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TEST AND TRAINING SIMULATOR FOR GROUND-BASED TELEOPERATED IN-ORBIT SERVICING

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Abstract

For the Post-IOC-Phase of COLUMBUS it is intended to use robotic devices for the routine operations of ground-based teleoperated In-Orbit Servicing. A hardware simulator for verification of the relevant in-orbit operations technologies, the Servicing Test Facility, is necessary which mainly will support the Flight Control Center for the Manned Space-Laboratories for operational specific tasks like system simulation, training of teleoperators, parallel operation simultaneously to actual in-orbit activities and for the verification of the ground operations segment for telerobotics. This paper describes the present status of definition for the facility functional and operational concept.

1. Introduction

In-Orbit Servicing has emerged as one of the paramount features of the COLUMBUS program, which is the European contribution to the International Space Station, to establish an open-end orbital infrastructure. It comprises maintenance, repair, supply, configuration change and experiment handling of the COLUMBUS elements and payloads. The Man-Tended Free Flyer (MTFF) is the basic element for the need of servicing inside and outside the module by telemanipulation and autonomously operated robotic devices. Simulation of servicing procedures is therefore a vital step in the direction of actual orbital operation to assure feasibility and reliability of procedures and to establish strategies involving a wide spectrum of eventualities.

In the current planning of ESA (*European Space Agency*) for the initial operational phase of the COLUMBUS elements APM (*Attached Pressurized Module*) and MTFF, the so-called IOC-Phase (*Initial Operational Capability*), it is not foreseen to perform In-Orbit Servicing by ground-based telemanipulations. In this phase, servicing tasks will be performed by astronauts in situ, either by extra-vehicular activities or with the aid of HERA, the Hermes manipulator arm, which will be operated by the crew on-board Hermes, the European orbiter. This servicing scenario will take place twice a year, each servicing mission requiring about 7 to 10 days of duration.

MTFF-internal manipulators will not be foreseen within the IOC-Phase. Correspondingly, within this phase the present MTFF operational concept does not consider ground-based teleoperated in-orbit servicing with the aid of robotic devices. On the other hand, since the last two or three years, ESA has established different studies and projects for technology development and demonstration for the use of Automation and Robotics (*A&R*) inside and outside the MTFF and the APM:

- EMATS (*Equipment Manipulation and Transportation System*) and EMS (*Experiment Manipulator System*) for internal robotic servicing [1,2],
- SMS (*Service Manipulator System*) technology like HERA for external servicing [3,4],
- BIAS (*Bi-Arm Servicer*) for internal and external servicing with two co-operative manipulators [5],

- ROSSA (*Robotics Spacecraft Servicing and Assembly*), analyzing a mission scenario of mostly automated payload operations by means of A&R within MTFF and APM, starting a few years after the begin of the COLUMBUS IOC-Phase [6].

Figure 1 illustrates different design approaches for MTFF-internal manipulators, being presently investigated in more detail by different ESA studies [1,6]: a) rack-external devices like *the single- or the multi-rack robot*, which are decentralized handling devices to serve one or several experiments, b) *the central transport robot*, which is a decentralized and general purpose handling device to serve all experiments, e.g. EMATS. In Figure 2 two different approaches for external manipulator design, partly still based on SMS technology [7], are sketched (both of having seven degrees of freedom): The first one shows one of the latest version of Fokker's relocatable HERA design [3], largely a symmetrical manipulator of about 11.5 m length with identical end effectors at both ends thus being able to walk over from Hermes to MTFF or even relocate on the MTFF and henceforth being permanently MTFF-based. The other one shows a manipulator concept studied by MBB/ERNO [4], the total length being 10.6 m. For comparison, ESA's former manipulator approach for external servicing, the SMS [7], had a total length of roughly 7.5 m. More recently, investigations about the operational working volume of an MTFF-based manipulator favourize travelling concepts guided either by a linear or a circular rail mounted on the exterior of the MTFF thus providing an additional degree of freedom for servicing operations [8].

Rather than in the IOC-Phase, in the so-called Post-IOC-Phase of COLUMBUS (formerly AOC, *Autonomous Operational Capability*) which will start about 2 to 4 years after IOC begins, it is intended to make use of the A&R technology to be developed. ESA's robotic technology programme, briefly described above, aims at this goal, also the German *Robotics Technology Experiment, ROTEX*, [9] which will be flown by the Space Shuttle on the next D2-mission, presently scheduled for late 1991. A basic objective of all these technological initiatives is to perform in-orbit robotic servicing during un-manned phases by telemanipulation from ground (cf. also [10,11]). The main reasons to do so are to reduce costs and risks for both the transportation and the operations and control as well as for the astronauts.

2. The Servicing Test Facility within the MSCC

Based on the ESA council meeting on ministerial level (Nov 10-11, 1987, The Hague), ESA entrusted DFVLR with the conductance for operating the COLUMBUS manned space laboratories: in case of APM, under NASA leadership, the *German Space Operations Center* (GSOC at the DFVLR site at Oberpfaffenhofen) will be responsible for the payload operations, in case of MTFF the responsibility for the operations of the complete system and the payloads (excluding Hermes visits) lies within GSOC management [12], execpt in those cases where the MTFF is within the operational command and control zone (CCZ) of the International Space Station *FREEDOM*. The planning and set-up of the *Manned Space Laboratories Control Center, MSCC*, has already started; its operational readiness is scheduled for 1991 since the German D2-mission should already be operated by the new complex.

For in-orbit operations technology the APM and the MTFF flight control center will be supported by three test facilities, the *In-Orbit Operations Simulation Facilities, IOSF*, which will be installed within the MSCC [13]:

- An European Proximity Operations Simulation (EPOS) Facility,
- A Servicing Test Facility (STF),
- A Test Facility for Large Flexible Spacecraft Control.

This ground infrastructure will be developed by the DFVLR at Oberpfaffenhofen with national and European fundings. The facilities will be used for technology development and space system operation of the future European space programs.

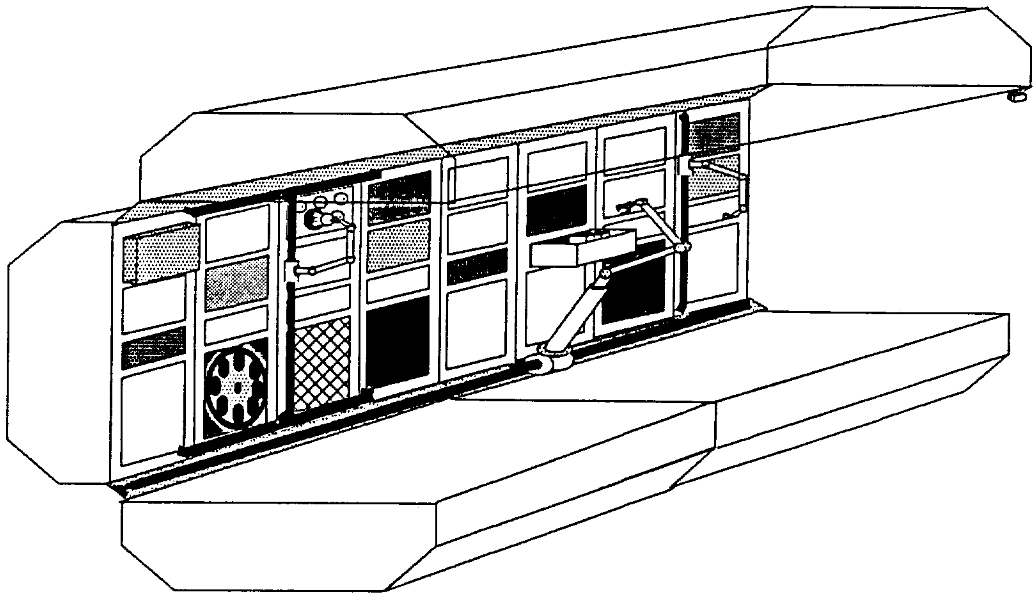

Figure 1. Functional drawing of different A&R concepts for MTFF internal servicing [6].

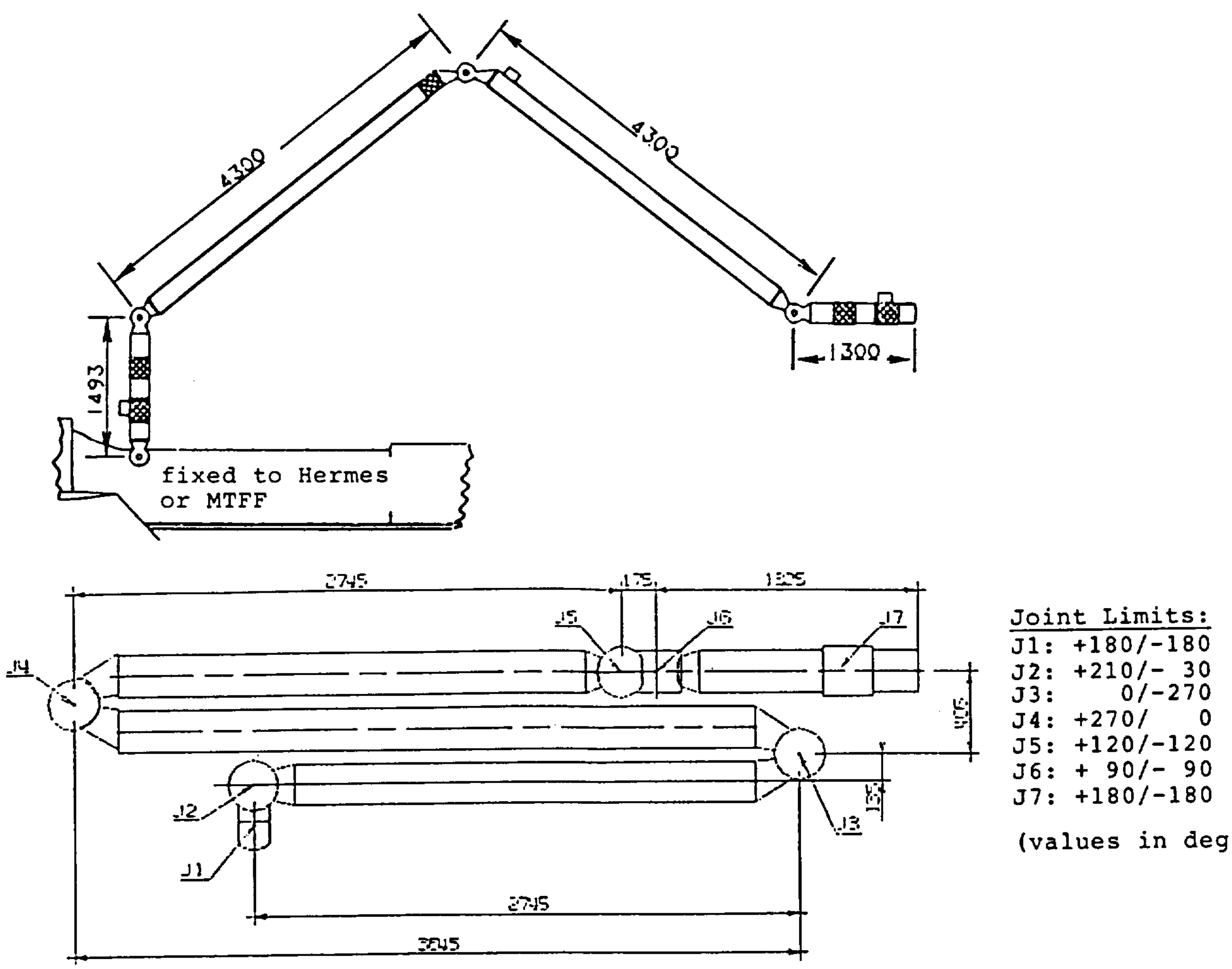

Figure 2. Large manipulator design for MTFF external servicing. Upper one: relocatable concept [3]; lower one: MBB/ERNO design [4].

The high costs of actual orbital operations imply a high degree of realism with regard to the simulation facilities on the ground to assure mission success even at a multitude of potential adverse events. Viewing this from a negative point of view, any programming or operator mistake would result in a tremendous amount of expenses in the case of an actual space mission as compared with costs incurring in an adequate simulation facility. Therefore all activities referring to teleoperated robotic routine operations must be planned and observed on ground. As a consequence, very early it proved to be extremely necessary to set up an adequate ground-based hardware simulator, the Servicing Test Facility, for in-orbit operations technology verification.

The STF is intended to be a *Test and Training Simulator for Ground-Based Teleoperated In-Orbit Robotic Servicing* during un-manned phases. With this intention, the STF is projected being a facility for the support of the MTFF *routine operations* during the Post-IOC-Phase. Because of the peculiar and complex pretensions, specifically to real-time flight operational support, the facility has to be in direct vicinity of the flight control center. The mean lifetime of the MTFF is projected for at least 30 years, and since the MSCC is in duty for all operational tasks, adequate provisions for a long-term operational concept have to be considered already in the current planning for later use in the Post-IOC-Phase.

3. High Fidelity Simulation Facility

Based on the future technological challenges described above it is essential to provide as far as possible a true-scale hardware simulator for the verification of the robotic servicing procedures under realistic conditions. The facility has to allow the implementation of important hardware components, possibly even flight specific hardware as e.g. end effectors or sensors, in a real-time and real-size simulation to increase the confidence in the ground operating system. Pure computer simulations will not be sufficient for the qualification of the ground operating system for robotic servicing tasks to guarantee mission success.

The STF therefore will provide the capability to perform the following spectrum of four main tasks [14-16]:

1. System simulation for the development and verification of mission procedures;
2. Teleoperator training with specific regards to signal delay times;
3. Verification of ground operations segment for in-orbit robotic tasks;
4. Simultaneous parallel simulation of on-going in-orbit routine operations during the Post-IOC-Phase.

While the first three tasks will support mainly all ground-based robotic activities in the ground operations preparatory phase, the parallel simulation will be a necessary task to be performed during the actual mission specifically for reasons of trouble shooting. Moreover, due to the signal delay times of several seconds (even up to about 10 sec during the Spacelab D1-mission) between ground and on-board system, actual status knowledge of the flight systems on ground is essential. In this case all telecommands may be transmitted to both systems in parallel, thus the ground-based operator will be able to observe the effects of manipulation in the ground facility in advance without time delay. Delayed on-board system information then will be played back to the STF via telemetry links and will be displayed additionally to the ground-based manipulator. Hence, it is possible to observe deviations between both systems and increase safety of the ground operating system.

Regarding specifically the inherent difficulties in the signal delay times the training philosophy and corresponding concepts for ground-based teleoperators must be based on high-fidelity equipment. Both the ground manipulator and animations of its computer simulated counterpart have to be provided to the operator by adequate monitoring devices having capabilities for

3D-stereoscopic imaging. According to the training philosophy three different steps shall be envisaged, each step gradually increasing in complexity:

1. *Training with ground manipulator (with time delays):*
   a. by direct view into the facility lab,
   b. by indirect view via video monitoring.
2. *Training by computer simulated animation using computer graphics system (with time delays):*
   a. for a dynamic model of the ground manipulator,
   b. for a dynamic model of the flight manipulator.
3. *Hybrid training:*
   a. by video monitoring of both the ground manipulator (without time delay) and the equivalent computer generated animation of the ground model (regarding time delay),
   b. by video monitoring of both the ground manipulator (without time delay) and the equivalent computer generated animation of the flight model (regarding time delay).

   This last training step is regarded to be of highest complexity. Monitoring of both images on two different screens would be a first approach, but the final aim should be an overlay of both images on one single screen.

For the purposes of teleoperator training and parallel operation to the onboard activities, it is essential to have the representative and detailed behaviour of the real manipulator and environment (internal and external) available on ground, as well. To assure conflict-free operations, the real manipulator geometry and kinematics must be available, including the geometry of the MTFF interieur and exterieur. Only for such a configuration of true-scale models it will be guaranteed that the teleoperator performs the manipulator activities within the bounds of the MTFF working area successfully.

The studies performed on the feasibility and the needs of the STF [14-16] have identified the following basic requirements:

- Representative behaviour of the manipulators and end effectors.
- Representative behaviour of the MTFF subsystem/payload mechanisms and functions as far as being relevant for automation and robotics.
- Representative video picture processing.
- Representative teleoperator station.

Regarding these functional and operational requirements the main STF components were identified giving:

- Replica of external and internal manipulator as far as possible in true scale with real onboard geometry and kinematics including control electronics. For the 1g-environment, the large length of about 11 m for the external manipulator requires a sufficiently stiff laboratory system in order to perform manipulations in all three dimensions. The real onboard dynamics will therefore be simulated by software.
- Replica or, if required, the real flight hardware of all flight end effectors to be connected to the manipulator.
- Software simulation of the onboard manipulator kinematics and dynamics, and of the onboard end effector kinematics and functions.
- Standardized software simulation system to allow for easy adaptation of different manipulator and end effector kinematic simulations.
- Teleoperator work station to allow for complete remote control of manipulator / end effector from ground, including 3D-display, status display, joystick / sensor ball control and signal delay simulation.
- Mockup of MTFF exterieur and interieur, as far as automation and robotics are concerned, in true scale as well as single standard ORU mockups and single racks.

- Lighting system, especially for sun simulation, shadowing effects.
- Telemetry / telecommand- and video-connection to the onboard manipulator system in real time to allow for remote control and simultaneous simulation (link via MSCC).
- Computing facilities for software simulation in real time, manipulator/equipment control, remote control station support, data recording and procedure development.
- Real-time 3D-stereoscopic graphic simulation system connected to the computer facilities for training purposes and rapid prototyping of In-Orbit Servicing procedures.
- If required in case of flight hardware implementation, clean room conditions are foreseen for operating the STF.

Moreover, for realistic teleoperator training of very detailed and sophisticated manipulations, where basically the end effector is used at the location of the object to be manipulated, the overall motion of the manipulator is not of main interest. In all these cases of servicing training tasks in the proximity of the object, it is very necessary to incorporate the manipulator dynamics as well as the forces and torques applied by the mechanisms of the MTFF specific objects. Here, the special simulation capabilities of EPOS will be favourably used. A close connection of both facilities, STF and EPOS, together with the MSCC is therefore required in order to guarantee for realistic simulations of In-Orbit Servicing teleoperations.

Figure 3 presents a functional overview of the Servicing Test Facility (a computer generated scene of the laboratory: the MTFF Mockup, the large 1g-lab manipulator, an internal manipulator, and the teleoperator workstation). Figure 3 also gives an overview of the complete ground-to-orbit scenario with interfaces to the other relevant ground-based facilities and the in-orbit COLUMBUS element MTFF.

4. Definition of the STF Basic Components

Presently, the Phase B Study for definition of the different basic hardware and software components has been finished. This refers to the electro-mechanical system of the laboratory manipulators for both the MTFF-internal and the -external robotics, and to the software and computer concept for operating the facility.

4.1 The Electro-Mechanical System

The manipulators and end effectors to be used inside and outside of the MTFF are still in the definition phase, and the final flight version may change according to the current specification. This important fact requires a flexible simulator design which can be easily adapted to different design modifications which especially applies for changes in manipulator geometry or in the kinematic behaviour. Therefore, the concept of a modular build-up of the STF is foreseen that allows gradual adaptation to the respective state of actual hardware equipment. This modular concept is used for both the hardware and the software simulation part of the STF. In case of the large external manipulator, the approach in Figure 2, lower one, was identified being the more complex one to be realized in the 1g-environment of the laboratory. Hence, once having qualified the more complex manipulator for operational readiness, less complex versions are regarded to apply as well.

Both the smaller internal robot and the large external manipulator must be operated in the lab in all three spatial dimensions and hence are strongly affected by gravity. Since no greater difficulties are expected to arise from the technical realization of a duplication of the internal robots, the most effort in the facility design therefore will originate from the hardware copy of the large manipulator. This replica of the flight version has been designed such as to physically simulate the flight-equivalent geometric and kinematic behaviour in all 3 dimensions. Obviously the dynamic behaviour will be much different since an almost very stiff construction is required. The major loads on the manipulator are given by the relatively high weights of the joint actuators rather than by the influence of the limb structure which will be made of lightweight material, CFRP. Moreover, the limb structure is designed in order to sustain elastic deflections within a dedicated margin (less than 10 cm end effector displacement for a worst case assumption of a horizontally cantilevered manipulator arm), and the necessary compensation of positioning inaccuracies due to the deformations will be performed by respective joint actuator commands. (Of course, closed loop control by telemanipulations via video sensor feedback will increase positioning accuracy without doubt.) Figure 3 gives an impression of the MTFF mockup and external lab manipulator arrangement: in case of linear or rotating manipulator travelling concepts, the MTFF mockup will be moved correspondingly with respect to the laboratory fixed manipulator base; appropriate provisions like rail guides are foreseen.

The torques exerted at the joints will be tremendously high as compared with those in the 0g-environment. Especially the bending moments at the shoulder joint actuator at the manipulator base are excessively high due to the exponential accumulation of the torques arising from the other actuator weights along the manipulator arm structure. For this reason proper actuator design was accomplished and moreover, the selection of specific actuator types influenced again the limb structural behaviour: A careful trade-off between both the joint actuator and the structural design was necessary. The final selection was to use HERA/SMS similar design with integrated electrical drive for the end effector joints and electrical drives with cyclo gearboxes or harmonic drives for the other joints. Optionally, the use of hydraulic torquers for the stronger actuators will be presently analyzed.

4.2 The Software and Computer Concept

The STF intelligent system is structured to fulfil the requirements of the different applications. A global design structure has been derived to allow the reuse of the same facility with only simple reconfigurations. The software simulation system is designed such that basically all configuration and construction dependent parameters of the manipulators, the end effectors and the MTFF can be stored in software tables which easily can be replaced. The control and table interpretation software ist therefore unchanged in case of manioulator changes. For MTFF external servicing the STF design concept is presented in Figure 4; the equivalent concept applies for internal servicing.

As far as possible, off-the-shelf computer systems are used with commercial software systems and networks. Moreover, use shall be made of the software capabilities of European systems supporting flight segment development like EUROSIM (*European Robotic Operations Simulator*) at ESTEC or CSF (*Columbus Simulation Facility*). All fast data processing in direct communication with the electronic or electric systems is performed around an IEEE 488 data bus and on dedicated micro-processors. The coordination of the different joint control processors (a decentralized joint control strategy for the large manipulator ist favoured), together with the associated transformation, will be performed on a dedicated minicomputer.

On the other hand, system supervision and activity coordination will be performed by one single authority, which is the STF simulation system, Figure 5. The corresponding simulation software acts as the central control system for the complete system set-up. All simulations, device coordinations, system supervision and programming tools operate here. For the graphic simulation a special hardware system is necessary that allows 3D real-time animation of robot manipulations, preferably for surface shaded volume models, by manual control via sensor ball or joysticks. The corresponding dynamic simulation requires a very powerful computing system together with a dedicated software package possibly tailored to the flight design (e.g. HERA simulation capabilities within EUROSIM). Man-machine interface is standardized by using off-the-shelf work station tools. State-of-the-art communication is by window mechanisms and pop-up menues/icons commanded by mouse.

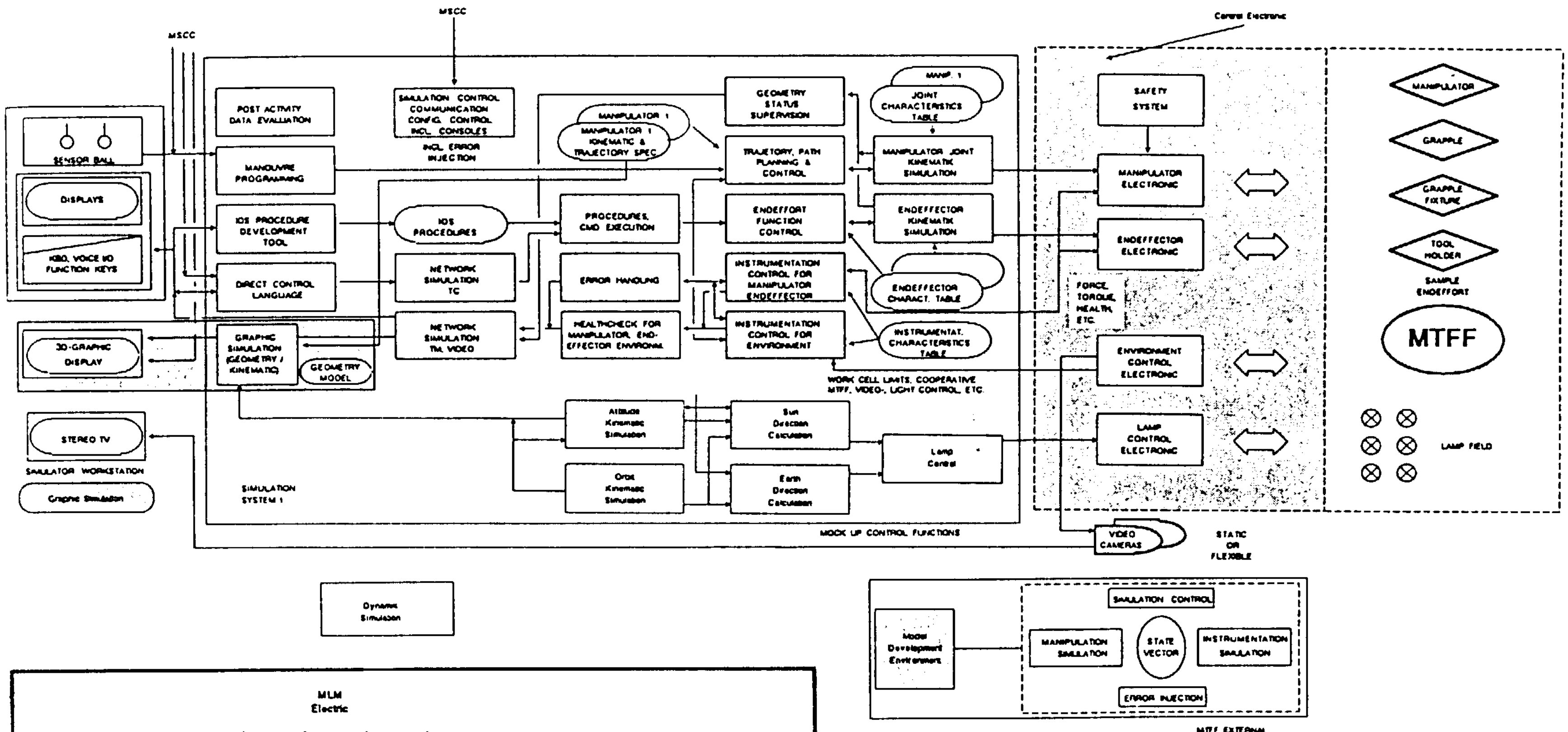

Figure 4. Software and computer concept.

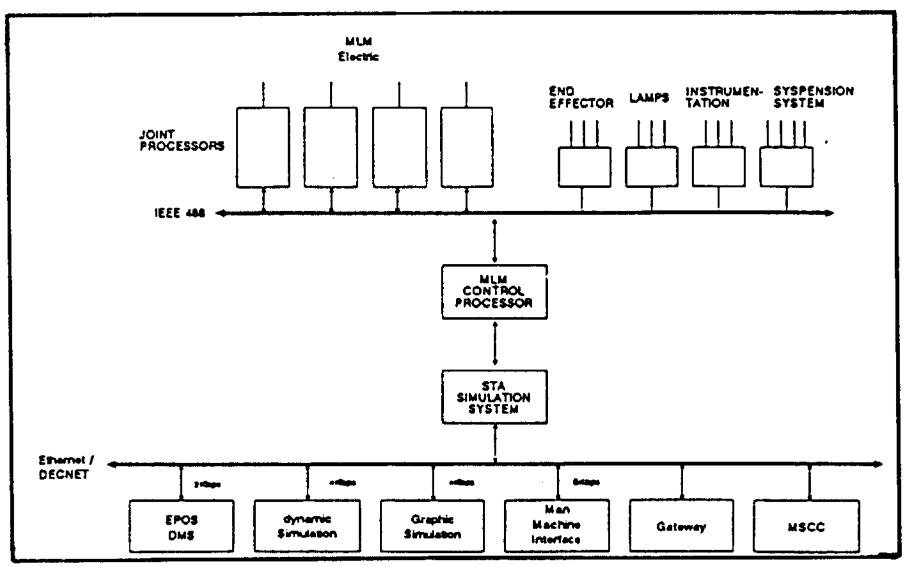

Figure 5. STF simulation system environment.

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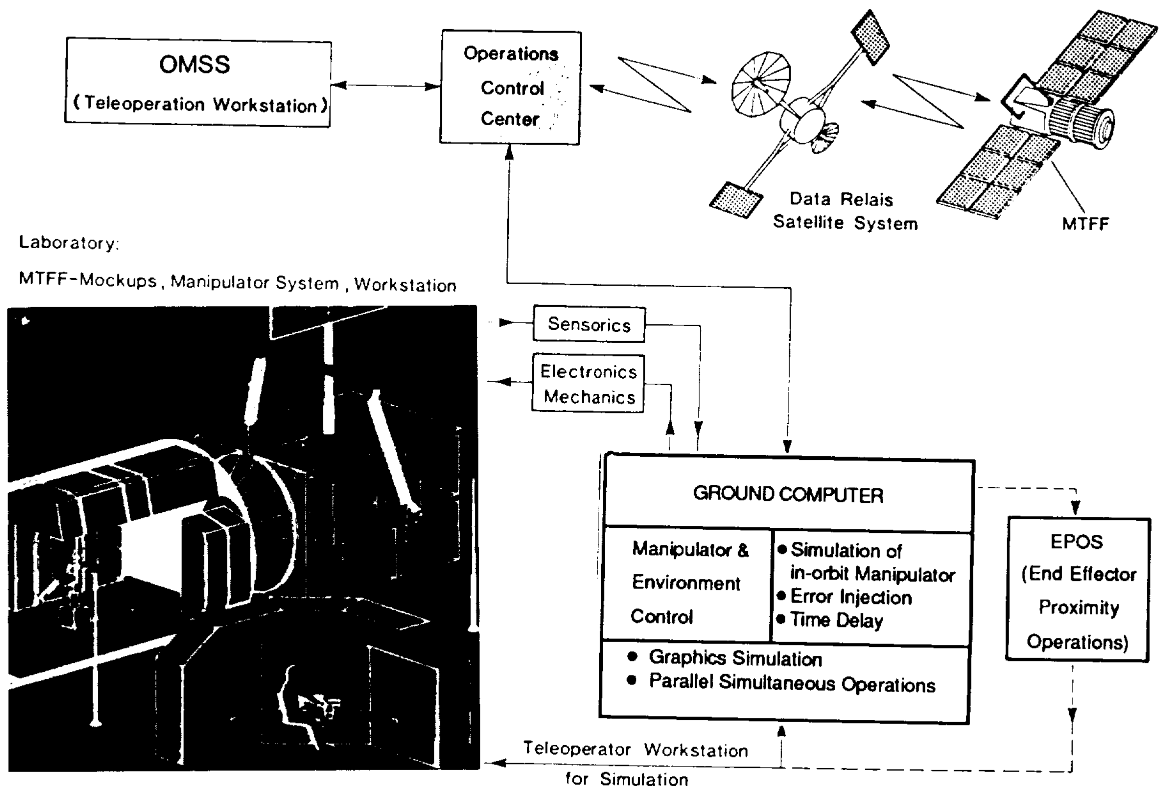

Figure 3. Functional overview of the Servicing Test Facility. Complete ground-to-orbit scenario.

5. Concluding Remarks

Rather than for technology development (cf. HERA 1g-Demonstrator facility, or MARS = MTFF A&R System Testbed) the Servicing Test Facility will be used dominantly for the support of the ground operating system within the MSCC for all ground-based teleoperated robotic routine operations. According to this objective, hardware and software components being typical for robotic servicing needs (e.g. teleoperator control station tailored to ground-based remote operations) shall largely be provided and incorporated within the facility by the specific developers. These can be ESA, industrial companies or non-profit institutions like universities or even DFVLR. The basic facility equipment is provided by DFVLR. The on-going activities for the facility set-up are presently faced with the detailed design of the basic components and studies on alternatives to real-sized hardware simulations such as scaled-down versions or cable-suspended manipulator designs.

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References

[1] Dornier System:
Equipment Manipulation and Transportation System (EMATS); International Automation and Robotics Workshop, ESTEC, 21-22 June 1988, Noordwijk, The Netherlands.

[2] Dornier System:
Automatic Sample Handling by Means of an Experiment Manipulation System (AHS/EMS); International Automation and Robotics Workshop, ESTEC, 21-22 June 1988, Noordwijk, The Netherlands.

[3] Fokker Space and Systems:
HERA Design Documentation; Report No. FSS-R-88-080, 14 July 1988, Amsterdam, The Netherlands.

[4] MBB/ERNO:
The HERA Manipulator Arm Limb Subsystem; Technical Proposal, Vol. 1, 12 Aug 1988, Bremen, Fed. Rep. of Germany.

[5] Matra Espace:
Bi-Arm Servicer (BIAS), Study Status and Potential Use; International Automation and Robotics Workshop, ESTEC, 21-22 June 1988, Noordwijk, The Netherlands.

[6] MBB/ERNO:
Study on Robotics, Spacecraft Servicing and Assembly (ROSSA); International Automation and Robotics Workshop, ESTEC, 21-22 June 1988, Noordwijk, The Netherlands.

[7] ESTEC:
Service Manipulator System, System Description Handbook; ESA-Document RTS/SMS/1/ESA/HBK, 7 March 1985, Noordwijk, The Netherlands.

[8] E.-L. Klingelhöfer, J. Puls:
Potentials of Robotic Operations on Board the Man-Tended Free-Flyer; 38th Congress of the International Astronautical Federation, Paper No. IAF-87-17, 10-17 Oct 1987, Brighton, United Kingdom.

[9] G. Hirzinger:
ROTEX, Germany's First Step into Space Robotics; AIAA/NASA First International Symposium on Space Automation and Robotics, Paper No. AIAA-88-5008, 29-30 Nov 1988, Arlington, VA, USA.

[10] R.H. Bentall, D. Kassing:
Man Tended Options for European Space Robotics; First European In-Orbit Operations Technology Symposium, 7-9 Sept 1987, Darmstadt, Fed. Rep. of Germany.

[11] ESA/ESTEC:
ESA Technology Research Programme for 1989 and Medium Term Plan for 1990-91; TD(89)1, 27 Nov 1988, Noordwijk, The Netherlands.

[12] J. Kehr, K. Reinel:
The Manned Space Laboratories Control Center (MSCC) at DFVLR, Oberpfaffenhofen; 39th Congress of the International Astronautical Federation, Paper No. IAF-88-087, 8-15 Oct 1988, Bangalore, India.

[13] K. Reinel, G. Heimbold, T. Lange, B. Schäfer:
Aufgaben der Simulationsanlagen für den Raumflugbetrieb im Betriebszentrum für bemannte Weltraumlabors; DFVLR Nachrichten, Vol. 54, June 1988.

[14] B. Brand, J. Puls, B. Schäfer:
Servicing Test Facility - Phase A Study; DFVLR IB 575-86/1, 19 Dec 1986, Oberpfaffenhofen, Fed. Rep. of Germany.

[15] MBB/ERNO:
Aufbau von Simulationsanlagen für den Raumflugbetrieb; Final Report, DFVLR Contract No. 5-575-4331, 15 Dec 1987, Oberpfaffenhofen, Fed. Rep. of Germany.

[16] MBB/ERNO, Dornier System:
Planung, Auslegung und Aufbau der Simulationsanlagen für das Betriebszentrum - Servicing Test Facility, Phase B Study; DFVLR Contract No. 5-575-4359, 8 Dec 1988, Oberpfaffenhofen, Fed. Rep. of Germany.