DLR's ROBOTICS LAB – RECENT DEVELOPMENTS IN SPACE ROBOTICS

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ABSTRACT

The paper gives an overview of DLR's latest developments and project experience in space robotics. From the technology point of view, progress in the design and development of light weight robots and articulated multifinger-hands as well as in the refinement of DLR's sensor-based, task level teleprogramming system MARCO (and its virtual reality concept) is reported. In addition DLR's experiences with NASDA's free flying space robot ETS VII in terms of sensor-controlled ground programming and dynamic robot-satellite interaction are outlined. Ongoing laboratory experiments towards free flying space robots (ESS) are supposed to prepare the basis for a European or German free-flyer project. And the design of endeffector technologies and ground control concepts for the robotic part of EuTEF on the International Space Station are fully underway.

1 INTRODUCTION

After four decades of manned space flight, where many activities have become routine, one might forget that the space environment continues to be extremely hostile to human beings. They have to be encapsulated in vehicles (for intra-vehicular activities IVA) or special, extremely expensive suits, which protect them from the hazard of the space environment (for extra- vehicular activities EVA). When comparing human skills with those of present-day robots of course human beings in general are by far superior, but when comparing the skill of an astronaut in a clumsy space-suit with that of the best available robot technology, then the differences are already going to disappear, the more if there is a remote control and monitoring capability on ground with arbitrarily high computational and human brain power. For IVA activities a robot basically would have to compare with the full human skill and mobility; however to be honest, many of the manual operations to be done in a space-laboratory environment are fairly simple standard operations, like handling parts, opening and closing doors, pulling drawers, pushing buttons etc. which have to be done just by stepping through extensive, written procedures. Real intuition and manual skill is particularly requested in non-nominal situation, e.g. when a tape recorder has to be repaired. Although it is not clear today when a multi-fingered robot hand might be as skilled as the human hand and when (if ever) a robot might show up real intelligence and autonomy, it nevertheless is obvious that even with today's technology and the available telerobotic concepts based on close cooperation between man (e.g. the ground operator) and machine there are many tasks in space, where robots can replace or at least augment human activities with reduced cost at least from a long-term perspective.

Thus we are convinced that automation and robotics (A&R) will become one of the most attractive areas in space technology, it will allow for experiment-handling, inspection, maintenance, 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 more justified than in many other areas of space technology.

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These are the reasons why DLR – after the big success of ROTEX, the first remotely controlled space robot (Ref. 1) - has increased its efforts towards the development of a new, smart generation of light-weight-robots with articulated hands (robonauts) and convenient remote programmability from ground. The progress we have made, the technologies we prepare for the EuTEF robot on the ISS and our recent experiences with NASDA's freeflying space robot ETS VII are outlined in the sequel.

2 DLR's LIGHT WEIGHT ROBOT DESIGN

Space robotics is assumed to become a major drive for a new generation of light-weight robots, which will find numerous terrestrial applications, e.g. on mobile platforms, too.

The design-philosophy of DLR's light-weight-robots is to achieve a type of manipulator similar to the kinematic redundancy of the human arm , i.e. with seven degrees of freedom, a load to weight ratio of between 1:3 and 1:2 (industrial robots ≈ 1:20), a total system-weight of less than 20 kg for arms with a reach space of up to 1,5 m, no bulky wiring on the robot (and no electronics cabinet as it comes with every industrial robot), and a high dynamic performance. As all modern robot control approaches are based on commanding joint torques, in the first carbon fibre type arm version (Fig. 1) showed up an inductive (13 bit, 1 KHz bandwidth) torque-measurement system that was an integral part of a double-planetary gearing system. A full inverse dynamics (joint torque) control system including a neural net learning system for compensating gravity modelling errors made use of it.

However the double-planetary gears (Fig. 1, right) with their extremely high reduction rate of 1 : 600 were very difficult to manufacture.

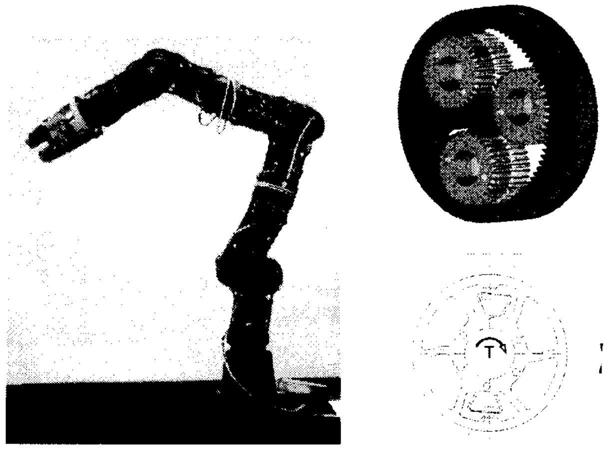


Fig. 1 DLR's first light-weight-robot with integrated electronics (left), double planetary gearing and inductive torque sensing (right))

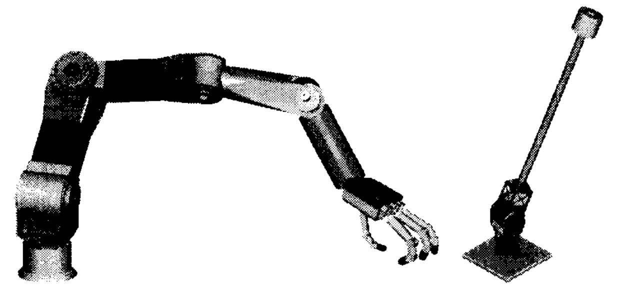


Fig. 2 The CAD model of DLR's new 7-dof light weight robonaut arm (left) and the testbed setup of joint 2 (right)

Meanwhile a new light weight robot design (Fig. 2) is underway which tries to make optimal use of all the experience gained with the above „reference" model. Its joints are based on special light-weight harmonic drives.

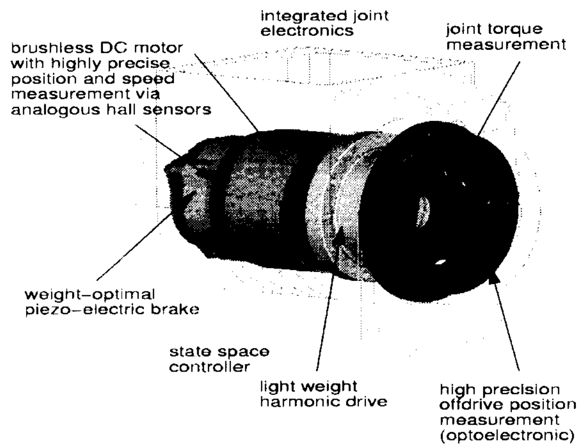


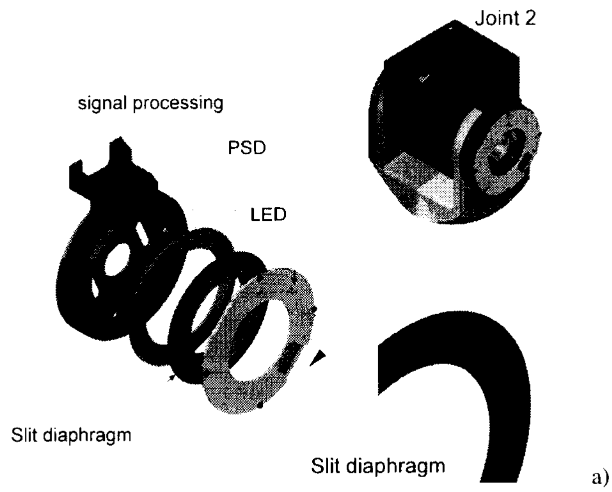
Fig. 3 Mechatronic components of DLR's new intelligent robot joint

In the drives we are measuring all relevant state variables, i.e. off-drive position, torque, motor position and speed (Fig. 3, 4a and 4b). For torque measurement we went back to strain gauge based systems. A first version of this new arm design uses socalled INLAND motors which were redesigned by us to provide hollow axes where all cabling is fed through.

A second version will use a new motor concept (Fig. 5) as developed in our lab, the optimized external rotor motor (OERM).

The electromagnetic torque generation to be delivered over a wide rotor speed range is realized by a multipole stator assembly interacting with rotor permanent magnet poles in a non-symmetrical configuration to virtually eliminate cogging effects. The dynamic performance is significantly enhanced by means of a special commutation control technique based on a single coil winding technique.

In view of the limited heat exchange to be realized with a compact design, the key design requirement is a large stall-torque-to-input-power-ratio. This number can be significantly enhanced as compared to conventional designs by careful tuning of geometrical dimensions and electromagnetic design parameters using magnetic field computations supporting a lumped parameter optimization process.



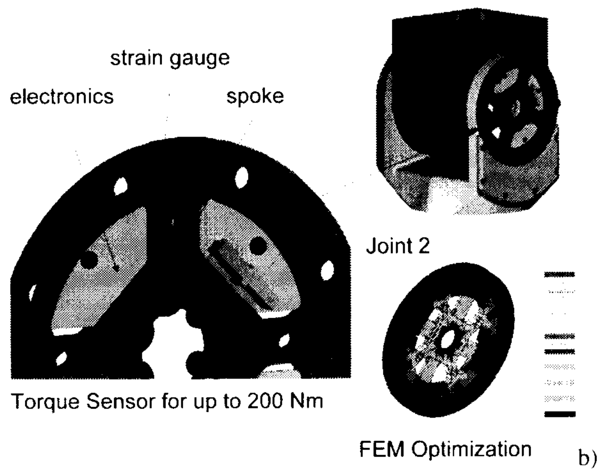
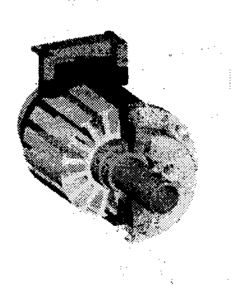
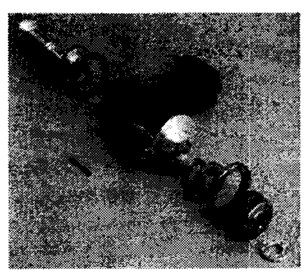


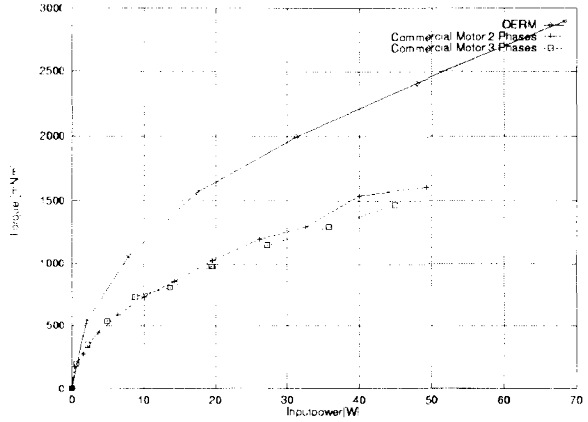
Fig. 4 Two sensors in DLR's new light weight robot (Fig. 2)
a) Off-drive joint angle sensor (resolation 0,01 degrees)
b) joint torque sensor
Not shown here are the hall sensors used for motor position measurement.



a): Joint 2 with OERM and piezo controlled brake



b): OERM with Harmonic Drive



c) Stall torque OERM vs. the best commercial motors

Fig. 5 *The Optimized External Rotor Motor (OERM) just needs about 38% of the stall torque input power which has been required by the best commercial motor used since, and moreover yields 50 % higher torques.*

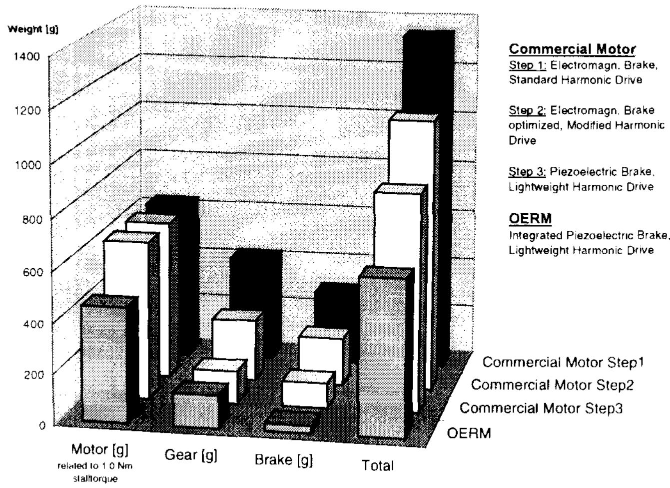


Fig. 6 The history of weight reduction in DLR's new LWR-Drive Units

The tedious history of weight reduction over the last two years is depicted in Fig. 6.

In the first step the (in our opinion) best commercially available high- end brushless DC- motor was combined with a slightly modified Harmonic Drive gear and a commercially available robot- safety-brake.

In the next steps the total weight was diminished by reducing weight in the Harmonic Drive's circular-spline and the development of a weight optimized, modified version of the original, commercially available electromagnetic brake, which has been replaced recently by DLR's new piezoelectric brake with a weight of less than half the original brake. Considerable further decrease of the drive-unit masses was reached by providing the Harmonic Drive with a new aluminum crafted wave generator and circular spline as developed in close cooperation with the company Harmonic Drive, so that it finally came out with only half the weight of the original part.

The biggest step towards an extremely lightweight construction was the development of a completely in-house designed Optimized External Rotor Motor (OERM) of high efficiency and stall torque with a highly integrated piezoelectric safety- brake. The mass of the motor related to the stall torque at equal power consumption is less than 72% of the originally used high- end motor and the weight of the integrated brake (30 g) is just 1/10 th of the weight of the commercial brake used in the first step (300g).

The combination of the new Optimized External Rotor Motor (OERM), integrated safetybrake and lightweight Harmonic Drive gear yields an extremely powerful lightweight jointdrive with a related mass of just 55% of the weight of the original high- end drive unit and a joint quality measure of J=250, where we have defined this measure as

$$J = \frac{T}{W} \cdot \frac{v_{max}}{(180°/sec)}$$

and where

$T[Nm]$	**= Output torque (max)**
$W[kg]$	**= Weight of joint**
$v_{max}[°/sec]$	**= maximal speed**

Indeed it is not trivial to compare the performance of light weight joints, as output torque related to overall weight is meaningless if one does not take in account the joints maximum rotational speed, which we normalize via 180°/sec, a value which is e.g. a good standard for terrestrial robots.

In summary, we are convinced that the enormous efforts we made to arrive at joints with ≈ 210 Nm output torque, 220°/sec and ≈ 1,2 kg weight including the brake system will pay out in the near future.

3 DLR's FOUR-FINGERED ARTICULATED HAND

For many space operations i.e. handling drawers, doors and bayonet closures (electric connectors) in an internal lab environment, two-finger grippers seem adequate and sufficient; the appropriate mechanical counterparts in the lab equipment are easily designed and realized even in a very late design stage.
For more complex manipulations future space robots (**robonauts**) should use articulated multifingered hands.

In contrast to existing robot hand designs, it was our declared goal to build a **multisensory 4 finger hand** with in total twelve degrees of freedom (3 active dof in each finger), **where all actuators, uniformly based on the position-force-controlled artificial muscle® (see e.g.** Ref. 2**), are integrated in the hand's palm or in the fingers directly** (Fig. 7, Fig. 8). This means the hand is fully modular and may be mounted on any robot. Force transmission in the fingers is realized by special tendons (highly molecular polyethylene), which are optimal in terms of low weight and backlash despite of fairly linear behavior.

Each finger shows up a 2 dof base joint realized by two artificial muscles® and a third actuator of this type integrated into the bottom finger link (phalanx proximal), thus, actuating the second link (phalanx medial) actively and, by elaborate coupling via a spring, the third link (phalanx distal) passively. **Every finger unit with its 3 active degrees of freedom integrates 28 sensors(!).**

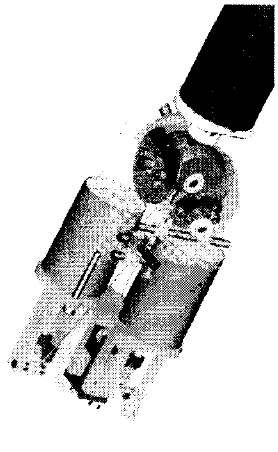


Fig. 7 The 2 degree of freedom base joint

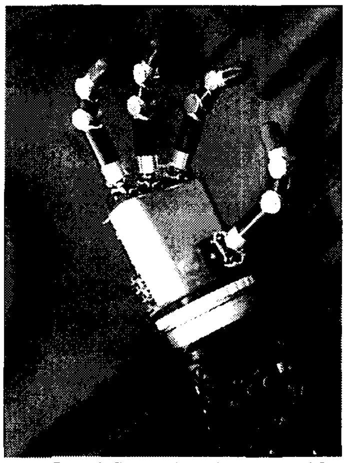


Fig. 8 Our 4 finger hand with its 12 actuators and 112 sensors integrates 1000 mechanical and 1500 electronic components

With 112 sensors, around 1000 mechanical and around 1500 electrical components the new hand is one of the most complex robot hands ever built. The fingers are position-force-controlled (impedance control), they are gravity compensated and they are prevented from colliding by appropriate collision avoidance algorithms. In addition recently a cartesian stiffness control scheme on hand level was implemented which turned out to be of crucial importance for all kinds of manipulation tasks. For more details see Ref. 3.

A number of telepresence demonstrations have meanwhile been performed using a dataglove, a polhemus tracker and on the „remote" site the robonaut consisting of a 7-dof light-weight robot on a 3-axis rail system, and the four-fingerhand (Fig. 9).

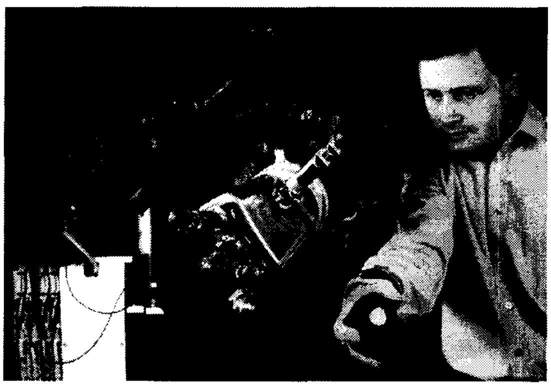


Fig. 9 Skill transfer from human hand to robot hand via data glove

A spacelab mockup in our lab allows to remotely pull drawers, grasp objects in the most natural way etc. The robonaut concept of the „prolonged arm" of man in space seems very realistic here (Fig. 2). Needless to say that in case of large delay all operations can be programmed and executed in a virtual environment using the MARCO telerobotic system (see section 4). Mapping the data glove signals into glove finger positions via neural nets (Fig. 10) as well as high and low level grasp planning modules for the position-force controlled fingers are meanwhile available for our hand (Fig. 11).

We have now started with the development of DLR hand II, which will show up an even higher degree of integration. As an example presently around 400 cables are coming out of the hand, they should be reduced down to less than 10 cables in DLR hand II

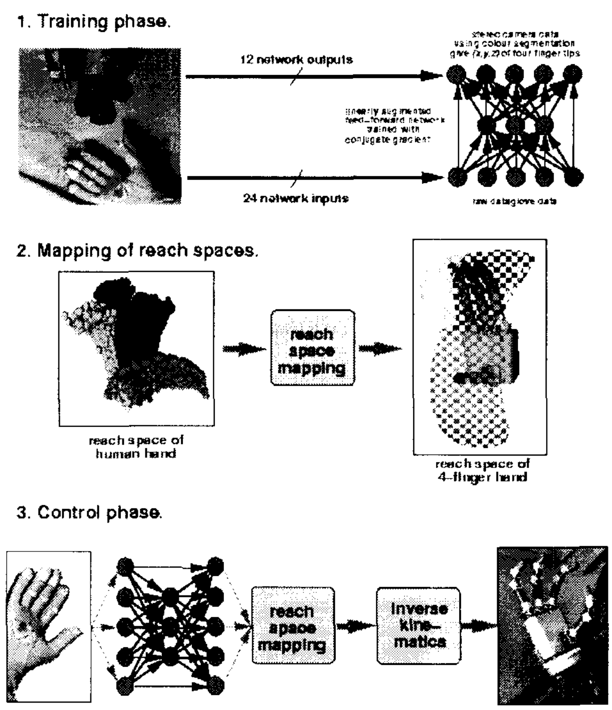


Fig. 10 Data glove control issues for 4 finger hand control

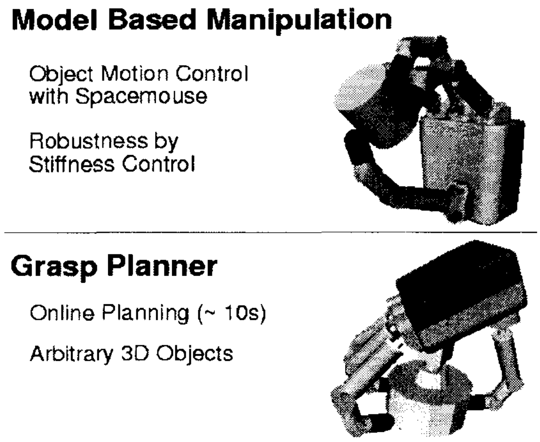


Fig. 11 High level manipulation and grasp planning skills are essential for efficient control of DLR's articulated hand

4 MARCO – DLR's TASK-DIRECTED SENSOR-BASED TELEPROGRAMMING SYSTEM

Following ROTEX we have focused our work in telerobotics on the design of a high-level task-directed robot programming system MARCO, which may be characterized as **learning by showing in a virtual environment** (Ref. 3) and which is applicable to the programming of terrestrial robots as well. The goal was to develop a unified concept for

- a flexible, highly interactive, **on-line programmable teleoperation station** as well as
- an **off-line programming environment**, which includes all the sensor-based control and local autonomy features as tested already in ROTEX, but in addition provides the possibility to program a robot system on an **implicit, task-oriented level.**

A non-specialist user - e.g. a payload expert - should be able to remotely control the robot system in case of internal servicing in a space station (i.e. in a well-defined environment). However, for external servicing (e.g. the repair of a defect satellite) high interactivity between man and machine is requested.

To fulfill the requirements of both application fields, we have developed a 2in2-layer-model, which represents the programming hierarchy from the executive to the planning level.

planning

Task	implicit layer
Operation	
Elemental Operation	explicit layer
Sensor Control Phase	

execution

Fig. 12 2in2-layer-model

Based on this 4 level hierarchy (Ref. 4), an operator working on the (implicit) task level does no longer need real robotic expertise. With a 3D cursor (controlled by a Space Mouse) or with a human-hand-simulator (controlled by a data-glove) he picks up any desired object in the virtual world, releases it, moves it to a new location and fixes it there. Sequences of these kind of operations are easily tied together as complex tasks; and before they are executed remotely, the simulated robot engaging its path planner demonstrates how it intends to perform the task **implying automatic collision avoidance**. For having the real stereo-graphic imagination we use either shutter glasses with stereo-monitors or polarized glasses with large screens where many observers can watch at the same time. Stereo impression is perfect in both cases.

Fig. 13 DLR's universal telerobotic station MARCO (Modular A&R COntroller) developed by contract with the German Space Agency

Nevertheless in the explicit layer (the learning phase) the robot expert has to show and demonstrate the elementary operations including the relevant sensory patterns and – if necessary – train the mapping between non-nominal sensory patterns and motion commands that servo into the nominal patterns later on in the real world. He performs these demonstrations by moving the robot's simulated gripper or hand (preferably without the arm) into the proximity of the objects to be handled (e.g. drawers, bajonet closures, doors in a lab environment), so that all sensory patterns are simulated correspondingly. The robot expert at this stage of course must have knowledge on position- and sensor-controlled subspaces (and must be able to define them, massively supported by MARCO functions), and he has to define how operations (e.g. remove bajonet closure) are composed by elementary operations (approach, touch, grasp, turn etc.).

MARCO's two-handed VI interface concept

Thus as a general observation, on the implicit as well as on the explicit layer statement we have to move around 3D-pointers or grippers / hands in the virtual lab environment. Using classical "immersive" cyberspace techniques with data-glove and helmet was not adequate for our approach, as the human arm's reaching space is fairly small (e.g. in a lab environment) and with head motions only very limited translational shifts of the simulated world are feasible. As a general observation an alternative to the position control devices "data-glove and helmet" is the velocity control device "Space Mouse", particularly if the robot system to be programmed has no articulated hand. Velocity control here means we may easily steer around an object in VR over arbitrary distances and rotations via small deflections (which command velocities) of an elastic sensorized cap. The second important observation (confirmed by extensive tests of car manufacturers in the context of 3D CAD-design) is that just as in real life two-handed operations when interacting with 3D-graphics are the optimum. Indeed whenever humans can make use of both hands, they will do (e.g. when carving, modelling, cutting). In the northern hemisphere for around 90 % of the people the right hand is the working hand, while the left hand is the guidance and observation hand, which holds the object to be worked on (vice versa for left-handers).

This ideal situation for a human is easily transferred to the VR interface scenario. A right-hander preferably moves around the whole virtual world in 6 dof with a Space Mouse in his left hand (the guidance hand), while with his right hand he moves around the 3D cursor with a second Space Mouse (velocity control, Fig. 14) or a simulated hand with a data glove (position control, Fig. 15). One should note that now even for the glove the problem of limited workspace disappears, because with the left hand the operator is always able to move the virtual lab world around such that the objects to be grasped are very close so that even in position control mode with a data glove only small, convenient motions of the operator's hand are requested to reach them.

More details on MARCO's high level user interface as are Java/VRML client techniques are given in Ref. 4.

One of the key features of the MARCO system is the implication of sensor-based autonomy using the above mentioned storage of nominal sensory patterns.

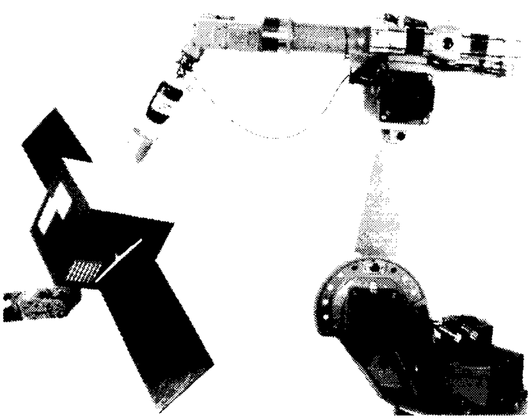
Fig. 14 Two handed VR-interface using two Space Mice (ETS VII scenario as example)

Fig. 15 Two handed VR-interface using Space Mouse and Data Glove (EuTEF scenario as example)

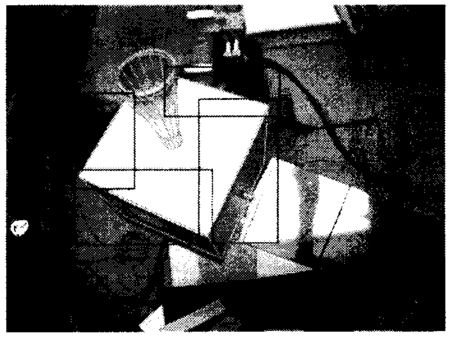
Indeed for comparing the real world with the virtual world, based on may be multisensory perception, and thus for either updating the world model or/and servoing into a nominal situation as learnt during the explicit layer training phase, MARCO provides several alternatives:

- if we have reliable CAD models of the objects and the environment and if we may assume that spatial 3D-contours are well detectable by a (mono or stereo) vision system, we prefer 3D-modelbased realtime tracking algorithms; in case of moving objects we additionally imply Kalman filters for estimating motions (Ref. 2). A typical example is the hardware simulated catching of free-floating satellite by a repair robot-satellite using two industrial robots in DLR's lab and a mulitsensory (vision, laser range, force-torque) capture tool; for more details see e.g. Ref. 2 and 4.

  By the way if the robot is supposed to generate 3D models autonomously when CAD models are not available, one of our preferred technologies is 3D reconstruction from stereo images -using Radial-Basis-Function neural networks (Fig. 17), Ref. 5 and 6.



(a)



(b)

Fig. 16 A two robot system as testbed for a satellite repair project.

(a) The robot on the left carries a mockup of a satellite, that is tracked by a camera mounted in the tool of the repair robot (right).
(b) Satellite tracking as seen from the repair manipulator's hand camera. The wire frame model of the target is projected into the live video image at the currently estimated pose.

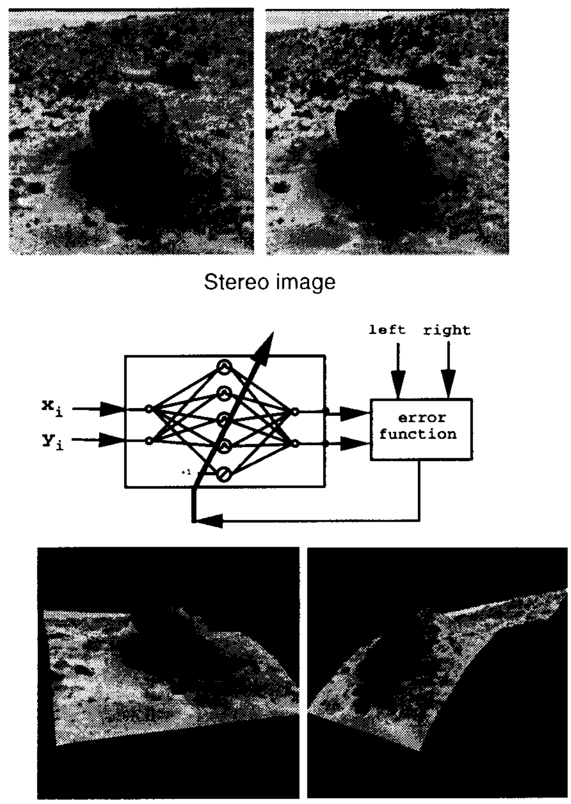


Fig. 17 3D-Reconstruction with neural networks
Example: stereo image of stone Yogi/Pathfinder Mars Mission

- if we have no 3D-CAD models or situations where they are not useful (e.g. if the camera does not see real 3D-contours) or where the sensor fusion aspect is prevailing (e.g. cameras combined with arrays of range finders), we prefer to train a linear mapping from sensory input patterns into corrective motions (that for example servo into some nominal relative position). Two alternatives have turned out to be very efficient here (Fig. 18).

  a) an analytical approach where the linear operator corresponds to the pseudoinverse of a Jacobian.
  b) a neural net approach using multilayer perceptrons.

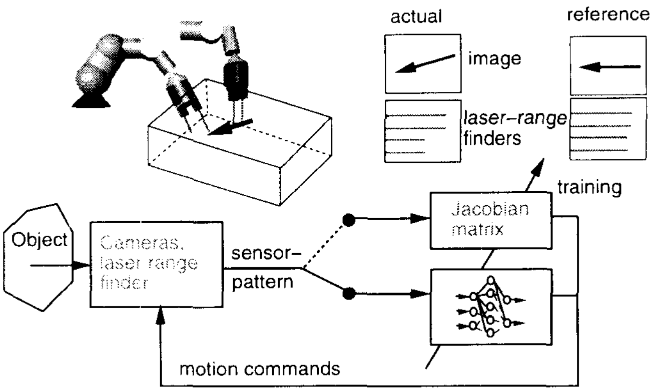


Fig. 18 Multisensory Servoing

In both cases the operator (or an automatic control scheme) has to move the robot gripper/hand slightly around some nominal situation in all six degrees of freedom.

Method a) has been used in the DLR-NASDA cooperation project GETEX with the ETS VII freeflying robot (see next section). In this case learning of the Jacobion was originally performed with simulated sensory patterns, and then repeated in Tsukuba/Japan with the real images yielding very simular results.

The sensorbased task-level-teleprogramming system MARCO, has reached meanwhile a high level of universality. It was not only used as ground control station for the ETS VII experiment (see section), but it is used also for technology studies of Germany's technology project Experimental Service Satellite ESS, as well as for remote ground control of EuTEF and for mobile terrestrical (fetch and bring services in hospitals) and planetary robot projects.

5 GETEX on ETS VII

From April 19 – 21 DLR (and the IRF Dortmund as subcontractor) had the opportunity (as offered by NASDA) to perform own experiments with NASDA's ETS VII free-flying space robot. Our goals were twofold:

- **To verify the performance of the MARCO telerobotic concept, in particular concerning the implicit task level programming capabilities as well as the sensor-based autonomy and world model update features.** A highlight was indeed the tele-programming of a peg-in-hole task, where in the virtual world we intentionally displaced the standby position of the peg from where the robot had to fetch it. Vision processing on ground using NASDA's tracking markers on the task board and the Jacobian matrix learning beforehand based on real images (as explained in the last chapter) caused the ETS VII robot to automatically and perfectly adapt to the unexpected situation. The peg-in-hole insertion as such (taking into account the fairly high tolerances) was less critical and of course made use of NASDA'S compliant motion commands.

- **To verify 6 dof dynamic models for the interaction between a robot and its free-flying carrier satellite.**

If a robot which is mounted on a spacecraft moves, it generates linear and angular momentum. In the case of an attitude and position controlled spacecraft, the attitude control system will permanently produce forces and torques compensating for the arm motion. The spacecraft may then be considered as inertial in the co-ordinates of an orbit-fixed system, and the problem of robot motion planning can be solved using the same methods as for terrestrial manipulators. While for the control of the spacecraft attitude electrically powered momentum wheels can be used as well as thrusters, for control of the spacecraft translation fuel consuming thrusters are the only actuators currently in use. For this reason and because the position errors are generally negligible, most satellites are only attitude controlled. Due to the linear momentum conservation, which states that the center of mass of the system comprising the robot and the satellite is constant, the motion of a manipulator mounted on the satellite will lead to a compensating motion of the satellite. The amount of satellite translation produced depends on the masses of the bodies constituting the system. For space robotic systems which are neither position nor attitude controlled the angular momentum conservation law leads further to a rotation of the spacecraft, by an amount which results from the mass and inertia properties of the manipulator links and the spacecraft. It is generally assumed that no external forces act on such *free-floating robots (Ref. 5 and Ref. 7)*. The free-floating mode of operation is of interest for space robots not only for the reason that attitude control fuel may be saved which augments the robot life-span, it will also be of importance during repair missions, when the servicing satellite is very close to or in contact with the target satellite: any action of the attitude control system of either of the two satellites during this phase would lead to a collision and thus to potential damage on the two spacecraft.

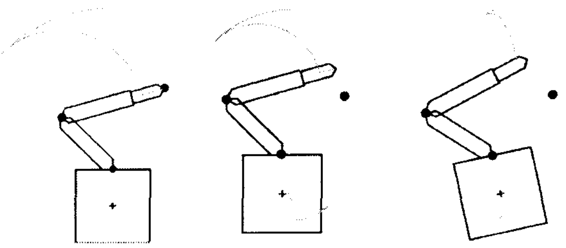


Fig. 19 The influence of the satellite attitude control mode on the path described by the robot end-effector - the same joint motion is carried out by a robot with a fixed base (left), an attitude controlled robot (middle) and a free-floating robot (right).

As long as the tasks performed with the robot are described in robot-fixed coordinates, the fact that the satellite position remains uncontrolled has no influence. If, however, the task is described with respect to an orbit-fixed co-ordinate system, as it would be the case for example for the capturing of a defect satellite, the satellite motion has to be taken into account (see Fig. 19). The equations relating the tool center point motion to the manipulator joint motion, which for robots with an inertially fixed base are purely kinematical equations, become thus dependent on dynamic parameters in the case of free-floating space robots. This influences the path planning methods which have to be applied. On one hand, singularities, that is joint configurations in which the robot is not controllable in cartesian co-ordinates, are no more a function of the robot kinematics only, but become dependent on the dynamic properties of the robot, too. Therefore, iterative methods based on the direct kinetic equations have to be used instead of the inverse kinematics equations. Moreover, the angular momentum equation makes the system nonholonomic (Ref. 9), which means that the satellite orientation is not a function of the current joint configuration only, but merely a function of the chosen path. Two different paths starting at the same initial configuration of the robot, and leading to the same final configuration, will therefore result in different amounts of satellite rotation – and thus in different final inertial tool center point positions, too. As a consequence, nonholonomy offers the possibility to do a re-orientation of the satellite using manipulator motion only, by simply carrying out a closed-loop manoeuvre in joint space. This kind of manoeuvre can be employed to significantly augment the workspace of the robot, since it allows to turn the satellite into any desired orientation, bringing back the manipulator into its reference configuration. The maximum workspace of a free-floating space robot is thus described by a hollow sphere of which the inner and outer radius are given by the minimum and maximum possible distance between the tool center point and the system center of mass. Another possibility resulting from nonholonomy is that any point which is inside the fixed-base workspace of the robot may be attained with zero satellite attitude error. In the simplest case, this may be done by planning and executing the manoeuvre as for a robot with a fixed base and adding a closed-loop re-orientation manoeuvre to compensate for the produced attitude error. Path planning for nonholonomic system has been investigated in the context of cars and wheel-driven robots (Ref. 9). While those systems may generally be considered as planar, the case of free-floating robots demands spatial methods.

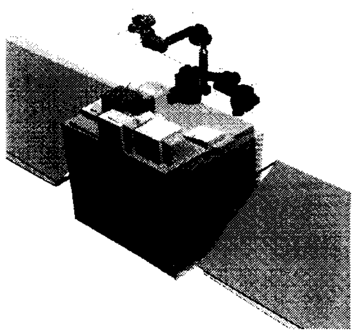


Fig. 20 Examples of *Dynamic Motion* manoeuvres carried out during the GETEX mission: simple point-to-point manoeuvre and re-orientation manoeuvre. The shaded robot indicates the reference position. The satellite reaction to the arm motion is scaled by a factor of 10 in this picture.

Whatever path planning method is applied to free-floating robots it is necessarily highly model-based. The parameters of the dynamic model have therefore to be known quite well. While this poses no problem for the geometric parameters and for the mass and inertia of the manipulator, the mass and the inertia of the spacecraft are subject to important changes during the lifetime of a servicing satellite. This is especially the case if the spacecraft is performing capturing or rendez-vous/docking like operations. One goal of GETEX has therefore been to identify the mass properties of the satellite after one year and a half of activity in orbit. Further objectives were the verification of the dynamic models and to obtain some insight into the nature and importance of the disturbances acting on a robotic satellite on low earth orbit. Additionally, the mission aimed at gathering data for the future design of controllers which combine the manipulator motion control with the satellite attitude control. To meet all these objectives, a variety of different manoeuvres were executed, which include simple point-to-point operations and closed-loop re-orientation manoeuvres (examples of which are given in
Fig. 20), sequences during which only one joint was active at a time as well as sequences during which all joints were moving simultaneously. The major constraints, due to mission security aspects, were the maximum satellite attitude error allowed by NASDA which was limited to $\pm 1.0°$ around each axis and the fact that the maximum tool center point velocity was limited, too. Furthermore, the reaction wheels were turning at a very low but non-zero constant velocity during the experiments, which introduced undesired torques into the system. Their effects will have to be considered during the evaluation of the mission results.

In total, over 110 minutes of dynamic motion experiments have been carried out, of which 52 minutes have been spent in free motion mode. The remaining time was used to repeat the experiments in reaction wheel attitude control mode for verification purposes. First evaluations of the measurement data confirm the need to account for external disturbance forces acting on the satellite, such as the gravity gradient torque and magnetic torque.

6 EuTEF on the International Space Station ISS

The European Technology Exposure Facility EuTEF, which basically consists of an Express Pallet on the outer truss structure of the ISS (Fig. 21), is supposed to be operated by a robot system.

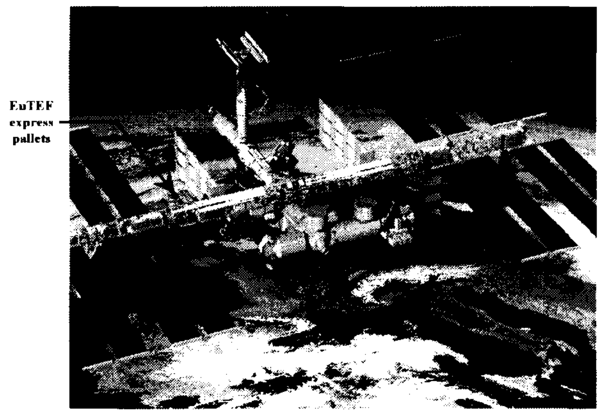


Fig. 21 International Space Station ISS (courtesy of ESA-ESTEC)

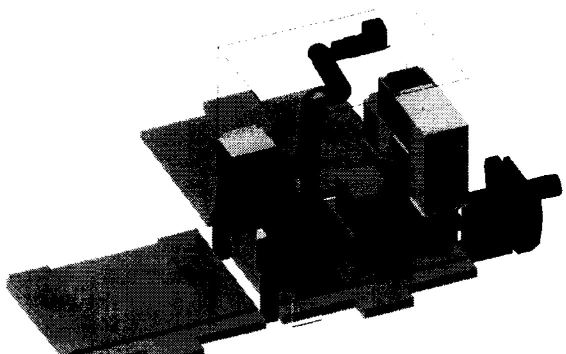


Fig. 22 EuTEF Scenario (courtesy of CGS)

Prime contractor of this ESA project is the Italian company CARLO GAVAZZI SPACE (CGS). The arm (a development of Tecnospazio) presumably is provided by the Italian space agency ASI, while DLR intends to contribute the design of the endeffector, is counterpart (the Standard Grasping Unit) and the MARCO ground control system. It is our declared goal to really push space robot technology forward in the framework of EuTEF by

a) refining the endeffector from a "basic" endeffector into a smart endeffector which allows for the onboard processing of force **and** stereo vision, similar to concept we applied in the GETEX-ETS VII project.

b) demonstrating by the powerful, high level ground control concept MARCO that fully remote control of **operational** space robot systems is feasible today.

The EuTEF robot is supposed to move around pallets and drawers, exposing them to sun, earth and stars, i.e. to perform operations which in the past needed e.g. complete reorientation of the shuttle. However safety is a key issue for this robot – not imaginable if it would for some reason (including programming errors) loose one of its loads. These necessities fully guide the endeffector's design and that of its complex counterpart, the *Standard Grasping Unit* (SGU).

During the past year DLR performed extensive studies on the design of the SGU to be used as the base for any *payload module* (PM) on the *Technology Exposure Facility* (TEF). This interface is robot operated via the *Basic End-Effector* (BEE) mounted to the robots wrist.

Due to the mutual interface the SGU and the BEE are jointly designed by DLR. The finalizing and the manufacturing of the SGU will be done by HTS in Switzerland and CGS in Italy. The BEE is a national contribution and therefore the development will be performed by DLR exclusively.

Each PM consists of the *standard body structure* (SBS) mounted on the SGU. It is placed on the ExPA base by means of the *standard receptacle* (SR). Fig. 23 shows an exploded view of this arrangement.

A set of *standard receptacles* (SR)is fixed to the ExPA. This allows a payload module to be docked to certain predefined positions on the ExPA thanks to the SGU. Each PM is interfaced mechanically **and** electrically. Furthermore it incorporates on its top a mechanical interface similar to the SR. This allows payloads being stacked on top of each other.

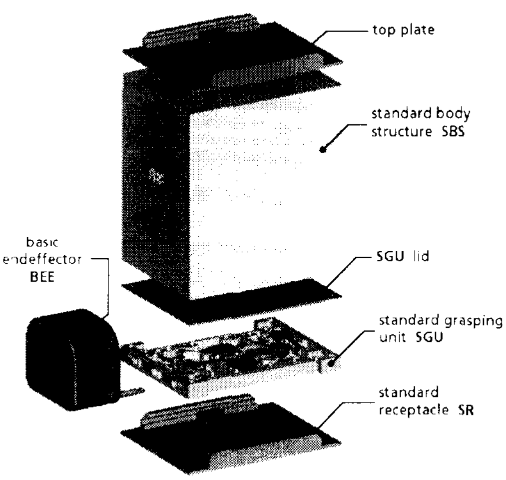


Fig. 23 Payload module PM (exploded view)

Fig. 24 takes a deeper look into the details of the SGU and the SR.

The payload docking interface has to withstand launch loads. The P-shaped receptacle clamps are prepared for this kind of load. They are slightly tapered to yield form closing contact with the blades of the SGU. To allow for easy insertion the receptacle clamps are chamfered noticeably thus yielding good guidance. To prevent jamming of the moving blades they are guided by a roller on each side (Fig. 24) thus reducing friction by a considerable amount. Two trigger pins on the SR are used to block the locking mechanism of the SGU whenever the PM is lifted off the SR.

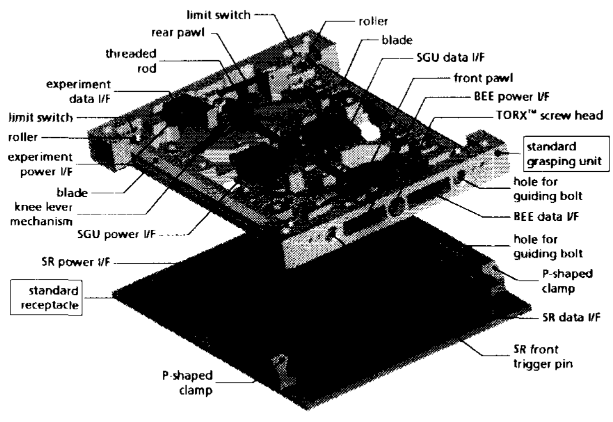


Fig. 24 SGU and SR (exploded view)

The SR routes power and data busses to the PM via two electrical connectors. These connectors are an integral part of the SR and thus aligned to its geometry.

The SGU incorporates three different mechanical/electrical interfaces: the *docking interface* towards the SR, the *grasping interface* for the BEE and the *experiment interface* towards the payload's experiment. Furthermore the SGU routes power and data busses to the PM's *top plate*, which in turn serves as SR for another PM (Fig. 23). This may be looked at as a fourth interface.

To initiate a *grasping action* the BEE is first inserted into the standard grasping interface. The alignment is supported by the guiding bolts. Being coupled the BEE drive operates the knee-lever mechanism by turning the threaded rod. It should be noted that this rod is locked by the front pawl until the BEE is inserted completely (Fig. 24). It should also be kept in mind, as indicated above, that this rod is locked by the SR's trigger pins *in either direction of motion* whenever the PM interface is lifted a small distance off it (front pawl and rear pawl). It is one of the benefits of the knee-lever arrangement that it yields **force balance within the rod**. Thus axial forces on the rod's bearings are zero under nominal conditions!

The threaded rod is linked to the BEE drive via a simple coupling element: It ends in a TORX™ screw head while the BEE drive is equipped with a matching screw driver shaft (compliant for proper insertion). Via the knee-lever mechanism the blades of the SGU may be opened thus releasing the lock of the SR. There is only a **relatively small torque** necessary for operation due to the gear ratio of the nuts on the threaded rod and the amplification effect of the knee-levers.

Following the very first movement of the blades the BEE is already mechanically latched to the SGU! This is done **well before** the payload module is unlocked. Together with the above mentioned pawls this prevents the PM from being lost due to erroneous commands.

During the undocking action the data and power busses are switched over to the robot in a make-before-break action. The docking action works inversely. The movement of the knee-lever mechanism is limited in either direction by a mechanical hard stop. Shortly before the hard stop positions limit switches are placed. This implies that a hard stop may be reached only, if the corresponding limit switch fails! The limit switch being used to detect the *closed position* will be reached shortly before final closure. This allows to build up proper closure forces while making up for tolerances of different SRs.

The SGU is a very delicate and most sensitive part as far as robustness, safety and reliability is concerned. So there are used **mechanical latches only** for safety reasons. Although there are electrical sensors the whole mechanism can be operated without. These sensors are used to ease the handling of the whole apparatus and for redundancy purposes.

The BEE (Fig. 25) is attached on top of a separate force/torque-sensor mounted to the robot wrist flange. The BEE operates on the SGU as mentioned above. Since the BEE is a vital part of the TEF experiment it is most sensitive as far as robustness, safety and reliability is concerned. Thus it is built up making use of a sophisticated mechanical design in favor of smart electronic equipment. Generally speaking, sensors are used for backup or redundancy purposes only. This imposes constraints on the robot arm where accuracy and repeatability is asked for.

The BEE grasping interface consists of a double pronged fork similar to fork lifts. The cylindrical prongs (guiding bolts) are equipped with rounded tips for easy insertion into the SGU. The tips are grooved to complement the *interface latch*. There are no sensors integrated into the prongs themselves. Any torque due to a displacement from the nominal position during fit in must be either detected by the force/torque sensor and compensated by the calculated compliance of the robot or the fitting procedure must rely on the robot's mechanical compliance! The latter case is mandatory anyhow to serve as backup solution in case of sensor failure.

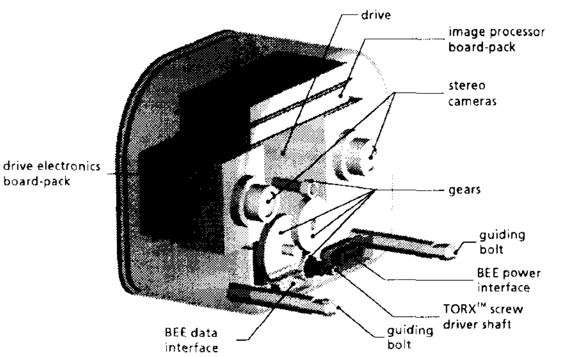


Fig. 25 BEE (semitransparent view)

The BEE's stereo cameras are instrumented for image processing. Compressed images are generated for transmission to the crew or the ground station via the MIL-STD bus. Furthermore adequate algorithms may be applied on the image data for control purposes **in the short local loop (local autonomy)**.

Prior to any mechanical contact the insertion process may be controlled by the above mentioned stereo cameras. The completion of the insertion is detected by a limit switch placed on the BEE's surface in the vicinity of the guiding bolts. The sensory aid is used to smooth the insertion process, but nevertheless it stays a backup solution, as told before.

As drive a hybrid stepper motor is an adequate solution. It combines high torque capabilities with a large number of steps per rotation. The electronic commutation logic allows to set the torque of the drive. It also allows to count the steps of the motor control and hence to measure incrementally the angle/turns of the spindle. With the help of the limit switches of the SGU there may be information retrieved on the absolute position of the blades. In case the limit switches fail, the drive is operated purely torque controlled. It is quite obvious that the drive electronics are on the 'critical path' as far as reliability is concerned. Therefore the drive electronics are built up in a redundant configuration.

CONCLUSON

Space robots in the future will take over more and more tasks from humans. Already at the space station – and even for its construction – a number of remarkable manipulator and robot systems will be active. However most of them will be more or less exclusively operated by astronauts, and this is one of our main concerns and disappointments. The real value of space robots lies in their remote programmability and controllability in combination with onboard autonomy, realizing the prolongation of human's arm into space. The relevant technologies including powerful and delay compensation 3D-graphics are available – it's our task to convince politicians and decision-makers in agencies that time is mature for the robotics age in space. As a consequent next step we try to help in making Eu-TEF the first fully remotely controlled **operational** space robot system. It is commonly accepted, that space robotics may become a major drive for many kinds of service robots – be it the light-weight aspect for mobile arms or the telepresence ideas in medical surgery of the future.

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