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Space robotics

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Abstract

This paper reviews the topic of space robotics. As an introduction, some definitions and the rationale for space robotics are given. The main differences between space and terrestrial robots are highlighted, and it is shown that they are driven by the peculiar environmental, system, and programmatic constraints of space missions. Some common objections against the use of space robotics are mentioned and rebutted.

A major part describes the typical architecture, sub-systems, and some key technologies of space robot systems. This distinguishes between 'manipulator arm' and 'rover' type robots. The interdisciplinary system character of space robotics is emphasized.

The currently perceived application scenarios for space robotics are introduced next: low-Earth-orbit applications for system servicing and payload tending, satellite servicing in geostationary Earth orbit, the assembly of large orbiting structures, and applications in exploration missions to the Moon, Mars, Mercury, comets, asteroids, and other celestial bodies. Throughout, the main robotic functions are presented and the most eminent robotic systems are described which have been operated or are under development.

The practical usage of space robots is illustrated in a final section. The concept of the robot as a transparent tool for the ground user is stressed, and a systematic methodology for developing investigations involving space robots is proposed. The paper closes with some suggestions for more 'non-conventional' scientific uses of space robots and general conclusions. High-level literature is indicated to deepen the appreciation and understanding of the technology and its applications.

(Some figures in this article are in colour only in the electronic version)

Contents

1. Introduction

1.1. Objectives

This paper aims to review the field of space robotics for the benefit of non-experts. It wants to provide an appreciation of the multiple constraints and technological disciplines which are involved in this fascinating field. To potential scientific users, the review shall demonstrate that robotic tools can provide powerful and versatile support to many different space applications.

For this purpose, the objectives of the paper are to

- motivate and define space robotics
- outline the typical 'anatomy', architecture, sub-systems and technologies for space robotic systems
- provide an overview of the main application scenarios and actual systems under development
- illustrate the practical use of space robotic systems.

Since the review does not address developers of space robotics, underlying theory and 'insider' jargon are avoided as much as possible. Technological challenges and solutions are covered to the extent of conveying a valuation of the complexity and technical maturity of the field. But primarily, the emphasis is on space robotics practice and applications.

1.2. Outline

After the introduction, section 2 gives a few fundamental definitions and lists the main reasons why space robotics can strongly enhance or even enable certain space missions. It also highlights the main differences between robotics in space and terrestrial applications.

Section 3 probes deeper 'inside' space robotics: for both robot arm systems and mobile robots (rovers), typical architectures and system breakdowns are given and the key sub-systems are introduced. The main message from this section is that robots are interdisciplinary systems integrating the expertise from quite different engineering domains. This is what makes it so fascinating for its developers, but also why they are often underestimated in mission and spacecraft system design.

Section 4 addresses the uses of space robotics, providing an overview of the main application scenarios. This is structured according to the destination of the space mission, such as low Earth orbit (LEO), geostationary Earth orbit (GEO), Moon, Mars, comets, etc. For each class, the major robotic tasks and constraints are highlighted and the most eminent robotic systems are mentioned which exist or are under development. More detail on applications and (European) systems is contained in the survey paper Putz (1998) and the other papers of that special journal issue.

Section 5 gives a better feeling on the practical usage of space robotic systems. It introduces the most important modes of operation, emphasizing the concept of 'interactive autonomy' which makes the robot a transparent and reliable tool for the user. For developing investigations involving space robots, it proposes a systematic methodology and modular multi-user facilities which reduce the development effort of the investigator. It ends with ideas of novel ways in which space robotics could be even more useful for scientific investigation in space.

The paper closes with conclusions and a few selected references (mainly survey papers or tutorials themselves).

1.3. Scope

Clearly, this review cannot be an exhaustive encyclopaedia of space robotics. In a concise yet systematic fashion, it tries to present the most important elements in order to give an overall appreciation of the potential and limitations of the field.

Regarding the scope of the applications, the review is written from a European perspective. The author is most familiar with Western European activities, but the application scenarios for space robotics are essentially shared by the main space powers, and the major contributions from the USA, Canada, Russia and Japan are duly covered. A good description of applications of arm-type robot systems from a more US-/Canadian viewpoint is contained in Skaar and Ruoff (1994).

It goes without saying that omissions in this review do not imply disrespect for the work in question, but are more likely due to the inherent space constraint which necessitates a subjective selection.

2. What is space robotics?

2.1. Terminology

Sometimes, any unmanned space probe is called a robotic spacecraft. This acknowledges the challenges of largely autonomous operation in a complex mission.

This review, however, focuses on *space robotics* 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.

See section 7.2 for some general sources of terminology and standards, tutorials and ‘encyclopaedias’.

2.2. The rationale for using robots in space

Simply spoken, the following useful *tasks* can be performed by robots in a space mission:

- transport, load and unload ‘payloads’
- position and orient ‘payloads’
- exert forces on the environment
- sense the environment
- move around on celestial bodies (on, under, or above the surface).

Here, the ‘payload’ is the object handled by the robot and should not be confused with the common aerospace term (‘payload’ versus ‘system’ or ‘platform’). A space robot payload can be a spacecraft payload element, but also a part of the spacecraft itself or even an astronaut.

The potential benefits are that space robots can

- support or replace humans in space for tasks which are
  - ∗ sufficiently predictable, but
  - ∗ too dangerous (e.g. because of the hostile environment),
  - ∗ too difficult (e.g. because of large masses involved, high precision and repeatability required, long duration), or
  - ∗ too boring/time consuming/expensive (e.g. routine handling of experiment logistics)
- enable tasks that would not be attempted by humans (in GEO, in pioneering missions to planets, comets etc).

Table 1. Environmental constraints and resulting design impacts.

Constraint	Typical design impact
Survive launch and landing loads (planetary landing!)	Support structures, holddown/release mechanisms, specially mounted electronic components, expensive test facilities
Function in vacuum	Careful materials selection, special lubrication, brushless motors preferred, certain sensing principles not applicable (e.g. ultrasonic), clean room integration and testing
Function under 'weightlessness' (orbital applications)	Everything has to be fastened, altered dynamic effects (highly nonlinear), very low backlash gearing
Function under extreme radiation exposure	Limited materials lifetime, shielded and hardened electronics, outdated computer performance (state-of-the-art computers not space compatible)
Function under extreme temp. and temp. variations, possibly in vacuum	Multi-layer insulation, radiators with heat pipes, distributed electric heaters, radioisotope heating units (RHUs) (planetary applications)
Function under extreme lighting and contrast conditions	Difficulty for vision and image processing
Function in extremely remote environment	Comprehensive testing before launch, essentially maintenance-free systems, adequate level of autonomy, in-orbit calibration and sensor-based control, effective ground operator interfaces

2.3. Main differences between space and terrestrial robots

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' or 'field robots'.

The particular requirements and constraints that drive the designs of space robots in a special direction can be classified 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 typical design impacts. A more detailed and quantified discussion is given in Putz (1998).

These constraints and some of the design impacts are of course typical for all space systems. Combined with a completely missing 'economy of scale', they give rise to the high development and manufacturing costs of space robotic systems. Another aspect is the distinct project nature of space robotics developments, which tends to lead to dedicated solutions and too little re-use. Attempts to lower development cost by using 'off-the-shelf' building blocks are being taken, but it has to be clear that the downside is increased risk and sometimes higher qualification and testing effort.

2.4. Some common objections against space robotics

A survey of space robotics should also mention some of the most prevalent objections which are sometimes raised against this relatively exotic and new field.

In the opinion of the author, objections can be traced to the following basic problems:

- Robotics is not one of the 'classical' space sub-systems and therefore not taught to aerospace engineers (lack of education).
- Too few successful applications of space robotics have been demonstrated (lack of practice).
- The previous two facts combine to create a general lack of awareness of the capabilities and limitations of space robotics. One frequently encounters gross extremes, either completely underestimating or completely overestimating robotics.

Table 2. System or programmatic constraints and resulting design impacts.

Constraint	Typical design impact
High system complexity	Professional system engineering and project management needed
Long lifetime	Maintenance-free design desired, built-in growth potential and upgradeability (e.g. re-programmability), 'orbital replaceable units' for maintenance
High reliability and safety	Product assurance measures, space system engineering standards, high documentation effort, 'inherently safe' design preferred, built-in failure tolerance (redundancy) and diagnostics, problems with 'non-deterministic' approaches (e.g. artificial intelligence)
On-board mass very limited and expensive (esp. planetary!)	Extremely lightweight designs, arms with noticeable elastic effects (control problem), high payload mass fraction needed, slow motions
On-board power/energy very limited and expensive	Low-power electronics, very high efficiency, limited computing resources, batteries always critical for rovers, slow motions
Communications with Earth very limited and expensive	Adequate degree of autonomy, built-in checking, sophisticated ground operator interfaces to cope with signal transmission delays
Preserve micro-gravity conditions	Smooth acceleration and low speeds, high actuator motion smoothness, high gear ratios, weak joints
Limited testability on Earth	High effort for thermal vacuum and launch loads testing, approximations for 0 g motion, sophisticated simulations to verify system behaviour in 0 g
Long planning and development	Problems of staff continuity and morale, technology in space often obsolete
Development in international co-operation	Often sub-optimal project efficiency from artificial work distribution, communications and logistics problems

- The inherent configuration changes due to robot motion and the actuation capacity may give rise to special risks. Very often, however, potential hazards from robotics are exaggerated and safety arguments are used as a pretext in order to avoid robotic solutions.
- Robotics has an image of being extremely complex (multi-disciplinary, with interfaces to many other sub-systems) and expensive. The operational benefits (especially the flexibility to react to unforeseen circumstances) are often hard to quantify in a cost trade-off. Ironically, once a robotic development is started, its cost is often underestimated.
- In the very conservative world of space engineering, where every mechanism and every piece of embedded software are considered potential failure sources, robot systems are seen as nightmares in terms of reliability. For mission-critical systems, this typically has to be resolved by extensively redundant implementations, which further increases the complexity of the systems.
- Like in the industrial world, there is existential fear of robotics even in the highly sophisticated world of space flight. Certain parties (which may be very powerful) believe they will lose if robotics solutions are introduced into a system: astronauts in crewed missions, developers of dedicated payload automation systems, etc. Internal payload tending robots, for instance, have been rejected so far mainly because of such insurmountable opposition.
- In terms of funding and management, space robotics suffers from being at the border of the 'system' and the 'payload'. Consider a robotic system that serves several payloads (e.g. a centralized payload-tending robot, or a planetary rover for instrument deployment): space systems people tend to shift responsibility for it to the payload, individual payload developers to the system. Unfortunately, the (politically motivated) high-level allocation of responsibilities of large space systems (such as the International Space Station (ISS)) often runs counter to system level efficiency.

- Politically, space flight is often justified as a ‘human adventure’. Robots, which often could do the same task at much lower cost, just do not offer the same degree of prestige or public appeal. An exception could be rovers with enough ‘personality’ to intrigue the general public, as was the case with the hugely popular Sojourner rover on the Mars Pathfinder mission in 1997.
- Economically, the cost efficiency and ‘return on investment’ of novel commercial robotic applications (such as satellite or space station servicing) are very hard to prove because dependable data on operations cost in alternative scenarios is often missing.

As a consequence, there is often widespread scepticism among space programme managers against the use of robotic solutions. Ironically, this antagonism is strongest where the technical challenges for robots are the least and where the lay person would see an obvious robot application (Space Station internal payload tending). The more difficult the scenario is, the more likely people are to embrace robotics—for lack of alternatives (e.g. planetary missions).

The remainder of this review will try to demonstrate that there is unique potential in space robotics, and that a quite mature technology foundation is available.

3. Some key space robotics sub-systems and technologies

This section shall give a first appreciation of the anatomy of space robot systems and some of the most important technological issues. Above all, it should show that space robots have to be considered as complete *systems*, involving a number of highly interacting and quite complex sub-systems from different disciplines. This makes them so challenging and fascinating for their community.

The basic structure employed here is to differentiate between robot arm systems and ‘mobile robots’ or rovers. Of course the two may occur together, such as when a rover carries a robot arm.

3.1. Manipulator arm-type robot systems

3.1.1. Typical architecture. A general breakdown of a typical robot arm system is illustrated in figure 1.

This architecture introduces the following sub-systems (s/s):

- The arm s/s which enables the fine manipulation (could consist of several co-operating arms).
- An optional relocation s/s to extend the motion range of the arm by moving its base around.
- The payload interface s/s which provides the crucial contact between robot and payload or environment (end effectors, tools), but also includes provisions for robot compatible payload/environment interfacing.
- The exteroceptive sensing s/s, which lets the robot sense its state w.r.t. the environment.
- The on-board control s/s (which may include analogue and digital hardware, software, but also crew operators).
- The ground control s/s which also typically involves hardware, software, and human operators (often distributed over several ground centres) to prepare, command and monitor the robot and payload operations.
- The ground support equipment for robot system testing, operations planning, operator training, troubleshooting during the mission.

Even though the robot is treated as a system of its own, it is considered embedded into a larger spacecraft system to which it interfaces in the space and ground segment.

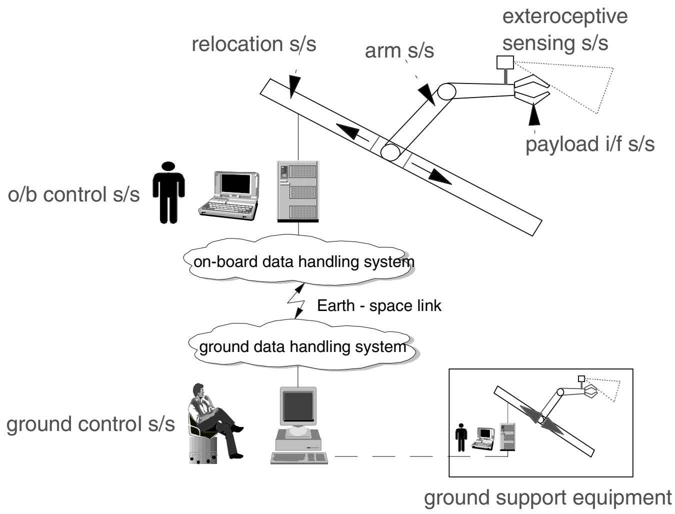

Figure 1. Architecture of a robot arm system.

Some key functions will be provided by the spacecraft system, such as the on-board and ground data handling and the Earth–space link.

3.1.2. System level issues. Here, two important decisions shall be discussed which affect the designs of all sub-systems: the choice of the automation concept and of the degree of autonomy.

The 'automation concept' denotes the system level approach towards automating the process at hand. Typically, the 'process' (e.g. a complex life science experiment, assembling a space station, repairing a failed satellite, collecting mineral samples on Mars) will not be completely automated by a single robot. The automation concept may consist of one or several robots co-operating with humans and dedicated automation systems (e.g. mechanisms). The task sharing will be based on the driving performance requirements and constraints, a judicious analysis of the different elements' strengths and weaknesses, the complexity of the resulting interfaces, the total system cost, but also equipment heritage and experience—see for example chapter 2 of Skaar and Ruoff (1994). No serious space robotic professional would promote robotic solutions unless they can be shown to be superior to alternative automation concepts.

Note, incidentally, that the distinction between a 'robot' and a 'mechanism' can be quite arbitrary. Traditionally, a 'robot' implies a certain 'intelligence' in the sense of programmability and flexible 'autonomous' reaction to changed circumstances. On the other hand, space robots can be quite simple (simplicity is always an asset, especially in space), and mechanisms in the age of mechatronics are also not dumb linkages any more. A debate on such terminology is always futile; clarity should come from a careful description of the system's design and operation.

A similarly misleading and often abused term is 'autonomy'. It does not make sense to talk of an 'autonomous system' as such; there is an infinite spectrum of degrees of autonomy. For example, a scale of 10 increasing degrees of automation is shown in Skaar and Ruoff (1994, p 45). Considering control autonomy (there is also power autonomy, thermal control autonomy etc), a clear picture can be obtained by using a functional reference model (FRM) for robot control, such as developed in Albus (1991) or Putz and Elfving (1992). Such an FRM breaks the overall functionality of controlling the robot (to automate a process) down into small, well understood single functions (such as trajectory planning, obstacle avoidance, joint position control). Traditionally, this will follow some sort of hierarchical architecture, identifying control layers. If such an FRM is used, one can easily define the degree of autonomy by stating how each individual function is implemented:

- in hardware, software or 'brainware' (human operation)
- on-board or on ground
- to be executed *a priori* (in a preparation phase) or *ad hoc* (during the utilization itself).

The lowest-level control loops (e.g. joint motor current control), requiring the fastest reactions, will always run in on-board software (or even hardware) during utilization. A robot would be considered highly 'autonomous' or 'intelligent' if even complex, high-level control functions (such as task planning or recovery from non-nominal events) are implemented in on-board software and run without preparation/pre-programming.

Some typical degrees of robot autonomy (but by no means the only realistic ones!) are

- 'teleoperation' or low-level telemanipulation by a crew operator (a 'low autonomy' mode where joint or tip velocities are commanded by a human who has to perform all the higher level planning)
- task level commanding from ground (tasks are motion sequences which have been pre-programmed and can be executed automatically), a 'medium autonomy' mode.

It is not at all trivial to select the appropriate degree of autonomy for the operation of a space robot. Important criteria are the general task predictability, the available on-board computing power and sensors, the communication time delays and bandwidth limitations. One can easily see the possible dilemmas, for example for planetary missions where remoteness requires higher autonomy, but neither task predictability nor on-board resources facilitate this.

3.1.3. The arm sub-system. A robot arm is a mechanical linkage of limbs connected by joints. Each joint or axis provides one rotatory or translatory *degree of freedom*. Several axes can be concentrated in a single point (e.g. cardanic or spherical joint). The number, type, and arrangement of the joints (the so-called kinematic structure of the arm) determine its dexterity. Full dexterity needs at least six joints in appropriate arrangement, then every point in the work volume can be reached with any desired orientation of the tool coordinate frame. Advanced arms have seven axes or more. The redundant degrees of freedom allow circumvention of problem zones (obstacles or kinematic 'singularities', where even minimal motions require high joint speeds), but also make the control problem more difficult (see section 3.1.7).

Most space robots use only rotatory joints: translatory joints create problems with power and data transmission and lubrication; robots with translatory joints often cannot be stowed compactly. A typical kinematic structure involves a two- or three-axis 'shoulder', a one-axis 'elbow', and a three-axis 'wrist'. Very simply speaking, shoulder and elbow provide the position of the tip, the wrist provides its orientation (e.g. expressed in pitch/roll/yaw).

A robot joint essentially contains actuators and sensors. The actuation chain includes a motor (always electrical for space applications, typically of brushless dc type), a gearbox with very high ratio (to allow high output torques with small motors) and the motor drive power and signals electronics. The joint sensors are also called 'proprioceptive' sensors: they measure important robot internal states (e.g. motor current and temperature, joint speed and position) for control and monitoring purposes.

Limbs are lightweight structures (typically from aluminium or carbon fibre composite materials) which have to provide high stiffness at low mass. Typically they house parts of the joint drive system (motors, gearboxes, electronics) and the harness. The harness is the bundle of all electric wires leading to the controller and to the power supply. With all the sensors in the joints, a typical harness can have much more than 100 wires. Since it should be routed inside the arm as much as possible, this can create significant difficulties for robot designers.

Advanced robot systems may have more than one arm: it is well known that more complex tasks benefit from bi-arm operation, and a shorter and stiffer arm (or 'leg') may be used to stabilize the multi-arm system w.r.t. its target during operation.

3.1.4. The relocation sub-system. If a 'large' work area has to be covered by a 'short' arm, the arm can be made relocatable by putting its base (shoulder) on a relocation s/s. This may be more appropriate than a larger arm, which typically would be less accurate and less dextrous. Moreover, the relocation s/s can be tailored to the desired shape of the work volume.

Some typical relocation concepts:

- The base may sit on a trolley that moves on a rail (one translatory degree of freedom for relocation, example: Mobile Servicing System (MSS) moving along the main truss of the ISS).
- In an obvious extension of the trolley principle, the arm may be mounted on a Cartesian two- or three-axis gantry system and translated throughout a prismatic work volume (example: the AMTS concept for COF internal payload tending—see section 4.1.3).
- The arm may self-relocate by stepping (doing 'flips'). This typically requires that the arm is completely symmetric. Then the wrist can attach to a new base point and become the new shoulder, upon which the shoulder releases and becomes the new wrist. The relocation s/s then essentially consists of the network of base points. An example is the European Robot Arm (ERA) on the ISS with seven joints in a 3–1–3 arrangement.
- The 'Charlotte' robot demonstrated once in the Space Shuttle pressurized laboratory was a box with end effector which moved in a 'spider web' (suspended by strings hooked into corners of the lab, moved around by pulling/releasing string in a coordinated way).
- Finally, 'free-flying' robots are small satellites with one or several arms. The satellites are moved around by their own attitude and orbit control sub-system (thrusters, momentum wheels). This offers maximum independence, but also implies the biggest safety risk for the environment.

3.1.5. The payload interface sub-system. Basically, two essential interfaces have to be covered here:

- The interface between the arm (wrist) and its payload (or directly with the environment).
- The interfaces between payloads that need to be handled by the robot and their attachment bases.

The first interface is typically provided by the so-called robot 'end effectors'. An end effector can be

- *Dedicated* to specific standardized grapple fixtures: in this case, all payloads to be handled by the robot have to be equipped with this standard grapple fixture (typically a small, passive, cube-like structure with geometric features that facilitate self-alignment and form closure during grasping) and possibly with standardized markers for visual alignment during grappling. The advantage is that the design (of the end effector, but also the control concept) can have maximum simplicity and the strength of the attachment can be maximized, but there is also little flexibility to go beyond the predicted operations.

- *General purpose* for free-form objects within a certain size limit: here, the most common end effector is a two-finger gripper (e.g. with parallel jaws), but more advanced multi-finger hands have also been prototyped. These end effectors and their control can be much more complex (possibly requiring computer vision to determine grasping strategies) and their reliability is much more difficult to achieve, but of course they offer maximum flexibility in unstructured environments (e.g. planetary applications).

More and more, robot end effectors are highly complex mechatronic systems incorporating many exteroceptive sensors (for distance, contact force/torque, touch/slippage, computer vision, etc) which can provide a high level of 'intelligence' to the robot operations. The most sophisticated end effector that has flown in space so far was the two-finger gripper of the ROTEX (Robotic Technology Experiment), built at the Institute of Robotics of the German Space Research Establishment (DLR) and described in Hirzinger *et al* (1993) see figure 2. It includes some 2000 mechatronic components in a very compact design and with a very simple serial bus interface. All the control processing and electronics of gripping, six-axis force/torque sensing, one forward-looking medium range distance sensor, eight forward- and inward-looking short-range distance sensors, two tactile sensor arrays, and a stereo camera pair are integrated into the hand.

Sometimes, the robot needs to use several specialized tools in sequence. This can be implemented via an automated tool exchange device (complicated), or by permanently carrying all tools (e.g. on some sort of carousel-type end effector).

The most critical function of any end effector is robust grasping. Robust latching/unlatching is also the core objective of the other important interface, between payloads and their supports. Note that, unlike in terrestrial environments, there is no gravity in orbital applications which will keep payloads in place, and safety regulations dictate that all payload items have to be positively contained (mechanically fixed) at all times.

The end effector has to be able to actuate payload latching/unlatching in a simple yet reliable way. Often, the same mechanical interface also has to provide structural attachment of the payloads during the heavy launch/landing loads. It is by no means trivial to design simple mechanisms which have this strength, but can easily be opened by end effectors with their very limited actuation force. Moreover, it has to be avoided by all means (ideally by mechanical design of mutual locking mechanisms) that, due to erroneous operations, objects become free in space and threaten the environment as projectiles.

Frequently, end effectors have to provide more than just mechanical attachment to the payloads: they may need to supply electrical power and data (via appropriate connectors) or mechanical actuation throughput (e.g. a 'screwdriver' interface) to more complex, 'active' payloads.

3.1.6. The exteroceptive sensing sub-system. For more advanced control strategies, the robot has to measure its state relative to its environment. This is called 'exteroceptive' sensing, as opposed to the 'proprioceptive' sensing which measures the robot's internal state (e.g. in the arm joints).

The most important exteroceptive sensors have already been mentioned in the context of end effectors. Indeed, they are often physically accommodated on the end effector.

- *Force/torque sensors* measure the six-dimensional generalized force exerted by the robot, e.g. at its tip. A drum-shaped force/torque sensor is typically mounted between the wrist and the end effector. The measurement principle is most commonly based on bridges of stain gauges. Calibration and measurement stability are the most critical problems.

- Distance or *proximity sensors* measure the distance of the robot to its target, or to obstacles. They may be mounted in the fingers of the end effector, looking forward or inward. Some are based on time-of-flight measurement of laser pulses.
- *Tactile sensors* measure the existence of contact (on/off) or the amount of pressure. Arrays of tactile sensors at the inside of gripper fingers can help to detect proper grasping or slippage.
- Robot *vision* is a huge topic by itself. Basically, camera images (e.g. from hand or overview cameras) are transmitted to the human operator or evaluated by image processing systems. Uses are for calibration, to recognize objects, determine grasp poses, detect non-nominal situations, build up computer models of poorly known environments, etc.

3.1.7. The on-board control sub-system. The control of the robotic operation is one of the most challenging functions of the robot system. Robot control is immensely popular in academic research, yet the gap between robot control theory and what is actually implemented could hardly be bigger (even in the 'sophisticated' space robots).

The 'control architecture' summarizes the distribution of the various control functions among several on-board control computers, ground control computers, and human operators on ground and possibly also on board. As mentioned already in section 3.1.2, the 'functional' or 'logical' architecture is often hierarchical (see for instance the FRM concept described in Albus (1991) and Putz and Elfving (1992)). The 'physical' or 'hardware' architecture can be 'centralized' (essentially one on-board controller from which all the wires to the individual joints go out) or 'decentralized' (e.g. distributed in several 'joint controllers' along the arm).

In a very simplified presentation, the *main on-board control functions* are:

- To interpret a motion program.
- To read measurements from sensors, and to transform them to appropriate coordinates.
- To determine the next target point and desired path shape (linear, circular, . . .).
- To interpolate between successive points of the desired path/trajectory.
- To transform from desired intermediate tip position/orientation to the necessary joint angles ('inverse kinematic transformation').
- To perform servo control of positions and speeds of each joint.
- To perform collision detection and safing.

The mathematical theory of robot control is quite complex, due to the high nonlinearity introduced by the many sines and cosines in the transformations. Here, we just want to introduce some of the most important concepts:

- Robot 'kinematics' refers to the (static) geometric relation between robot link positions and joint angles. Both directions of this relation need to be determined periodically in the algorithms for digital robot control:
  - ∗ The *forward kinematic transformation* computes the resulting tip position/orientation for given joint values. It can always be calculated from a fairly straightforward algorithm and necessarily yields one unique result.
  - ∗ The *inverse kinematic transformation* problem is to determine the necessary joint values to achieve a desired tip position/orientation. This is much more difficult and amounts to solving a set of nonlinear algebraic equations. Depending on the kinematic structure of the arm and the desired tip pose, the problem may have no solution (the desired point is not reachable), one unique solution, or multiple solutions. The latter is typically the case for a 'kinematically redundant' arm having more than six axes (such as the human arm): there are infinitely many possible 'poses' to reach any given point

and orientation. The popularity of six-axis arms stems from the fact that, for judicious choices of axes configuration, the inverse kinematic problem has a few (typically two or four) explicit algebraic solutions, which makes the control algorithms run much faster. So far, this has been the only feasible way to achieve the required high update rates for digital control. With kinematic redundancy, one normally uses iterative numerical approximations to solve the inverse kinematic problem. This amounts to a nonlinear optimization problem, and one can impose criteria (cost functions) to find the 'best' solution (such as minimizing the motion energy, or maximizing the distance from obstacles or kinematic singularities).

* *Kinematic singularities* occur when the inverse kinematic problem degenerates (the Jacobian of the transformation becomes singular), resulting in a local loss of degrees of motion freedom. One example is when an elbow joint is precisely stretched out, even when the joint can continue to move to the other side (unlike the human arm): momentarily, no 'outwards' movement is possible. Since it is very delicate to move though kinematic singularities in a controlled way, path planning always tries to avoid them.

- Robot 'dynamics' describes the relation of link velocities/forces to joint velocities/torques. Again, there is the forward and the inverse dynamic transformation problem. In kinematic singularities, the dynamic transformation also degenerates and a finite tip velocity necessitates an infinitely high joint speed (practically, at least one joint would exceed its allowed maximum speed and thereby raise a contingency).

Rather than dwelling further on control theory, I give some comments on robot telemanipulation by a crew operator ('on-board teleoperation'). As outlined in section 3.1.2, an astronaut may command the robot at many possible levels of the control hierarchy:

- In low-level telemanipulation, the operator commands the robot tip position. The human has to perform all path planning, interpolation, and collision avoidance, but can react quickly to unforeseen events. This is the standard control mode used in the US/Canadian space robots such as the venerable Shuttle RMS.
- In task-level commanding, the operator selects and parametrizes pre-programmed tasks (e.g. UNLOCK a unit, OPEN a door, INSTALL a sample) whose details are predictable (but may be very delicate).

In terms of command input devices, there is a variety of possibilities:

- The 'American' preference is to use two 'joysticks' as in piloting an aircraft: three-axis translation is commanded by one hand, three-axis orientation by the other.
- In the 'European' preference, where there is more heritage from industrial robotics rather than from pilot-trained astronauts, often the six axes of motion are commanded by one hand (e.g. by a 6D 'sensor ball' or 'space mouse').
- Beyond the continuous input of the velocity, menus and switches are needed to command end effectors, to select reference coordinate systems and important parameters such as speed, etc.

The most important output devices providing feedback on the robot state are

- Multiple camera views (scene overview, looking out of the hand).
- Displays of tip position, joint angles, possibly distances/forces/tactile patterns.

Needless to say, there are fundamental ergonomic problems in the intuitive presentation of all this information to the operator. It is important that the user interface is reviewed or even designed by experienced users rather than by control specialists.

A completely different approach to teleoperation is the so-called ‘master/slave operation’ which is known from manipulators in nuclear facilities. Here, the operator guides a master arm, which is a scaled kinematic replica of the ‘real’ arm and is controlled to follow the motion as a slave. In advanced systems, even force feedback is provided to the master.

3.1.8. The ground control sub-system. Again, one encounters fundamentally different philosophies concerning the amount of ground control for space robots:

- The USA/Canada so far rely completely on on-board teleoperation (the astronauts insist on ‘flying’ the robot themselves), everything else is considered too risky or unreliable.
- Europe, however, plans to make judicious use of off-line programming technology (probably because of the stronger industrial automation background, where off-line programming is the predominant mode).

In this approach, ground stations have to implement the higher-level control functions such as

- Robot program preparation and verification: task programs are ‘written’ and ‘tested’ using 3D graphics simulation. Of course this works only as far as the tasks and their environment are predictable and can be modelled well enough (but this is the case in almost all orbital applications).
- Robot commanding (using menus of tasks) and monitoring (the measured motion is displayed in 3D graphics and compared with the expected behaviour). Since ground control is at a medium high level, all time-critical control loops are closed on board and time delays in commanding and monitoring are no problem.
- The situation is different if one opts for telemanipulation from ground. This is in principle like telemanipulation by crew, but now time delays are a big problem since the ground operator is in the time-critical control loop. Even for LEO missions, round-trip time delays can be up to 10 s (due to complicated communication paths via several geostationary data relay satellites and ground stations). Here one can resort to predictive simulation: the synthetic computer graphics (‘virtual reality’) environment presents the predicted state at the moment in the future when the command will be executed. This sophisticated mode has successfully been demonstrated in the German ROTEX technology demonstration experiment (Hirzinger *et al* 1993), where even a free-floating object could be caught under ground operator supervision.

A very comprehensive treatment of the psychological (cognitive, human factors) aspects of teleoperation is given in chapter 3 of Skaar and Ruoff (1994). An overview of some of the most advanced teleoperator systems developed at NASA is contained in chapter 5 of Skaar and Ruoff (1994).

An integral and important ground control function is *payload commanding and monitoring*. One typical application of space robotics is ‘laboratory automation’, e.g. for Spacelab-type micro-gravity facilities. In this scenario, the scientists on ground should be able to use the robot as a transparent tool to support their experiments (‘telepresence’, ‘telescience’):

- At additional ground stations, preferably at the user home base, the scientist plans the experiment.
- Where the experiment plan includes logistics commands assigned to the space robot (e.g. ‘exchange sample’, ‘put probe into furnace’, ‘close freezer door’), they are forwarded to the robot control and executed as robot tasks. Ideally, the scientist should not even be aware whether such tasks are executed by a robot or by crew.

- That way, multiple scientists may share the common resource of the space robot tending to multiple experiment facilities.
- Finally, the scientist monitors the progress of the experiment, being shown only information relevant to the process (e.g. temperature profile, effects in fluids, microbial growth, etc).

Critical technologies for this kind of telescience are

- On-board image processing to compress the amount of raw data which has to be downlinked.
- Multi-media communications to provide the feeling of 'tele-presence' to the ground investigator.
- Interactive programming techniques to allow flexible modifications to tasks.

3.1.9. The ground support equipment. It should not be underestimated that quite sophisticated ground support equipment is needed in a robotic mission for

- *Testing*: Since micro-gravity effects can never be completely reproduced on Earth, high importance is placed on simulation to verify the system behaviour. As a further complication, the robots will be mass optimized to work in space and thus may be too weak to perform their tasks on Earth. This gives rise to more or less adequate weight off-loading systems (which always restrict the motions that can be verified on ground).
- *Operations planning* (in the preparation phase, but also during the mission for re-planning).
- *Training* of operators (crew and/or ground personnel): this may involve neutral buoyancy facilities (huge water tanks where the mission is enacted by divers).
- *Troubleshooting* during the mission.

With all of this, the ground support equipment can be very expensive since multiple replicas of the whole robot system may have to be built (to various degrees of fidelity). Chapter 17 of Skaar and Ruoff (1994) gives an impression of the complexity of the test facilities for the ISS assembly robotics operations.

3.2. Mobile robots (rovers)

3.2.1. Typical architecture. A breakdown of a typical rover system is shown in figure 3. It identifies the following sub-systems:

- The payload, which is the ultimate justification of the rover.
- The structure and locomotion s/s (chassis) which accommodates all the other s/s and enables mobility.
- The power generation s/s (which could include lander-based elements).
- The communications s/s (which could include lander-based elements).
- The thermal control s/s.
- The on-board control s/s (with analogue and digital hardware and software, possibly distributed between lander and rover, in manned missions possibly including human operators).
- The ground control s/s (which may be distributed over several ground centres and will typically include human operators) to prepare, command and monitor the rover and payload operations.
- The flight support equipment (auxiliary flight equipment, e.g. on the lander, for the support of the rover).
- The ground support equipment, for rover system testing, operations planning, operator training, troubleshooting during the mission.

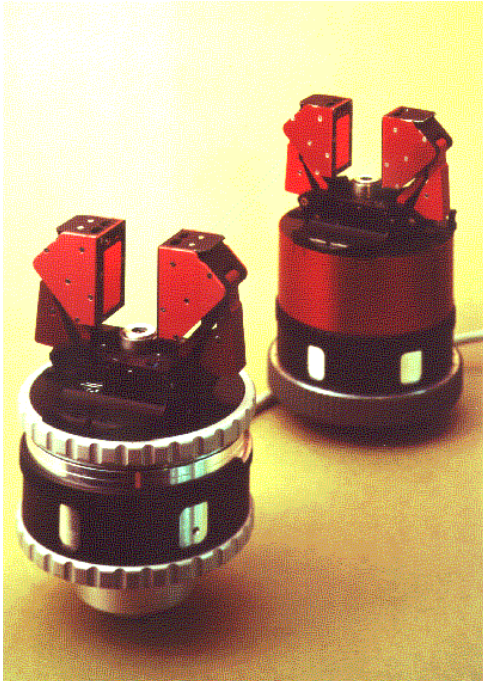

Figure 2. Two generations of the DLR end effector (courtesy of DLR).

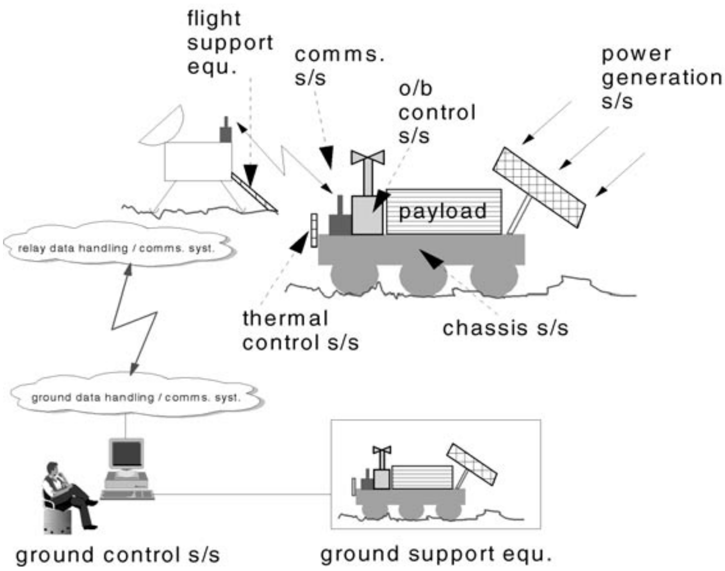

Figure 3. Architecture of a space rover system.

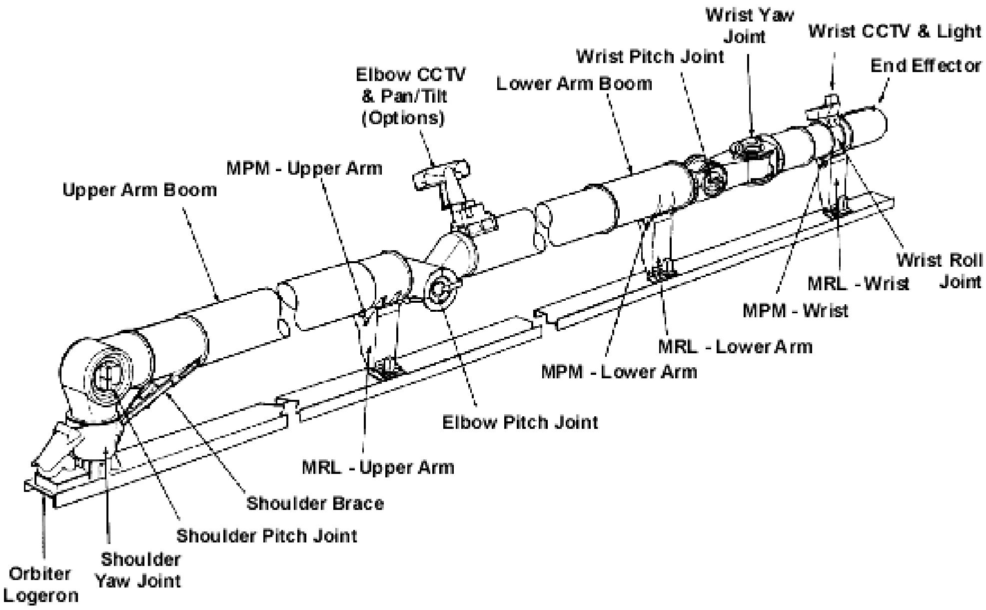

Figure 4. The Space Shuttle RMS (courtesy Canadian Space Agency).

Figure 5. The Shuttle RMS during the Hubble Space Telescope repair mission.

Figure 6. The MSS of the ISS (artist's impression, courtesy MD Robotics).

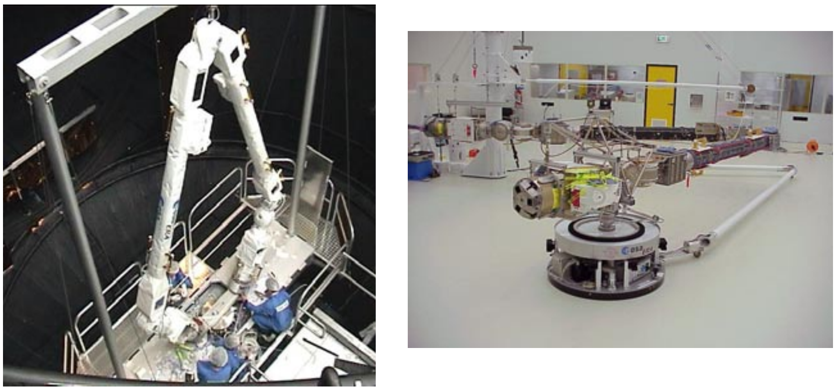

Figure 7. The ERA during test.

The most popular research topics for rovers concern locomotion and control. In a real space mission, however, the most critical sub-system often turns out to be power generation.

Even more than with robot arms, proper system engineering of a space rover is very important (after all, a rover is a spacecraft of its own, but subject to much more diverse influences than a 'flying' one). It is relatively easy to have a rover prototype move around impressively in a research lab, but it is hard to have it survive lunar nights or Martian sandstorms and even carry some useful payload. . . .

Note that many other kinds of mobile robots have been proposed for space missions (flying 'aerobots', swimming 'hydrobots', burrowing moles, hopping probes, etc). Their architecture will be quite different, certainly for the locomotion part, and typically will be highly specialized to the environment and application. Many general principles of the sub-systems outlined in the sequel, however, will remain valid. The broad discussion will focus on rover systems, since they are still the most dominant and mature devices.

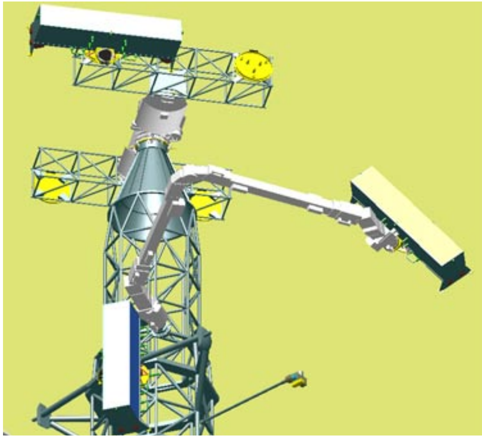

Figure 8. ERA installing a solar array package (computer generated image courtesy of Fokker Space B.V.).

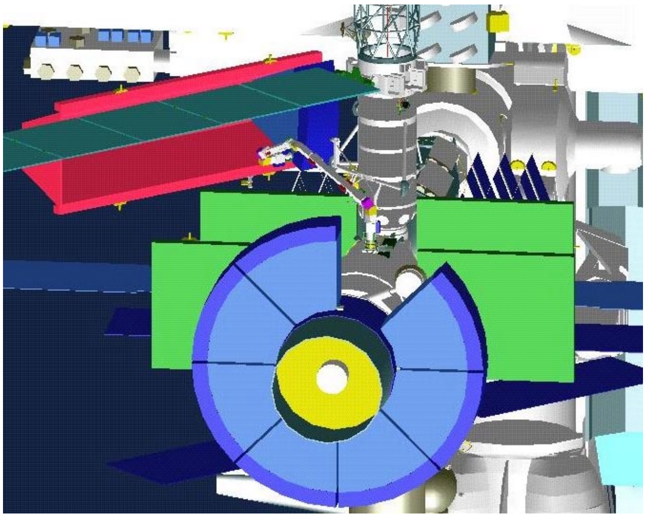

Figure 9. ERA assembling the x-ray evolving universe spectroscopy (XEUS) Mirror Spacecraft (MSC) (computer generated image).

3.2.2. System level issues. Even though there is no generally accepted 'standard' terminology, one tends to speak of rover classes according to the vehicle's size and capabilities:

- *large rovers* with a mass around 1000 kg: exemplified by the Lunokhods of the 1970s, this class now has to be considered extinct since no mission can afford to transport such masses to the Moon or planets anymore (this may change with possible human exploration of Mars, but the cost is formidable)
- *mini-rovers* with a mass around 100 kg, a roving range of about 100 km and relatively high degree of autonomy (example: Marsokhods)
- *micro-rovers* with a mass around or less than 10 kg, some 100 m range and little autonomy (example: Mars Pathfinder Sojourner)
- *nano-rovers* with a mass of less than 1 kg—this is the current technology frontier.

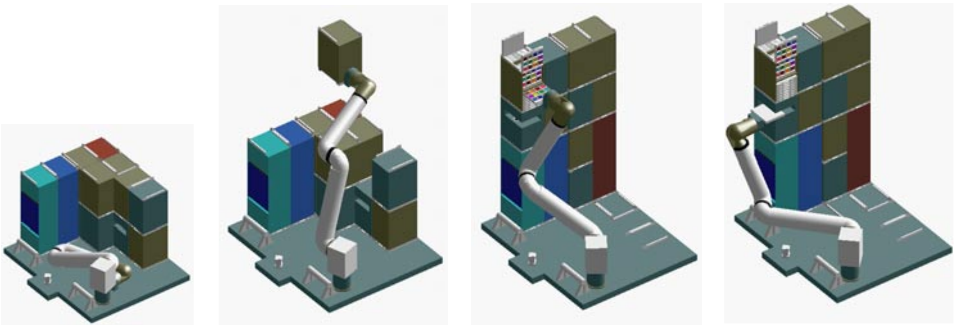

Figure 10. An external payload tending scenario: the robot arm configures payload modules for exposure and inserts a payload tray for *in situ* materials properties analysis.

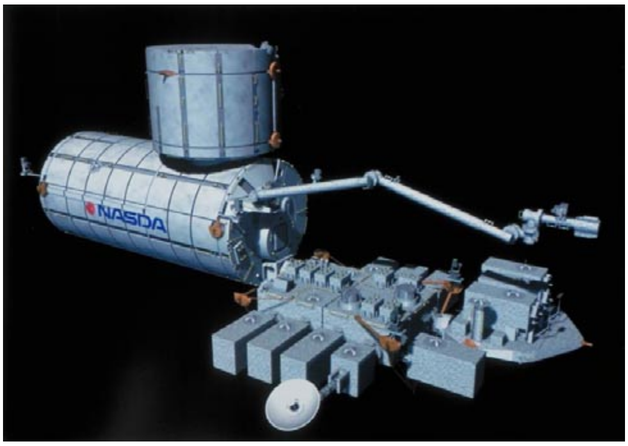

Figure 11. The JEM with the JEM-RMS (courtesy NASDA).

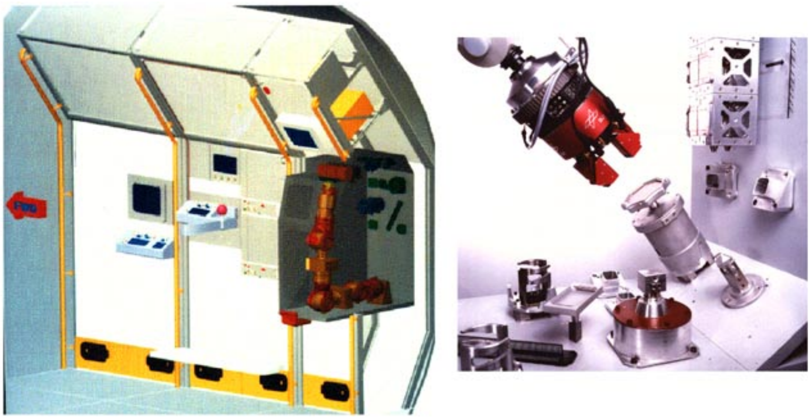

Figure 12. Environment and workcell of the ROTEX flight technology demonstration (courtesy DLR).

Chronologically, there is a clear evolution towards smaller vehicles. This is due not only to technological advances (miniaturization), but also to the shrinking mission budgets. . . .

Figure 13. The ROTEX end effector capturing a free floating object in space (courtesy DLR).

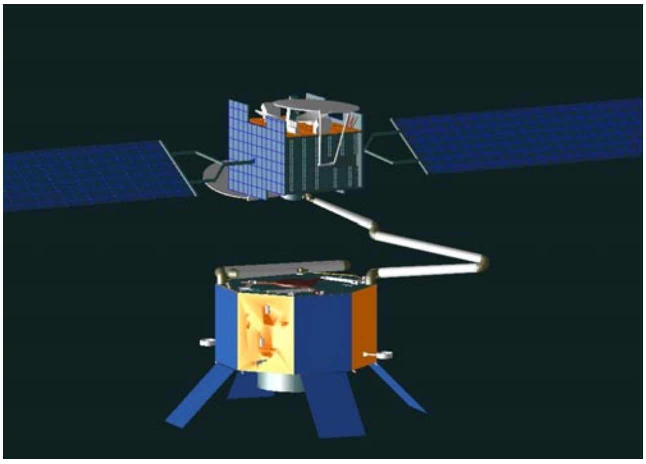

Figure 14. A possible geostationary servicing scenario: the GSV (below) has approached and captured a failed satellite.

As with robot arm systems, the concept of autonomy is heavily emphasized and often abused for rovers. Again, we prefer to talk about degrees of autonomy depending on the allocation of control functions. It should be realized, however, that very different 'kinds' of autonomy are relevant for a rover mission: autonomy w.r.t. ground control, w.r.t. the lander spacecraft, w.r.t. sunlight, etc. Most discussions about rover autonomy mean the absence of humans in control functions.

In choosing the degree of rover autonomy, one encounters substantially different constraints as compared to orbital robotics. The environment (terrain, obstacles, target objects) is unstructured (natural, not man-made) and much less predictable, there is typically much less on-board computing power available, and communications time delays are much longer (signal round trip for Mars up to 40 min).

As a final system consideration to be mentioned here, rover scenarios can benefit strongly from co-operative strategies involving other spacecraft of the same or previous missions:

- The rover may use a lander for communications, control, power supply, thermal control (shelter).
- The rover may use a (planetary) orbiter for communications and control (localization).
- For long-range exploration (e.g. into dark lunar craters), quite sophisticated artificial infrastructure may have to be built up (systems of beacons/relay stations etc).

More system-level issues for the design of a rover-based (lunar) exploration mission are given in Novara *et al* (1998).

3.2.3. The rover payload. If a rover mission is not to be considered purely a robot technology demonstration, the most important function of the rover is to accommodate and support payloads. In true scientific missions, the rover design has to be optimized for payload accommodation.

Typical payloads for the kind of early exploration missions expected for the near future include

- (panoramic) cameras
- environment/geochemical/geophysical analysis instruments (close-up imagers, thermal probes, spectrometers, etc)
- small arms and/or drills to collect samples and place instruments.

A survey of the scientific objectives of (European) planetary missions and more details on the resulting payloads for rovers is given in Chicarro *et al* (1998).

Rover payload mass is a highly scarce resource. Typical mass breakdowns for mini-rovers allocate approximately 30–40% to the chassis, 20% to the power s/s, 25% to control/communications/harness, and 10% to thermal control. This leaves only 5–15% for the payload! Clearly, the rover payload mass fraction (rover payload mass as a percentage of the total rover flight segment mass) can be an important mission cost driver. The rover payload mass determines the rover mass, which determines the lander mass, which determines the spacecraft mass, which determines the development and launch cost. In practice, of course, it is the other way round and the scientific community has to live with the few kg of rover payload which remains. Drastically increasing the payload mass fraction is therefore a main objective for newer-generation rover designs. Up to 50% is believed feasible for Mars geochemistry micro-rovers currently under development in Europe (Bertrand *et al* 1998).

3.2.4. The structure and locomotion sub-system (chassis). The essential locomotion function is to get enough traction on the terrain to move safely in a desired direction at reasonable speed, overcoming obstacles of a reasonable size in order to enable longer traverses and to simplify piloting. This 'trafficability' problem is made difficult because the terrain is typically rough (clearly 'off-road' conditions), with areas of loose sand, steep slopes (30°–40° for craters) and obstacles. Note that low gravity (Mars has about $1/3$ g, the Moon about $1/6$ g, comets and asteroids can have as little as 10^{-6} g) makes traction on loose soil even more difficult, especially for very light vehicles. The classical theory of trafficability was developed by Bekker (1960) at General Motors in the 1960s.

Over the past hundreds of years, human ingenuity has come up with an amazing spectrum of *locomotion concepts*, many of which have been proposed for planetary rovers. In reality, however, all rovers ever operated on the Moon or on Mars were wheeled vehicles.

- *Wheels* are certainly the classical concept, starting with the Soviet Lunokhods (figure 16), which were eight-wheelers (mainly for redundancy reasons). Wheeled locomotion is simple and well understood. A main disadvantage is that wheels give limited traction.

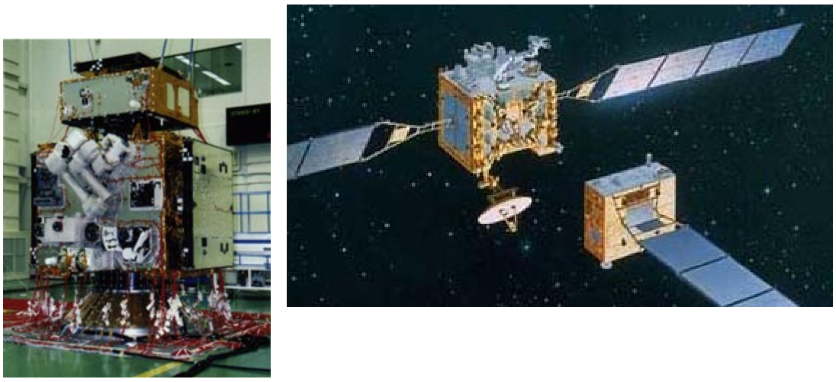

Figure 15. ETS-7 readied for launch (left), artist's view of in-orbit operations (right, courtesy NASDA).

Better traction would require larger and wider wheels, which runs counter to the size and mass constraints. Micro-rovers on the Moon are already severely handicapped in their slope climbing capability because their low mass in the low gravity environment does not give them enough traction. The state of the art for difficult terrain currently are six-wheeled chassis with more or less sophisticated suspension systems to adapt to terrain irregularities, with all wheels driven in synchronized ways, and optional wheel steerability. (Even without steerable wheels, a rover can make 'differential turns' by driving the wheels of each side at different speeds, even directions.) The Mars Pathfinder 'Sojourner' micro-rover (Matijevic and Shirley 1997) is an example of a 'rocker–bogie' suspension on a rigid chassis (see figure 18). Rockers and bogies are passive wheel articulation mechanisms which allow all wheels to maintain soil contact even in very uneven terrain. The Russian Marsokhod rovers (e.g. see figure 17) have articulated chassis (three chassis segments linked by active or passive translatory or rotatory joints). This allows a very sophisticated mode of 'wheeled walking' (worm-like peristaltic motion) which gives amazing slope climbing and obstacle overcoming capabilities, but at the expense of very low speeds and high control efforts.

- *Tracks* (like in military tanks) give the best traction because of their large contact surface. Problems are that they tend to be heavy and vulnerable against particles which may get stuck and block the tracks. On the other hand, completely sealed tracks can be very robust and the concave overall shape can accommodate sub-systems very well (see figure 21).
- *Legged* locomotion is a very popular research topic, with many successful zoological examples. Typical legged vehicles are insect-like with six legs of one to three degrees of freedom each. Legs offer the best dexterity in very difficult terrain, have potentially low power consumption and inherent redundancy. On the other hand, they can be mechanically very complicated and difficult to control. A key term here is 'gait', the pattern of synchronized motion of the legs. A popular example of legged rovers is the Dante robot tested in Antarctica and Alaska. A more exotic variant was the Soviet-built 'cross-country skiing' rover PROP-M launched to Mars (see section 4.3.2).

Ultimately, mobile space robots need not necessarily be surface-bound:

- In the milli-gravity worlds of comets and asteroids, traction from the surface is extremely low. Larger distance locomotion is then better performed in sequences of controlled ballistic flights ('hopping' robots, such as the PROP-P built for a failed Soviet Phobos mission, or the Nanorover proposed by the JPL for an asteroid mission).

Figure 16. Lunokhod 1.

Figure 17. A Marsokhod mini-rover during field tests (courtesy of NASA).

- Flying or floating robots (‘aerobots’) have been proposed and built for the global exploration of planets with an atmosphere (e.g. Mars, Venus or Titan). Aerobots can be automatic balloons that make use of very predictable wind patterns at different altitudes. Thus, only the vertical motion has to be controlled (including landing and take-off), while the horizontal motion is naturally provided. Alternatively, the flight principles of ‘Zeppelin’-type dirigibles (airships) could also be employed. Many possible combinations can be envisioned (rigid/non-rigid hulls, steerable/non-steerable fins, etc). Also fixed-wing and rotary-wing aircraft have been designed for aerial exploration of Mars.
- Some scientific investigations (e.g. the search for past life on Mars) are interested in (very) deep underground soil measurements or samples. In order to avoid impossibly large drilling systems, burrowing probes or ‘moles’ (which completely disappear into the soil and may or may not have steering functions) are under development for such purposes.

Figure 18. Scene from the Sojourner mission (courtesy NASA).

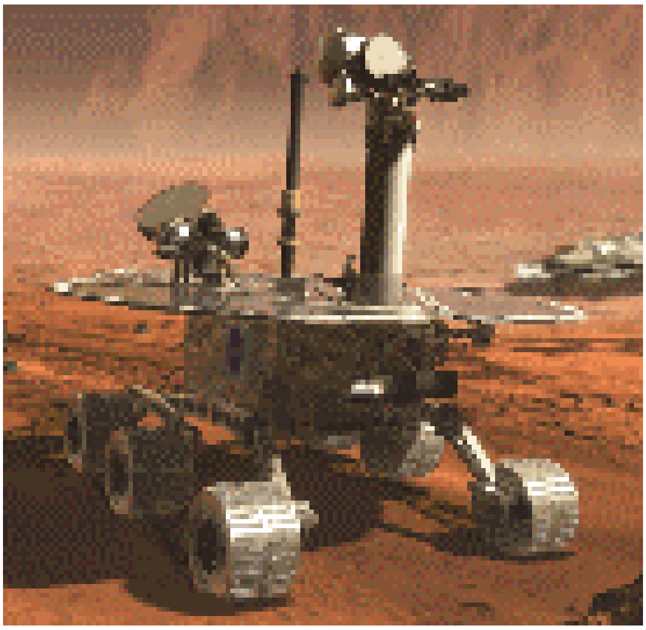

Figure 19. The Athena rover (courtesy NASA).

- Europa, a moon of Jupiter, is a fascinating target for exploration because it could harbour existing life in our solar system (see also section 4.3.4). It has a thick outer crust of ice, below which a global ocean of liquid water is believed to exist. To reach the bottom of this ocean, a robotic probe would first have to penetrate some 10 km of ice ('cryobot' melting its way down) and then turn into a submarine ('hydrobot'), all the while operating in extreme autonomy (Atkinson 1999).

3.2.5. The power generation sub-system. This is often the most critical rover sub-system, certainly for long-duration explorations. Extended Moon missions are particularly difficult because of the long nights (14 Earth days on average), where no power regeneration is available and environment temperatures drop to very low values (possibly below $-200\,^{\circ}$C).

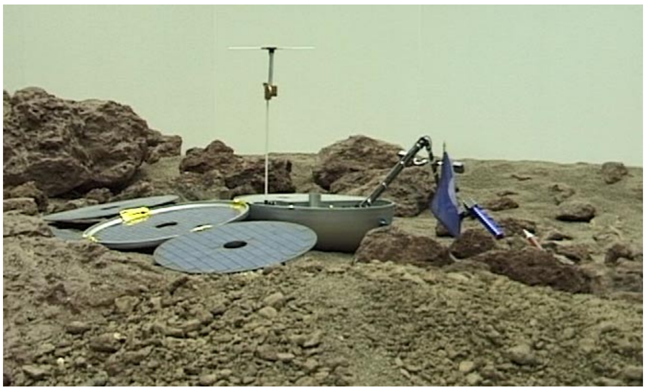

Figure 20. Mockup of the Beagle 2 lander with its instrument positioning arm.

Figure 21. The Nanokhod micro-rover.

The principal power generation concepts for rovers are the same as for any spacecraft. Some considerations:

- *Solar arrays* with rechargeable (secondary) batteries for buffering and supplying peak power are often the preferred solution, provided that enough panel size can be accommodated. This may be difficult for very small rovers. Of course, solar power does not work during periods of local occultation (dark craters!) and during the night. In polar areas, where solar elevation is always low, the solar panels cannot be horizontal but must be vertical. None of the possible solutions is without serious constraints:
  - ∗ Fixed arrays on a single side see varying solar aspect (including no Sun at all) during motion in different directions, so the whole vehicle needs to periodically reorient for recharging (which complicates longer traverses).
  - ∗ To be independent of the motion direction, solar arrays should be mounted vertically on all sides. This might not provide enough area, may obstruct the operation of the vehicle and its payloads, and is very prone to dust accumulation and mechanical damage.

  * The best solution would be a pointable solar array, with the obvious penalty of the added mass and complexity.
- Chemical batteries make the vehicle very independent, but pose a number of other problems:
  * They are typically the most sensitive equipment w.r.t. low temperatures, so they tend to drive the thermal control concept and draw additional power for their own climatization.
  * Space-qualified primary (non-rechargeable) batteries have quite limited lifetime (this was the—fully predicted—cause of death of the Mars Pathfinder Sojourner rover).
  * Rechargeable batteries suffer from low mass efficiency—sizing them for typical operations profiles is typically prohibitive in terms of mass.
- In many ways, the 'ideal' power plant on a rover would be the radioisotope thermal generator (RTG), a primary power source with plentiful lifetime and reasonable mass efficiency. This is what has powered the huge Lunokhod rovers. At the moment, it would appear as the only technically viable solution for a permanent robotic presence on Mars or the Moon (including many long nights). At the same time, it also provides the thermal control s/s more than enough heat 'for free'. Because of the potential safety risk from the plutonium fuel, however, RTGs have become politically unacceptable, certainly in Europe. It is also true that RTGs are very expensive and reliable procurement sources may no longer be available.
- A new power generation technology that could eventually replace RTGs is regenerative fuel cells (RFCs). At the moment, however, they are still considered immature and their mass efficiency is poor.
- One can try to avoid many of the above problems by having no power generation s/s on-board the rover at all, but drawing energy from the lander by means of a tether. A tether, which can also carry data for the communications s/s, of course creates other problems:
  * it needs a mechanism for reeling (wire is paid out from the rover to avoid friction of the tether over the surface),
  * it limits the range of the rover (this may be perfectly acceptable for local instrument deployment devices),
  * it constrains the rover's dexterity or places additional burden on its control, and
  * it constitutes a hazard for the rover to get entangled when backing up or crossing its own path.

3.2.6. The communications sub-system. This appears to be the 'easiest' of all rover sub-systems. After all, standard spacecraft communications equipment (typically radio frequency based) can be used. Still, Sojourner had its biggest problems with an unreliable communications sub-system.

In general, a few important system issues have to be resolved concerning the appropriate overall communications configuration:

- The simplest design is for a link *rover–lander–Earth*, as with Sojourner. This needs the least instrumentation on the rover, but it also limits the rover's manoeuvrability if the communications principle requires a line-of-sight contact. The rover cannot go beyond the lander's horizon (typically 1 km on Mars) and can be shaded by local topography. This is why high masts are big assets.
- For longer-range (over the lander's horizon) or longer-duration (beyond the lander's lifetime) exploration, one could establish a direct rover–Earth link. This needs heavier equipment on the rover (powerful transponder, sizeable antenna, possibly with a pointing

mechanism) and is currently unfeasible for micro- and nano-rovers. It needs line-of-sight contact with Earth, so it fails on the far side or in deep polar craters of the Moon, and will not be permanently available.

- The highest rover manoeuvrability could be achieved if a planetary orbiter is available as a communications relay node (rover–orbiter–Earth link). Of course this is a significant additional investment, but it may be a mission element anyway (possibly of an earlier mission) where it can be used for complementary science and for detailed surface mapping (for landing and for rover exploration). The visibility windows will constrain rover operations, and data storage capacity may be required on the orbiter.
- For future large-scale rover 'traffic' as envisaged in some space plans, a network of *relay stations* would have to be set up (this is in itself a task for planetary robots).

3.2.7. The thermal control sub-system. The thermal environment for planetary rover missions is very *severe*, with extremely low temperatures during the nights or in permanent darkness (down to $-240\,^{\circ}$C on the Moon?) and possibly very high diurnal temperature excursions depending on the latitude. For hitherto unexplored regions (e.g. the lunar pole areas), no reliable thermal models are available.

In principle, the conventional spacecraft thermal control measures can be applied (passive thermal control via appropriate multi-layer insulation; active thermal control by means of electric heaters, radiators, heatpipes). RHUs, which use tiny pellets containing plutonium, would be the technically ideal solution for night-time survival, but also suffer from political acceptance problems (much less than RTGs, however). Survival could also make use of shelters, e.g. the lander or covers of planetary 'sand' (regolith, which is an excellent thermal isolator).

The future trend concerning thermal control may be to avoid it completely, by using novel low-temperature survivable electronics (normally, the rover does not need to operate during the cold periods). This would be a necessity for further miniaturization (nano-rovers), since such small devices cannot accommodate a 'warm box' any more. It turns out that even conventional electronics can survive much lower temperatures than specified, they just have not been tested for these cases. Again, the limiting elements for thermal control are batteries.

3.2.8. The on-board control sub-system. For rovers, the typical control architecture is hierarchical, with several nested layers of control functions. The simple architecture of Martin Alvarez and Putz (1996) defines two main layers: navigation and piloting. Beware that there is no 'standard' terminology here, and certainly the rover 'navigation' has not the same functionality as the spacecraft 'navigation' of 'guidance, navigation and control' (the rover term is essentially taken from the nautical usage).

In this architecture, *piloting* is the lower layer and typically implemented on board (not necessarily only on the rover—the lander can also offer resources for rover piloting!).

The piloting function is comparable to driving a car in an unfamiliar environment. It has no concept of absolute localization and completely relies on the navigation function to provide it with direction commands. The pilot is competent at determining a local path (trajectory) to reach the next 'way point' (selected by the navigator), and at following this path despite intermediate hazards (e.g. local obstacles). Finally, the pilot controls the actuators of the locomotion s/s (wheels/tracks/legs).

The most important piloting sensors include

- Stereo cameras (images can be evaluated to yield a 'digital elevation map' of the region immediately ahead; structured lighting such as laser striping can be used to make elevation patterns more obvious).

- Odometric sensors (e.g. wheel revolution counters) which are supposed to measure the covered distance, but will be fooled by slippage.
- Inertial sensors (gyroscopes, accelerometers) to keep the 'bearing'—since they are integrating devices, their biggest problem is the drift over time (this was the biggest limitation in the Sojourner control system).
- 'Whiskers' or laser sensors to detect impending collision.
- The sensors of the locomotion sub-system (encoders, tachometers, inclinometers, contact sensors).

Navigation is the function of the higher control layer. Implementation on board is very difficult, but needed for the highest degrees of autonomy (to perform long traverses without ground contact, e.g. in deep craters). The navigation function is like having to determine how to go from 'here' to a distant place, say Paris: the navigator has to establish a global strategy to reach a prescribed point on the planet. There are several important difficulties involved:

- The rover needs a good global map at sufficient resolution (e.g. from previous missions, or from the orbiting or descent phase).
- The rover has to absolutely localize itself on this map, i.e. answer the question, Where am I right now? Note that absolute localization is expressed in 'world coordinates' such as '25° N/17° E', while relative localization puts environment features in 'vehicle coordinates' such as 'right/left/ahead/at 10 o'clock/2.5 m away'.

Essentially, the navigation function has to generate a sequence of 'corridors' between 'waypoints' (landmarks) which it considers feasible for the pilot to follow. All details are entrusted to the skills of the pilot who only reports back when it has reached the waypoints (positive case, awaiting new directions) or when it is forced out of the corridor because of unexpected conditions, e.g. unmodelled obstacles (negative case, awaiting a replanning). This shows that navigation has to be well aware of the capabilities and limitations of the functions implemented in the piloting layer. It also shows a typical trade-off: waypoints must not be spaced too far apart (otherwise the pilot will not be able to safely reach them), but they also must not be spaced too closely because this would invoke the complex navigation calculations too often, thereby slowing down the motion to an unacceptable extent.

Navigation sensors for absolute localization can be combinations of star sensors, sun sensors, Earth sensors, inclinometers, and cameras (to recognize landmarks). The computational challenge is to handle the complex planetary and celestial kinematics models on board. A simpler solution would be to perform absolute localization with 'external' means, such as an orbiter (if available).

Apart from the 'classical' control approaches, which are based on a hierarchical decomposition of plans (encoded in motion programs) and deterministic implementations of lower-level control algorithms, a number of 'non-conventional' control schemes have also been appearing in space robotics:

- Fuzzy controllers apply 'common-sense' control rules and take the unavoidable inaccuracies of sensor measurements and mapping information into account.
- Behavioural schemes are one way of imitating how humans or animals control their motion. In pure behavioural control architectures there is no concept of planning or modelling. Control is achieved by implementing several parallel or concurrent behaviours which are essentially reactions to the stimuli provided by selected sensor inputs. It is surprising to see what 'intelligent' function can be achieved by just a few simple behaviours such as 'move towards goal point', 'avoid obstacle' etc. Hybrid schemes use a functional hierarchy with planning at a higher layer which judiciously invokes and parametrizes the appropriate behaviours at piloting level.

An advantage of both fuzzy and behavioural controllers is that they typically require relatively little on-board computer power. This is offset by their somewhat non-deterministic character which makes them difficult to verify.

3.2.9. The ground control sub-system. Whenever possible, *navigation* will be performed on ground. There, the computer power for map handling and absolute localization is no problem, and human perception makes vision-based interpretations much simpler. Communications time delays and bandwidth are no problem either (as long as the on-board piloting is reliable and safe), since only new goals/waypoints have to be uplinked at very infrequent instances. Sophisticated computer graphics ('virtual reality') helps to display 3D maps, perform planning and verification by simulation. Essential models include the terrain characteristics (for trafficability and power profile analyses), landmarks, communications constraints, shadow zones, and rover piloting performance characteristics.

Ground-based piloting or 'telemanipulation from ground' is really only needed when one cannot trust the 'autopilot' (in complex obstacle situations, or when the rover reports a problem). Then, a ground operator has to 'drive' the rover directly by issuing speed and direction commands. This was done for the Lunokhods over almost 50 km, but proved extremely tiring for the operators. One needs to downlink stereo camera images or digital elevation models in 'real time' (relative to the rover speed), which requires large communications bandwidths. Time delays become critical: the distance covered by the rover during the ground pilot 'reaction time' has to be negligible. In practice, this means that rover telemanipulation is possible for slow rovers on the Moon, but clearly impossible for Mars.

3.2.10. The support equipment. Here, *flight support equipment* shall denote lander-based equipment that exists exclusively for the benefit of the rover and therefore has to be counted to its mass budget. This may include

- Mechanisms for rover stowage during launch, cruise, descent, and landing.
- Mechanisms for safe release of the rover from the lander (e.g. ramps).
- Any communications, control, or power supply equipment on the lander (e.g. computers, tether components).

As in the case of robot arm systems, ground support equipment can be quite complex, comprising

- Test equipment, especially equipment needed to reproduce driving on the planetary soil. This may involve weight off-loading systems for the rover and the use of 'soil simulants' (terrestrial soil which is believed to approximate Moon/Mars soil). Note that the soil properties in unexplored areas are not precisely known, but can only be extrapolated by analogy. If done seriously, 'soil channels' are absolutely non-trivial, taking into account the complex scaling laws for the relevant mechanical properties of soil under different gravity conditions.
- Equipment for mission planning and ground operator training can be largely identical to the ground control s/s, with simulators taking the part of the actual rover.

4. Main applications of space robotics

Space robotics can be and has been applied in many completely different mission scenarios. Applications can conveniently be structured according to the 'destination' of the spaceflight mission. Table 3 is a very simplified overview of the resulting classes with their main objectives.

Table 3. Survey of potential space robotics applications.

Scenario	Application	Typical objectives
LEO systems (Space Shuttle, Space Stations)	(External) system servicing (from attached or free-flying base)	Release and retrieval of payloads, transport and assembly of station elements, transport/assembly/refuelling of spacecraft at Shuttle/Station, support to and transport of astronauts, installation/removal of payloads, systematic inspection of shell, preventive/corrective maintenance
	External payload tending	Inspection and routine logistics manipulation of (exposure) payload units, 'remote hand' for telescience
	Internal payload tending	Inspection and routine logistics manipulation of (micro-gravity) payload units, 'remote hand' for telescience
Other (Earth) orbital systems	Satellite servicing	Inspection and assessment of satellite after deployment, simple repair, de-orbiting of expired satellites
	In-orbit assembly	In-orbit assembly of huge space structures (antennas, mirrors, solar sails, interferometers, etc)
Solar system exploration and exploitation	Moon exploration/exploitation	Local/regional/global surface exploration, instrument deployment, sample collection, base building, mining, resource processing, infrastructure logistics, support to humans
	Mars exploration/exploitation	Same as for Moon, plus search for past life and aerial survey/exploration
	Mercury exploration	Instrument deployment, sample collection
	Comet/asteroid exploration	Instrument deployment, sample collection, asteroid 'mining'
	Exploration of other bodies	Surface/atmospheric/underground exploration, instrument deployment, sample collection

4.1. Applications in low Earth orbit

The LEO, at 300–700 km altitude, is the domain of manned space missions. The US Skylab and Space Shuttle, the Russian Space Station Mir, and the ISS are all LEO systems. All robotic applications in LEO therefore have an important element of crew interaction or operation.

The most familiar space robot to date is probably the Canadian-built Remote Manipulator System (RMS, also called 'Canadarm') of NASA's Space Transportation System (official name of the US 'Space Shuttle'), see Skaar and Ruoff (1994) and NASA (1988), with an impressive operations record over almost 20 years (see figure 4).

The main applications of the Shuttle RMS are to take satellites from the cargo bay and to 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 it was operated by a European astronaut, Claude Nicollier (see figure 5)).

For the upcoming era of the football-field-sized ISS, an impressive array of robot systems is being developed. The largest ones will be used to support astronauts in the assembly of the Station from its modules and to exchange large orbital exchangeable units (ORUs). Besides this 'system servicing' function, another set of robots will be dedicated to groups of payloads to support their logistics and experimentation ('payload tending').

4.1.1. System servicing on the International Space Station. The US segment of the ISS will be serviced by the Canadian-built MSS described in Skaar and Ruoff (1994) or Sallaberger (1997) see figure 6. The MSS will consist of two major robotic sub-systems:

- The Space Station RMS (SS-RMS) is essentially a larger version (18 m long) of the Shuttle RMS. It travels on a trolley (Mobile Base S/S, MBS) along the main truss of the ISS, but also can 'step' among base points.
- The special-purpose dextrous manipulator (SPDM) is a bi-arm system (each arm is 3.5 m long and has seven axes) which can be attached to the tip of the MSS as a complex 'end effector' for more complex assembly and installation operations.

The MSS will be controlled from a crew operator inside the ISS.

Chapter 16 of Skaar and Ruoff (1994) describes the scenarios planned for initial assembly of the Space Station (it talks about a precursor version of the ISS, but the illustration is still valid) and points out the roles of the SS-RMS, but also the venerable old Shuttle RMS.

The USA had a very substantial programme to build a similar bi-arm servicing system (the Flight Telerobotic Servicer), but this was cancelled due to funding constraints and because of the functional overlap with the Canadian-provided SPDM.

The main European contribution will be the ERA described in Boumans and Heemskerk (1998), responsible for servicing the Russian segment of the ISS. There, ERA will transport large Station elements (such as folded solar array or radiator packages) and exchange ORUs. ERA is a completely symmetric seven-axis arm with an extended length of 11.3 m. A peculiar feature is that ERA can relocate itself along a system of attachment ports on the Russian truss (Science and Power Platform) by alternately switching the roles of end effector and shoulder base. ERA can be operated from either inside the Station or from a cosmonaut performing an EVA, but not from Earth. Its launch date will depend on the progress of the Russian element launches.

The large ISS system servicing robots MSS and ERA will also be capable of servicing other spacecraft which use the ISS as an orbiting servicing hub. One such scenario is currently being developed at ESA in the form of the XEUS mission. XEUS is a planned next-generation orbiting x-ray observatory. For its superior optical performance, it needs a mirror of 10 m diameter and a focal length of 50 m. While the immense focal length will be realized by splitting the telescope into two separate spacecraft flying in highly accurate constellation, the MSC will still be too big for launch in one piece. It will be assembled by robotic means while the MSC is docked to the ISS. This very complex operation will involve all three large robots in concert: the Shuttle RMS will unload a container with mirror segments from the Shuttle arriving at one end of the ISS and pass the container on to the SS-RMS. The SS-RMS will hold the container in place for the ERA to take out segment by segment and install them on the MSC docked on the opposite side of the Station (see figure 9). The complete container turnaround cycle will take some 11 working days to complete and involve about 1 km of total transport path with very low clearance against the complex appendages of the ISS (see figures 7 and 8).

Since both the MSS and the ERA operate from bases that are attached to the main trusses of the ISS, they cannot reach more peripheral areas of the huge ISS. There is growing awareness that this will not be sufficient to safeguard the immense international investment by regular and thorough inspection and maintenance (which is clearly beyond the capacity of astronauts on EVAs). This has defined the need for more flexible system servicing robots on free-flying platforms. Many such systems have been studied or prototyped, e.g. the NASA Orbital Manoeuvring Vehicle or Ranger, but none is approved for development yet. So far, only precursor demonstrations of small free-flying inspection devices have been performed (e.g. of the small German Inspector system on Mir in late 1997). It is expected, however, that free-flying servicing robots will appear when the cost of routine ISS operations becomes clearer. Then, small robot systems for quasi-permanent internal inspection of the module shells for cracks or impact damage will also be required.

4.1.2. External payload tending. A large number of experiment payloads from many different disciplines (Earth observation, astronomy, micro-gravity sciences, environment monitoring, various space technology developments) will be accommodated on ISS external platforms for medium to long-term operation (several years' increments). Many of them need or profit from manipulative servicing for routine logistics handling of sub-units: opening and closing exposure windows, periodically inspecting and analysing materials samples, pointing of sensors, rearranging of payload boxes on platforms to time-share the most attractive viewing locations, etc. Astronaut operation for these purposes will be unaffordable and dedicated mechanisms for each individual task are either not feasible or much too heavy. On the other hand, the large-system servicing robots discussed in the previous section are not suitable or unavailable for these more dextrous and precise dedicated fine operations on payloads. This has given rise to the class of *external payload tending robots*. Such a robot is part of a payload platform infrastructure and centrally performs all of its logistics, sensing and actuation services.

The typical operations and benefits are described in Aceti *et al* (1998) for the particular case of a technology exposure facility (TEF) see figure 10. This would be a highly modular multi-user facility, providing long-term exposure and *in situ* analysis to a multitude of experiments from the domains of environmental monitoring and in-orbit verification of new spacecraft components.

One such robot system under development is the Japanese JEM-RMS (RMS for the Japanese Experiment Module (JEM) see figure 11) described in Kuwao *et al* (1997). The JEM itself consists of a main arm and a Small Fine Arm. A successful demonstration flight was performed on the Shuttle in August 1997.

Europe also is quite active in this field, currently developing several systems for the ISS:

- EUROPA (External Use of Robotics for Payload Automation, Mugnuolo *et al* (1999)) will occupy one part of an exposure pallet. EUROPA is in the first place a technology demonstration of this novel robotic function, featuring among others a supervisory control mode of robotic operation after in-orbit calibration. Here, all commanding and monitoring happens on Earth at a medium level of abstraction, while all low-level tasks are performed automatically on board. This effectively copes with the very infrequent availability of the ground-space link. After the initial demonstration of its technological capabilities and performance, EUROPA will also perform tending of the first 'real' scientific payloads.
- Another system will be dedicated to the external exposure 'balcony' of the European laboratory module of the ISS. Tradeoffs on the precise configuration are still being discussed at the time of this writing. A minimum solution would be a short arm dedicated to a single payload platform. More flexibility would be gained from putting this arm on a short rail such that it can reach and tend to all four payload platforms mounted there. A maximum solution would also foresee an airlock through which the arm could move payload modules into the laboratory and receive new ones, thereby avoiding the need for external logistics.

4.1.3. Internal payload tending. Historically, this is the 'oldest' field that has been worked on in Europe (but not elsewhere!). A pressurized laboratory module of the ISS with many facility racks accommodating dozens of different experiment payloads is very similar to a terrestrial lab or 'factory'. Many experiments have a strong need for logistics resupply in the form of routine transport of small samples (suitably housed material probes or biological specimens) between storage compartments, heater furnaces, freezers, incubators, etc. A central robot shared among several facilities could significantly reduce the overall mass, volume, power, and development cost compared with multiple dedicated payload internal mechanisms.

While such a concept seems obvious in a terrestrial automation scenario, it has been surprisingly difficult to get accepted in the ISS environment. The technical feasibility and the availability of the robotics technologies has been amply demonstrated, e.g. in the very successful ROTEX on the Space Shuttle (Hirzinger *et al* 1993) see figures 12 and 13 or in a complete pre-development of an AMTS (automated manipulation and transportation system). Still, no such system is currently approved for development. Maybe the (hoped for) success of the external robot systems together with the low crew availability for routine internal payload operations and the high pressure to save on operational cost will combine to revive the interest in this class of systems.

4.2. Other applications in Earth orbit

Once we move away from the LEO and the Space Stations, we enter the domain of unmanned systems, where robotics plays an even more crucial role.

4.2.1. Robotic satellite servicing. The GEO is the domain of the commercial or military market of communications and Earth observation satellites. The rapid growth of this market has led to a problem of 'overcrowding' of the most attractive 'slots'. Moreover, there have been several publicized (and probably more unpublicized) failures where a correctly deployed satellite would not fully perform because of some malfunction (which often was as 'trivial' as a solar array or antenna deployment mechanism getting stuck). These are insurance cases worth hundreds of millions of dollars, yet not even a reliable *in situ* assessment of the problem (and hence the responsibility) is possible.

This is the background for the concept of robotized geostationary servicing vehicles (GSVs). A GSV is a satellite which can 'float' around the GEO to perform inspection and simple repair tasks on failed satellites or to remove expired satellites from their valuable slots ('graveyarding'). ESA has performed system studies of GSV concepts, which have demonstrated technical feasibility (Visentin and Brown 1998) see figure 14. Also, Germany has devoted significant space robotics research programmes to the design of an (experimental) servicing satellite.

In 1998/9, Japan performed the very successful Engineering Test Satellite (ETS) VII mission (see Oda and Inaba (1999) and the more detailed papers on ETS-VII at the same conference). ETS-VII consisted of a larger 'chaser' and a smaller 'target' satellite, launched together and only separated for special in-orbit manoeuvres (see figure 15). The chaser was equipped with two different robot arms. Several Japanese and European space agencies were able to demonstrate a rich variety of operations concerning ground tracking, rendezvous, capture and berthing, inspection, robotic exchange of replaceable units, and key tasks for refuelling.

Despite this technological readiness, the question of commercial viability of GSVs is still unresolved. The trend seems to be away from large, very expensive multi-functional satellites towards redundant constellations of many identical small, relatively cheap satellites. This might make the individual satellite almost disposable and therefore not warrant its servicing in orbit. On the other hand, there are indications that military constellations are already employing simple means of on-board robotic servicing for their (classified) satellite fleets.

4.2.2. Robotic assembly of large orbiting structures. In the early scenarios of the ISS, elaborate node-by-node robotic assembly of large structural truss elements had been planned. Economic realities, however, forced the planned Station to become smaller and smaller. Consequently, the assembly procedures were also significantly simplified. In the current concept, only some robotic assistance to human EVAs is required for the assembly of large parts launched as a whole.

However, several very ambitious space missions currently studied for possible flights in the next 10–50 years involve huge structures exceeding the size and complexity of the ISS. This is the case for large antennas, telescope mirrors, solar array fields for orbital power stations, or spacecraft compounds for human interplanetary missions. Such large structures cannot be launched as a whole, but rely on in-orbit assembly and deployment by robotic systems.

One early example using the ISS as a servicing hub (assembly of the XEUS MSC) has been described in section 4.1.1. Most other structures would probably be in much more distant orbits, or they would hover in libration points (gravitational equilibrium points, e.g. between the Earth and the Moon, or between the Earth and the Sun). The required robot arm systems, however, would initially be very similar to the large servicing arms on the ISS.

4.3. Applications in solar system exploration missions

An important class of space missions exploring our solar system involves landing spacecraft on planets or moons and performing *in situ* work on the surface. For the time being, all such missions will be unmanned—an obvious challenge for robotic systems, especially of the mobile (rover) kind.

4.3.1. Robotics for Moon missions. More than 25 years after the ‘golden age’ of lunar exploration, worldwide interest is shifting back to the Moon. Back then, Russia had successfully operated two large unmanned rovers (Lunokhod 1 in 1970, see figure 16 and Lunokhod 2 in 1973) and the US Apollo programme had used a manned rover (the Lunar Roving Vehicle (LRV)).

Control of these rovers was necessarily simple. The LRV was a light dune-buggy-like car driven by astronauts in spacesuits, and the Lunokhods were teleoperated from the ground based on camera views. All of these missions were in low-latitude regions of the Moon.

In the mid-1990s, the Moon started to receive higher interest again. Now, strategic interest focused on the polar areas which are still largely uncharted territory. Some of this interest was sparked by the highly publicized remote-sensing observations from the American Clementine mission, which seemed to indicate a likelihood of water ice in the dark polar craters.

ESA proposed a European Moon Programme which would lead to human settlements in four distinct phases. Several studies of landing missions were performed. One of it would land on the highest peak close to the South Pole of the Moon. Because of its unique location, this peak receives almost permanent sunlight (other parts of the Moon see ‘night’ for an average of half a month, which is a huge problem for thermal control and power generation). Moreover, it is very close to a deep crater which sees the opposite phenomenon: parts of it are probably permanently shaded and thus could contain large reservoirs of water ice, an essential resource for potential human settlements. This ‘Peak of Eternal Light’ is clearly of special significance for future permanent lunar outposts.

Moon surface exploration missions require rovers for exploration and deployment of instruments, and robot arms to deposit 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 (Novara *et al* 1998).

Japan has also announced an ambitious Moon exploration programme, to culminate in permanently manned bases and agricultural facilities. The first group of missions called SELENE would begin with simple impactors and could later involve a soft lander and a rover (currently proposed for the 2006 timeframe). Technologically, an impressive rover programme has been built up within a few years.

In the USA, the NASA programmes now concentrate mostly on Mars exploration (see the next section). The space exploration initiative (SEI) which foresaw a return to the Moon was a political failure. Recent NASA plans for a human exploration and development of space include a human lunar return (as a possible stepping stone towards a human Mars mission), with a heavy emphasis on intelligent robotics.

Commercial US plans have been announced for a Moon rover to be remotely controlled from theme parks on Earth (LunaCorp). Certainly, the rover technology is available, but funding, as always, is unclear.

4.3.2. Robotics for Mars missions. After giving up the race to the Moon, the Soviets vigorously turned to unmanned Mars exploration in the 1970s. In particular, the company VNII Transmash, builder of the Lunokhods, engineered and tested an incredible variety of vehicles over some 15 years.

PROP-M, a small 'skiing' rover, was even sent on a Mars mission in 1971, but the mission was lost before landing. The culmination of the Soviet work was the Marsokhod family of very dextrous six-wheeled mini-rovers (well above 100 kg). These vehicles, with their impressive climbing and obstacle surpassing capabilities, are still very popular around the world as chassis for ground demonstrations (see figure 17). Also in the area of micro-rovers, Transmash generated many ideas which are now being continued in the West.

After the demise of the Soviet Union, however, no more funding was available and unfortunately no Mars landing mission materialized where these devices could be used.

The USA had their big Mars missions Viking 1 and 2 in 1976. The Vikings had a simple sampling arm, but it was too short to reach the interesting rocks which were clearly in camera view. Since Viking did not bring the confirmation of past life on Mars which had been the main objective of the missions, the US abandoned Mars exploration for a long time.

In Europe, the initial interest in space rovers focused mostly on autonomous control techniques. France built a number of ground prototypes of large and mini-rovers and especially focused on vision-based navigation technologies, where significant practical experience was obtained. The largest European planetary rover test facility was established at the CNES site in Toulouse. The last carrier for their work was the development of the I-ARES ground demonstrator (Boissier 1998), to which VNII Transmash contributed possibly the most sophisticated six-wheeled mini-rover chassis to date. Unfortunately, no mission was funded which could carry such a large device to Mars.

It was only with their new 'faster, better, cheaper' missions that NASA revitalized international Mars exploration. The Mars Pathfinder mission in 1997 nicely coincided with speculations about fossil evidence of past life (stimulated by the finding of a Martian meteorite in Antarctica which showed fossil-like features) and became a huge publicity success. The well known Sojourner micro-rover (Matijevic and Shirley 1997) was built at JPL. It is a 12 kg member of the Rocky series of wheeled rovers using the 'rocker–bogie' suspension concept (see figure 18). It had a very light arm to deploy and retrieve the single scientific payload, a (German) alpha-proton-x-ray spectrometer. The surface operations were intentionally very conservative, with the rover circling the lander at a short distance. The outstanding success of Sojourner has to be appreciated especially in view of the fast and (relatively) cheap development.

Boosted by Mars Pathfinder and the search for fossils, tremendous momentum was created around the world for Mars exploration missions. NASA announced a very ambitious programme involving several missions every two years, when orbit kinematics facilitate them. Rovers would be central elements of every surface exploration.

Unfortunately, the approach turned out to be too ambitious. When the first two missions (Mars climate orbiter and Mars polar lander) were lost, NASA turned to a much more conservative programme. In its current version, the next rover mission (Twin Mars Exploration Rovers) will be launched in 2003. Two identical 130 kg rovers of the 'Athena' type (see figure 19) will be directly landed in two opposite regions of Mars and be operated over some 90 days. Mars sample return missions using long-range science rovers have been postponed to after 2010.

A recent overview of the most impressive NASA developments in the field of Mars rovers is provided in Weisbin *et al* (1999).

After Mars Pathfinder, also ESA started to focus on Mars landing missions. Mars Express (Schmidt *et al* 1999) is an approved science mission to be launched in 2003. Its lander, Beagle-2 (see figure 20), will feature a simple robot arm to position a set of instruments and to launch a robotic mole (a pointed tube which can propel itself into loose sand and retrieve underground samples or perform *in situ* analyses).

For a possible follow-on mission to Mars Express (possibly Mars Express 2 in 2005), ESA has also developed a micro-rover (Bertrand *et al* 1999). It is called Nanokhod because it is loosely based on an early Russian development. It shall carry a package of four geochemistry instruments around the immediate vicinity of the lander and perform multiple analyses of rocks. The tracked system with a central instrument box will receive power and commands from the lander by a tether (see figure 21). Compared with the Sojourner rover, the Nanokhod should provide superior scientific support (more instruments with correlated measurements, better positioning dexterity) at much lower mass: the total system mass is only 2.5 kg including 1.2 kg of science payload.

The main investigations of the Mars Express lander are from the field of exobiology, the search for traces of past life on Mars. It is now believed that organic material can only be found several metres below the surface, in layers protected from the sterilizing effect of the strong UV radiation. This is why the US Viking mission, which only analysed surface samples, could not find any evidence of past life. Crucial tools for exobiology therefore are *robotic drill systems*. At very low mass and stowage volume, they have to reach significant depths and return samples without pollution from higher soil layers. ESA has developed very promising prototypes of a small and compact system which can automatically assemble a 2 m drill string from 10 pieces, obtain samples from different drill depths and locations, store them on a micro-rover, and feed them to analysis instruments on the lander.

4.3.3. 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 NASA Deep Space 4 or the ESA Rosetta projects have been conceived, with the challenging objective of landing on a comet and analysing its chemical composition (or even returning a sample to Earth).

There are formidable difficulties associated with robotics devices such as the Rosetta Drill, Sample and Distribution System. The systems have to be extremely lightweight, but they have to work properly in surfaces whose mechanical characteristics are uncertain by several orders of magnitude (from loose snow to hard ice). They absolutely must not pollute the indigenous material, and they have to avoid warming up the icy surface on contact (otherwise the frozen comet would literally repel the device by sublimation).

Since comets are so small, their gravity field is extremely weak (milli- to micro-g). This means that special anchoring devices have to be used to resist the robot's actuation forces. In case mobility over the surface is required, conventional wheeled, tracked or walking locomotion will be very inefficient because the lightweight machine would get very little traction on the surface and the slightest impulse would catapult it off the ground. Ballistic motion ('hopping') is being investigated as a possible locomotion concept.

Asteroids are typically even smaller than comets. In the extreme case, with the asteroid of comparable mass as the spacecraft, 'landing' becomes more like berthing, and the robotics problem is essentially the same as for free-flying servicers. Japan is planning the MUSES-C mission to the asteroid Nereus in 2003, with a sample return in 2006. The Japanese spacecraft would not land but try to perform sample collection by capturing ejecta from a projectile impact. For some time NASA had planned a participation with a JPL-built nano-rover of less than 1 kg mass which could 'hop' around the asteroid by pulling together its two chassis halves, but this very ambitious mission had to be cancelled.

Apart from the scientific interest, there is also a potentially huge commercial stake in soft-landing missions to asteroids. Asteroids mainly consist of precious metals and could be viewed as orbiting natural resources, waiting to be exploited by daring human entrepreneurs. Several companies have proposed business plans for *asteroid mining*. While many technological, financial and legal problems remain to be solved it is clear that robotic devices will be essential for these scenarios.

4.3.4. Robotics for missions to other solar system bodies. ESA has recently approved a major science mission named BepiColombo which shall be launched to *Mercury* in 2009. Apart from two Mercury orbiters, it will include a lander dedicated to environmental, geochemical and geophysical investigations very similar to Mars landers. In the present baseline, the lander payload will include a micro-rover which can be derived from the Mars Nanokhod, and a mole similar to the one on the Mars Express Beagle-2 lander. Particular design challenges from operating on this planet very close to the Sun come from the thermal environment, but this depends very much on the time of (Mercury) day or night when the landing and operations will be scheduled. At dawn, the temperatures on Mercury are comparable to the ones on Mars.

Recent NASA plans (for a timeframe well beyond 2005) include a *Titan* Biologic Explorer (to search for life) and a *Venus* laboratory (to determine the history of the planet). In both cases, aerobots (robotic balloons) could be used (see section 3.2.4).

Other fascinating targets for robotic exploration include the Jupiter moon *Europa*, where life could exist, and the Mars moon *Phobos* that has interest as a possible relay station for Mars exploration. For Europa, which is believed to have a liquid ocean under a crust of ice, highly challenging robotic scenarios have been proposed (Atkinson 1999): penetrate kilometres of ice (by melting it with 'cryobots'), then turn into a submarine robot ('hydrobot') and locate living organisms.

5. Using space robotics

5.1. A robot is a tool for the (scientific) user

It may have become apparent in the preceding survey that space robots exist for the benefit of users and their applications. A lot of robotic technology is available and has been demonstrated in space. This has provided a rich set of 'building blocks' which can be configured for specific applications.

Many of these technologies have been developed with the express intention to make the actual robot as 'transparent' to the user as possible. Roboticists have come a long way from the first-generation systems which burdened their operators with digital displays of joint angles and currents and five different coordinate systems to be aware of. The progress in robot control is mainly being employed to 'hide' those details from the users, by encapsulating them in robust low- and medium-level activity programmes which use sophisticated sensor-based control to cope with imperfections in the environment modelling. In the '*interactive autonomy*' mode of operation, the (end) user on ground is provided with menus of tasks which are meaningful for the application, and which can be parametrized and flexibly composed into experiment plans. During their execution, the user can monitor the progress of the automated process via displays that are again tailored to the application, not to the robotic technology.

In practical mission implementations, this can be realized by separating a central 'Robot Monitoring and Command Station' from one or more (possibly decentralized) '*Payload Monitoring and Command Stations*' at 'User Home Bases'. Such a ground architecture will be implemented in European ISS robotic missions like EUROPA (Mugnuolo *et al* 1999), which could be the first space robot system geared to productively support ground-based investigators. This scenario is described briefly in section 3.1.8 and Aceti *et al* (1998).

5.2. Developing investigations involving space robots

Making the above-mentioned operations successful requires close co-operation between engineers and scientists from an early stage. This is not always easy. Long before the actual mission, it is often hard to get scientists seriously interested. If they do co-operate, they tend to speak a completely different language. In the beginning, engineers want 'requirements' (which the scientists are unable or reluctant to formulate) and scientists want 'tools' (which the engineers do not have ready yet, because they are waiting for the requirements).

This crucial first phase has to be overcome by mutual efforts. Scientists have to be patient, undergoing numerous interviews in order to extract an understanding of functions, performances, operations, interfaces, and budgets. Engineers have to dare to make assumptions and establish concepts to be shown to the users for critique. Even though this is not very popular, documentation is important because it clarifies the thinking and understanding. If you cannot write it down clearly, then you probably do not understand it. Written requirements are invaluable tools to establish common understanding, remove inconsistencies and establish priorities for tradeoffs.

It pays to follow a systematic phased development approach, and the first phases (user requirements definition, system requirements definition) are the most crucial ones: any changes to them later on will have drastic effect on the development time and cost. A system development methodology for space automation and robotics systems has been established in Putz and Elfving (1992). It compiles good practices and offers computer tools to support them. As one method to support the user requirements phase, a semi-formal 'activity analysis' language has proved very successful in facilitating the communication between users and developers. This stresses the importance of a careful description of the ultimately expected operation, from which everything else can be derived in a systematic fashion.

Very valuable means to establish baselines quickly are computer simulations and laboratory prototyping:

In state-of-the-art computer-aided engineering systems, the whole automated scenario can be quickly modelled, simulated, and analysed in its full 3D complexity. Parameter variations and tradeoffs can be done easily. A nice side benefit is that impressive *animations* can be produced which may be very instrumental in convincing decision-makers and funding agencies.

The next step is rapid prototyping of the baseline concept. This can undergo several stages of increasing fidelity and cost. For each laboratory demonstration and test, the objectives should be clearly stated, to make sure that one invests in the right aspect of the system. For test-beds of space robotic systems, judicious use can be made of low-cost industrial robot equipment which can be made to emulate the functionality, key interfaces, and operations of the actual system. This can go a long way before real engineering models have to be built.

In the design phase, both the robot and the payload side should be permanently questioned to achieve the most efficient overall system. This is the idea behind 'design for automation' which has revolutionized the terrestrial manufacturing industry. Slight design modifications to the payload (e.g. by providing standard grapple fixtures or by adding co-operative mating geometry) can greatly reduce the complexity and cost of the automation task.

The development phases of robot systems and payloads will run in parallel, so careful interface controlling is essential. Depending on the complexity of the payloads, models of differing representativity may be used to ascertain the proper co-operation.

The difficulties of fully testing space robot systems (in fact, any space systems) on Earth have been addressed in earlier sections. Air bearing tables, weight off-loading devices and other ground support equipment all provide only partial verification of the system behaviour in different gravity fields. Again, the judicious use of (dynamic) simulation is very important.

The moment of truth comes in integration and end-to-end acceptance testing, when all parts of the system come together for the first time before they are sent off to a possibly long journey prior to actual usage. But this is not specific for robotized systems.

It is realized that scientific or technological users do not find this cycle attractive. It takes too long, is too expensive, and involves too much documentation of issues remote from the investigators' core interests. That is why first attempts have been made at streamlining the development process for the users by providing modular multi-user robotized facilities like the TEF for exposure payloads on the ISS (Aceti *et al* 1998).

There, standardized experiment 'boxes' would be supplied to investigators to be 'filled' with their payloads. This takes care of the external interface issues. By virtue of the dextrous robot arm on the TEF, these experiment modules can be rearranged on their orbital platform (to time-share the most attractive viewing spots) and loaded to logistics resupply platforms. Drawers or trays in the experiment modules can be opened, inspected, extracted and inserted according to pre-programmed profiles, for instance to point them or to put them into on-board analysis instruments.

All of that means that only the absolute minimum of experiment essential hardware has to be provided by the investigator, with simple, checklist-type documentation. Even the possibility of proprietary 'black-box' payloads should be given, where the contents of the investigation and its technology do not have to be revealed in order to protect commercial or scientific interests. The modularity also will reduce the required lead times and the 'online' analysis will speed up the scientific exploitation, such that experimentation cycle times should become compatible with typical research expectations (e.g. a doctoral thesis).

5.3. Some other possible scientific uses of space robotics

An analysis of the application scenarios for space robotics (section 4) shows that so far, space robots are being built mainly for 'technical' uses (deploying satellites from the Shuttle, building up the Space Station, carrying payloads around, performing inspection and maintenance, repairing satellites, assembling large systems). The 'scientific' uses are currently limited to modest deployment of instruments on the Moon or Mars. On the ISS, the EUROPA system could be the first where robotics is used directly for the benefit of scientific or technological investigations.

This does not at all exhaust the potential of robotic tools, especially their flexibility and capabilities to perform programmable sensing and actuation tasks. With a little fantasy, much more unconventional use could be made of robotics. Rösgen and Putz (1997), for instance, suggest using robots on the ISS (basically the systems which will already be there) to

- Point and move sensor probes according to prescribed trajectories in the immediate environment of the Station, for instance to obtain 3D profile measurements of
    - plasma/wall interactions,
    - spatially non-uniform solar wind or wake effects,
    - magnetic fields.

- Point and move probes for in-flight calibration and tests of new sensors (such as atomic oxygen probes, particle analysers).
- Perform *in situ* measurement of materials properties (e.g. elastic modulus) by grasping a mechanically constrained test item, exerting a programmed force/displacement on it, and providing position or force measurements (dynamic exposure tests, accelerated ageing/fatigue tests); measurement results could be obtained 'online' without returning physical samples.
- Point or move a thermal baffle/sunshade/shield for tests (e.g. plasma analysis with electrostatic shielding, ultrahigh-vacuum tests with wake shielding, propulsion tests with exhaust shielding) under defined conditions (decoupled from the ISS orientation).
- Point and move (in programmable 3D scans) a plasma diagnostics package in the plume of a (novel) thruster for testing of new propulsion technology.
- Exert velocity and acceleration profiles (quite complex 3D motion patterns are possible) on a tank with sloshing liquid in order to perform fluid dynamics experiments or verify 'liquid sloshing' dynamics models.
- Point a mirror or antenna w.r.t. the ISS or an inertial reference frame in order to operate large telescopes or antennas, where the focal plane instruments could be inside the Station and look through a window at the robot-held primary mirror/dish.
- Grasp one end of a tether and excite oscillations, providing position and force measurements in order to do programmable dynamic testing of tethers.

Similar scenarios could also be envisaged on the surface of the Moon or Mars, where very unique conditions could be exploited, such as

- The exceptionally high seismic stability of the Moon (e.g. as a base for large interferometers).
- The absence of radio frequency pollution on the far side of the Moon (RF-wise the 'cleanest' place in the Universe).

6. Conclusions

This review has presented some of the technology and potential of robotic systems in space applications.

It has introduced general architectures for both robot arm systems and rover systems. The interdisciplinary system character of space robotics has been stressed, and the main subsystems have been described. Some of the key technologies were addressed. It was emphasized that most of them are available as building blocks that can be relatively easily combined into applications.

The 'conventional' applications scenarios for space robotics have been outlined, covering LEO, GEO, and planetary missions. It was shown that space robots are not at all new, with the Shuttle arms in duty since 1981 and unmanned rovers operating on the Moon in the early 1970s. With the start of the ISS era, however, space robotics should get a new boost: at least five different (external) space robot systems will become operational in the next five years. This could very well stimulate applications in similar scenarios, such as for laboratory internal automation or free-flying maintenance. Commercial interests could call for robots policing the GEO and repairing satellites, and scientific exploration of the solar system will employ (mobile) robots on Mars, Mercury, comets and the Moon.

Finally, the concept of space robots as transparent tools for Earth-based users has been emphasized and some less conventional uses of space robots for scientific investigations have been suggested. It is strongly believed that space robotics has huge potential, only small parts of which are currently exploited.

Such novel applications, however, can really only emerge from an intensive interaction and brainstorming of scientists, space roboticists, and space systems experts. To initiate this, some basic awareness by scientists is needed of the principal capabilities of space robotics. Contributing to that was one of the main intentions of this review.

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Ellery A 2000 *An Introduction to Space Robotics* (Chichester: Praxis)

Skaar S B and Ruoff C F (ed) 1994 Teleoperation and robotics in space *(Progr. in Astron. and Aeron. vol 161)* (Washington, DC: AIAA)

Possibly the only textbook on space rovers is Kemurdjian A *et al* 1993 *Planetokhody, (in Russian, availability of an English version unclear at the time of this writing)* ISBN 5-217-01207-2

Many useful tutorials are contained in

Dorf R C (ed) 1988 *Int. Encyclopaedia of Robotics: Applications and Automation* vol 3 (New York: Wiley)

Shapiro S C 1987 *Encyclopaedia of Artificial Intelligence* (New York: Wiley)

Relevant terminology and standards can be found in

Standard Vocabulary for Space Automation and Robotics AIAA S-066-1995

Manipulating Industrial Robots—Vocabulary (with annex in 6 languages), ISO/TR 8373

Some special issues of scientific *journals* on space robotics are

1993 *IEEE J. Robot. Auton. Syst.* **9** 5

1998 *Robot. Auton. Syst.* **23**

Some international *conferences* relevant for space robotics are

SPACE (ASCE Int. Conf. on Engineering, Construction and Operations in Space)—bi-annual, in the US

i-SAIRAS (Int. Symposium on AI, Robotics and Automation in Space)—bi-annual, around the world

ASTRA (ESA Symposium on Advanced Space Technologies for Robotics and Automation)—bi-annual, at ESTEC in Noordwijk (The Netherlands)

IFAC Workshop on Space Robotics (SPRO)—for the first time in 1998

IFAC Conf. on Intelligent Autonomous Vehicles (IAV)—bi-annual