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ASI Technology for Robotics Applications in Space

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Abstract

This work summarizes Italian space Agency activities in the field of space robotics. Special attention is given to those technologies related to realistic application scenario such as ISS utilization and planetary exploration (Mars exploration, Comet nucleus investigation).

1 Introduction

In this work, an overview on Italian Space Agency (ASI) space robotics activities is given. Space robotics started in 1988 with the SPIDER system (Space Inspection Device for Extravehicular Repair. SPIDER, a free-flyer space robot equipped with a bi-arm manipulation, docking arm and vision system, was conceived as technological challenge, in order to push development in field such as manipulation, vision and control. In this framework, the SPIDER manipulation system was developed and intensively tested (environmental and performance test. This system is now the key point for the EUROPA (External Use of Robotics for payload Automation) mission. EUROPA main goal is to demonstrate in orbit the benefits operating payload installed on the express pallet by mean of a robotics, which allows interaction from ground without ISS crew intervention (unless a non-nominal condition requires it). Still considering ISS utilization as potential application scenario, on 1996 the PAT (Payload Tutor) system was proposed to NASA for the automation of the operation on the express rack, internal to ISS. PAT represents the evolution of the SPIDER Manipulation system, in terms of dimensions and performances, and it has the main goal to increase ISS utilization time in terms of operations required by the experiments.

In addition, considering the national expertise on vision system, ASI promoted technological transfer process in order to utilize a stereovision system developed for underwater application.

In mean time, some progresses have been made on drill-sampling technologies for planetary exploration mission. After a first phase of evaluation, the SD2 (Sampling, Drill & Distribution) system has been proposed and developed in the framework of ROSETTA ESA mission. Taking advantage of the know-how gained, similar system has been proposed to NASA for the Mars Exploration program.

Other fields of interest during last decade concern Man Machine Interface and smart robot hand.

In order to support ASI programs, further investments have been made to develop the Center for Space Robotics CRS) in Matera (Italy). CRS is a ground infrastructure aimed to support functional and performance test of flight models, and/or test new procedures and methods for robot control using industrial based bi-arm system.

In addition CRS will hold the EUROPA Ground Segment, in order to support EUROPA mission in terms of operation planning, verification and simulation, mission execution monitoring, mission data collection and distribution. A suitable environment will be available to experimenters in order to program and verify sequences for their own experiment operation using SPIDER manipulation system.

2 SPIDER Manipulation System

2.1 Robot Arm

SPIDER Robot Arm, a 7 dof sensorized robot arm designed for payload servicing outside the Space Station. Intended for 0G operation, the arm is also operative in 1g condition in a restricted workspace. Based on human arm configuration, it has 7 rotational joints, each powered by an electromechanical actuator group (motor, gearbox, in/out resolver, brake). All cabling is internal to the Arm structure except the harness from wrist to End Effector.

Figure 1: SPIDER Manipulation System

Parameters Performances (in 0g conditions):

- Load carrying (COG at 500 mm): *up to 250 kg*
- Max. actuation force (isotropic): *25 N (100 N short period < 10 s)*
- Max. actuation torque (joint min value): *30 Nm (50 Nm short period < 10 s)*
- Position repeatability: *1 mm*
- Orientation repeatability: *0.05 °*
- Position accuracy: *3 mm*
- Orientation accuracy: *0.1 °*
- Max. speed (limited by S/W): *0.1 m/s linear*; *0.1 rad/s rotational*
- Mass: *58 kg*
- Stowing volume: *520x960x310* mm^3
- Power consumption: *30W to 130W*
- Thermal environment
  -40 °C to +80°C (operational)
  -60 °C to +150°C (survival)

The next step, currently under definition, is to update the SPIDER Arm design in order to strongly reduce the total mass (target: 50%), using composite materials and carbon fiber

2.2 End Effector

SPIDER End Effector is a simple 2 finger EE equipped with tactile sensors to monitor the force exerted during gripping operation.

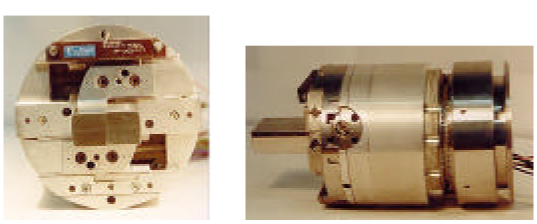

Figure 2: SPIDER End Effector (EM)

EE main features:

- max opening width: *82 mm*
- min opening width: *0 mm*
- max dimension grasping object: *75 mm*
- max grasping force: *200 N*
- power consumption: *6 W*

Next generation EE, currently under definition will be based on a multi-finger EE, equipped with active matrix - like tactile sensor. Vision sensor and proximity sensor will be integrated into the new generation EE.

2.3 Force/Torque sensor

SPIDER Arm F/T sensor, is a strain gauge based sensor, developed to measure and control the force/torque exerted by the arm during servicing operation. The F/T local electronics is integrated within the sensor. It is mounted on the wrist and the following are the key features.

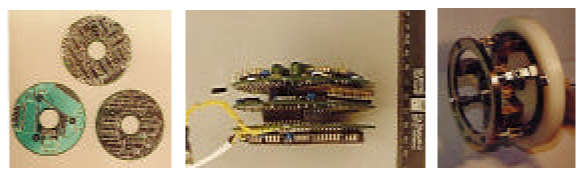

Figure 3: F/T sensor (electronics and mechanical spring)

- measuring range: ± *200N*, ± *20 Nm*
- measuring accuracy: ± *3%*
- measuring resolution: *0.1 N*, *0.01 Nm*
- overload protection: ± *2000 N*, ± *200 Nm*
- Stiffness:
  400 kN/m (displacement)
  3300 Nm/rad (rotational)
- power consumption: *< 2 W*

2.4 Tactile sensor

SPIDER EE Tactile sensor is a simple strain gauge sensor designed to monitor the force exerted by the EE jaws during grasping operations. The measured force can be up to 200N with 3% accuracy and 0.1N resolution.

3 Stereovision measurement system

Starting from underwater technology made available by Italian firm, ASI decided to fund the space version of a stereovision measurement system. This decision was taken after testing intensively the already available technology (Hw and Sw).
The project will last three years and will produce as output the EM of the SVMS (Stereo Vision Measurement System). This development will be

performed using the ISS (external) as reference application scenario.
The SVMS will be able to provide:

- Accurate pose of objects to be manipulated
- Tracking of such objects to allow interventions even with relative motion between arm base and objects
- 3D soil mapping
- Metric survey

The system includes a stereovision imaging unit, mounted on a pan and tilt unit (PTU). The flight segment processor will be based on VME boards, including frame grabbers, CPU, and interface boards for the PTU and for communications. Main performances of SVMS are in the table below

Baseline	250 mm
HFOV	40°
Stereovision Total error	6 mm @ 2m 3 mm @ 1m
Repeatability	3 mm @ 2 m 0.8 mm @ 1 m
Single view	10 mm @ 2 m
Tracking/measurement rate	4 Hz
Illumination conditions	From full daylight, to eclipse conditions (with illuminator)

4 Advanced Man Machine Interface

ASI's Advanced Man-Machine Interface project aims to implement an MMI for space robots characterized by:

- high degree of modularity;
- 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;
- possibility to simulate any prepared mission, in order to check safety and other parameters related to the mission before really executing it;
- wide range of autonomy levels in teleoperation;
- a high level of re-configurability.

The MMI design and implementation complies with ESA standards, 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 developed, as well as the emulators of the robots it operates (mainly a free flyer space robot and a planetary rover).
An emulated Communication Channel is in charge of delaying and adding 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.
A wide set of Virtual Reality I/O devices, 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 robots' operations.
The operator can view the operating scene from several different Points of View (PoV), both in preparation/simulation and in execution phase.

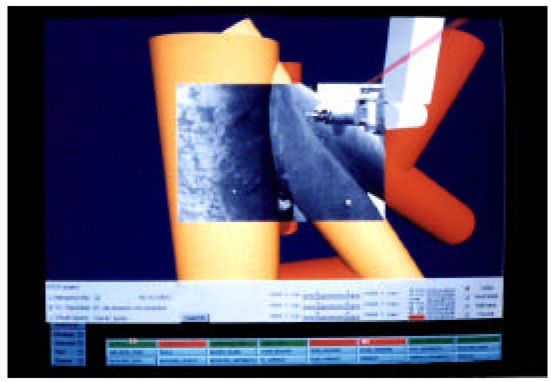

Figure 4: TV-picture overlaid to graphics: TV-camera PoV. Example from an underwater application

6 EUROPA (External Use of Robotics for Payload Automation)

The EUROPA mission is aimed to perform first a realistic end-to-end robotic technology demonstration to show the advantages and the feasibility of a versatile robotically tended exposure payload infrastructure. Afterwards this infrastructure shall allow exposure payloads or payload units to be installed, pointed, serviced/manipulated, inspected, analyses and retrieved in a flexible way without need of human EVA. EUROPA is built around a medium-size dexterous robot arm (SPIDER Arm). It can perform the following tasks:

- installation/removal of small payload containers on exposure attachment ports;
- handling of payload units (experiment samples or sample cassettes) for the purpose of scientific/technological investigations;
- close-up visual inspection of payload units by means of a camera.

All of the above tasks can be monitored from ground, using the ground reference model of the whole facility, allowing end user to interact directly from ground with its experiment in orbit. No crew intervention is required during nominal operations.
EUROPA is a ESA-ASI mission, as long term cooperation for space robotics. Main ESA contribution concerns the Robot Calibration platform, the task board, the scientific payload and the ground control station.

6.1 EUROPA main elements

As shown in Figure 5, the following are the key elements for EUROPA:
Express Pallet Adapter (EPA) - One of the 6 pallet that can be accommodated on each Express pallet. Its dimensions (WxLxH) are 34x46x49" (0.86x1.16x124 m);
SPIDER Robot Arm - The 7 dof robot arm developed by ASI and designed for external space station environment, equipped with a Force/Torque sensor on the wrist and 2 sensorized fingers End Effector;
Avionics - Includes mainly the drive electronics, the robot controller, on-board data handling and the power distribution unit;
RCP - Robot calibration platform and performances assessment assembly;
TaskBoard – it will allow performances measurements of the force&torque sensor and the pose accuracy in the tool reference frame..
Payload - The ESA provided scientific payload (fluid science) to be operated by the robotic arm.

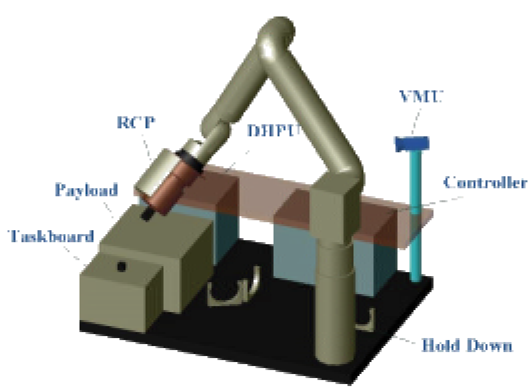

Figure 5: EUROPA layout

Current planning foresees the completion of all EUROPA elements in 40 months, starting from June 2001. EUROPA mission is currently scheduled by NASA by September 2005, due to the delay on the express pallet.

7 PAT – Payload Tutor

In 1996, a call for proposal was issued by NASA (NRA 15-OG3-6-16P), with the aim to collect ideas to enhance operations on Space Station. Among more than 120 proposals to NASA, one of the three selected was a concept proposed by ASI for Internal Automation, called Payload Tutor (PAT) and consisting in a small "relocatable" robotics system which can be mounted by the crew close to the rack to be serviced.
The rationale for the proposal was that ISS operation concept may foresee the utilisation of the attached lab continuously over 24 hours. This implies to have a certain number of astronauts, availability of each one (to follow specific experiment demands) is naturally restricted by:

- performance of other, parallel running activities;
- skill level and his trained experience;
- human motoric capabilities;
- time for ISS "routine" operations

Internal robotics can replace the crew for some tasks for operations and payload servicing.
In particular for operations it can be used for all those tasks like actuate a mechanism (e.g. rotate a knob, push a button, actuate a switch), remove a sample, insert a sample; for payload servicing it can be used for inspection and replaceable of consumable.
This approach allows:

- savings of crew time (crew can be released from all repetitive tasks);
- increasing of ISS utilisation (different experiments can be performed in parallel);
- increasing of mission success (tedious tasks are left to the robotics system);
- on-ground interaction with the experiment, without crew intervention.

Care is given in the concept to safety aspects, so to ensure that, in any condition, the robot shall not cause any hazard to the crew. In addition, it shall allow the crew to quickly move away the Robot to access the rack on which it is operating.

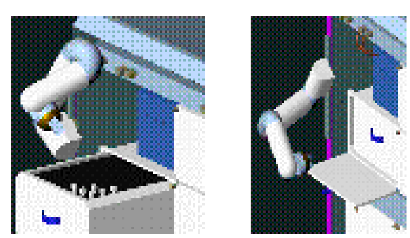

Figure 6: PAT operations concept

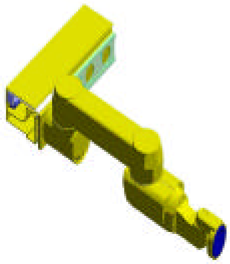

Figure 7: PAT robot arm concept

PAT program is going to be started by July 2001, and the first prototype shall be ready in 36 months. Then, environmental and performances test at system level will be started.

8 Drilling Sampling Technologies

In the framework of ESA/ASI technological program cooperation, strong effort has been given to drilling&sampling system for planetary exploration application. ASI promoted Italian firm in bread-boarding development and test in order to acquire the right know-how to cope with the Rosetta Mission requirements and Mars Exploration program requirements.

8.1 Comet Nucleus Sample Return Sampling & Anchoring devices

ESA funded work, to develop and test corer tool, surface tool and anchor in preparation of the Rosetta mission.

- Corer Tool - drill and collect a core (dia 150mm, length 1400mm) of soft and hard material, with harder grains, under comet conditions
- Surface Tool - collect soft and medium hard material with harder grains (dia 150mm, length 600mm)
- Anchor - penetrate inside soft and hard materials and withstand reaction forces due to drill operation (length 1300mm, mass 3.4 Kg)

A test campaign has been completed in vacuum at -160°C.

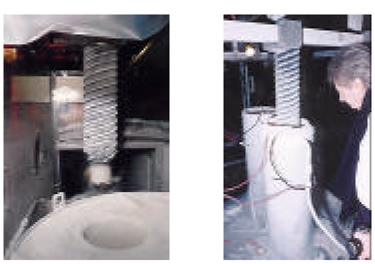

Figure 8: Corer during test campaign

8.2 Small Sample Acquisition/Distribution Tool (SSADT)

ESA funded work to develop and test a small device equipped with different tools for surface sampling, for planetary and cometary in-situ investigation missions. The main characteristics are:

- 3 dof
- automatics tools exchange
- operate from 0.3m above surface
- mass: 1.76 Kg
- power: 5W
- sample: few grains (0.2 cm^3)

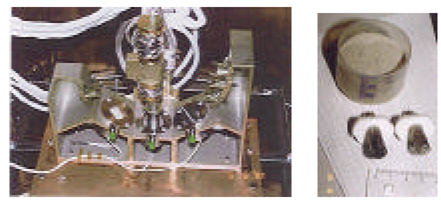

Figure 9: SSADT prototype (left) and its tool(right)

8.3 SD^2 –Sampling Drill & Distribution

In the framework of the ESA ROSETTA mission, ASI is responsible of the SD2 sub-system, whose main goal is to drill the comet surface (ones the Rosetta-Lander is anchored) and to distribute samples to scientific instruments for composition analysis. The ROSETTA mission profile is the following:

Major event	*Nominal date*
Launch	12 January 2003
Mars gravity assist	26 August 2005
First Earth gravity assist	21 November 2005
Otawara flyby	11 July 2006
Second Earth gravity assist	28 November 2007
Siwa flyby	24 July 2008
Comet Rendezvous manoeuvre	29 November 2011

SD2 System is in charge of drilling the comet soil to collect several samples of material at different measured depths and discharge them into suitable ovens for the subsequent scientific analysis (by CIVA, COSAC, PTOLEMY instrumentation). SD2 consists of the following major parts:

- an integrated drill-sampler tool for the actual sample collection
- a carousel accommodating 26 ovens for sample storage;
- a volume checker to press the samples into the ovens
- an electronic unit with on-flight reconfigurable software to manage the whole system

8.3.1 SD2 features

- Soil drilling depth: 230 mm (with a clearance between lander balcony and surface of 300 mm)
- Collected sample size: 6 – 34 mm^3 (each sample, before volume checker action)
- Soil type (cometary environment): flufy stuff up to 4 Mpa
- Environmental operative condition: vacuum with temperature of –140°C
- Mass: 3.8kg for the mechanical unit, 1kg for the electronic unit, 0.5kg for the harness
- Power: <1.5W in st-by; 10-14W while operating
- Time to collect one sample at comet surface depth, including discharge into the oven: about 1.5 hours
- Time to collect one sample at max. depth, including discharge into the oven: about 3.5 hours

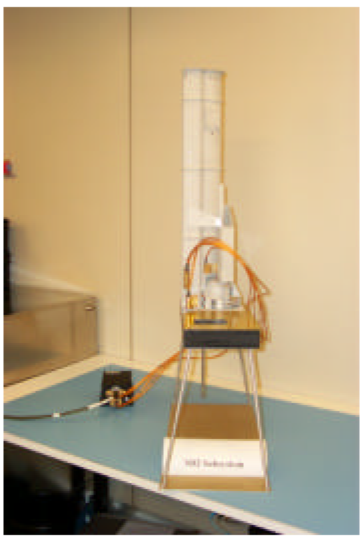

Figure 10: SD2 integrated

8.3.2 SD2 main technologies employed

Mechanical Unit:

- Carbon fiber for structural parts (low thermal deformations and low mass), with electrically conductive coating
- Bearings and gears with dry lubrication (restriction: to be used in vacuum)
- Utilisation of motors with no brushes
- All technologies compliant with low temperature (-150°C, LN2 shock testing were performed in several occasions for the purpose of worst case verification)

Electronic Unit:

- Extensive use of FPGAs
- manufactured with SMD technology
- SW developed in accordance with BSSC (95) 2

Currently, SD2 has been fully tested (thermal/vacuum, vibration); the FM is completed (both Hw and Sw).

8.4 Drilling Concepts for Mars Exploration

In the framework of ASI-NASA co-operation on the mars exploration program, ASI is evaluating drilling concept to meet mission requirement expressed by the scientific community during the MEPAG activity (the working group stated by NASA to assess the Mars exploration mission architecture for the next decade). Here, some of the concepts under evaluation are described briefly.

8.4.1 Drill Sampler Tool (DST)

DST is based on traditional technology (it is a drill) and is targeted to depth up to 1.5...2 meters using extendable drill rods.

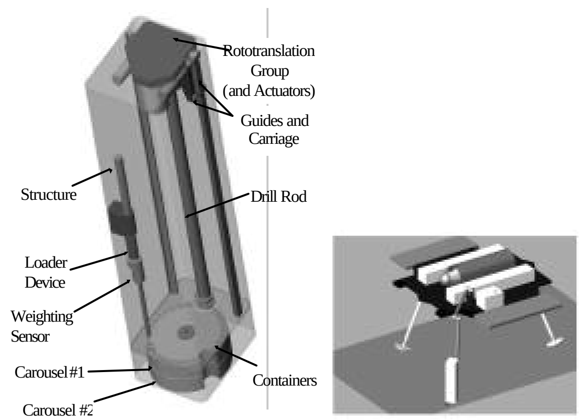

Figure 11: DST concept and its accommodation on a Mars Lander

It allows sample acquisition compatible with various soil properties and delivery of the samples to scientific in-situ analysis instruments located at the host platform "down-hole" science is also possible to the extent allowed by envelope available inside the drill tool for accommodation of sensors and gauges. Limits for the drilling depth for this concept is mainly a risk of drill tool jamming and high power needed to overcome friction between the tool and a borehole.

8.4.2 Other Concept under study

Coiled Tubing Drill (CTD) utilises a riser/conductor unit for the penetration into the unconsolidated overburden, of a coiled tubing drill string for boring the hole, and of a compressed gas lift system for removing the drill cuttings from the hole during the drilling (based on traditional oil field equipment). The goal is to achieve 20 metres of depth.

Worm concept, utilises high frequency vibrations or rotary drilling/cutting tools to progress the bit through the soil, utilising barbs or tracks to put axial pressure on the bit. This is an innovative technology, although vibrating pile drivers are currently in use and development of ultrasonic drills is underway. Potentially this solution could permit drilling to great depths (1000 m) as it does not require drill cuttings removal or return to the surface.

9 Center for Space Robotics (CRS)

CRS is located at Matera, south Italy. Built with cooperation between ASI and local government, it shall act as ground simulation and test facility. No environmental test facility is currently located there. 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.

Figure 13: ASI Center for Space Robotics

In the framework of EUROPA mission, CRS will hold the ground segment, based on the following:

- the Ground Reference Model (GRM) of the Flight Segment
- the Ground Support Equipment (GSE).

The EUROPA Ground Segment is based on the following modules:

- Ground Reference Model (GRM) to:
  - prepare and verify the robotic missions before their execution on-board
  - support from ground the Operative Phase of the Mission
- 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.

The GRM is composed by:

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

The GSE is composed by:

- equipment to simulate the 0-g condition for the arm (1-g Compensation Assembly)
- network of workstations connected to ASInet and, through this, to NASA
- calibration system for the manipulator based on the Optotrack measurement system
- calibration S/S
- additonal task board (task board 2) for test of the operational capabilities of the manipulator GRM in performing general purpose tasks
- Ground Control Station, based on the RMC/PV provided by ESA and, the Advanced Man Machine Interface developed by ASI

Figure 14: 1g Compensation Assembly for EUROPA

Concerning the industrial based bi-arm test bed, it make use of 2 manipulators with 6 dof COMAU robot arm, and are aim to robotic servicing demonstration activities (ROSED) such as:

- Truss structure assembly
- Teleoperation
- Force/torque base control
- Bi-arm co-operative control
- Vision based control

The manipulators are equipped with wrist force/torque sensor. In addition, a stereovision system is installed on the end effector. The visions system is able to perform real time tracking and 3D pose measurement of selected object.

The following picture shows the ROSED test bed.

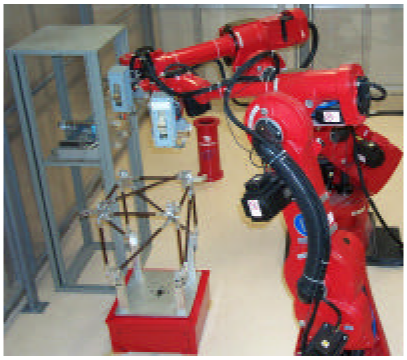

Figure 15: ROSED testbed

10 Conclusions

The main ASI activities in space robotics have been shortly presented in this paper. Special attention has been give to those activities related to realistic application scenario, that is ISS utilization and planetary exploration. In addition to that, ASI pays great attention to research activity in cooperation with Italian universities. This is seen as "source of knowledge" to make step forward in space programs. Further details on the activities here summarized can be found in specific papers.

References

[1] R.Mugnuolo, F.Bracciaferri, F.Didot, G.Colombina, E.Pozzi, *EUROPA (External Use of Robotics for Payloads Automation)*, in Proc. 5th International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

[2] S.Di Pippo, R.Mugnuolo, F.Bracciaferri, W.B.Williams, G.Videntin, G.Colombina, E.Pozzi , *Payload Tutor (PAT)*, Proc. 5th International Symposium on Artificial Intelligence, Robotics and Automation in Space, 1-3 June 1999 (ESA SP-440)

[3] K.Wittmann, B. Feuerbacher, S. Ulamenc, H. Roseenbauer. J.P.Bibring, D. Moura, R. Mugnuolo, S. Di Pippo, K. Szego, G. Haerendel, *Rosetta Lander In situ Characterization of a Comet Nucleus*, Acta Astronautic, Elsevier Science Ltd 1999, Vol.45, Nos 4-9, pp 389-395, 1999