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THE NETHERLANDS

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SPACE AUTOMATION AND ROBOTICS FOR MICROGRAVITY EXPERIMENT APPLICATIONS; PRELIMINARY IDENTIFICATION OF RESEARCH AND DEVELOPMENT TOPICS

by

P. Dieleman and C.N.A. Pronk

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NLR CONTRACT RAPPORT

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SUMMARY

A short study has been carried out by NLR to identify Research and Development (R&D) areas in the field of Automation and Robotics (A&R) for space applications which may be relevant for Dutch space industry to participate in.
The report at hand gives an overview of space A&R activities and a preliminary identification of R&D topics, whereby special attention is given to items related to the use of A&R in supporting microgravity experiment facilities located inside a pressurized spacecraft.
Main attention is focused on activities which take place in the ESA/ESTEC framework with emphasis on the need of A&R technology for Columbus.
The report will be used as a starting point for a detailed evaluation of present requirements and identification of R&D needs.
This evaluation will then be used to identify, classify and select those areas relevant for Dutch space industry and research institutes.
This should result in a project proposal to NIVR by a consortium of Dutch industries and institutes. The project should aim at enhancement of the Dutch technological position within ESTEC in the field of space related A&R. An early shortlist of possible projects is included in this report.

CONTENTS

(30 pages in total)

GLOSSARY

Automation	The use of machines to effect initiation, control, modification, or termination of system/subsystem processes in a predefined or modeled set of circumstances. (...) The terms hard automation and flexible (or soft) automation define subsets of automation [MEI,85]
Autonomy	The ability to function as an independent unit or element, over an extended period of time, performing a variety of actions necessary to achieve pre-designated objectives, while responding to stimuli produced by integrally-contained sensors [MEI,85]
External Robotics	Robotics applied outside a spacecraft, i.e. form of EVA.
Internal Robotics	Robotics applied inside a, possibly pressurized, spacecraft, i.e. form of IVA
Robotics	Use of robotic means to carry out certain tasks. A specialized discipline within the broader fields of autonomy and automation [MEI,85]
Telemanipulation	Teleoperation, applied to manipulator systems, where continuous detailed commands have to be provided by the human operator, via control input devices such as joysticks or replicas (master arms) [WIN,90]
Teleoperation	The Technique of using remotely controlled devices which receive instructions from a human operator to perform some action at a "remote location", i.e. across a barrier, for instance, a distance, the hostility of an environment or the physical magnitude of the task to be performed [WIN,90]
Telepresence	The ability to transfer a human's sensory perception (...) to a remote site for the purpose of improved teleoperation performance. At the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions. At the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite [MEI,89].

Telerobotics	Teleoperation applied to manipulator systems [WIN,90]
Telescience	Telepresence by a scientist in support of a scientific experiment

ACRONYMS

A&R	Automation and Robotics
CAT	Columbus Automation Testbed
CWS	Crew Work Station
EMATS	Equipment Manipulation And Transportation System
EMS	Experiment Manipulation System
EUROSIM	EUropean Real-time Operations SIMulator
EVA	Extra Vehicular Activities
GIPAS	Ground Infrastructure for Payload Automation and Servicing
HERA	Hermes Robot Arm
HILT	Hardware-In-the-Loop Tests
HSF	HERA Simulation Facility
HTF	HERA Test Facility
IOI	In-Orbit Infrastructure
IVA	Intra Vehicular Activities
JEM	Japanese Experiment Module
JEMRMS	Japanese Experiment Module Remote Manipulator System
MMI	Man-Machine Interface
MTFF	Man-Tended Free Flyer (now: Columbus Free-Flying Laboratory)
NBF	Neutral Buoyancy Facility
OMV	Orbital Maneuvering Vehicle
PODI	Prototype Optical Diagnostics Instrument
RMS	Remote Manipulator System
ROSSA	Robotics, Spacecraft Servicing and Assembly in Space
ROTEX	RObot Technology EXperiment
R&D	Research and Development
SMS	Service Manipulator System
SSRMS	Space Station Remote Manipulator System
SSS	Satellite Servicer System
TM/TC	TeleMonitoring/TeleCommanding
TTB	Telescience TestBed

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= parttime unmanned ?

1 INTRODUCTION

Automation and Robotics (A&R) is expected to play a major role as a tool to support manned and un-manned operations using the future European In-Orbit Infrastructure (IOI) [KIR,89]. A high level of automation is important for manned or man-tended spacecraft due to the restricted crew time available during the manned periods. In case the spacecraft is (part-time) un-manned, like the Columbus Free-Flying Laboratory, automation is even more demanding. Application of A&R could also improve the safety and reliability of the operations at hand. Several studies have indicated that A&R devices are well suited for supporting, replacing and complementing astronauts in performing their tasks.

At this moment involvement of Dutch space industry in Space A&R is limited. Up to now major effort has been directed towards HERA design and development. It is the intention of Dutch space industry and institutes to extend the activities in A&R applied in space [NIS,89]. NIVR and NLR have initiated a study to investigate possible areas where Dutch involvement, especially within ESA/ESTEC framework, could be substantiated. This report is a result of the study performed[1].

The report aims to provide a starting point in the detailed evaluation of requirements for space A&R systems and definition of essential near-future R&D activities. To this purpose this report is structured as follows:
Chapter 2 gives the study objective.
Chapter 3 defines the scope of the study and the approach followed.
Chapter 4 provides an overview of relevant studies and literature in the area of A&R, with main attention paid to European activities.

1 A draft version (no.4) of this report entitled "Space Automation and Robotics for Microgee Applications; Identification of Topics and Environment for Research and Development" was issued at 900315, distributed to NIVR (900409), FSS and SPE, and commented upon by FSS and SPE. The completion of the report was delayed by the preparation of the proposal, being the studies first priority output.

Chapter 5 gives a preliminary identification of R&D needs in internal A&R, also referred to as 'IA&R', where special attention is given to the use of A&R systems located inside pressurized spacecraft in support of microgravity experiment facilities. ESA/ESTEC activities are regarded most relevant, with emphasis on Columbus.
Chapter 6 contains a list of possible projects involving these R&D topics.
Chapter 7 lists the conclusions from the present report.
Chapter 8 gives a list of references.

2 STUDY OBJECTIVES

The objective of the present study is twofold:

- Identify R&D topics and goals in space A&R for the next decade, both concerning required technologies and supporting facilities needed;
- Define a project and prepare a project proposal based on selected R&D topics, in cooperation with Dutch space industry.

The project proposed should provide a sound basis for the project team members in the Netherlands to:

- keep up-to-date and expand expertise in A&R;
- initiate development of qualified products for space A&R applications;
- establish a 'recognized' position within the European space market in A&R.

This should facilitate participation in relevant space projects (such as Columbus) based on obtained IA&R knowledge and available products and/or facilities. The project should also have the potential to generate technology spin-off for terrestrial applications.

Major inputs for in the identification of R&D needs are:

- Present A&R concepts and related activities in the European Space community;
- Relevant technological knowledge and experience available within Dutch

companies and institutes;

- Relevant infrastructure available in support of the R&D activities.

3 STUDY SCOPE AND APPROACH

In space A&R a major subdivision is made in:

- external A&R, indicating the use of a manipulator in free space;
- internal A&R, using the manipulator inside a, possibly pressurized, space plane.

This subdivision is important because of the large differences in size, technology, type of applications and operation of the robotics devices used externally and internally. In this report we concentrate on A&R within the scope of internal robotics based on the following rationale:

- Internal robotics is expected to have a larger range and variety of applications than external robotics within the scope of the current European IOI framework. Where external systems will be used mainly for standard ORU exchange and inspection tasks, internal systems are expected to be used for general servicing tasks and in support of operating numerous microgravity experiment facilities;
- Internal robotics can (and probably will) be used in support of microgravity experiment facilities on which expertise is available (e.g. NLR, FSS);
- Computer simulation experience in external robotics is available and could form a good starting point for simulation of internal robotics. This applies for both model- and tool software;
- Internal robotics allows for relatively easy-to-build 1-g 3-D full scale physical simulators to form a test-bed for functional and technology tests;
- For internal robotics to be cost effective and efficient a certain degree of automation/autonomy of the system is important. This means that many telerobotics, teleoperation, telepresence and telescience control aspects have to be carefully studied (e.g. MMI design, time

delay's, TM/TC limitations, safety, reliability). Dutch institutes and industries are active in this field;

- Internal robotics may be a tool for the experimenter from the utilisation centre. The definition and set-up of a Dutch Utilisation Centre is considered.

The use of internal A&R can result in several concepts, such as:

- Rack external systems, i.e. a system to support multiple racks and facilities;
- Rack internal system, i.e. a system to support a single (experiment) facility with a work volume restricted to that facility.

Because of the multi-purpose and programmable nature of rack external systems these are often referred to as 'soft automation'. Facility or rack dedicated systems with limited functionalities are referred to as 'hard automation', although several functions may be programmable. The choice which type of automation shall be selected for further R&D will not be made in this report.

The approach followed during the study is as follows:

1. A glossary of R&D activities in Europe, the USA and Japan related to space application of A&R systems is made, followed by a preliminary identification of major R&D items in A&R;
2. A detailed evaluation of requirements and identification of R&D needs will be carried out;
3. This evaluation will be used to identify, classify and select those areas relevant for Dutch industry and research institutes;
4. From those areas a selection has to be made, resulting in a project proposal to NIVR by a consortium of Dutch space industries and institutes.

The remainder of this report describes the results of the first step in the approach outlined above.

4 OVERVIEW OF SPACE AUTOMATION AND ROBOTICS ACTIVITIES

A proper choice of near future R&D activities requires a good insight in the present status of A&R designs and technologies for application in space. This chapter gives a brief description of present and near future space activities in the field of space A&R, with emphasis on the European situation. This chapter is concluded with some remarks on microgravity experiment facilities, which may provide the main drivers for A&R technology development.

Note that this chapter only gives a preliminary overview and is to be reviewed and completed in the remainder of the study.

4.1 Europe

Insight in and knowledge of activities as carried out in Europe are of major relevance to identify R&D needs. R&D in the field of space A&R is going on for several years now within the European Space community. In recent years the activities have concentrated on robotics systems aimed to support the European In-Orbit Infrastructure (IOI) [COL,89].

A&R elements foreseen to be present in the European IOI are:

- External robotics:
  - HERA; Hermes Robot Arm [HAM,89];
  - BIAS; BI-Arm Servicer [AND,89].) verschil?
- Internal robotics: Rack external!
  - EMATS; Equipment Manipulation and Transportation System [PEU,89];
  - Experiment-dedicated rack-mounted A&R systems [ROS,89]. Rack Internal!

Some relevant completed ESA studies for internal A&R are:

- EMS (Experiment Manipulator System) by Dornier [EMS,86];
- EMATS [EMA,89]; Dornier et al
- ROSSA (Robotics Spacecraft Servicing and Assembly) and rider [ROS,89]; MBB/ERNO

From these studies EMATS provides the most detailed development plan including a list of R&D topics which are of major interest.

Studies which also address internal A&R are:

- MTFF Utilisation study [MTF,88]; MBB/ERNO et al
- APM Utilisation study [APM,88]; Aeritalia et al
- Control studies, especially aimed at external robotics:
  - Teleoperation and control [BAE,89]; British Aerospace
  - Robotic Intelligence (Laben) [LAB,89];
  - Control Techniques (Dornier).

At present several technology studies are carried out which are relevant for internal A&R such as:

- Micro-gravity compatible drives study (MBB/ERNO);
- Standard hierarchical control electronics and S/W (DORNIER).

A proper identification of possible problems in a complex design needs verification by means of a test-bed with sufficient realism for the test objectives [CAR,89]. Much attention has been paid to the use of facilities which provide means for physical and/or computer simulations to assist the design and to identify and study major operational aspects of these robotics devices [FEH,87].

ESA has started the development of (physical and computer) simulation facilities as part of the ground infrastructure which should play a central role in the design and development of robotics systems. These ground facilities are:

- General facilities (at ESTEC):
  - EUROSIM; European Real-time Operations Simulator being a real-time computer simulation facility including possibilities for Hardware-In-the-Loop Tests (HILT) and high-fidelity visualisation [PRO,87];
  - ROSED; 1-g physical simulation for external robotics operations and sub-systems demonstration [WIN,89].

- Dedicated facilities:
    - CAT; Columbus Automation Testbed for internal A&R demonstration of EMATS concept [EMA,89];
    - GIPAS; Ground Infrastructure for Payload Automation and Servicing in support of EMATS operation (training, simulation, mission development, technology test-bed) [EMA,89];
    - HSF; HERA dedicated simulation facilities both non-real time and real time [PRI,89];
    - HERA flat-floor facility (HERA Test Facility HTF);
    - Test-beds like the Crew Work Station and the Telescience Test-Bed [TTB,89];
    - EVA training facilities like a Neutral Buoyancy Facility (NBF).

Planned relevant European, but non-ESA, facilities and experiments are:

- ROTEX: Robot Technology Experiment (Shuttle D2-mission 1992) [HIR,89];
- STF : Simulation and Test Facility, a 1-g compatible testbed at GSOC for operations studies for both internal and external robotics. The facility is planned to be part of the Manned Space-laboratories Control Center (MSCC) at GSOC [SCH,89] .

Next to these facilities several test-beds were realised by industries, research institutes and universities to enable the study of specific operational and technological aspects of systems based on A&R concepts. Some of these test-beds are listed in Appendix A, demonstrating the importance assigned to robotics test-beds in support of research activities.

The European facilities which are directly related to the study of internal A&R aspects are:

- ROTEX, which is a demonstrator for operations demonstration, but NOT aimed at demonstration of microgee compatibility.
- CAT, which enables both physical and computer simulation of operational aspects and forms a test-bed for new technologies. A first realisation may use major ROTEX developments.
- EUROSIM, which enables simulation of both internal and external

robotics aspects (prototype available soon with application in external robotics; HERA).

- GIPAS, which may re-use major parts of CAT and also may use EUROSIM.

The present HERA Training Study intends to provide an overview of existing and planned facilities with emphasis on trainings aspects of external robotics. The outcome may be relevant to complement the overview given above.

4.2 United States and Canada

An overview of recent activities in the field of A&R can be found in the Proceedings of the NASA conference on Space Telerobotics held in early 1989 [ROD,89]. The conference proceedings provide an extensive overview of topics addressed at NASA Centers (Ames, Goddard, Langley, Johnson), Research institutes like JPL, several universities (e.g. MIT, Stanford, CMU) and Canada.

From this it can be concluded that JPL acts as the central research institute in the field of robotics R&D within the USA. Especially for research in teleoperation a large test-bed is developed: The JPL/NASA Telerobot Demonstrator System is a research testbed for the development, integration and testing of advanced robot control technologies ([ROD,89], VOL II, pp.51-74).

NASA Centers are involved in development of A&R technologies and systems which are part of the Space Station infrastructure. Universities carry out more basic research (e.g. artificial intelligence) funded by and on requests of NASA. The efforts within NASA concentrate on the development of the Flight Telerobotic Servicer (e.g. [ROD,89] VOL III pp. 435-500) which should be NASA's first operational space robot. Other projects are the Orbital Maneuvering Vehicle (OMV), which should provide a free-flying robot system (FTS attached) for assembly and servicing tasks, and the Satellite Servicer System (SSS) which is a robotised system for capture and retrieval of satellites for maintenance and repair purposes. Finally research in the area of mobile (e.g. legged or wheeled) robots is carried out in support of the Mars Rover/Sample Return Mission.

Canada has its Remote Manipulation System (RMS) operational for the US shuttle. Experiments to demonstrate possible technological enhancements of the RMS, such as force control using a more advanced End-Effector are under study. At present the Space Station Remote Manipulator System (SSRMS), located on a mobile base attached to a Space Station truss, is under development for the Canadian Space Agency under contract with SPAR and subcontractors. Canada also develops the two-armed Special Purpose Dextrous Manipulator (SPDM) as an intelligent End-effector for the SSRMS. Research related with these A&R systems is done at several universities (e.g. Toronto) and companies (e.g. CAE) throughout Canada.

No information was found of internal A&R systems for NASA, which could be compared with ESA's EMATS concept.

4.3 Japan

The first generation of space robots is planned for the Japanese Experiment Module (JEM), which is attached to Space Station Freedom [ODA,89]. The robot system consists of the JEM Remote Manipulator System (JEMRMS) which contains a large manipulator (length about 10 metres) for global positioning and a small fine manipulator consisting of two arms (length about 1.5 metres each).

Next generations robot systems are presently under research and intended for use in the Japanese COSMO-LAB [UME,89]. Robot systems are mainly developed for extra-vehicular activities. Also research is done in the area of mobile robots.

It is advisable to follow closely developments at NASDA (Japan) [SRF,89] and industries involved, considering their ambitious robotics program.

4.4 Relation with microgravity experiment facilities

For the specification of A&R requirements and the identification of specific R&D needs in the field of A&R a detailed description of the microgravity experiment facilities is needed. Unfortunately the present definition status of ESA facilities is rather immature and has the form of Science Team, Pre-phase A or (for some facilities) Phase-A studies. An overview of the present status can be found in [SEI,90] and [HAR,89]. Consequently the A&R system designer is left with many unanswered questions.

An artificial solution for this problem was found in defining so-called reference payloads for both the Free-Flying Laboratory and the Attached Laboratory [EMA,89]. These reference payloads can provide a preliminary indication of functions and operations which could be provided by an A&R system and were used, for instance in the EMATS study.

In [SEI,90] research topics and facilities are split in three separate groups:

- Life science;
- Materials science;
- Fluid science.

A&R aims at applications comprising servicing operations by means of material handling and facility operation. The next chapter lists R&D items that need to be addressed in order to fully exploit the potential of A&R usage taking into account constraints imposed by the use of the system in a space environment (e.g. mass and power), remote system operation (e.g. delay and limited TM/TC capacity) and laboratory requirements (e.g. microgravity level disturbances).

5 IDENTIFICATION OF R&D NEEDS IN SPACE A&R IN EUROPE

Being a relatively new item in space technology many A&R topics can be identified that need to be developed and demonstrated. This chapter gives a preliminary overview of these items.

A high level classification gives the following subdivision:
a. Application and operational aspects;
b. Systems technology;
c. Component technology.

An important input for identification of (near-)future needs is the technology development program for internal robotics as formulated during the EMATS study [EMA,89]. This program includes the development of a Columbus Automation Testbed (CAT) and a dedicated ground infrastructure (GIPAS) in support of technology and operations R&D. Also several critical technology items were identified and a technology assessment based on current status was given.
It is expected that the ROTEX experiment, planned for D2 mission 1992, will also lead to new insights and required technology improvements/changes for internal robotics.
An important notion is the need for mutual adaptation of design to allow for more easy, safe and reliable use of space A&R. Knowledge from terrestrial industrial experience in A&R should be used, but treated with great care [VAR,89].
R&D needs in space telerobotics identified by NASA in 1988 can be found in [SCH,88].

A first review of literature and study reports gives the following preliminary list of R&D topics:
1. Application specific aspects (e.g. microgravity level);
2. System technology (telescience, telepresence, teleoperation, telerobotics):
    a. Feasibility of partly automated microgee related operations by

means of general or dedicated A&R means within technological constraints imposed by:

- Experimenter MMI; (man machine interface)
- TM/TC limitations; tele monitoring / tele control
- Crew MMI;
- Manipulator;
- Experiment, and
- Environment.

b. Optimisation of operations taking into account:
   - Experiment design (design for automation);
   - Disturbances of microgravity level;
   - Safety;
   - Reliability;
   - Time;
   - Energy.

3. Component or subsystem technology:
   a. User support procedures (including means for (re-)programming the system);
   b. Handcontrollers and related control means (possibly including additional feedback information, such as force reflection);
   c. Predictive displays and related visual feedback and feedforward techniques (including means for 3D perception in support of telepresence);
   d. Microgravity compatible control (including all levels of control from strategic level down to joint servo's);
   e. Safety control (e.g. prevent damage to experiments);
   f. Reliability control (e.g. robustness w.r.t. environmental uncertainties or sensor errors);
   g. Actuators and gears;
   h. Standardised end-effectors (incl. exchange) and experiment interfaces;
   i. Sensors;
   j. H/W and S/W development standards.

Note that this list is preliminary and therefore may be incomplete.

From this list it can be concluded that there are many topics, ranging from system level to component level, requiring considerable R&D efforts to make A&R technology a more useful tool for application in space. From literature it can be concluded that R&D activities on many of these topics is carried out by many European and non-European organisations, both research institutes and industry. It is therefore important to define a clear set of goals and criteria before selecting a specific (set of) R&D item(s) and related product(s) to be developed. This is addressed in the next chapter.

Eis: niet te zeer afhankelijk van niet te beinvloeden beslissingen elders (autonoom concept tav experimenten?)

6 DEFINITION OF AN R&D PROJECT IN SPACE A&R IN THE NETHERLANDS

In this chapter preliminary R&D goals for a Dutch A&R project are derived from the present activities in space A&R and the needs in A&R as applied to microgravity identified sofar and given in the previous chapters. Next a shortlist of candidate projects is given.

An important aspect in the project definition is flexibility of the research environment. To enable changes and updates of the design both H/W and S/W used for experimentation and demonstration purposes should have a flexible set-up. Although flexibility initially will cause higher cost it will allow for, at least partial, re-use which eventually reduces development cost. Consequently the following aspects should be taken into account:

- Modularity of both H/W and S/W;
- Availability: use (commercially) available H/W and S/W where possible;
- Generality: don't spend (too) much time and money on dedicated equipment. ?

pleit voor PODI connected IA&R

6.1 Project goals and criteria

Within the prescribed scope the goal is to carry out R&D in internal A&R as applied to microgravity experiment facilities which is complementary to ESA activities. For this purpose the project will result in:

- an operational R&D facility, and/or
- a demonstrated technology or concept resulting from R&D activities (either on-ground or flight).

Selection of the project should at least be based on the following criteria:

- technical need for technology development based on requirements imposed by microgravity experimentation (Principle Investigator, facility designers);
- technical knowledge and experience available;
- relevant equipment already available;
- required budget for manpower, facilities/tools;
- financial support of Dutch government (incl. NIVR);
- technical and financial support of ESA;
- spin-off to other space or non-space applications.

6.2 Preliminary list of projects

Based on a first qualitative trade-off using above criteria the following candidate projects are identified:

a. (re)design for automation, applied to (TELE-)PODI

   Study on "design-for-automation" principles applied to space internal A&R for:

   - Microgee facility design;
   - Microgee experiment design (experiment volume, diagnostics etc.);
   - Microgee facility operation and control;
   - Requirements on robotics devices (e.g. disturbances/ minimum reaction robots both on payload and environment).

   This should result in a redesign of the (teleoperated) Prototype

Optical Diagnostics Instrument (PODI) [ASS,87] mechanical part and experiment interfaces where an A&R device is used for:

- experiment inspection/observation, and/or
- experiment cell exchange, and/or
- instrument passenger exchange.

b. Simulation based study of operational aspects
Development of an internal A&R application within an environment like EUROSIM including a fluid science experiment facility and including a test-bed for a Utilisation Centre and/or the Crew Work Station. Research on teleoperation related problems, using this EUROSIM application, such as:

- MMI aspects;
- TM/TC aspects for telescience/telepresence;
- Control aspects for local autonomy with special attention to:
  - microgee compatibility;
  - safety;
  - reliability.

Columbus Automation Testbed

c. Hardware test-bed based study of operational aspects
Create a test-bed using a CAT-replica or dedicated robotics device including appropriate experiment facility (mechanical part of model payload) in order to:

- Develop and/or test strategies for teleoperation and/or telescience;
- Use test-bed for functional demonstration of teleoperation/telescience experiments.

d. Microgravity compatible drives
Design of microgravity-compatible linear and/or rotary joint for CAT or experiment-dedicated mechanism, including (local) joint control H/W and S/W. Build and test prototype.

e. End-effectors and interfaces

Design of dedicated end-effectors and tools for experiment handling and support, including required sensors, control equipment and interfaces (e.g. power, data, fluid).

7 CONCLUSIONS

The objectives, scope and approach of the study carried out for NIVR have been outlined. In addition an overview of space A&R activities, a preliminary identification of R&D needs in this area and a description of initial work performed in the definition of a Dutch national space A&R R&D project is given.

Next steps during the remainder of this study:

- Identification of R&D needs for internal A&R systems based on detailed reviews of requirements on microgravity research facilities defined (if available) and a detailed review of studies on A&R usage in support of experiment facilities;
- Selection of R&D item(s) and project definition;
- Preparation of project proposal for NIVR and/or ESA.

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APPENDIX A
Automation and robotics test-beds

This appendix lists automation and robotics test-beds with a relation to space activities as found in the proceedings of the second European In-Orbit Operations Symposium (Toulouse, september 1989, ESA SP-297). References to these proceedings given in this appendix are coded [AUT, EIOOTS PAG], where AUT indicates the author and PAG the page number. This list certainly is not complete but merely gives an overview, at least for the European part, of facilities relevant for space A&R R&D activities. Especially the list op USA and Japanese testbeds is apt to further extension.

I Europe

1. ESTEC

- Test-bed built by British Aerospace (BAe) for study of remotely controlled manipulator. System based on ASEA IRb-6, in-house developed General Purpose Robot Controller, Programmable delay, Workstation with different hand-controllers (e.g. DLR and CAE 6DOF devices) [Evans, EIOOTS 167].
- Small manipulator for study of manipulator control using camera images (mono/stereo vision, single/multiple camera images).
- CAT planned for 1991 [de Peuter, EIOOTS 129].
- Breadboard RISC based computer for A&R applications [Elfving, EIOOTS 393].

2. France

- "System Simulation Facility" at Toulouse Space Center. 1-g manipulator (scale 1:4), Hermes cockpit mock-up. Tests for operational use [Runavot, EIOOTS 51].
- Testbed by CNES. Study of Hermes MMI for HERA operations [Bourdon-Henry, EIOOTS 161]
- BIAS Testbeds by MATRA. First consists of two manipulators used in nuclear reactors. The second test-bed consists of two cooperating Manutec R15 manipulators [Andre, EIOOTS 191].

3. Germany

- ROTEX 'prototype(s)' at DLR based on available technology. Ref. [Hir,1989]
- STF planned for TBD at Manned Space Laboratories COntrol Center (MSSC) at DLR [Schafer, EIOOTS 31]
- Test-bed for study of hierarchical control concept using Manutec R3 industrial robot [Tolle, EIOOTS 183]

4. Italy

- Test-bed by Technomare/Agenzia Spaziale Italiana based on underwater manipulator. Demonstration of supervisory control [Prendin, EIOOTS 429]
- Telemanipulation testbed, based on PUMA 562 manipulator and several sensors (e.g. force/torque, tactile, vision) by Centro Spazio [Andrenucci, EIOOTS 439].

5. England

- Test-bed build by British Aerospace for ESTEC, see under 'ESTEC'

6. Norway

- Marintek plans test-bed for underwater systems. Ref [Berg, EIOOTS 273]

7. Netherlands

- HSF-P at FSS (copy at ESTEC) [Prins, EIOOTS 315].

<u>II USA</u>

- On-Orbit Servicer Test-bed at JPL including two cooperating PUMA-type manipulators. Test-bed to be used for demonstration of technology, evaluation of operations, identify system 'issues' and performance criteria [Marzwell, EIOOTS 151].
- Test-bed for NASREM hierarchical control concept at NIST (formerly NBS) [Lumia, EIOOTS 361]. Test-bed contains Robotics Research Corporation manipulator.

<u>III Japan</u>

1. NASDA

- planned for 1990 at Tsukuba Space Center and based on standard industrial robot(s). Facility used for operational tests and HILT [Mitsushige, EIOOTS 47]

2. Tohoku University

- Force control experiment using a Hitachi Industrial robot and a force-torque controller [Uchiyama, EIOOTS 173].