Vision & Interactive Autonomy Bi-Lateral Experiments on the Japanese Satellite ETS-VII

Daniele G. Galardini, Konstantinos Kapellos and Eric Maesen
TRASYS Space - Leuvensesteenweg 510, Bus 43, 1930 Zaventem, Belgium
Gianfranco Visentin and Frédéric Didot
ESTEC – Keplerlaan 1, 2201 Noordwijk, The Netherlands

ABSTRACT

In April 1998 the **V**ision & **I**nteractive **A**utonomy **B**i-**L**ateral **E**xperiments (**VIABLE**) project on the ETS-VII engineering satellite of NASDA, the Japanese Space Agency, entered in its final phase. This first collaboration between ESA and NASDA has the scope to test the Interactive Autonomy concept for space robotics and to investigate advanced vision-based techniques for robot positioning and calibration. Thanks to the ETS-VII environment, several experiments have been performed in April 1999 using the ETS-VII robot arm and the on-board available utilities. Fine positioning, compliance control, camera calibration, robot calibration, force/torque sensor calibration are at present the experiences foreseen.

The project development is carried out by TRASYS Space as prime contractor. The ground station for robot monitoring and control has integrated ESA develoments as well as university S/W toolbox, and experiences have been extensively studied and validated with a robot simulator prior to the operations phase. During the operations phase, the robot tasks are executed in the satellite environment and the actual robot movements are shown concurrently to the simulation. Besides the interest of the experiences themeselves, VIABLE would show the possibility to adapt existing software for high-level robot task control to a robot using low-level control statements used to command the ETS-VII on-board robot.

Finally, the re-use/adaptation of existing products and the collaboration between different Space Agencies has provided a series of technical and management returns (lessons learned), from which will benefit future robotics space missions.

The paper is organized as follows. Section one will describe the on-board/on-ground environment and the constraints to which the developers have to adapt the control system. Solutions to implement the VIABLE on-ground control station will then be given in Section 2. A description of the experiments and of the main attempts will be presented in Section 3. Considerations on managing international projects and final remarks will conclude the paper.

Section 1: System Description

Figure 1.1 shows the overall ETS-VII robot environment. Following paragraphs describe briefly the available hardware to support both the Interactive Autonomy experiments and the Vision-Based Control experiments.

1.1 ETS-VII Robot Arm

The ETS-VII robot arm (ERA), mounted on the satellite platform, is a six degrees of freedom manipulator of approximately 2 m in a fully stretched configuration. A force/torque sensor is mounted on the last joint. The performance characteristics of the robot arm are shown in Table 1.1.

	POSITION	ATTITUDE
Pose accuracy	10 mm	1 deg
Path accuracy	30 mm	3 deg
Pose repeatab.	2.5 mm	0.13 deg
Max. tip speed	50 mm/sec	5 deg/sec
Speed acc.	10 %	10 %

Table 1.1: Robot arm characteristics

Proc. Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

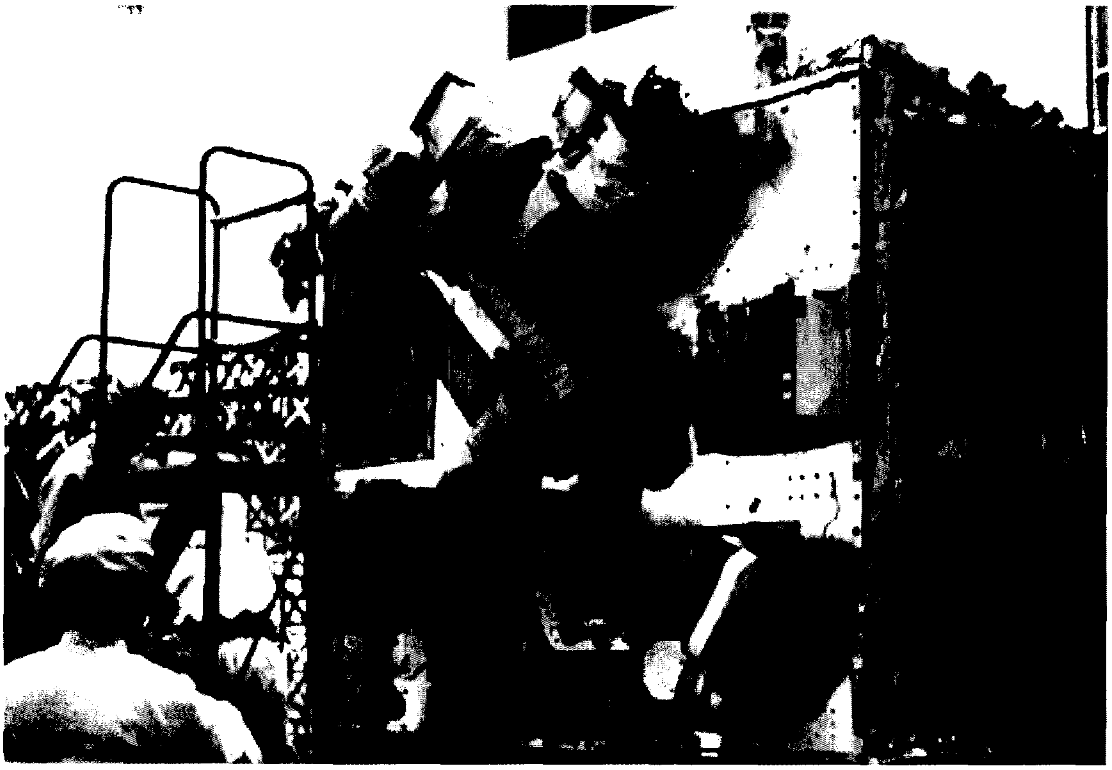


Figure 1.1: ETS-VII Robot arm and its environment

1.2 Arm End-Effector

The end-effector is attached to the f/t sensor. It can be equipped with different grapple fixtures (GPF) to handle payloads (P/L). As a result, the end-effector provides the following functions:

- grasps a GPF attached to the P/L;
- provides torque to P/L via GPF;
- provides electrical interface with P/L via GPF.

For VIABLE experiments it is allowed to use the standard GPF only.

1.3 Vision System

The on-board vision system consists of two sets of cameras. The arm hand camera (AHC) set is mounted on the end-effector and the arm monitor camera (AMC) set is mounted on the first joint of the robot arm. Each set contains two B/W CCD cameras, a primary one and a redundant one. All cameras have a 668 by 485 pixel resolution and a fixed focal length. Video data of any two cameras are sent to ground each 250 ms. JPEG video data compression is used to reduce the video data size to 1.2 Mbps.
A video data processing (VDP) unit is present on-board for measuring misalignments by using a 3-point alignment marker and computing the relative position and attitude of three white circle images of the marker in the video image. This computation takes less than 0.5 sec. For experiment execution, video data transmission to the ground control station can occur in two modes: either 4 Hz AHC + 1 Hz AMC or 2 Hz AHC/AMC + 2 Hz AHC/AMC.

1.4 On-Board Controller

The robot mission on-board controller (RMOC) together with the arm drive electronics (ADE) controls ERA. While the latter performs joint servoing at a rate of 5 ms and sensor signal processing, the former is responsible for arm trajectory control and compliance control (maximum rate 250 ms).
Note that the robot arm motion plan, i.e. path and speed, is modified in order not to disturb the satellite attitude motion.

1.5 Taskboard

The taskboard consists of functional items supporting the evaluation of the robot arm performance and arm motion characteristics. Experiments with the different items can only be performed with the Taskboard Tool Handling (TBTL) device, which is to be attached to the external robot arm (ERA) end-effector.
The functional items are:

- force/torque sensor calibration unit (spring coil with scale) whose the displacement can be measured with the arm hand camera as it is located close to a linear scale;
- a peg, permanently fixed to the TBTL, diameter 18 mm, with two different holes (diameters 18.4 and 19 mm);

- a slider handle to be operated with the peg for testing contact motion;
- a linear scale (1mm resolution);
- a sine curve surface to test contact motion;
- and a small chained floating ball.

1.6 Arm Control Modes

The arm can be controlled in three different modes:

1. joint position control mode (absolute or relative);
2. Cartesian position control mode (straight line);
3. Cartesian compliance control mode.

Ground station commanding is possible:

- either by uplinking continuous (every 250 ms) incremental setpoints (position & attitude or joint angle commands), called point of resolution (POR),
- or by uplinking robot telecommands (straight path motion, single joint movements).

1.7 Modes of Operations

The ETS-VII robot supports three modes of operation:

1. pre-programmed execution mode: the robot motion plan consists of robot telecommands whose validity (correctness, collisions and interference with satellite attitude control) is verified prior to execution;
2. telemanipulation: incremental positions (POR) are sent each 250 ms and interpolation is performed by the on-board robot controller;
3. real-time execution mode: used for the floating ball capturing experiment assisted by the vision data processing unit.

The on-board robot arm will be controlled from a ground control station at NASDA Tsukuba Space Center, Japan. As said the ground operator will receive real time images of the robot arm motion that he can use together with the predictive CAD simulator for supervision.

The time delay in the communication link is around 4 s.

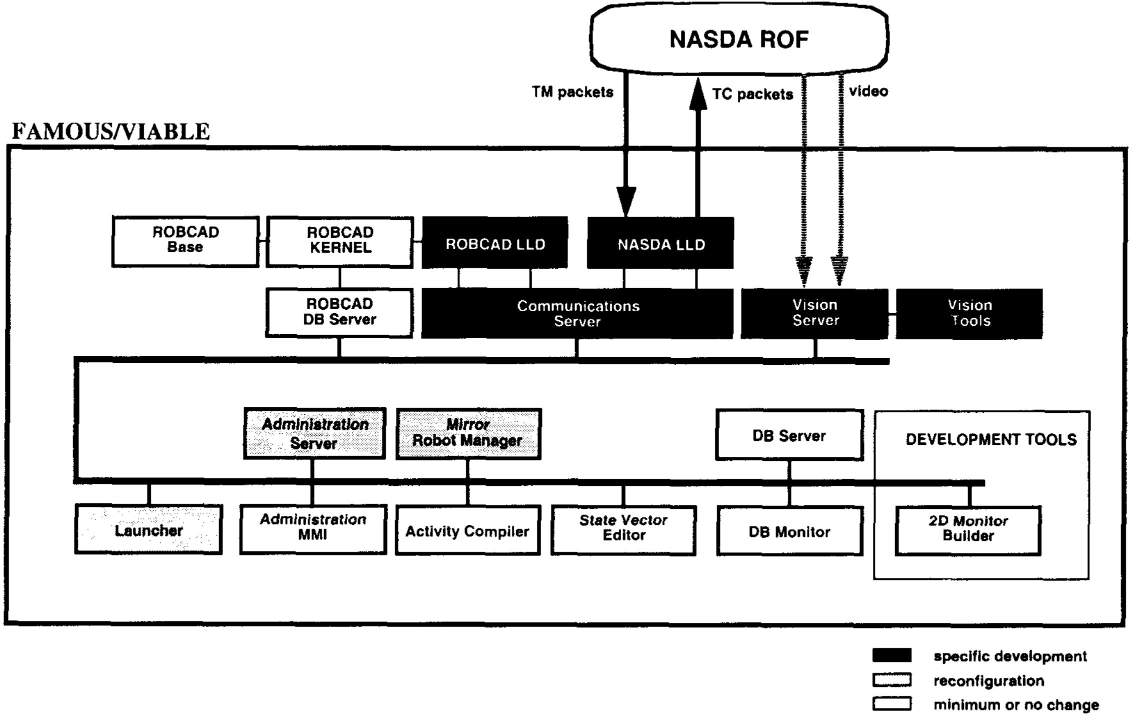


Figure 2.1 – VIABLE station general description

Section 2: ETS-VII Ground Testbed

The VIABLE station is integrating the FAMOUS/Generic system, a previous ESA development which has led to a general purpose and project independent software.designed to actively support an on-ground operator for the preparation and execution of space-based robotic experiments. The framework has to be *instantiated* (by addition of dedicated software or by configuration of existing software) to support the VIABLE experiments. This is mostly due to different and project specific robot languages and communication protocols. Figure 2.1 shows the resulting VIABLE station architecture and the interface with the NASDA Robot Operator Facility (NASDA ROF), i.e. the NASDA mission control center that has the final authority in uploading commands. Grayed boxes identify the specific VIABLE software components. The VIABLE station is organised as a series of servers and clients components:

- servers provide standard services to the calling components (e.g. access to the workcell model, or communications with the robot via the NASDA ROF);
- the clients are basically MMI with (very) limited processingcapabilities, from which the user operates or monitors events.

The components are mostly based on Tcl/Tk, and are integrated with each other using Tcl-DP. The Communications Server is the central monitoring and control component for VIABLE. The Low-Level Drivers (LLD) transform high-level requests into basic telecommands for the real NASDA robot and/or to the simulated robot. ROBCAD is the kernel software for simulation and workcell representation.

Section 3: VIABLE Experiments

3.1 IA Robot Manipulation

The Interactive Autonomy (IA) operational concept has been devised in order to enable the use of robots by non-experts. It includes two aspects:

Interactivity. A first case of interactivity is when an user has to adapt his experiment plan with new parameters. A second one of interactivity concerns the anomalies or divergences between the expected experiment results and the actual ones. The interactions are performed from the ground, making use of pre-programmed nominal or recovery sequences. In both cases, the operator does not interact at servo-level but using pre-programmed sequences that can be considered as macro commands.

The nominal task of the robot is prepared on ground using an off-line programming system, supported by CAD simulation. The safe execution (e.g. against collision) is particularly verified. Once the tasks has been validated, these are ready for non-interrupted execution.

Autonomy. Due to the functionality offered by the NASDA ETS-VII robot, the resulting autonomy is reduced to the execution of simple low-level commands. To increase the abstraction level of each task an interpreter between high-level commands (compound tasks) and low-level commands (ERL commands) will be provided. As shown in Figure 3.1, such interpreter also uses the telemetry data to control what the low-level commands need to be uploaded. Therefore, from the end-user's point of view the compound task abstraction level will be maintained high when from the developer's point of view the system will present a low level of abstraction even in the compound task description.

Remember that compound tasks are sets of commands whose execution is carried out in a completely autonomous way. The interaction between the operator and the robot is limited to initiat these tasks and to monitor their execution.

IA operations and expected advantages

For VIABLE, the IA operations are broken down into four different phases:

- Station development: encoding of control concepts in modular form and creating templates for supporting the envisaged operations (on-ground);
- Compound tasks preparation: interactive programming of high level commands (compound tasks) and verification by simulation (on-ground);
- Mission simulation: use of the VIABLE station to simulate operations (e.g. for training);
- Mission operations: autonomous execution (on-board) of the above-prepared compound tasks with high level monitoring (on-ground) by the VIABLE station. Moreover, contingency procedures for releasing the control to NASDA and, if possible, for recovering the operations (on-ground) have been established;
- Post-mission analysis: the post-mission data analysis.

In other words, the operator by means of an off-line programming tool composes each compound task (i.e. macro command). Then the compound task is parameterised and validated by simulation during the mission simulation phase.

For the VIABLE mission, the major advantages foreseen using IA instead of telemanipulation are:

- safety of the execution that is guaranteed by validation of the tasks by the programming and simulation tool in addition to the monitoring by the human operator of telemetry data communicated to the ground segment;
- more predictable performance and better reliability;
- lower demand on operator skill and workload, enabling a scientist to concentrate only on his experiment;
- safe task execution due to testing and validation of pre-programming effort;
- faster task execution.

Notice that a prerequisite for applying IA is the availability of a robot with very predictable Cartesian and dynamic behaviour. In case of poor robot repeatability and accuracy, as on ETS-VII, a higher level of interaction by operator is foreseen when precision positioning has to be guaranteed. Otherwise, higher autonomy could be maintained.

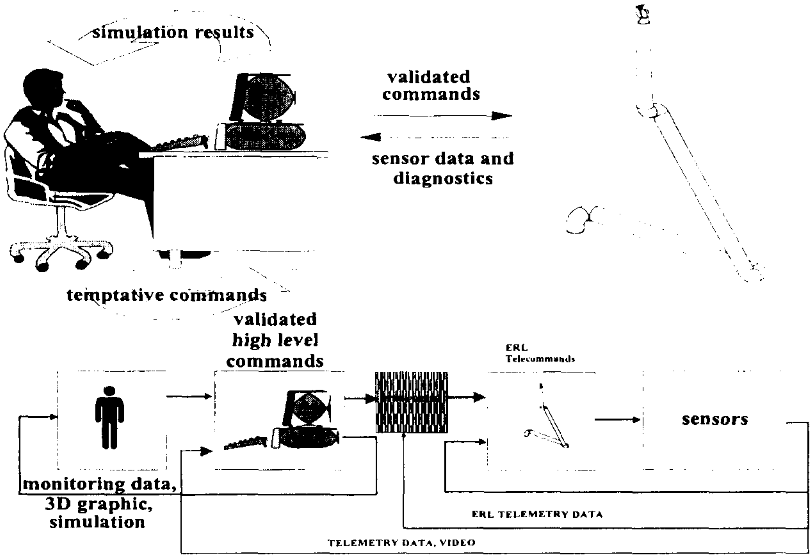


Figure 3.1: Control loops in VIABLE Interactive Autonomy.

3.2 VBRC Experiments

The operation phases for Vision-Based Robot Control (VBRC) experiments are the same as for IA experiments.

The major expected advantages of the VBRC experiments are:

- to assist the operator during the IA experiments, e.g. to refine positions, to retrieve the slider position;
- to calibrate the cameras parameters that are unknown. The completion of this item is required before the use of the Vision Tools for combined IA/VBRC experiments;
- to validate an innovative algorithm to obtain eye-hand calibration from images only;
- to provide material for post-mission robot calibration.

The following examples will help appreciate the expected additional benefits.

VBRC/IA Peg-Into-Hole Experiment

The robot moves blindly to a position above the hole.The cameras take images and these are augmented by Vision Tools. This means that the markers and the holes from the CAD model will be displayed directly on the image. Also the impact point of the peg will be drawn on the image. Then, an ellipse fitting is applied to the original images (only in a restricted area: close to the projection of the CAD hole) and from the difference between the hole in the images and the projected impact point, an update for the robot position is computed.

The robot performs this update, images are taken and these are again augmented. If necessary, a new update is performed and the robot finally uses force feedback to insert the peg into the hole. This will help the operator in the execution of a safe experience, reducing torques and forces on the robot end-effector. An example of the features offered by Vision Tools is given in Figure 3.2 which shows a first Breadboard Prototype with marker position superimposed.

Eye-Hand Calibration

An innovative algorithm has been developed to obtain eye-hand calibration from images only without any need to touch the grapple.

The procedure computes the eye-hand calibration in two stages. First the translation between camera and robot-tip is computed, then the rotational component is searched for. For the eye-hand translation, 3 equidistant views are taken from the markers and an Euclidean reconstruction is found. Then, the robot is rotated with a known rotation, again 3 equidistant views of the markers are taken and the reconstruction is computed. From both reconstructions and the known rotation, the translation between camera and robot can be found. For the eye-hand rotation, a starting point for the camera is selected. Then, the camera is moved in 3 orthogonal directions and for each direction two images are taken. From these views, the rotational component of the eye-hand calibration is found using vanishing points.

This procedure is considered as an advanced experiment with high scientific significance.

Conclusions

VIABLE is the result of a collaboration between NASDA and ESA. From a

Project Management point of view, the following points are worth to mention:

1. direct, and even personnel, contact between the technical people of both sides dramatically enhance mutual understanding (and therefore solving) of the difficulties;
2. the whole management chain should actively relay and support communication of up-to-dated technical information (documents, engineering models, and even piece of code) or, when this is unfortunately the case, dare to quickly and explicitly declare an information as missing or lost;
3. common definitions and conventions must be clearly stated and published to avoid misunderstandings between partners;
4. what are the allowed and not allowed operations must be clearly defined and explained by the participating agencies, for example in the form of typical and representative utilisations scenarios

We would like to stress again the importance of a project management that acts even at technical level following the exchanges between the partners and avoiding project re-engineering.

Technically, VIABLE re-uses previous ESA developments for the ground station implementation.

Finally, VIABLE has been the first project demonstrating in-orbit the Interactive Autonomy mode of. The operations (Figures 3.3-7) at NASDA Space Center in Tsukuba, Japan, between April 3 and 6, 1999. The scientific analysis of VIABLE mission is foreseen in next months in collaboration with University research centers.

Acknowledgements

The authors would like to thank all NASDA officers and particularly Dr M. Oda, Mr. N. Inaba and Dr. N. Doi for the help and support in the succesful realization of the VIABLE mission.

References

1. Oda, M., et al - ETSVII, Space Robot in-Orbit Experiment Satellite. Proceedings of the IEEE International Conference on Robotics and Automation, Minneapolis,
2. NASDA - ETS-VII NASDA ground system for DARA(ESA) ground system interface, Issue B, 2-Sept-97
3. NASDA - Interface specification between NASDA and foreign space agencies on ETSVII robot experiments, 10 May 1996
4. NASDA - Interface Control Specification (ICS) Part II On-Ground Systems and Mission Operations (Preliminary Draft), 13-May-96
5. TRASYS-VIABLE Operation Plan Document, VIA-TRA-TN-OPP V1.0, 20/08/98
6. TRASYS-VIABLE Experiment Definition Review VIA-TRA-TN-EDRD V1.0, 11/06/98

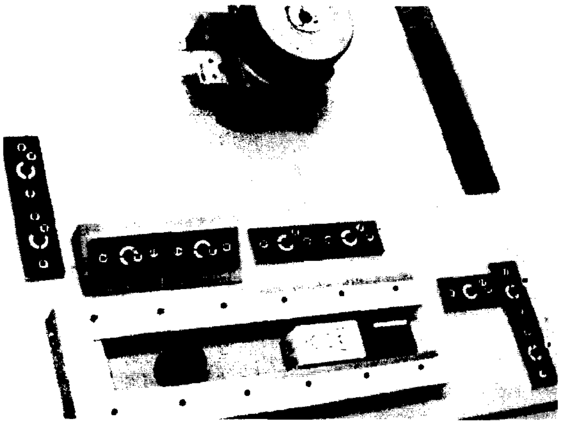
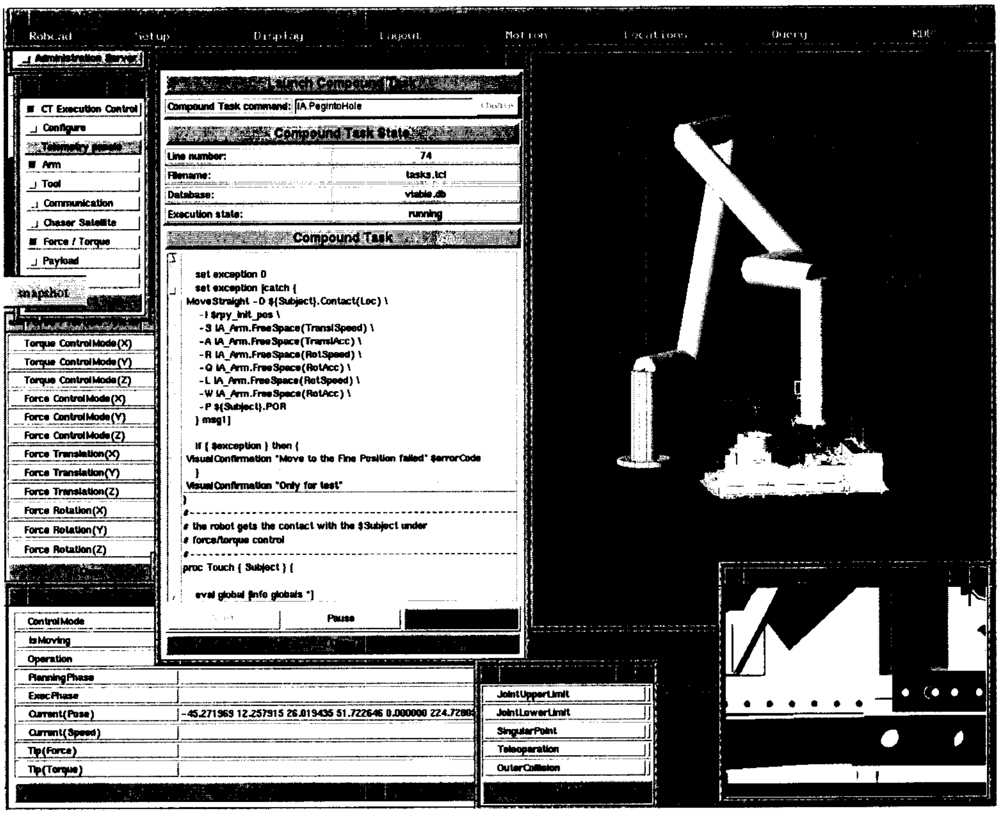


Figure 3.2: Prototype with marker position superimposed



Compound Task command: IA.PegIntoHole

Line number:	74
Filename:	tasks.tcl
Database:	viable.db
Execution state:	running

```
  set exception 0
  set exception [catch {
MoveStraight -D ${Subject}.Contact(Loc) \
   -I $rpy_init_pos \
   -S IA_Arm.FreeSpace(TranslSpeed) \
   -A IA_Arm.FreeSpace(TranslAcc) \
   -R IA_Arm.FreeSpace(RotSpeed) \
   -Q IA_Arm.FreeSpace(RotAcc) \
   -L IA_Arm.FreeSpace(RotSpeed) \
   -W IA_Arm.FreeSpace(RotAcc) \
   -P ${Subject}.POR
  } msg1]

  if { $exception } then {
VisualConfirmation "Move to the Fine Position failed" $errorCode
  }
VisualConfirmation "Only for test"
}
#-----------------------------------------------------
# the robot gets the contact with the $Subject under
# force/torque control
#-----------------------------------------------------
proc Touch { Subject } {

  eval global [info globals *]
```

ControlMode	
IsMoving	
Operation	
PlanningPhase	
ExecPhase	
Current(Pose)	-45.271969 12.257915 26.019435 51.722646 0.000000 224.7280
Current(Speed)	
Tip(Force)	
Tip(Torque)	

Fig 3.4: The VIABLE Station layout

Fig. 3.4: The ESA/TRASYS team during the operation in Tsukuba

Fig. 3.5: The NASDA Team during Operations