Sensor-Based Space Robotics—ROTEX and Its Telerobotic Features

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***Abstract*—In early 1993 the space robot technology experiment ROTEX has flown with space-shuttle COLUMBIA (spacelab mission D2 on flight STS-55 from April 26 to May 6). A multisensory robot on board the space-craft successfully worked in autonomous modes, teleoperated by astronauts, as well as in different telerobotic ground control modes. These include on-line teleoperation and telesensor-programming, a task-level oriented programming technique involving "learning by showing" concepts in a virtual environment. The robot's key features were its multisensory gripper and the local sensory feedback schemes that are the basis for shared autonomy. The corresponding man–machine interface concepts using a 6-DOF nonforce-reflecting control ball and visual feedback to the human operator are explained. Stereographic simulation on ground was used to predict not only the robot's free motion but even the sensor based path refinement on board; prototype tasks performed by this space robot were the assembly of a truss structure, connecting/disconnecting an electrical plug (orbit replaceable unit exchange ORU), and grasping free-floating objects.**

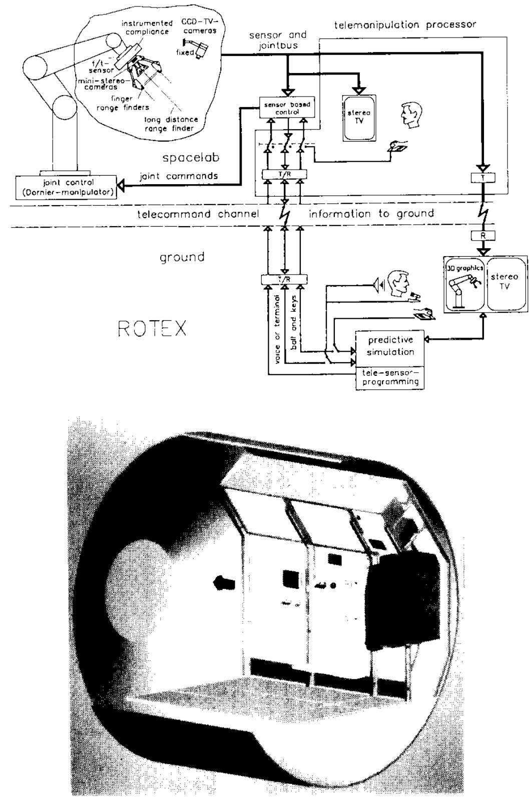

Fig. 1. Schematic representation of ROTEX (upper part) and integration in spacelab (picture, courtesy of DORNIER).

I. Introduction

Automation and robotics (A&R) will become one of the most attractive areas in space technology, 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.

This is one of the main reasons why several activities toward space robotics have started in a number of countries, one of the largest projects being the space station's mobile servicing center (MSC) with its two-arm special dexterous manipulator system to be built by the Canadian space agency. NASA's own big robot project, the flight telerobotic servicer (FTS), was cut down some time ago apparently due to excessive development costs, but we are sure that for a space station reduced in size, and may be only temporarily habited by astronauts, the use of robots will become a major issue again. Other remarkable mid-term projects are the Japanese space station "remote manipulator system" (JEM-RMS) or the Japanese ETS-VII project, a experimental flight telerobotic servicer for maintenance and repair of space systems. While the shuttle manipulator arm, which has been flown with the space-shuttle a number of times in the past (including spectacular actions like the solar-max satellite rescue in 1984), may be seen as a predecessor system for the Canadian MSC, there has been no space robot experience in Europe in the past. The European Space Agency ESA is going to prepare the use of robots in the European part COLUMBUS of the space station. Apparently those nations having less background and history in manned spaceflight have a strong interest in space robotics. On the other side we have a strong belief that 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 successfully flown now in space (spacelab mission D2 on shuttle flight STS 55 from April 26 to May 6, 93). ROTEX contained as much sensor-based on-board autonomy as possible from the present state of technology,

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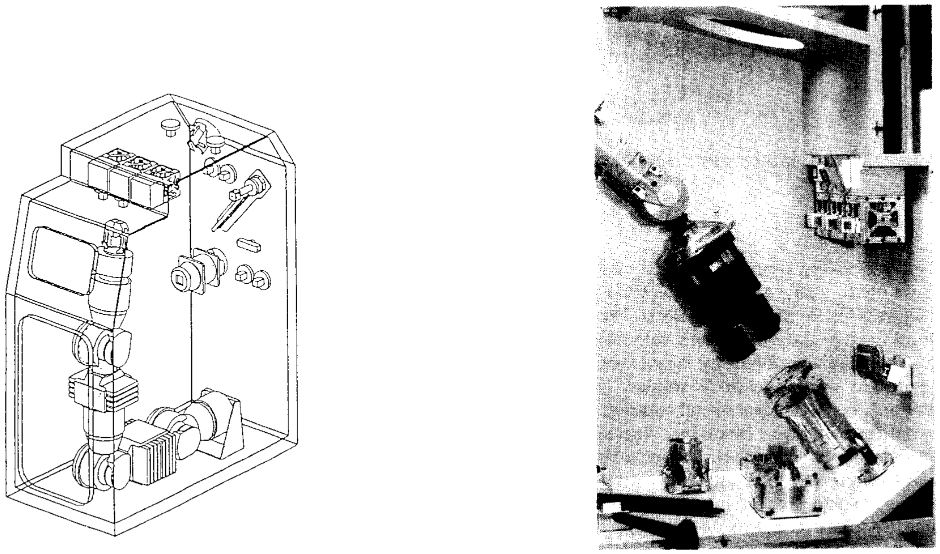


(a) (b)

Fig. 2. ROTEX robot and experiment set-up in spacelab rack (a) and in DLR laboratory (b), where the multisensory gripper is below the three-part truss structure just in front of the bajonet closure (the "ORU").

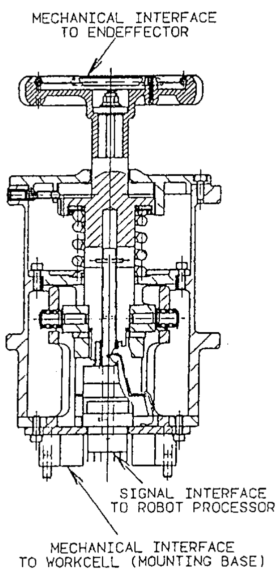


Fig. 3. ORU-exchange using a "bajonet closure."

but on the other side assumed that for many years cooperation between man and machine based on powerful telerobotic structures will be the foundation of high-performance space robot systems operable especially from a ground station, too. Thus ROTEX tried to prepare all operational modes that 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). The key features of this space robot project are explained in the sequel.

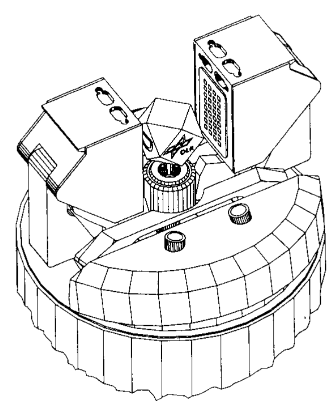


Fig. 4. Grasping a floating object.

II. ROTEX Overall Configuration

The experiment's main features were as follows (see Fig. 1):

- A small, six-axis robot (working space ~1 m) flew inside a space-lab rack (see Fig. 2). Its gripper was provided with a number of sensors, especially two 6-axis force-torque wrist sensors, tactile arrays, grasping force control, an array of nine 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:
  - — assembling a mechanical truss structure
  - — connecting/disconnecting an electrical plug (orbit-replaceable-unit-ORU-exchange using a "bajonet closure," see Fig. 3)
  - — grasping a floating object (see Fig. 4)

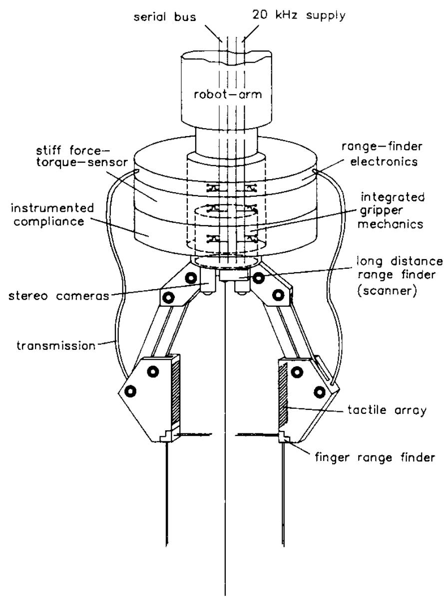


Fig. 5. Schematic drawing of the multisensory end effector (gripper).

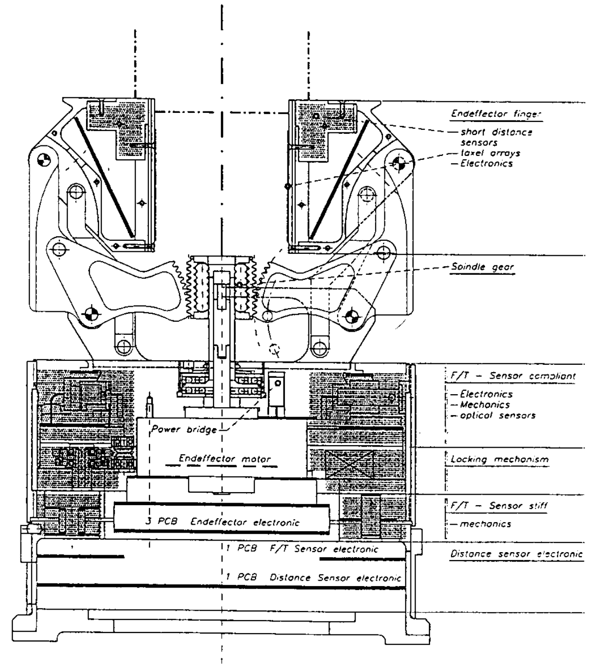


Fig. 6. Gripper section drawing.

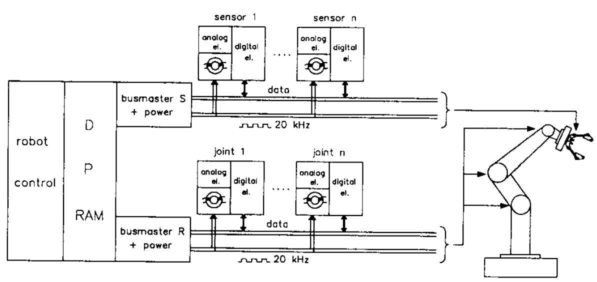


Fig. 7. Information and power transfer in the ROTEX multisensory gripper and in the joints developed for a new light-weight robot used for astronaut training.

- The operational modes were
  - — automatic (preprogramming on ground, reprogramming from ground)
  - — teleoperation on board (astronauts using stereo-TV-monitor)
  - — teleoperation from ground (using predictive computer graphics) via human operators and machine intelligence as well
  - — tele-sensor-programming (learning by showing in a completely simulated world on ground including sensory perception with sensorbased execution later on-board).
- The main 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 combination of a complex, multisensory robot system with powerful man–machine interfaces (as are 3-D stereo-computer graphics, 6-DOF control ball, stereo imaging), that allow teleoperation from ground, too.

DLR had the overall technical direction (prime investigator) and developed the sensory, mechatronics, and telerobotic systems described in this paper. Other important contributions came from the space companies DORNIER (built the arm's flight model) and MBB (provided the stereo cameras and TV transmission), the University of Paderborn (joint controller design) the Fraunhofer Institute IPK in Berlin (in-flight calibration and conventional off-line programming), the University of Dortmund (coordinate transformation, collision detection, μg-path planning) and the University of the Bundeswehr in Munich (collaboration in the free-flyer experiment).

Local sensory feedback from the multisensory gripper was a key issue in the telerobotic concepts used, so we will address the gripper's components in more detail.

III. The Multisensory Gripper

The gripper sensors belong 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 Figs. 5 and 7). Using a high speed serial bus only two signal wires are coming out of the gripper (carrying all sensory

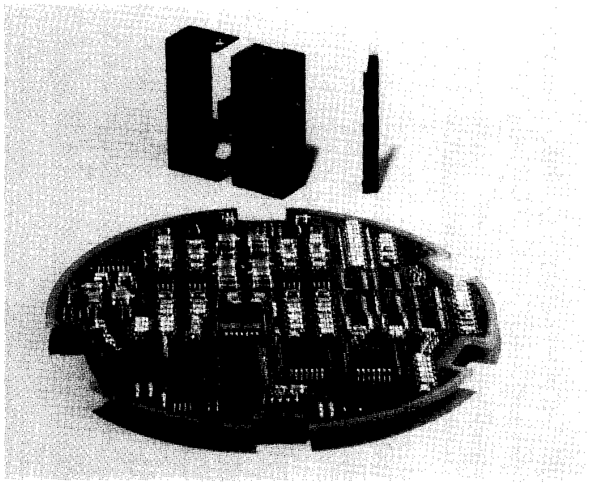


Fig. 8. Medium range sensor and wrist electronic board for all range finders.

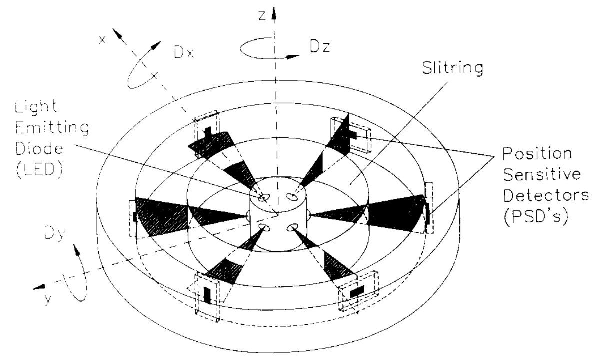
information), augmented by two 20-kHz power supply wires, from which the sensors derive their dc-power supply voltages via tiny transformers themselves.

This same concept with a "busmaster" board exchanging all relevant information with the robot control system via a nearly delay-less dualport-memory is used also (see Fig. 7) to connect all joints of a new light-weight astronaut training manipulator (see below). Up to now the serial bus speed has been 375 kBaud, but will now be raised up to 4 MBaud.

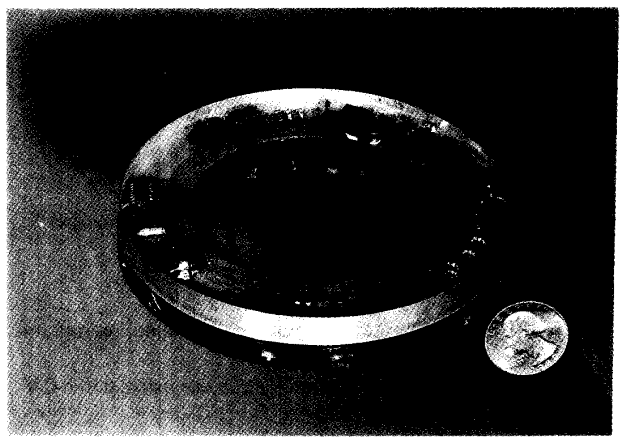
In the gripper 15 sensors are provided, in particular (see Figs. 5 and 6):

a) An array of 9 laser range finders based on triangulation, one "big" sensor (i.e., half the size of a match box) for the wider range of 3–35 cm (see Fig. 8), and smaller ones in each finger for lower ranges of 0–3 cm.
b) A tactile array of 4 × 8 sensing elements (conductive rubber "taxels") in each finger developed by Fachhochschule Aalen. The dimensions of the tactile area is 32 × 16 mm. The binary state of each taxel is serially transmitted through analog multiplexers without additional wiring.
c) A "stiff" 6 axis force—torque sensor based on strain—gauge measurements and a compliant optical one. Originally it seemed necessary to make a final decision between these two principles, but as indicated in Fig. 5 and 6 they finally were combined into a ring—shaped system around the gripper drive, the instrumented compliance being lockable and unlockable electrically. Shaping these sensors as rings around the gripper drive shows up different advantages:
   - It does not prolong the axial wrist length.
   - It brings the measurement system nearer to the origin of forces—torques and yields a better ratio of torque range to force range than achievable with a compact form.

   The optically measuring instrumented compliance (see Fig. 9) was, e.g., described in [10].



(a)



(b)

Fig. 9. (a) Schematic diagram and (b) ring-shape realization of the instrumented compliance.

   The stiff, strain—gauged force—torque sensor is a new design no longer based on spokes or bars but membranes. It performs automatic temperature compensation based on the temperature characteristic as stored during the calibration process. The ring-shaped form of this new sensor containing all electronics and preprocessing may be seen in Fig. 10.
d) A pair of tiny stereo CCD-cameras, the CCD's plus optics plus minimum electronics taking a volume smaller than a match—box, too.
e) An electrical gripper drive, the motor of which is treated like a sensor with respect to the data bus and the 20 kHz power supply connections. The design criteria for this drive are outlined in the next chapter.

With more than 1000 tiny SMD electronic (see Fig. 11) and several hundred mechanical components the ROTEX gripper is probably the most complex multisensory end-effector that has been built so far. The gripper was not space qualifiable on component level especially because SMD technology is not yet generally permitted in space, so it had to undergo vibration, temperature, off-gasing and EMC-tests as a whole. As a positive experience during the flight all gripper sensory and drive systems (which were permanently sending their tem-

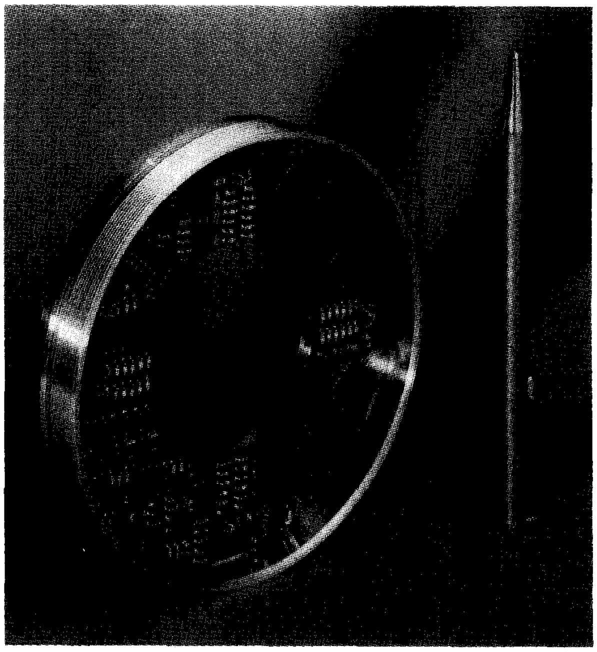


Fig. 10. Ring-shape structure of the end effector's membrane-based strain gauge sensor with all preprocessing integrated.

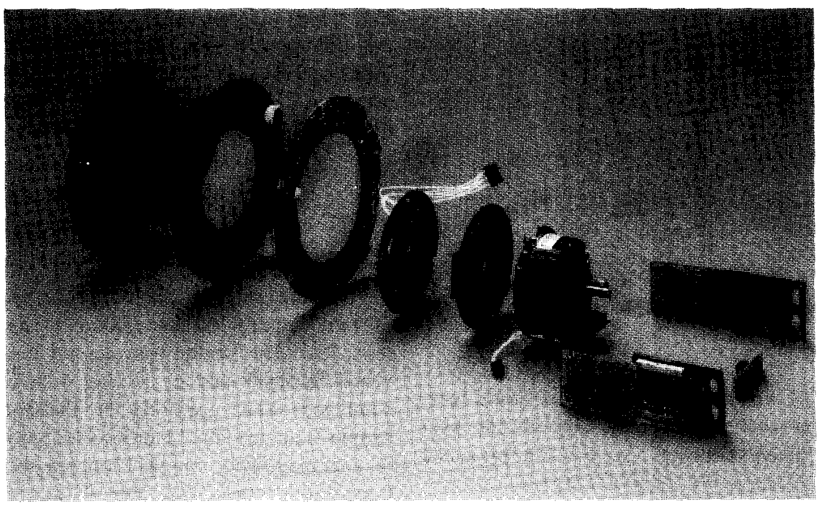


Fig. 11. The multisensory ROTEX gripper integrates more than 1000 tiny SMD-components.

peratures down in addition to the measuring values) remained below 40°C, while being operable up to 80°C. All components worked absolutely reliable.

IV. Actuators

Space technology may become a major development drive for advanced light weight robots. For ROTEX two design problems were of crucial interest:

a) to arrive at an electrical gripper drive that allows fine positioning and reasonable grasp force feedforward control with grasping forces up $\approx$ 300 N (the gripper without sensors weighing $\approx$ 10 N).

b) to arrive at revolute joint drives for a 1g-compatible training manipulator with very high reduction but extremely compact construction and integrated torque measurement and control. Indeed the robot arm flight model as built by the space company DORNIER could not sustain itself in a 1g environment.

A. Rotational–Translational Gearing

In the gripper the problem is to transform the motor's high-speed rotational motion into a fairly slow axial motion to move

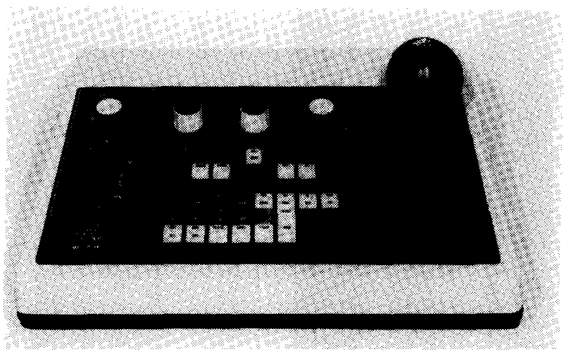


Fig. 12. ROTEX on-ground telecommand system with control ball and gripper position/force control joysticks.

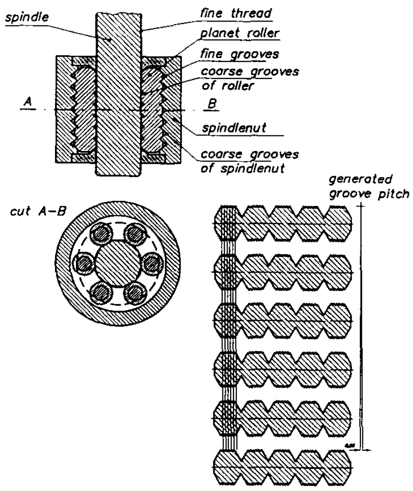


Fig. 13. A new spindle concept for the gripper drive.

the fingers (see Fig. 6). For this type of transmission a new, extremely low friction mechanical spindle concept has been designed based on a "phase shift trick" (see Fig. 13, for details see [10]).

What we gained with this motor–gearing combination is a small prismatic drive (applicable also in a robot joint), which used as gripper drive allows to exert grasp forces up to 300 N with a gripper weight of 5 N and a grasp speed of about 15 cm/sec; without measuring and feeding back grasp forces we arrived at a feedforward grasp force control resolution of $\approx$ 1–2 N (< 1 \% of max force) with high repeatability. Reduction rate referring to the finger rotation is $\approx 1:1000$.

B. Rotational–Rotational Gearing

The "phase-shift" ideas as applied to the aforementioned spindle concept have meanwhile been transferred to pure rotational gearings, too (for details see e.g., [10]). In an advanced version these gearings will imply inductive torque sensing and feedback control integrated in the joints (see Fig.

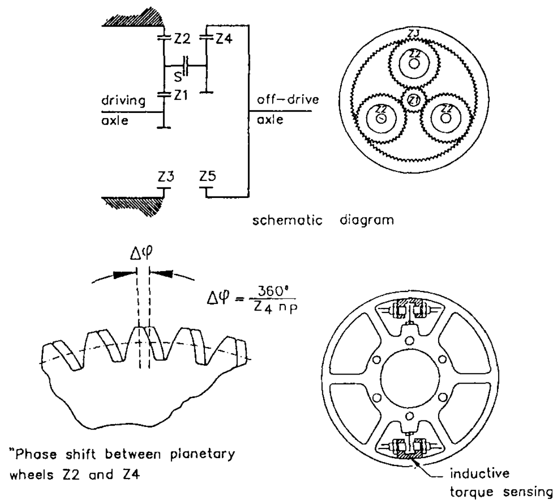


Fig. 14. The new compact, high reduction gearing with integrated torque measurement and control.

14). For a light-weight 1:1 replica of the ROTEX arm, the new joint design was integrated into a carbon fiber grid construction (see Fig. 15(b) and [10]). As the ROTEX flight model (see Fig. 15(a)) was not able to sustain itself in 1 g environment, this light-weight robot design aiming at a 1:1 ratio between load capability and own weight (100N both) was used for the astronaut training on ground and is thought to be a first step toward a real light-weight space robot.

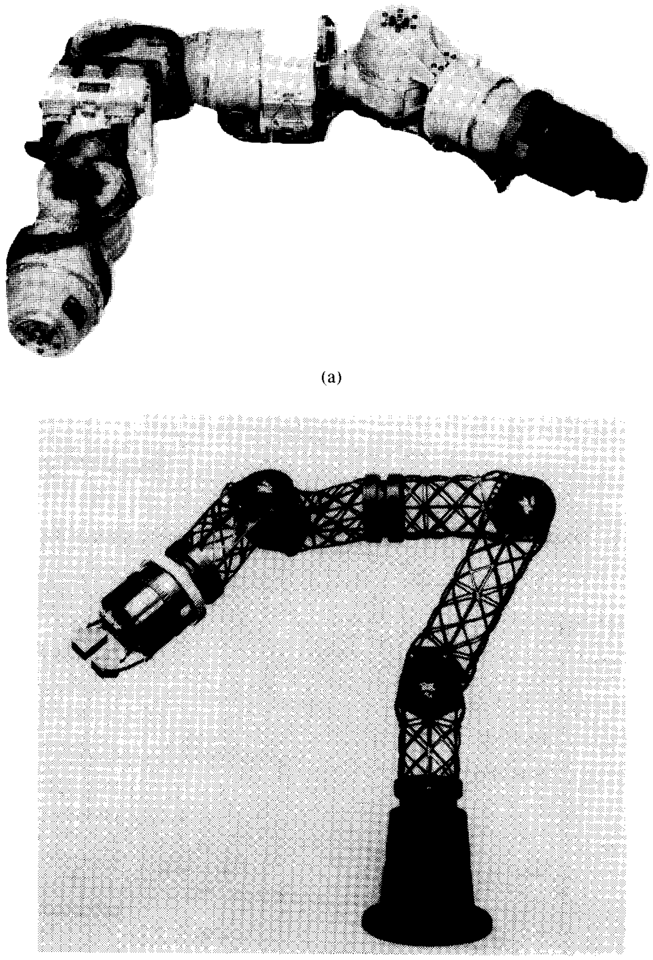
V. The Telerobotic Concepts

A. Shared Control and Man-Machine Interfaces

The fine motion planning concept of ROTEX is a "shared" control concept based on local sensory feedback (e.g., [5]). The human operator—if needed—is involved via visual feedback and by issuing 6-DOF feedforward control commands when operating the socalled "control ball." This simple man–machine interface is based on the integration of a miniaturized, compact version of the compliant 6-axis force-torque sensor (see Fig. 9) into a hollow plastic ball. Thus commands generated via the human hand are originally force-torque commands as well ("dual" interpretation). In ROTEX these hand-controllers (see Fig. 12) were not only used on-board by the astronauts, but also by the ground operators when operating the graphically simulated robot, or when moving around the whole (graphically simulated) workcell scenery (i.e., the operator is steering himself around the virtual world). A new version of this technology, the "space control mouse," seems to become a standard input device for 3-D graphics systems now.

The main features of our shared control philosophy—briefly outlined—are (see Figs. 16 and 17):

Rudimentary commands $\boldsymbol{\Delta x}$ are derived either from the control ball's forces-torques $\boldsymbol{f}$ (using a sort of artificial stiffness relation $\boldsymbol{\Delta x} = \boldsymbol{S}_x^{-1}\boldsymbol{f}$) or from a path generator



(a)

(b)

Fig. 15. (a) ROTEX flight robot built by DORNIER (courtesy of DORNIER). (b) DLR-light-weight training robot for astronaut training.

connecting preprogrammed points (Δx being the difference between the path generator's, i.e., "master's," position and the commanded "slave" robot position x_{com}). Due to the above-mentioned artificial stiffness relation these commands are interpreted in a dual way, i.e., in case of free robot motion they are interpreted as pure translational/rotational commands; however if the robot senses contact with the environment, they are projected into the mutually orthogonal "sensor-controlled" (index \\, f) and "position-controlled" (index p) subspaces, following the *constraint (c-) frame concept* of *Mason* [4]. These subspaces are generated by the robot autonomously using *a priori* information about the relevant phase of the task and actual sensory information: in a future stage the robot is supposed to discriminate the different task phases (e.g., in a peg-in-hole or assembly task) automatically. Of course the component Δx_p projected into the position controlled subspace is used to feed the position controller; the component f_f projected into the sensor-controlled subspace is either compared with the sensed forces f_{sens} to feed (via the robot's Cartesian stiffness S_R) the orthogonally complementary force control law, (which in fact is another position controller realizing "active compliance control" and yielding a velocity $\dot{x}_f$), or it is neglegted and replaced by some nominal force vector f_{nom} to be kept constant, e.g., in case of contour following (representing classical hybrid force control). We prefer to talk about sensor-controlled instead of force-controlled subspaces, as nontactile (e.g., distance) information may be interpreted as pseudoforce information easily, the more as we are using the robot's positional interface anyway. However we omit details as treated in [5] concerning transformations between the different Cartesian frames (e.g., hand system, inertial system, etc.). Note that in case of telemanipulation via a human operator although we are not feeding the forces back to the human arm (as does "bilateral" force control with the well-known stability problems in case of delays), the operator is sure that the robot is fully under his control and he easily may lock up doors, assemble parts or plug in connectors. In other words,

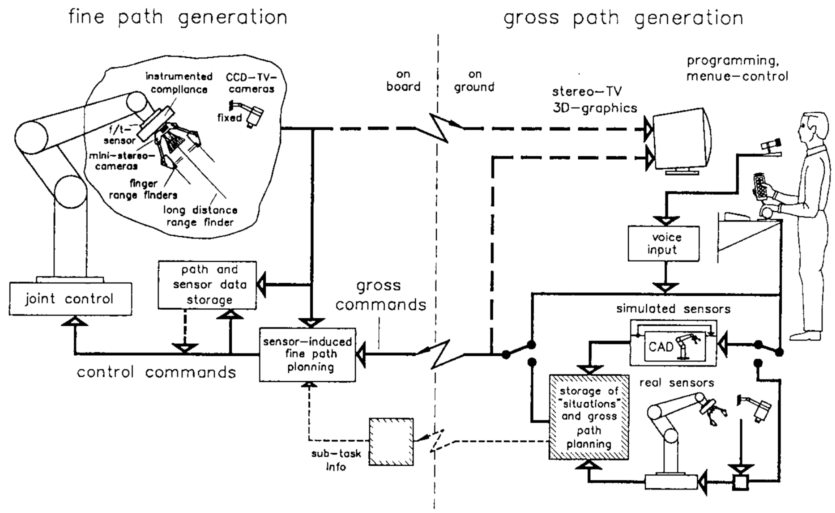


Fig. 16. Overall loop structures for the sensor-based telerobotic concept of ROTEX.

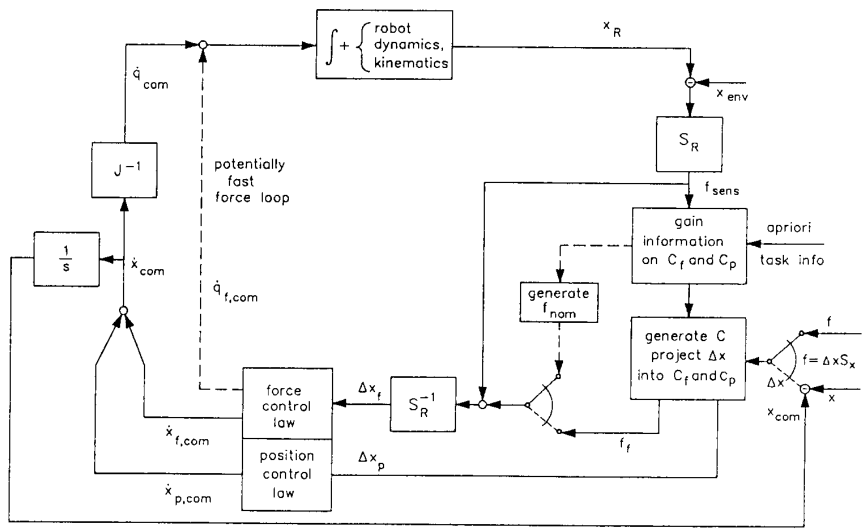


Fig. 17. The local closed loop concept with automatic generation of force and position controlled directions and artificial robot stiffness.

the human operator (via stereovision and 3-D graphics) is enclosed in the feedback loop on a very high level but low band-width, while the low level sensory loops are closed on-board at the robot directly with high bandwidth. Thus we prepare a supervisory control technique [7] that will allow to shift more and more autonomy to the robot in the future, without changing the basic structure of Fig. 16, and always offering real-time human intervention. One of the main issues here is that in case of nonnegligible time delays stereo-visual feedback is replaced by predictive stereo graphics, leaving the basic structures untouched, independent on whether astronauts or on ground personnel are operating the robot in space. In ROTEX the astronauts looking at a small TV-monitor used shutter glasses synchronized with the left-right-camera image display switching with 60 Hz. The same shutter technique was used in the ground station graphics and video displays (see Fig. 27).

B. Predictive Control and Telesensor-Programming

When teleoperating a robot in a spacecraft from ground or from another spacecraft so far away that a relay satellite is necessary for communication, the delay times are the crucial problem. In ROTEX the loop delays varied from 5–7 sec (Fig. 20). Predictive computer graphics seems to be the only way to overcome this problem. Fig. 21, e.g., outlines that in an on-line mode a human operator at the remote workstation may handle the control ball by looking at a "predicted" graphics model of the robot. The control commands issued to this instantaneously

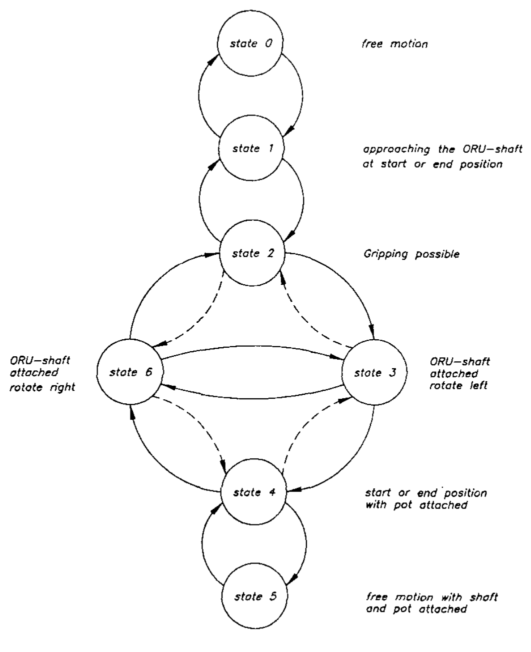


Fig. 18. ORU experiment graph.

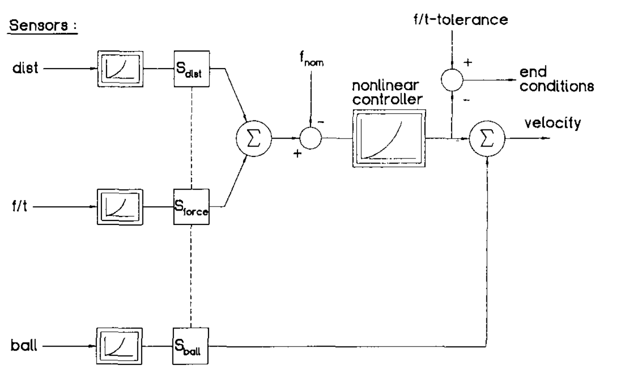


Fig. 19. Detailed shared control part.

reacting robot simulator are sent to the remote robot as well, using the time-delayed transmission links.

But, e.g., in case of an assembly operation, realistic real-time simulation of robot environment *and* sensory perception is required so that the predictive graphics motion implies sensor-based fine path generation in an on-line closed loop scheme, thus imitating the real system with its local on-board sensory feedback (Fig. 21(a)). Complex tasks are split up into elemental moves for which a certain constraint-frame and sensor type configuration holds (defined by the operator), which allows the simulated (as well as the real) robot to refine the gross commands autonomously. We have coined the term "tele-sensor-programming," which includes these sensor-based on-line teleoperation techniques (providing, e.g., remote active compliance) as well as the corresponding off-line version which may be characterized as "sensor-based teaching by showing." The robot is hereby graphically guided through the task (off-line on ground), storing not only the relevant hand frames but also the corresponding nominal sensory patterns (graphically simulated) for later (e.g., associative) recall and reference (Fig. 16) in the on-board execution phase, after these data sets have been sent up. Thus we might talk of storing "situations." Indeed this mode of tele-sensor-programming is a form of 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.

The elemental move concept implied here requests various definitions and procedures, in particular the following:

- Defining (or graphically demonstrating) the initial and goal situations (positions augmented by nominal sensory patterns).
- Providing the *a priori* knowledge on the C-space configuration.
- 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.

Realistic simulation of the robot's environment and especially the sensory information (Fig. 22) presumably perceived by the real robot is of crucial importance for this approach.

Two levels of world modeling were involved in the ROTEX ground control station:

1) *Coarse modeling on object level:* In addition to approximating each workcell (including robot) part by a convex polytope for fast object detection on distance sensor level, an alternative approach partitions the space occupied by the objects on a polyhedron level, similar to a cell-tree representation. We have implemented an efficient index structure on convex closed polyhedron with the advantage of a fast yet very precise search for actually interesting objects. Application of this object representation is the computation of object intersection with the rays of the laser scanner as well as collision detection. Of course a fast restriction of the interesting regions to a minimal number of polyhedra is desired. These interesting regions (leaves of the cell tree) are mapped into the local databases on which the realtime laser distance simulation runs.

   The leaves of the cell-tree characterize the interesting regions. Each leaf wears a local data base on which the sensorsimulation runs. As the cell-tree is specified only for convex polyhedrons, the knots passed during object selection consist of the convex hulls of the objects involved.

   In the leaves (local databases) of the cell-tree—i.e., after object selection— a relation is evaluated which

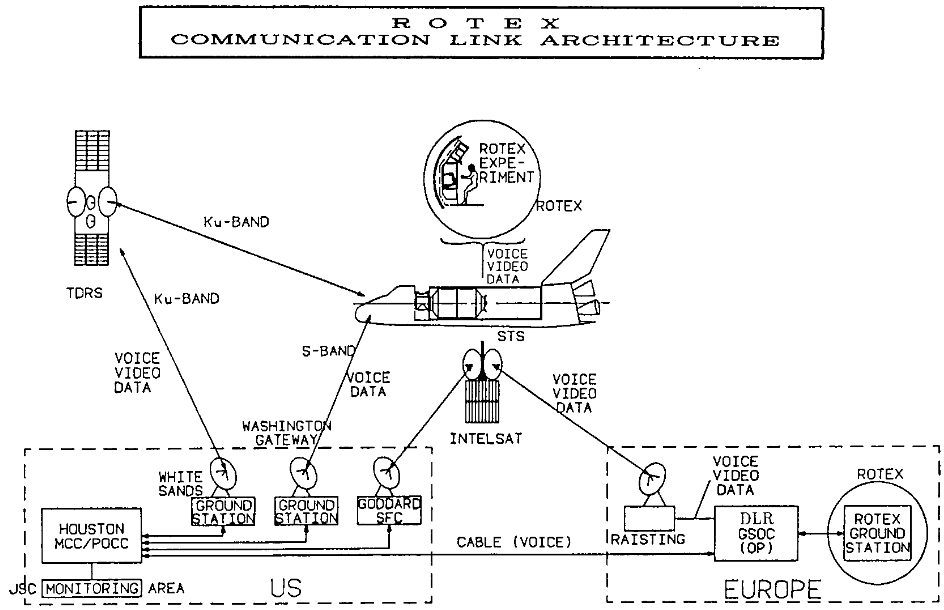


Fig. 20. The ROTEX signal transmission loops (courtesy of DORNIER).

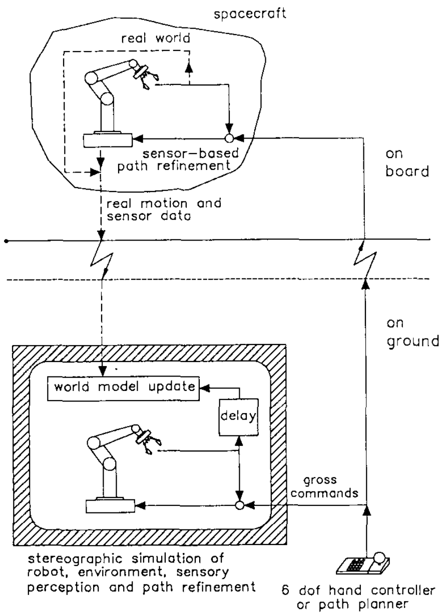
assigns the real areas of, e.g., a concave original object to the areas of the convex hull. This area relation is generated during construction of the geometric world model. Intersection and interference checks preceded by a corresponding object selection are thus realizable in an efficient way for convex as well as for concave objects.

For force simulations, the interesting regions are determined in a similar way based on the motion direction of the tool center point and a potential overlapping of the gripper parts mounted at the robot's tool center point with all other parts of the workcell lying within a predefined collision range.

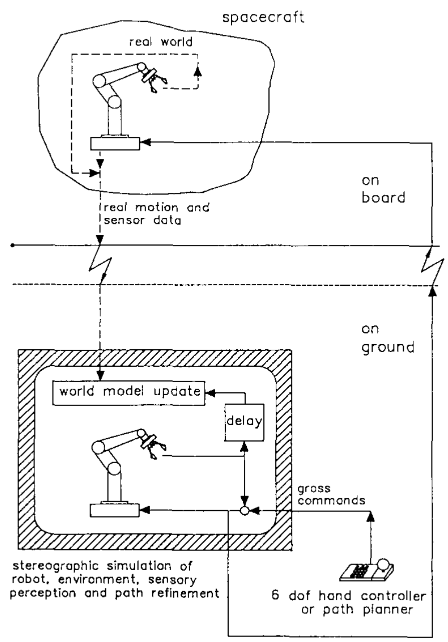
2) *Fine modeling on surface level (local data base level):* After determining the colliding objects, a fine modeling on surface level of the object representation, e.g., for precise laser range simulation, is important. An exact boundary representation model is available via the geometry modeler CATIA. After modification and extension of the given data basis different local databases are accessible which refer to the single objects only. For the range finder simulations we assume that the optical features of the object surfaces are negligible and that it is sufficient to work on the geometric models of the workcell parts.

In case of simulation of the force-torque sensor we have to distinguish between two different cases of manipulating an object in the workcell. First we consider the case where the robot gripper is moving in the free space or approaching an object or in contact with colliding parts. The available information about the geometrical interferences is used first to classify the contact type, second to determine the corresponding constraint equations. Each contact represents a natural motion constraint and a corresponding artificial force constraint. In building the constraint equations we follow the approach given in [19]. Compliance of environment as well as friction is not taken into account due to low motion speed of the robot. At the same reason we can even neglect all the robot's dynamics. In case of contact between gripper and environment the resulting motion and force constraints act in the directions of the corresponding surface orientations expressed by the known normals in the contact points. Given this constraint equations and the sensor stiffness matrix we can easily calculate the forces and torques in the virtual environment. In practice there are a lot of problems to be solved: to determine the motion constraint equations, we have to consider the linear independency of the resulting equation system. To get realtime solutions for building consistent linear independent constraint equations we have developed a sophisticated algorithm to exactly determine quality and quantity of the contact type.

In the case where the robot has grasped an object mounted in the environment, a closed kinematical chain exists between the environment and the robot (e.g., the robot grasps the ORU and has first to activate the bajonet closure mechanism before moving around the ORU). In this situation of a kinematical dependency between robot and environment, we cannot calculate the simulated forces and torques via the interference check described before. In this case we determine the virtual deviation of the simulated gripper frame from the predefined frame in the idealized gripping position, which is known at the task level. Given this deviation, constraint equations can be determined which can be used to calculate the forces and torques in a similar way as before.



(a)



(b)

Fig. 21. 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).

The problem to choose the interference check or to use the virtual deviation within the kinematical chain for emulating the force-torque sensor is solved via the phase selection concept described earlier in this paper.

There are errors expected in the sensor simulation, and therefore not only the gross commands of the TM command

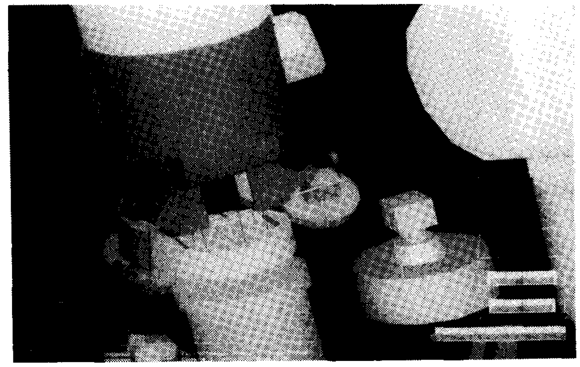


Fig. 22. Sensorsimulation: Range finder simulation in the "virtual" workcell environment. In addition to the five simulated rays out of the gripper (see Fig. 5) the bars in the right lower corner indicate the same simulated (bright) and the corresponding real (dark) range values as registrated by the real robot.

device (control ball) are fed into the simulation system, but also the real sensor data coming back from space (including the real robot position) are used to improve the robot's and its sensor's models (world model update in Fig. 21(a)). In ROTEX, all sensory systems worked perfectly and the deviations between presimulated and real sensory data were minimal (Fig. 23). This was one of the many positive surprises of ROTEX.

C. The Orbit-Replaceable-Unit (ORU) Exchange as an Example

The aforementioned shared control techniques are explained in more detail by hand of the detailed task activities of the ORU experiment, which includes a bajonet closure (see Fig. 2) screwing operation:

Like other hierarchical robot control approaches [15] the ORU-experiment is managed at least on three levels.

- In a first *task planning level* the ORU-task is decomposed into seven subtasks as a necessary presupposition for shared control.
- In the *task coordination level* the subtasks are coordinated with the elementary transactions that lead into the different mounting or assembly states. They are treated as knots of a mounting-graph-data-structure while the elementary actions represent the branches of it (see Fig. 18).

The main conditions that cause transients from one mounting state to the other are summarized below and are managed like rules of an expert system:

$0 \rightarrow 1$ the four small distance range finders pointing "downwards" (gripper axis or z-direction) send valid data (distance in z-direction < 30 mm)

$1 \rightarrow 2$ distance in z-direction ≈ 0, f/t_z indicates contact in z-direction

$2 \rightarrow 3$ gripper open $\rightarrow$ ORU-shaft-attached turning counter-clockwise (note that by *opening* the gripper the kinematic chain between gripper and ORU-shaft, i.e., the wheel like grapple fixture upper part of the ORU is closed)

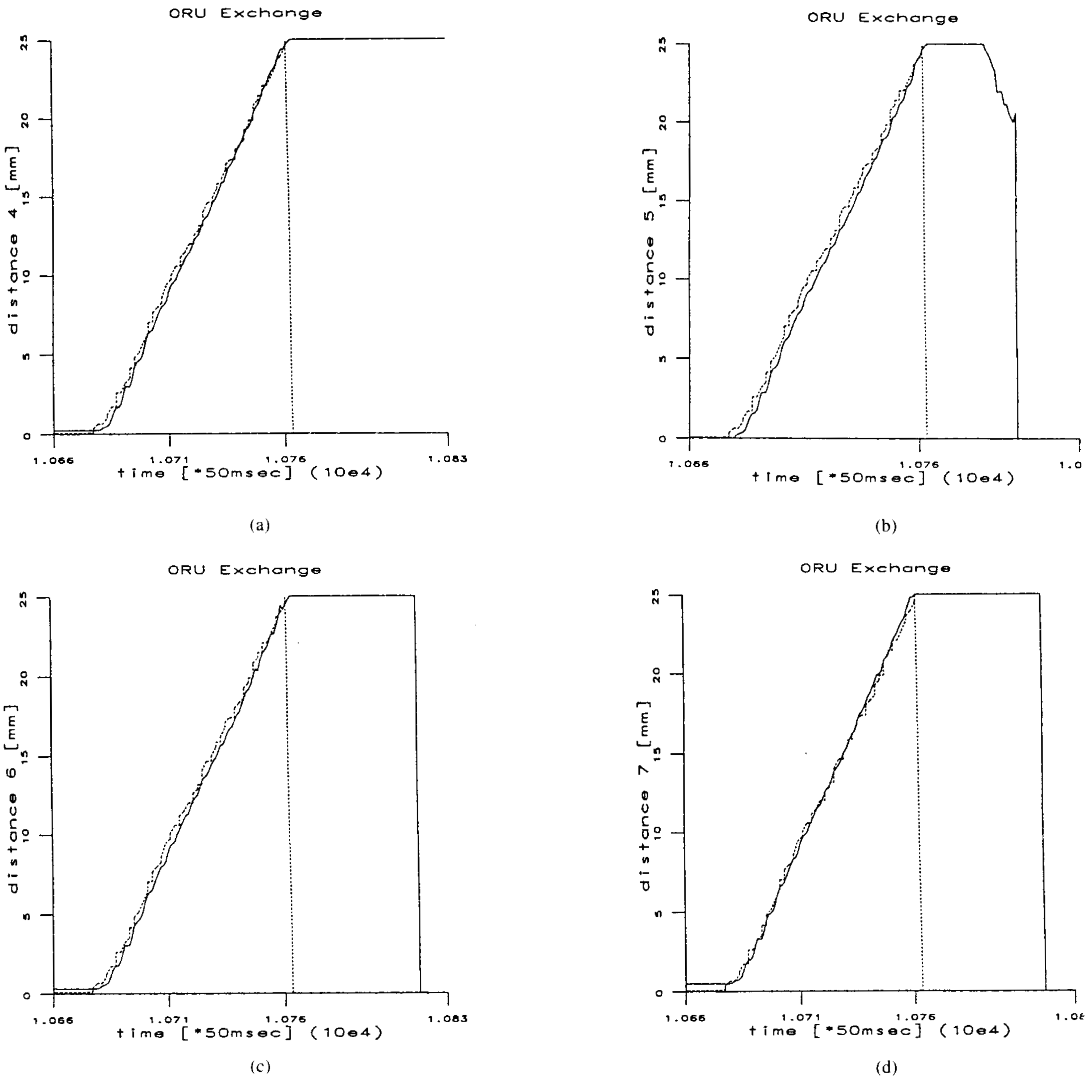


Fig. 23. Correlation between presimulated (for comparison delayed) and real sensory data (in closed loop each) was nearly perfect in ROTEX. These recordings of the four finger-range-finders pointing "downwards" were made during sensor-based teleoperation when removing from the ORU bajonet closure (see Fig. 22). (a) Distance 4 mm. (b) Distance 5 mm. (c) Distance 6 mm. (d) Distance 7 mm.

$3 \rightarrow 4$ A major torque component arises in positive z-direction

$4 \rightarrow 5$ no forces observable and tool-center-point-(TCP)-frame out of start or end position of ORU

The other transitions may be derived very easily.
In each of the mounting states an appropriate control phase is active with a set of parameters for sensordata selection and non linear control law as well as nominal sensordata and end-condition data. In Fig. 19 S_{dist}, S_{force}, and S_{ball} represent the selection matrices via which the different sensordata are connected to the sumup knot and compare position involving the nominal force/torque data. Thereby all sensordata are treated as generalized pseudo forces or torques including distance values and sensor ball data.

- In the *task execution level* the different control phases are activated dependent on the mounting states. In case of teleoperation the operator has the possibility to select the appropriate control phase via push bottons or he may be supported by a mounting state recognizing algorithm (MSR) that will be replaced by a neural net in the future. The MSR is already used to transmit *a priori* information of constrained phases to the online sensor simulation on ground.

Note that the ORU exchange task is typical for shared autonomy concepts, as, e.g., the "elemental move" gross command "turn the shaft" implies that due to the local force feedback loops a screwing operation is automati-

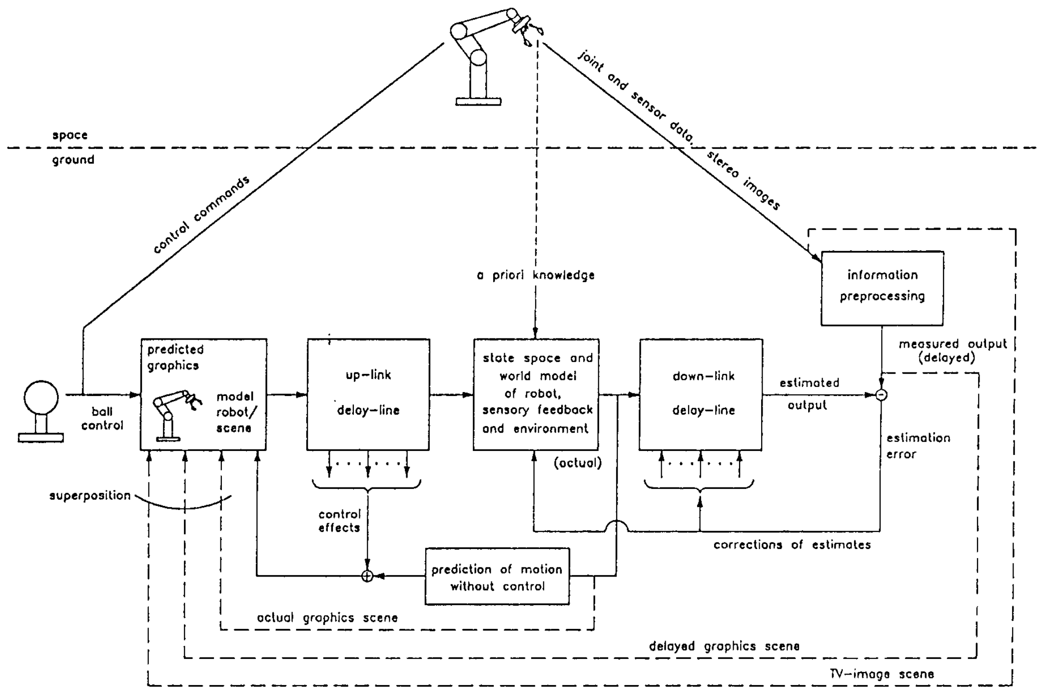


Fig. 24. Block structure of predictive estimation scheme.

cally generated trying to compensate for the arising forces along the z-rotation axis.

D. Catching a Floating Object

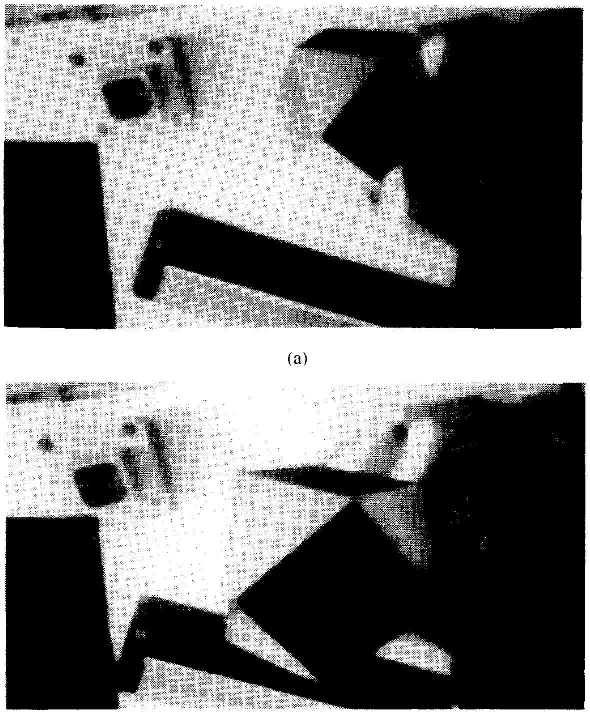
There was only one exception from the local sensory feedback concept in ROTEX. It refers to (stereo-) image processing. In the definition phase of ROTEX (around 1986) no space qualifiable image processing hardware was available; nevertheless we took this as a real challenge for the experiment "catching a free-floating object from ground" (see Fig. 21(b)) 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; one is based on the "dynamic vision approach" as given in [20], using only one of the two tiny hand-cameras, the other one is a full stereo approach realized in a multitranspuper system. In both cases the thus "measured" object poses are 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 (see Fig. 23); this Kalman filter [9], [21] 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 via shared control, or purely autonomously (i.e., solving an automatic rendezvous and docking problem). Fig. 25 shows photos of the TV-scene out of one of the hand cameras immediately before successful, automatic grasping from ground despite of 6 s round-trip delay, following the image processing approach in [20].

A summarizing representation of the telesensor-programming concept realized in ROTEX is given in Fig. 26.

In the telerobotic ground station (Fig. 27) 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 that may be varied by a control ball or its recent successor, the miniaturized "space-control-mouse." During the ROTEX mission we did not overlay real and simulated images, instead the real end-effector'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 (see Fig. 22), while an additional SGI system displayed the time history of simulated and real sensory signals shifted by the actual delays, thus correlated in time (see Fig. 23).

VI. Conclusion

ROTEX was Europe's first active step into space robotics. It proved that already today complex multisensory space robot systems can be successfully operated in the most different modes with fast transients between these modes allowing to quickly adapt to different situations. For example during the flight when the robot was supposed to move back from



(a)

(b)

Fig. 25. Two subsequent TV-images out of one of the hand cameras shortly before grasping the free flyer automatically from ground. The dark areas at the left and right lower part are the gripper jaws.

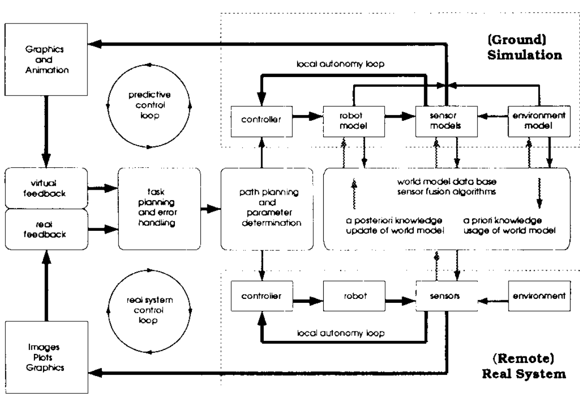


Fig. 26. The telesensor-programming concept of ROTEX.

an arbitrary contactless situation into its standby position automatic path planing was applied, while when in contact with the environment a more cautious ground teleoperation was chosen. We clearly state that two key issues were crucial for making ROTEX a unique event and a big success

— the multisensory gripper and, tightly connected, the local sensory feedback concept based on shared autonomy
— the predictive stereographics simulation based on world models that include sensory perception and feedback

Delays of up to 7 s (permanently registrated) were thus compensated without major problems. The ROTEX control

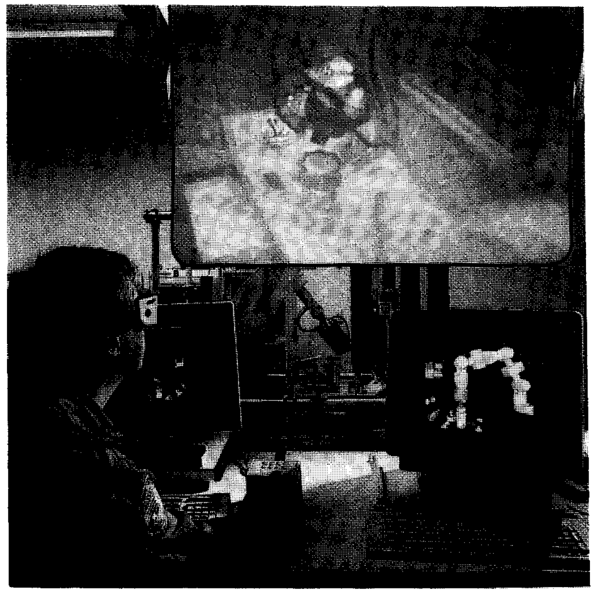


Fig. 27. A part of the telerobotic ground station that was used for training by the astronauts, too.

structures are thus that in the future the human operator may step more and more toward even higher on-board autonomy without changing the loop structures. However we feel that for a number of years remotely operated robots will show up limited intelligence only, so that human "anytime" intervention will remain important for a long time to come.

ROTEX has not been an operational system that might have helped the astronauts to do their job. It was an experimental system that helped to convince the space community that amazing tasks can be performed even from ground by a flexible space robot system that is reasonably based on cooperation between man and machine. In the same way the absolutely positive and ambitious attitude of the astronauts handling the robot helped to avoid fruitless discussions around "man or machine" (see Fig. 27).

Finally we believe that the sensor-based technologies and the telesensor-programming concept involved in ROTEX will find a number of terrestrial spin-off applications, e.g., in the wide field of off-line robot programming.

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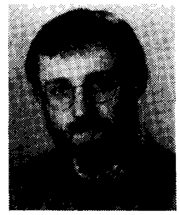

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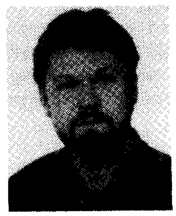

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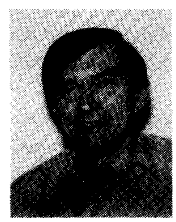

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