ADVANCED MOTION-FORCE CONTROLLER FOR SPACE ARMS: EXPERIMENTAL RESULTS WITH THE GROUND REFERENCE MODEL OF EUROPA MISSION

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INTRODUCTION

EUROPA (External Use of Robotics for Payload Automation) is a robotic experiment formerly designed to fly on the International Space Station (ISS) and to perform a realistic end-to-end robotic technology demonstration in exposed environment. The overall scenario is depicted in Figure 1. The robotic workcell design includes:

- the robotic arm, based on the existing ASI 7 dof SPIDER arm, used to execute the robotic experiments
- the robot controller, to control arm motion and to perform safety checks
- the data handling and power unit (DHPU), taking care of interfacing with ISS and of power supply of all the units
- the scientific payload and task-board (SPTB), where significant robotic experiments are housed
- the hold down mechanism, to latch arm during launch and re-entry phases.

While the development of the Flight Segment (FS) of the EUROPA mission has been frozen, the Ground Reference Model (GRM) is completing the final tests in the ASI Center for Space Robotics (CRS), in Matera, Italy.
The GRM is functionally equivalent to the FS. The GRM version of the new controller has been integrated with the GRM arm, which was developed in the SPIDER project. The test set-up also includes (see Figure 2 and Figure 3):

- the 1g compensation system of the arm, to simulate the 0g conditions
- the so-called “task-board 2”, equipped with different interchangeable modules (e.g. drawer, crank, peg) relevant to the execution of a wide range of robotic tasks
- the TV Trackmeter, i.e. a stereo vision system installed at the arm wrist, for measuring 3D coordinates of points in the workcell for calibration purpose ([1])
- the Rodym® -Optotrak optical measurement system, for measuring performances in free space
- the Control Station, based on a suitable re-instantiation for Europa of the ASI Advanced MMI ([1]).

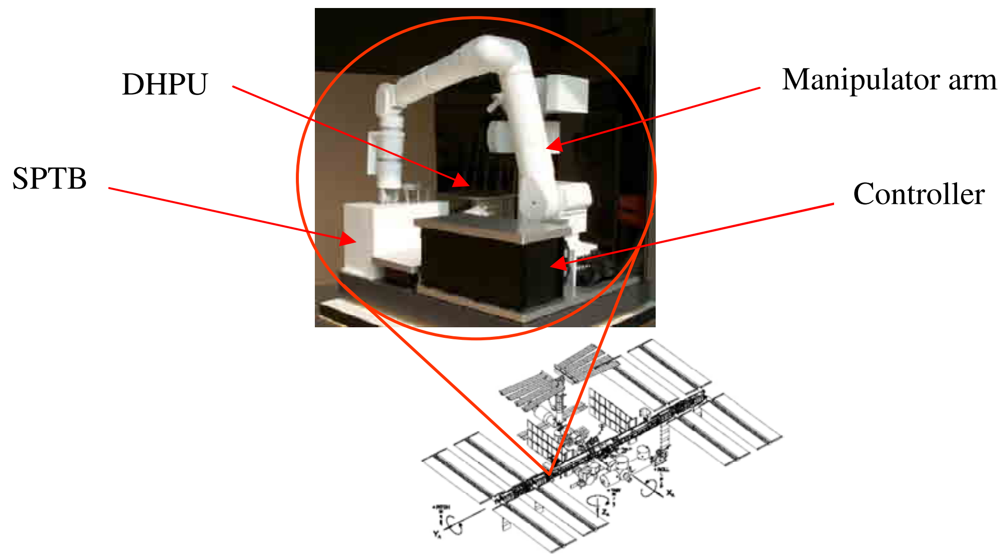


Figure 1 Mission scenario of EUROPA Flight Segment on the ISS (FS mock-up shown)

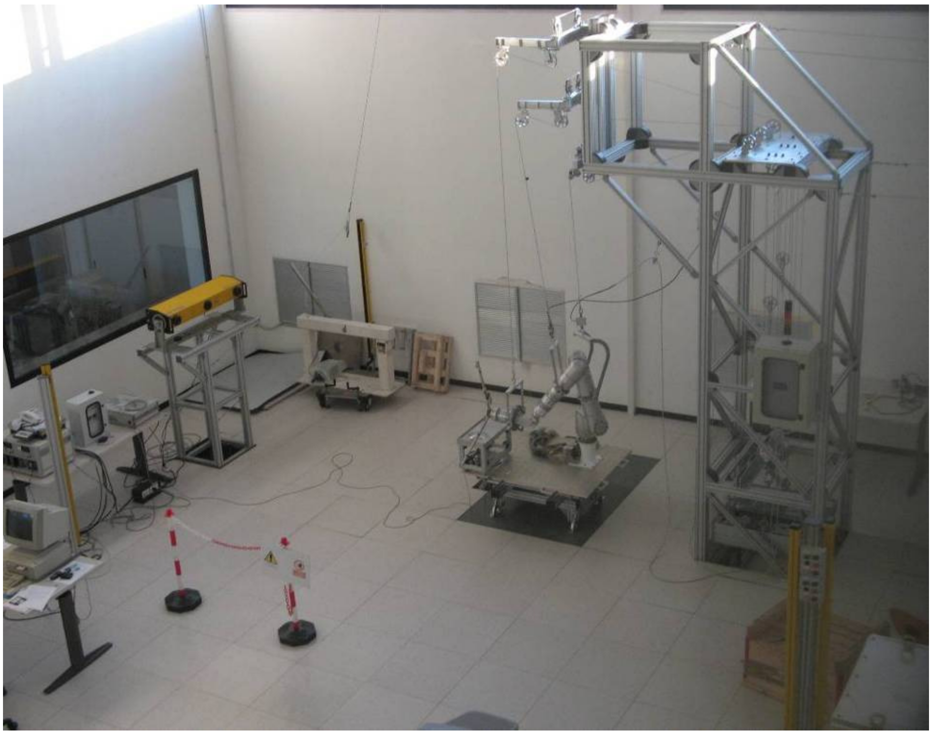


Figure 2 Experimental set-up at ASI laboratory

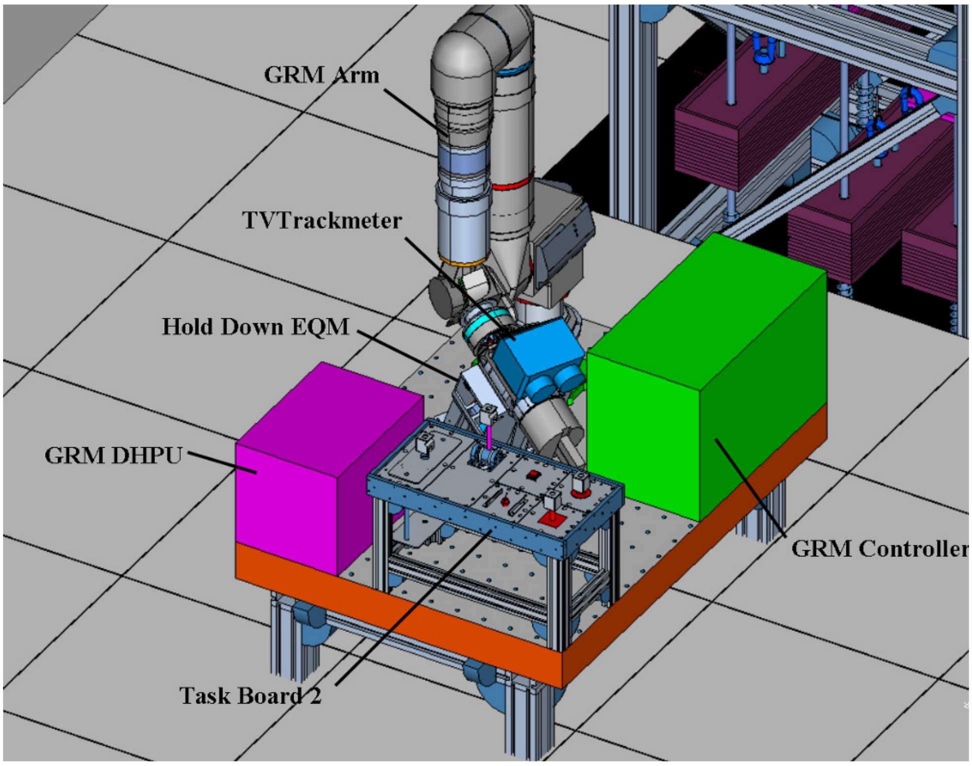


Figure 3 The Ground Reference Model

ROBOT CONTROLLER

The EUROPA robot controller, as part of the EUROPA Flight Segment, is a new development. It is dedicated to controlling the robot arm (seven dof), to provide the necessary computing power to include sophisticated control algorithms and reach a high degree of autonomy for the on-board operations.

Its hardware is implemented by a VME crate where the following boards are housed:

- Main CPU board, implemented by AITECH$^{(TM)}$ S210 board provided with a PPC750 @ 233MHz processor, 64Mb RAM, 64Mb File flash, 8 Mb User flash, 2 Mb boot flash, 2 RS422 serial lines, 1 ethernet controller
- Four Driver boards, providing power to the arm motors and motor shaft resolvers acquisition
- two microcontroller boards, based on 8086 processor, used for both output shaft resolvers acquisition and independent safety checks, as from Computer Based Control System (CBCS) approach ([4])
- one I/O board, used for digital I/O and Force/Torque Sensor acquisition. Digital I/O are mainly connected with the hold down presence sensors
- one Power supply board

The EUROPA arm controller software architecture and coding have been developed using Rational Rose RealTime CASE tool and WindRiver Tornado II running on WIN32 host platform. Target operating system is VxWorks$^{(TM)}$ 5.4. The average CPU load is in the order of 27 % with servo loop running at 500 Hz. Of course great part of the CPU power is used by the robotic control modules to close the cartesian servo loop.

The Controller has successfully passed the Safety Review 0/1 with NASA.

The rest of the paper will focus on the innovative features of the SW Robotic Controller and provide a summary of the experimental results achieved in Matera, at ASI CRS.

ROBOT CONTROL SOFTWARE

The outstanding features of the Robot Control software derive from its being specifically developed for telerobotic applications in space. They include:

- Hybrid motion/force control, with a dynamics decoupling scheme in the cartesian space. Explicit force control is implemented along the selected axes.
- Exploitation of arm redundancy by adding a suitable constraint to the kinematic equations (the so called “Arm Angle”, defined as the angle between a reference plane and the plane passing through arm) to directly control arm configuration e.g. to avoid obstacles or protrusions from the allowed workspace.
- Versatile PDL2-like language called EPL (Europa Programming Language), and relevant interpreter, to program arm motion with a complete set of control instructions and flow control instructions (e.g. IF, WHILE).
- Safety handling module performing all the checks required by Computer Based Control Approach against the hazards related to collision and impact energy.
- Full configurability of the arm parameters by means of text files.

The Robot Control software is structured according a NASREM-like architecture, and implements the following levels (in top-down order):

- *Task Level Controller*, whose main function is to implement a virtual machine able to execute the byte code produced by EPL language compiler and linker
- *EMove Level Controller*, whose main function is to process elementary moves coming from Task level. When an elementary move is received, a set of motion primitives is generated for both arm and gripper subsystem and sent (all together) to the underlying Primitive level controller for execution
- *Primitive Level Controller*, mainly composed of two modules: one dedicated to execution of primitives coming from EMove level, and one dedicate to execution of teleoperation inputs
- *Servo Level Controller*, whose function is to generate, at a fixed rate, the current setpoints for the motor driver boards controlling the eight motors of the arm and gripper. Inputs for the control loop are obtained through linear interpolation of servo setpoints coming from Primitive level controller.

EUROPA arm has seven degrees of freedom and is kinematically redundant, since six joints are sufficient for generic end-effector position and orientation. The approach used to manage the redundancy is based on the introduction of the so-called arm angle (see [2]), and based on the arm self motion capability (the elbow can make exactly a circle around the line connecting two points of the shoulder and of the wrist that are fixed). The redundancy is solved by adding, as additional task the arm has to accomplish, the control of the elbow position along the circle travelled during self motion. For more details reference can be made to [5].

The Arm can be commanded in two modes: joint mode and cartesian mode.
In joint mode, arm motor currents are computed through seven PID controllers each one controlling one joint; in cartesian mode a cartesian hybrid position/force control loop, with explicit control of the interaction force with the environment. The functional block diagram of the control software is shown in Figure 4. This control scheme has been derived from [3].

As it can be seen in Figure 4 the inputs of the control loop are the desired force F_d, the desired position P_d and the desired arm angle aa_d. The task specification matrices Ω and $\tilde{\Omega}$, are built up starting from user specification of force and position controlled direction in a suitable task frame. $L_0(q)$ is the inertia matrix in the operational space and allows, with Coriolis, centrifugal and gravity term μ, the dynamic decoupling, in such a way that the tool becomes equivalent to a single unit mass. The transpose jacobian $J_0^T(q)$, built up from base jacobian, and arm angle jacobian, is used to convert generalized forces from operational space to joint space. Note that through L_0 large variations of inertia to be controlled at the end effector, e.g. due to grabbing of large payloads, can be compensated, improving the dynamic performances of the system.
Finally, no explicit inverse kinematics is foreseen in the loop.

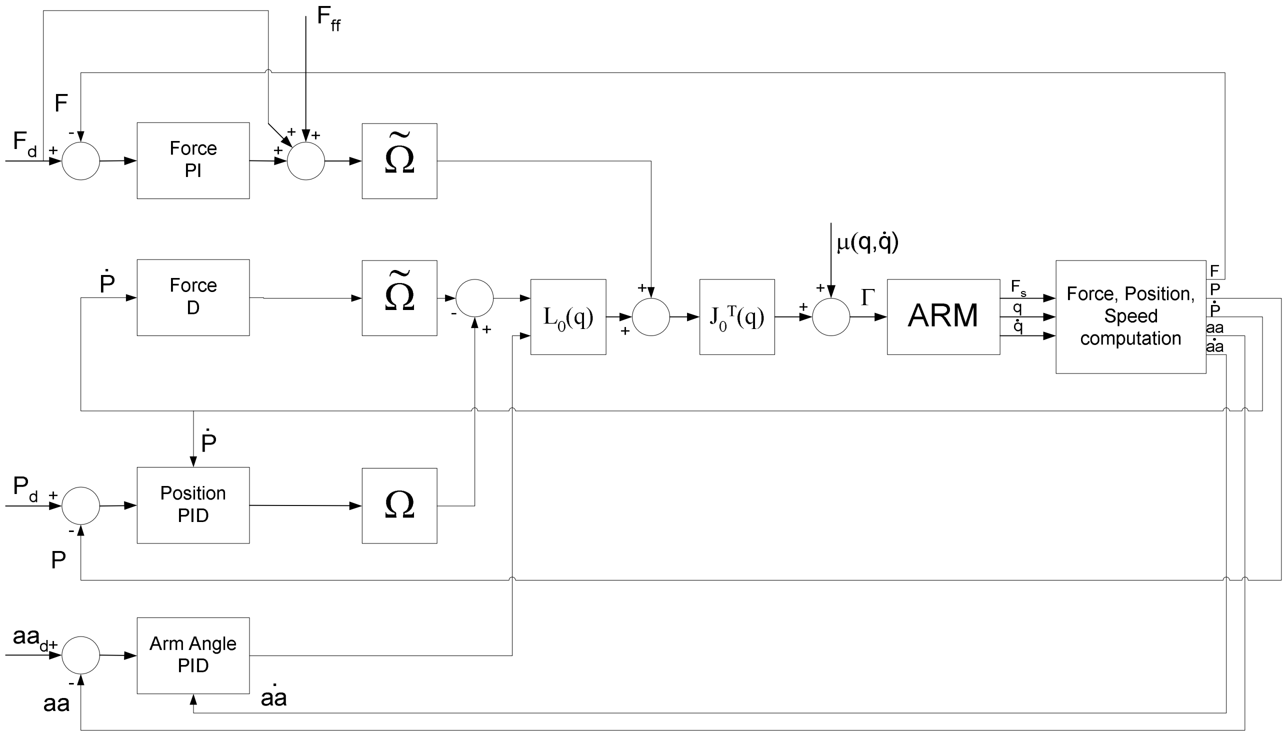


Figure 4 Arm cartesian hybrid position/force control scheme

EUROPA arm controller is fully configurable through a set of ASCII databases that can be updated from the operator. They are mainly divided in three categories:

- Robotic Controller Databases: they contain all the parameters related to robotic system controller
- Safety Databases: they contain all the parameters related to safety module
- Environment databases: they contain the description of the environment the arm has to interact with, in terms of objects position, actions that can be executed on each object, and motion parameters.

Robotic programs are written using EPL language, a versatile novel robotic language that allows operator to perform arm motion, controller status management and flexible data processing.
EPL is a programming language, directly derived from PDL2, already used in previous projects, with specific features for programming EUROPA robotic applications.
A program is divided in three sections:

- prototype section, where the program prototype is specified defining its name, input arguments and returned value
- declaration section, where variables, constants and functions used in the program shall be declared
- statement section, where the body of the program is written.

EPL programs are compiled and linked to produce a byte-code that can be sent to task level controller virtual machine for interpretation. This can be done using the EPLc and EPLlink programs: a compiler and a linker expressly developed for the EPL language. Further information about the features of EPL is provided in [5].

The robotic programs are edited, compiled, run and monitored from the Control Station shown in Figure 5.

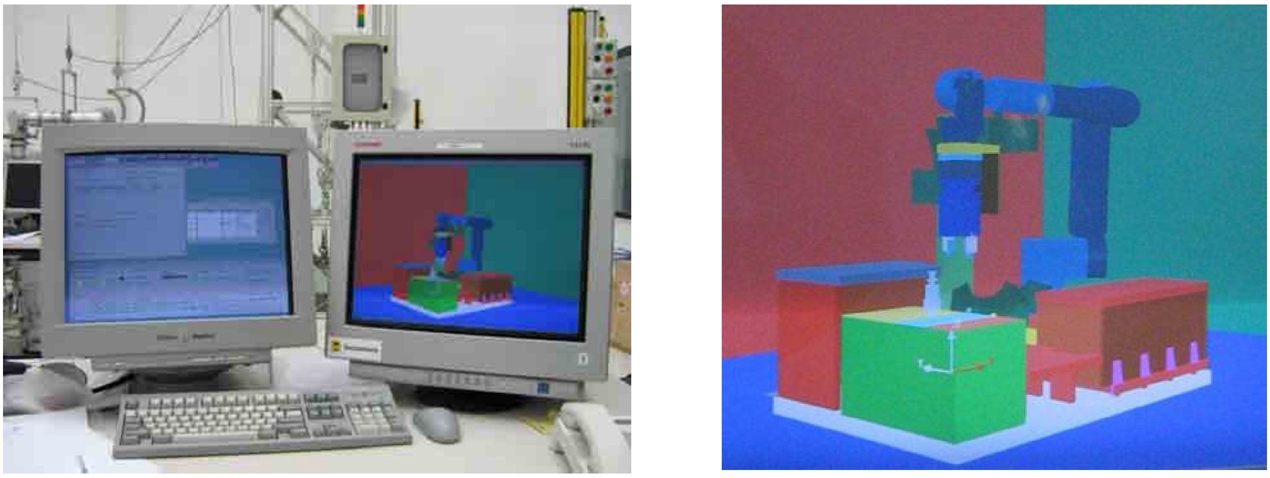


Figure 5 The Control Station (Advanced MMI tailored to EUROPA operation)

ROBOTIC ARM

The robotic arm of the EUROPA GRM is the SPIDER arm developed in the nineties, in the framework of the ASI technological development program. As known, it is a dexterous arm featuring seven dofs.
While its motion capability in free space has been repeatedly tested in the past with the Comau C3G controller, this is the first time that it has been integrated with a motion/force control system and its capability to perform compliant motion in contact with the work cell has been tested. In particular the achievement of effective performances in automatic force control is challenging since the arm was not designed for this purpose. The main limiting factors are:

- high ratio transmission gears in the joints, which limits the mechanical bandwidth
- substantial non-linear friction in the joints
- no provision for the measurement of the output torque at joint level
- structural resonance at the arm wrist due to the gripper – force/torque sensor assembly.

PERFORMED TESTS AND MEASURED PERFORMANCES

In the course of the performed test session, several experiments have been executed, both to verify the performances of the motion-force control system and to demonstrate the execution of the experiments foreseen for the mission.
Among others, the following experiments have been successfully executed:

- stow and deploy of the arm with respect to the configuration for launch
- verification of performances in joint and cartesian space (in free space)
- local calibration, using the vision system mounted at the end effector
- attach/detach, i. e grasping of a grapple fixture, automatically aligning to it
- verification of the capability to apply fixed values of force and torque using a dedicated checkout unit
- sliding in contact of an unknown surface
- peg in hole
- peg in hole with lock/unlock mechanism (bayonet type)
- automatic alignment of a flat object in contact with a surface
- open/close of a hinged panel
- operation of passive linear sliding mechanism
- operation of a passive rotational mechanism (crank-like)
- open/close of a drawer.

The Global position accuracy and repeatability of the arm, measured in five points according to the ISO 9283 standard is reported in Table 1.
Such results are in line with the accuracy and repeatability figures expected for the GRM system.

The results of the force/torque checkout experiment, to verify the arm capability to apply forces and torques in contact with the environment are shown in Figure 6.
More in general the system has demonstrated the capability to successfully execute a wide range of sensor based manipulation primitives, with on-line adaptation to a partially unknown environment.
A representative set of executed tasks is shown in Figure 7.

Figure 8 shows the arm execution of the classic peg-in-hole task, with automatic alignment of the peg to the hole axis. Bayonet-type locking/unlocking of the inserted peg has also been performed.

Table 1 Pose accuracy and repeatability

Point	Pose Accuracy [mm]
	PA
P1	0.52
P2	2.37
P3	2.05
P4	1.13
P5	1.49

Point	Orientation Accuracy [degrees]		
	Or_a	Or_b	Or_c
P1	0.11	0.01	0.32
P2	0.32	0.04	0.23
P3	0.26	0.38	0.18
P4	0.51	0.18	0.35
P5	0.44	0.48	0.08

Point	Pose Repeatability [mm]
	PR
P1	0.19
P2	0.26
P3	0.20
P4	0.19
P5	0.35

Point	Orientation Repeatability [degree]		
	Or_a	Or_b	Or_c
P1	0.014	0.008	0.009
P2	0.014	0.013	0.016
P3	0.011	0.008	0.012
P4	0.013	0.017	0.013
P5	0.025	0.026	0.026

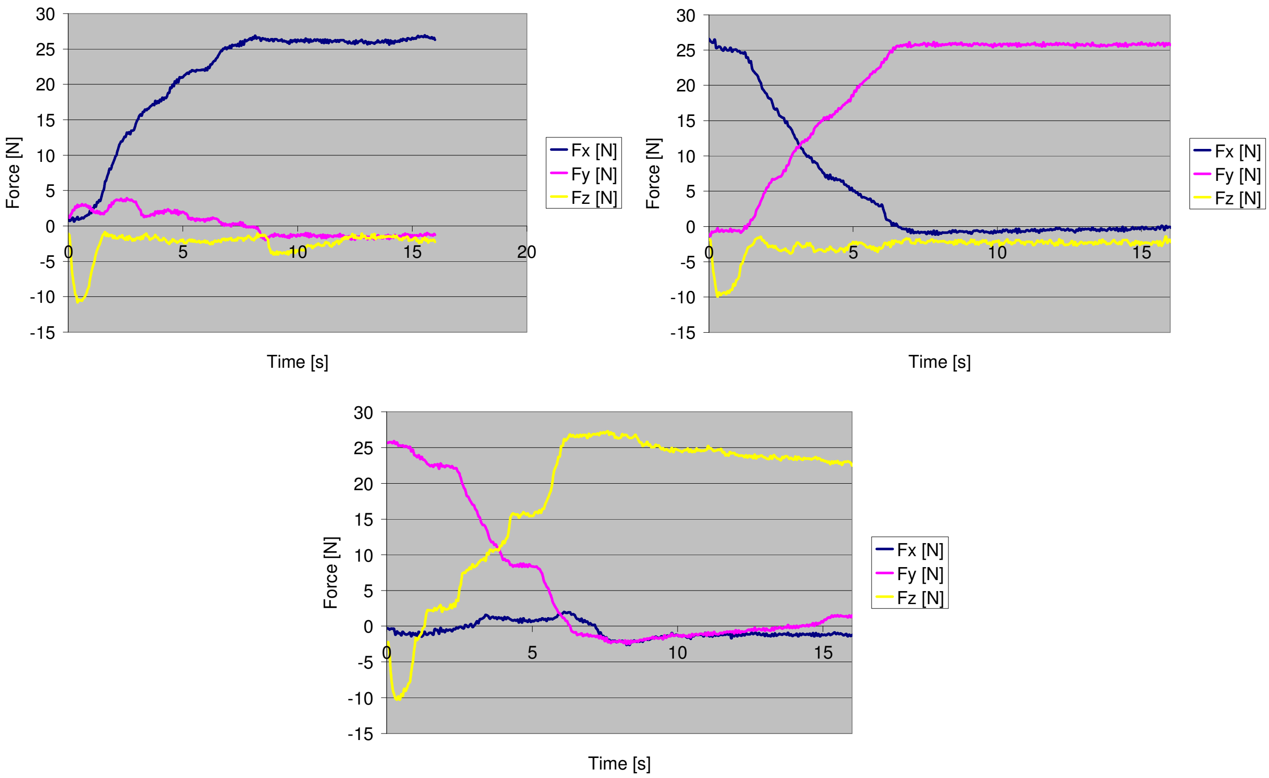
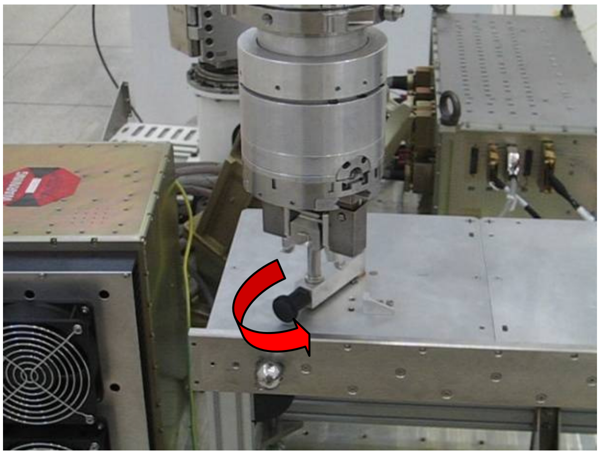
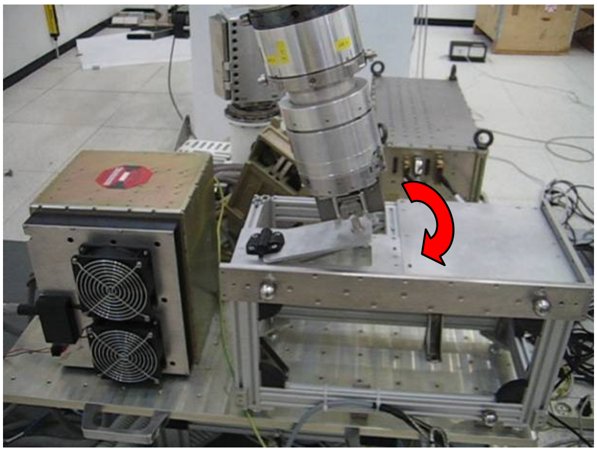
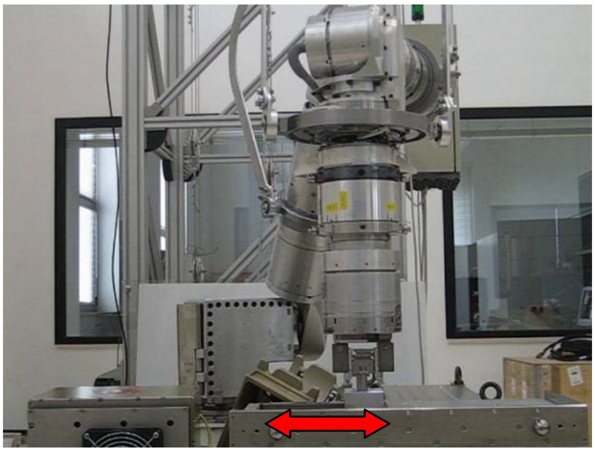
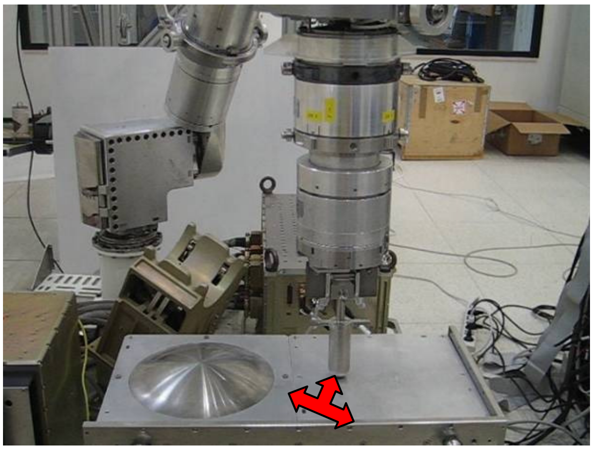


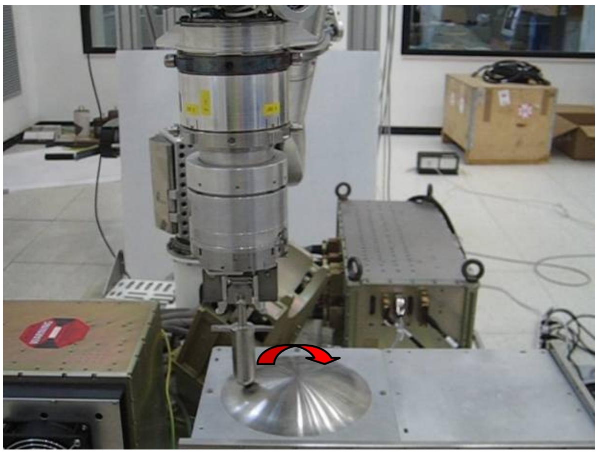
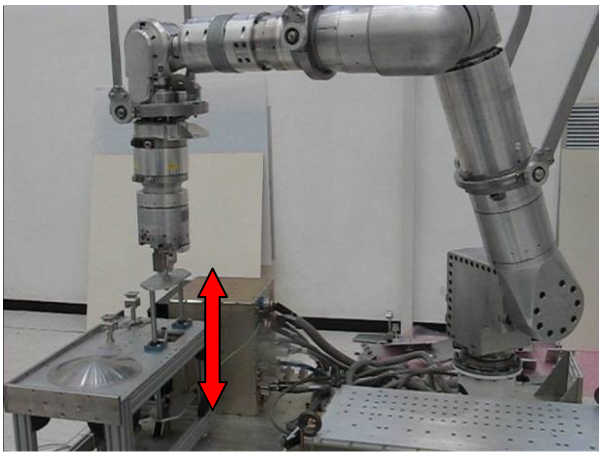
Figure 6 Force/torque checkout experiment: application of 25 N linear force along x, y and z axes respectively (each plot reports the three force components measured by the sensor)

(a) (b)

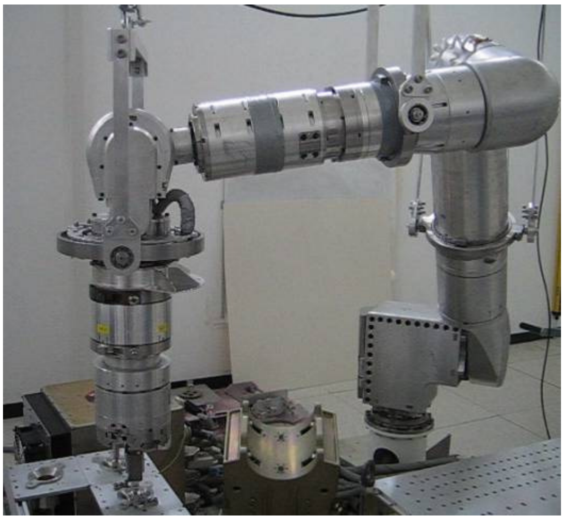



(c) (d)

(e) (f)

Figure 7 Execution of sensor based primitives: (a) turning of a crank; (b) hinge; (c) slider; (d) sliding on a planar surface; (e) sliding on a curved surface; (f) drawer



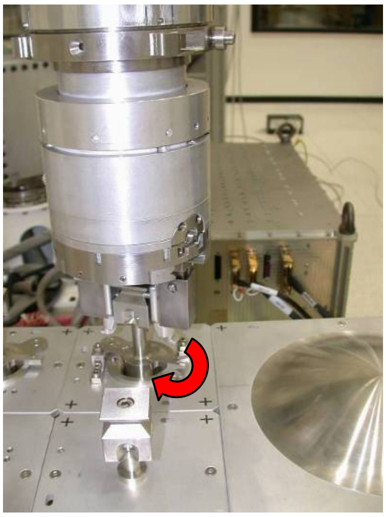


Figure 8 Execution of peg-in-hole task, with final locking of the peg (bayonet-type)

CONCLUSIONS

The EUROPA GRM robotic system (manipulator and controller) has successfully demonstrated its capability to perform a wide range of motion and force manipulation primitives, with a powerful programming flexibility.
As far as known, such a complete set provides unprecedented features for a space robotic manipulation system.
The implemented GRM system represents a sound basis for the implementation of the EUROPA mission, if any.

References

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