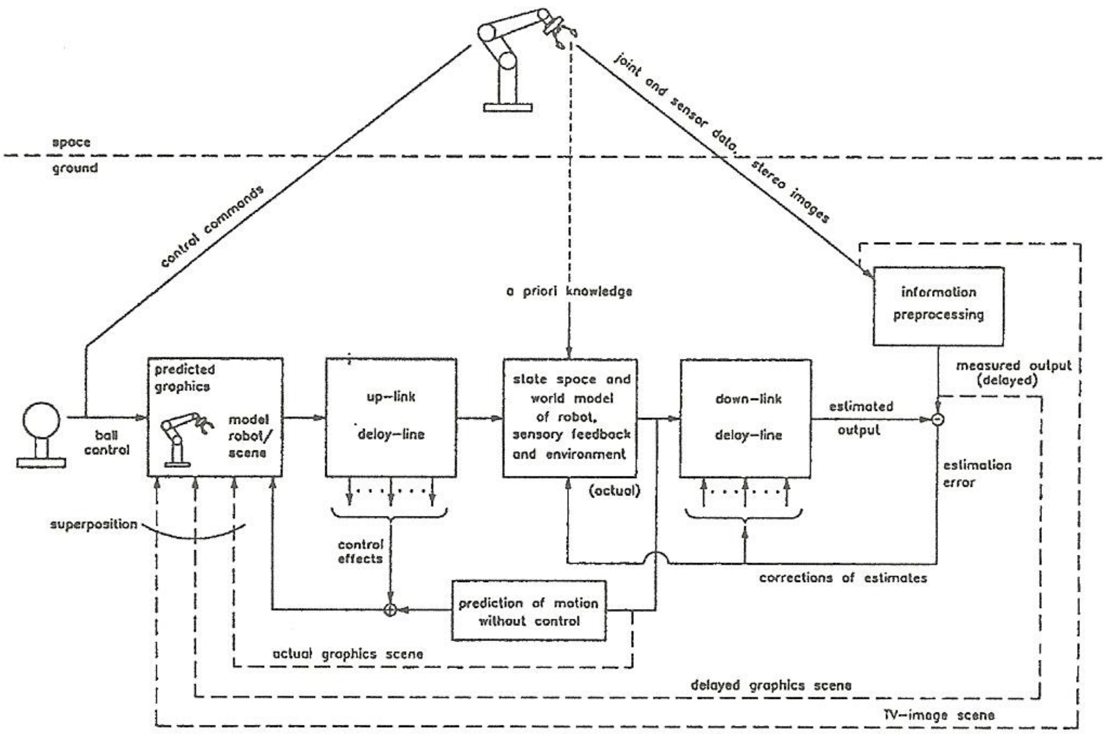


Fig. 4 Block diagram of the various control and simulation loops for ROTEX during flight

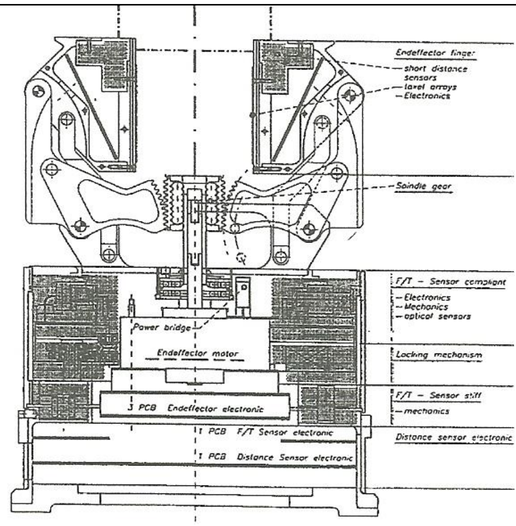


Fig. 5 Multisensory gripper schematics

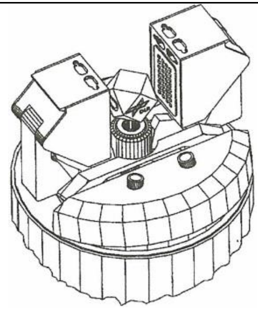
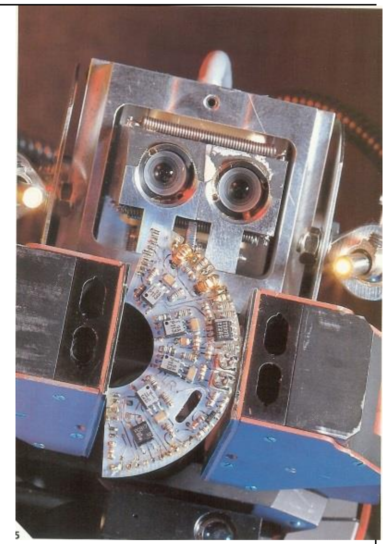


Fig. 6 shows the catching of a free floating object.

Fig. 7 Gripper with 2 CCD cameras eyes holding an electronic component ▶



The Multisensory Gripper

The gripper sensors belonged to the new generation of DLR robot sensors based on a multisensory concept with all analog preprocessing and digital computations performed inside each sensor or at least in the wrist in a completely modular way (see Fig 5). Using a high speed serial bus only two signal wires are coming out of the gripper (carrying all sensory information), augmented by two 20-kHz power supply wires, from which the sensors derive their DC-power supply voltages via tiny transformers.

In the gripper 15 sensors are provided, in particular an array of 9 laser range finders, a tactile array of 4x8 sensing elements, a "stiff" 6 axis force-torque sensor based on strain-gauge measurements a compliant optical one, a pair of small stereo CCD cameras (eyes) and an electrical gripper drive (see Figs. 5 and 7).

Catching a floating Object

There was only one exception from the local sensory feedback concept in ROTEX. It refers to (stereo-) image processing. In the definition phase of ROTEX (around 1986) no space qualified image processing hardware was available; nevertheless this was accepted as a real challenge for the experiment "catching a free-floating object from ground" (see catching sequence in Fig. 8). In contrast to contact operations as necessary in case of assembly here a nearly perfect environmental model was assumed, as the dynamics of an object floating in zero g are well known. CCD-camera information on the object's free-flyer's pose (relative to the gripper) was provided on ground using alternative schemes; one is based on the "dynamic vision approach" as given in [5], using only one of the two small CCD cameras, the alternative is a full stereo approach realized in a multi-transputer system. In both cases the measured" object poses are compared with estimates as calculated by an extended Kalman filter that simulated the up- and down-link delays as well as robot and free-flyer models; this Kalman filter predicted (and graphically displayed the situation that would occur in the spacecraft after the up-link delay has elapsed and thus allowed to close the "grasp loop" either purely operator controlled, or via shared control, or purely autonomously (i.e., solving an automatic rendezvous and docking problem). Fig. 8 shows photos of the TV-scene as seen by one of the CCD cameras immediately before successful, automatic grasping of the object from ground despite of 6 s round-trip delay time, following the "dynamic vision" image processing approach as described in [5].

The odds for a completely successful ROTEX mission, in particular the gripping of a free floating, weightlessness object in space were considered not to be highly favorable – therefore, Gerd Hirzinger, developer and prime investigator for the experiment said very relieved in an interview directly after the successful grappling of the cube: “I know now that success and failure can be very close.”

However G. Hirzinger and his team were convinced that automation and robotics (A&R) would become one of the most attractive areas in space technology, facilitating experiment-handling, material processing, assembly and servicing with a very limited amount of highly expensive manned missions (especially reducing dangerous extravehicular activities). They also concluded that extensive technology transfer from space to Earth seems to be much more justified than in many other areas of space technology. [3]

These expectations became very true with the highly successful technology transfer from DLR to industry (KUKA) and finally to China (Midea) 23 years after the ROTEX flight on Spacelab D2.

Fig.8 The ROTEX gripper catches the free floating cube-like object as seen by one of the two CCD cameras in the gripper, control loop was closed via ground station (see also Fig. 4)

Watch the original video of the historical first time grappling of a free floating cube in weightlessness [ROTEX.wmv].

References

[1] Rigobert Kaiser, BR online (18.7.2016): Midea hat Dreiviertel-Mehrheit

[2] Light-Weight Robotics (DLR) http://www.dlr.de/rm/en/desktopdefault.aspx/tabid-3803/

[3] Robot Technology Experiment on Spacelab D2 Mission: ROTEX (1993) http://www.dlr.de/rm/en/desktopdefault.aspx/tabid-3827/5969_read-8744

[4] Sensor-Based Space Robotics-ROTEX and Its Telerobotic Features, Gerd Hirzinger, Bemhard Brunner, Johannes Dietrich, and Johann Heindl http://202.114.9.17/xnsj/01OO0012.pdf

[5] D. Dickmanns “4D-dynamic scene analysis with integral spatio-temporal models,” presented at the Fourth Int. Symp, Robotics Res., Santa Cruz, CA, Aug. 1985.