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Space robotics in Europe: A survey

P. Putz *

ESA/ESTEC, Postbox 299, 2200 AG Noordwijk, Netherlands

Abstract

Europe has been very active in developing space robotics systems and technology for close to 15 years. This survey paper serves as the introduction to the Special Issue on Space Robotics in Europe. It first highlights the most significant differences between space and terrestrial robots. Next, it structures the space applications scenarios into internal and external robotics in Low Earth Orbit (essentially the Space Stations), robotics for servicing of geostationary satellites, for in-orbit assembly of large space structures, and mobile robots (rovers) and manipulator-type robotics for surface operations on the Moon, on Mars, on comets and on asteroids. Finally, it gives an overview of the major European space robotic technology research and development programs. From this context, it extensively refers to the individual papers of this Special Issue for more in-depth treatment. © 1998 Elsevier Science B.V.

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1. Introduction

1.1. Background

Space missions pose unique requirements and opportunities for the application of *automation and robotics (A&R)* technologies. There is a very loose definition which calls every unmanned space probe a robotic spacecraft, rightfully referring to the challenges of largely autonomous operation in a complex mission. But even discarding this and focussing on space robotics elements in a more narrow sense (systems involving arms for manipulation or some kind of locomotion device for mobility and having the flexibility to perform varying tasks), there is a wide array of uses in the scope of space missions, giving rise to challenging problems and ingenious solutions.

A recent *Workshop on "Advanced Space Technologies for Robot Applications (ASTRA'96)"* organized by the European Space Agency (ESA) assembled the (West) European space A&R community from academic, industrial, and government organizations. The resulting Proceedings [16] give a comprehensive overview of current mission applications, R&D programmes, and individual technological developments.

1.2. Objectives of this Special Issue

A selected number of highlights from the ASTRA '96 Workshop will be reported in somewhat more depth in this Special Issue. The main objective is to provide a "snapshot" of the *status of space A&R work in Western Europe at the end of 1996*, by outlining the problems posed from the diverse space missions where Europe currently envisages a participation, and surveying some key development work which is performed to solve these problems.

* Fax: +31 71 565 5419; e-mail: pputz@estec.esa.nl

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1.3. Outline of the paper

This introductory paper wants to identify the overall context of the field, provide some additional background, and finally point to the individual papers of the Special Issue. First, Section 2 highlights the main differences between a space robot system and robots for terrestrial use. Section 3 surveys the potential applications of space A&R, classified by the space mission destination (Low Earth Orbit, Geostationary Earth Orbit, Moon, Mars, comets, etc.). The particular robotic tasks and constraints are highlighted as well as the major robot systems which exist or are under development for these applications. Section 4 gives an overview of some key space robotic technology development programs which are underway in Europe, classified by international organization or country. This will show the diversity and depth of work which is going on, even in a time of increasingly scarce public funding for this kind of R&D.

This article and this Special Issue necessarily will not be exhaustive. In scope, they are clearly written from an ESA perspective and *restricted to Western European activities*, where an intensive harmonization and information exchange exists between work sponsored by ESA and by national entities (thanks to AGAR, an ESA Advisory Group on space A&R). Thus the survey covers only superficially the very significant space robotics work in the US and in Japan, and the reader is referred to the rich publication available on this.

For practical reasons two other countries are not covered much, even though they would be more than deserving: Russia and Canada.

Considerable expertise on space robotics exists in *Russia*. Remotely controlled rovers have been operated on the Moon some 25 years ago, and manipulator arms are installed on the Mir Space Station. Even though cooperative developments with ESA are starting, not enough is known by us about plans and achievements there.

Canada, an associate member state of ESA, is the world leader in space robotics experience, having built the robot arm of the Space Shuttle and collected more than 15 years of space operations expertise with it. In the framework of the International Space Station, Canada will provide the largest robot system, including a trolley-based version of the RMS and a two-arm Special Purpose Dexterous Manipulator. This work, however, is done in cooperation with NASA and shall therefore be mentioned only briefly in this survey.

2. What is so special about a space robot?

In many ways, robot systems for space applications are very different from the more familiar terrestrial robots, be they industrial robots in production automation, or the newer kind of “service robots”.

Somewhat simplifying, one can classify the *peculiar requirements and constraints* which drive the designs of space robots in a special direction into two groups. Table 1 summarizes major space *environmental* constraints and typical design impacts, while Table 2 compiles key space *system and programmatic* constraints and their impacts. While obviously these tables are very superficial, they already give a glimpse of the particularly difficult (but challenging) problems.

Among others, these constraints (which are typical for all space systems) give rise to the very *high development and manufacturing costs* that have been obstacles for more widespread acceptance in the past. Another main reason, of course, is the completely missing “economy of scale” due to the experimental prototype nature of these developments. Only recently, intensive efforts have started to make the whole process leaner (“smaller, faster, cheaper”), for instance by judiciously applying selected terrestrial technologies. It is clear, however, that hard physical limits cannot be fooled, and that one must be ready to accept increased risk as a penalty.

3. Potential applications of space robotics

Space robotics can be and has been applied in many completely different mission scenarios. For the purpose of a survey, the applications can be conveniently structured according to the “destinations” of the spaceflight mission. Tables 3 and 4 show this classification and for each class the most prominent robotic system names. These space robot systems will all be treated in this Special Issue.

Table 1
Major space environmental constraints and resulting design impacts

Constraint	Typical features	Typical design impacts
Survive launch loads	16 g linear acceleration 145 dB acoustic noise	Dedicated mechanical design of supporting structures Holddown and release mechanisms needed Specially mounted electronic components Expensive test facilities needed
Survive landing loads (planetary missions)	Soft landing: more benign than launch loads Descent to Mars: 19 g linear deceleration Landing on Mars: 40 m/s impact speed	Same as for launch loads Need shock absorbers (air-bags)
Function in vacuum	LEO: 10^{-3} Pa GEO: 10^{-15} Pa	Only carefully selected materials can be used (non-outgassing) Special lubrication means (e.g. dry) Preferably brushless DC motors with electronic commutation Certain sensing principles cannot be used (e.g. ultrasonic) Clean room integration and testing necessary
Function under "weightlessness" (orbital applications)	Larger stations not below 10^{-6} g	No stable preferred positions, everything has to be fastened Altered dynamic effects (when gravity term disappears, highly nonlinear effects start to dominate) Very low backlash gearing needed
Function under extreme radiation exposure	Total dose: 10^6 rad/year (Space Station) Protons and heavy ions	Limited materials life time Electronics: needs shielding and special "hardened" technology (insensitive/protected against latchups) Typically, cannot use latest terrestrial computer performance
Function under extreme temperatures, possibly combined with vacuum	"Thermal vacuum": cannot use convection for heat dissipation Space Station external: −120 to +60°C Moon: −230 to +130°C Mars: −130 to +20°C	Multi-layer insulation Radiators with heat pipes Distributed electric heaters Radioisotope heating units (RHUs) for planetary applications
Function under extreme lighting and contrast conditions		Increased difficulty for vision and image processing
Function in extremely remote environment	Mostly unmanned systems: nobody can fix problems "on site" Long delays in signal transmission	Comprehensive testing before launch Essentially maintenance free systems needed Adequate level of autonomy needed In-orbit calibration and sensor-based control to cope with unavoidable inaccuracies (no "teach-in" possible) Effective ground operator interfaces needed

The maturity of the listed robot systems is encoded through line types as follows:
- **RMS** has been productively used in space;
- **(PROP-M)** was built but never used as intended (e.g. mission failed);
- ***ROTEX*** was experimentally demonstrated in space;
- *ERA* manufacturing ongoing or completed, future productive use approved;
- *AMTS* study/development phase has been performed or is ongoing.

These tables immediately show up one of the characteristic features of space robotics: even though there

Table 2
Space system and programmatic constraints with resulting design impacts

Constraint	Typical features	Key design impacts
High system complexity	Often > 10 subsystems from different contractors Often poorly understood requirements and constraints	"System engineering" needed: clear development phases, top-down analysis and design, bottom-up integration and testing, clear traceability of requirements and effects Professional project management needed: time planning, cost estimation, risk management, negotiation with users and hosts, etc.
Long life time	Often > 10 years	Maintenance free designs (lubrication, electronics) Built-in growth potential and upgradeability (re-programmability) "Orbital replaceable units" for maintenance
Extremely high reliability and safety	Unmanned systems: reliability > 80% Man-rated systems: reliability > 95% Triple fail-safe barriers against catastrophic hazards	Extensive "product assurance" measures and "space system engineering standards" (e.g. for software development) – high documentation effort! "Inherently safe design" preferred: safety independent of software or operational procedures Problems with "non-deterministic" approaches (e.g. art. neural networks, fuzzy control, artificial intelligence) Built-in diagnostics Failure tolerance: redundancy of critical components
On-board mass very limited and expensive	Shuttle: > 10 000$ /kg Moon, Mars: much more	Extremely lightweight designs (e.g. composite materials) Very slim designs with noticeable elastic effects (control problem!) Need to achieve very high ratio payload mass/robot mass
On-board power and energy very limited	Extreme cases: night-time survival on Moon/Mars	Extremely low-power electronics needed Need to achieve very high efficiency Limitation on computer resources (processing, memory) Mobile robots: batteries always problematic (mass, thermal control)
Communications with Earth very limited and expensive	Mir: only a few times 10 min per day Space Station: up to 10 s round trip signal delays Moon: > 10 s round trip signal delay Mars: up to 40 min round trip signal delay	Varying degrees of autonomy needed "Telerobotics": shared manual/automatic modes Need sophisticated ground operator interfaces to cope with signal delays (predictive simulation) Extensive built-in self-checking means
Micro-gravity conditions	Robot motion must not disturb micro-g environment for other payloads	Very smooth acceleration profiles Very low motion speeds (typically < 1 cm/s) – also good for safety! Actuators with high motion smoothness needed Robot joints can be very weak (also good for safety!) Very high gear ratios
Limited testability on Earth	Cannot fully re-create 0 g in 3D 0 g robots may be too weak to operate under 1 g	High effort for thermal vacuum and launch loads testing Approximations for 0 g: air bearing tables, suspensions, water tanks Need for sophisticated simulations to verify system behavior in 0 g (with "hardware in the loop")
Long planning and development times	> 10 years for major missions	Problems of staff continuity and morale When flight operations come, technology may well be obsolete
Development in international cooperation	ESA: 14 member states with precisely defined "geographical return" requirement	Often sub-optimal project efficiency from artificial work distribution Often communications and logistics problems

Table 3
Potential robotics applications in low earth orbit (LEO)

Application class	Main characteristics	Typical objectives	Major robot systems
Module internal	More benign environment (Earth-like pressure, temperatures) Micro-gravity condition and requirement Major safety requirements due to human presence "Competition" with astronauts No robot system accepted for productive use yet	Tending of (microgravity) experiments	***ROTEX*** (D, 1993) *EMATS, AMTS* (ESA) *BIOROB* (ESA) ***Charlotte*** (USA, 1995)
Module external	Harsh environment (vacuum, temperature extremes, radiation) Less "competition" with astronauts: robotics is recognized as essential or highly desirable		
Space shuttle external	Relatively short periods of space operation (1–3 weeks) Teleoperated by astronauts on board	"Crane" operations in the cargo bay (essentially pick-and-place)	***Remote Manipulator System*** (Canada, since 1981)
Space Station external	Extremely long orbital lifetime requirement (10 years)		
Mir external system servicing	Manual master/slave operation by cosmonauts	Install/remove payloads	PELIKAN (Russia, 1998–)
Mir external payload tending	Preprogrammed automatic operation with ground supervision (communication to Earth very scarce)	Inspection and tending of (exposure) payloads	JERICO (ESA, Italy, 1999–)
ISS external system servicing (from an attached base)	Extremely high reliability requirements (huge investment to protect) Large work area, hence mobile robot base Commanded from astronaut inside or outside Station	Transport and assembly of Space Station elements Transport of astronauts	ERA (ESA, 1999–) Mobile servicing system (Canada, 1999–) *Flight Telerobotic Servicer* (NASA)
ISS external system servicing (from a free-flying base)	Particular safety hazards (free-flying) Multi-arm systems	Systematic inspection of Space Station shell Preventive/corrective maintenance	*OMV* (NASA) *Ranger* (NASA) *SPIDER* (Italy)
ISS external payload tending	Local to payload platform Preprogrammed automatic operation with ground supervision Can dramatically increase utilization efficiency	Inspection and tending of (exposure) payloads	JEM-RMS (Japan, 2002–) Robotized Technology Exposure Facility (ESA) *PELIKAN – ISS* (Russia)

is an immensely rich scope of potential applications, only a handful of (relatively simple) systems has actually been built and operated so far. To a large extent, this is because of the high cost of these systems. But one also notes that with the start of the International Space Station (ISS) era (around 1998), a big boost for "real" space robotics can be expected.

3.1. *Applications in Low Earth Orbit*

The Low Earth Orbit (LEO), actually a whole band of orbits between 300 and 700 km altitude, is the domain of today's *manned space missions*. The US Skylab, the Space Shuttle, the Russian Space Station Mir, and the planned International Space Station (ISS) all

Table 4
Other potential space robot applications

Application class	Main characteristics	Typical objectives	Major robot systems developments
Geostationary Earth Orbit (GEO)	High commercial relevance	Inspection and assessment of satellites in orbit	*GSV* (ESA)
	Potentially ideal communication possibilities	Simple repair tasks	***ETS-7*** (Japan, 1998)
	High launch cost	De-orbiting of expired satellites	*ESS* (Germany)
	Unmanned		
Other orbits	Future science missions (e.g. for sun observation)	In-orbit assembly of huge structures (e.g. antennas)	*Concept studies* (NASA, ESA)
	Extremely remote		
	Unmanned		
Moon landing	Vacuum, regional temperature extremes, radiation	Exploration: roving, instrument deployment, sample collection	**Lunokhod 1&2** (Soviet Union, 1970, 1973)
	Possibly no direct communication (far side, polar craters)	Base building	*Concept studies* (NASA)
	Possibly permanent darkness (polar craters)	Mining	*LEDA rover and robots* (ESA, France, Italy, Germany)
	Terrain varying from sandy to rocky, crater slopes	Resource processing	*Entertainment robots* (USA)?
	Unmanned for the medium future		
Mars landing	Climate effects (e.g. dust storms)	Exploration: roving, instrument deployment, sample collection, search for past life	**Viking arm** (NASA, 1976)
	Unmanned		
	Very remote		
	Landed mass very limited		**(PROP-M)** (Soviet Union, 1971)
			Marsokhod (Russia)
			Sojourner (NASA, 1997)
			Nanokhod/IDD (Germany)
Comet/Asteroid landing	Extremely remote	Instrument deployment	*Rosetta Drill,*
			Sample & Distribution System (Italy)
	Very low gravity	Sample collection	??? (NASA)
			Concept studies (Japan)

belong to this class. The orbits are just high enough to be practically free of destabilizing dynamic disturbances, but as low as possible to minimize launch cost.

Apart from human physiology interest (to investigate the effects of weightlessness on astronauts), the main *application* field has always been a microgravity research. The term "microgravity" refers to the typical level of "weightlessness" on such manned missions: due to various disturbances (remaining atmospheric drag, moving machinery, but most of all man motion), some 10^{-6} g acceleration will continue to act on every mass. With a typical orbit duration of 90 min, this is also an excellent vantage point for "missions to planet Earth": for an orbit inclination of more than 50° (as for the ISS), the subtended region covers 90% of the populated world.

3.1.1. Module internal robotics

Historically, this is probably the "oldest" field which has been worked on in Europe (but not in the US!). Undoubtedly influenced by the high level of factory automation, it did not take long after the first European microgravity payloads were conceived (e.g. for the unmanned EUropean REtrievable CArrier, EURECA) before one began to design robotized systems that would automate the experiments.

The typical materials or life science payloads routinely need to transport small samples (suitable housed materials probes or biological specimen) between storage compartments, heater furnaces, freezers, incubators, etc. Whereas the first (and still standard) solutions were dedicated payload internal mechanisms (carroussels, lifts, feeders), the overall mass, volume, and power need can be significantly reduced by employing some sort of central robot system which is shared among several facilities.

Relevant work on robotics for European space laboratory automation is summarized in [15]. The major concept that was designed for the internal automation of the European laboratory of the ISS under the name *EMATS* (Equipment Manipulation and Transportation System) [13] also went through in a complete pre-development phase under the title *AMTS* (Automated Manipulation and Transportation System). EMATS/AMTS essentially consisted of one 7-axes dexterous arm of about 2 m length whose base could move throughout the central aisle of the laboratory on a 3-axes cartesian gantry system.

The AMTS work, however, was stopped before going into detailed design and manufacturing. In part, this was due to the large budgetary problems and overall programmatic uncertainty about the European role in the ISS at the time, but the core issue is that internal robotics has never managed to overcome the opposition of astronauts and proponents of dedicated facility automation.

This is even more regrettable since the technical feasibility of intelligently sensorized internal robot systems has been very convincingly demonstrated in the successful German *ROTEX* (Robotic Technology Experiment) [6] in a Spacelab mission on the Shuttle.

In the meantime, NASA had never officially worked on internal robotics (because of the same constraints). Only one privately funded robot called "*Charlotte*" (a box with a gripper, moving in the center of a web of strings hooked to corners of the laboratory aisle) was demonstrated on the Shuttle. Its further application perspectives in the ISS are unclear.

The paper [5] in this issue includes a *current outlook* for internal robotics in the ISS. It is the firm belief of the authors that some time after the initial operation of the ISS, the need for rack or laboratory level robotics automation will present itself very strongly again. Even though the actual number of facilities to be serviced is not so large any more (after all the cost reduction which had to be done), a number of factors will probably combine to give rise to a renaissance: the (hoped) success of the external robot systems by that time (see later on), the expected growing interest from the user community, the extremely low crew availability for routine payload operations, but most importantly the high pressure to save on operations cost.

In summary, the section on "internal robotics" is still a sad one. Despite the almost obvious benefits and fully manageable technology, no real activity is going on in that area currently. But the technical similarity with other systems (external payload tending robots) is high, such that internal robotics could be revived quickly if needed.

3.1.2. Module external robotics

3.1.2.1. Space shuttle robotics. Even though there is no European development to report, the "Shuttle arm" has to be mentioned here because it is probably the most widely known space robot to date. The *Remote Manipulator System (RMS)*, as it is officially known, is a Canadian development ("Canadarm") from the late 1970's and has built up an impressive operations record over more than 15 years. An astronaut teleoperates it with two aircraft pilot joysticks from the Shuttle aft flight deck. The main applications are to take satellites from the Shuttle cargo bay and release them into space, but also to carry astronauts on its tip to perform delicate extra-vehicular activities (EVAs). Possibly the most impressive use of the RMS has been in the capture and repair of the Hubble Space Telescope (where the arm was operated by a European astronaut, Claude Nicollier).

3.1.2.2. Robotics on the Russian Space Station Mir. The Mir station, which has been in orbit for more than 10 years, is currently the world's best resource for longer duration experimentation in *preparation of the ISS*. Even though the designed lifetime of Mir has already expired, it shall be kept in operation until the ISS can "take over" around 2000. Russia is still adding more elements and systems, but with a view of re-use on the ISS.

In terms of robotics, there are *currently two external arms for system servicing* on Mir: one for re-berthing station modules, and one for helping cosmonauts to transport equipment along the length of the station.

Both arms are completely passive (no motors) and are teleoperated by muscle force from a mechanically coupled master arm inside the station.

The same applies for a new external servicing arm called *PELICAN* which is currently under development. It was planned to be mounted on the SPEKTR module in 1997. It would be able to take payloads out of an airlock and install them on standard interface "nests", thereby avoiding the costly and dangerous human spacewalks. After the accident on SPEKTR in the summer of 1997, it is expected that PELICAN shall be mounted on the Russian Segment of the ISS, if Russian budgets allow.

There was also a European development for the SPEKTR module: by late 1998, the *JERICO* system should demonstrate and productively perform external payload tending operations in direct cooperation with the PELICAN system. The 7-axes dexterous JERICO arm (a contribution of the Italian Space Agency) would automatically perform the routine handling of sub-units of the payloads installed by PELICAN. Preprogrammed automatic operation with high-level interaction ("interactive autonomy") is not only a technology demonstration objective, it is also necessary because of the very restricted communications availability with Earth: after Russia had to abandon most of her past ground control stations, only a few short communication windows with the station exist per day. The JERICO system is more fully covered in this issue [4]. After the SPEKTR accident, also JERICO is now planned to be installed on the Russian segment of the ISS in 1999.

3.1.2.3. Robotics on the planned International Space Station (ISS). As already done in the overview table, the ISS external robotics "world" can be structured into:

- system servicing robots with attached base,
- system servicing robots on free-flying vehicles,
- external payload tending robots.

System servicing robots with attached base will be the biggest robot systems on the Space Station, and they are under manufacturing for productive use from 1999 on.

- On the US segment, there will be the Canadian-built *Mobile Servicing System (MSS)*, consisting of essentially a larger version of the Shuttle arm (Space Station Remote Manipulator System or SS-RMS), travelling along the main truss on a trolley, and the Special Purpose Dexterous Manipulator (SPDM), a bi-arm system which can be mounted as an "end effector" on the SS-RMS. The main tasks of the MSS will be to transport large Space Station elements (such as solar arrays or radiators) for initial assembly of the Station, and to exchange orbital replaceable units (ORUs) such as payload carrying platforms.
- On the Russian Segment, the *European Robot Arm (ERA)* will be used for very much the same tasks. The ERA, which is the subject of [2] in this issue, is the largest European space robotics development to date and has a long development history which is recounted in the paper. It is a completely symmetric 7-axes arm which can relocate itself along a system of attachment ports on the Russian truss by alternately switching the roles of end effector and shoulder base.

One notes the absence of US-developed systems for this key function. One NASA development, the *Flight Telerobotic Servicer (FTS)*, was cancelled midway through the development phase because of funding problems.

There is a growing awareness that the above systems will not be sufficient to maintain the huge Space Station. To safeguard this immense investment, the outer shell and also the large appendages (solar arrays, radiators) have to be routinely and systematically inspected to detect any cracks or impact damage from debris or micro-meteorites. This is far beyond the capacity of astronauts on spacewalks, which would also not be affordable. This has given rise to a call for more flexible *system servicing robots on free-flying platforms*. Such systems had been studied much earlier (e.g. the NASA Orbital Maneuvering Vehicle, OMV, but also by ESA), but were abandoned as overly complex until the Station operations cost issue became so urgent. No free flying robot systems have been approved yet, but many studies are going on, both in the US and in Europe. A NASA demonstration flight of the 3-arm *Ranger* system is planned for 1998.

Finally, there should also be smaller robot systems on the ISS for *external payload tending* (similar to the JERICO system on Mir). Indeed, such developments are going on, for instance in the scope of the ESA

Technology Exposure Facility. The European view is presented in [5] in this issue. A firmly planned element will be a robot arm on the Japanese Experiment Module, the *JEM-RMS*.

3.2. Other orbital applications

With the easy-to-reach LEO, we leave behind the domain of manned space missions and enter the world of commercial or scientific satellites.

3.2.1. Geostationary servicing robots

The *Geostationary Earth Orbit (GEO)* has an altitude of some 36 000 km and an orbital period of precisely one day, such that from Earth a satellite in GEO appears to be stationary over a certain point on the equator. This feature is used extensively for communication satellites, but also civil and military Earth observation satellites.

There is a huge *commercial market* in these systems, to the effect that the GEO is becoming more and more crowded in its most attractive locations (at the longitudes of North America and Europe). Not all satellite operators adhere to the convention that dead satellites have to be boosted into "graveyard orbits" (because this shortens the precious operational use). Moreover, there have been several publicized (and probably a few unpublicized) failures where the correctly deployed satellite would not fully perform because of some malfunction (which could be as simple as the solar array deployment mechanism getting stuck). Those are insurance cases worth hundreds of millions of dollars, yet no reliable in situ assessment of the problem (and hence the responsibility) is possible.

This is the background for the ideas of robotized *geostationary servicing vehicles (GSV)*, which would be satellites which can "fly" around the GEO to perform inspection, graveyarding, and simple repair tasks on failed or expired satellites. Paper [19] in this issue summarizes the ESA work in this area. The German *ESS (Experimental Servicing Satellite)* program is developing technology for a servicing demonstration, and the Japanese *Engineering Test Satellite (ETS) 7* will perform such a demonstration in 1998. There seems to be a very high interest in the Japanese communications' business in installing such systems. Still, it is debatable whether a commercial GSV could return its high initial investment.

3.2.2. Robotics for scientific satellites

Another potential application for space robotics is in the framework of certain very ambitious science missions which are currently under study by NASA and ESA. Solar observation missions, e.g., could involve huge (football field size) telescope antennas and mirrors in orbit around an equilibrium point between Earth and the Sun. Such large structures could not be launched as a whole but would rely on *in-orbit assembly and deployment* by robotic systems. This would also yield better mass efficiency, higher stiffness and accuracy, more structural options, and a higher reliability of deployment. Still, these developments are only in very early system study phases [8].

3.3. Applications in solar system exploration missions

An important class of space missions exploring our solar system involves to land spacecraft on planets and to perform in situ work on the surface. Nowadays, all such missions would have to be unmanned, at least in their first phases – an obvious challenge for robotic systems, especially of the mobile (rover) kind.

3.3.1. Robotics for Moon missions

After the success of the US *Apollo* program in the 1960s and early 1970s (and after the end of the space race which characterized that period of the Cold War), interest in the Moon waned. It is less well known that the Soviet Union, in 1970 and 1973, successfully landed and operated two huge unmanned rovers (*Lunokhod* 1 and 2) which were teleoperated from Earth over distances of more than 100 km.

Only recently, more than 25 years later, a worldwide renaissance of studies for Moon exploration missions occurred, driven by the high possible benefits for science (of, on, and from the Moon) and technology (as a stepping stone and testbed for more complex planetary exploration missions).

Paper [10] in this issue covers the roles which robotics can play in the proposed European Moon Program, more specifically in a possible first landing mission which was designed under the name *LEDA* (Lunar European Demonstration Approach). LEDA and another currently studied European mission, *EuroMoon* 2000™, would land close to the lunar South pole. This area has never been visited yet and is of extreme geological and strategic interest: the bottom of deep craters close to the pole are probably permanently shaded, making them the coldest spots in the solar system, and could contain ice which had been imported by impacting comets and permanently trapped. Not only would water on the Moon be a sensational discovery, it could constitute a valuable resource for human bases and to produce fuel for launches from the Moon.

Other currently studied science missions to the Moon which would critically depend on robotics are summarized in [8], e.g. requiring the precise deployment of 300 receiver elements in a spiral pattern over an area of 40 km diameter on the far side of the Moon (to create a very low frequency antenna shielded from the interferences emanating from the Earth), or the deployment of a kilometric baseline imaging interferometer.

Missions like LEDA would need *rovers* that can traverse some 100 km of poorly known and difficult terrain, and *robot arms* that can deploy scientific sensors, drill or dig or chip off soil samples and feed them to analysis instruments. Later, robots would have to construct lunar bases, assemble structures, deploy antennas and shelters, perform mining to gain mineral resources, automate processing facilities, and maintain the whole infrastructure. Ref. [1] in this issue summarizes rover technology development and ground demonstration work going on in France to prepare for such applications.

3.3.2. *Robotics for Mars missions*

Boosted by the recent speculations about fossil evidence of past life and the hugely popular Mars Pathfinder mission by NASA, tremendous momentum currently exists around the world for Mars exploration missions. Every two years, several missions will be launched, and *rovers* will be central elements for every surface exploration.

In the past, nobody collected more experience in Mars rover design than the Soviets. After the Lunokhod era, they had turned their attention to Mars exploration and tested an amazing panoply of locomotion chassis. One small system called *PROP-M* (a "skiing" rover) was launched to Mars, but the spacecraft was lost before the rover could prove itself. The culmination of the Russian developments is the so-called *Marsokhod* family, a class of very agile 6-wheeled rovers which are capable of a peristaltic "wheeled walking" mode to climb very steep and sandy slopes. These vehicles are big and heavy (in excess of 100 kg), however, and no mission carrying such big payloads has materialized in the Russian or international space programs yet. But Russia has become the world's supplier of rover chassis for ground demonstrations.

In the US, the NASA Jet Propulsion Laboratory has become the world leader in very small and lightweight rovers, the *Rocky* family based on a 6-wheel or 4-wheel rocker-bogie chassis. One such device called *Sojourner* was onboard the Mars Pathfinder mission which landed on Mars in July 1997 and captured worldwide attention by its traverse, images and geochemical analyses. JPL is continuing work on ever smaller rovers which should become passengers of every future Mars mission.

Besides the French work on *mini-rovers* (in particular vision-based navigation, see [1] in this issue), European efforts are also focussing on very small mobile robots (*micro-rovers* of a few kg mass) which shall deploy science instruments in the immediate vicinity of the landing site. This application stems from the frustration of the US Viking lander missions: the lander had a small robot arm, but its reach was just too short to analyze the rocks which were visible on the camera images. So close and yet so far ... [3] in this issue summarizes the scientific applications of so called *Instrument Deployment Devices (IDDs)*. ESA work in this area is building upon significant experience in Germany, where the Russian *Nanokhod* concept of a tumbling vehicle was developed to high maturity ([18] in this issue).

3.3.3. *Robotics for missions to comets and asteroids*

Comets are believed to hold the key to understanding the origin of our solar system. This is why missions like the ESA *Rosetta* project have been conceived, with the challenging objective of landing on a comet and analyzing its chemical composition. The original goal of even returning a sample had to be abandoned for cost reasons.

Paper [11] in this issue summarizes the role of robotics devices in such a cometary landing mission (*Rosetta Drill, Sample, and Distribution System*). Not only do the systems have to be extremely lightweight to make the very long trip, but also the mechanical properties of the surface to be drilled and sampled are only known in very wide ranges (from soft snow to hard ice).

Since the target comets are so small, they exhibit only very weak gravity (milli- to micro-g). This means that special anchoring devices have to be used to react the robot forces. In case *mobility* over the surface is required, conventional wheeled or walking locomotion will be very inefficient, and ballistic motion ("hopping") is being investigated ([17] in this issue).

A similar situation arises for missions to *asteroids*, as currently studied in Japan. With the asteroid of comparable size as the spacecraft, "landing" becomes more like berthing, and the robotics problem is close to the one in free flying servicers.

4. European technology programs in space robotics

4.1. The ESA technology R&D program

Within ESA's technology R&D program, space robotic activities are mainly funded from the mandatory *Technology Research Program* and from the optional *General Support Technology Program* [12]. The former concentrates on more fundamental or generic topics, while the latter aims at pre-developing and pre-qualifying components or building blocks to be subsequently used in space missions. This pre-qualification includes, as a very important element, in-orbit demonstrations, which are the most convincing maturity tests.

Table 5 (taken from [12]) lists some recent or current R&D activities, classified by technology area, and shows their main application domains (in the sense of Section 3). A few of the activities are described in more detail in separate papers of this Special Issue. Just the titles and the structure give an impression of the scope of this program. The funding level is approximately 5 million ECU per year, but the majority of this goes into the in-orbit demonstrations.

4.2. Some major national technology programs

This section outlines some of the major national European technology development programs for space robotics. It does not intend to be exhaustive, but covers essentially the programs presented at the ASTRA'96 Workshop [16].

4.2.1. France

While France has in the past strongly worked on internal LEO robotics (also building up their own testbed for Space Station facility automation) and external LEO robotics (having a strong role in the precursor work to ERA), the emphasis has lately shifted exclusively to *mobile robotics*. After significant systems work on large Mars rovers (Véhicule Autonome Planetaire, VAP), the current carrier project funded (and performed) by the French Space Agency CNES is IARES (Illustrateur Autonome de Robotique mobile pour l'Exploration Spatiale). Paper [1] describes the highlights of the work on a ground demonstrator of a mini-rover for lunar exploration. At their Toulouse site, CNES and several French research organizations have established the largest West European test site for mobile robots (GEROMS).

4.2.2. Germany

With the highly successful 1993 *ROTEX* (Robotic Technology Experiment) [6], Germany demonstrated a wide array of space robotics technologies in a Spacelab mission on the Shuttle.

The very impressive research and development work performed at the German Aerospace Laboratory *DLR* since then is summarized in [7]. The emphasis is on lightweight, intelligently sensorized robot arms and end effectors and on telerobotics control concepts employing the whole range of currently available robotics sensors and graphics-based user interfaces.

The major frame development funded by the German Space Agency DARA, the *ESS (Experimental Servicing Satellite)*, is targeting the servicing of uncooperative satellites (e.g. in GEO) using robots on free-flying platforms. Robotic technology is being developed in this context in the areas of vision- and proximity sensor-based capture, the dynamics of the chaser/robot/target compound, tooling, and control software architectures (MARCOS, Modular A&R COntrol System).

A major R&D activity funded jointly by Daimler Benz and DLR is the ASR (advanced servicing robot) project.

Table 5
Some ESA R&D activities in space robotics with possible application areas

Technology area	R&D activity	Int. LEO	Ext. LEO	GEO	Other orb.	Plan. expl.
A&R Systems	External service manipulator system (technol. preparation for ERA)		x			
	Bi-arm servicer systems		x			
	Internal equipmt. Manipul. and transportation system [13]	x				
	System and control development methodology [14]	x	x	x	x	x
	Integrated payload automation	x				
	In-orbit robot calibration techniques	x	x	x	x	x
	Robotics for lunar exploration					x
	Bioscreening with robotics	x				
	Robotic assembly of large space structures				x	
	Micro robots: Components and control	?				?
Support equipment	Space station Columbus automation & robotics testbed	x				
	A&R testbed for external servicing		x			
	Planetary surface operations testbed					x
Ground segment	Ground operator station for interactive autonomy	x	x	x	x	x
	virtual reality-based ground operator I/F	x	x	x	x	x
Mobility	EMATS gantry sub-system [13]	x				
	Micro-robots for scientific applications [18]					x
Manipulation	External service manipulator system (ERA preparation)		x			
	EMATS arm sub-system [13]	x				
	Micro-gravity compatible drives	x	x			
	Compact direct-drive joint actuators based on magnetic gearing	x	x	x	x	x
	Small and lightweight robot arms for planetary exploration					x
	Intelligent Robot Axis	x	x	x	x	x
End effectors, payload I/F	Gripper for external servicing		x	x	x	x
	Instrumented modular end-effectors	x	x	x	x	x
	Payload interfaces for external robotic servicing		x	x	x	x
	Tools for lunar exploration					x
Sensors	Micro sensor technology for space A&R	x	x	x	x	x
	Sensors for automatic robot calibration	x	x	x	x	x
	Stereo vision for space robot applications		x	x	x	x
	Guidance and into the ground exploration radar					x
Control	Control development methodology [14]	x	x	x	x	x
	Exterocoeptive sensor based robot control	x	x	x	x	x
	Common controller for European space A&R	x	x	x	x	x
	Servo and power electronics for space A&R	x	x	x	x	x
	Intelligent robot axis with decentralized joint control	x	x	x	x	x
	Micro-robots: Components and Control	?				?
In-orbit demos	JERICO [4]		x			
	Vision and interactive autonomy experiment on Japanese ETS-7			x		
	Experimental GEO inspecting vehicle			x		
	Bioscreening with robotics on Mir	x				
	LEDA [10]					x

Research laboratories from DLR and the Max Planck Institute have gained extensive experience in the development and testing of *micro-robots for scientific instrument deployment* in Mars or Moon missions, this was precursor work to [18].

Finally, German scientists are among the main investigators of cometary landing missions, and also engineering work has been done in studying possible *mobility concepts in milli-gravity environments* [17].

4.2.3. *Italy*

Italy is clearly one of the most active supporters of space robotics work in Europe. One major national development program is the *SPIDER* project, which is aiming at free-flying robotic vehicle systems and among others has produced a robot arm fully qualified for use in external space environment [9]. This arm will be one of the major Italian contributions to the JERICO system for Mir [4]. A controlled joint subsystem has been successfully tested and evaluated in the EUROMIR 95 mission.

Italy shall also be responsible for the robotics subsystem of the *Rosetta* cometary landing mission. Paper [11] summarizes this work to produce the Drill, Sample, and Distribution System.

5. Conclusions and outlook

This survey paper has summarized the different application scenarios which Europe currently sees for space robotics, and given a brief overview of the most notable R&D activities in this area. Hopefully it could give a flavor of the fascination which is inherent in this field, the main driving force which helps us overcome even difficult programmatic and economic periods.

The conclusions and outlook should be optimistic. There is huge potential in space robotics, and it is being more and more acknowledged. With the beginning of the Space Station era before the year 2000, five different (external) space robot systems should go into productive operation, in a truly international cooperation and utilization. This should stimulate the use of robots in similar applications, such as for laboratory internal automation or for free-flying maintenance. Commercial interests could call for robots policing and repairing geostationary satellites, and scientific exploration of the solar system will employ (mobile) robots on Mars, the Moon, and possibly comets.

Even though by far not as much funding has been invested as in the US, Canada, Russia, or Japan, Europe is believed to have a fairly strong technological position. This is very much supported by the excellent academic and industrial base in terrestrial robotics. In that sense, the technology transfer clearly works both ways: space robotics has to build on elements researched and pre-developed with the much larger budgets of terrestrial automation, but it can also return commercializable results to the non-space market, as some very impressive results have already proved.

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References

[1] L. Boissier, IARES-L: A ground demonstrator of planetary rover technologies, Journal of Robotics and Autonomous Systems (1998) 89–97.

[2] R. Boumans, C. Heemskerk, The European Robot Arm for the International Space Station, Journal of Robotics and Autonomous Systems (1998), this issue.

[3] A. Chicarro, G. Scoon, P. Putz, Scientific applications of robotic systems on planetary missions, Journal of Robotics and Autonomous Systems (1998) 65–72.

[4] F. Didot, J. Dettmann, S. Losito, D. Torfs, G. Colombina, JERICO: A demonstration of autonomous robotic servicing on the Mir Space Station, Journal of Robotics and Autonomous Systems (1998) 29–36.

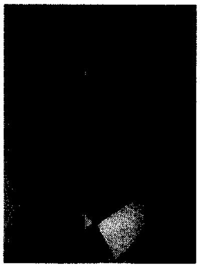
[5] S. Di Pippo, G. Colombina, R. Boumans, P. Putz, Future potential applications of robotics for the International Space Station, Journal of Robotics and Autonomous Systems (1998) 37–43.

[6] G. Hirzinger, B. Brunner, J. Dietrich, J. Heindl, Sensor-based space robotics – ROTEX and its telerobotic features, IEEE Transactions on Robotics and Automation 9 (5) (1993) 649–663.

[7] G. Hirzinger, B. Brunner, K. Landzettel, J. Schott, Preparing a new generation of space robots – A survey of research at DLR, Journal of Robotics and Autonomous Systems (1998) 99–106.

[8] R.J. Laurance, Future science missions and robotics, Proceedings of the 4th ESA Workshop on Advanced Space Technologies for Robot Applications (ASTRA '96), ESA Doc. Ref. WPP-122, 1996.

[9] R. Mugnuolo, S. Di Pippo, P.G. Magnani, E. Re, The SPIDER manipulation system: The Italian approach to space automation, Journal of Robotics and Autonomous Systems (1998) 79–88.
[10] M. Novara, P. Putz, L. Maréchal, S. Losito, Robotics for lunar surface exploration, Journal of Robotics and Autonomous Systems (1998) 53–63.
[11] E. Pozzi, R. Mugnuolo, Robotics for the ROSETTA cometary landing mission, Journal of Robotics and Autonomous Systems (1998) 73–77.
[12] P. Putz, The ESA R&D Programme for Space A&R, Proceedings of the 4th ESA Workshop on Advanced Space Technologies for Robot Applications (ASTRA '96), ESA Doc. Ref. WPP-122, 1996.
[13] P. Putz, G. Colombina, W. De Peuter, EMATS, A robot-based equipment manipulation and transportation system for the Columbus Free Flying Laboratory, Acta Astronautica 29 (3) (1993) 205–211.
[14] P. Putz, A. Elfving, ESA's control development methodology for space A&R systems, in: M. Jamshidi et al. (Eds.), Robotics and Manufacturing: Recent Trends in Research, Education, and Applications, vol. 4, ASME Press, New York, 1992, pp. 487–492.
[15] P. Putz, W. Lork, H. Siemann, Internal automation and robotics concepts and developments for the European Space Station Laboratories, Proceedings of the 1992 IEEE International Conference on Robotics and Automation (Workshop on Robotics for Orbital Applications), 1992.
[16] P. Putz, M. Van Winnendael (Eds.), Proceedings of the 4th ESA Workshop on Advanced Space Technologies for Robot Applications (ASTRA '96), ESA Doc. Ref. WPP-122, 1996.
[17] L. Richter, Principles for robotic mobility on minor solar system bodies, Journal of Robotics and Autonomous Systems (1998) 117–124.
[18] L. Richter, K. Schilling, M.C. Bernasconi, R. Rieder, C. Garcia-Marirrodriga, Mobile micro-robots for scientific instrument deployment on planets, Journal of Robotics and Autonomous Systems (1998) 107–115.
[19] G. Visentin, D.L. Brown, robotics for geostationary satellite servicing, Journal of Robotics and Autonomous Systems (1998) 45–51.



Peter Putz received a diploma in Electrical Engineering from the Technical University in Vienna, Austria, in 1981, and a Ph.D. in Computer and Systems Engineering from the Rensselaer Polytechnic Institute (RPI) in the USA in 1985. From 1985 to 1993, he worked at DASA/Dornier in Germany as a project manager and head of a group responsible for space robot system analysis and simulation. During this period, he was also part of the team developing the first European space robot technology demonstration experiment, ROTEX. Since 1993, he has been with the European Space Research and Technology Center (ESTEC) of the European Space Agency (ESA) in Noordwijk, Netherlands, currently as the Head of the Automation and Robotics Section. His responsibilities include technology R&D in all areas of space automation and robotics as applied to the European space programs. He is also a lecturer on space automation and robotics at the International Space University in Strasbourg, France. He has published some 70 technical articles in the fields of computer-aided control system design, CAE tools for robot system development, robot control, and space robot systems. Dr. Putz is a member of the IEEE and the German VDI.