The EUROPA Ground Segment

R. Leone - S. Losito - R. Mugnuolo - A. Olivieri - F. Pasquali (ASI)
F. Didot (ESA-ESTEC)
M. Favaretto - R. Finotello - A. Terribile (Tecnomare SpA)

ABSTRACT

For more than 10 years ASI has carried out extensive research and development work in the area of space robotics. The dexterous manipulation of payloads has been studied in depth and key subsystems have been developed.
In the framework of an ASI/NASA agreement for the Space Station utilization ASI defined the mission EUROPA (External Use of RObotics for Payloads Automation) to be flown on the ISS utilization flight UF3. For the implementation of the mission ASI is finalizing an agreement with ESA which foresees ESA contribution for a scientific P/L, the Robot Calibration Platform, the Remote Monitoring and Control and Preparation and Verification (RMC/PV) and the Facility Monitoring and Command (FMC) SW packages for ground station.
The purpose of the mission is to install the SPIDER robotic arm on an Express Pallet Adapter (EPA) and to carry out servicing operations of scientific payloads. A Ground Control Station will allow the end users to interact with the experiments without the need for astronaut time.

The EUROPA Ground Control station will be installed in the new ASI Center for Space Robotics (CRS) based in Matera (Italy).
The Center shall feature for EUROPA program and for other future programs:

- clean room and integration laboratories
- facilities for test of robotic systems
- facilities for congress and workshop
- advanced Man-Machine Interface for end-to-end operations.

The present paper is mostly focused on:

- the Ground Reference Model (GRM) of the Flight Segment
- the Ground Support Equipment (GSE), including in particular the Ground Control Station which will be based on the RMC/PV and the FMC SW packages provided by ESA
- the Center for Space Robotics
- the advanced Man-Machine Interface.

INTRODUCTION

EUROPA Mission shall be an end-to-end demonstration in space environment of robotics technologies aimed to highlight the benefit of automatic payload servicing in extravehicular environment with a robotic manipulator.
The Ground Segment to be produced is finalized to support the Flight Segment of EUROPA Mission with the following main activities:

- configuration and preparation of a Center for Space Robotics (CRS) for supporting FM testing prior to launch and FM control
- development of tools to command and monitor the robotic mission from ground during in-flight operations
- development of tools to simulate on ground the flight system in order to verify the robotic experiment (GRM)
- development of tools to support the integration and test of the Flight system on ground (GSE)
- development of equipment for training of the astronauts for in-flight operations.
- development of equipment for training of the astronauts for EVA in contingency.

GROUND SEGMENT DESCRIPTION

The EUROPA Ground Segment is based on the following modules:

- the replica of the EUROPA flight system, the Ground Reference Model (GRM) to be used to:
  - prepare and verify the robotic missions before their execution on-board
  - support from ground the Operative Phase of the Mission

- the Ground Support Equipment (GSE) to be used to:
  - support the on-ground testing of the flight system.
  - support and control from ground the Operative Phase of the Mission.

They will be both located at the Center for Space Robotics in Matera.

The Ground Reference Model (GRM) of the Flight Segment

The GRM is composed by:

- the SPIDER arm with the End Effector (EE) and the Force/Torque sensor (FTS) already developed in a previous ASI contract (*Figure 1*).
- the EM of the On-Board Data Handling system
- the EM of the Controller and of the arm joint driver system
- the ground replica of the hold down system
- the ground replica of the Robot Calibration Platform (RCP) supplied by ESA
- the ground replica of the task board supplied by ESA
- the ground replica of the scientific P/L supplied by ESA
- the ground replica of Express Pallet Adapter (EPA) connected to the ground replica of the interfaces of the Express Pallet (ExP).

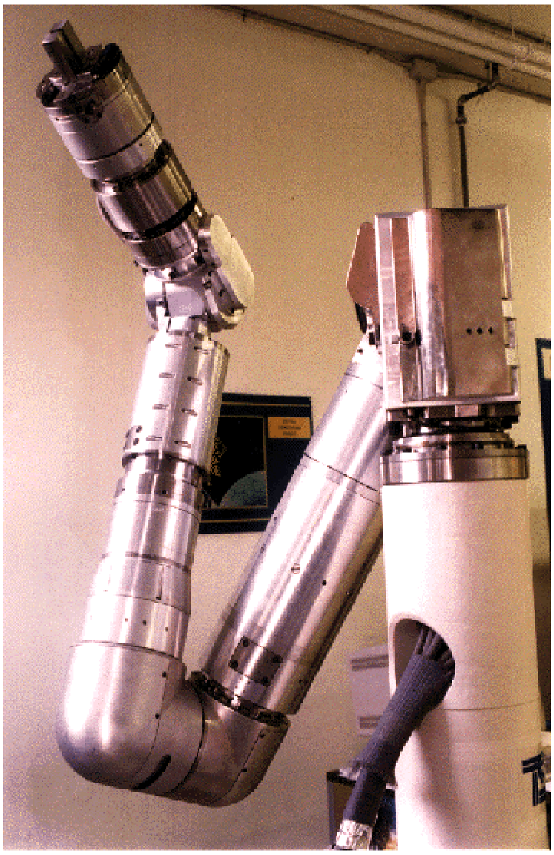

Figure 1 - EM Arm

The GRM arm is an anthropomorphic manipulator featuring seven joints, all simultaneously commanded in order to manage the seven dof's in an optimal way.
The arm harness allows the internal cabling of the FTS, the RCP and the EE.

For transport and emergency operations the arm can be divided in three main parts: the shoulder, the elbow and the wrist assemblies.
The FTS measures force and torque at the EE caused by the interaction with the environment.
The EE is a gripper, mounted on the arm wrist. Two tactile sensors mounted on the gripper are used to monitor the gripping force.

The Controller, the Emergency Unit and the driver have to be a functional replica of the Flight Model.
The Controller, Drivers and Emergency Unit are integrated in a single mechanical box.
Additional functions relevant to the verification and performance tests and the functions relevant to teleoperation are provided in the ground replica of the controller.

The ground replica of the hold-down has the same functions as the FM, used to block the arm during the launch phase.

The RCP mock-up, mounted between the arm wrist and the FTS/EE assembly, provides the measurements for the calibration and performance checking of the arm.

The Ground Support Equipment (GSE)

THE GSE is composed by:

- the equipment to simulate the 0-g condition for the arm (1-g Compensation equipment)
- a network of workstations connected to ASInet and, through this, to NASA
- a calibration system for the manipulator based on the Optotrack measurement system
- alternative calibration S/S
- an alternative task board (task board 2) for test of the operational capabilities of the manipulator GRM in performing general purpose tasks
- the Ground Control Station, with the optional Communication Emulator

The 1g Compensation System is developed in order to apply vertical forces counteracting the gravity forces to the mass center of the arm link and to reduce the gravity effects on the joints number 1, 2 and 3.

The calibration on Ground of the GRM will be based on the use of the RCP GRM but other two calibration approaches will be used, with optical sensors mounted on the manipulator end effector:

- TVTrackmeter (TVT), stereoscopic vision system implemented by Tecnomare in ROSED program (Figure 2)
- TVMono, TVcamera for monoscopic vision measurement.

The two systems will feature the following functions:

- robot calibration by computing some set of parameters of the arm kinematics (joint positionsensor offset and, if necessary, other kinematics parameters such as the length of the link)
- workcell calibration by measuring the position of target objects with respect to the robot.

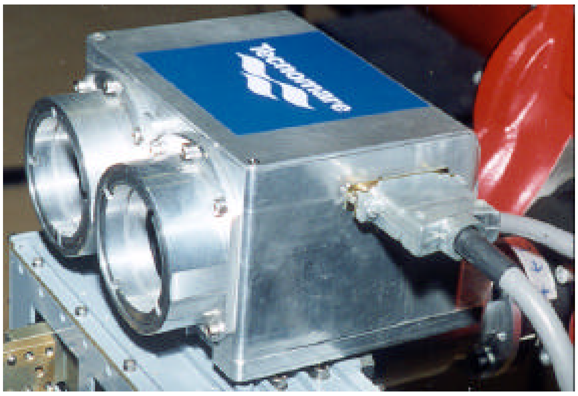

Figure 2 - TVTrackmeter (ROSED program)

The TVTrackmeter also performs the "object reconstruction": the recognition of some geometric primitives (point, line, plane, quadrilateral, cylinder), suchas objects of the environment with the measurement of the geometric parameters and their position with respect to the robot.
Both the sensors will measure the position of target points in the environment (using passive target and not active ones as the RCP) and their output will be used by ad hoc developed SW for the robot calibration.

The MMI Ground Station is connected either to the Flight Segment or to the GRM and is the interface of the EUROPA Operator in the Ground Segment.
As a reference the MMI Ground Station features the functionalities of the RMC/PV station developed by ESA and is based on the following nominal operational mode:

- the robotic system executes pre-checked robotic programs which are sequences of robotic commands, composed by commands of tasks and actions provided by the arm Controller in ISS mode.
- the Operator writes and store the programs using an editor
- the Operator verifies the programs on-ground before their execution in-flight by using the SW simulator and the Ground Reference Model
- the Operator commands the execution of the robotic program in automatic mode or in Interactive Autonomy[1] mode, with insertion of human interaction in the phases requiring human knowledge in order to define the mission prosecution
- during the execution (with some delay dependent by the communication channel) the Operator follows the mission phases through the graphic display of the status of the system in the MMI Ground Station
- in emergency mode, the Operator commands using the MMI the single joints of the arm through the Emergency Unit by requiring delta position of a joint.

The main functions of the MMI Ground Station are:

- configuration
  - programming of the characteristics and parameters of the interface of the robotic system with the working environment
  - management of the interface with the on-ground calibration systems or the in-flight calibration system (RCP)
  - programming of the graphic environment for the virtual display of the EUROPA workcell
- preparation and verification
  - editing, storage and verification through simulation of the EUROPA robotic programs
- remote monitoring and control
  - execution and supervision command
  - monitoring of all the phases of the Mission of EUROPA system
  - management of the interface with the remote monitoring and control station of the P/L's
- emergency command
  - command of the single joint motion.

The MMI Ground Station will be also used to support the Crew Operator which is using the Flight MMI: the robotic programs will be prepared and verified on Ground and sent to the Controller and the Flight MMI.The Crew Operator will then command and monitor the execution.
For program verification, the MMI Ground Station features the Controller Emulator and some stubs for the Controller Emulator to be connected during the simulation for the verification of the robotic programs. They receive the commands for the Controller and compute without true feed-back from the arm and the field the output of the arm sensors.

The MMI Ground Station is based on:

- RMC/PV (Remote Monitoring & Control / Preparation Verification) and the FMC (Facility Monitoring & Control) workstation for the preparation and execution of robotic missions provided by ESA (baseline)
- MMI from ASI/Tecnomare contract “Interfaccia Uomo Macchina Avanzata”, further described in the

[1] The robotic programs are composed of macro-task and the robotic system waits for the authorization of the Operator to continue the program execution to the next macro-task.

following section of the paper (as a possible alternative).

The GSE will be used to support the on-ground test of the Flight Segment before the launch. The configuration of the FS integrated with the GSE is described in Figure 3.

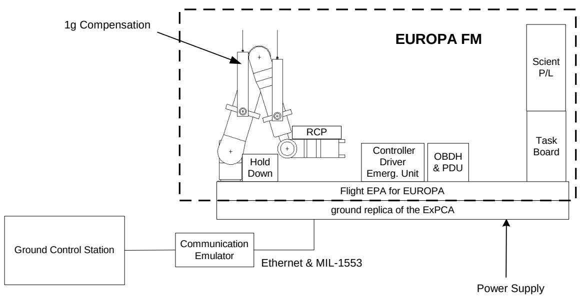

Figure 3 - Configuration of FS integrated with GSE

The GRM will be integrated with the GSE in order to emulate the flight system for the preparation of the robotic missions and to support the operations of EUROPA on the ISS. The GRM-GSE integrated configuration is described in Figure 4.

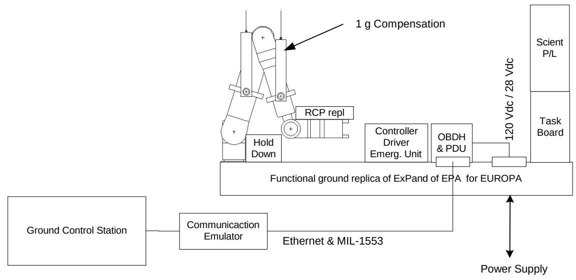

Figure 4 - Configuration of GRM integrated with GSE

THE CENTER FOR SPACE ROBOTICS

The EUROPA Ground Segment is located in the new Center for Space Robotics in ASI Matera.
The CRS will provide:

* a robotic research and operational center for space robotics, capable to support various technologic and scientific missions based on robotics.
* on-ground data handling with connection to ASI-net and NASA-net, with capabilities to connect to other Space Centers;
* integration and test facilities with clean-room, laboratories and test-beds simulating planetary soil,
* parts of the GSE listed above for EUROPA: 1g compensation, calibration, MMI

The sketch in Figure 5 is the detail of the integration and test laboratories as configured for test of EUROPA (on the right) and of a dual arm system for robotic servicing demonstration (on the left).

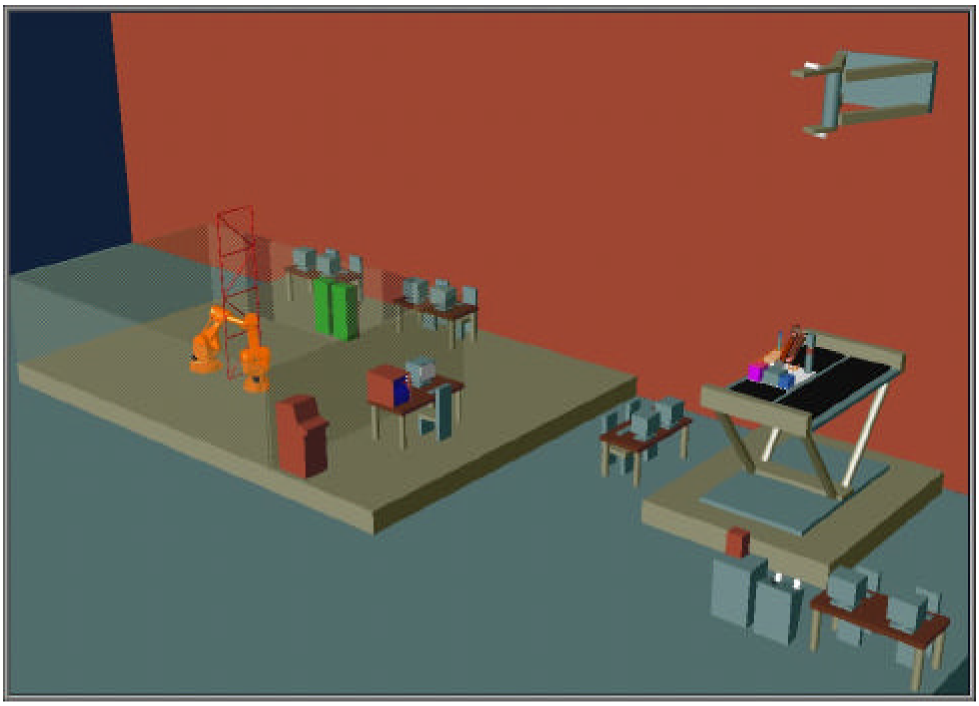

Figure 5 - Center for Space Robotics with EUROPA (right) and ROSED (Robotic Servicing Demonstration - left)

THE ADVANCED MAN-MACHINE INTERFACE

ASI's Advanced Man-Machine Interface project, being developed by Tecnomare, aims at implementing an MMI for space robots characterized by:

- a high degree of modularity, that contributes to increase the reliability, safety and autonomy of reference space robotic systems;
- an increased level of perception of the environment for the human operator, thanks to techniques of Virtual and Augmented Reality, and of motion prediction to minimize time-delay effects;
- the possibility to simulate any prepared mission, in order to check safety and other parameters (power consumption, radio visibility, time duration, etc.) related to the mission before really executing it;
- a wide range of autonomy levels in teleoperation, varying from Manual Control to Shared Control, from Traded Control to completely Autonomous Control;
- a high level of re-configurability, that makes easy to re-use the MMI with different robotic systems.

The MMI design and implementation complies with ESA standards[2], in order to allow development of solutions as part of ESA co-operation programs.

In the first phase of the project, a prototype of the MMI is being developed, along with the emulators of the robots it operates.

The systems emulated are:

- SPIDER, the free-flyer carrier for extravehicular inspection, maintenance and repair, that will operate on the ISS equipped with two robotic manipulators, TV and auxiliary subsystems;
- a Moon exploration rover, complete with its lander (equipped with a robotic arm), the rover robotic payload (arm, TV subsystem, experiment kit) and the Moon terrain.

An emulated Communication Channel introduces delay and noise to the messages to/from the robots, in order to propose to the human controller operational conditions as close as possible to the real ones.

The controllers of both the robotic systems are emulated accordingly to the SAREM architecture. The SAREM (Spider Architecture Reference Model) Architecture, identified by ASI, has remarkable analogies with the NASREM Architecture by NASA: it defines a hierarchical and modular structure to design and develop control systems for space robots, and permits to make modular and, above all, to parallelize complex control processes, in order to achieve autonomous, stable and adaptive reaction capabilities.

The need to close locally the control loops, giving the robot system autonomous perceptive and decisional capabilities, arises from:

- the necessity to cut down the work load of the ground or flight operator, in order to minimize the risk of errors due to induced fatigue;
- the necessity to solve problems related to time-delay effect and to limitation of the communication channel, in the remote direct control of the robot by an operator located at great distance from the robot itself.

A wide set of Virtual Reality I/O devices (ranging from head-tracker to spaceball, from stereo-glasses to 3D-mouse), high-definition 3D graphic representation of the robots and the environment (or terrain), together with graphic clues, TV picture overlaid to graphics, predicted (*phantom*) robot visualization contribute to improve perception of the environment and to facilitate control from remote of the robots.

The operator can view the operating scene from several different Points of View (PoV), selectable by mouse, among, for example, robot's front view, robot's rear view, TV-camera's view, free-fly view, free-walk view, top view, etc., both in preparation/simulation and in execution phase.

A Human Supervisor oversees all the operations carried out by the Human Controller, and can take control of the system if an emergency situation is not properly managed by him.

Moreover, the MMI feature a Trainer interface, which allows a Supervisor with training task to inject noise or to alter status variables in order to check the behaviour of the Trainee.

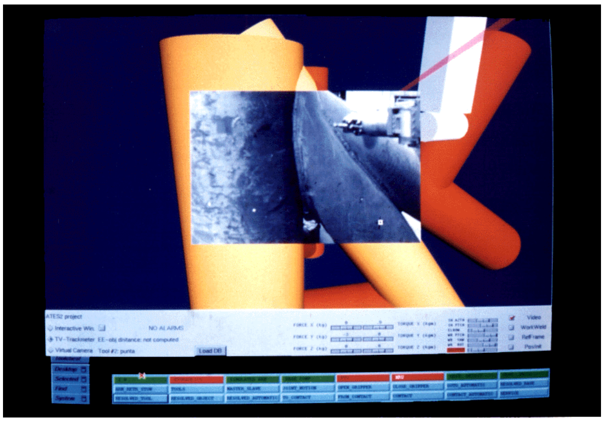

Figure 6: TV-picture overlaid to graphics: TV-camera PoV. Example from an underwater application

Such features require a high-performance Graphics Processing Unit, therefore a Silicon Graphics® Onyx2™ Reality™ Workstation has been identified as target

[2] Main ESA standards followed in the MMI project development are:

- ESA PSS-05-0 "ESA software engineering standard"
- ESA PSS-03-70 "Human Factor"

machine, while IRIS Performer™ will be the 3D rendering toolkit that will support the real-time, multi-processing, interactive application. For the same reasons, in order to implement robotic controllers and physical emulators, hard-real time VME unit (based on PowerPC™ board) running real-time POSIX-compliant Operating System has been identified.

The MMI project also includes the implementation of a Development Environment that integrates the software packages and the hardware needed to support all the development and maintenance activities related to the MMI itself.

Such an environment provides ASI with a facility for testing and prototypes of new interface methodologies, to be located in ASI CSR in Matera, Italy.

To fully comply with ESA PSS-05 standard, a set of software tools has been selected to support all the development phases, ranging from ClearCase®[3] (for Configuration Control issues) to Doors®[4] (for requirement management, mainly in the User and System Requirement phases), from Teamwork®[5] (to develop a Logical Model of the systems following a Structured Analysis approach, in the System Requirement Phase) to HoodNICE®[6] (to perform the architectural design of the system complying with the Hood method), to a set of tools for profiling, coverage, testing, metrics, reliability, safety purposes.

[3] ClearCase is a registered trademark of Rational Software Corp.

[4] Doors is a registered trademark of QSS Inc.

[5] Teamwork is a registered trademark of Computer Associates International, Inc.

[6] HoodNICE is a registered trademark of Intecs Sistemi S.p.A.

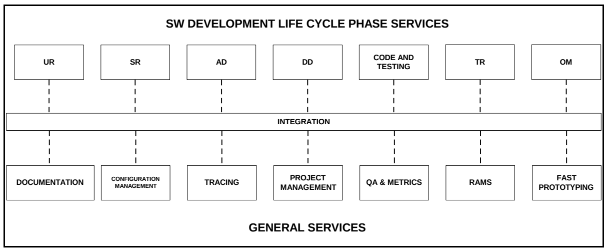

Figure 7: Development Environment: SW representation

Hardware tools that will be available in the Development Environment range from Processing Units (graphics, hard real-time, general purpose, net server) to 3- and 6-DoF joysticks, from head-tracker to 6-DoF tracking device, from stereoscopic visual device to head-mounted display.

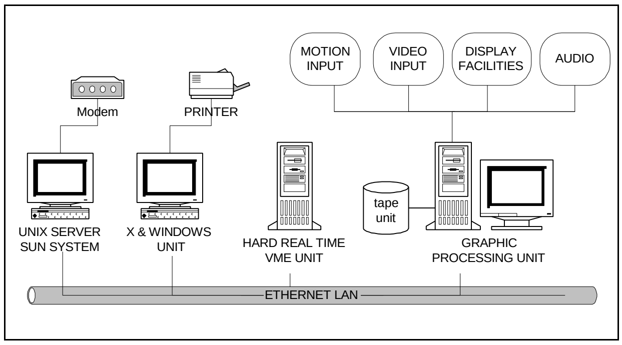

Figure 8: Development Environment: HW representation