1994 IEEE INTERNATIONAL CONFERENCE ON
ROBOTICS AND
AUTOMATION

May 8-13, 1994
Princess Resort
San Diego, California

ROTEX -
The First Remotely Controlled Robot in Space

G. Hirzinger and B. Brunner, J. Dietrich, J. Heindl

D L R Oberpfaffenhofen
(German Aerospace Research Establishment)
D-82234 Wessling, Germany
e-mail: df28@master.df.op.dlr.de

Abstract

End of April 93 for the first time in the history of space flight a small, multisensory robot has performed a number of prototype tasks on board a spacecraft (spacelab D2 on shuttle COLUMBIA) in the most different operational modes that are feasible today, namely preprogrammed (and reprogrammed from ground), remotely controlled (teleoperated) by the astronauts using a control ball and a stereo-TV-monitor, but also remotely controlled from ground via the human operator as well as via machine intelligence. In these operational modes the robot successfully closed and opened connector plugs (bayonet closure), assembled structures from single parts and captured a free-floating object.

Several key technologies made this space robot technology experiment ROTEX a big success and a unique event: multisensory gripper technology, local (shared autonomy) sensory feedback control concepts, and the powerful delay-compensating 3D-graphics simulation (predictive simulation) in the telerobotic ground station. This paper focusses on the tele-sensor-programming aproach and the predictive simulation used for remote ground control.

1 Introduction

We have a strong belief that automation and robotics (A&R) will become one of the most attractive areas in space technology, as it will allow for experiment-handling, material processing, assembly and servicing with a very limited amount of highly expensive manned missions (especially reducing dangerous extravehicular activities). The expectation of an extensive technology transfer from space to earth seems to be much more justified than in many other areas of space technology.

On the other side for complex, partly autonomous robots with extensive ground control capabilities it would be too risky to leap from zero experience to a fully operational system; therefore we have proposed in 1986 the space robot technology experiment ROTEX, which has meanwhile successfully flown in space (spacelab mission D2 on shuttle flight STS 55 from April 26 to May 6, 93).

The experiment's main features were as follows:

- A small, six-axis robot (working space ~ 1 m) flew inside a space-lab rack (fig. 1). Its gripper (fig. 2, for details see e.g. /8/) was provided with a number of sensors, especially two 6-axis force-torque wrist sensors, tactile arrays, grasping force control, an array of 9 laser-range finders and a tiny pair of stereo cameras to provide a stereo image out of the gripper; in addition a fixed pair of cameras provided a stereo image of the robot's working area.
- In order to demonstrate servicing prototype capabilities three basic tasks were performed (fig. 2):
  - a) assembling a mechanical truss structure from three identical cube-link parts
  - b) connecting/disconnecting an electrical plug (orbit-replaceable-unit-ORU-exchange using a "bayonet closure")
  - c) grasping a floating object
- A variety of operational modes was verified (fig. 3),
  - teleoperation on board (astronauts using stereo-TV-monitor)
  - teleoperation from ground (using predictive computer graphics) via human operators and machine intelligence as well

  - sensor-based off-line programming (teaching by showing in a virtual graphics environment on ground including sensory perception, with sensorbased automatic execution later on-board).

  The operational modes were based on a unified control approach for which we have coined the term *tele-sensor-programming*.

- Typical goals of the experiment were:

  - To verify joint control (including friction models) under zero gravity as well as μg-motion planning concepts based on the requirement that the robot's accelerations while moving must not disturb any μg-experiments nearby.
  - To demonstrate and verify the use of DLR's sensorbased 6 dof-handcontrollers ("control balls") under zero gravity.
  - To demonstrate the performance of a complex, multisensory robot system with powerful man-machine-interfaces (as are 3D-stereo-computergraphics, 6 dof control ball, stereo imaging), in a variety of operational modes that especially include on-line teleoperation and off-line programming from ground.

ROTEX contained as much sensor-based on-board autonomy as possible from the present state of technology, but on the other side assumed that for many years cooperation between man and machine via powerful telerobotic structures will form the basis for high-performance space robot systems operable especially from a ground station, too. Thus ROTEX tried to prepare all operational modes which we can foresee in the coming years (not including the perfectly intelligent robot that would not need any human supervisor), and it also tried to prepare the most different applications by not restricting its prototype tasks to internal servicing operations, but also aiming at assembly and external servicing (e.g. grasping a floating satellite). As the robot arm flight model built by space company DORNIER could not sustain itself unter gravity, we developed a carbon fibre based ultralight kinematic 1:1 replica for the astronaut training which we feel was an important step towards a new generation of light-weight robots /13/.

2 Telerobotic Control: The Tele-Sensor-Programming Approach

The telerobotic control in ROTEX was in a unified way based on our *tele-sensorprogramming* approach; it comprises on-line teleoperation on board and on ground as well as sensorbased-off-line programming on ground and subsequent on-board execution (following kind of a "learning by showing" philosophy). Basically this approach has two main features

- a *shared control concept* (see e.g. /3/, /5/) based on local sensory feedback at the robot's site (i.e. on-board or in a predictive ground simulation), by which gross commands were refined autonomously providing the robot with a modest kind of sensory intelligence (fig. 4a and 4b). However due to processor limitations, on-board sensory feedback in ROTEX was restricted to force-torque and range finder signals (see below). Active compliance as well as hybrid (pseudo-)force control using nominal sensory patterns in the sensor-controlled subspace, based on MASON's C-frame-concept /2/ was realized locally. Gross commands in this framework may originate from a human operator handling the control or sensor ball (a 6 dof non-force-reflecting hand controller) or alternatively from an automatic path planner. The techniques used for projecting gross commands into the position and sensor-controlled subspaces have been discussed in a number of previous papers (e.g. /3/, /5/). Feedback to the human operator - in case of on-line teleoperation - was provided only via the visual system, i.g. for the astronaut via stereo TV images, for the ground operateur mainly via predictive stereo graphics (the stereo TV images being an add-on for verification). This allowed us to realize a unified control structure despite of the fairly large round-trip signal delays of up to 7 seconds; and for the future allows to shift more and more autonomy towards the robot without changing the basic structures. Indeed predictive 3D-stereographic simulation was a key issue for the big success of this space robot experiment, and in our opinion is the only efficient way to cope with large signal delays. Of course for these kind of ideas to work the same control structures and path planners had to be realized on-board as well as in the predictive graphics ground station. And this in turn meant that not only the robot's free motion but also its sensory perception and feedback behaviour had to be realized in the "virtual environment" on ground.

- an *elemental move* concept, i.e. any complex task like the dismounting and remounting of the bayonet closure is assumed to be composed of elemental moves, for which a certain constraint-frame- and sensor-type-configuration holds (to be selected by the operator e.g. using a set of predefined alternatives), so that automatic sensorbased path refinement is clearly defined during these motion primitives.

Basically the elemental move concept as realized in the ROTEX system requests various definitions and procedures, in particular

- defining (or graphically demonstrating) the nominal initial and goal *situations* (positions or hand frames augmented by nominal sensory patterns); of course in case of on-line teleoperation the gross-path in between is also given by the operator, else it is generated later (i.e. on-board) by the path planner.
- providing the a-priori knowledge on the C-space configuration and the type of shared control (active compliance or using nominal sensory patterns).
- procedures for mapping sensory errors into positional/rotational errors (e.g. using a neural net training that allows to realize sensor fusion, too).
- procedures for mapping positional/rotational errors into motion commands.
- procedures for recognizing actual and goal states, thus determining e.g. the end of an elemental move. It seems worth mentioning that of course the robot in its real world in general is not able to reach both precisely, the nominal position as well as the nominal sensory pattern; this conflict was resolved easily by using projections of these nominal data into the position and sensorcontrolled subspaces. If in the goal state all 6 degrees of freedom are sensor-controlled, then in correspondence with a "relative reference philosophy" explained below of course the sensor information has absolute priority.

An impressive verification of these concepts was given during the mission when the ground operator in on-line teleoperation stepped through the ORU-exchange task **without** waiting at the end of the elemental moves until the robot in space had confirmed reaching the goal situation of the corresponding elemental move. On the other side we were able to on-line teleoperate in the virtual environment, but send up the gross commands at some arbitrary time later, e.g. after finding a satisfactory motion.

To us it seems important to emphasize again that the ROTEX tele-sensor-programming concept with its elemental move features comprises sensorbased on-line teleoperation e.g. via predictive graphics simulation (including e.g. remote active compliance) as well as a corresponding off-line-programming version, which may be characterized as "sensorbased teaching by showing". Hereby the robot is graphically guided through the task (off-line on ground), storing the relevant nominal situations (graphically simulated) for later (e.g. associative) recall and reference in the on-board execution phase, after these data packages have been sent up to the on-board path planner. Indeed this mode of tele-sensor-programming is a form of task-oriented, implicit, off-line-programming which tries to overcome the well-known problems of conventional approaches, especially the fact that simulated and real world are not identical. But instead of e.g. calibrating the robot (which is only half the story) **tele-sensor-programming** provides the real robot with simulated sensory data that refer to **relative** positions between gripper and environment, thus compensating for any kind of inaccuracies in the absolute positions of robot and real world.

Realistic simulation of the robot's environment and especially the sensory information (fig. 5) presumably perceived by the real robot was of crucial importance for this approach.

A more detailed discussion of the graphical simulation, especially sensory perception is given in /12/ or in /14/.

Nevertheless there are errors to be expected in any graphics simulation compared with the real world and therefore not only e.g. the gross commands of the TM command device (control ball) were fed into the simulation system, but also the real sensor data coming back from space (including the real robot position) were displayed, recorded and compared with the presimulated ones (fig. 4a). In a future stage not yet realized in the D2-flight these comparisons might lead to an automatic update of e.g. world model, sensor models etc.. All sensory systems of ROTEX worked perfectly and the deviations between presimulated and real sensory data were minimal (fig. 6). This was one of the many positive surprises of ROTEX.

In the telerobotic ground station a number of computers were connected via a VME-bus shared memory concept, especially powerful SGI (Silicon Graphics) "power vision" systems that allowed to display (in stereographic technology) the different artifical workcell views in parallel, simulating the workcell cameras, the hand cameras and an optional observer view which was varied by a control ball. During the ROTEX mission we did not overlay real and simulated images, instead the real endeffector's position was indicated by the hand frame and the real gripper's position by two patches in the graphics scene. In addition the graphics system permanently displayed real and simulated sensory data in form of overlayed bars (fig. 5) or dots (in case of the tactile arrays, see lower left part of fig. 5), while an additional SGI system displayed the time history of simulated and real sensory signals shifted by the actual delays, thus correlated in time (fig. 6).

3 Catching the 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 qualifiable image processing hardware was available; nevertheless we took this as a real challenge for the experiment "catching a free-floating object from ground" (fig. 4b). In contrast to contact operations as necessary in case of assembly we may deal here with a nearly perfect world model, as the dynamics of an object floating in zero g are well known. Hand-camera information on the free-flyer's pose (relative to the gripper) was provided on ground using alternative schemes; the one applied during the successful grasp was based on the "dynamic vision approach" as given in /10/, using only one of the two tiny hand-cameras, the other one was a full stereo approach realized in a multitransputer system. In both cases the thus "measured" object poses were compared with estimates as issued by an extended Kalman filter that simulates the up- and down-link delays as well as robot and free-flyer models; this Kalman filter /5/, /11/ predicts (and graphically displays) the situation that will occur in the spacecraft after the up-link delay has elapsed and thus allows to close the "grasp loop" either purely operator controlled, or purely autonomously (i.e. solving an automatic rendezvous and docking problem). Thus the shared control concept in case of the remote capture was reduced to switching between the two extremal situations. Fig. 7 shows photos of the TV-scene out of one of the hand cameras immediately before successful, fully automatic grasping from ground despite of 6,5 sec round-trip delay, following the image processing approach in /10/. This automatic, ground-controlled capture of the free-flyer was one of the many spectacular actions of ROTEX. In a similar way spectacular was the on-board teleoperation by the German astronaut Hans Schlegel, especially in case of catching the free-flyer. The astronaut had no problem in controlling simultaneously 6 degrees of freedom using the control ball, he even was so highly motivated to train with the robot, that he spent nearly one hour of his sleeping time and during this period caught the free-floating object five times; after each release the object floated through the workcell being reflected at side walls and task-board parts like a billard ball.

4 Conclusion

For the first time in the history of space flight a small, multisensory robot (i.e. provided with modest local intelligence) has performed a number of prototype tasks on board a spacecraft in the most different operational modes that are feasible today.

Key technologies for the success of ROTEX have been

- the multisensory gripper technology; with 16 sensors and more than 1000 electronic components the ROTEX gripper presumably is the most complicated robot gripper built so far; nevertheless it worked perfectly during the mission. The stereo images out of the hand camera as well as those from the workcell camera were impressive.
- local (*shared autonomy*) sensory feedback control concepts, refining gross commands autonomously by intelligent sensory processing
- powerful delay-compensating 3D-stereo-graphic simulation (predictive simulation), which included the robot's sensory behaviour.

In addition to the overall performance observations the initialization phase showed interesting effects when different adaptive joint control parameters including friction observers were uploaded. Due to missing gravity the joints had no preloading and thus the controllers had to get along with backlash effects etc.. Evaluation of observed friction models is underway, performed by our colleagues from the university of Paderborn.

In-flight-calibration of the robot using the fingertip laser range finders improved its positioning performance.

The experiment also clearly showed that the information and control structures in mission control centres for future space robot applications should be improved, allowing the robot operator on ground direct access to the different types of uplinks and providing him with a continuous TV-transmission link.

Close cooperation between man (astronaut or ground operator) and machine comprising different levels of robot autonomy was the basis for the success of ROTEX. It was clearly proven that a robot system configured in this flexible way of arbitrary and fast switching between the most different operational modes will be a powerful tool in assisting man in future space flight projects and it was impressively shown that even large delays can be compensated by appropriate estimation and pre-simulation concepts.

5 References

/1/ S.Lee, G. Bekey, A.K. Bejczy, "Computer control of space-borne teleoperators with sensory feedback", Proceedings IEEE Conference on Robotics and Automation, S. 205-214, St. Louis, Missouri, 25-28 March 1985.

/2/ M.T. Mason, "Compliance and force control for computer controlled manipulators", IEEE Trans. on Systems, Man and Cybernetics, Vol SMC-11, No. 6 (1981, 418-432).

/3/ G. Hirzinger, K. Landzettel, "Sensory feedback structures for robots with supervised learning". Proceedings IEEE Conference, Int. Conference on Robotics and Automation, S. 627-635, St. Louis, Missouri, March 1985.

/4/ T.B. Sheridan, "Human supervisory control of robot systems". Proceedings IEEE Conference, Int. Conference on Robotics and Automation, San Francisco, April 7-10, 1986.

/5/ G. Hirzinger, J. Heindl, K. Landzettel, "Predictive and knowledge-based telerobotic control concepts". IEEE Conference on Robotics and Automation, Scottsdale, Arizona, May 14-19, 1989.

/6/ S. Hayati, S.T. Venkataraman, "Design and Implementation of a Robot Control System with Traded and Shared Control Capability", Proceedings IEEE Conference Robotics and Automation, Scottsdale, 1989.

/7/ L. Conway, R. Volz, M. Walker, "Tele-Autonomous Systems: Methods and Architectures for Intermingling Autonomous and Telerobotic Technology", Proceedings IEEE Conference Robotics and Automation, Raleigh, 1987.

/8/ G. Hirzinger, J. Dietrich, B. Gombert, J. Heindl, K. Landzettel, J. Schott, "The sensory and telerobotic aspects of the space robot technology experiment ROTEX", Proc. i-SAIRAS 2th Int. Symposium Artificial Intelligence, Robotics and Automation, in Space, Toulouse, France, Sept.30-Oct.2, 1992.

/9/ J. Funda, R.P. Paul, "Efficient control of a robotic system for time-delayed environments". Proceedings of the Fifth International Conference on Robotics and Automation, pages 133-137, 1989.

/10/ D. Dickmanns, "4D-dynamic scene analysis with integral spatio-temporal models", Fourth Int. Symposium on Robotics Research, Santa Cruz, Aug. 1987.

/11/ Christian Fagerer and Gerhard Hirzinger, "Predictive Telerobotic Concept for Grasping a Floating Object", Proc. IFAC Workshop on Spacecraft Automation and On-Board Autonomous Mission Control, Darmstadt, Sept. 1992

/12/ B. Brunner, G. Hirzinger, K. Landzettel, J. Heindl, "Multisensory shared autonomy and telesensor-programming – key issues in the space robot technology experiment ROTEX", IROS'93 International Conference on Intelligent Robots and Systems, Yokohama, Japan, July 26-30, 1993.

/13/ G. Hirzinger, A. Baader, R. Koeppe, M. Schedl, "Towards a new generation of multisensory light-weight robots with learning capabilities", IFAC'93 World Congress, Sydney, Australia, July 18-23, 1993.

/14/ G. Hirzinger, "ROTEX - The first Robot in Space", Proc. '93 ICAR Sixth International Conference on Advanced Robotics, Tokyo, 1993.

/15/ Won S. Kim, Paul G. Backes, Samad Hayati, Eva Bokor, Jet Propulsion Laboratory, "Orbital Replacement Unit Changeout Experiments with a Telerobot Testbed System", IEEE'91, Sacramento, Aug. 7-12, 1991.

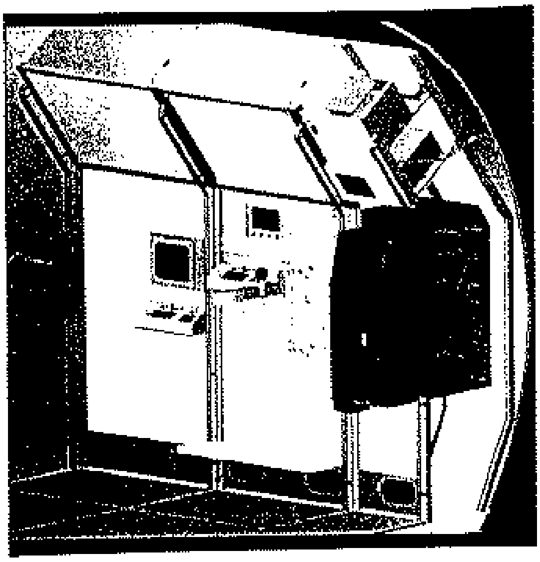

Fig. 1 ROTEX integration in spacelab (courtesy of DORNIER)

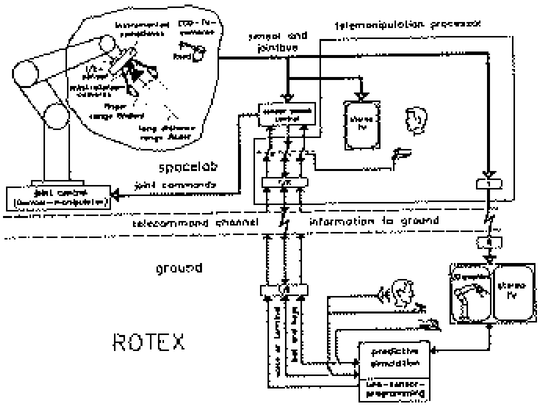

Fig. 3 The ROTEX control structures

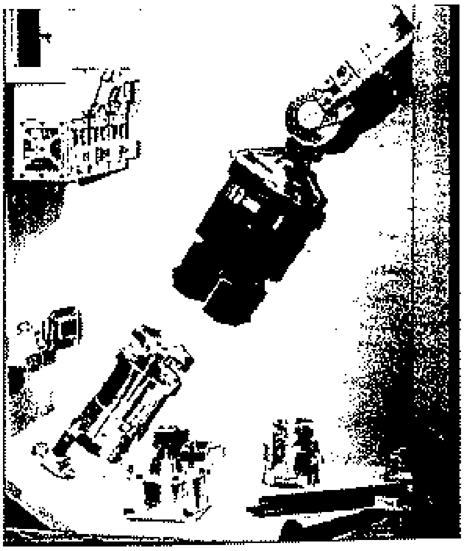

Fig. 2
ROTEX robot and experiment set-up in DLR laboratory, where the multisensory gripper is in just front of the bayonet closure (the "ORU"). The three-part truss structure is in the upper left corner. The lower left corner the free-flyer's fixture is visible. With more than 1000 electronic and several hundred mechanical elements the gripper is presumably the most complex one built so far.

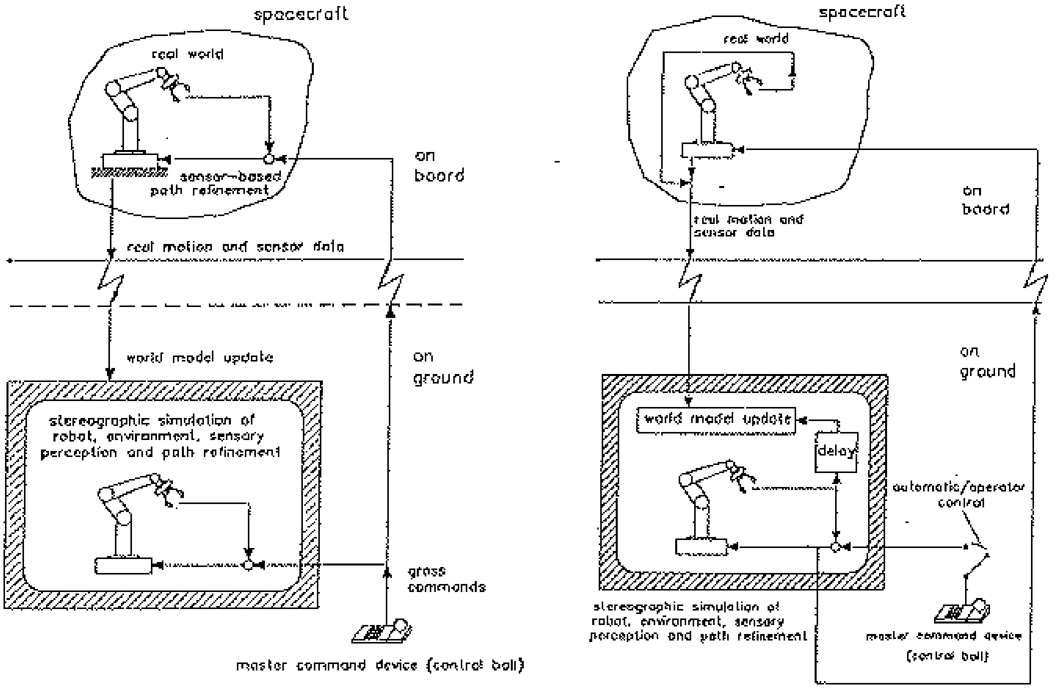

Fig. 4
Presimulation of sensory perception and path refinement in case of teleoperation from ground
a) local on-board sensory feedback (e.g. tactile contact)
b) sensory feedback via groundstation (grasping a free-flyer)

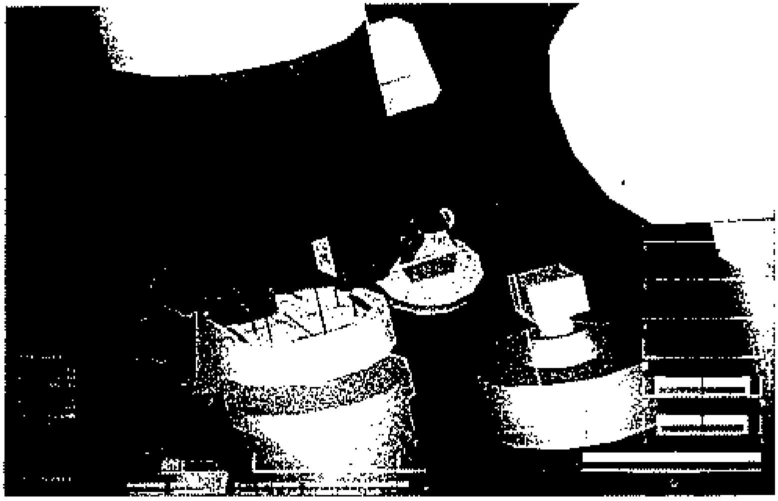

Fig. 5
Sensorsimulation:
Range finder simulation in the "virtual" workcell environment. In addition to the 5 simulated rays out of the gripper the bars in the right lower corner indicate the same simulated (bright) and the corresponding real (dark) range values as registered by the real robot.

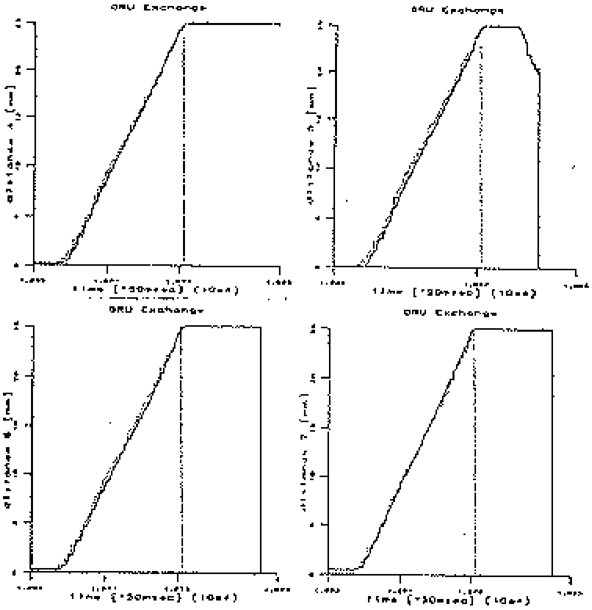

Fig. 6
Correlation between presimulated (for comparison delayed) and real sensory data (in closed loop each) was nearly perfect in ROTEX. These recordings of the four finger-range-finders pointing "downwards" were made during sensor-based teleoperation when removing the ORU bayonet closure (fig. 5).

Fig. 7
Two subsequent TV-images out of one of the hand cameras shortly before grasping the free flyer automatically from ground despite of 6 sec. round-trip-delay. The dark areas at the left upper and lower part are the gripper jaws.