ETS VII Symposium, Tokyo, Japan, March 14th, 2000

DLR/NASDA's Joint Robotics Experiments on ETS VII

K. Landzettel, B. Brunner, K. Deutrich, G. Hirzinger, G. Schreiber, B.M. Steinmetz,

DLR Oberpfaffenhofen
German Aerospace Center
Institute of Robotics and System Dynamics
D-82234 Wessling
Klaus.Landzettel@dlr.de

1 Introduction and Overview

The project GETEX (German ETS-VII Experiment) is based on the (MOU) Memorandum Of Understanding, which was signed between the National Space Development Agency (NASDA) of Japan and the Deutsche Agentur für Raumfahrtangelegenheiten (DARA).

After the success of ROTEX, the first remotely controlled robot in space, DLR has focused its work in telerobotics on the design of a high-level task-oriented robot programming system, which is characterized as learning by showing in a virtual environment. The goal was to develop a unified concept for a flexible, highly interactive, on-line programmable teleoperation ground station as well as an off-line programming system, which includes all the sensor-based control features already tested in ROTEX[i], but in addition provides the feasibility to program a robot system at an implicit, task-directed level, including a high degree of on-board autonomy.

This means that a non-specialist user like a payload expert will be able to control a remote robot system e.g. for internal servicing within a space station, i.e. in a well-known environment. This requires a sophisticated man-machine-interface, which hides the robot control details and provides an intuitive programming interface. For that reason, we have developed a network-transparent graphical user interface, based on the quasi-standards VRML and Java. Using a task-level protocol is the preferable method to remotely operate robots as it demands only extreme narrow band connections and does not bother about large time delays. The user interacts via the virtual view with the real environment, as (s)he has only to define, what (s)he wants to do, not how it has to be done (Fig. 3). Supported operations are e.g. open/close a door/drawer, pick&place an orbital replaceable unit etc.

However, for external servicing with free-flying robots, e.g. the repair of a defect satellite, high interactivity between man and machine is required, because the remote environment will be mainly unknown. All the well-known problems w.r.t. teleoperation under long time delays can only be solved by the predictive graphics approach. One of the main requirements is the feasibility to update the simulated world according to the real world as well as to provide local autonomy based on intelligent sensor data processing without large a priori knowledge.

To fulfill the requirements of both application fields, we have developed a 2in2-layer model[ii], which represents the programming and control structure from the executive to the planning level in a hierarchical way (Fig. 1). According to the application requirements the user can use the necessary and sufficient level of commanding and programming or switch between the different layers especially in case of failure detection and recovery.

This control and programming system may be used for several applications: the task-oriented non-expert programming layer is demonstrated by the implementation of a net-browser VRML plugin[iii] to control a prototypic intravehicular environment, an extension of the ROTEX workcell, at the task level without any knowledge of robotics.

As a realistic test, the ground control facilities of our system were used in April ’99 to remotely control the Japanese ETS-VII[IV] robot, the first robot in free space. As mentioned above, the main goals of DLR’s contribution within the GETEX project were the utilization of the world model update concept using the real video images, to verify our task-level programming approach including on-board autonomy via selected image features and force-torque information as well as the verification of the dynamic simulation due to the interactions between robot and carrier.
Our cooperation with NASDA w.r.t. to the dynamics verification was one important step towards a free-flying service satellite.

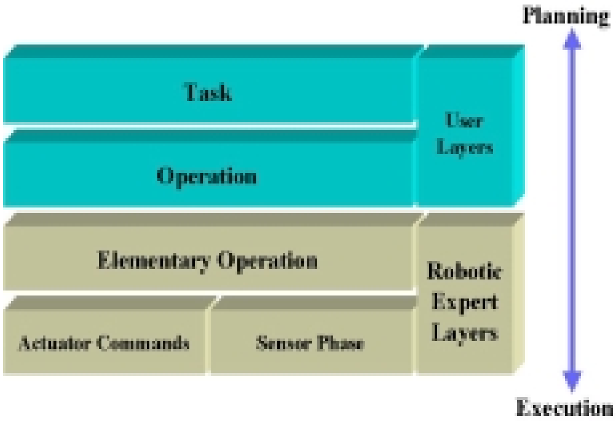


Fig. 1 MARCO 2in2-layer-model

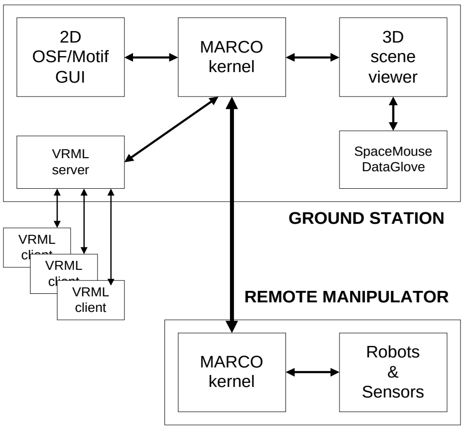


Fig. 2 User Interface Structure

Fig. 3 MARCO User Interface

2 The GETEX Experiments on ETS-VII

From April 19-21, 1999 DLR’s MARCO[V] telerobotic and -programming system was used to control the robot arm on the Japanese ETS-VII satellite.

The main goals of this GErman Technology EXperiment on ETS-VII (GETEX) were:

- to verify a MARCO-based telerobotic ground control station for remote control of a free-floating robot, in particular
- to perform a peg-in-hole experiment, using VR methods and the „vision&force“ control scheme, by closing sensor control loops directly on-board (force) and via the ground track (vision), thus proving MARCO’s sensor-based autonomy features,
- to conduct experiments with relevance to the dynamic behavior of ETS-VII in free motion mode and thus to verify the existing dynamic models.

All experiments could be performed very successfully. To implement the User Interface Structure as depicted in Fig. 3, we had to add some modules for communication with the Japanese ground control system, but not to change the overall MARCO ground control structure.

To check and test our interfaces as well as our MARCO control station within the ETS-VII scenario, an on-line simulator has been developed, which emulates the remotely operated robot, its command interfaces and its environment. The simulator is able to emulate all different modes, timing, the environmental interactions, and the prediction of satellite attitude while moving the robot arm. This kind of simulation has turned up to be very useful for proofing software correctness while interacting with the telerobot.

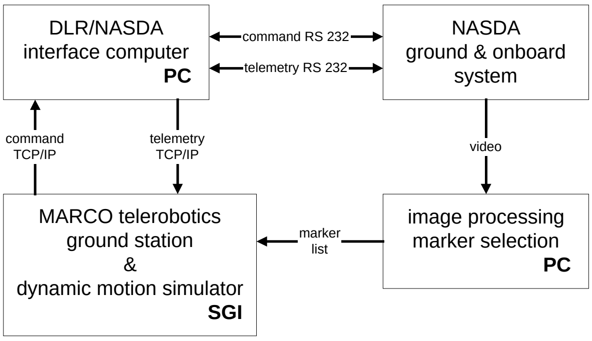


Fig. 4 GETEX ground control configuration

The original MARCO kernel couldn't be implemented on-board the ETS-VII, because only the ElemOp-Layer (see Fig. 1, Elementary Operation) was available on-board. All the other layers were implemented as add-ons on-ground, but this was no limitation to the verification of our task-level programming methods, because the downlink feedback data were rich enough to parameterize the next ElemOp according to the current execution state.

It should be mentioned, that the know-how, gained during the phase of adapting the MARCO system to the ETS-VII constraints, will be very useful for further space robot missions.

All the experiments were available live at Internet via Video transmission and a VRML simulation which showed the current robot and satellite status in an expressive way[vi]. In principal it would have been possible to control the task execution via our Java/VRML interface from any point all over the world without restrictions e.g. concerning time delay.

2.1 Peg-in-hole experiment, using VR methods and the „vision&force“ control scheme

After teaching the desired peg-in-hole task in the VR environment, i.e. pick TBTL (TaskBoard TooL), see Fig. 5, and place it into HOLE A, see Fig. 6, the execution was started and performed fully automatically on-board.

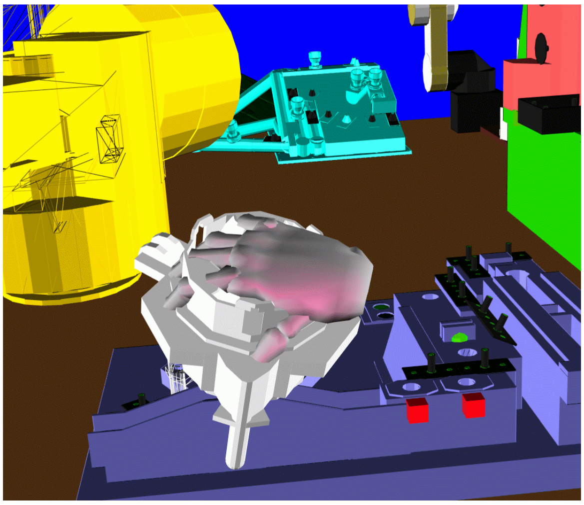


Fig. 5 Pick TBTL

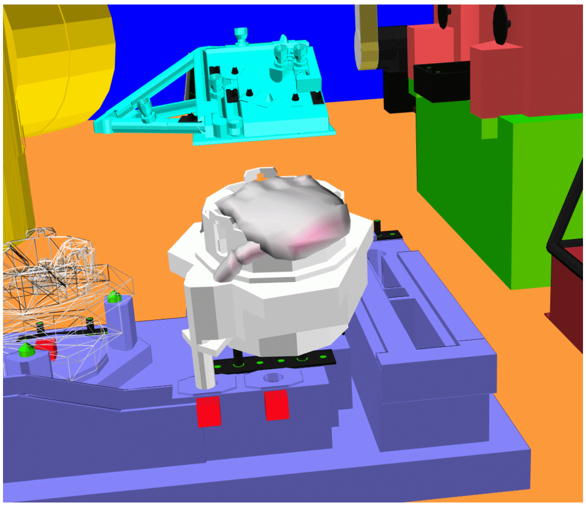


Fig. 6 Place TBTL

To get the TBTL, we first carried out a visual servoing task. For that job we used the markers mounted all over the TaskBoard. Originally, these markers should help the operator to teleoperate the TCP (Tool Center Point) into the accurate grasping position over the TBTL or another part mounted on the TaskBoard: for each camera lens of the stereo pair, three corresponding markers have to be aligned as well as the middle have to be centered within the outer ring (see Fig. 7). Now, we used these operator-markers for controlling the robot autonomously over the TBTL grasping position.

To extract the markers from the video image we used a blob-finding algorithm (supported by the MIL Matrox Image Library), described in the following:

due to the extreme contrast inside a marker (bright spots on a black background, see Fig. 7) as well as strong fluctuations of illumination, the grayscale image of the task board is reduced to a standardized ternary image (black/gray/white).

This conversion is based on an illumination estimation derived from intensity histograms of a limited image history and the last set of verified markers, if there are any.

Furthermore the identification of new marker locations is performed in tree stages:

1. Noise and drop outs of adjustable size will be eliminated by adaptive standard filters (e.g. convolution methods).
2. Each spot of appropriate form, size, and structure, which is fully included, will be extracted out of ternary image.
3. Both measured features of each spot and a scalable marker model are used for a statistical conformity analysis of measured and predicted background intensity distribution.

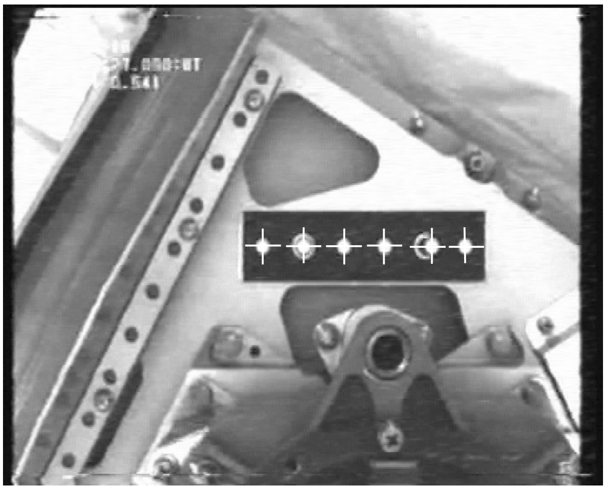


Fig. 7 View out of the left hand camera, showing the tracking markers for visual servoing

The necessary reference features as well as the marker models for the outlined selection are estimated starting from the last valid marker set (if any), the elapsed time, and the intensity distribution of the current grayscale image. The detected markers are tagged in the grayscale image. Their center of gravity coordinates are available on request.

Because this algorithm delivered more „markers“ as desired, e.g. due to bad lighting conditions, we selected the markers interactively and checked the resulting control command before sending it to the real robot. All the control algorithms we applied at the real environment were parametrized and tested on our ground station, which provides the necessary sensor simulation as well as sophisticated graphical tools for VR visualization.

As mentioned above we used the marker features in the video image to control the TCP of the robot autonomously into the desired sensor-related pose. For that reason we have developed an approach, which doesn't need any calibration. The control law may be written as

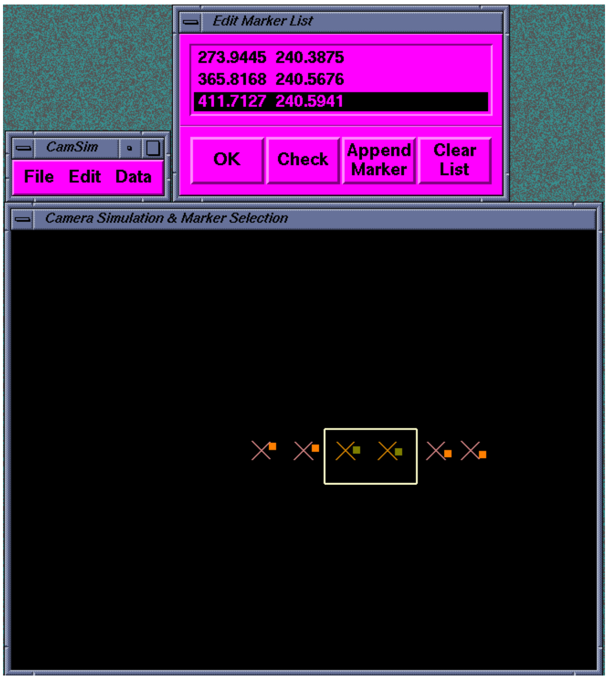
$$v_c = \alpha\, C\, (s-s^*)$$

where (s-s*) is the vector-valued deviation between the current and the nominal sensory pattern indicating the displacement of the current robot pose x from the nominal pose x*. v_c is the velocity command, α represents a scalar dynamic expression, at least a real constant, determining the closed control loop behavior, and C represents a projection operator used for mapping the sensor space onto the (cartesian) control space. C is determined by neural network learning[vii] or using analytical methods[viii].

Here we have applied the analytical method for determination of C, which is represented by the pseudoinverse of the Jacobian matrix of the m deviations in the sensor space w.r.t. the n deviations in the control space. For that we moved the robot's TCP a little bit around in all n=6 degree of freedoms, recorded the corresponding sensor values and generated the Jacobian from the resulting difference quotients.

$$J_{i,j} = \left.\frac{\partial y_i}{\partial x_j}\right|_{x^*} \quad i = 1..m,\ j = 1..n$$

We performed the experimental determination of C in our simulation environment as well as in the real one. The result was nearly the same, due to the accuracy of our camera calibration, that we applied in the simulation. The intrinsic camera parameters have been estimated using an in-house developed camera calibration tool, the external could be easily extracted from the available CAD data.



273.9445 240.3875
365.8168 240.5676
411.7127 240.5941

Fig. 8 marker selection from real video image

To explain the accuracy, the respective simulated and measured pixel coordinates in the case that the (simulated resp. real) camera is looking straight onto the TBTL are shown in Table 1. They differ only in the subpixel domain.

	X1	Y1	X3	Y3	X4	Y4
real	273.80	240.17	365.70	240.35	411.60	240.37
sim	273.94	240.38	365.81	240.56	411.71	240.59

Table 1 measured and simulated pixel coordinates

The goal was to find the markers in the live video image and to generate the appropriate straight path command to move the robot into the desired (sensor-defined) target pose. To verify the vision-based sensor control loop, we moved the TCP intentionally into a position different from the target pose (a few centimeters in all translational directions and about 20 degrees in z-rotation).

After 3 cycles (with $\alpha = 1$), the target pose was reached. Because the blob-finding algorithm delivered more „markers“ as desired, e.g. due to bad lighting conditions, we selected the markers interactively and checked the resulting control command before sending it to the real robot. Fig. 8 shows the simulated(■) and the real(**X**) markers, with the interactive selection frame.

The differences between the ■ and **X** markers in Fig. 8 result from a different TCP pose, to show the two representations. If real and simulated TCP are the in the same pose, the real and simulated markers have nearly the same 2D-coordinates.

2.2 Dynamic Motion Experiments

2.2.1 A major part of the GETEX experiment time was allocated to the so-called Dynamic Motion experiments, which consisted of a series of maneuvers carried out by the manipulator while the attitude control system of ETS-VII was switched off. (Please see [ix] for a detailed description of the Dynamic Motion experiment results.)

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[x,xi]. The free-floating mode of operation is of interest for space robots not only for the reason that attitude control fuel may be saved what augments the robot life-span, it will also be of importance during repair missions.
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. 9). The equations relating the TCP 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, due to the fact that the momentum equations are used to describe the satellite motion.

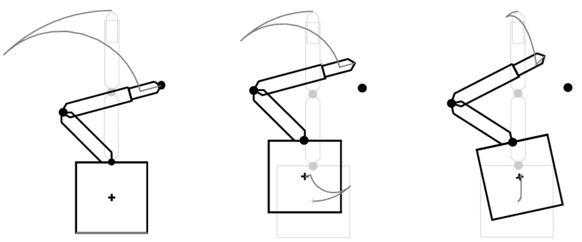


Fig. 9 The influence of the satellite attitude control mode on the path described by the robot end-effector - the same joint motion is carried out by a robot with a fixed base (left), an attitude controlled robot (middle) and a free-floating robot (right).

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 coordinates, 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 kinematic equations have to be used instead of the inverse kinematics equations. Moreover, the angular momentum equation makes the system nonholonomic[xii], 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 pathes 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 TCP 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 maneuver in joint space.

This kind of maneuver can be applied 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 TCP 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 maneuver as for a robot with a fixed base and adding a closed-loop re-orientation maneuver to compensate for the produced attitude error. Path planning for nonholonomic system has been investigated in the context of cars and wheel-driven robots[xiii]. While those systems may generally be considered as planar, the case of free-floating robots demands spatial methods.

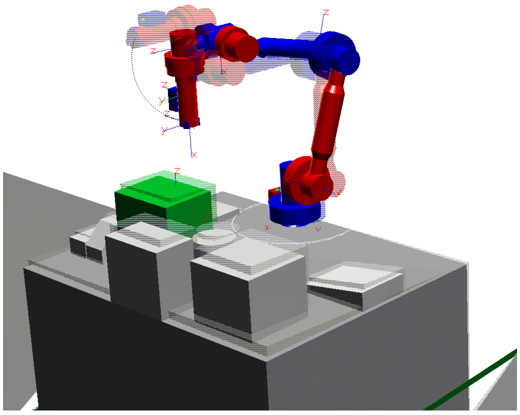


Fig. 10 Example of simple point-to-point maneuver carried out during the GETEX mission. the shaded robot indicates the reference position. The satellite reaction to the arm motion is scaled by a factor of 10 in this picture.

Whatever path planning method is applied to free-floating robots 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 rendezvous/docking like operations.

One goal of the GETEX experiments 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 maneuvers were executed by the manipulator, while the attitude control system of ETS-VII was switched off.

These so-called Dynamic Motion Experiments include simple point-to-point operations (see Fig. 10) and closed-loop re-orientation maneuvers 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 $\pm 1.0^{\circ}$ around each axis and the fact that the maximum TCP 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.

2.2.1.1 Assessment of the dynamic experiments of GETEX

In the GETEX experiment the following maneuvers of the manipulator on-board the ETS-VII satellite were performed:

- point-to-point maneuvers

- maneuvers to determine a variation of the attitude of the satellite
- optimized maneuvers to minimize satellite base motion or manipulator joint motion (minimum energy maneuvers)

These maneuvers were performed successfully in the sense that the end-effector was successfully brought to the final desired position, in relation to the satellite, for each of the point-to-point and optimized manœuvres. This validated the model of the satellite-manipulator system used for calculating the executed paths and performing the simulations. The restrictions imposed by hardware safety requirements during the experiments (collision avoidance and limited workspace, limited tip-speed velocity, limited attitude variation of the satellite) were all met to an acceptable degree.

The experimental results also have shown that the modeling of the external torque acting on the satellite (standard disturbances which act on orbiting space systems) have to be included in the overall model of the system, if maneuvers of the manipulator need to be referenced to inertial space, or to another spacecraft. In developing the model used for this experiment, in fact, it was assumed that such disturbances were negligible for the purpose of the experiment. This is because the duration of the maneuvers was thought to be short enough to neglect any external action on the satellite.

The results have instead shown a substantial drift of the satellite in time, of about one degree every ten minutes around each axis of the orbital frame of reference. This was not expected and resulted in a partial failure of the second maneuvers listed above, since it was not possible to determine the rotation of the satellite with respect to inertial space during the experiment. However, despite this unexpected behavior of the system, all maneuvers were performed while satisfying the limitations on satellite attitude variations of 1 degree about each axis to an acceptable degree.

The external actions mentioned above have now been modeled successfully, such that the model of the system as a whole has been updated. The disturbances were found to be primarily due to two factors:

- The residual angular momentum of the reaction wheels on-board gave rise to an apparent torque which acted on the system. This gave rise to a relative motion of the satellite with respect to the orbital frame of reference.
- The gravity gradient is the primary natural disturbance in low Earth orbit and was in fact found to give rise to a substantial effect on the motion of the satellite w.r.t. the orbital frame of reference.

The simulation of such disturbances with the updated model of the ETS-VII satellite was found to be in good agreement with the experimental results.

As a conclusion, the GETEX dynamic motion experiment has been useful in

- validating the model of the ETS-VII satellite-manipulator system for maneuvers referenced in the satellite's frame,
- realizing that it is necessary to account for the external disturbances acting on a spacecraft in low Earth orbit for a correct modeling of the maneuvers referenced in the fixed inertial frame, and
- developing a model for the external disturbances which was validated with the experimental data.

2.3 Conclusion

We have performed the GETEX mission at ETS-VII with very successful results, i.e. in applying the vision&force control scheme to the peg-in-hole environment of the ETS-VII TaskBoard as well as in verifying our dynamic models of free-floating space robots. Now we believe that the extensive use of robotics, e.g. at the International Space Station or as a free-flying servicing satellite[xiv] including intelligent robot arms and grippers, should be pushed by all industrial and political partners.

2.4 Acknowledgement

We'd like to gratefully thank all the Japanese colleagues at NASDA for their very helpful support during the preparation, tests and operational phases.

---

[i] G. Hirzinger, B. Brunner, J. Dietrich, J. Heindl, „ROTEX – the First Remotely Controlled Robot in Space,“, IEEE Conf. on Robotics and Automation, San Diego, May 1994

[ii] B. Brunner, K. Landzettel, B.M. Steinmetz, G. Hirzinger, „TeleSensorProgramming – a task-directed programming approach for sensor-based space robots“, Int. Conf. On Advanced Robotics (ICAR'95), Sant Feliu de Guixols, Spain, Sept. 1995

[iii] http://www.robotic.dlr.de/Joerg.Vogel/Vrml/Rotex/

[iv] M. Oda, K. Kibe, F. Yamagata, „ETS-VII – Space Robot In-Orbit Experiment Satellite“, IEEE Conf. on Robotics and Automation, Minneapolis, April 1996

[v] K. Landzettel, B. Brunner, K. Deutrich, G. Hirzinger, G. Schreiber, B.M. Steinmetz, "DLR's Experiments on the ETS VII Space Robot Mission" *'99 ICAR, the 9th International Conference on Advanced Robotics, Keidanren Hall in Tokyo, Japan, October 25 to 27, 1999*

[vi] http://getex.robotic.dlr.de

[vii] G. Wei, G. Hirzinger, B. Brunner, "Sensorimotion coordination and sensor fusion by neural networks", Proc. IEEE Int. Conf. on Neural Networks, San Francisco, 1993

[viii] B. Brunner, K. Arbter, G. Hirzinger, "Task Directed Programming of Sensor Based Robots", IROS '94, Munich, Sept. 12-16, 1994

[ix] R.Lampariello, K.Deutrich, „Getex Dynamic Motion Experiments: A First Analysis“, *ETS VII Symposium, Tokyo, Japan, March 14th, 2000*

[x] Longman, R.W., Lindberg, R.E. and Zedd, M.F., "Satellite-mounted Robot Manipulators – New kinematic and Reaction Moment Compensation", International Journal of Robotics Research, 3, 1987.

[xi] 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.

[xii] Nakamura, Y. and Mukherjee, R., "Nonholonomic Path Planning of Space Robots via a Bidirectional Approach", IEEE Transactions on Robotics and Automation, 4, 1991.

[xiii] Li, Z. and Canny, J.F., "Nonholonomic Motion Planning", Kluwer Academic Publishers, 1993.

[xiv] K. Landzettel, B. Brunner, G. Hirzinger, „The Telerobotic Concepts for ESS“, IARP Workshop on Space Robotics, Montreal, July 6-8, 1994