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SPACE AUTOMATION AND ROBOTICS IN SUPPORT OF MICROGRAVITY EXPERIMENT APPLICATIONS; RESEARCH AND DEVELOPMENT ACTIVITIES

by

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SUMMARY

This document contains an overview of results from studies on Automation and Robotics (A&R) within the European space community. The scope of the overview is limited to the results related to internal vehicular activities, with emphasis on the support of microgravity experimentation. Other research areas, such as internal servicing and external servicing are shortly discussed.

In order to complete the overview of present state-of-the-art space A&R, some results of non-European studies are discussed and incorporated.

The overview is used to identify and classify Research and Development (R&D) needs in the field of internal automation and robotics within the European space programme, and to identify the possibilities for participation in these activities by industries and institutes in the Netherlands.

CONTENTS

(44 pages in total)

LIST OF ACRONYMS

A&R	Automation and Robotics
AID	A&R In-orbit Demonstration
AMF	Automatic Mirror Furnace
ASH	Automatic Sample Handling
BIAS	Bi-Arm Servicer
CAL	Columbus Attached Laboratory
CAT	Columbus Automation Testbed
CFFL	Columbus Free-Flying Laboratory
CWS	Crew Work Station
EMATS	Equipment Manipulation And Transportation System
EMS	Experiment Manipulator System
EUROSIM	EUropean Real-time Operations Simulator
EVA	Extra Vehicular Activity
HERA	HErmes Robot Arm
IA&R	Internal A&R
IVA	Internal Vehicular Activity
NBF	Neutral Buoyancy Facility
R&D	Research and Development
ROSE	RObotics Servicing Experiment
ROSED	ROSE Demonstration
ROSSA	RObotic Spacecraft Servicing and Assembly
ROTEX	RObotic Technology EXperiment
SMS	Service Manipulator System
TRP	Technology Research Programme
TDP	Technology Demonstration Programme

1 OBJECTIVES AND SCOPE

This report is meant to provide an overview of Research and Development (R&D) activities that have been performed and planned in order to realize Space Automation and Robotics (A&R) systems within the present European space programme and scenarios. The document focusses on the application of A&R in relation to the microgravity research activities, often called Internal Automation and Robotics (IA&R). The inventory of activities is considered to provide a basis for the assessment of future activities for industries and institutes in the Netherlands, but related to the European Space Programme.

The particular interest in IA&R has been brought forth by a number of Dutch industries, that are already working in the area of robotics, and has also been revealed by the presently limited contribution of Dutch industries to the R&D activities in the field of IA&R.

The interest for participation of the Netherlands has mainly been driven by the increased scope of R&D activities to be performed in the field of IA&R within the ESA programme, now and in the future. Servicing tasks are supposed to be a main class of activities within the planned Columbus laboratories. Reasons to start a programme for IA&R in support of Columbus payloads have been discussed regularly (see Refs. 6, 28, 32, 33).
For a substantial contribution to the development programme a considerable level of knowledge and experience in IA&R is required. A compilation of experience and knowledge in the Netherlands could lead to a recognizable position within the field of IA&R, which enlarges the possibility on participation in the ESA programme. In particular, the technology areas of lightweight constructions, drive systems, and control strategies satisfying the operational requirements are to be mentioned here.

The purpose of this document is to provide an inventory of all activities in this area within the European space community, but related study activities in A&R applied to External Vehicular Activities (EVA), and non-European study results are to be mentioned as well. The objective of identification and compilation of R&D activities is considered to be a basis for selection of particular R&D activities in IA&R, which may result in participation in future ESA projects and in a spin-off to other applications.

This report contains a number of R&D needs considered to be relevant within the present scope of ESA's IA&R research programme. In order to support the selection procedure, the activities are to be related to the planned missions and operations concerning the application of A&R.

2 ANALYSIS OF APPLICATIONS

2.1 Introduction

The European space R&D activities in A&R result from the present ESA Technology Research and Development Programme (Ref. 5). The following technological themes are applicable to the subject:

- microgravity utilisation;
- deep space & observatory facilities;
- manned systems and platforms;
- in-orbit operations and servicing.

The themes mentioned above may require very different strategies for implementation of A&R. Therefore, the interest will be focussed on the mission oriented application of microgravity utilisation and the infrastructure oriented application of in-orbit operations and servicing. These two areas will shortly be discussed in separate sections.
The manned aspect will depend on the system or platform that will be used for microgravity experiments. Experimental conditions and interfaces will require human interaction in space (Columbus laboratories) and/or human interaction from the ground segment (teleoperation, telescience). The aspect of manned interaction will be addressed in a separate section. The themes mentioned above are the basis for an ESA technology R&D programme for A&R. The results of the studies will be presented and future plans will be discussed. An inventory of activities is made by synthesis of the study results according to a classification.

2.2 Microgravity research applications

2.2.1 Microgravity experiments

Microgravity conditions open a new avenue for experimental research due to the elimination gravity-driven convection, the lack of sedimentation and buoyancy, and the absence of fluidstatic pressure.

Three main areas of microgravity research categories can be identified:
- life sciences (biological, human, animal, cell);
- materials sciences (metals and alloys, glasses, ceramics, etc.);
- fluid sciences (physics, combustion).

In the US similar areas of microgee experiments have been identified for the national programme, but the classification is more towards production (Ref. 37).

Identification of experiments to be performed onboard the Columbus modules, the Columbus Free-Flying Laboratory (CFFL) and the Columbus Attached Laboratory (CAL), is still in progress. The selection and definition of experiments is the responsibility of the users, such as national agencies and principal investigators. ESA will provide the necessary utilities and facilities to enable an optimal use of the laboratories (see Refs. 17, 18).
A microgravity reference mission has been defined for the CFFL to enable the analysis and definition of utilisation requirements. The reference payload for this mission, called the MIC-400 mission, comprises a set of reference microgravity facilities. An extensive analysis for accommodation of the reference payload has been given in reference 18. The MIC-400 reference payload has been used in most of the studies concerning internal A&R in order to provide the basis for operational analysis. Another list of facilities has been published recently (see Ref. 19).

On a cooperative basis with organisations outside Europe, a joint science utilisation study has been performed in which a coordinated science test mission set has been defined. This test mission set includes all the data necessary to optimise the coverage of microgravity applications within the present space programmes for Europe (ESA), USA (NASA), Japan (NASDA), and Canada (CSA). See reference 38.

Individual microgravity experiments are under investigation to be implemented within the utilisation concept. An example is BIOLAB (Ref. 21). The development of most of the experiments is still in a definition phase, which is part of the preparation phase (phase A, or pre-phase A). The development of utilisation aspects or facilities is in phase B (Ref. 21).

2.2.2 Experiment requirements

The different categories of microgee experiments, and also the experiments within a category, impose quite different experimental requirements on the facilities. The experimental requirements can be classified into two major features, the experiment conditions and the typical experiment duration (Ref. 20). Other payload classifications are used to identify the impact of accommodation or the requirements on crew support.

The experiment condition requirements for a particular experiment will determine the facility type. This will establish whether the facility is suitable for manned or unmanned operation, and this will, in combination with the typical experiment duration, determine the type of space carrier.

Some experimental requirements are:
- presence of man;
- soft gripping (animals, plants);
- incubation and nutrient supply;
- fuel supply;
- illumination;
- static or dynamic containment;
- mechanical stimulation;
- allowed microgravity disturbance level;
- electrical stimulation;
- thermal stimulation;
- exposure to radiation;
- thermostatic control (stability);
- temperature level;
- temperature stability;
- pressure control;

- concentration control;
- manipulation;
- diagnostics;
- observation (optical);
- data processing;
- sample return.

In fact, all these requirements can be classified into four major types of experiment requirements:
- conditioning;
- stimuli initiation;
- diagnostics;
- logistics and support.

The experimental conditions, and in particular the experiment time duration, will determine the platform to be used as carrier. Presently the following carriers are applicable (available or planned):
- Space Laboratory (D2);
- experiment platform (EURECA);
- Columbus Free Flying Laboratory (CFFL);
- Columbus Attached Laboratory to Space Station Freedom (CAL);
- Sounding rockets;
- Airplane (parabolic flight);
- Biokosmos.

For some of the carriers manned support in experimentation is possible. However, since the crew time availability to support experiments is very limited, the experiments should be automated as much as possible. This is one of the requirements imposed by the facilities on the microgravity experiments. In case full automation is not possible, possibilities for teleoperation from the ground segment are to be investigated (telescience). Other requirements are the limited budgets on volume, mass, and power consumption. Therefore, experiments should be designed towards multi-user experiment facilities, which are mandated by the resources limits.

In order to optimize the resources to the experimental requirements, a classification of requirements may be used. Within the scope of this document such a classification will be given as far as the needs for automation and robotics are concerned. The results may be used to analyse the needs for automation and robotics technology research and development in the Netherlands. A classification will be presented on experimental characteristics.

In general the experiments can be characterized by the following items:

- experiment cell characteristics:
  - o cell dimensions and volume;
  - o cell mass, centre of mass;
  - o cell shape, deformation characteristics.

- interfaces:
  - o operational interfaces (handling, experiment control);
  - o mechanical interfaces (support, gripping, clamping);
  - o electrical interfaces (stimuli, output data, power);
  - o other (nutrient, fluid, temperature).

- experimental conditions (level, accuracy):
  - o illumination;
  - o temperature;
  - o dynamics disturbances (microgee level);
  - o air pressure;
  - o radiation;

- experiment duration:
  - o seconds to minutes;
  - o minutes to hours;
  - o hours to days;
  - o days to months.

- support systems:
  - o mechanical support;
  - o electrical support;
  - o communication;
  - o data storage;
  - o experiment cell storage racks.

The requirement for optimization of resources provides an hierarchical system set-up:

- series of experiment samples can be processed in a sequence under identical or similar conditions and with identical or similar stimuli;
- different series of experiment samples may use one or more experiment facilities which provide the necessary conditions, stimuli, diagnostics, and data processing (might be a platform);
- a number of facilities, probably using similar resources, are to be combined into one or more laboratory racks;
- a laboratory will include a particular number of racks (Spacelab, Free-flyer, Attached lab.).

In NASA, the systems are divided in five categories, with decreasing user influence (Ref. 38):

1 - payloads: user experiment hardware;
2 - laboratory support equipment: microscopes, cameras, freezers, etc;
3 - general lab support facilities: glove boxes, work benches, etc;
4 - outfitting subsystems: vacuum vent, materials management subsystems, fluid management subsystems, etc;
5 - core subsystems: power, data, thermal, etc.

On each system level A&R technologies can be applied, dependent on the special purpose character of the operations and tasks to be performed.

2.2.3 Operational requirements

The following categories of operations can be distinguished according to the system levels:

- experiment dedicated operations;
- experiment facility dedicated operations;
- experiment rack dedicated operations;
- laboratory operations.

Operational interfaces between the four categories shall be provided to enable an optimized operations concept.

Experiment dedicated operations concern:

- experiment preparation activities:
  - o preparation of first experiment (may by crew);
  - o insertion of samples;
  - o connecting;
  - o switching;
    - . power
    - . data lines
    - . valves (gas, fluid, air)
  - o check and calibration of the experiment sample.
- experiment execution:
  - o dedicated transport of samples;
  - o position control and calibration of samples;
  - o process switch on;
  - o execution (heating/cooling/melting);
  - o conditioning control;
  - o experiment restart(if necessary).
- post experiment activities:
  - o switch-off;
  - o check-out;
  - o conditioning;
  - o deconnecting;
  - o removal of sample.

Experiment facility dedicated operations concern:

- facility preparation activities:
  - o removal of the sample magazine from the sample storage drawer or rack;
  - o open/close drawer;
  - o transportation of the magazine;
  - o precise positioning;
  - o insertion of the magazine into the experiment dedicated storage location;
  - o connecting and switch-on of facility resources (fluid, gas, power, etc);
  - o calibration of the facility subsystems.
- facility operation:
  - o conditioning (temperature, air pressure, disturbances,etc);
  - o experiment monitoring from teleoperator station;
  - o archival of experiment results.

- post experiment facility operations:
  - o exchange of sample magazins;
  - o cleaning of the facility;
  - o servicing (e.g. instrument exchange);
  - o (dis-)connecting and/or switch-off and check-out;
  - o waiting for next preparation (dormant).

Rack dedicated operations concern:

- preparation phase:
  - o switching;
  - o logistics (exchange of magazins and drawers).
- operational phase:
  - o managing of operations;
  - o data transfer;
  - o monitoring of the required support functions.
- post operational phase:
  - o logistics of payload to particular payload racks;
  - o exchange of facilities or facility elements (if required);
  - o switch-off and check-out.

Laboratory operations concern:

- preparation phase:
  - o laboratory power-up;
  - o communication;
  - o experiment programme start-up;
  - o checking and calibration of required support functions.
- operational phase:
  - o monitoring of support functions;
  - o control of required conditions.
- post operational phase:
  - o logistics to outside the laboratory;
  - o servicing.

The potential operators for the tasks to be performed are hybrid system concepts which may include:

- the astronaut (crew);
- astronaut assisted manipulators or mechanisms;

- experiment dedicated mechanisms (automated);
- rack internal handling mechanisms (automated);
- (multi-)rack external robot (partly automated);
- laboratory robot (partly automated).

The automated system elements will be based on a concept of teleoperation and autonomy.

Summarizing, three modes of operations will be possible:

- the human operator control mode
  In this mode the crew member will operate the onboard system interactively, or by means of teleoperator systems in case of specific experimental or servicing conditions. The operator might be on a remote location (e.g. somewhere in Space Station).
- the ground teleoperation mode
  In this mode the system will be operated from the ground by a ground based operations support system, which will include a human operator.The tele-operator mode is supposed to be a supervisory mode.
- the automatic mode
  In this mode the operations are completely automated. Human intervention will be possible, both from the space segment and the ground segment.

A combination of control concepts is recommended.

2.3 In-orbit operations and servicing

This theme covers a wide range of operational activities, such as rendezvous and docking, external servicing, assembly, internal servicing. In fact, within the scope of this report internal servicing activities are the only applicable activities to be dealt with. They are a subset of so-called Internal Vehicular Activities (IVA).

Servicing activities will be different for the space elements which are planned to be serviced. For instance, the Free-flyer servicing scenario differs from the servicing scenario for the Attached laboratory.

Since all servicing activities, directly related to experiment facilities, have already been discussed under section 2.2, in this section only laboratory servicing will be dealt with. A distinction should be made between manned and unmanned servicing.
Unmanned servicing activities will be performed by A&R systems. Besides a certain degree of autonomy, most of the servicing operations will be performed under control of a ground station in the teleoperation mode. Manned servicing operations will be performed by the crew. For the Columbus Free-flying Laboratory internal servicing will be performed by a laboratory robot, presently called EMATS, which may support the Hermes crew in servicing during the manned phase. For the Columbus Attached Laboratory, Space-station crew will perform internal servicing, probably supported by laboratory servicing support equipment, under an automatic mode, or a teleoperator mode by the crew.

Servicing operations include:
- logistics support (payload handling and inspection);
- assembly/disassembly of racks;
- laboratory reconfiguration;
- facility reconfiguration;
- maintenance and repair;
- facility operations, such as:
  - o cleaning;
  - o observation, inspection;
  - o opening/closing of doors/drawers.

A&R systems may support logistics, facility reconfiguration, facility operations and maintenance. Repair tasks could be performed in case of nominal operations. Non-nominal operations will be performed under the teleoperation mode.

Definition of requirements for A&R systems in support of internal servicing will include the following items:
- operational constraints;
- crew support/interaction;
- ground support/interaction;
- required autonomy;
- control flexibility (different modes of operation);
- dexterity in manipulation;

- complexity of tasks;
- range of motion;
- complexity of the environment (obstacles, restricted areas);
- load capabilities;
- mechanical interface capabilities;
- allowed disturbances (microgee compatibility):
  - o to the payload;
  - o to the environment.
- observation functions and performances;
- cleaning aspects;
- logistic aspects.

All these items should be addressed in order to realize a design concept for an internal A&R servicing system.

2.4 Manned versus unmanned operations

Crew availability onboard Columbus elements is envisaged to be very limited. The crew access time to the Columbus Free-FLying Laboratory is limited to a period of 5 to 8 days, two times a year. This period will be used to service the Free-flyer. No time is left for experiment control activities. Servicing will include the exchange of storage racks including experiment results, products and data. Onboard the Columbus Attached Laboratory crew will be needed to keep the system running by assembly, logistics, maintenance and repair. In particular, crew support is considered to be necessary to allow transfer of laboratory products to earth. Therefore, cooperation between crew and laboratory equipment is necessary. However, provisions will be made to allow crew interventions with the other onboard processes.

In general, it is concluded that most of the operations covering the field of experimentation and laboratory servicing will be automated, or operated from the ground by teleoperations. Some of the operations will be designed to allow crew intervention, in case automation is difficult or in case intervention is necessary due to required human resources (e.g. judgement, intelligence, decisions).

Manned operations onboard the Columbus facilities could be performed by the crew, directly or by means of computer assisted devices. These devices might be controlled from a remote location by the crew. Devices can also be controlled from a ground-based system including operator by means of teleoperation. Teleoperation is the technique which provides the extension of a human operators sensing and manipulation capabilities to a remote location (i.e. a barrier e.g. a distance) using remotely controlled devices.

When teleoperation concerns manipulating devices or robots, the term telemanipulation or telerobotics should be introduced. The degree of human operator involvement in telemanipulation may vary from direct or manual control via computer assisted control to supervisory control. Short term applications of telerobotic systems are considered to be single man-machine systems that allow to overcome the restrictions and shortcomings of telemanipulation and autonomy. A wide range of operational modes will be possible with varying degrees of autonomy and human intervention.

When teleoperation concerns the control and observation of experiments, the term telescience is to be used. Telescience is an operating mode which will allow experiments to be performed under conditions similar to those in terrestrial laboratories.

Automation and Robotics is supposed to provide an increased productivity and service capability onboard the columbus elements and is expected to provide an increased probability for mission success.

In general it is concluded that for space the ultimate goal is to have a teleoperation system with a high degree of autonomy which also has the capability of human intervention and control at a variety of levels. As an intermediate goal, the system should include a high performance teleoperator interface to an architecture that can support the evolution from teleoperation to autonomy.

3 RESEARCH ACTIVITIES IN AUTOMATION AND ROBOTICS

3.1 Introduction

An overview of R&D activities on A&R in space will be given. The whole range of activities, with emphasis on internal A&R, will be discussed. A&R technology research activities may be used for internal and external A&R.
First, a list of the main study areas is given. The studies will be outlined in the subsequent sections.

ESA R&D activities in IA&R:

- IA&R system studies.
- Development and test support activities for IA&R.
- Related external A&R system studies.
- Development and test support activities for external A&R.
- Related A&R technology studies.

Other non-European activities:

- US activities (NASA).
- R&D activities in Japan (NASDA).

3.2 System studies on Internal Automation and Robotics

Two parallel studies on Experiment Manipulator Subsystems (EMS) started in 1984, one by Microbo SA, and the other by Dornier et.al. (Refs. 7, 8). For both studies the objective was to design a manipulator system inside the Automatic Mirror Furnace (AMF) experiment facility, considered to be a EURECA reference payload, to exchange lamps and experiment samples. In addition the feasibility of the concept had to be established and a development programme had to be defined. Microbo SA came to a design of dedicated mechanisms, a gantry mechanism. The Dornier team developed two conceptual designs of robot systems. A skeleton concept was designed to allow comparison to dedicated mechanisms. It has four degrees of freedom, which is sufficient for the required manipulations. The number of operations (exchanges) increased from 24 to 100. An advanced concept presented a highly reliable robot system with advanced instrumentation.

The concept allows external loop control with exteroceptive sensors, which is considered to provide an increased mission success due to the high degree of automation. It was concluded that these concepts of soft automation were cost saving with respect to the use of hard automation concepts (dedicated mechanisms).

The Dornier concept, presented above, was used to start a study in 1986 on design of a general purpose servicing support system for the microgravity facilities onboard the Columbus Free-flying Laboratory, Automatic Sample Handling (ASH) (Ref. 10). The study included an inventory of handling needs of the potential users in the Columbus programme, a detailed design of a manipulator concept, and identification of demonstration needs and technology needs. Due to the lack of quantitative experiment facility data, the Experiment Manipulator System (EMS) concept presented in this study was proposed to be adopted as a technology model. The model was proposed to be a basis for a phased evolution of the Equipment Manipulation And Transportation System (EMATS) concept for the Free-flyer, and for development of an EMS for the Attached lab. In addition the model could be used for related studies on IA&R.

In 1989 a study on investigation of a complete automation system for the Columbus Free-flying Laboratory was finished by a team with Dornier (Ref. 12). The purpose of this study on EMATS was to investigate the utilisation of robotics in order to provide the means for manipulative interactions from the ground and for transfer of supplies within the laboratory and to/from the servicing vehicle. In addition a concept was to be derived suitable for application and for adoption as a technology model, which is focussed on relevant technology developments. The EMATS concept consists of a rail-based manipulator system which in fact has a total number of eight degrees of freedom to enlarge the workspace of the manipulator. The EMATS concept is driven by the results of the previous studies, by realistic estimates of technology risks, feasibility, and reliability. It has a rather small impact on the payload design, instead of dedicated mechanisms.

In 1988 the study of Robotics Spacecraft Servicing and Assembly (ROSSA) in Space was finished by a team with MBB/ERNO (Ref. 9). The purpose of this study was to get indications of the process of development of advancing European A&R

technologies, mainly on the area of European Space Station development. In fact this resulted in a number of concepts for external robotics, based on a micro-gravity experimentation scenario and an in-orbit assembly scenario build up to enhance the Free-flyer towards a space station.
The rider of this study, which finished 1989, included many results concerning internal A&R techniques (Ref. 11).

A dedicated robotic experiment study has been initiated to support the development of robotics technologies for internal robotics, ROTEX (Ref. 25). This experiment is set up for the space flight mission D-2. The purpose of the experiment is to test technological and operational aspects of internal robotics within an experiment facility.

Future ESA study activities on development of IA&R systems will mainly be concentrated on the development of EMATS. The EMATS follow-on study programme contains the following elements:

- EMATS preliminary design (phase B), to be started 1990;
- Columbus Automation Testbed based on the EMATS concept, EMATS/CAT, starting 1990-1992 (see next section);
- A&R In-orbit Demonstration based on the EMATS concept, EMATS/AID, planned for 1994-95 (see next section);
- Ground Infrastructure for Payload Automation and Servicing, GIPAS, not yet planned;
- integration of EMATS and Columbus, planned for 1997-98.

Except for ROTEX, no study activities are planned for the development of experiment dedicated support systems. The development approach is based on the distinction that should be made between payload specific A&R systems and laboratory common equipment. ESA is supposed to be responsible for the laboratory common equipment and will support the development of payload specific A&R, which is the responsibility of the users.

3.3 Development and test support for IA&R

As part of the Technology Demonstration Plan (TDP), Technospazio has set up an In-Orbit Technology Demonstration study on critical components for robotics. The purpose of the study is to prepare a test flight which enables the measurements of the microgee performance of a classical robot joint. This is because of the technological challenge to meet the requirements of 10E-6 g. The scope of the study comprises both IVA and rack internal dedicated drive mechanisms (Ref. 30).

In 1990 the study on the Columbus Automation Testbed for the EMATS concept was started by a team with Technospazio (EMATS/CAT).
The purpose of this study is to demonstrate a robot based automation concept for payloads in the Columbus pressurized modules based on terrestrial existing technologies. The testbed could be used for payload development support, and for development of mission software (planning S/W). The testbed will also provide a point of contact for initiation of new A&R technology developments.
User requirements for development of internal A&R systems are to be defined using the Space Station User Panel (SSUP) and by conducting experiments with the EMATS/CAT so evaluating the requirements. The Columbus Automation and Robotics Testbed is to be integrated at ESTEC in a Columbus Element mock-up.

As a precursor of the CAT facility the Internal Automation and Robotics Technology Test Bed (IARTTB) has been proposed by ESA. This testbed is a workcell for the EMATS technology model, according to a Columbus payload mock-up. The workcell will contain a number of reference payloads and grappling mechanisms on cassettes, drawers, tools, and samples to provide a testbed for A&R technologies. It will be installed at ESTEC (Ref. 29).

As part of the development programme for EMATS, an A&R In-orbit Demonstration (AID) mission has been proposed to verify the microgee performance and to perform a fully operational sequence of payload servicing with a Columbus representative payload. Besides the demonstration of A&R technologies, the AID is meant to validate and demonstrate the A&R concept applications to users and astronauts. The demonstration is planned to be implemented during a spacelab mission in 1994-95.
The research characteristics of the AID are:
- 1 manipulator arm of up to 8 axes;

- use of specially developed microgee compatible drives;
- EMATS representative control S/W and control electronics.

The ROTEX development is considered to be a precursor of the EMATS/AID. Parts of ROTEX are supposed to be suitable for development of The AID mission. For ROTEX, see section 3.1.

Two related studies could be mentioned under the heading of development and test support, but are not directly meant to support the development of A&R technologies. The Crew Work Station (CWS) testbed, studied by a team with MBB/ERNO, is meant to support the development of Man-Machine Interfaces (MMI) as far it concerns onboard operations. The MMI concept will be used to enable crew to operate internal and external robots (Ref. 36). The Telescience TestBed study by a team with MATRA is meant to support the communication aspects of ground based control of onboard operations. Internal manipulators might be controlled from a ground station under restricted conditions (Ref. 35).

3.4 External robotics system studies

During the last decade a number of system studies on external robotics have been performed. These studies will be mentioned here for completeness of the overview on R&D activities in space A&R.

The first European manipulator concept has been proposed in a study by a Matra team. The Service Manipulator System (SMS) has been developed up to a detailed design. It still supports the development of the HERA. From the SMS concept a Robotics Servicing Experiment (ROSE) was initiated and studied by a team with Sener. The purpose of the experiment was to support technology development of space robotics onboard the EURECA free-flyer.

The SMS has been used as a precursor of the Hermes Robot Arm (HERA), which is planned to support external servicing of the Columbus Free-flying Laboratory. HERA will be operated from the Hermes spaceplane. The manipulator arm design has reached the development phase C/D. Fokker (FSS) is the main contractor.

The ROSSA study, mentioned earlier in this report, also provides some concepts for external robotics. These concept however are very preliminary, but will have their impact on future robotics concepts. For future complex autonomous servicing tasks, a Bi-Arm Servicer (BIAS) concept is presently investigated. The

technological manipulator aspects are supposed to be according to the robots mentioned before. The BIAS concept is studied by Matra.
Most of the studies mentioned in this sections are reported in general literature on robotics study activities (See Refs. 1, 2, 3, 4).

3.5 External A&R facilities

Studies on development and test support facilities for external A&R systems and operations are mentioned here for the purpose of completeness:

- European Real-time Operations Simulator, EUROSIM;
- HERA Simulation Facilities, HSF;
- HERA Test Facility, HTF;
- ROSE Demonstration, ROSED;
- Neutral Buoyancy Facility, NBF;
- Servicing Test Facility (STF) at DLR, Oberpfaffenhofen.

These facilities and the related studies are reported in the general reports and conference proceedings on European space operations and technologies. See also sections 3.4.

3.6 Related ESA studies on A&R

In this section an overview of ESA studies on related A&R aspects will be given. The studies are meant to support development of both internal and external A&R systems.

1 Survey of State of the Art in Robotics and AI
This study, performed by Dornier and Matra, has been initiated to establish the state of the art in robotics and Artificial Intelligence, and to provide the requirements to set up a robotics research programme.

2 Control Loops with Human Operators in Space Operations
Since space robots were supposed to be controlled by human operators, a study on the human engineering aspects of operator controlled servicing tasks were studied by NLR and Fokker.

3 Design Techniques for Robots

The design aspects of space robotics were studied by a team with Fokker. All aspects were concerned: manipulator, control, planning, hardware and software, sensors. This basic research has been used to support development of SMS and HERA.

4 Teleoperation and Control

The successive study of control loops with human operators was directed towards teleoperation of manipulators. Special attention was paid to the man-machine interfaces (controllers and monitors). The study was performed by a team with BAe (Ref. 15). Presently, the third study on this subject has been started. The MMI is interfaced to a laboratory manipulator at ESTEC.

5 Robotic Intelligence

This study has been set up to bring artificial intelligence to a more mature level in support of space robotics. The purpose is to set up a prototype, which -by its general structure- has the function of a testbed. The study has been performed by a team with Laben (Ref. 13).

6 Control Techniques

This study has been performed by a team with Dornier Systems (Ref. 31). The main objective is to establish an A&R control reference architecture. The first step was to define a functional reference model, which has to be refined in a control reference architecture in the second phase. The study was started from basic requirements. Existing control architectures were studied such as:

- NASREM;
- ESPRIT 623;
- IMAS (Intelligent Mobile Autonomous Systems).

Preliminary conclusions (still under discussion):

NASREM approach is very good for the execution levels but its data structure is not very suitable for the planning levels. For the higher levels the ESPRIT approach is better.

7 Microgee Compatible Drives

This study started in 1989 by a team with MBB/ERNO. The main objective is to develop a rotary drive system including control which is optimized concerning the microgee compatibility requirements.

8 Stereovision, Mission Requirements Study

This study was performed by Technospazio (Ref. 16). The purpose of the study was to derive the functional and performance requirements for stereovision in case of two mission concepts, a BIAS mission and a deep space mission. Additional study activities were focussed on consolidation of requirements concerning the use of stereovision and on autonomy of task execution.

9 Sensor Based Robot Control study

This study will start in 1990. The main objective is to analyse A&R task relevant sensor based control and instrumentation concepts, primarily focusing on compliance control.

10 Autonomous Robot Control and Simulation study

This study started in 1990 by a team with Technospazio. The objective is to establish a reference model for task execution planning and programming to be implemented and tested by means of a prototype realisation based on existing software components.

The study started from the existing off-line programming system ESPRIT 623 and add path planning, sequence planning, etc.

3.7 Other R&D activities

3.7.1 NASA study activities

Space A&R studies in the United States have a broad spectrum of items. Most of the present activities are focussed on the automation of Space Station Freedom. In the past many studies have been performed on the design, development and operation of the Shuttle Remote Manipulator System (SRMS), or Canadarm. Many studies concern the human operator aspects of the long flexible arm. Present studies concern the succesor of the SRMS for Freedom, the SSRMS. In addition a teleoperated Flight Telerobotics Servicer (FTS) will be developed. Only minor effort will be delivered to the development of space laboratory robots. Some studies will be done, but they are meant to support the crew. Autonomy is not the primary objective of US internal robotics. For an overview of R&D items, see references 22, 23, 26, 34.

3.7.2 A&R research activities in Japan by NASDA

Very advanced A&R concept are studied by the Japanese space research institutes. An overview of present activities is given in reference JSU-89. Many activities are concentrated on autonomy and man-machine interfaces (Ref. 24, 27).

3.8 Classification of activities

An overview of study activities on space automation and robotics has been given in previous sections. In order to draw conclusions on the coverage of required research items, the European studies should be classified. A preliminary list of classification items is given.

Status of the R&D activities:

- completed;
- running;
- planned;
- required.

System level:

- space project/mission/application/operation/system;
- technology (s/s, component, unit);
- support facilities/capabilities (development-, operational-)

Applications:

- internal servicing;
- Others (e.g. assembly, demonstration).

Technology areas:

- Robotics;
  - o TBS.
- Automation;
  - o hard automation;
  - o soft automation.
- Human operator aspects;
  - o TBS.
- Interfaces;
  - o TBS.
- support facilities;
  - o TBS.

Relevance within scope of this study:

- high (directly related to the subject of IA&R technologies);
- low (only coverage of a research area related to IA&R).

Development phase (A,B,C,D):

- studies (basic);
- studies (feasibility);
- design and development;
- test and verification;
- operation.

Geographic distribution:

- TBS.

4 REQUIRED R&D ACTIVITIES IN EUROPEAN SPACE A&R

4.1 Introduction

The purpose of this chapter is to give a summary of potential R&D activities for Internal A&R, based on the description of microgravity applications, given in chapter 2, and the present R&D activities given in chapter 3. The R&D needs will be identified within the scope of the present ESA programme. Some R&D needs for space A&R have been specified in references 14 and 34.

4.2 The ESA programme

The ESA technology Research and Development programme contains a number of themes that can be mission oriented and infrastructure oriented.

The internal A&R activities are elements of the following themes:

- mission oriented:
  - o microgravity utilisation.
- infrastructure oriented:
  - o manned systems and platforms;
  - o In-orbit operations and servicing.

For realisation of the programme, the programme structure contains three sub-programmes:

- basic Technology Research Programme (TRP), applicable to medium- and long-term missions;
- Supporting Technology Programmes to different programmes and projects (STP), for demonstration of specific technology areas;
- in-orbit Technology Demonstration Programme (TDP), for demonstration of technologies that can not be tested on ground.

The TRP distinguishes a number of technology areas, that cover the basic needs for realisation of the programme. Technology areas that are directly relevant to the subject are:

- data handling;
- simulation and man-machine technologies;
- control systems;
- structures and mechanics;
- instrument technologies (sensors);
- ground systems.

The following topics were identified within the in-orbit servicing programme of ESA:

- general robotics;
- extra-vehicle robotics;
- intra-vehicle robotics;
- advanced robotics;

- servicing aids and interfaces;
- simulators.

In its programme, ESA makes a distinction between current, medium term (2-5 year), and long term (5-10 year) activities.

4.3 Identification of needs

In this section the R&D needs for A&R will be identified according to a top-down approach. Starting with the ESA programme for space utilisation, and the scope of this report concerning microgravity application, the A&R system concept is elaborated to the level of components and required technologies to enable the design and development of a complete system.

The following steps are taken as a guide to identify the R&D needs:
- microgravity application analysis;
- A&R concept analysis;
- A&R operations analysis;
- A&R system analysis;
- Automation technologies;
- Robotics technologies;
- human operator involvement;
- interfaces;
- ground support facilities.

These main R&D items will be elaborated in the subsequent sections.

4.3.1 Microgravity applications analysis

This research area addresses the analysis and specification of requirements for the experimentation in the microgravity environment. Problems related to the functions, the environment, the infrastructure, and the operations, are to be specified. The following items are to be investigated.

- number and type of experiments;
- identification of a reference payload;
- experiment functions to be implemented:
  - o conditioning;
  - o observation, diagnostics;
  - o stimulation;
  - o storage.
- experiment interfaces:
  - o mechanical (dimensions, weight, fixation);
  - o electrical (power, data);
  - o operational (gripping, manipulating,etc).
- operational aspects:
  - o experimentation tasks;
  - o servicing tasks;
  - o maintenance tasks;
  - o human operator tasks.
- performance aspects:
  - o accuracy of conditioning;
  - o timing aspects (duration, accuracy);
  - o onboard test and verification.
- environment aspects;
  - o microgee disturbances;
  - o temperature, light, radiation.
- ground support functions:
  - o preparation;
  - o experimentation;
  - o post processing.

These items are to be analysed as far as system or laboratory constraints are available. A trade off analysis will result in a description which enables the definition of a A&R concept.

4.3.2 A&R concept analysis

The A&R concept will strongly depend on the scope of the required activities to be performed. In case dedicated experiment support is required, a hard automation concept will be obvious. When overall servicing activities are to be automated, a soft automation concept will be advised.

The concept analysis will address the following functions:

- conceptual design of:
  - o onboard functions;
  - o ground support functions;
  - o communication concept.
- task distribution between crew, system and ground segment;
- level of autonomy;
- safety and reliability aspects;
- demonstration and verification aspects;
- design and development aspects;
- documentation.

A refinement of the concept may result in decisions on modularity of the system set-up.

4.3.3 A&R operations analysis

The application analysis and the A&R concept analysis will allow an operations analysis for the A&R system concept. The most important aspects to be considered are:

- manned activities;
- automated activities;
- teleoperation functions:
  - o from a remote location in space;
  - o from the ground segment.
- operational interfaces;
  - o communication characteristics;
  - o time delays.

- high level control tasks:
  - o mission preparation;
  - o mission planning;
  - o task distribution;
  - o high level sensor based control.
- Man-Machine Interface functions;
- telepresence functions;
- training programmes.

4.3.4 A&R systems analysis

The analyses mentioned above may be used to refine the A&R system concept on subsystem and component level, based on overall performances. The system will have the following main subsystems:

- automation subsystem;
- robotics and mechanism subsystem;
- man-machine interface subsystem or teleoperator facility;
- communication subsystem;
- ground support subsystem.

For each of the subsystems the most important characteristics and performances are to be specified. There is a need to support this kind of analysis and research activities by means of general purpose analysis techniques.

The aspects to be investigated for each of the subsystems will be given below.

- automation subsystem:
  - o motion trajectories;
  - o fine/coarse motion control;
  - o dynamic range of motion/control;
  - o number of operations to be performed;
  - o mass memory characteristics;
  - o sensor information to be processed.

- robotics and mechanism subsystem:
  - o kinematics and dynamics;
  - o payload characteristics;
  - o allowed disturbances;
  - o number and type of sensors.

- man-machine interface subsystem or teleoperator facility:
  - o controllers (passive and active);
  - o visual display systems;
  - o graphic visualisation and animation.

- communication subsystem:
  - o onboard data handling;
  - o TM/TC;
  - o ground communication characteristics.

- ground support subsystem:
  - o development support;
  - o simulation and test support;
  - o training support;
  - o operations support;
  - o post operations support.

4.3.5 Automation technologies

On the level of technology research activities for automation, the following subjects can be identified:

- on-board data handling;
- operations planning techniques with support technologies (e.g. ES);
- programming and intelligence;
- high level planning and reprogramming software
- obstacle avoidance;
- autonomy;
- knowledge base for health and fault management;
- emergency/error handling;

- artificial intelligence techniques;
- standardised control algorithms;
- hardware technologies.

4.3.6 Robotics technologies

Robotics technology research activities that could be identified are:

- standardisation in technologies;
- mechanical structure:
  - o lightweight constructions (limbs, rails).
- electrical architecture;
- thermal characteristics;
- servo control hardware and software;
- drivers/actuators;
  - o microgee compatibility;
  - o modularity of joints;
  - o integration technologies.
- sensors:
  - o sensor integration techniques;
  - o miniaturisation.
- exteroceptive sensors:
  - o vision system technologies;
- latch mechanisms:
  - o microgee compatible latch mechanisms.
- end effector mechanisms;
  - o gripper technologies (soft-hard gripping);
  - o conditioning functions;
  - o integrated sensor functions (e.g. force/torque).
- tool mechanisms technologies:
  - o tool exchange mechanisms (standardisation);
- linear drive mechanisms;
- cable and connectors;
- work cell layout design;
- dedicated mechanisms (reduced dexterous manipulators);
- electronics design technologies.

4.3.7 Human operator involvement

Technology and organisation aspects requiring research activities are:

- crew efficiency aspects;
- teleoperation techniques;
- telepresence technologies;
- telescience aspects;
- MMI
  - o predictive displays;
  - o 3-D reconstruction and visualisation.

This list is not considered to be complete.

4.3.8 Interfaces

Integration of all subsystems, requires the use of optimized interfaces.
Some areas for research are:

- communication:
  - o procedures;
  - o time delays.
- data interfaces;
  - o optical data transmission;
  - o radio frequency data link;
- power transmission technologies:
  - o optical power transmission;
  - o sliding contacts (space qualified).
- resources.

4.3.9 Ground support facilities

Ground support facilities have to be equipped with state-of-the-art technologies, in order to provide the most efficient development progress. Areas for research are:

- development support:
  - o A&R demonstration and test bed;
  - o in-orbit demonstration.
- test and simulation support:
  - o modelling and simulation of contact;
  - o efficient dynamics simulation (real-time, non-real-time);
  - o toolbox.
- training support facilities;
- operational support;
  - o ground telerobotic control support software;
  - o 3-dimensional graphics simulation;
  - o ground planning and reprogramming support.
- post operational support.

4.4 Classification of needs

A classification of R&D needs is supposed to be related to the scheduling of priorities. The priority will depend on the readiness level of the required technologies, and the expected time for development, which will depend on complexity.

Readiness levels for technologies are:

- not available;
- available in other application areas (undersea, power plants, etc);
- basic principles;
- conceptual design;
- analytical and/or experimental tests performed;
- functional/performance demonstration;
- prototype tested;
- engineering model tested;
- available.

5 CONCLUSIONS

The objective of this report was to summarize the present activities in internal Automation and Robotics (A&R) and to identify and prepare a classification of the Research and Development (R&D) needs to enable the development of a system that fulfils the operational requirements for an automated microgee experiment laboratory.

A description and operational analysis of microgravity applications has been given within the scope of the study objective to identify (R&D) needs for automation and robotics.

An overview of the present and near-term planned R&D activities in A&R is given. Special attention has been given to the European space R&D activities.

Finally an overview of technology R&D items are presented. These items cover the whole range of activities to be performed in order to make a realistic and feasible concept for internal A&R. The eventual selection of R&D should be based on a priority analysis, which will depend on the present technology readiness level of the particular subjects. This selection still has to be performed. A preliminary selection is proposed in reference 39. In addition, the selection will be based on the possible theoretical and technological support in the Netherlands, and on the possible applications within the microgravity research area. Moreover, the relation with the external robotics activities in space (HERA) has to be identified, and also the relation with existing knowledge and experience in the field of earth robotics.

In order to realize a R&D programme for IA&R in the Netherlands, some remarks are added:

- existing technologies are to be reused as much as possible;
- duplication of existing activities within the European space community can not be avoided;
- it is recommended in principle to harmonize the programme with the present activities in the field of A&R in the Netherlands.

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