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Automation and Robotics for COLUMBUS

An Implementation Concept for the Free Flying Laboratory (MTFF)

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Abstract

With nearly fourty percent of the funding, Germany is the main contributor to the European COLUMBUS Programme, followed by Italy, France and further ESA member states. The COLUMBUS elements are the Attached Laboratory (APM) to be permanently attached to the Space Station FREEDOM, the polar platform (PPF) and the Man Tended Free Flyer (MTFF). The latter element is regarded to be of special interest for the german micro-g community.

Until now the implementation of A&R Technologies has not been included as part of the system concept for the COLUMBUS laboratory modules. Yet especially for the Free Flyer a high degree of A&R will be indispensible.

An A&R system concept and implementation options for A&R are given to make the COLUMBUS labs "intelligent" laboratories in orbit.

1. Introduction

1.1 The COLUMBUS Elements

The space segment of the COLUMBUS Programme [1,2,3] - the european contribution to the International Space Station FREEDOM (ISS) - consists of the three elements

- Attached Laboratory (APM);
- Polar Platform (PPF);
- Free Flying Laboratory (MTFF).

The APM will be permanently attached to the ISS. Its primary utilisation will be research in the fields of life sciences and materials sciences under the conditions of microgravity. The launch date for the APM, currently proposed for June 1998, and will depend on the assembly sequence of the ISS.

The PPF will be a complementary element to the U.S. polar platform. According to the present plan the platform could be ready for launch in 1997. To allow sufficient time for the development of the PPF P/Ls, the launch might be delayed for a year.

The MTFF in its baseline design consits of a pressurized laboratory (PM) and a resource module (RM) attached to the lab. Its orbit is planned to boomerang the ISS and be serviced there, which means that the MTFF had to return to the space station and be berthed and docked. A second servicing option for the MTFF is that it will be visited by HERMES, the latter launched by ARIANE 5, for a period of some days twice a year (latest planning: once a year). The manned HERMES spacecraft and the launcher AR5 are both currently under development in resepctive european programmes which are managed - as the COLUMBUS programme is - by the European Space Agency ESA.

Following latest considerations in the programme [4] the APM might be reduced in size. This would make it possible to launch the APM fully equipped with its P/L and takes into account that during the initial phase the ISS will be operated in a man tended mode until it reaches the "permanently manned capability" or even its "eight man-crew capability".

Latest plans for the MTFF propose to make it completely independant from the space station. This would simplify the interfaces as the MTFF would then only need to be compatible with HERMES. The RvD capability of the MTFF - that means the design of the RM - could be significantly reduced as HERMES in that case will be the chaser and MTFF the target only. The operational life of the MTFF would be limited by the life of the solar panels. The replacement of those is beyond the planned capabilities of HERMES.

1.2 Operational Aspects

The idea of the Space Station FREEDOM programme and consequently the COLUMBUS programme - as it started in the middle of the last decade - was to establish a permanently manned infrastructure in a low earth orbit. The planned resources in orbit, the in orbit servicing capability and the continuous schedule of access to space were to fulfill the requirements of potential users to a near optimum. A crew of eight seemed sufficient for the operation of the space segment.

In Europe the operational envelope of the MTFF - man tended pressurized laboratory, visited twice (once) a year for some days by a crew of three for servicing and optional manned experimentation - seemed to demand a high degree of internal automation and robotics for its proper nominal operation.

A more thorough analysis of the time required for P/L operations in the APM (equipped with a set of model P/Ls, based on SPACELAB experience) versus the available crew time, derived from a possible crew of eight and the terms given in the MOU [5] between the participating partners in the space station programme, revealed that crew time would not be sufficient [6]. It clearly indicated that the APM will need a relatively high degree of automation and robotics in order to make the best use of it in an scientific and economical sense.

In Germany, partner in the COLUMBUS programme sharing 38 percent of its cost, the lack of automation and robotics technology in the COLUMBUS baseline design was estimated as a severe deficit concerning the utilization and operability of the elements of the programme. Consequently two activities were started. First, in order to demonstrate the available technology during the '93 SPACELAB D-2 mission the project "Robotic Technology Experiment" (ROTEX) [7] was initialised. Currently ROTEX has passed its system test and expects its integration into the SPACELAB module. Second, a serious of studies was launched on basis of a national A&R promotion concept [8]. Among those the study "Modules as Intelligent Laboratories in Orbit" (MILORT) [9] which worked out an A&R concept and a preferred implementation option for the planned laboratories in orbit, taking the free flying laboratory as the most challenging example.

2. Definition of the A&R System Concept

The definition of the A&R system could take into account the results of a number of related studies and projects, e.g. EMATS [10], which had already been performed or which were running in parallel under ESA or national contract.

2.1 The MTFF Configuration

The technical concept of the MTFF which was taken as baseline for the A&R system concept was taken from the COLUMBUS C/D proposal delivered to ESA in 1989.

The pressurized laboratory module of the MTFF forms a shell with an inner diameter of 4216 mm and accomodates 4 rows of 8 single rack equivalents (SRE) according to the "International Standard Rack". The inner arrangement is "1-g" oriented with a floor and a ceiling. It houses 4 stand-offs in symmetrical configuration to accommodate the 4 rows of racks.

A free area of approximately 2197 mm * 2197 mm between the racks gives working space for the crew. Protrusions of up to 100 mm are allowed at any rack location.

Utility lines are connected to the stand offs and routed through the rack bottom structure to the rear side. The necessary P/L cooling is accomplished by the avionics air cooling loop and/or by the water cooling loop. Each of these loops is designed for a maximum total heat load of 4 kW.

The EPS provides 4.8 kW peak / 4.0 kW average to payloads. For each lateral P/L double rack location the available power is 3 kW peak / 2 kW average. Voltage level at rack I/F is 120 V DC.

The communication subsystem provides a Ka-band downlink with 100 Mbps and a 2.5 Mbps uplink for transmission of multiplexed system and payload data. Up to 6 P/L data medium rate channels can be transmitted simultaneously to ground. A 5 minutes gap in transmission is allowed for turning the antenna from one to the other data relay satellite (DRS). The video interface will be standard RGB plus synchro signal. This allows either one color signal or three monochrome signals to be transmitted simultaneously. Two P/L video channels are available. Tape recording is available on-board.

P/L services include the P/L manager unit, LAN communication, central database service and storage, telemetry/telecommand services, data acquisition and command via standard transmission and acquisition units (STAUs) and monitoring/limit checking by the P/L manager unit. A caution and warning system will be available.

2.2 Tasks for Internal Automation and Robotics

The following list gives an overview on the possible tasks which will have to be performed by the internal A&R system:

Payloads

- nominal payload handling;
- servicing, includes inspection, cleaning, replacement of consumables, retrieval and disposition of products and waste;
- modification, reconfiguration.

System

- nominal operation;
- servicing, includes inspection, cleaning, replenishment of consumables, preventive and corrective maintenance and implementation of upgraded equipment.

2.3 A&R System

The A&R system will consist of several parts forming a hybrid system (fig. 1). The system as a whole might be described hirarchially by 3 shells, the system shell, in which the facility shell is embedded which itself contains the experiment shell.

2.3.1 Robotics

A robotic subsystem consisting of two 6-DOF manipulators each based on a 2-axes gantry which allows vertical and horizontal movement through the laboratory will perform the tasks involving manipulation or inspection, such as sample exchange or else. It will be operated in different modes:

- from ground in teleoperation / telemanipulation *)
- from ground via predefined path planning *)
- from ground via command macros
- o/b executing predefined tasks *)
- o/b autonomous

*) will be demonstrated by ROTEX on SPACELAB D-2 mission

The horizontal rails (HRU) of the both sides of the laboratory are interconnected in the aft cone. This enables each robot to move to the opposite side of the lab (fig. 2).

The workspace of one of the manipulators is determined by its kinematic parameters:

-	longitudinal range (rail system)	5433 mm
-	vertical range (rail system)	1655 mm
-	streched arm	1430 mm
-	shoulder joint	360 deg.
-	elbow pitch	240 deg.
-	1st and last wrist	360 deg.
-	middle wrist (axisis no. 5)	240 deg.

It can be seen that the the lab will be equipped with a manipulator subsystem of high dexterity.

The architecture of the robot control system (fig. 3) will follow the NASREM [11] approach. The DARA/ESA project MARS/ARCOS which is about to start will define and implement such a robotic control system for A&R ground testbeds at ESA/ESTEC, Noordwijk (Netherlands) and in Germany. The implementation will be the basis for the development of the flight system.

The robotic subsystem includes sensors which either are manipulator internal or external. The sensor concept comprises

- angular encoders (17 bit resolution)
- linear encoders
- force/torque sensors (ranges: force 10N, torque 20 Nm)
- distance sensors
- optical sensors (vision system)

The proposed End Effector (EE) concept foresees an interchangeable standard EE. This will allow to attach special tools directly to the manipulator arm.

2.3.2 Payload Internal Automation

It is assumed that the scientists will be responible for the P/L facilities and the experiments to be performed. It is also assumed that the responsibles will make extended use of hardautomation in order to reach a high performance. From a system point of view, only the A&R services and interfaces need to be defined and a set of standardized building blocks might be offered:

The electrical components relevant to automation are

- actuators, switches, relays, sensors, transducers, transmitters, pick-ups, motors.

More complex modules are

- single board and/or modular controllers, micro-computers, intelligent driver/controller modules.

In the frame of the COLUMBUS programme basic modules (CPU, memory, network interface unit (NIU), ...) are already under evaluation. Additional cards with special I/O or intelligent co-processors will have to be developed.

A standardized S/W architecture should be used which will be identical for MTFF subsystems and A&R. It will run on all nodes of the avionics H/W architecture consisting of 4 major layers: - the network layer, the operating system layer, the servicing layer and the application layer.

2.3.3 Expert Systems, FDIR, Mission Planning

The investigation of the applicability of expert systems and artificial intelligence to robotics on-board the MTFF has been guided by pragmatic considerations. According to this

- robot FDIR (fault detection, isolation and recovery)
- integrated mission and robot activity planning and execution

were identified as definitely required for the realization of on-board robotics.

The main purpose of robot FDIR will be

- to ensure safe operations
- to maximize mission success
- to provide exact information for servicing and repair to be performed during the rare visits by man.

The FDIR system foresees component failure handling (CFH) and task failure handling (TFH). As TFH is much more complex than CFH, it is expected that the initial on-board capability will provide only for the detection of deviations and corresponding saving actions. Diagnosis and repair as well as replanning shall be performed on-ground.

On-board operations of sub-systems and payloads will be defined by the Master Timeline and executed by the system and mission management of the MTFF. To include a robotic system into on-board operations will mean to

- include robot actions into the Master Timeline generation,
- include robot-specific task decompositions - and its complement on the P/L side - for o/b execution into the sytem and mission management plan.

2.3.4 Man Machine Interface

The traditional MMI consisting of video screens, switches and joysticks may not be advanced enough for full operation of the MTFF from ground. The ROTEX D-2 ground station will use in telemanipulation mode video screens, a predictive graphics system and sensor-balls to control the robot on-board SPACELAB D-2. There will be no force reflection to the operator.

A more advanced MMI could possibly be reached making use of techniques which today are summarized under the name of "virtual reality". Extensive use of such technologies could give a new quality to future manned space flight: to be virtually in space. That is to feel, to see, to work, to do experiments as if one would be in an orbital laboratory, in an observatory on the rear side of moon or at some other location in space, but physically to be on earth.

DARA will kick-off a project named VITAL to demonstrate and assess the possible implementation of "virtual reality" techniques into the man machine interface of the MTFF's automation and robotic system.

3. Implementation Options

The implementation of a complex system as the automation and robotics system into the COLUMBUS programme might be performed in different ways. The A&R system may not be considered as purely another subsystem or a user facility like the other experiment set-ups. In principle three different implementation options can be identified, implementation as:

- (1) autonomous payload
- (2) payload supplied facility
- (3) subsystem

For each of the above mentioned A&R elements an individual implementation strategy might be given.

- central robot system	>	(?) different options avail.
- payload internal automation	>	(2) integral part of P/L
- robotic FDIR system	>	(3) extension of nominal system
- robotics mission management	>	(3) integrated in nominal system
- man machine interface	>	ground segment

Two trades were performed for the central robotic system in order to find the optimal concept. As a constraint applicable to both trades it had to be regarded that the COLUMBUS programme was in its transition from phase B into the development and construction phase C/D.

Trade 1, technical criteria:

- reliability, availability
- safety
- materials selection
- COLUMBUS standards
- impacts on space segment design
- impacts on space segment operations
- ease of implementation
- ease of adaptation
- concept definition
- concept analysis
- concept trade evaluations
- number of interfaces
- complexity of interfaces
- manufacturing
- S/W development

Trade 2, programmatical criteria

- development control
- documentation effort
- development risks
- integration steps
- implementation schedule
- verification criteria definition
- verification method evaluation
- verification level definition
- integration sequences
- integration schedule
- add-on development responsibility
- administration for operations

The result was that the subsystem option was seen as the preferred option for the implementation of the central robotic system (fig. 4,5,6).

The development of the A&R system (fig. 7) depends on several support facilities. Major support functions are performed by testbeds where the A&R technology and operations may be developped, verified, analyzed, demonstrated and improved. A number of testbeds are under construction in Europe, some of those in a quasi-finished operational status.

MARS - Modules A&R System Testbed	Bremen (Germany)
STA - Simulation and Test Assembly	Oberpfaffenhofen (Germany)
CAT - COLUMBUS Automation Testbed	Noordwijk (Netherlands)
CWST - Crew Workstation Testbed	Noordwijk (Netherlands)
TTB - Telescience Testbed	Noordwijk (Netherlands)

For the in-flight demonstration of A&R technology in preparation for COLUMBUS the ESA "COLUMBUS Precursor Flights" programme [12] will be used. One of the A&R oriented proposals is "BIOSCREENING". The purpose of this experiment - seen from an A&R point of view - is to demonstrate the co-operation of a robotic arm and the Biorack facility. The experiment should fly on the European SPACELAB E-1 mission in '94.

4. Conclusions

The need for an A&R system in the COLUMBUS laboratories has been proved by several studies and is generally accepted now. It has been shown that although the programme is moving in the development and construction phase it is not too late to bring in an A&R system, partly as an additional subsystem partly as payload supplied facility. The results for the free flying laboratory in principle can be applied also to the attached lab.

It now needs some effort by the partners in the programme COLUMBUS to bring the development of the A&R system under control of the COLUMBUS system development at ESA. When in the past ESA followed the "permanent manned" option it now seems that there are strong hints that ESA will change its attitude. J.M. Luton, the Director General of ESA, stated recently [13]: "... Astronauts operating manned systems should be used only for essential tasks which cannot be performed without human intervention..." and "... The free-flyer, which can be visited and tended by astronauts from time to time with the help of HERMES, sets the proper course for the future development of robotics."

[1] "Resolution on Participation in the Space Station Programme", 31-Jan-85, ESA/C-M/LXVII-Res.2 (final)

[2] "Resolution on the European Long Term Plan and Programme", 10-Nov-87, ESA/C-M/LXXX-Res.1 (final)

[3] "Declaration on the COLUMBUS Development Programme", 15-Dec-87, 29-Jun-89, ESA/PB-COL/XVIII-Dec.1 (final), Rev.3

[4] ESA/C-WG(91)WP/22, 14-May-91

[5] "MoU - Übereinkünfte betreffend die Raumstation", 18-Oct-88, ESA/C(88)74

[6] "ROSSA - Robotics Spacecraft Servicing and Assembly in Space", ESA Contract 6837

[7] "ROTEX - Robotic Technology Experiment on Spacelab D-2", DARA Contract 01TT8701

[8] "Automatisierungstechnologien für die Raumfahrt", Bonn 15-Mar-89, BMFT

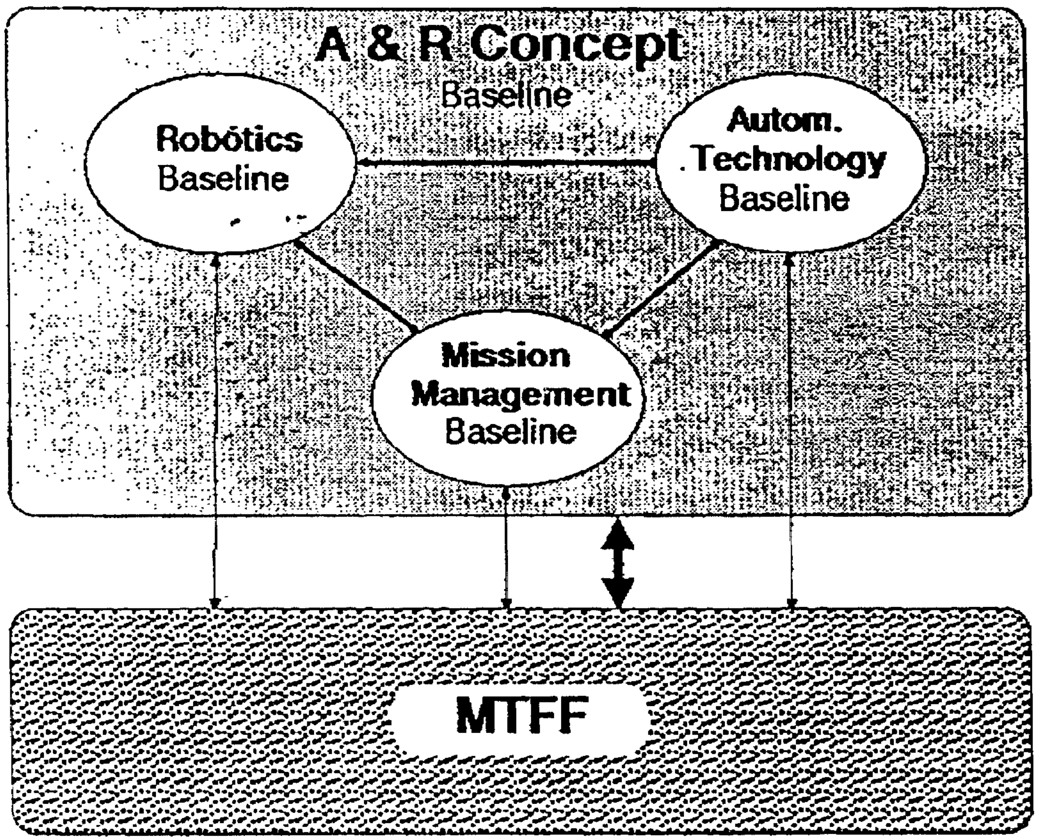
[9] "MILORT - Modules as Intelligent Laboratories in Orbit", Final Report, Bremen 1-Aug-90, DARA Contract 01 RS 8855

[10] "EMATS - Equipment Manipulation and Transportation System", Final Report, ESA Contract 7412/87

[11] AIAA-87-1687 "Software Architecture For Manufacturing And Space Robotics", J.S.Albus et al., 2nd AIAA/NASA/USAF Symposium on Automation, Robotics and Advanced Computing for the National Space Program, Arlington VA 9/11-Mar-87

[12] "COLUMBUS Precursor Flights", Call for Proposals and Ideas, ESA Paris 1-Nov-90

[13] ESA Bulletin No. 66, p. 9ff., 1-May-91, Paris ESA/HQ



Robotics
- Central Robot System

Mission Management
- Robotics Mission Management
- Failure Detection, Isolation, Recovery (FDIR)

Automation Technology
- Communication/DMS
- BITE
- Payload Internal Automation

Mission Planning

COLUMBUS FREE FLYING LABORATORY (MTFF)
- Interfaces
- Architecture
- Operational concept

Fig. 1 A&R Baseline Concept

Central Robotics System (EMATS)

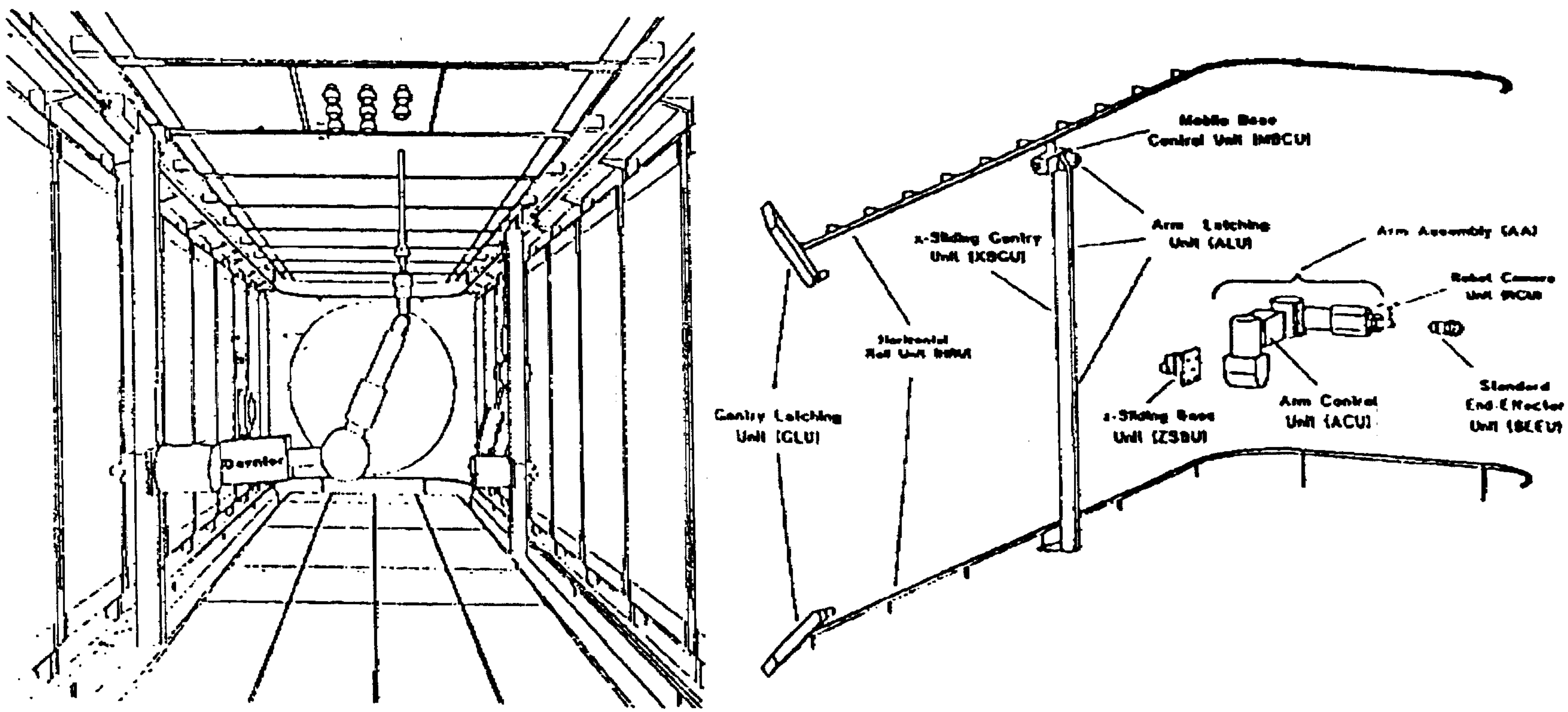


Fig. 2 Central Robotics System

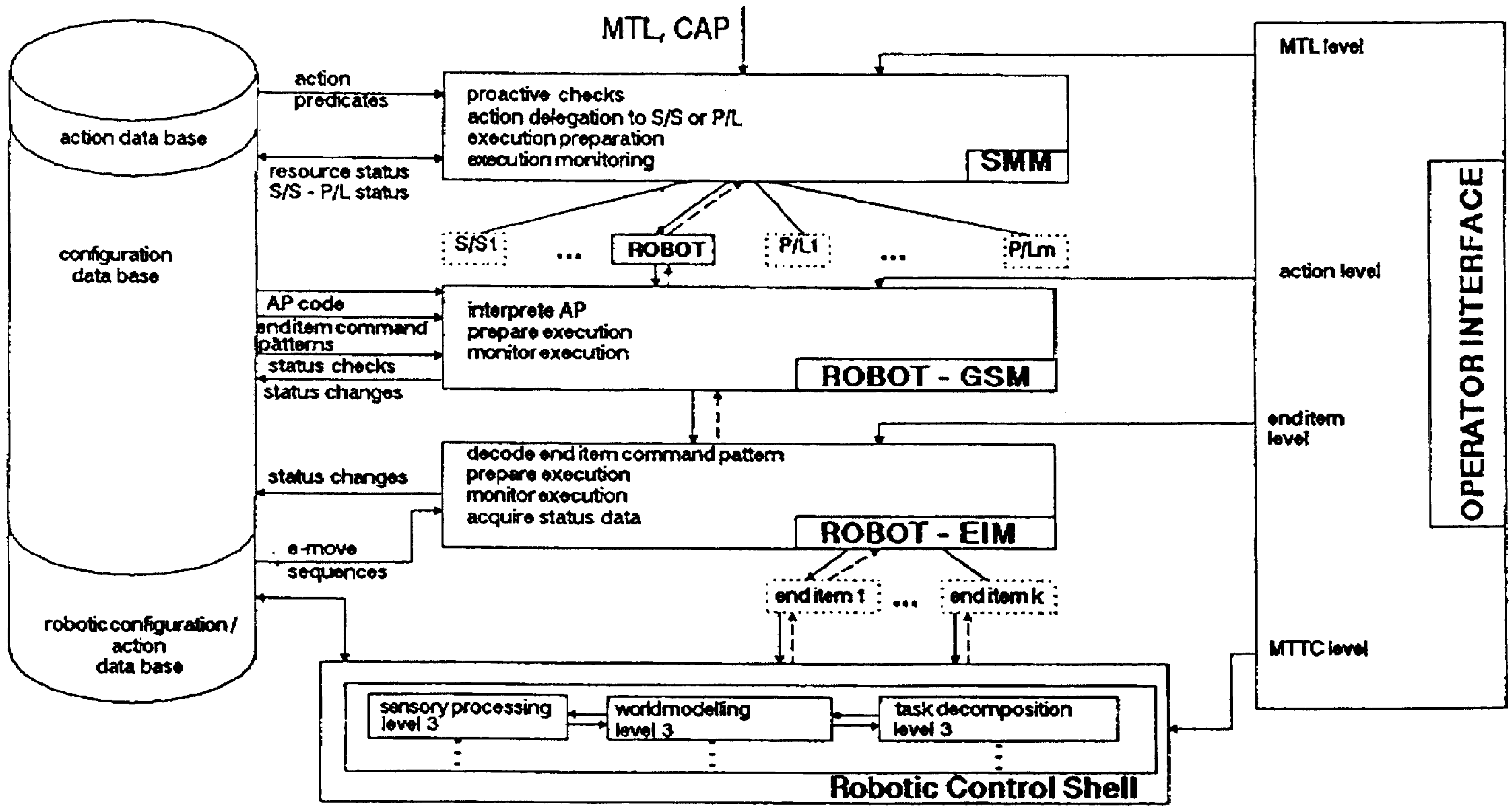


Fig. 3 Robotic Control System - Architecture

For the implementation of central robotics syst in the MTFF (APM) two different options are availal

Implementation of central robotics system as	Implementat of central robotics syst
PAYLOAD SUPPLIED FACILITY	**INTEGF ED MTFF S=SYSTEM**

The implementation options differ in:

Technical impacts — Degree of Integration into COLUMBUS Sys Development

- **Technical Requirements**
- **System Engineering**
- **Interface Definition/Management**
- **Qualification Standards, AIV**

Programmatical impacts — Degree of Integration into COLUMBUS Fro Development Plan

- **Independent Project vs. integral part of C BUS Program**
- **Allocation of Budgets (mass, power, volu c.)**
- **Financial Resources**

Fig. 4 Implementation Options (1)

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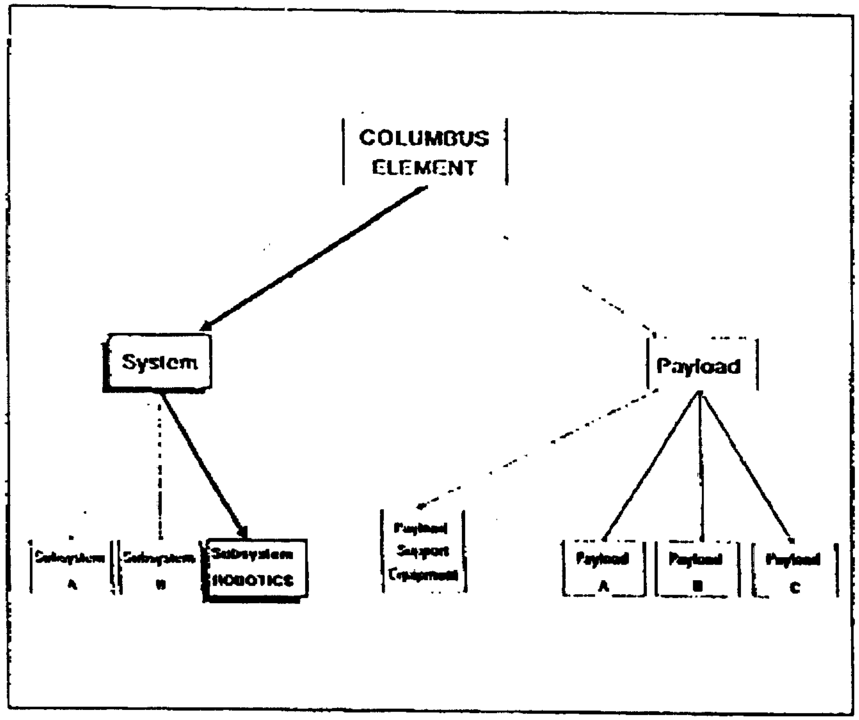
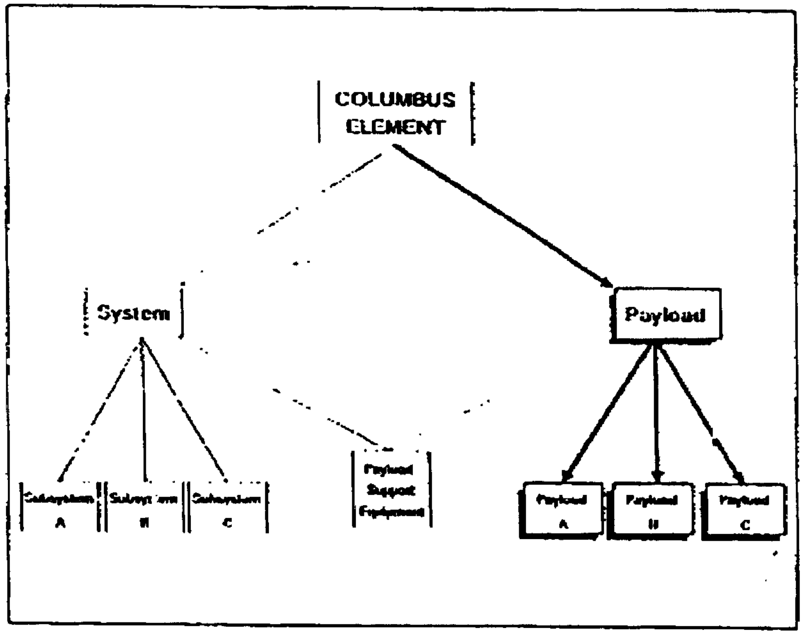
Implementation of Central Robot as COLUMBUS Subsystem



- **Optimization of on-board overall System for MTFF and APM**
- **Commonality between MTFF and APM**
- **Integral part of COLUMBUS Program Development Plan**
- **Extension of COLUMBUS C/D contract for Robotics subsystem development**
  - allocation of additional budgets
  - allocation of additional financial resources
- **Possibility of step-by-step integration of Robotics subsysytem**
  - rails prior to launch
  - integration of 1. Robot prior to launch preferred
  - integration of 2. Robot until 3. Servicing cycle recommended

Fig. 5 Implementation Options (2)

Implementation of P/L Internal Automation as Payload Supplied Equipment



- o **Implementation of P/L Internal Automation as integral part of the payload**
  - Multi User Facilities
  - Payload Instruments

- o **Establishing of a set of fully developed and qualified standard automation equipment to enable an optimum and costeffective payload development.**

Fig. 6 Implementation Options (3)

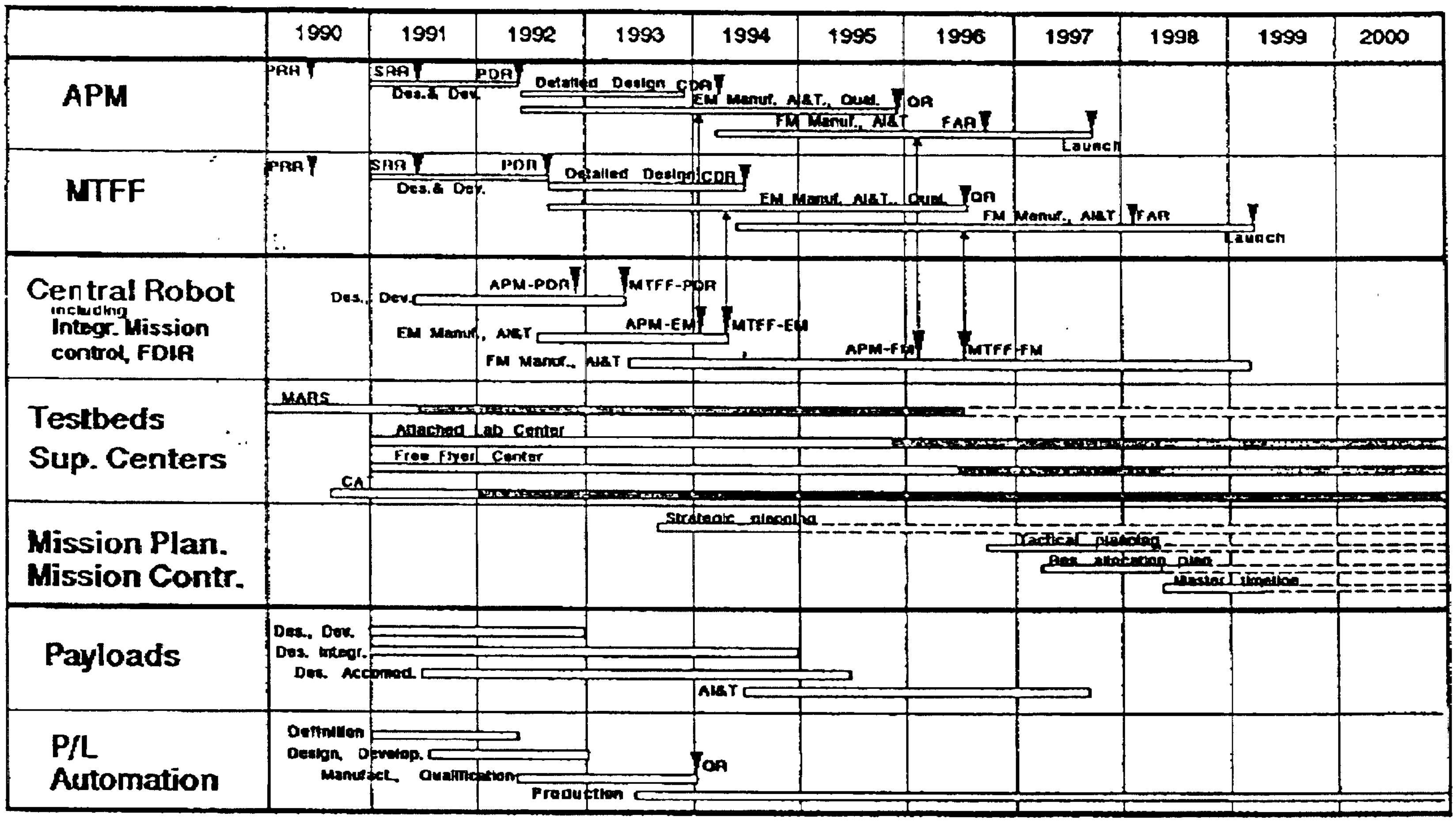


Fig. 7 A&R Development Plan