Testing Space Robotics on the Japanese ETS-VII Satellite

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In April 1998, the first collaboration between ESA and NASDA on space robotics culminated in a very successful demonstration on the Japanese Engineering Test Satellite (ETS) VII. From an ESA control station at NASDA's Tsukuba Space Centre in Japan, a team of ESA and industry staff commanded the satellite's robot arm through a series of a advanced manoeuvres in a demonstration that will contribute to future applications of space robotics. The data collected will allow us to quantify the exact performance and reliability achievable with such modes of control. Apart from its technical success, this joint experiment was also a very positive experience at the personal level due to the excellent spirit of professional dedication and co-operation between the Japanese and European teams.

Introduction

ETS-VII (Engineering Test Satellite VII) is a NASDA programme designed to test key rendezvous, docking and robotics technologies in space. The Japanese space agency has built, launched and operates this test satellite, equipped with a robotic manipulator and a small subsatellite, to carry out such experiments. In response to a NASDA call for co-operation, ESA proposed two experiments to be conducted on-board ETS-VII. The ESA proposal was accepted with the understanding that NASDA and ESA would jointly co-operate in the development and operation of the two experiments.

Following the initial contacts, the International Relations offices of the two agencies worked together to establish a Memorandum of Understanding (MOU) that would govern the co-operation. Belgium expressed its willingness to fund the activities involved in implementing the experiments, under the ESA Technology Demonstration Programme (TDP) and General Support Technology Programme (GSTP).

After an open competitive tender, the Vision Interactive Autonomy Bi-Lateral Experiment on ETS-VII (VIABLE) contract for experiment implementation was awarded to a consortium led by TRASYS Space, with the VISICS group of the Katholieke Universiteit Leuven and Space Application Services.

The ESA rationale for the co-operation

There are several reasons why the ESA Technical and Operational Support Directorate has pursued co-operation within the ETS-VII project. Firstly, earlier ESA research and development (R&D) activities have developed several space-robotics technologies to a high level of maturity. Their feasibility has been proven mainly through ground-based demonstrations. However, in-flight demonstrations are essential for full acceptance of these technologies, but are difficult to organise because they are expensive and not readily covered by R&D funding. Consequently, when the ETS-VII project opened its doors to international cooperation, it presented a unique flight-demonstration opportunity.

Secondly, ETS-VII features the first, and so far the only, satellite-mounted robot arm to be remotely controlled from the ground. This unique characteristic was particularly interesting for demonstrating technologies relevant to satellite servicing which ESA had been studying for some time.

Thirdly, there was strong interest in developing co-operation with NASDA on space-robotics issues. There is an increasing need for international co-operation at all levels in space projects, and NASDA with ETS-VII and its JEM robotic system is promoting itself as an authoritative partner for space-robotics activities. It was therefore important for ESA to establish first contacts with such a key player.

The ETS-VII system

ETS-VII (Fig. 1) consists of two satellites: the 'chaser' and the 'target'. During rendezvous-and-docking (RVD) experiments, the chaser releases the target and drifts away to distances of up to 9 km. Subsequently, a rendezvous manoeuvre brings the chaser back close to the target and a docking between the two is performed. The chaser is also equipped with a robotic platform (Fig. 2), which allows assessment of the following technologies:

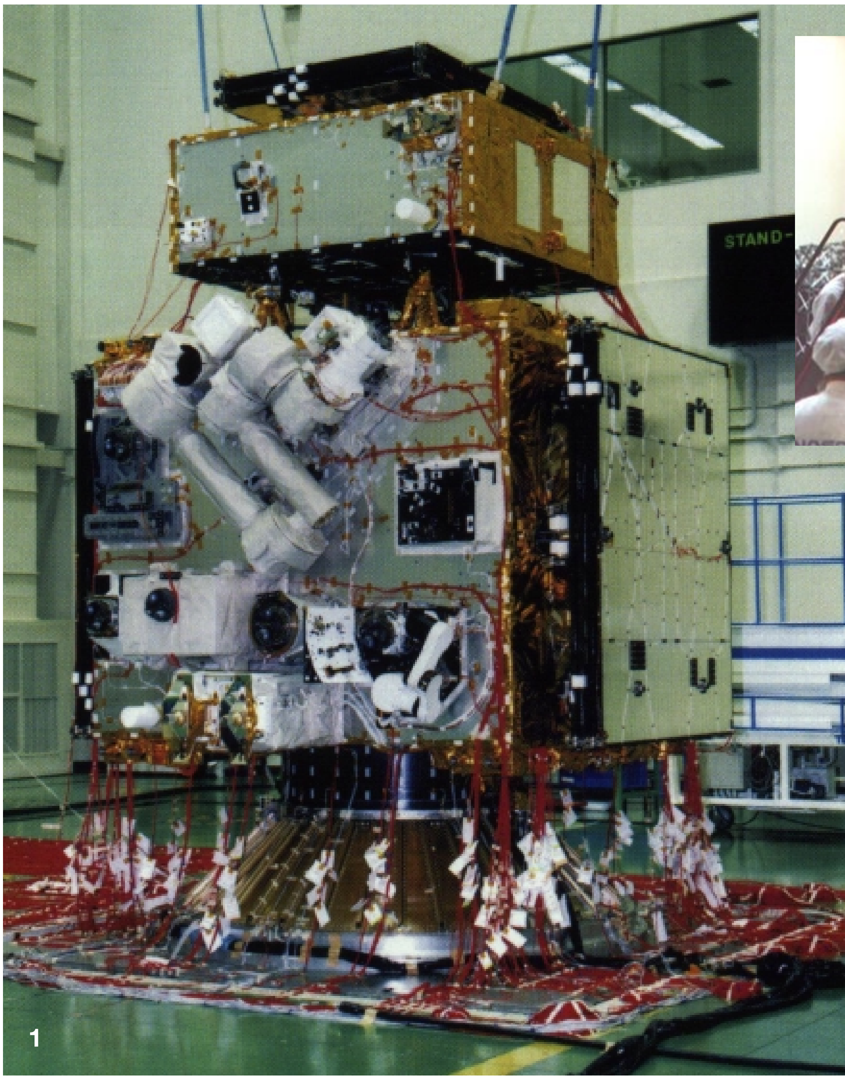

Figure 1. The ETS-VII satellite system undergoing vibration testing at NASDA's Tsukuba Space Centre (TKSC)

Figure 2. The robotics platform during final integration at TKSC

– teleoperation in the presence of time-delayed and limited-capacity telecommunication
– coordinated control of satellite and robot arm
– in-orbit satellite servicing.

The MOU allowed ESA to carry out the experiments using two elements of the robotics platform: the external robot arm and task board.

The ETS-VII space and ground segments are linked via the NASA TDRS data-relay satellites. Figure 3 provides an overview of the communications chain. This communication set-up allows one to extend the radio visibility of the satellite system, enabling operation windows of up to 45 min duration.

The ESA experiments

The two experiments proposed by ESA aimed, within the limitations imposed by the already settled satellite configuration, to assess the efficacy of two technologies developed under ESA R&D activities: the Interactive Autonomy robotic control mode, and computer-vision-assisted robotic control. Given that the configuration of the ETS-VII flight segment had already been finalised, the experiments could only be implemented as additions to the ground segment. Therefore they consisted of specific software which would run on the so-called 'ESA Terminal' to be connected to the ETS-VII robotics ground-control segment.

The Interactive Autonomy Experiment

In the Interactive Autonomy (IA) robotic control mode, robot operations are analysed and broken down into a modular and hierarchical set of activities and related parameters. This breakdown has the effect that robot operations become programmed sequences of:
– autonomous robot manipulations, and
– robot-user interactions

in a way that optimises flexibility and efficiency. Such a mode has many advantages. Pre-programming and verification via simulation guarantee enhanced safety during the execution of robotic tasks. More predictable performance and better reliability are achieved. There is lower demand on operator skills and a reduced workload, allowing the robot to be operated by non-robotics specialists.

Interaction with the user happens basically on two occasions:
– when the user wants to change the autonomous robot operations
– when a divergence or an anomaly occurs between the expected manipulation results and the actual results.

In both cases, the interaction is limited to the selection of activities, and related parameters, that the robot has to execute autonomously. The activities and parameters that can be selected are limited to those that are meaningful and safe for the current robot and robot-environment configuration.

The Vision Based Robot Control (VBRC) Experiment

Computer vision to enhance robotic control is the subject of many research projects all over the World and particularly in Europe, where knowledge on this technology is quite strong. The technology, using cameras as enhanced means of perception and with the help of sophisticated software, allows the robotic working environment to be assessed exactly, without a-priori knowledge. The technology can therefore be used to boost autonomy in robotic operations, as well as to increase the performances of human-operated robot systems. The VIABLE experiment foresaw experiment sequences to prove the validity of this technology.

Through the VIABLE activities, the technology developed and first validated on the ground has been demonstrated successfully in a space environment under real illumination conditions.

The challenges of ETS-VII

The main technical challenges that the experiment developers had to face were linked to the fact that ETS-VII had not originally been conceived to support the ESA experiments. Because NASDA had set up a ground segment capable of hosting guest experimenters (Fig. 3), the main limitations stemmed from the flight segment.

For the IA experiment, the functionality offered by the basic NASDA ETS-VII robot controller did not allow great autonomy. Due to its main utilisation as a tele-operated system, it could only execute simple, low-level trajectory commands. To enhance autonomy, an Autonomous Executive able to understand high-level commands was introduced by ESA, to serve as a front-end to the ETS-VII robot operation facility.

On the VBRC side, the problems resided in the generation and transmission of video pictures from the flight segment. The two wrist-mounted cameras used by the experiment were designed to provide visual feedback to human operators. The cameras had not been built or calibrated specifically for computer-vision purposes. Moreover, the video signal was transmitted using JPEG compression, which preserves the appearance of the pictures, but introduces artefacts that disturb computer-vision algorithms. The vision algorithms had to be re-engineered by ESA to cope with these unusual working conditions.

The development of the experiments

The time available for the development of the experiments was rather short. In fact, the industrial development contract could not be started until the MOU had been finalised and signed by the Directors of both Agencies. Due to the lengthy finalisation process, the real

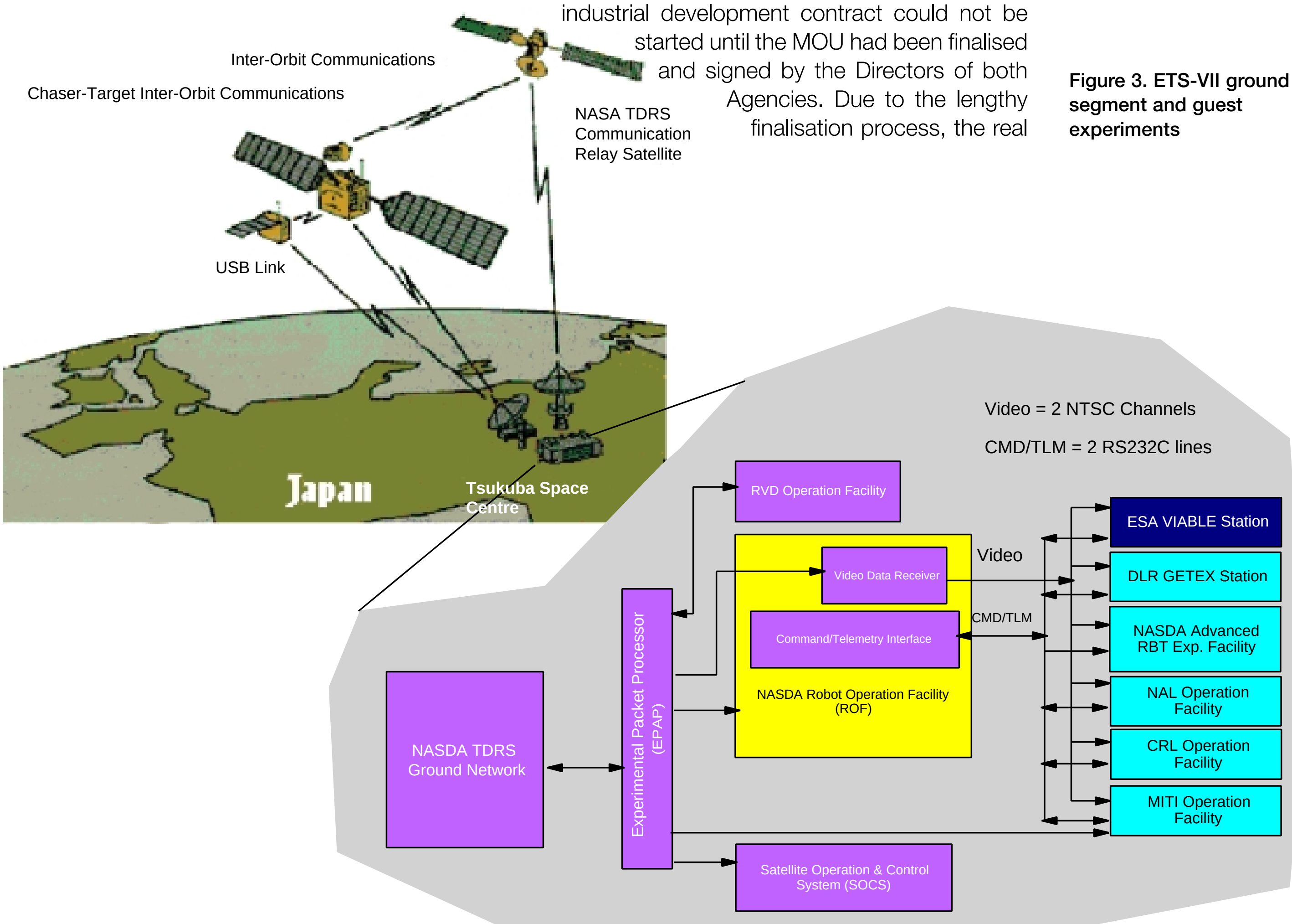

Figure 3. ETS-VII ground segment and guest experiments

effort could not start before April 1998, even though the mission was fixed for April 1999.

However, the developers were not starting from scratch in that the ‘ESA Terminal’ could be based on the ‘FAMOUS’ system. This is an ESA technology development that provides a general-purpose, project-independent software framework, designed to actively support a ground-based operator in the preparation and execution of space-based robotic experiments. The framework had to be instantiated (by the addition of dedicated software or the configuration of existing software) to support the VIABLE experiments. Moreover, a large part of the computer-vision experiment could be based on the ‘TargetJR’ system. This is a large integrated Image Understanding (IU) environment, designed both as a computer-vision research tool and as a platform for building end-user IU applications.

Mission time

After about one year of development work, it was time for the mission. NASDA had reserved the use of the ETS-VII ground segment for ESA for two weeks starting on 29 April. The first week was devoted to the rehearsal of the experiments on the ETS-VII ground simulator, the second to the in-flight experiment execution itself.

Figure 4. Video sequence from an IA experiment (top-to-bottom and left-to-right). In a single picture, the left image shows a robot-hand camera view, and the right image a robot-base camera view. The robot tool slides over a sinusoidal profile under strict force control. This classical robotics test is representative of many robotic operations, such as rubbing a surface. In IA, the complete operation was initiated by invoking a single command and related parameter (force level)

The European team consisted of two ESA and three industry staff members. The first week of experiment rehearsal was very satisfactory. The ‘ESA Terminal’ had already been installed in the ETS-VII ground operations network a few weeks earlier, at the time of an electrical interface compatibility test. However, the rehearsal was the first occasion on which full interaction between the Terminal and the ETS-VII ground segment could be tested. Remarkably, only very minor problems were identified and these were easily corrected.

The experiment execution

The schedule for the execution of the ESA experiments foresaw three days of operations with four 45-minute operating windows per day. The following text has been extracted from the mission logbook:

Day one, 6 April

Ten minutes before the first window, NASDA reported that they could not contact the satellite. Analysis showed that it was a TDRS problem, and this was confirmed by NASA. Unfortunately, the previous day (after the ETS-VII initialisation) NASA had performed an update to the TDRS ground software, and a newly introduced bug prevented TDRS operation during the first and second windows. This necessitated a major rescheduling of the ESA experiments, with the new schedule being even more demanding than the original one, featuring five experiment windows over the next two days.

Aside from this initial problem, all of the VBRC experiment sequences that could be executed in the remaining windows on day 1 were successful in performing measurements on the ETS-VII robotic equipment and testing the vision algorithms.

Day two, 7 April

This was the second day of operation and, as all experiments were dealing with contact operations, had the highest risk of problems occurring. During these operations, the robot tool would come into physical contact with various items on the satellite, calling for careful commanding in order to avoid exerting excessive forces on them.

Regrettably, our first experiment sequence was aborted due to what later analysis showed to be a miscalibration of the robot joint sensors. This problem again resulted in some major work in adapting the experiment sequences. Thanks to the experience and support of the ETS-VII team and the flexibility of the ‘ESA Terminal’, the remaining contact operations could be performed flawlessly.

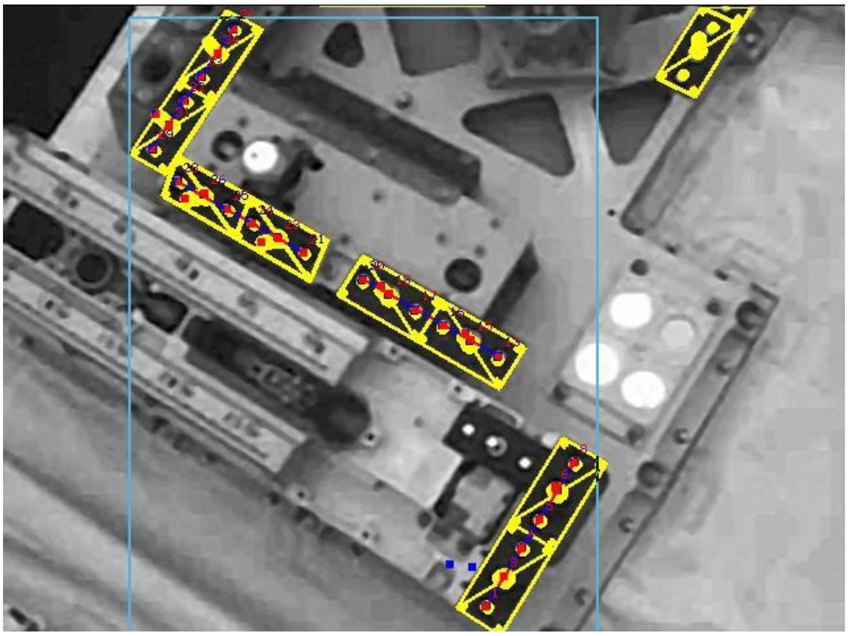

Figure 5. The computer-vision algorithms provide the robot controller with an exact perception of the working environment. Here the position of some task-board markers is identified and computer-generated clues are superimposed on the camera picture. In VBRC, this feature enables the robot to find out autonomously where the subjects of its manipulation are located

Day three, 8 April

After an early start, with the window briefing at 03:00AM, the day looked promising. Based on the experiences of the previous days, all indications were that the ESA Terminal was performing well. In the event, all experiment sequences worked correctly and no real problems were experienced. On the contrary, some sequences went faster than expected, so that it was even possible to run additional sequences during the last window.

The experiment results

Final evaluation of the mission data is still in progress at the time of writing, but some general conclusions can already be drawn. The IA robot mode of operation has been applied successfully during a real robotics mission and its benefits demonstrated (Fig. 4). The difficulties encountered even served to offer an additional positive validation of the performance of IA. This conclusion has great importance for the robotics applications on the International Space Station, which will make use of various forms of IA (ERA, the Technology Exposure Facility).

The VBRC experiment demonstrated the computer-vision support to autonomous robot control (Fig. 5) as well as to human tele-operation (Fig. 6) in a real mission scenario. Additional capabilities that will be useful for robot operations with non-cooperative objects have also been successfully demonstrated (Fig. 7).

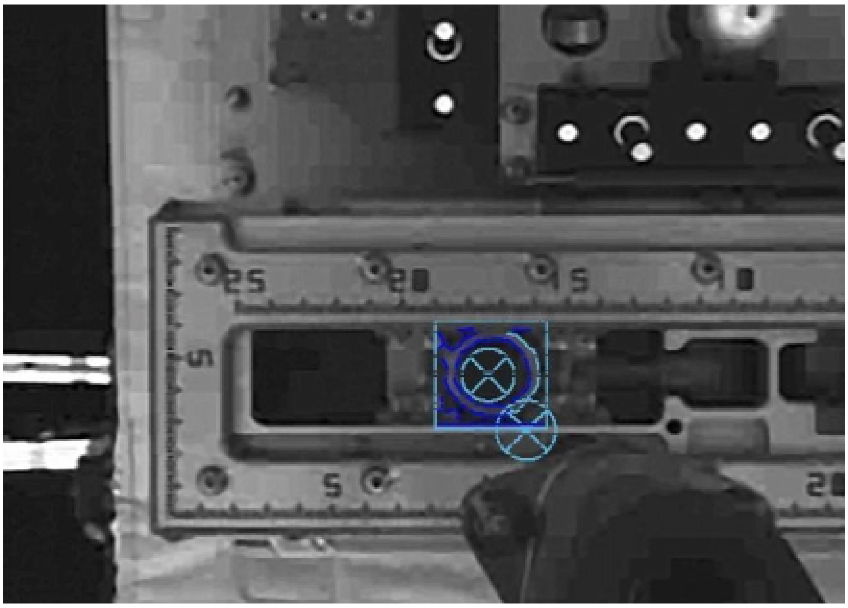

Figure 6. The hole in the task-board slider is identified by the computer vision (dark blue) and the current and updated impact points of the peg are presented to the robot operator with visual clues (light blue). Here, the computer vision is providing the robot operator with additional information that helps in performing the peg-into-hole operation more quickly and more accurately.

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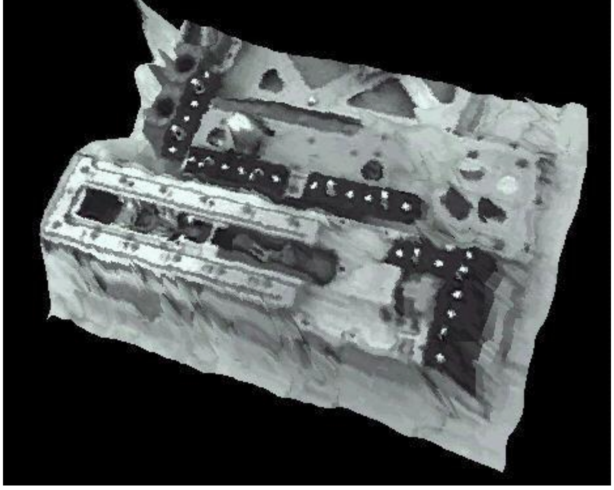

Figure 7. By processing a sequence of images taken from the robot-hand camera, the geometry of the slider element of the task-board can be reconstructed. This VRBC feature enables robots to operate successfully in a previously unknown working environment