Space robotics – DLR`s telerobotic concepts, lightweight arms and articulated hands

G. Hirzinger, B. Brunner, K. Landzettel, I. Schaefer, N. Sporer, J. Butterfaß, M. Schedl

DLR Oberpfaffenhofen
German Aerospace Center
Institute of Robotics and Mechatronics
D-82234 Weßling
Gerd.Hirzinger@dlr.de

Abstract

The paper briefly outlines DLR's experience with real space robot missions (ROTEX and ETS VII). It then discusses forthcoming project in Germany around or independent of the space station ISS, where the telerobotic system MARCO would represent a common baseline. Finally it describes our efforts in developing a new generation of "mechatronic" ultra-light weight arms with multifingered hands. The second arm generation is operable now and the third one (approaching present-day technical limits) is in preparation. In a similar way DLR's four-fingered hand II was a big step towards higher reliability and yet better performance. Artificial robonauts for space are a central goal now for the Europeans as well as for NASA.

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). And the expectation of an extensive technology transfer from space to earth seems to be more justified than in many other areas of space technology.

2. DLR's first space robot projects

Our first big experience with space robotics has been ROTEX (Fig. 1) the first remotely controlled robot in space [1]. It flew with Spacelab-Mission D2 inside shuttle COLUMBIA in April '93 and performed several prototype tasks (e. g. assembly and catching a free-floating object) in different operational modes, e. g. remotely programmed, but also on-line teleoperated by man and machine intelligence. Its success was essentially based on

- multisensory gripper technologies
- local autonomy using the above sensory feedback capabilities
- predictive graphics simulation compensating for 5 – 7 seconds delay

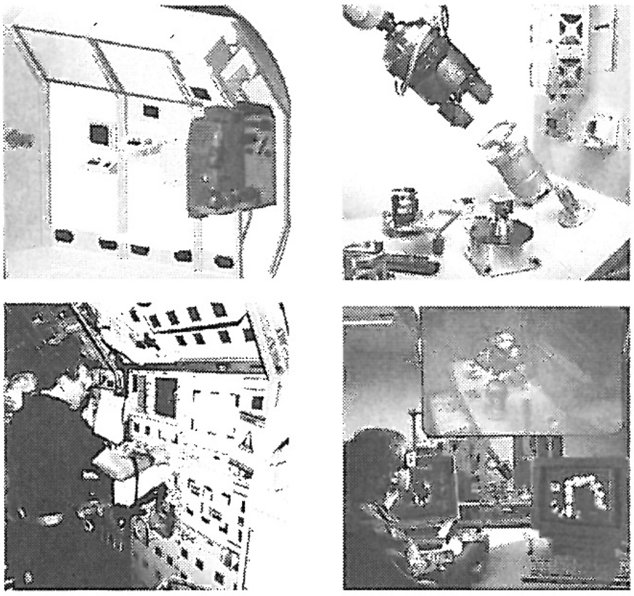


Fig. 1 ROTEX – the first remotely controlled space robot

We gained our second big space robot experience with NASDA's ETS VII project, the first free-flying space robot, who was operable for around two years. In April '99 we got the permission by our Japanese friends to remotely program and control their robot from Tsukuba / Japan. The project called GETEX (German Technology Experiment) was again very successful (as was the whole ETS VII mission); our goals in particular had been:

- To verify the performance of the MARCO telerobotic concept (see below), 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 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. A major part of the GETEX experiment time was allocated to these experiments, which consisted of a series of manoeuvres carried out by the manipulator while the attitude control system of ETS-VII was switched off.

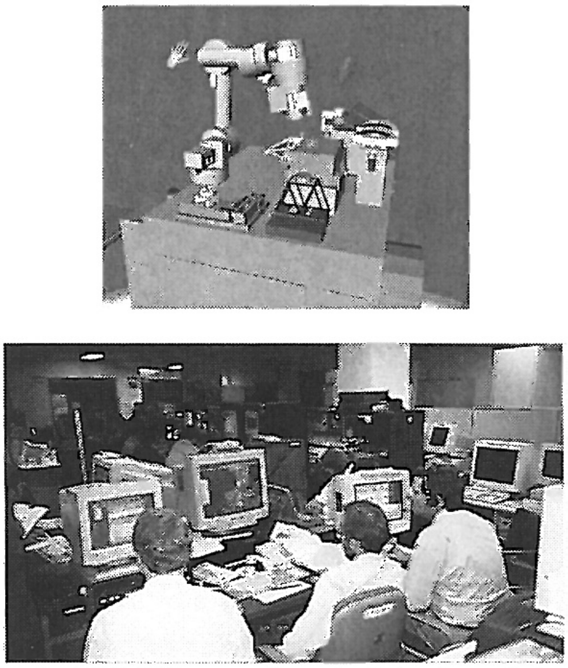


Fig. 2 ETS VII ground control via the task-level programming system MARCO

In such a mode of operation, a space robot consisting of a manipulator and a satellite is generally considered to be free of external forces. The robot therefore is assumed to have constant angular momentum, due to the law of the conservation of angular momentum, which means that if the arm moves and thus introduces angular momentum into the system, the satellite reacts with a compensating motion. The amount of satellite rotation produced depends on the mass and inertia of the bodies which constitute the system. The description of a TCP trajectory in orbit-fixed coordinates, as it is necessary e.g. for the capturing of a defect satellite, has to account for the satellite reaction. The experiments conducted during the GETEX mission aimed at a verification of the existing models of free-floating space robots and at the identification of the dynamic model parameters such as the satellite inertia tensor. A further goal was to obtain some insight into the nature and importance of disturbances acting on a robotic satellite in low Earth orbit and to gather data for the future design of controllers which will combine the manipulator motion control with the satellite attitude control. Therefore, a variety of different manoeuvres were executed (an example of which is shown in (Fig. 3), which include simple point-to-point operations and closed-loop re-orientation manoeuvres, sequences during which only one joint was active at a time as well as sequences during which all joints were moving simultaneously.

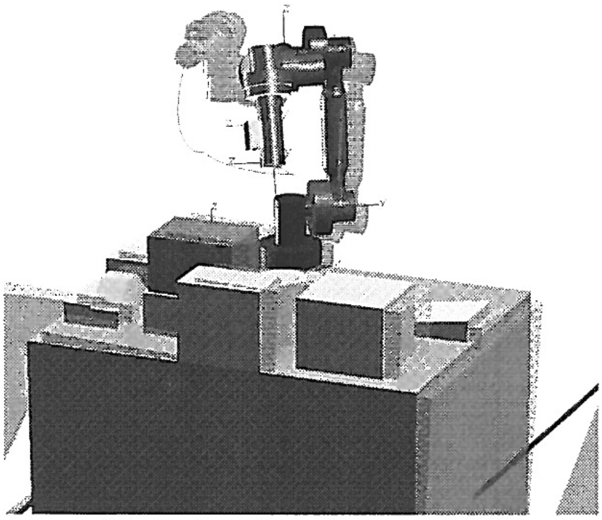


Fig. 3 Example of a Dynamic Motion manoeuvre carried out during the GETEX mission. The shaded robot indicates the reference position. The satellite reaction to the arm motion is scaled by a factor of 10 in this picture.

The major constraint, due to mission security aspects, was the maximum satellite attitude error allowed by NASDA, which was limited to ±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.

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. Evaluations of the measurement data confirmed the need to account for external disturbance forces acting on the satellite, such as the gravity gradient torque and magnetic torque [5].

3. Preparing the future

Germany is near to a decision as to where the next step in space robotics will move. There are two major alternatives:

a) free-flying systems

The technology study on the experimental servicing satellite (ESS) applies robotics to solve the problem of servicing a non-cooperative target in or near to a geostationary orbit, a region of space still out of reach to manned spaceflight. A three-month demonstration flight of ESS has been planned and all phases of its mission have been defined. These include the acquisition, inspection and servicing of an orbiting satellite through to parking it in a *graveyard* – orbit.

For that external servicing task high interactivity between man and machine is required, because the remote environment will be mainly unknown. The MARCO system (see below) will be used to give the system the local autonomy by intelligent sensor data processing. Because all the satellites, built so far, are not equipped for servicing, the final stages of approach and the subsequent capture of the target are the most critical phases of the mission.

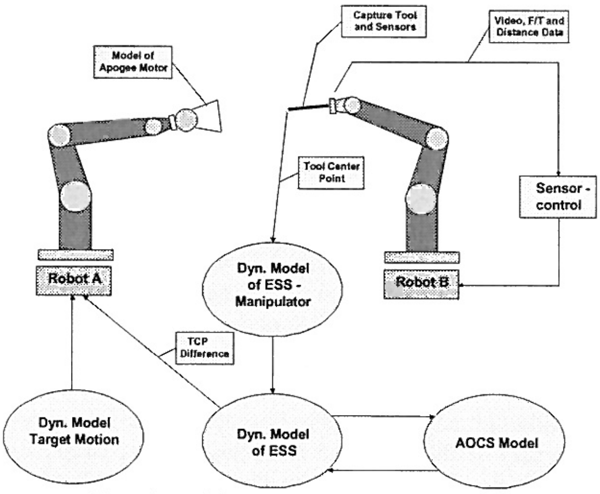


Fig. 4 ESS simulation and testbed

The manipulator of ESS, equipped with a multisensory capturing tool, must follow the residual movements of a selected object on the target (e.g. the main thruster or "apogee motor") by means of an image processing system whose data are passed through an extended Kalman filtering process. With the robot controller monitoring laser distance sensor values, force, torque and travel, the capture tool is inserted into the cone of the thruster.

To simulate the dynamic behavior of the chaser during robot motions, we have arranged two KUKA robots as shown in Fig. 4. Robot B is used to carry out the capturing task, Robot A emulates the entire dynamic relation between the chaser and the target satellite, where the dynamic coupling with the AOCS is included.

After capturing the target satellite, the ensemble is stabilized and reoriented. To free the manipulator for servicing activities and to provide a stiff mechanical coupling, the target satellite then is grasped by means of a simple embracing mechanism (Fig. 6).

To perform its servicing tasks, the robot replaces the capture tool with an appropriate servicing tool such as a scissors or a gripper. This requires that a tool adaptor, fitted with an integrated force and torque sensor and a stereo camera, is attached to the manipulator‘s endmost section. The tool exchange process is executed automatically, but control of the repair task itself must be shared between the machine and a human operator at the ground station. To counter the transmission time delay, a predictive graphical simulation of the robot‘s behaviour in its environment is used at the ground station.

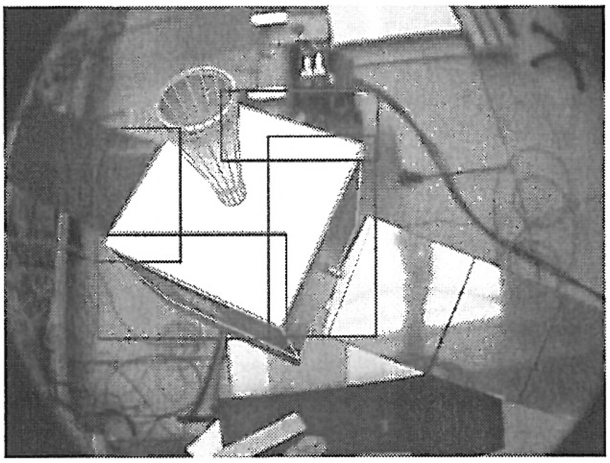


Fig. 5 Tracking of target's apogee as seen from the wrist-mounted hand camera. The wireframe model of the target is projected into the live video image at the currently estimated pose.

Although ESS is a highly complex automatic system, it is easy to maintain and its architecture is simple and extendable. This implies the use of modular hardware and software.

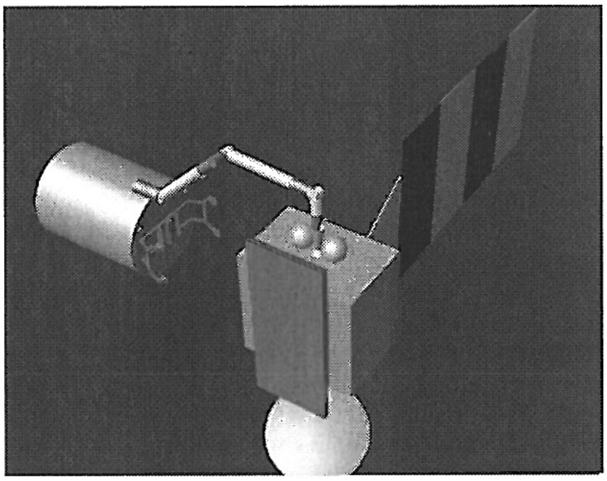


Fig. 6 An artist's view of ESS, catching the apogee of TV-Sat-1

The "tumbling" target would not necessarily be in a geostationary object. Indeed a few space systems no longer controllable have been identified on lower orbits, which might become dangerous for earth, as they will not completely burn out when passing the atmosphere. Thus grasping them with a robot (e.g. with a more articulated hand if no apogee motor is usable) and drawing them down in a well-defined way might become an important service in the framework of future garbage collection systems (Fig. 7)

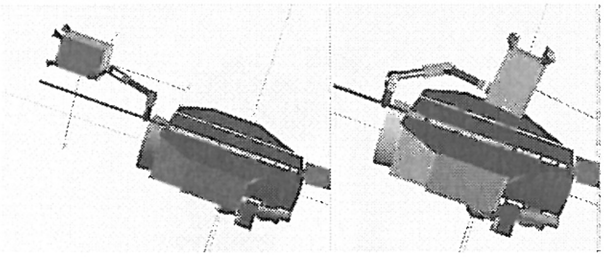


Fig. 7 Catching a worn-out satellite to render it harmless

b) Systems at the international space station ISS

The most remarkable system at ISS is Canada´s Mobile Servicing Center, a three arm system with a long (≈ 17m) arm and two smaller arms (≈ 3,5) on top of it. Canada has put a major part of its space budget into this remarkable technology; nevertheless in the past we have repeatedly criticized, that the arms were only controllable by astronauts – typically with 1mm/see, at least in our opinion a waste of time. We are very happy that a close cooperation exists meanwhile between CSA and DLR aiming at an efficient ground control of the arms using the telerobotic system MARCO (see below). However it seems realistic that in addition Germany will fly its own space station robot MISSIS (a modular inspection and payload handling system)

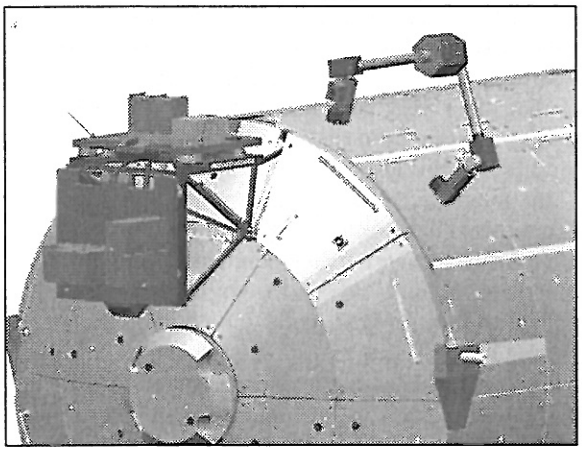


Fig. 8 MISSIS-a climbing and payload handling space station system

The robot kinematics is fully symmetric with seven degrees of freedom, using the so called T-handles for climbing over the European COLUMBUS module COF. These T-handles are usable by the astronauts to perform inspection tasks, being spread over the whole space station. In times the robot would not be used for inspection tasks of the COF´s outer surface, it might take up a specialized gripper (Fig. 9) and handle payloads with techniques as shown in Fig. 10 and Fig. 11. Payload handling must be absolutely safe at he space station, otherwise robotics would be "dead" quickly.

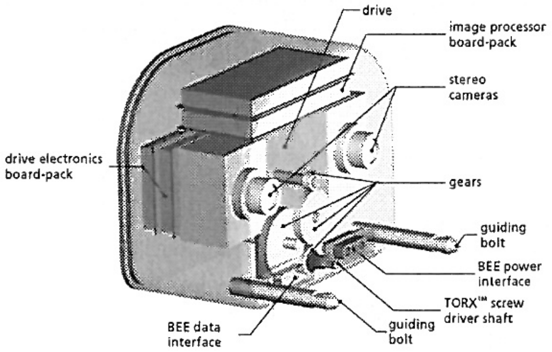


Fig. 9 Sensor-based endeffector

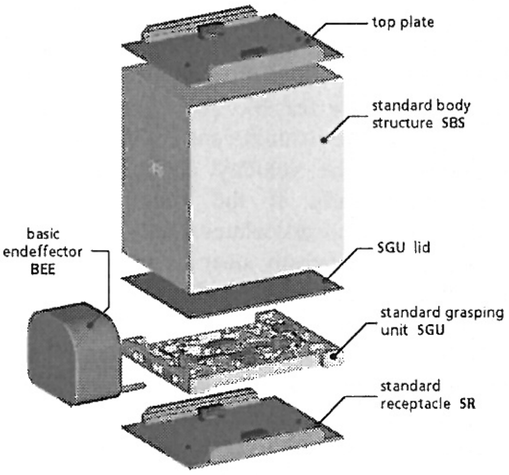


Fig. 10 Payload module

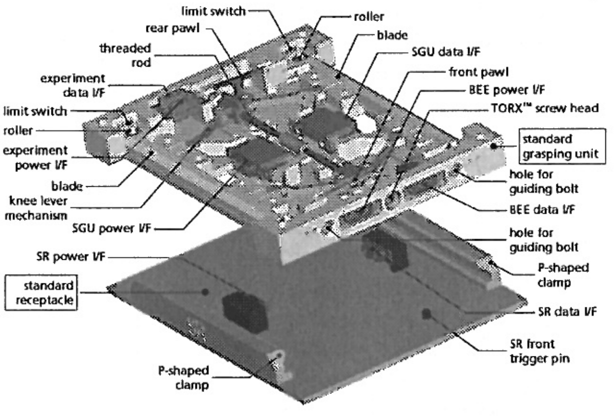


Fig. 11 Standard grasping unit and Standard receptacle

4. MARCO – DLR's Task-Directed Sensor-based Teleprogramming System

Based on the ROTEX experience (Fig. 12), 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** 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 teleoperation station based on predictive ground simulation (including sensorbased local autonomy) see Fig. 12 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.

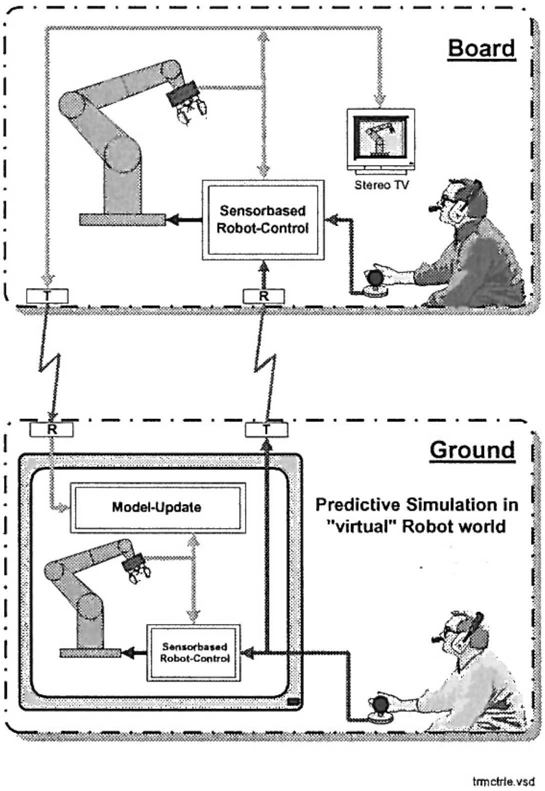
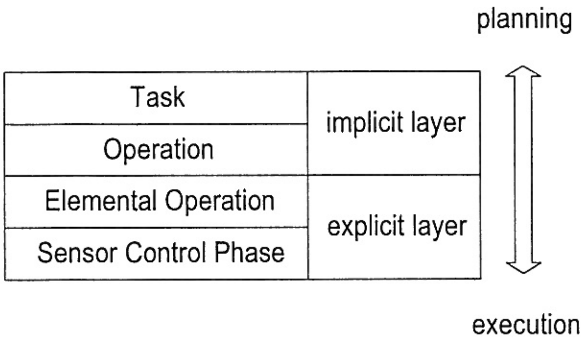


Fig. 12 ROTEX telerobotic control concept

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 fulfil 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.



Task	implicit layer
Operation	
Elemental Operation	explicit layer
Sensor Control Phase	

Fig. 13 2in2-layer-model

Based on this 4 level hierarchy, 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**.

Fig. 14 DLR's universal telerobotic station MARCO (Modular A&R Controller)

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 sensorcontrolled 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 VR 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 casily 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. 15) or a simulated hand with a data glove (position control, Fig. 16).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.

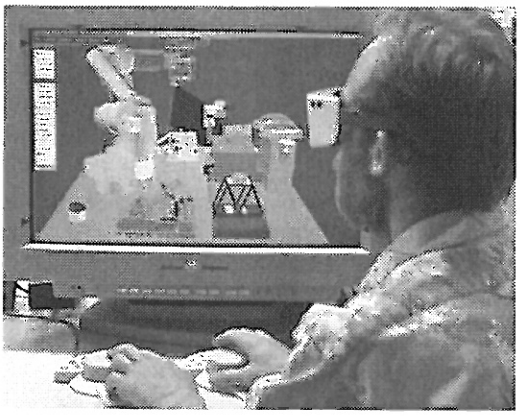


Fig. 15 Two handed VR-interface using two Space Mice (ETS VII scenario as example)

Fig. 16 Two handed VR-interface using Space Mouse and Data Glove (space station scenario as example)

More details on MARCO's high level user interface as are Java/VRML client techniques as indicated in Fig. 17 are given in Ref. [4].

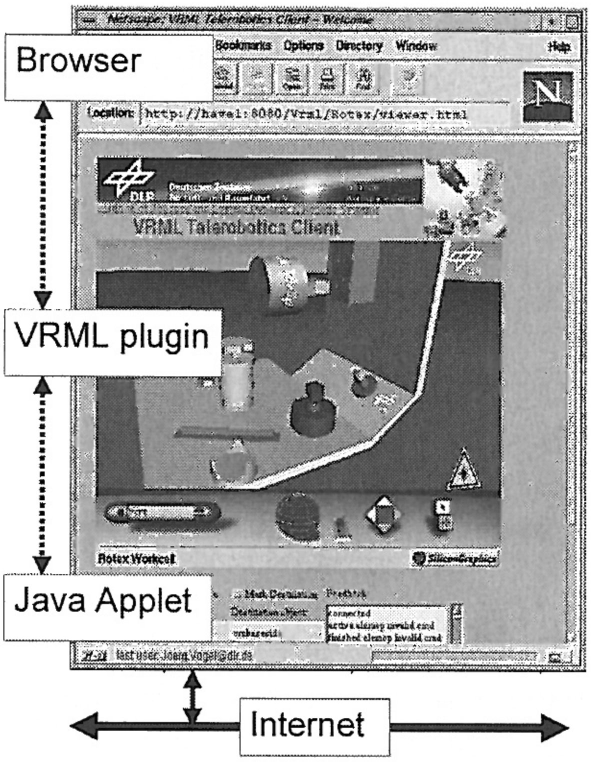


Fig. 17 Internet-Programming with VRML /3D JAVA

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, but it was used also for technology studies of Germany's technology project Experimental Service Satellite ESS, as well as for remote ground control of a new, climbing space station robot, and for mobile terrestrial and planetary robot projects.

5 LIGHT-WEIGHT ARMS AND MULTIFINGERED HANDS

5.1. General remarks

What we definitely need for space (as a technology driver) but also for the wide variety of future terrestrial service robot applications, are sensor-controlled light-weight arms (in contrast to the stiff and heavy industrial solutions) and articulated, multifingered hands, which come closer and closer to the delicate human performance. Two of these arms combined with an arrangement of a stereo camera pair tends to provide such a system with humanoid appearance and thus provokes the "robonaut" terminology (Fig. 18). NASA has recently presented remarkable results in this context.

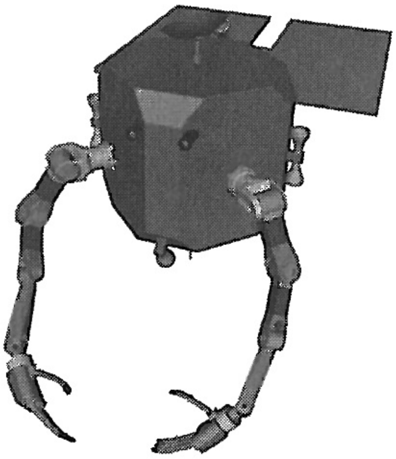


Fig. 18 DLR's Robonaut concept for a free-flying robot satellite with two arms and two articulated hands

5.2. ARM MECHANICS AND JOINT DRIVES

The design-philosophy of DLR's light-weight-robots (Fig. 19)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 better than 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, joint torque control (allowing programmable impedance, stiffness and damping) was a must for us.

Another must for us has been the use of precise motor position sensing, and link angular sensing.

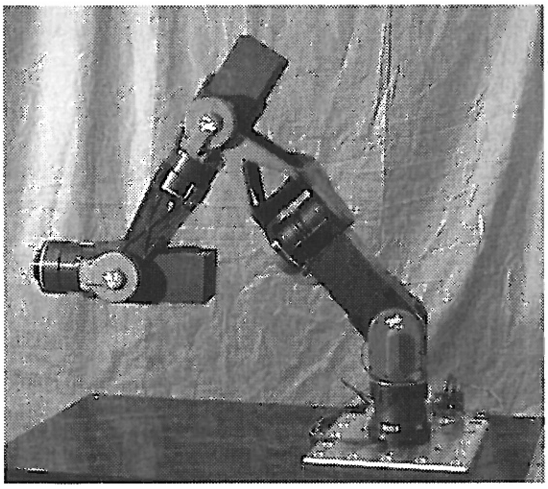


Fig. 19 DLR's second light-weight robot generation

Each joint contains a torque sensor, a link position sensor and a motor position sensor. Furthermore, all joints are equipped with electromagnetic brakes. All these components, including motor and gear are placed inside the housing to be as space-saving as possible. We use motors without housing, special short and light-weight Harmonic Drive gears and modified electromagnetic brakes with reduced power consumption and decreased weight.

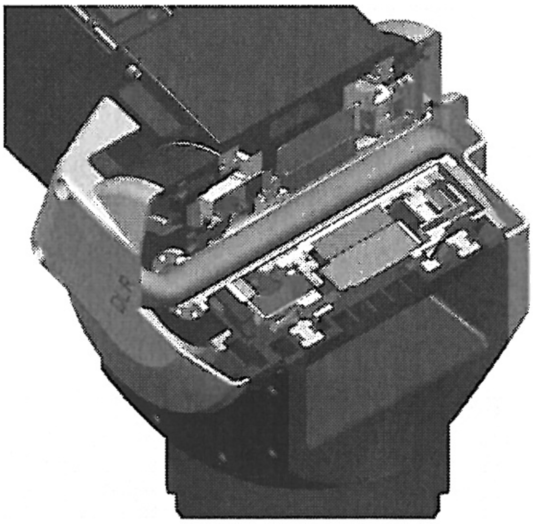


Fig. 20 Cross section of joint 2

The gears are provided with aluminum crafted wave generators and circular splines. All housings are made of aluminum (saving 40 % weight) and are designed to transfer thermal energy from the motor to the surrounding air. All joints are equipped with hollow shafts for the internal cabling.

5.3. ELECTRONIC COMPONENTS OF THE LIGHT-WEIGHT ROBOT

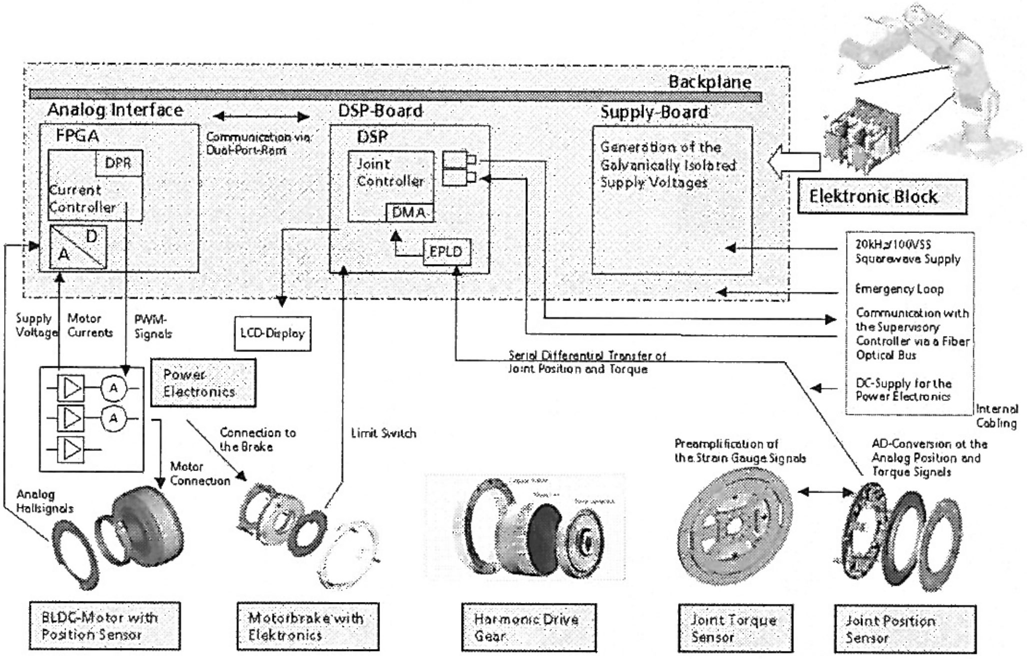


Fig. 21 Components of the light-weight robot

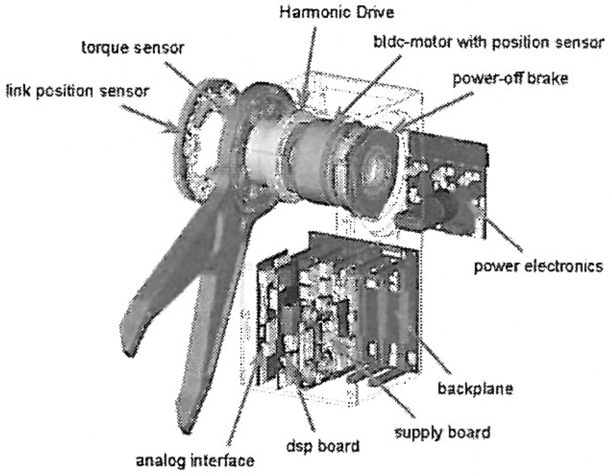


Fig. 22 The intelligent joint

For setup and maintenance reasons we have decided to use a backplane concept for the main electronic boards (Fig. 22).

One backplane is designed for carrying electronics for two joints. Joint 7 and 6, Joint 5 and 4, Joint 3 and 2 share each one electronic block, which is integrated in the robot structure. The electronics for joint 1 is located in the base of the robot.

The electronic block is built up with a backplane, a supply board, two DSP boards and two analog interfaces.

The electronics of the whole robots consumes less than 80W. The 20 KHz/100 V power supply (galvanically decoupled) had successfully been used already in the ROTEX mission, the first remotely controlled space robot.

The robot joints communicate via a fiber optical bus system. The standardized SERCOS protocol, which is a real time bus system, is used. The desired and actual motor position, link torque and link position are transmitted every millisecond. Status and supervisory signals like temperatures, voltages and error messages are transferred by means of the acyclic channel, which is defined by SERCOS as well.

On a joint-integrated DSP, the joint torque control algorithms run with 3 KHz and artificial joint impedances may be commanded from the external PC-based cartesian controller.

Two analog hallsensors are integrated into the motor to measure the magnetic field of the rotor and thus allow for precise position control. Thus we were able to meet the challenging space restrictions. The two sensors have a displacement so that their outputs correspond to a sine and cosine signal. With the sine and cosine the motor position is calculated.

Each joint is equipped with a safety brake. An intelligent drive electronics reduces the power dissipation of the brake by the factor of 10. As a result the brake could be redesigned in collaboration with the manufacturer. The total mass went down from 281g to 155g.

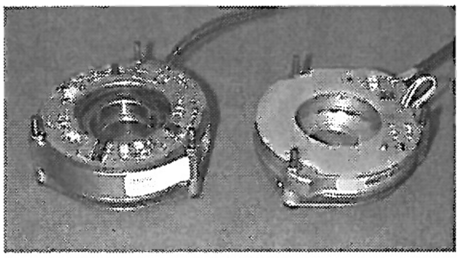


Fig. 23 Original and redesigned safety brake

An essential feature of our robot is torque sensing and control. The deformation of radial beams is measured by strain gauges (Fig. 24). The resistance variation of the strain gauges is proportional to the applied torque. By using eight strain gauges temperature effects and transverse forces can be compensated.

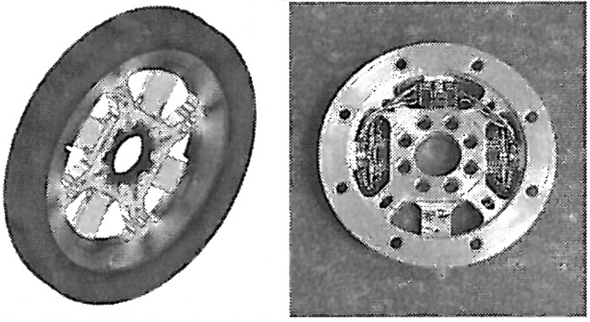


Fig. 24 FEM calculation and real torque sensor

The link position sensor is able to measure the off-drive position with an accuracy of 0,01°. As the absolute position is measured no reference sequences have to be performed during the power up of the robot. The sensor has a flat shape and allows the use of a huge hallow shaft. The analog joint position sensor signal as well as the torque signal are digitized and transferred via a serial, high speed, differential communication to the DSP-board.

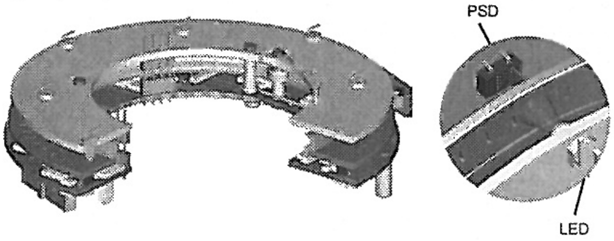


Fig. 25 link position sensor

5.4. ROBOT CONTROL (impedance control)

Considering the application fields for which this robot was designed, a main focus obviously had to be the ability to perform compliant manipulation in contact with an unknown environment. The robot should be able to guarantee the safety of humans interacting with it not only at the TCP, but also along the entire robot structure. This was one of the main motivations for introducing torque sensors in each joint, allowing not only gravity compensation (thus emulating outer space conditions), but also stiffness and impedance control.

Another challenging control problem results from the light-weight design of the robot, which inherently leads to increased joint elasticity. Since the links can be regarded as rigid compared to the joints, a flexible joint robot model can be assumed. This implies a fourth order model for each joint. Therefore, by measuring the motor position q_m and the joint torque τ and by computing the numerical derivatives dq_m and $d\tau$, the complete joint state can be obtained. Our control strategy is to use the available sensors to implement the desired task behavior as well as to compensate the effects of joint elasticity.

The first stage in the controller development was a joint state feedback controller with compensation of gravity and friction (Fig. 26).

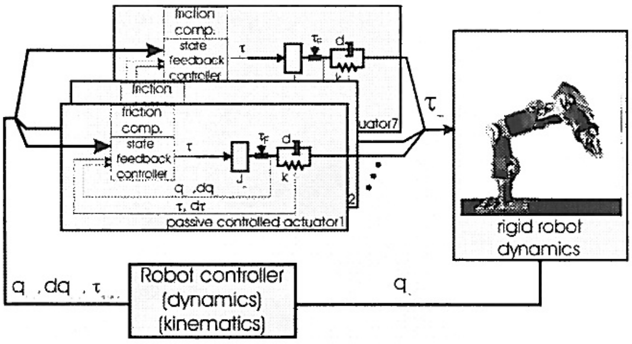


Fig. 26 state feedback controller with gravity compensation

An important feature of this controller structure is that, by a suitable parameterization, it can be used to provide a position, a torque, as well as an impedance controller. In fact, the position and the torque controllers are implemented as special cases of the impedance controller, for maximal and zero stiffness respectively. The gains are computed online, to provide the desired joint stiffness and damping. The state feedback controller is implemented in a decentralized manner on the signal processors in each joint, with a high sampling rate (3kHz).

The Cartesian position control uses a singularity robust inverse kinematics module for redundant manipulators. It enables collision avoidance and the optimization of additional task dependent criterions.

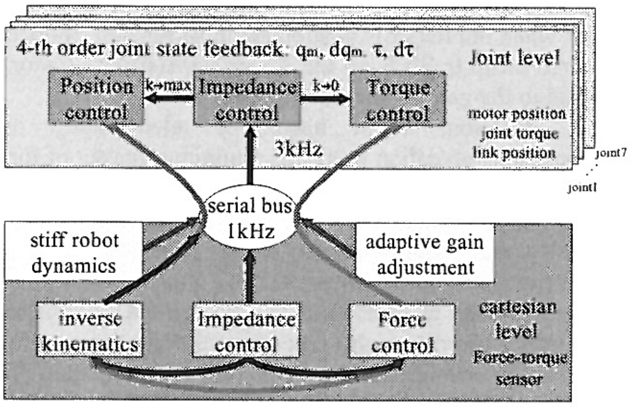


Fig. 27 controller architecture

Our next steps try to continuously reduce weight by using a self-developed, specialized multipole motor ROBODRIVE, a new piezo brake (weighting only 30g), more carbon fiber technology and higher joint modularity. As a central goal we try to further optimize the joint performance index as I defined and proposed in [10].

Thus while the present arm weighs 17kg and carries 8kg, our final goal is a weight around 12 kg and a load in that same order, while keeping the extremely low power consumption of typically less than 200 W.

5.5. ROBONAUT HANDS – Hand I

In 1997 DLR developed one of the first articulated hands with completely integrated actuators and electronics.

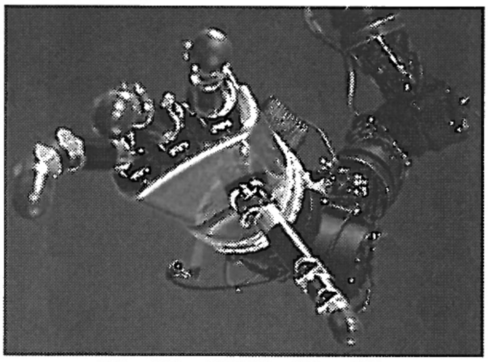


Fig. 28 DLR's Hand I.

This well known hand has been in use for several years and has been a very useful tool for research and development of grasping. The main problems remaining were maintenance and the many cables (400) leading out from the Hand. The experiences with Hand I accumulated to a level that enabled us to design a new hand according to a fully integrated mechatronics concept which yields a reasonably better performance in grasping and manipulation and therefore accelerates further developments.

5.6. DLR HAND II

Due to maintenance problems with Hand I and in order to reduce weight and production costs the fingers and base joints of Hand II were realized as an open skeleton-structure. The open structure is covered by 4 semi shells and one 2-component fingertip housing realized in stereolitography and vacuum mold.

This enables us to test the influence of different shapes of the outer surfaces on grasping tasks without redesigning finger parts.

The main target developing Hand II from the beginning has been the improvement of the grasping- performance in case of precision- and power-grasp. Therefore the design of Hand II was based on performance-tests with scalable virtual models as seen in Fig. 29.

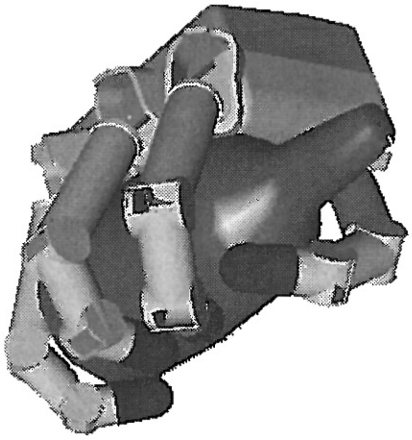


Fig. 29 Optimization of kinematics with scalable hand model

On the other hand performing precision-grasps/fine-manipulation requires huge regions of intersection of the ranges of motion and the opposition of thumb and ring-finger (Fig. 30). Therefore Hand II was designed with an additional degree of freedom which enables to use the hand in 2 different configurations. This degree of freedom is a slow motion type to reduce weight and complexity of the system. This “adaptive palm” motion of the first and the fourth finger are both realized with just one brushed dc actuator using a spindle gear. In Fig. 31 real precision and power grasp are shown with the 13 dof hand II.

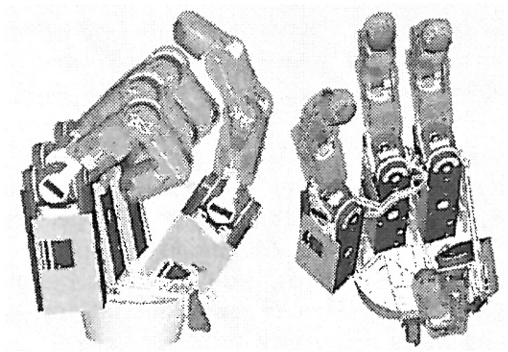


Fig. 30 Simulation of Hand II in power grasp and fine manipulation configuration

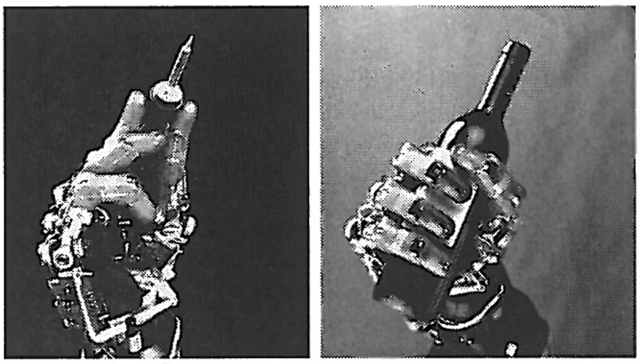


Fig. 31 Precision and powergrasp

The three independent joints (there is one additional coupled joint) of each finger are equipped with appropriate actuators. The actuation systems essentially consist of brushless dc-motors, tooth belts, harmonic drive gears and bevel gears in the base joint. The configuration differs between the different joints. The base joint with its two degrees of freedom is of differential bevel gear type, the harmonic drive gears for geometric reasons being directly coupled to the motors. The differential type of joint (Fig. 32) allows to use the full power of the two actuators for flexion or extension.

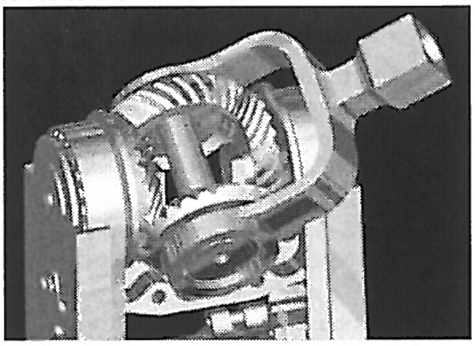


Fig. 32 Differential bevel gear of the new basejoint.

Since this is the motion where most of the available torque has to be applied, it allows to use the torque of both actuators jointly for most of the time. This means that we can utilize smaller motors. The actuation system in the medial joint is designed to meet the conditions in the base joint when the finger is in stretched position and can apply a force of up to 30 N on the finger tip. Here the motor is linked to the gear by the transmission belt.

A dexterous robot hand for teleoperation and autonomous operation needs (as a minimum) a set of force and position sensors. Various other sensors add to this basic scheme. Each joint is equipped with strain gauge based joint torque sensors and specially designed potentiometers based on conductive plastic. Besides the torque sensors in each joint we designed a tiny (20mm diameter, 16mm height) six dimensional force torque sensor for each finger tip with full digital output. The force and torque measure ranges are 10 N for Fx and Fy, 40 N for Fz, 150 Nmm for Mx, My and Mz respectively.

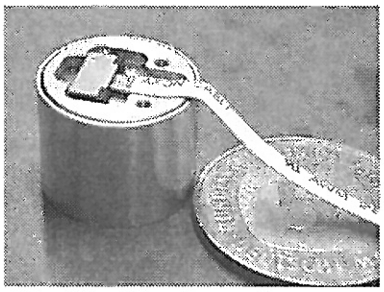


Fig. 33 The fingertip sensor

All electronics needed locally is integrated into the hand. However the control of the fingers and the hand is done by an external computer. In order to use the hand freely on different manipulators and to reduce cables and the possibility of noise in the sensor signals, we decided to design a fully integrated serial communication system. Each finger holds one communication controller in its base unit (see Fig. 34).

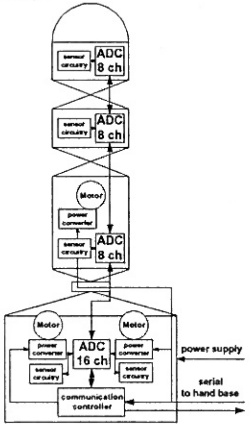


Fig. 34 Electronics and communication in a finger.

This controller is responsible for the collection and distribution of all information of interest. Furthermore it does some reasonable signal processing.

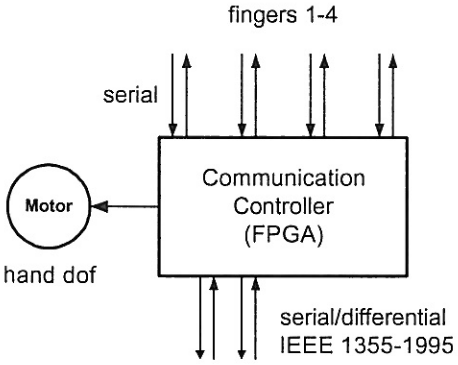


Fig. 35 The communication controller in the hand base links the fingers to external computers

It collects the data of all five ADCs per finger with together 40 channels of 12 bit resolution each and transmits these data to the communication controller in the hand base (see Fig. 35). On the other hand it distributes the data from the control scheme to the actuators for finger control. The communication controller in the hand base links the serial data stream of each finger to the data stream of the external control computer. By this hardware architecture we are able to limit the number of external cables of DLR's Hand II to a four line power supply and an eight line communication interface since the data is transmitted via differential lines. This interface even provides the possibility of using a quick-lock adaptor for autonomous tool exchange. **Reducing external cabling from 400 (in Hand I) to 12 here, is one of the major steps forward in our new hand.**

When a robot hand performs any fine manipulation, there is always need that the fingertip should be soft in the direction normal to the contact surface and hard tangential to the contact surface. Thus the impedance should be adaptable to the orientation of the fingertip. Therefore, a cartesian impedance controller has been developed, where the fingertips behave like a programmable spring.

6. CONCLUSION

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 lightweight arms, articulated hands and powerful and delay compensation telerobotic systems 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 pushing forward 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.

References

[1] G. Hirzinger, Sensor-based space robotics – ROTEX and its telerobotic features", IEEE Transactions on Robotics and Automation, vol. 9, No. 5, Oct. 1993.

[2] K. Landzettel, B. Brunner, G. Hirzinger, I. Schaefer, M. Fischer, M. Grebenstein, N. Sporer, J. Schott, „Space robotics – recent advances in DLR's Robotics Lab", ASTRA 98

[3] M. Fischer, P. van der Smagt, G. Hirzinger, Learning techniques in a dataglove based telemanipulation system for the DLR hand. IEEE International Conference on Robotics and Automation (ICRA), 1998

[4] B. Brunner, K. Landzettel, G. Schreiber, B.M. Steinmetz, G. Hirzinger, "A universal task-level grund control and programming system for space robot applications, iSAIRAS 5th Int. Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 99, ESTEC, Noordwijk

[5] R. Lampariello, Freeflying Robots – Inertial Parameters, Identification and Control Strategies, ASTRA 2000 Workshop ESTEC, Noordwijk

[6] Dubowsky, S. and Papadopoulos, E., "The Kinematics, Dynamics and Control of Free-Flying and Free-Floating Space Robotic Systems", IEEE Transactions on robotics and Automation, 5, 1993.

[7] Stieber, M.E. Hunter, D., Abramovici, A: Overview of the Mobile Servicing System for the International Space Station, 5th International Symposium on Artificial Intelligence, Robotics and Automation in Space, Noordwijk, Netherlands, 1999

[8] Toru Kasai, Mitsushige Oda, Takashi Suzuki: Results of the ETS-7 Mission – Rendezvous Docking and Space Robotics Experiments, Proc. Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space

[9] W. S. Kim, P. S. Schenker, A. K. Bejczy, S. Leake, and S. Ollendorf: An Advanced Operator Interface Design with Preview/Predictive Displays for Ground-Controlled - Space Telerobotic Servicing, SPIE Conference 2057, Telemanipulator Technology and Space Telerobotics, pp. 96-107, Boston, MA, Sept. 1993.

[10] Hirzinger, et al.: DLR's Robotics Lab - Recent developments in Space Robotics. 5th Intern. Symposium on Artificial Intelligence, Robotics and Automation, Noordwijk, ESTEC, (1999).