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Space Robotics in Europe, a compendium

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Abstract

This paper provides an overview of currently envisaged European space missions and application scenarios where A&R plays/could play a major role. The current status of European research and development programmes in the field of space A&R, is also illustrated together with new technology trends for space A&R as perceived by ASI, CNES, DLR and ESA.

1. Introduction

Since last ISAIRAS the European Space Robotics community has not been idle. Despite the scarce mission opportunities, technology developments have continued relentless. On one hand the increased pressure on Space budget has started the much needed revision of the efficiency of space missions (which in long term can only benefit Robotics and Autonomy). On the other hand the same pressure and the need to fullfil international commitments is blocking the initiation of new exciting robotic missions.

2. Autonomy at system level

Autonomy can be implemented on-board or/and on-ground, for nominal or critical operations.

Today, operation and data system processing are currently implemented on-board most satellites with certain degree of reflexive automatism, e.g. through the execution of pre-defined time tagged macro command or modes switching (e.g. 24h or 48h nominal operation guarantee with fail safe mode capability), constrained by the orbit(s) or mission profile (e.g. small visibility window and limited ground contact time for LEO, penalizing round trip delay for deep space satellite, etc..).

In this simple and reliable practice of spacecraft commanding & data processing, the ground segment is the unique point of decision & mission adaptation, of information extraction and operation, of mission product distribution, and of maintenance. User(s) or Principle Investigator(s) are accessing the same payload data, through the satellite control centre.

Future space missions ask for more efficient and useable

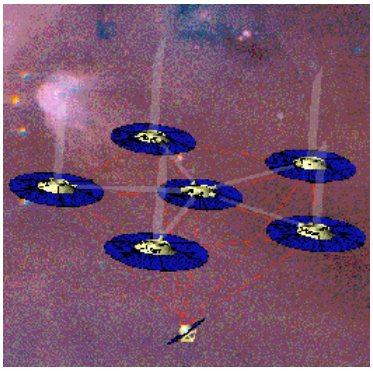


Illustration 1: Artist's impression of the Darwin spacecrafts flying in formation

delivery of data/information and mission products, in a faster time frame, and with higher interactive involvement of the multiple users / customer. Despite

new operational scenarios and challenging mission profiles also enhanced and reliable performances, and secure and cheaper access to space are demanded.

This can only be achieved with a different and more sophisticated operation and commanding scheme, and with suitable data representation and finally knowledge-based utilization.

Since few years, ESA has been developing technology prototypes in the field of autonomy (see [Var2002]).

Some o these developments were also adopted by ESA satellites like **Proba** (a technology-demonstration micro-satellite for LEO observation) and **Rosetta** for rendez-vous with the comet Wirtanen. Proba, launched in

Illustration 2: The Beagle 2 robot arm deploys the mole (mockup)

October 2001, implements in-orbit autonomous 3 D attitude manoeuvre profiles execution and autonomous adaptation of the imager operational sequence, on each specific user request. Rosetta represents for Europe one of the most challenging mission for spacecraft autonomy, especially for the navigation & AOCS mission profiles and for the FDIR mechanisms within various operational modes.

Autonomy is there triggered by on on-board events (e.g. loss of sun or earth pointing) which possibly affect mission critical functionalities, and could lead to mission loss. In Rosetta all autonomy features were based on deterministic algorithmic techniques.

The ESA technology programme for system automation goes on, targeting both ground segment and space segment. The technology produced will enable future challenging type of missions like **Darwin**, the deep space interferometry mission, (see Illustration 1) or **Hyper-Spectra,** an Earth Observation mission and will help reduce cost of exploitation (e.g for the GMES Earth Monitoring programme)

3. Robotics as mission enabling technology

3.1. Planetary exploration

ESA is in variuos stages of implementation of planetary exploration missions in which robotics will play a fundamental role, without which the mission would either be impossible or achieve much lesser goals.

The **Mars Express** mission, due to be launched in the summer of 2003, will land its Beagle 2 Lander, which is contributed by a British team under a remarkable public-private partnership arrangement.

The Beagle 2 lander is also where Mars Express will have its robotic elements. Illustration 2 shows a mockup of the lander with the small robot arm which will position a package of tools and scientific instruments at its end. These will enable the main objective of the mission, namely to analyse soil samples for the existence of organic matter giving evidence of past life on Mars.

Another important planetary mission is **BEPICOLOMBO**. This mission due to be launched in 2009 initially aimed at delivering a small lander (~60 kg) with an integrated geochemistry package. The package consists of instruments which need to be precisely positioned onto their investigation subjects. ESA has developed a micro-rover and associated control system to carry out this task (see §3.1.1)

Finally ESA has recently started the AURORA

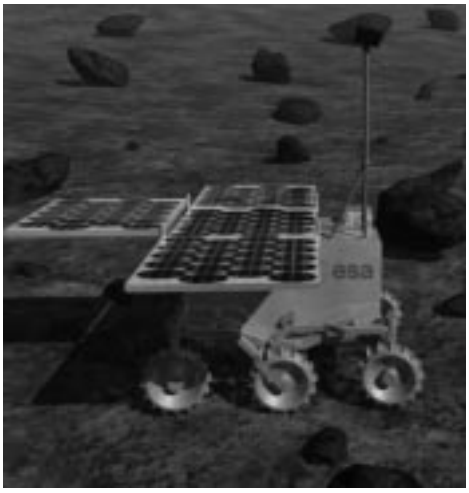


Illustration 3:artis's view of the ExoMars rover

programme. **Exo-Mars** is the first Aurora Flagship mission to be assessed. Its aim is to further characterise the biological environment on Mars in preparation for robotic missions and then human exploration.

This mission will feature a Mars orbiter, a descent module and a Mars rover (see Illustration 3)

Using conventional solar arrays to generate electricity, the Rover will be able to travel a few kilometres over the surface of Mars. Included in its approximately 40 kg exobiology payload will be a lightweight drilling system (possibly as the one in §3.1.2), a sampling and handling device, and a set of scientific instruments to search for signs of past or present life.

The vehicle must be able of operating autonomously. For this the rover will rely on state-of-the-art autonomous navigation software (see § 3.1.2).

3.1.1. ESA Micro-rovers and local navigation

The most mature micro rover concept developed at ESA is called Nanokhod in honour of an early Russian concept on which it is loosely based. The Nanokhod has to accommodate and fine position a set of 4 science instruments totalling about 1.1 kg of mass. The current design and engineering model can do this with an overall mass of only 2.6 kg, i.e. a very high payload mass fraction of 43 %. This is only possible due to an extremely high degree of integration of the subsystems (structure and locomotion, electrical power, control and data handling, thermal control) and payloads.

One reason why such low mass could be achieved is that electrical power and data are transmitted from the lander via 2 extremely thin tether cables consisting of 30 wires each. The tether is paid out from the rover, which gives it a range of up to 100 m (perfectly sufficient for the foreseen missions).

ESA has also developed a complete end-to-end control system which allows to program the autonomous motion

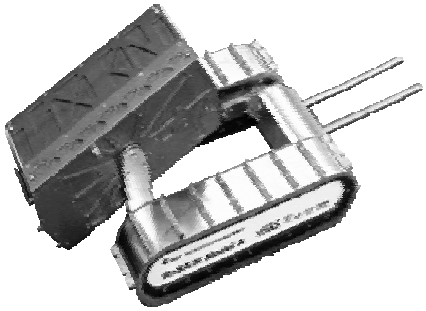


Illustration 4: NANOKHOD micro-rover

of the rover. This comprises:

(1) an Imaging Head (IH) mounted on a mast of some 1.5m height on the lander and fitted with a stereo camera system. This enables the localization /tracking of rover and the generation a map of the terrain around the lander.; (2) a computer (“on-lander control system”) that controls the Imaging Head, the cameras and the rover; (3) A ground control station that implements the user control interface.

The operation of the system is articulated in the phases:

(1) Terrain Modelling: Images of the site around the lander are acquired and transmitted to the on-ground station. A360º panorama is segmented into 4 circular rings. Each ring is segmented in 30 sections (12° azimuth), for each section a stereo image pair is

recorded. Launch and landing shocks and thermal effects are likely to change some of IH's geometrical properties which therefore have to be calibrated. The calibration works by using only images of the terrain and uses recent developments in computer vision. After the calibration, 3D models of the planetary terrain are generated using all stereo-pairs. The output is a Digital Elevation Map (DEM), a Triangulated Mesh Model (TMM) and texture and thematic maps.

Illustration 5: ASI DeeDri sampling tool: drilling configuration (right) coring configuration (right)

(2) Programming: the primary scientific objective of the Nanokhod rover is to apply its instruments to surface features deemed "interesting" by the Principal Investigator (PI). The ground station provides the PI with a reconstructed view of the lander site where points that should be visited by the Nanokhod can be selected. The station implements also path-planning tools used to compute a route between the current position of the rover and the desired destination. The tools will optimize resources (e.g. time to traverse,energy) and minimize risks (e.g. risk of tipping over, risk of entangling the tether). The output route consists of a sequence of Path Segments, that are normally traversed using "Move To" Actions run by the on-lander control system. The operator may modify a computed route, impose intermediate way points, and even alternative Actions (climb an obstacle, or overcome a trench).

(3) Execution: The ground station allows to upload the programmed sequence and play the telemetry stream (collected at the next communication window) to verify the motion of the Nanokhod.

3.1.2. ASI drilling and sampling systems

ASI has funded the development of an integrated deep drilling (DeeDri) and sampling system. The tool prototype produced (see Illustration 5), consists of a hollow steel tube equipped with an auger thread on the outer surface and a drill tip at the lower end. The tool drills a hole 35-mm in diameter and its central part (piston) can be withdrawn so to form a volume to allow sample core to be collected inside this opening. The core sample collected is approximately 14-mm in diameter and 25-mm in length. The mechanism allows collecting not only core samples but also powder-like samples. The tool diameter can be scaled down to allow drilling and sampling functionality with a lower demand of power and force/torque actions.

3.1.3.CNES Autonomous navigation

The landing site for a planetary exploration mission is usually selected according to safety considerations and is not necessary the most interesting from the scientific point of view. When a ground operator using waypoints defines the rover path, the operator ability is limited, in rocky terrain, by the availability of a 3D model to perform the planning and by the rover deviation from the planned trajectory. The locomotion autonomy should allow the rover to progress towards a distant goal in an unknown environment and without any intervention from the Earth. The operations of the rover are based on the following typical sequence, for locomotion phases :

During a communication window with the Earth, the rover transmits all available information including surrounding landscape images.

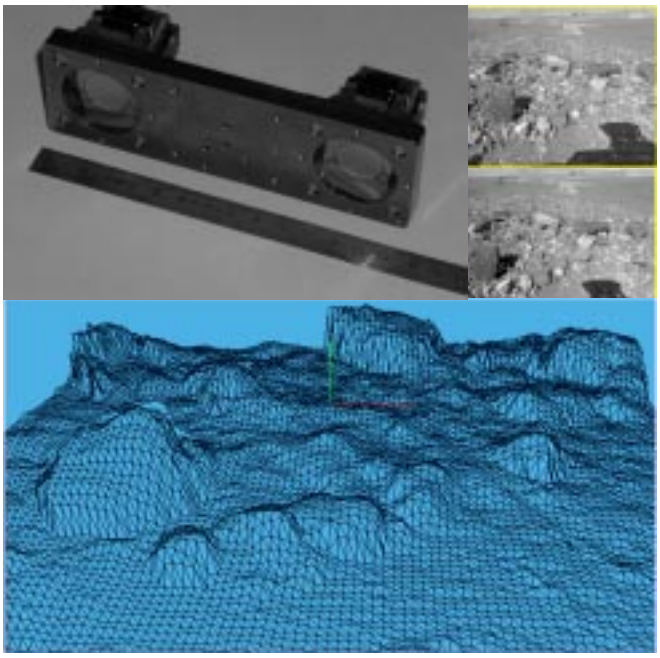


Illustration 6: Stereo device (top-left), image pair and corresponding elevation model computed on-board

It receives before the end of the window the objective(s) for locomotion until the next window, elaborated by the control center. This objective can be a simple heading, coordinates, heading and distance … and can be very far away. No knowledge of the terrain is supposed at this stage.

The rover starts a locomotion cycle, described hereafter, which allows to progress in the direction of the final goal assigned.

This cycle will be repeated until reaching the objective.

The on–board cycle is based on 3D environment modeling using stereovision. The Digital Elevation Model obtained is then analyzed to determine, for each pixel of the DEM, whether the rover could cross this cell or not, and to give a difficulty score to the cell if it is navigable. Path planning on a single perception is not sufficient to cover long distances: the search for a feasible trajectory fails rapidly when obstacles are detected in the small region analyzed, and the rover cannot avoid entering in dead end areas of a few meters long. To overcome this problem, the current perception is merged with the previous ones. An optimal path is then computed and executed. Optimal perceptions are also planned by the algorithm.

The navigation map corresponding to a stereo pair is merged with previous ones before planning a path.

The autonomous navigation algorithms are run at the

Illustration 7: Simulator's view of IARES rover crossing a complex terrain

stops of the rover, after taking stereo images. The necessary time to run the algorithms will induce a mission time loss that has been minimized by adequate implementation. The computing time for the whole software is 3.3 s on a Winsystems LBC586 board running at 133MHz. This less than 5% of the total mission time. The necessary memory to implement the algorithms and their data is 3Mbytes.

3.1.3.1. CNES Simulator

A real time simulator has been developed to allow fast and easy to reproduce tests of the autonomous mode.

The first function of the simulator is to represent the natural rover environment:

- The terrain itself is modeled and displayed with a

sufficient resolution to represent the contacts between the rover wheels and the soil. A typical resolution varies between 2 and 5 centimeters for a mini-rover. The terrain size that can be displayed in real time is wide enough to offer a sufficient variety of local topologies (typically 100m x 100m).

- 0.7 milliseconds to place the rover on the terrain (using the IARES chassis that features 19 degrees of freedom)

obtained on a Sun Blade 2000 mono-processor workstation, allows real time display at full terrain resolution with complete rover graphics.

Illustration 8: CNES new test facility : external, covered and computer areas

- The ambient conditions, and in particular the lighting of the landscape are adjustable to simulate several hour and seasons and several hypothesis on the local albedo light, thus giving realistic images.

The rover model includes exact kinematics to deliver correct chassis configuration parameters. To provide this, all the elements possibly in contact with ground are modeled and checked.

The rover simulation also includes sensors and actuators modeling to provide the necessary inputs and outputs to the on-board software. These interfaces are respected at functional level but also at software level so that an on-board computer running the operational code could be connected indifferently to the rover or to the simulator.

In addition, the simulator gives to the operator the possibility to select the viewing point and provides the interface to vary all parameters.

The computing times :

- 59 milliseconds to display a 80 x 80 m terrain using a 40 millimeters pitch grid

The simulator architecture allows representing several rovers with different kinematics.

3.1.3.2. CNES Test site

A new site has been built for future tests. It features a covered 15 x 15 m area for all-weather integration of the rovers, an external area (about 5000 square meters wide and a computer room with a direct view on both terrains. Real time monitoring of the rover position during tests has also been implemented on the new facility.

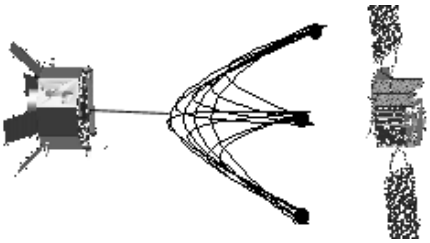


Illustration 9: An artist's view of ROGER capturing a target satellite

3.1.4. Satellite Servicing

European efforts on the subject have been renewed with

continued work at ESA on the Robotics Geostationary Restorer (ROGER) and at DLR. The ROGER concept promotes management of the GEO crowding through the use of a servicing spacecraft for voluntary re-orbiting into graveyard orbit. The concept, preliminarly investigated by ESA, implements well proven techniques for redez-vous to the target, as well as very innovative means for satellite capture.

At DLR satellite servicing remains a priority with continued work on technology demonstration. Most recently, past developments on the subject have been target of a renewed interest (satellite capture tool).

3.2. Robotics as system enhancement

Illustration 10: ERA under EMC tests (credit DutchSpace)

3.2.1. ERA

The European Robot Arm (ERA) is intended for use on the Russian segment of the International Space Station (ISS). Currently the Flight Model is planned to be delivered by 2003 for a launch in 2005.

The ERA is presently undergoing the final tests before delivery to ESA. However due to the high uncertainty of the schedule of the ISS Russian segment, and most recently of the whole ISS assembly schedule, it is highly unlikely that the launch date will be maintained.

3.2.2. EUROBOT

ESA has recently proposed a new robotic system for the ISS. This system named **Eurobot**, is intended to help or even replace EVA crew. The robot does not emulate human features and tries to exploits of all possible robotic advantages. The system features three 7-dof identical arms radially arranged around a cylyndrical body. The arms (similar to the LWR-III at §3.2.2.1) are multi-functional and may be used as "arm" or "leg". On top of the cylinder a cap implements a tool carousel. Each arm may pick-up/release wrist mounted tools at selected locations on the carousel. These tools may be specialised (e.g. wrench) or general purpose (e.g. a gripper, or artificial- hand as the HAND-II in §3.2.2.2). The bottom of the cylinder features a second rotational cap with a radially protruding imaging head. This hosts a stereo pair of cameras with pan&tilt capabilities. The head can be rotated to be in between any pair of arms.

Eurobot is in the preliminary phases of development, however a functional demonstrator is being implemented, with some operations (walking) already possible.

3.2.2.1. DLR Lightweight robot arms

Since the ROTEX experience the DLR has been pursuing the development of a small size space robot (1-2m size) which should be able to work in a “1g gravity” mode. DLR is now at its third generation (see Illustration 14) of such light-weight robots (LWR).

The latest robot arm (LWR-III) is based on a fully modular joint-link-assemby system, with only a few basic components, namely three one-dof robot joint–link

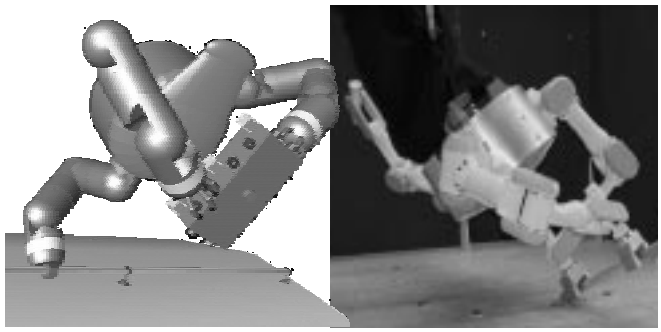


Illustration 11: EUROBOT artist's view (left) and its functional demonstrator (right)

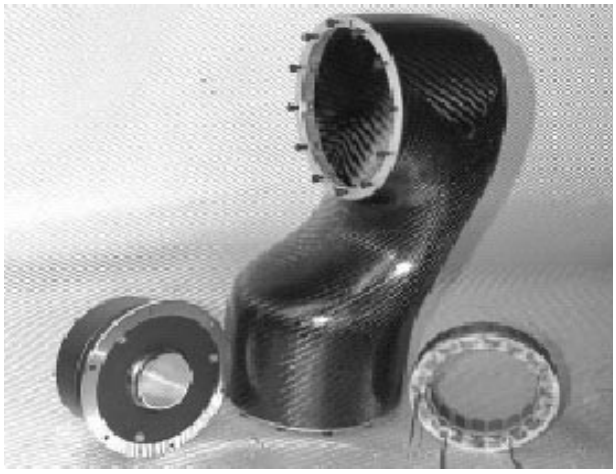


Illustration 12: A disassembled LWR-III joint with ROBODrive (left)

types and a two-dof wrist joint. Two schemes of joints (inline and offset) allow for different arm configurations (Illustration 13). The asymmetrical version offers high packed stowing of the arm

For LWR-III the key achievements are a new motor generation, ultralight-weight brakes and ultra-light carbon fibre structure.

Conventionally the only choice for robot designers was to use the best general purpose off-the-shelf motors. These are not optimized for robotic applications which demand slow rotational speed though high dynamics, permanently reversing operation around zero speed, minimal weight and low power losses.

Thanks to a concurrent engineering and optimization process, which took in account all the electromagnetic and other physical effects, short copper paths, optimal coil winding and coil filling aspects between the magnetic iron poles the DLR's high energy ROBOdrive was born. This has only half of the weight and half of the power losses of the (to our knowledge) best available

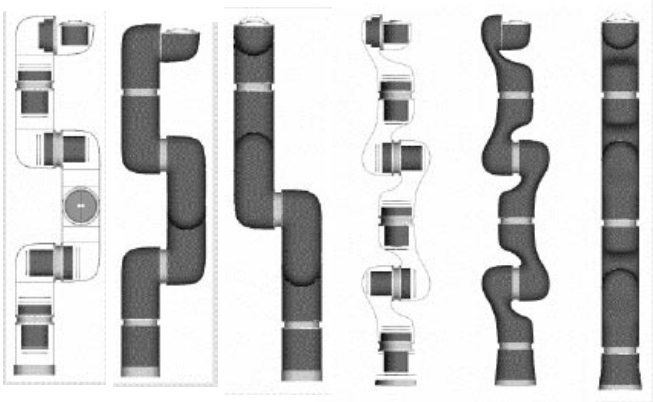


Illustration 13: Two possible configurations (asymetrical and Symmetrical)

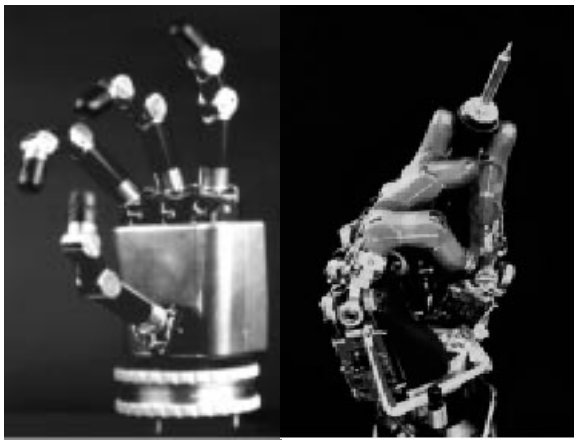
Illustration 14: Three generations of DLR lightweight robot arms: LWR-I (Top-left) LWR-II (Bottom-left) and LWR-III (Right)

motors. Finally while the developement of piezoelectric brakes weighing only ~70g was undertaken a further concurrent engineering and optimization process lead to an extremely weightreduced electromagnetic brake version (~30g for the ball-shaped wrist joints).

3.2.2.2.DLR Robotic hands

In 1997 DLR developed one of the first articulated hands with completely integrated actuators and electronics. This well known hand has been in use for several years and has been a very useful tool for research and development of grasping. The main problems remaining were maintenance and the many cables (400) leading out from the Hand. With this experience behind,

the new Hand-II was designed according to a fully integrated mechatronics concept. Fingers and base joints of Hand II were realized as an open skeleton- structure.



This is covered by 4 semi shells and one 2-component fingertip housing realized. This enables to test the influence of different shapes of the outer surfaces on grasping tasks without redesigning finger parts. In order to improve grasping- performance for precision- and power-grasp, the design of Hand II made use of scalable virtual models.

All local electronics is integrated into the hand. In order to reduce cables and the possibility of noise in the sensor, a cascaded integrated serial communication system was inrtroduced. Each finger holds one communication controller in its base unit. This controller acquires 40 channels @ 12 bit resolution, and processes and distribute data to a communication controller in the hand base. Conversely it distributes data from the hand base controller to the actuators for finger control. The communication controller in the hand base links the serial data stream of each finger to the data stream of an external control computer.

Arm LWR-III is now equipped with DLR's Hand-II. Thanks to the hardware architecture of the hand only 12 wires lead out of the hand and are guided inside the hollow shafts of the robot joints.

4. Conclusions

Since last ISAIRAS robotics missions and corresponding technology developments have continued to be actively promoted/pursued by the European Space Robotics Community. For many possible applications, the level of technology readyness is approaching flight status. In fact it is very likely that after the pressure on space budgets is alleviated, major European all-robotic missions will find their way to fly.

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