Development of the European Technology Exposure Facility

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ABSTRACT - The European Technology Exposure Facility (EuTEF) is a novel multi-user facility for technology research and assessment in Low-Earth Orbit. It will be developed by the Carlo Gavazzi Space under contract with ESA with strong contributions from the Italian and German national space agencies in the area of the robotics sub-system.

EuTEF will be launched in late 2002 and installed externally on an Express Pallet of the ISS by exploiting the robotic systems of the ISS (MSS). After installation it shall provide a total of three years of in-orbit experimentation time.

One of the innovative features of EuTEF is the presence of a small, dexterous robot arm with pre-programmed automatic operation. The selected operation mode for the experiment execution is called Interactive Autonomy being a mid point between full automation and teleoperation. By Interactive Autonomy a set of complex sequence can be safely executed by the robotic system with the minimum involvement of the operator at the ground station.

The robotic arm acts, via an end effector, on a set of standard boxes called Payload Modules (PMs), containing the experiments. The end effector provides both mechanical and electrical interfaces to the PMs. The PMs have standard dimensions and are characterized by standard mechanical and electrical interfaces. The PMs can be relocated and stacked allowing to place them in the most beneficial locations in orbit, according to an experimentation schedule. The continuity of the electrical connection (power and data) to the PMs during the relocation constitutes a chief features of EuTEF system, allowing the experiment to be prosecuted during relocation. A PM contains trays filled by specimens to be exposed to the space environment. The robotic arm can open and close experiment trays in the PMs in order to provide pre-programmed and controlled exposure profiles. The PMs can be visually inspected via a stereo camera and a lighting unit mounted on the end effector. It can provide visual inspection of the contents of experiment trays and PMs. A PM or a tray can be pointed into desired directions for prescribed periods compensating the ISS orbiting, for example for sustained solar exposure.

EuTEF is endowed with an Environment Monitoring Station providing centralized source of environmental data such as, e.g., radiation, pressure, contamination, and oxygen flux. These data can be used to correlate experiment results with the in orbit environment condition. A Material Property Laboratory is installed on EuTEF and it composed by a spectroreflectometer and a microscope for superficial inspection of the specimens. The robotic arm can bring a drawer to the analysis instruments for in-situ materials property investigations.

The arm enables the logistics re-supply by exchanging "old" and "new" Payload Modules in the case of a new upload. To investigators from many space technology domains, the EuTEF provides the advantages of low cost access to space exposure, short experiment lead time, high operational flexibility, rapid (quasi-online) availability of experiment results, and confidentiality of the contents and results of the investigation.

The EuTEF development started in the early 1999. The main areas of development accomplished in the first phase of the program are the design of a suitable end effector endowed with a stereo camera, lighting unit and on-board electronics, the design of the robotic arm based on the previous ASI SPIDER program results, the definition of the ground segment and flight segment S/W-H/W architecture. The present paper describes the current development status corresponding to the assessed review of the system requirements.

1 Introduction

As part of a bartering agreement between ESA and NASA, ESA negotiated access to 3 Express Pallet Adapters (ExPA) locations during the early utilisation phase of the International Space Station (ISS), for a period of three years.

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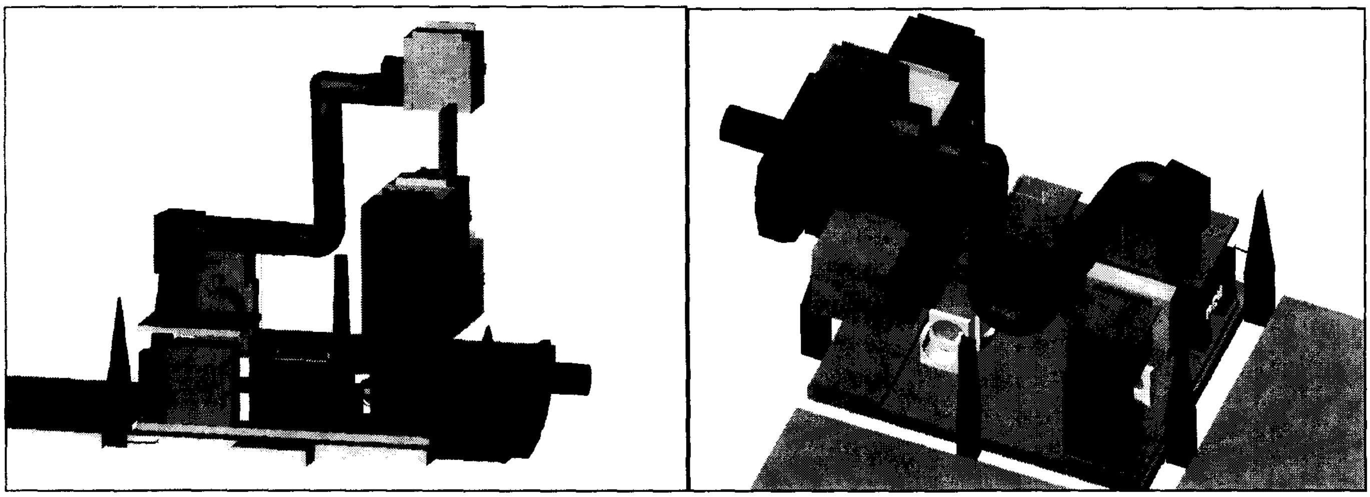

Figure 1 EuTEF in orbit operation (Some structural part has been blanked for clarity)

One of the ExPA has been allocated to the EuTEF mission that will be installed with the Utilisation Flights number 4 (UF4) on ISS external sites on the external structure of the ISS, the so called Express Pallet (ExP) at the S3 truss attached site onto the outboard zenith pointing ExP (see Figure 2).

Carlo Gavazzi Space (CGS) was awarded by ESA the role of integrating the European Technology Exposure Facility and as such CGS is in charge of defining the EuTEF facility in all its aspects. The activity comprises the definition of the mission phases, of the programmatic and technical interfaces with the experimenters, the design, developing, manufacturing of the EuTEF facility, the analytical and physical integration of the payloads, up to achieving safety certification of the integrated EuTEF in NASA and the on-orbit commissioning.

The EuTEF project is currently carrying out the Phase B activity aimed to achieve the design specification at system and sub-systems level ready for the subsequent manufacturing activity (Phase C/D). The System Requirement Review is planned for middle of June and the Preliminary Design Review will be on October 7th, 1999. The Phase C/D will start presumably in November and will last two years ending with the EuTEF delivery at NASA KSC and on-orbit installation with the UF4 launch.

Three key aspects characterizes EuTEF driving its design:

- the presence of large set of Investigations to be carried out in a 3 year mission duration in external space environment;
- the presence of a small dexterous robotic arm allowing to change on-orbit facility configuration;
- the requirements to provide the Experimenters with a quasi on-line access to their scientific data.

The EuTEF activity will be performed in an external space environment with limited control from ground segment implying a high degree of autonomy of the facility. For example, the robotics operations are based on a set of primitive function that can be executed autonomously by the robotic subsystem allowing the relocation of payloads, the tracking of external target. This concept has been called Interactive Autonomy and is described in Section 1.5.5.

The EuTEF thermal environment allows only limited power dissipation capability and impose to EuTEF a wide range of temperature leading to a challenging mechanical and thermal design. This has also strong impact on the payloads operations that have to be scheduled based on these constraints. A novel thermal design approach is under study in order to cope with a multi-configuration facility.

The Ground Segment in conjunction with the functionality provided by the Flight Segment will allow the Investigator to have quasi on-online access to their scientific data. In obtaining that CGS is exploiting the ultimate software technology in term of networked system and of space system autonomy able to react to asynchronous request coming from the users.

In the following Sections the EuTEF system is described pointing out the key aspect of current development.

1.2 Mission Phases

During its lifetime EuTEF is operated according to the following mission phases:

Integration and Test Phase - The integration and test phase encompasses all processing activities from equipment assembly up to acceptance testing of EuTEF.

Launch Phase - The launch phase begins at the instant of NSTS lift-off and ends when the NSTS is docked to the ISS

STS docked Phase - This phase starts when the NSTS is docked to the ISS and ends when EuTEF or ExP is handed over by the SSRMS robotic arm.

Transfer NSTS /ISS - This phase starts when EuTEF or ExP is handed over by the SSRMS and ends when

EuTEF or ExP is installed at the S3 attached site. During this phase the power to EuTEF is not continuously available.

In Orbit Commissioning Phase - This phase starts when EuTEF is installed at the S3 attached site and ends after initialization and in orbit testing. It will be dedicated to initiate Instruments and support equipment, to perform initial check-out and to tests the different operational modes.

Operational Phase - This phase starts at the end of the in orbit commissioning phase and covers the time when EuTEF is in operational or stand by mode under control of the ground segment.

Return Flight - This phase starts when the NSTS is de-docked from the ISS and ends with the NSTS landing.

Typical phase duration are given in Table 1

1.3 EuTEF Overall Block Diagram

The System General Block diagram is shown in Figure 2 where the following major blocks are identified.

- EuTEF Flight Segment
- Express Pallet System (ExPS)
- International Space Station (ISS) Flight Segment
- ISS Ground Segment

PHASE	DURATION
Storage	up to 1 year
Transportation/Launch Site Check-out	4 months
Launch & Flights Phase	48 hours
STS docked Phase	Up to 11 days
Transfer NSTS/ISS	Several hours
In orbit Commissioning Phase	2 to 3 weeks
Operational Phase	18 months to 36 months
Reboost Phase	3 days , every 90 days
Transfer ISS/NSTS	Several hours
STS Docked Phase	Several days
Return Flight	6 to 12 hours

Table 1 Typical Mission Phases Duration

- EuTEF Ground Segment

ISS Flight and Ground Segments architecture is hidden in the block diagram, being these details outside the scope of this preliminary description, concentrated on EuTEF interface aspects.

The purpose of the diagram is in fact to provide an overview of the EuTEF Context with special regard to Data and Control Flow aspects.

The **EuTEF Flight Segment** interfaces the **ISS Flight Segment** via the **Express Pallet System.** EuTEF is accommodated on a platform called Express Pallet Adapter (ExPA) providing the mechanical and electrical I/Fs (See Figure 4).

The major electrical interfaces provided via the Express Pallet Adapter (ExPA) are:

Power Interface, via which the electrical power is provided to the EuTEF Flight Segment for its operation. ExPA interface makes available to EuTEF 120 V and 28 V power outlets.

EuTEF provides ISS with CCSDS Telemetry (TM) Packets via the MIL STD 1553B Interface. These Packets are then downlinked by ISS to Ground.

- Analog Input Lines to ExPA, used to monitor directly EuTEF analog parameters, like temperature
- Digital Input / Output Lines, used to control EuTEF via discrete lines and to read its status

Data Handling Interface, via which Data and Commands are exchanged between EuTEF and ISS. Data Interface is implemented via a dual redundant MIL STD 1553B Interface via which are exchanged CCSDS Telementry / Telecommand (TM/TC) Packets. Additional Data Handling interfaces include an Ethernet link, used for the transmission to Ground of Scientific Data.

The ISS Flight Segment downlinks Telemetry data to its Ground Segment while the ISS Ground Segment uplinks Telecommands to its Flight Segment.

The **ISS Ground Segment** provides EuTEF with the following major services in a transparent way:

- delivers EuTEF downlinked TM Data to EuTEF Ground Segment
- receives from EuTEF Ground Segment requests of Telecommands issue to its Flight Segment and takes care to uplink the requested Telecommands to ISS Flight Segment for eventual delivery to EuTEF

The EuTEF Ground segment is described in the following Section.

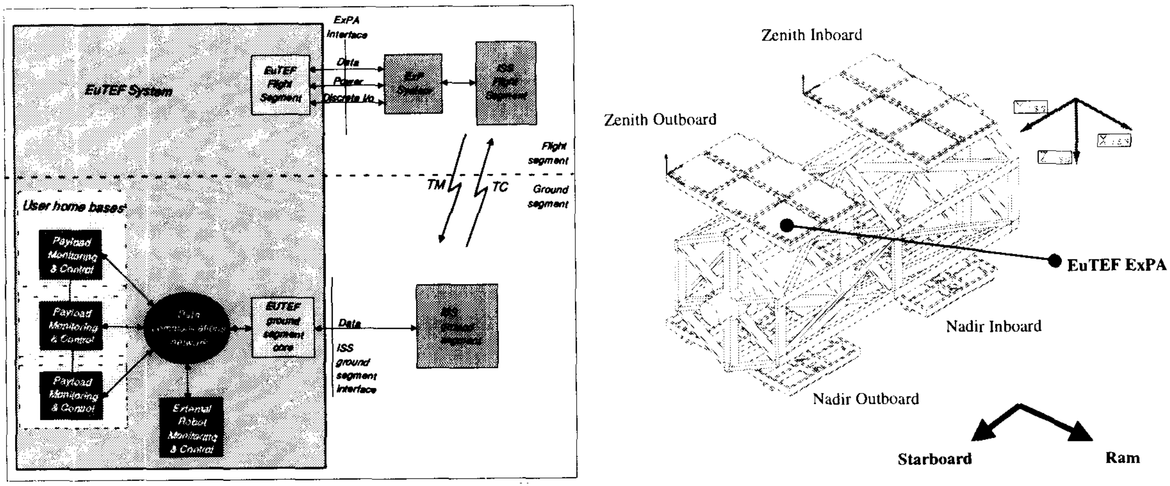

Figure 2 EuTEF System level block diagram and the ExP system

1.4 EuTEF Ground Segment

The **EuTEF Ground Segment** is a distributed system consisting of the following major blocks:

- A centralized block conventionally called as the **EuTEF Ground Segment CORE**, which actually interfaces the ISS Ground Segment. This block implements also centralized functions like EuTEF Monitoring and Control, Data Archiving, Data Presentation, Operations Preparation and Validation. The Monitoring and Control Tasks include also the ones related to Robot Operations. A further task of the Core Block is to handle the interfaces with the other blocks of the EuTEF Ground Segment distributed architecture, like Payload Monitoring / Control and External Robot Monitoring / Control.
- The **Payload Monitoring and Control** blocks, located at the Investigators User Home Bases. The tasks allocated to these blocks include:
  - Specification of the Experiments to be run on the Payloads during the EuTEF experimental sessions. The Experiments Specifications prepared by the Investigators are then subjected to a centralized Scheduling Process (running in CORE block, see Section 1.4.1) for a compatibility check with the requirements of the other Investigators and with the EuTEF and ISS constraints.
  - Monitoring of the Payload TM Data generated on board and actually delivered to the Payload Monitoring & Control block from the EuTEF Ground Segment Core block.
  - Issue of Control Command to the Payload. These commands are actually forwarded to the Core Block that takes care of verifying their compatibility with the experimental session in progress and with Facility status and constraints.
- The **External Robot Monitoring and Control** block. This block provides the same Robot Monitoring and Control functions built-in in the Core block but located remotely.

The EuTEF Ground Segment provides I/Fs to these external S/Ss allowing remote connection to the Ground Segment Core. A Data Communications Network linking the Core block to the distributed EuTEF Ground Segment elements like the External Robot Monitoring and Control Block and the Payload Monitoring and Control Blocks located at the User Home Bases based on a TCP/IP connection.

1.4.1 Investigation timeline definition

In this Section a brief description of the process aimed to obtain the facility operation timeline is provided. The necessity to schedule the activity of EuTEF comes from the limited resource in term of power, data rate, thermal dissipation, etc.. available at system level. These resources are below of the summation of the Experimenters needs preventing the possibility to have simultaneous operations of all the payloads.

Each Experimenter submits its specific requests to EuTEF in terms of:

- investigation operation program to be executed;
- resource usage;
- execution time line;
- investigation specific information.

We call this specification *EuTEF Investigation Specifications* (EIS). The EIS are coded using a specific high level language called EISL (EuTEF Investigation Specification Language). The set of EISs has to be merged by the EuTEF operation control center in a unique sequence of EuTEF operations to be uploaded on the Flight Segment and executed (see Figure 3).

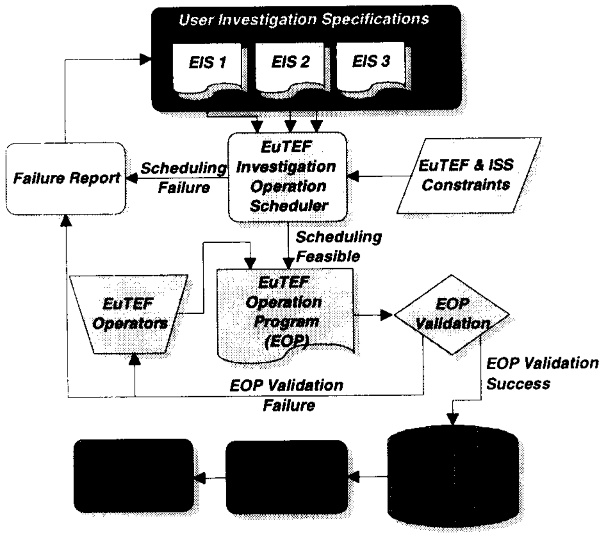

Figure 3 EuTEF Operation Program Generation - The data flow diagram shows the validation loop necessary to obtain an EOP

The scheduling activity define the time-line for every EuTEF operation taking into account the following:

- the investigation specifications (EISs);
- the cost (time and resource usage) of every EuTEF elementary operation;
- the EuTEF system constraints;
- the ISS constraints.

This computer aided process allows to optimize the usage of resources that are critical for EuTEF activity, such as, e.g., power, data link, thermal dissipation and to synchronize EuTEF with ISS modes and ISS time windows for EuTEF operations. We take advantage, during the EuTEF Operations Scheduling Process of:

- time dependent resource usage;
- the possibility to set experiment in survival mode;
- the possibility to delay investigation start time;

to find a EuTEF Operation Program that minimize the execution time and that does not violate the system constraints.

1.5 EuTEF Flight Segment

EuTEF will be accommodated in zenith outboard pallet and from this position will have Ram, Starboard and Zenith open field view (see Figure 1 and Figure 2). On Ram direction side there will be some ExP structures (a Scuff-Plate and a Robot-Guide) that can partially shade objects located at a height less then about 300mm. EuTEF envelop (available volume) on ExPA measures 1168 x 863 x 1244 mm (See Figure 4)

In Figure 1 is depicted the operational configuration of EuTEF. The following major EuTEF functional blocks are identified:

- Facility Infrastructure including:

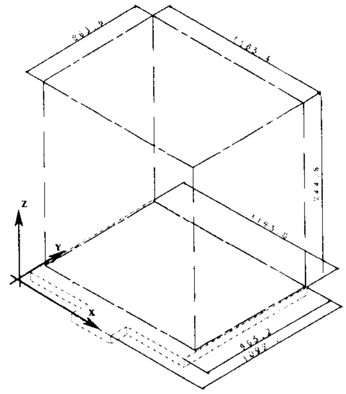

Figure 4 The standard ExPA with the EuTEF available envelope

- EuTEF Support Structure
- EuTEF Avionics
- Environment Monitoring Station (EMS)
- Materials Properties Laboratory (MPL)
- Robotic Subsystem
- Payload Modules Set including:
  - Payload Modules
  - Trays

The **EuTEF Support Structure**, mounted on the Express Pallet Adapter Plate, provides the physical support onto which all the EuTEF parts are integrated. In Figure 1 it has been blanked allowing to see the EuTEF avionics.

The **EuTEF Avionics** (see Figure 5) is in charge of providing EuTEF elements with all the required services in terms of Electrical Power supply and of centralized Supervision, Control and Monitoring.

A further task of Avionics is to handle the electrical EuTEF interfaces to ExPA i.e.:

- Power Interface, to be further conditioned and distributed to the EuTEF elements
- Data Interface, via which EuTEF delivers to ISS TM / Video data and receives Commands and Ancillary Data.

Among the Supervision and Control tasks it is worth to mention the execution of the EuTEF Operations Programs. The Avionics is also in charge of performing the following further major functions:

- ISS Commands Reception, Interpretation and Delivery to the actual EuTEF element in charge of their eventual execution
- TM Data Acquisition (HK, Science and Video) from the various EuTEF elements, Formatting in accordance with the applicable CCSDS standards and delivery to ISS
- Monitoring of the various EuTEF elements on the base of the acquired TM HK data.

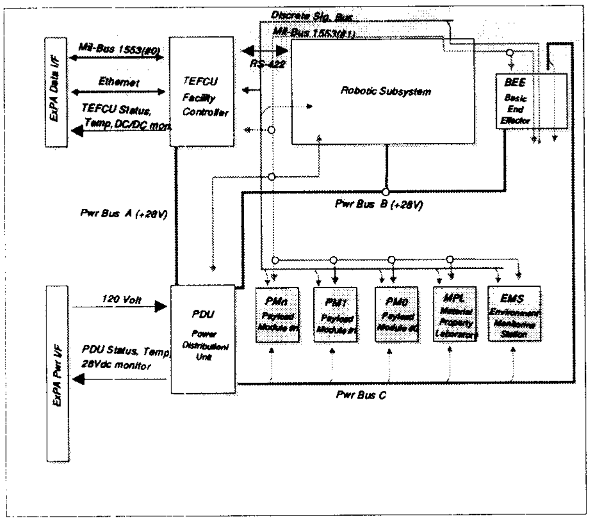

Figure 5 EuTEF Avionics Architecture

The Monitoring process produces TM reports to Ground in case of limit exceeding on parameters under surveillance. In case of critical situations automatic recovery actions (i.e. put EuTEF in a safe configuration) are implemented as well.

A **Material Properties Laboratory (MPL)** is part of the Facility Infrastructure with the purpose of measuring the thermo-optical properties of the material samples exposed to the Space Environment. The MPL is endowed with a spectroreflectometer and a microscope.

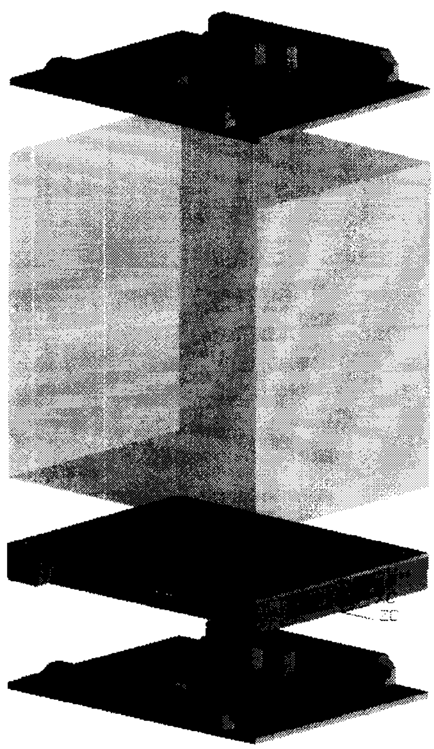

Figure 6 PM architecture

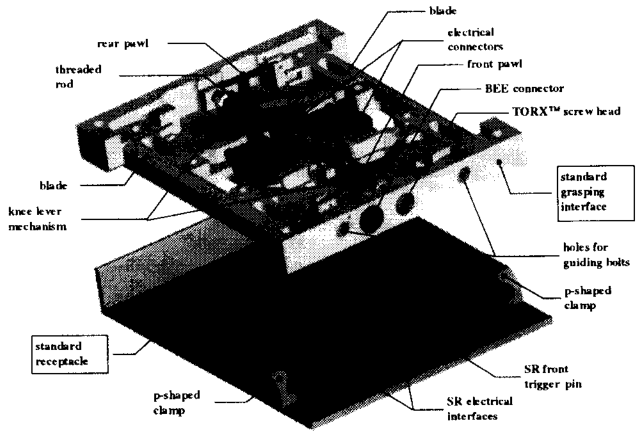

Figure 7 EuTEF Standard Grasping Unit

At this purpose it is equipped with one slot where Trays can be temporarily inserted by means of the Robot S/S. MPL allows measuring properties like emissivity, solar absorptivity and reflectivity. The microscope provides visual inspection of the superficial characteristics of the samples

An **Environment Monitoring Station (EMS)** provides EuTEF with centralized measurement capabilities for Pressure, Atomic Oxygen and Contamination.

1.5.3 Investigation Interfaces

EuTEF foresees the following three kind of investigations:

1. Investigation to be carried out with a dedicated hardware (Instrument)
2. Robotics Investigation requiring or not dedicated hardware
3. Set of sample to be exposed at space environment

The investigation 1) and 2) will be accommodated inside Payload Modules, while the 3) in the Tray system.

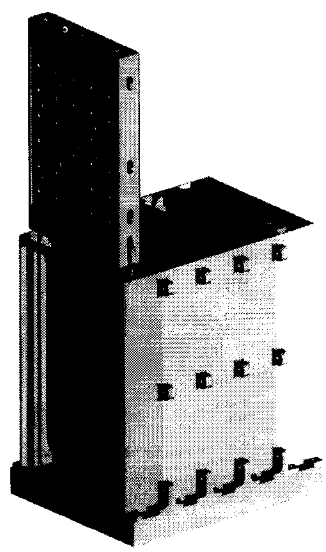

Figure 8 The Tray System

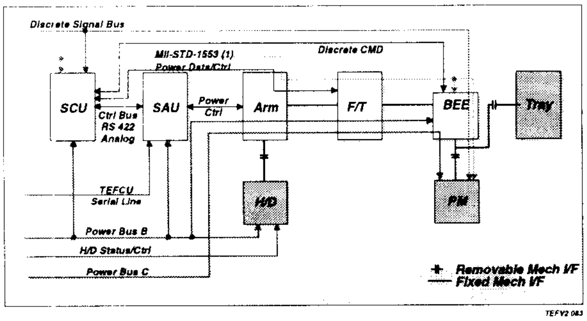

Figure 9 Robotic S/S architecture

The **Payload Modules (PMs)** are exploited for the accommodation of the various Instruments onto which it is required to perform Investigations. All PMs have the same base dimensions and identical Mechanical/Thermal/Electrical interfaces. The external envelope, as first design iteration, foresees two different PM dimensions (single and double) : 210 x 270 x 310 mm and 210 x 270 x 600 mm. The PM can be relocated in different exposure configurations by means of the Robot S/S. In order to allow that, a dedicated mechanism, called Standard Grasping Unit (see Figure 7), is mounted below each PM allowing them to be removed and safely latched in a new position inside receptacle attached to the EuTEF support structure.

The PM electrical I/F provides a 210 W @ 28V power interface, a MIL-STD-1553B serial bus data interface, a set of digital command to be used for instrument low level control, such as thermal control command, and a analog signal to measure the Instrument inside temperature. All these I/Fs are continuously connected to the facility avionics also during relocation.

Trays are exploited for providing time-limited exposure of small subjects pasted on their surface. As in the case of PMs, Trays are manipulated by means of the Robot S/S that can slide in and out the Tray. Trays are mounted inside dedicated PMs (see Figure 8) from which they can be fully extracted and moved independently to inserted in the MPL for in situ the measurement of superficial properties.

1.5.4 Robotic Subsystem

The **Robotic Subsystem** is in charge of performing all the EuTEF Operations that require physical movement of items like Payload Modules and Trays in order to implement the Investigation required by the Experimenter. Also Robotics investigation will be performed.

These required operations include actions like Open and Close Trays, Install and Remove Payload Modules into / from EuTEF receptacles, Point Trays / Payload Modules to a defined direction (see Section 1.5.5).

The Robotic Subsystem includes the following main items (see Figure 9):

- Robot Avionics, constituted by the Robot Control Unit (RCU) and the Servo Amplifier Unit (SAU).

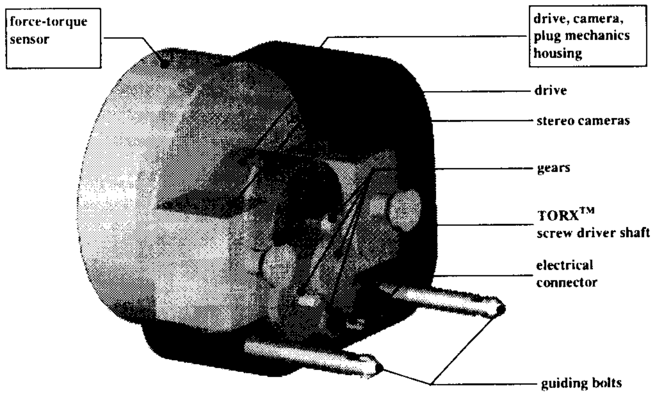

Figure 10 EuTEF Basic End Effector

- Robot Arm
- Force Torque sensor
- Basic End Effector (BEE)
- Hold Down Mechanism

The robot arm will be provided by the Italian Space Agency ASI and is constituted by a 7 d.o.f. anthropomorphic arm with endowed force torque sensor and hold down mechanism. The robot avionics will be developed by Carlo Gavazzi Space. The Basic End Effector will be developed by the German space agency DLR.

The **BEE**, permanently attached to the Robot Arm, is provided with a Standard Grasping Interface (SGI), featuring mechanical and electrical interfaces, to grasp all EuTEF items provided with SGI (Payload Modules, Trays, EMS). The design concept of the BEE is presented in Figure 10. The BEE is endowed with a screw driver shaft to actuate the SGU mechanism, with to guiding bolts and a connector providing power and data connection to the grasped payload during relocation. BEE includes a Stereo Camera and a lighting unit allowing scene and close-up visual inspection.

The **Hold Down Mechanism** is exploited for blocking the Robot Arm to the ExPA during launch/reentry phases. This active mechanism will be based on paraffin actuators and is endowed with redundant mechanisms preventing a catastrophic hazard represented by failures during the robot arm stowing operation.

1.5.5 Interactive Autonomy

The Interactive autonomy concept has been developed in order to reduce the necessity of continuos control from ground or on-board crew member of the robotics operations. As an example in Table 2 are presented a subset of the tasks that the robotic subsystem can be performed autonomously with ideally no control from ground. This idea has to be supported by a careful design in order to cope with the performance and safety requirements of the robotic operations.

The robotic arm due to its mechanical design aimed in reducing its mass and to the thermal deformation an expected total error of ± 5 mm, ± 0.1 degrees. A sensorial feedback is required also for the simpler contact operation, and therefore the Robotic Arm is endowed with a force/torque sensor. The stereo camera mounted in the Basic End Effector is foreseen to be used during non-nominal operation in case of F/T sensor failure. The design of the mechanical I/Fs has to tackle this expected error and shall provide guiding surfaces allowing a smooth insertion of the BEE in the SGU and the SGU in the receptacle. Also the on-board computer has to provide force/torque algorithm to be tailored for the provided mechanical I/Fs.

The Interactive Autonomy operations have to be provided as a service to the payload and not only as a technology demonstration and due to the inherent risk of failure, are a big issue from the safety point of view. In term of safety theory they are classified as catastrophic hazards due to the risk of accidental release of the grasped object, such as the PM. In that case the PM will become a free fly object with obvious risks for the ISS.

The design of all the involved mechanism shall comply to a double fault tolerant design, meaning that shall be three independent inhibit/path that control failures classified as catastrophic hazard. As an example the mutual design of the BEE and of the SGU foresees that, when the PM is grasped and outside of the receptacle:

- the BEE motor cannot be powered also if a power on command is issued;
- the guiding bolts are both independently latched inside the SGU;
- the rotation of the BEE motor shaft is mechanically inhibited.

This inhibits are released if and only if the SGU is safely engaged inside the receptacles.

A redundant set of switch and current loop are provided in each moving subject allowing the TEFCU and the RCU to monitor the status of the facility also after a non-nominal power down/power up phase of EuTEF.

From ground any of the Interactive Autonomy tasks depicted in Table 2 can be issued to the facility using an object oriented MMI allowing to select graphically object and target position. The tasks are executed under complete control of the RCU, while the TEFCU provide monitoring and inhibit function of the robot activity in order to reduce the risk of facility damage in case of RCU failure. From ground the robot activity is continuously monitored based on the RCU TM and in case of unexpected behavior the task can be aborted.

2 Conclusions

This paper has presented the current status of the development of the EuTEF facility corresponding to the System Requirement Review pending on middle of June. Some of the key features of the EuTEF design has been highlighted although, for sake of brevity, some other important aspects, such as e.g. thermal design, structural design, are here missing. The manufacturing, integration and testing phase will last for two years ending with the launch of the facility in late 2002 by UF4.

3 Reference

J. Dettmann, G. Visentin, R. Aceti, D. Andresen, "European Technology Facility" *Proc. of the 2nd European Symposium on the Utilization of the ISS, ESA-ESTEC, November 1998.*

Robotic Tasks
RT1 : ActuateObject Approach and grasp a SGI, then exert a prescribed force/torque until termination condition is met. Ungrasp and retract.
RT2 : CloseTray Approach, grasp the Tray, insert it to the fully closed position. Ungrasp and retract with the arm.
RT4 : InstallPM Approach the grasped PM to a docking location. Install it in the receptacle. Ungrasp and retract with the arm.
RT8 : PointPM/PointTray Orient the PM/Tray attached to the arm in a prescribed direction
RT11 : TrackObject Point the object attached to the arm to a moving external object given the trajectory in EuTEF co-ordinates
RT12 : TransportPM/TransporTray Move the PM/Tray attached to the arm to a prescribed position or along a trajectory without contact to the environment

Table 2 Interactive Autonomy Robot Tasks