Free-Flying Micro Operator Study

Executive Summary

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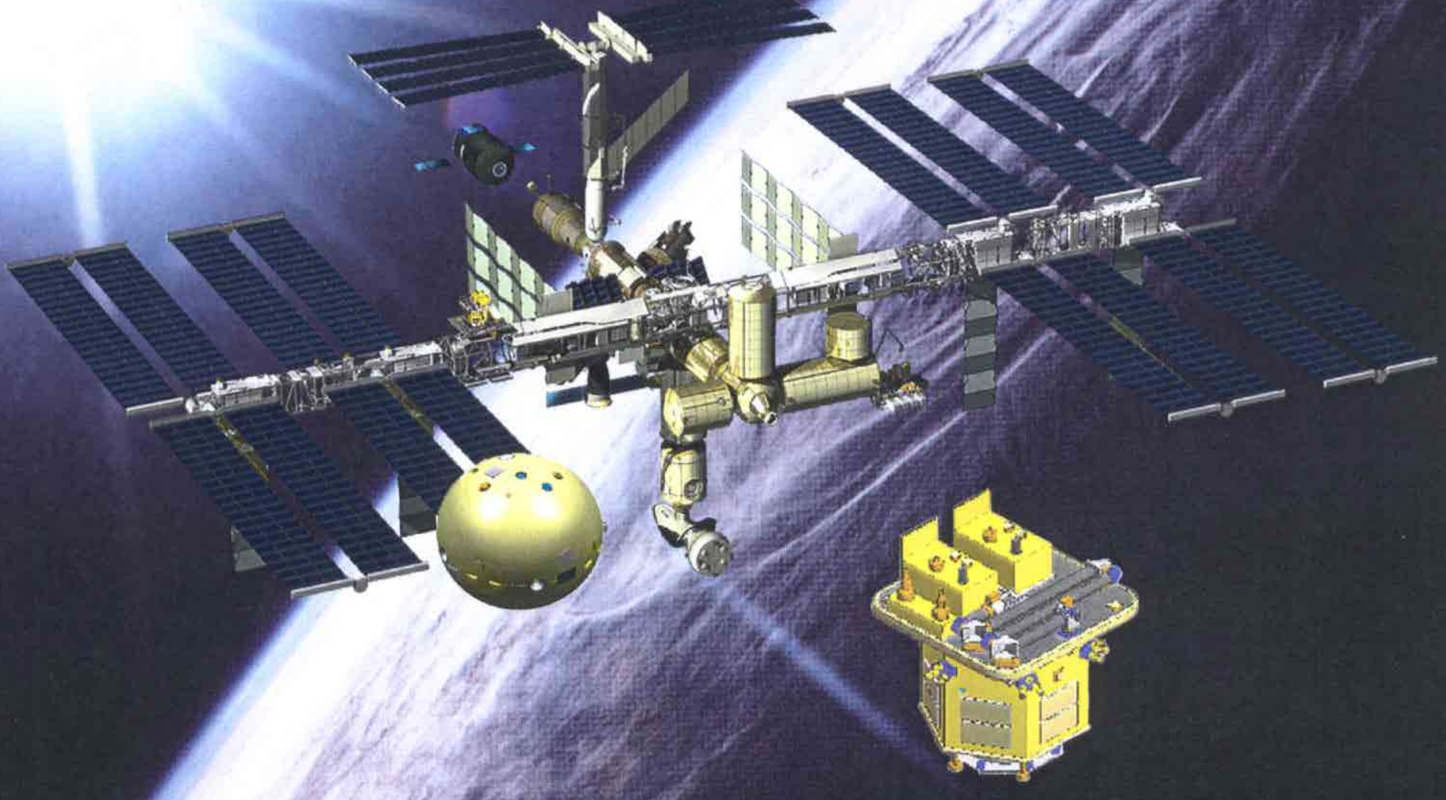

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Daimler-Chrysler Aerospace
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ALENIA
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Space Division

MATRA MARCONI SPACE

Title

Free-Flying Micro Operators Study

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SUMMARY

This executive summary gives a survey of the main results achieved during the study and lists the resulting recommendations, especially with respect to the technology R&D and a possible FFMO programme implementation.

In the opinion of the three involved companies, the FFMO programme represents a very interesting system to provide the International Space Station with services (inspection, servicing, relay satellite), to ensure the servicing of external payloads, or to support small free flying payloads.

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1. INTRODUCTION

In the frame of the International Space Station utilisation and operations, there are potential missions for a system of small vehicles (Free-Flying Micro-Operators, FFMO) capable of providing attractive services in the field of inspection, maintenance and operations support.

Some of these missions are planned or could be done with existing systems (EVA, SSRMS), but these systems have operational limitations and result in important costs.

The foreseen FFMOs will be able to move anywhere around and close to the Station. To that aim, they will have a small mass and small size, and thus rely on miniaturisation techniques, in particular on micro-technologies. They should also take into account the safety constraints of the Station. Its small size gives a high flexibility to the FFMO, but limits its range and duration of utilisation and makes necessary a support from the ISS.

ESA issued this Free-Flying Micro-Operator study in order to:

- identify what are the potential and most promising missions for the FFMO
- define and assess what would be the adequate system and vehicle concepts designs
- evaluate the qualitative advantages (costs, time, risks) of FFMO operations with respect to baseline
- identify the benefit of using micro technologies.

Matra Marconi Space is leading a team of European industries with DASA and ALENIASPAZIO to study the missions and the derived vehicles. IMM (Institut für Mikrotechnik Mainz) supported the team for micro nano-technologies aspects.

The study was divided into two parts:

- the first part was dedicated to the identification of potential missions and to the definition and trade-off of possible system concepts for each potential mission. This part was concluded by the selection of three reference missions
- the detailed design of the system and vehicle concept and the associated programmatic for each of the selected reference missions.

POTENTIAL MISSIONS

The identification of the possible FFMO missions has been based on systematic investigations of all potential applications of a free flyer in support to the ISS, and also in other types of orbits from LEO to GEO and planetary ones.

These investigations have led to identify more than 30 possible applications, which have been combined into 10 families of candidate missions.

An extensive review of these candidate missions has been conducted with emphasis on their interest and feasibility. Mission characteristics, including operations, ΔV's and major safety requirements, have been established for each of the above applications to verify if the constraints were compatible with a micro-operator. Some of the missions have been evaluated as too ambitious and rejected. That is the case of the rescue mission (in particular EVA rescue), or support to ISS build up.

Finally 7 candidate missions have been kept, in agreement with ESA, for the preliminary system concept analysis and trade off activities. They are:

- ***ISS inspection and monitoring by fly around.*** It provides first class views of ISS for operational support. This inspection is performed at a 100 to 200m distance.
- ***ISS close range inspection.*** This inspection is performed at a few meters distance. It provides a detailed inspection of a specific area of the ISS (or attached vehicles).
- ***ISS surface inspection and repair.*** This inspection requires contact between the inspected ISS area and the vehicle. The objective is to perform micro inspection and surface repair (patching on a hole, etc)
- ***ISS external payloads servicing mission.*** The objective is to perform inspection, exchange of payload element (or full payload), exchange of sample unit, etc
- ***Inspection and servicing of spacecraft in LEO.*** That mission is dedicated to spacecraft coorbiting with the ISS. Inspection and servicing as described above could be done.
- ***Support to free flying payloads.*** The mission objective is to provide resources to payloads, which need to be in free flight, at a short distance from ISS.
- ***Inspection and servicing of a constellation.*** The objective is to perform inspection and servicing of all the satellites of a constellation located on the same orbit plane

Among the other possible missions, the following ones can be quoted:

- the communication relay application: to use FFMO as a communication relay between ISS and EVAs, or incoming vehicles in order to extend the ISS communication coverage. It can be covered from main requirements point of view by both the close range inspection and the support to free flying payloads

- the inspection or servicing of spacecraft in LEO (non coorbiting) or GEO: it can be covered by the servicing of constellation
- the cooperation with EVA astronauts: depending on the type of support (to provide lighting during EVA operations, or to transport equipment to astronauts for instance), the mission itself could be similar to the inspection or servicing, but the safety aspects will be different.
- The Space probe: it is a specific mission, with a FFMO released from a motherspacecraft to fly to a planet or asteroid. The mission can be compared to the support to free flying payloads, but it would be a one shot mission in a different environment. The main commonality remains the utilisation of miniaturisation techniques, micro technologies and of some architecture.

2. SYSTEM ASPECTS

Each candidate mission is fulfilled by one or several alternative FFMO systems. The definition of the FFMO system has to consider several elements, as illustrated on figure 3/1. The main drivers for the identification of alternative systems are:

- *the maintenance strategy* together with the location of the storage port. Four options have been identified: no in orbit maintenance (single shot mission), external storage and maintenance (for battery reloading) without refuelling, external storage and maintenance (battery reloading) with refuelling, storage and maintenance within the ISS (exchange of batteries and tanks).

- *the capture mode* when flying back to the host system: direct docking, capture by dedicated robotics or capture by EVA

- *the configuration of the vehicle*: it could be a compact and homogeneous vehicle without any appendages or a modular vehicle with a plate for payload installation

- *the end of life*; which could be a recovery on ground, or a destruction via atmospheric burn of garbage orbit

- *the type of launcher*: STS, or AR5 or other expendable launcher

- *the control command mode*. Three possible solutions: fully remote control/ teleoperation (All GNC and propulsion commands elaborated by the crew), autonomous capability and partial remote control (the crew to send authorisations for sequence of operations), fully autonomous capability (still monitoring by crew for safety aspects).

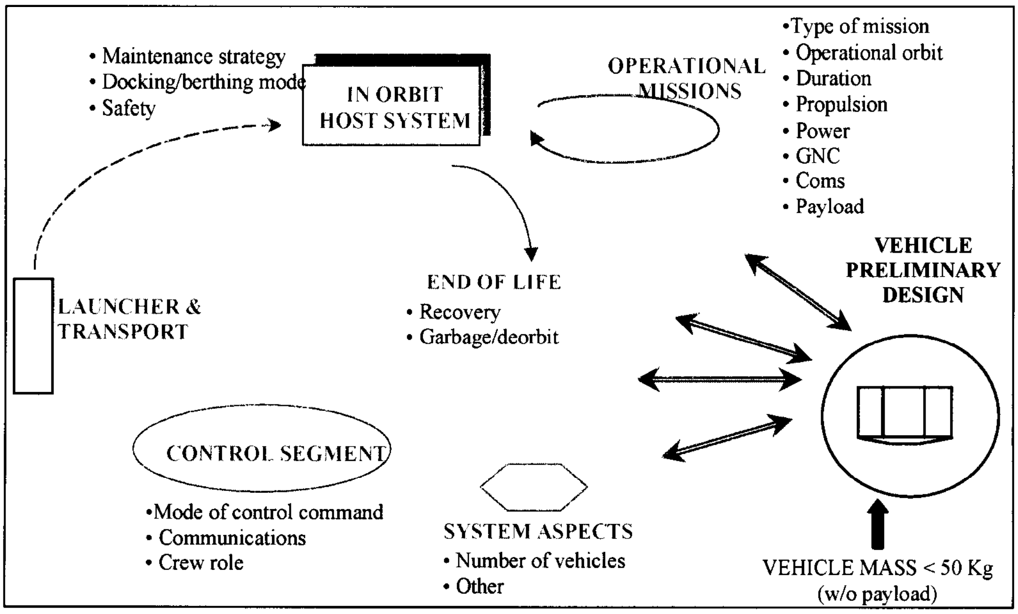


Figure 3/1: Elements of system concept

The safety aspects constitute a key driver for the design of the vehicle, especially when the host system is the International Space Station (ISS). The proposed safety approach takes into account the low mass and velocities of the vehicles to avoid a too complex design, especially with respect to fault tolerance. Two types of vehicles can be considered:

- the intrinsically safe vehicle which could nominally be 0 failure tolerant (FT), as any critical hazard cannot result in catastrophic or critical events. However, not to leave debris in the vicinity of the ISS, it shall be tolerant to one failure for those functions necessary to perform docking/berthing. Examples of intrinsically safe vehicle are small spherical shape vehicle without edges or appendages.

- the non-intrinsically safe vehicle. Such a vehicle should be in principle 2 FT. However, due to its low kinetic energy, any hazard will not result in catastrophic event. Therefore, the vehicle shall be 1 FT on the functions necessary for the return and docking, with a maximum allowable kinetic energy, a capability of being trashed, an immediate return to storage port after one failure of a critical function.

Based on these drivers, one or several alternative system concepts have been identified and assessed for each of the seven candidate missions. This assessment relied, for each mission, on a comparison between the alternative system concepts (technical and life cycle cost criteria) and on an assessment of interest and usefulness of using FFMO (qualitative economical and operational comparison with non-FFMO systems).

This evaluation leads to the following results:

- Inspection far/ close range of ISS (it gathers the first two missions)

  One system identified, based on a mono-task spherical shape vehicle with payload integrated in the vehicle, designed to be intrinsically safe and fully remote controlled, and dedicated to the ISS inspection missions. The storage and maintenance of the vehicle is done inside the pressurised zone. It allows inspecting all the parts of the ISS and gives more flexibility than using SSRMS and lower costs than EVA.

- ISS surface inspection and repair

  One system identified, based on a modular design vehicle, with a payload plate and externally stored on ISS. Maintenance (battery reloading and refuelling) is performed at its external storage port. It allows to inspect the whole ISS surface for small anomalies detection and repair (patches, etc).

- Servicing of external payloads

  Only one system has been identified, based on a modular design vehicle with a payload plate on which is mounted the robotics system. It is externally stored on ISS with battery reloading and refuelling capability at the storage port. It could service or exchange small payloads not individually exchangeable by another way (e.g. SSRMS).

- Servicing of spacecraft

  Four options have been defined and assessed, all based on a modular design vehicle externally stored on the ISS. They differ by the maintenance strategy: maintenance and refuelling at the storage port, maintenance at storage port without refuelling, no maintenance (single mission), support by a carrier (for power constraints). The first option is the preferred one. This concept may be applied to other missions.

- Support to free flying payloads

  Three options have been defined and assessed, all based on a modular design vehicle externally stored on the ISS and having a large autonomy with a partial remote control. The three options considered maintenance and refuelling at the storage port, maintenance at storage port without refuelling and no maintenance (single mission). The first option is the preferred one. This mission is interesting for small payloads due to the high number of flight opportunities. The system concept is applicable to all missions requiring a small platform.

- Inspection/servicing of constellation

  Three options were considered: a vehicle dedicated to a satellite and stored on it (maintenance on the satellite), a vehicle dedicated to one orbit plane with storage and maintenance on an any satellite, a vehicle dedicated to an orbit plane and stored on a carrier. In the last option, the carrier can participate to the placement of the constellation satellites. Inspection of a satellite having a failure or support in case of anomalies (deployment problems, telemetry, listening, etc) could be useful to understand the potential failures.

Finally, ***three missions*** have been selected together with ESA for a more detailed analysis.

- ➢ Far and close inspection, with a small monotask and spherical shape vehicle, storage and maintenance inside the ISS, and a teleoperated system.
- ➢ Inspection with contact and repair, with a modular configuration vehicle, external storage and maintenance, autonomy in free flight
- ➢ Servicing of ISS and external payloads, with same system features as inspection with contact.

That has led to the definition of ***two different systems and associated vehicles***, one for the inspection mission, the other one for the inspection with contact and servicing missions. In the last case, a common vehicle can be defined, with identified specifics for each mission.

3. INSPECTION MISSION

3.1-Mission and system requirements

The reference inspection mission includes two types of missions:

- the ISS core inspection and monitoring in distances between 50m and several hundreds of meters
- the ISS close range inspection and monitoring in distances between 1m and 100m

The differences between these two missions are marginal from a hardware point of view. The reference mission can be fulfilled by the "MICROS" system.

MICROS represents a miniaturized multi-purpose, multi-mission platform operating in close vicinity of the ISS and of ISS visiting vehicles (between 1m and 200m). In addition to the far and close inspection of ISS surfaces and ISS visiting vehicles, MICROS shall also perform EVA support and payload operations tasks (e.g. environment monitoring).

The typical MICROS mission profiles are illustrated on figure 4.1/1. Detailed descriptions of the two reference missions including their operational steps are given in reference document 3.

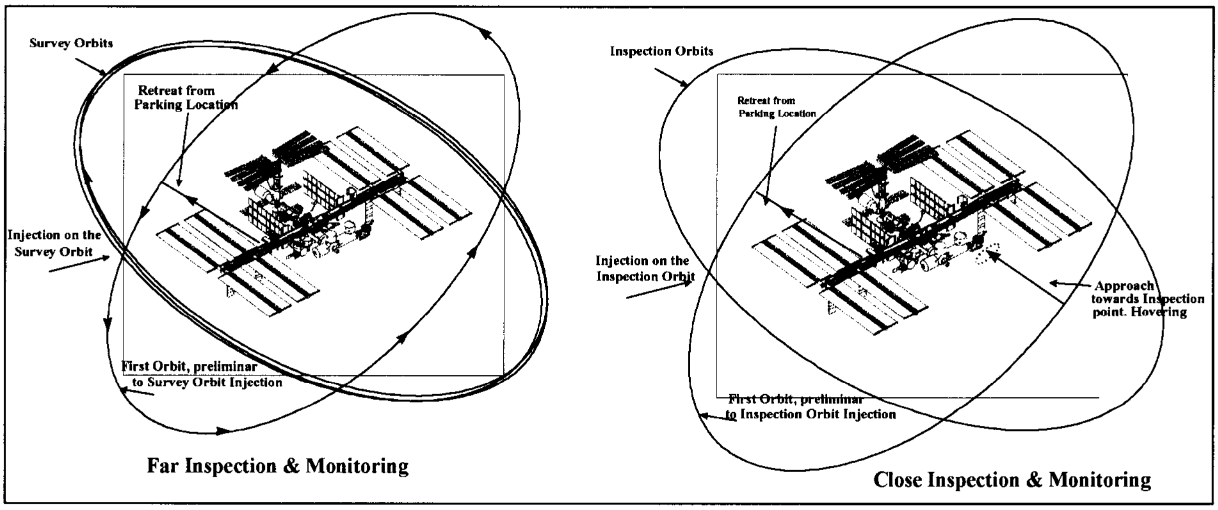


Figure 4.1/1: Far and close inspection missions: Mission Profiles

The MICROS vehicle will be transported by the Space Shuttle inside a mid-deck locker to the ISS and retrieved to earth at the end of the operational period. In between the missions, MICROS will be stored inside the ISS at its storage location (e.g. rack drawer).

The typical on-orbit mission sequence is as follows :

- transport from storage location to the MCS
- pre-flight check-out with the help of the MCS
- transport to airlock and attachment to intermediate parking position inside the airlock

- airlock cycle, i.e. closure of inner hatch/opening of outer hatch, subsequent departure from the airlock
- on-orbit inspection mission
- return to airlock
- airlock cycle
- transport to MCS
- post flight check-out
- transport to storage location

3.2- MICROS system description and main characteristics

The complete MICROS system consists of following elements :

- MICROS spacecraft
- Monitoring & Control Station (MCS) inside the ISS
- Airborne Support Equipment (ASE) including transport and additional communication devices on the ISS
- Ground Support Equipment (GSE)

The main characteristics and technical data of MICROS system are given in tables 4.2/1 and 4.2/2.

The MICROS vehicle with a diameter of 240 mm and a mass of about 7kg can only be realised by the utilisation of microtechnology products to the maximum extent possible today. It is a three axis stabilised vehicle with a total on-orbit lifetime of approximately three years. Within this lifetime the spacecraft is able to perform one mission per month with maximum mission duration of up to 10 hours. This mission time covers one complete EVA shift of 6 hours and the vehicle is able to support the EVA crew during their mission.

MICROS is equipped with video and IR cameras for inspection purposes and with standardized P/L interfaces allowing the attachment of microinstruments, -sensors (e.g. microspectrometer for environmental monitoring purposes). A total P/L mass of 3 kg can be installed on MICROS.

The MICROS vehicle is compatible with EVA constraints and airlock dimensions and is serviced and maintained (refueling, battery exchange, P/L exchange etc.) inside ISS by IVA astronauts.

Due to its soft cover, its low mass and its low thrust level the spacecraft has a zero-failure tolerant (FT) architecture in nearly all area. In order to increase the overall system reliability a 1-FT has been incorporated in specific area (e.g. thrusters). This approach will have to be discussed with ISS.

Missions	**- ISS inspection (1m - 200m)**
	- EVA Support
	- P/L operation
Orbit	**"co-orbiting" with ISS**
- Height	**350 - 450 km**
- Inclination	**51.6°**
Orientation	**selectable**
Stabilization	**three-axes**
On-Orbit Lifetime	**about 3 years**
No. of Missions	**1 mission / month**
Mission Duration	**up to 10 hours**
Failure Tolerance Level	**0-FT (1-FT in specific areas)**

Table 4.2/1: MICROS Main Characteristics

Mass	**- 10 kg**
Dimensions	**football sized S/C, d = 240 mm**
Power	**15 W at 12 VDC**
Data Transfer	**S - Band**
Pointing Accuracy	**0.05° all axes (tbc)**
Data Interface	**tbd**

Table 4.2/2: Basic Technical Data

3.3-Technical Description

MICROS is a "ball" type spacecraft with a soft outer cover and a rigid inner structure. The soft cover may be realised by foamrubber or by a thin, flexible metal mesh with cuttings and perforations as required (e.g. for thrusters, camera head etc.) and is detachable to allow access to the internal equipment for maintenance purposes. The spacecraft main body will be designed nearly without any protrusions to avoid potential crew injuries and damages of the ISS surfaces.

The inner structure consists of two light-weight, horizontal plates, which allow the accommodation of the required subsystem and P/L equipment. The distribution of the subsystem equipment into the three resulting floors is mainly driven by aspects like equipment dimensions resp. available volume under the outer cover, placement of the centre of gravity near at the geometrical centre and not by functional dependences and relations between the different boxes. However, all equipment required for video navigation and inspection purposes is concentrated on the upper floor and the reaction wheel (RW) units including drive electronics are located near the centre of gravity.

The housings of the two exchangeable battery packs are designed as load carrying structure, i.e. the upper and center plates are directely fixed to the battery housings.

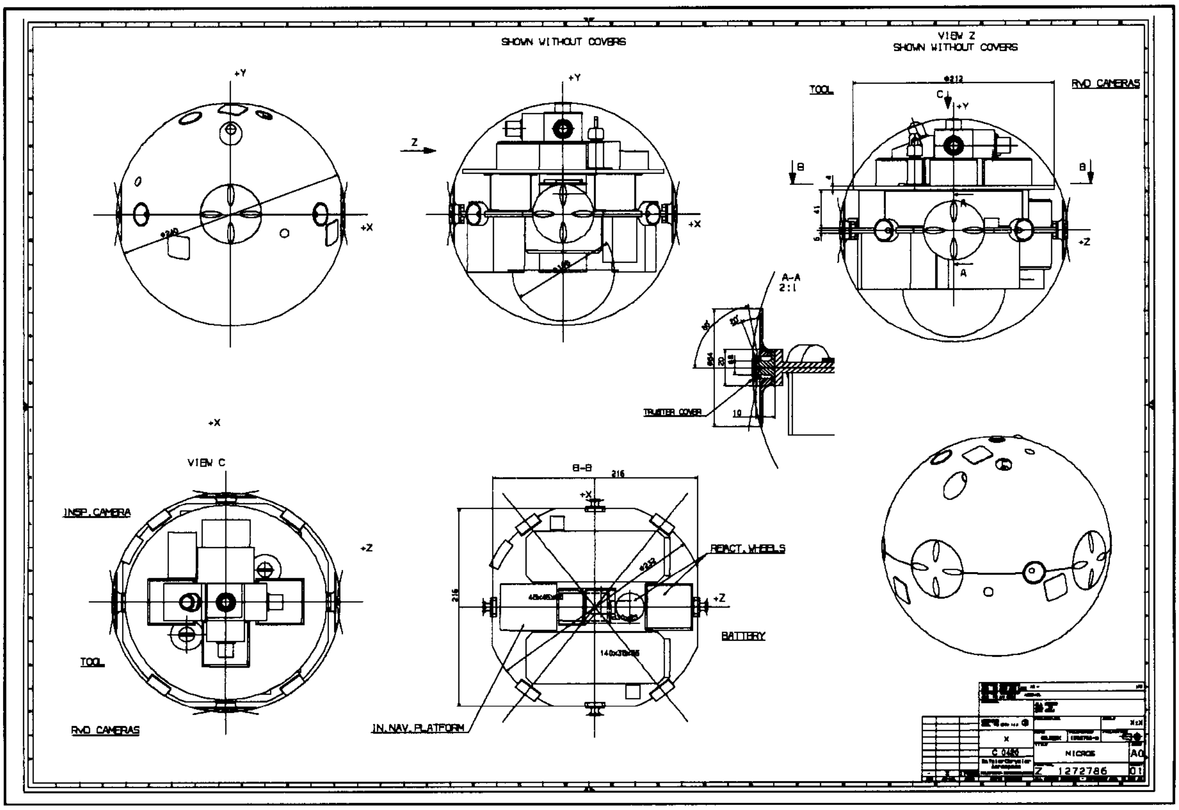


Figure 4.3/1: MICROS configuration

The center plate is realized as a hot inflatable aluminum sandwich base plate and contains the fuel lines, high and low pressure fuel valves, the tank interface, and the mechanical interface to the four thruster clusters, each with four thrusters. In addition to that, the center plate has a "standard" hole pattern with inserts allowing the fixation of equipment boxes to the plate.

Spaced equally around the sphere are six small, flashing lights in different colours that make MICROS visible to the EVA crew or operator in darkness and six small close distance sensors giving a warning signal if the vehicle is closer than 1m to any surface. Furthermore, the outer cover is marked by stripes, arrows, dots and rectangles in black and red. These markings assist the EVA crew and operator in determining the orientation of the MICROS vehicle.

The MICROS spacecraft and the MCS will have a 0-FT avionics architecture. This approach can be realized since the low mass of the vehicle in combination with the soft outer cover and the low thrust level will not result in catastrophic or critical hazards in the failure case. In this context catastrophic hazards are defined as disabling or fatal personnel injuries or loss of the ISS, critical hazards are

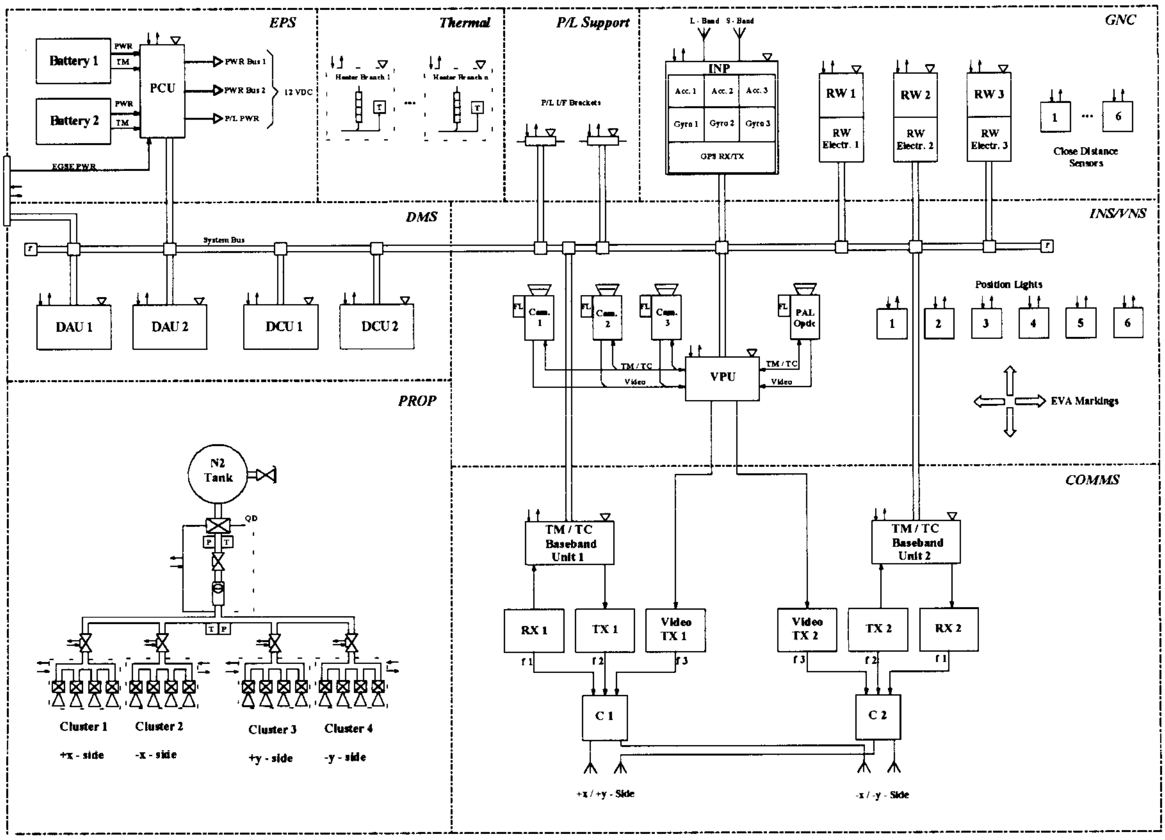


Figure 4.3/2: MICROS architecture

defined as non-disabling personnel injuries, severe occupational illness, or loss of major ISS element, on-orbit life-sustaining function or an emergency function. However, in order to increase the overall system reliability and to achieve an excellent manoeuvrability some system functions will be designed 1-FT (e.g. thrust generation).

3.4-Programmatic Aspects

MICROS represents a new type of spacecraft based on the utilization of microtechnology components to the maximum extent possible. The development and qualification of microtechnology components is very cost intensive and cannot be paid by the space community alone. For this reason the following ground rules have to be applied to guarantee a cost efficient MICROS realization :

- maximum utilization of existing, qualified hardware and software from other space programmes to minimize the need for MICROS specific developments
- utilization resp. upgrade of equipment available in commercial or MIL-STD quality
- close cooperation with microtechnology experts outside the space business
- open competition on all levels (components, box/unit, subsystem) for all non-recurring resp. non-procurement items as well as for all procurement items
- attempt to get co-funding from source outside the space community (e.g. ministry of research, µ-technology budget)

MICROS will have a life cycle with 'conventional' project phases (Phase A to E) with the following durations (see figure 4.4/1):

- Phase A :	9 months
- Phase B :	12 months
- Phase C/D :	22 months incl. pre-launch activities at launch site
- Phase E :	10 years in total

The development approach relies on three system level models:

- a Digital Mock-up, which consists in a CATIA 3D model and a Virtual Reality Model, for general design, support activities and generation of manufacturing and integration drawings.
- a Structure and Thermal model for structural and thermal qualification on system level.
- an Engineering Qualification Model, developed in three steps: an Engineering Test Model, comprising flight representative avionics components, allowing early development and functional qualification and test of electrical/ avionics functions; this model is upgraded into an Engineering Model, for functional test, qualification and validation of operational procedures; then, this model is refurbished and used as ground reference model during the operational phase.

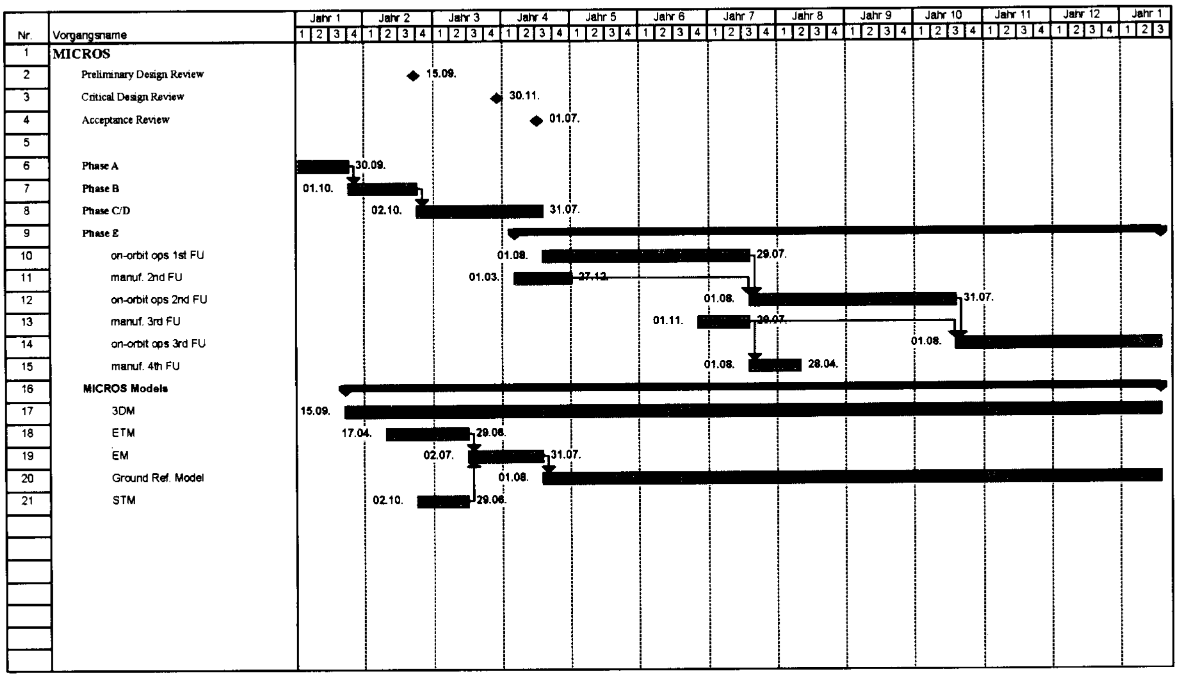


Figure 4.4/1: MICROS master schedule

The operational Phase E (10 years) includes :

- manufacturing , integration and test of the flight units no.2 to no.4
- launch and retrieval of the flight units with the Space Shuttle
- airborne support equipment
- additional ISS communication devices
- maintenance / resupply of the MICROS S/C (tank / battery exchange)
- costs of ISS resources (power, data transfer)
- EVA/IVA support
- ground support

4. SERVICING MISSION AND INSPECTION WITH CONTACT MISSION

4.1- Mission and system requirements

The analysis of these two reference missions in term of scenarios, constraints and requirements leads to define an FFMO system called SERVISS, capable of fulfilling both missions with the adequate adaptations.

The SERVISS vehicle is a versatile platform capable of the replacement of ISS or payload ORU, of external payloads exchange, of external payloads in situ analysis, of exchange and return of payload samples to the ISS and of ISS inspection with contact and patch repair

The typical mission profile of a SERVISS mission is shown on figure 5.1/1.

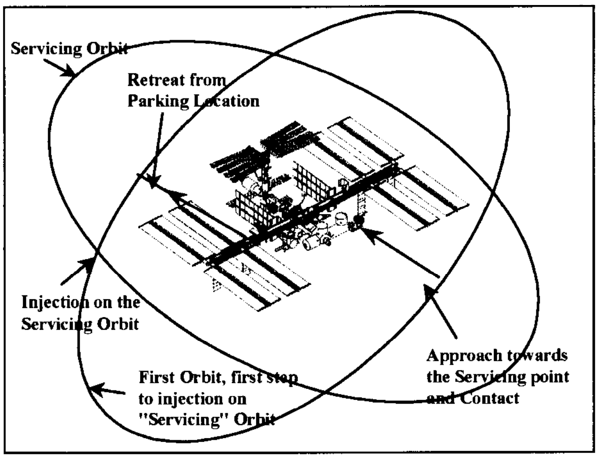


Figure 5.1/1: Servicing mission typical profile

The main requirements of the SERVISS mission are:

- Mission duration of 12h at the maximum (at least 6 hours of servicing mission).
- SERVISS vehicle externally stored on the ISS: no EVA or robotics required for the maintenance
- Vehicle in orbit lifetime of 2 years, during which up to 12 missions can be carried out
- Autonomous free flying navigation and control
- No catastrophic hazard on ISS
- Vehicle mass less than 50 Kg (without payload and any robotic system)
- System compatible with the Express Pallet envelope (mass size, power)

4.2-SERVISS system description

The SERVISS system from launch to its recovery by the STS is illustrated on the figure 5.2/1.

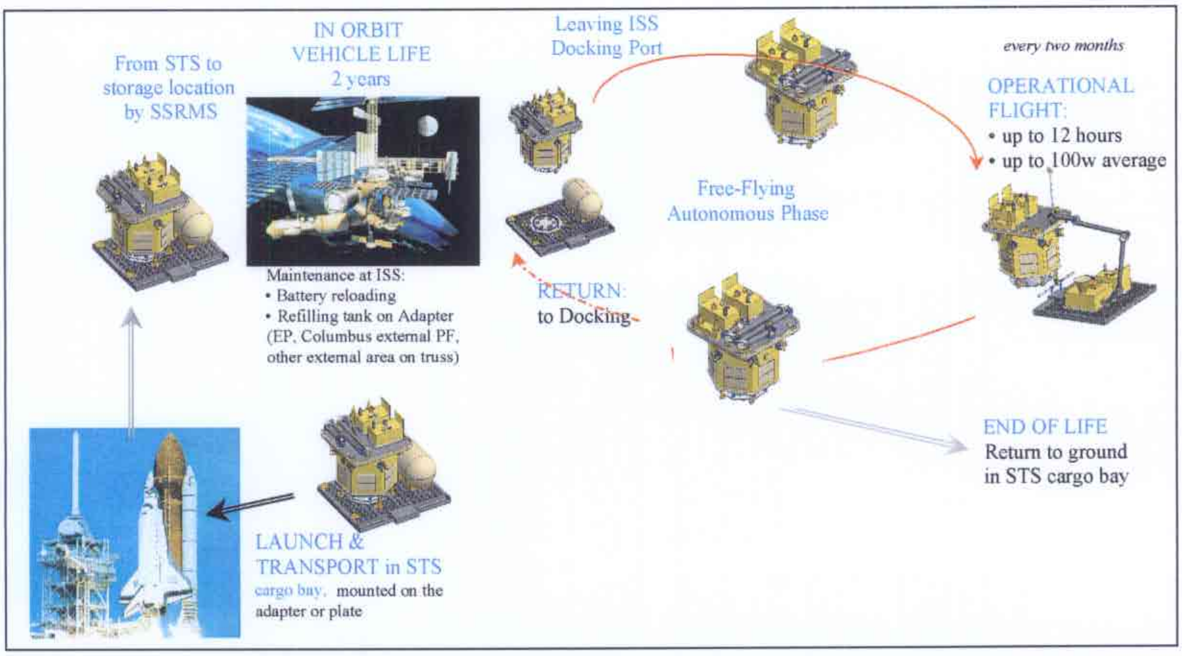


Figure 5.2/1: Illustration of SERVISS system and utilisation scenario

It is transported and stored on an Express Pallet adapter (EPA). Therefore, it is considered as an Adapter payload: it does not require any additional resource from the Station, power recharge and data exchange being ensured through the Adapters connections. As shown on figure 5.2/2, the SERVISS system includes also a refilling tank for refilling the vehicle in cold gas, the half docking port with the adequate connections, and targets for the final approach and docking sensors.

Due to its low mass and low velocity, the SERVISS vehicle has a kinetic energy low enough not to generate any catastrophic hazard to ISS. In addition, edges and corners of the vehicle are covered, as much as possible, by a soft material to absorb contact energy. Consequently, the SERVISS is one failure tolerant on all functions required to perform free flight and return to the docking port (mainly avionics and propulsion). This approach will have to be discussed with ISS.

The control command of the vehicle depends on the operational phase. During free-flying phases (i.e. including docking and contact with the Station), the vehicle is autonomous, with hold points where a crewmember authorises the next operations sequence. However, the crewmember can send commands to the vehicle in contingency case. In attached phases, most of the envisaged tasks will be teleoperated from the Station.

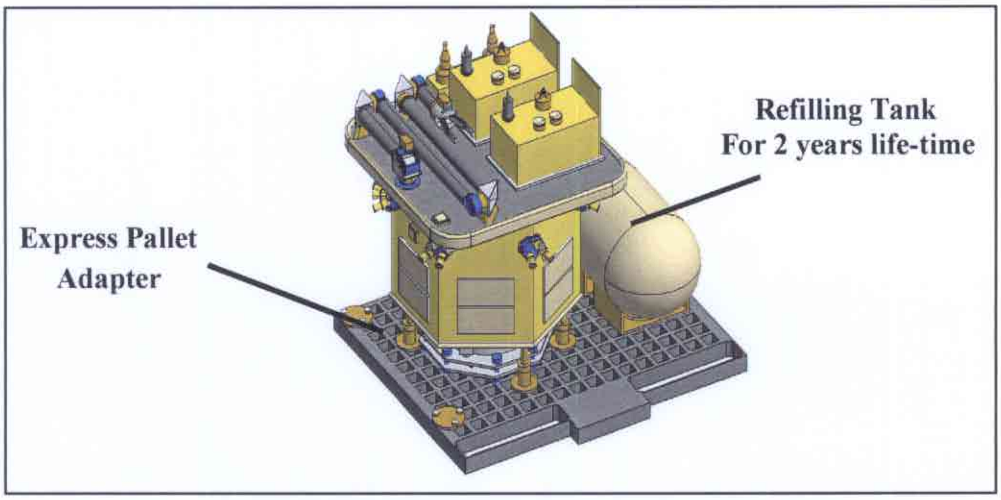


Figure 5.2/2: SERV-ISS vehicle on its storage base

4.3- Vehicle design

The SERVISS vehicle concept is modular, and, as shown on figure 5.3/1, is comprising of:

- A payload module (M3) to accommodate the ORUs, the small payloads and the servicing instrumentation (robotic system, tools for contact inspection and repair)
- A resources module (M1) for the main vehicle free flying capabilities and subsystems
- A docking/grasping module (M2), with all the means dedicated to docking at storage port and grasping of working site

The mass of the vehicle, without payload and instrumentation, is less than 50 Kg. The payload mass shall be 30 Kg at the maximum, so that the SERVISS mass in servicing configuration is about 90kg.

Structure and Mechanisms

The vehicle has a cylindrical-hexagonal shape (figure 5.3/2). The primary structure is lightweight and made of six supporting aluminium struts, two hexagonal rings for adaptation of the upper and lower plates and six lateral panels. Most of equipment are mounted on the lateral panels (avionics and batteries). The thrusters are mounted on the supporting structure.

The vehicle size (60 cm diameter and 75 cm height, payload excluded) is driven by the payload size, in particular the ORU's footprints. The payload module size varies with the mission. The servicing one is the most constraining (due to instrumentation) leading to a square payload plate of 80cm side.

The docking mechanism is designed to ensure latching and mechanical, power, data and fluidic connections, to provide a spring motion at separation and to sustain the launch and re-entry loads.

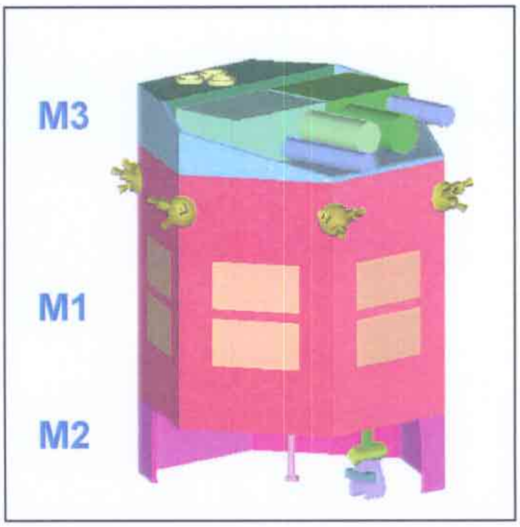


Figure 5.3/1: Modular concept of SERVISS

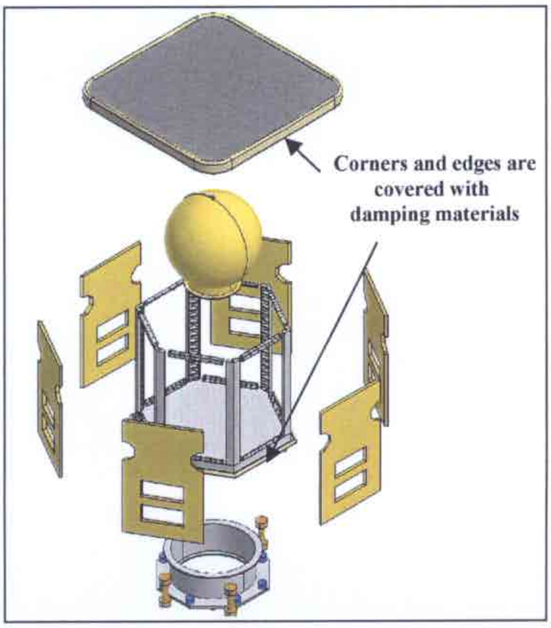


Figure 5.3/2: SERVISS vehicle structure

Mechanical and electromagnetic concepts have been considered, both adapted from already existing docking ports. The grasping mechanism is designed to allow the capture of a non-cooperative working site through handrails. It will also allow the vehicle to bend towards ISS surface during the surface inspection and repair tasks, and to reach the area to be inspected or repaired.

Avionics

The avionics architecture is driven by the mass, power consumption and size constraints. One possible design is to concentrate all the electronic functions (processor, memories, RF heads, micro gyros, GPS receivers, sensors electronic, propulsion control, thermal driver, propulsion driver, etc) into one single box, a central management unit. Miniaturisation and micro technologies will be of great benefit to reach this objective of the "system in a box".

The relevant SERVISS avionics architecture is illustrated on figure 5.3/3. It is based on two redundant central management units, which share the same sets of sensors and actuators and which are in hot redundancy during the critical phases and in cold redundancy when not in critical phases.

The peripherals are connected to the avionics boxes, through serial lines for data exchange or through video connections for camera optics or optical sensors (high data rate). A bus is planned between the central management units and the robotic electronic unit, in charge of the robotic processing.

The interfaces between the vehicle and the ISS in docked mode are ensured via an umbilical connection to Express Pallet Adapter for power and data. Through this connection, the ISS powers and monitors the heaters, monitors the safety critical parameters and manages the refilling operations.

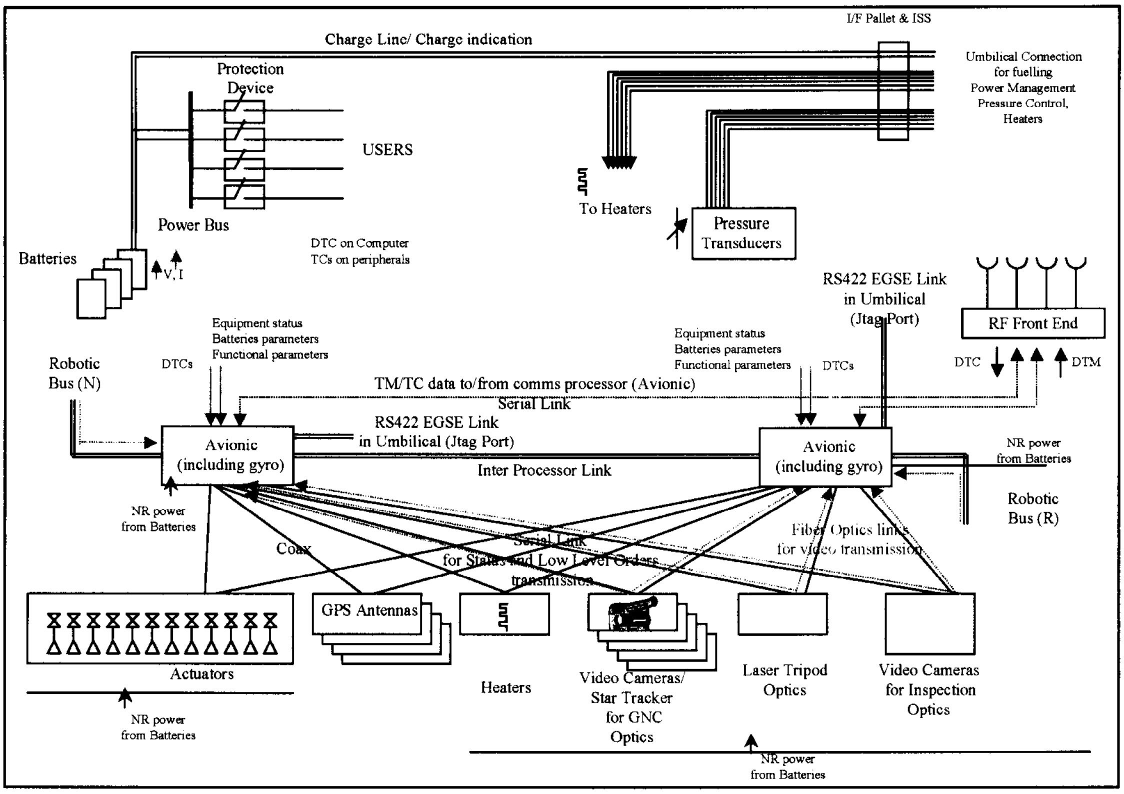


Figure 5.3/3: Avionics architecture

12 Lithium-ion rechargeable batteries provide an energy capability of about 1.3Kwh, for an estimated power consumption of about 910 Wh. The margin could be used in contingency cases. These batteries are recharged at the storage port after each mission. Protection devices will be implemented to avoid short circuit consequences. Converters within the units will allow for the adequate voltage.

The communication subsystem is designed to offer an omni directional coverage in S band, whatever the SERVISS attitude is. Four antennae are mounted around the vehicle. The data rates are 8Kb/s for TM and TC, and 3 Mb/s for the video.

GNC

The GNC subsystem is based on an autonomous navigation system, allowing autonomous control of the vehicle in all free-flying phases. The GNC equipment include a gyro package in each avionics central management unit, star sensors (three sensors are implemented to provide the widest possible angle), one laser tripod for proximity operations, three APS based cameras, one position light.

The attitude is provided in all free-flying phases by the combination of a star tracker with the 3 axes gyros for propagation. Absolute position is given in real time and autonomously by a GPS receiver. The relative navigation is performed by an on-board propagator of the orbital dynamics, the long term drift being suppressed with the support of optical vision means, through the identification of pre-defined landmarks on the ISS structure. Landmarks are either geometrical surfaces or volumes constitutive of the ISS, or points or patterns unambiguously defined on ISS. The capture of these landmarks is performed through the star trackers in the camera mode.

Docking on the storage port is possible thanks to the targets (reflectors) implemented on the storage port. The image of these reflectors is captured by 2 cameras located underneath the upper plate. The processing of these images allow for range, range rates, LOS and attitude determination.

Approach to and contact with the working site is ensured through the image processing of 3 cameras and the range and range rate provided by the tripod. Their implementation is shown on figure 5.3/4.

Propulsion

The SERVISS propulsion is based on cold gas, with one spherical tank of 40 cm diameter within the resource module. The tank is pressurised at 50 bars, contains 2 Kg of cold gas providing a DeltaV of 15 m/s and is refilled after each mission. The thruster configuration (see figure 5.3/4) is derived from the GNC controllability and manoeuvrability analysis. It is based on a nominal set of three clusters of three small thrusters each. The thrust generated by each thruster has been estimated to 0.1N to cover the required manoeuvrability in case of loss of attitude. For failure tolerance purpose, the configuration is doubled leading to 6 clusters of 3 thrusters each.

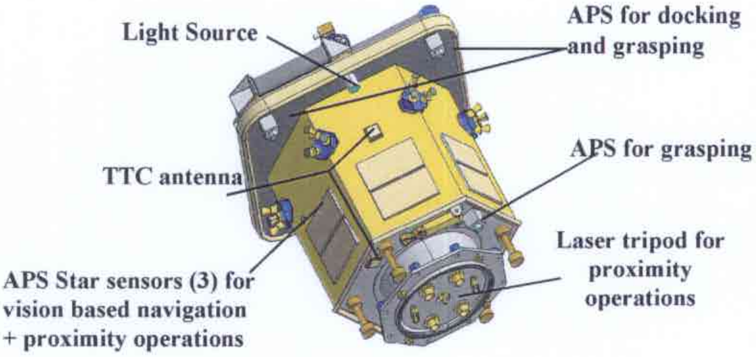
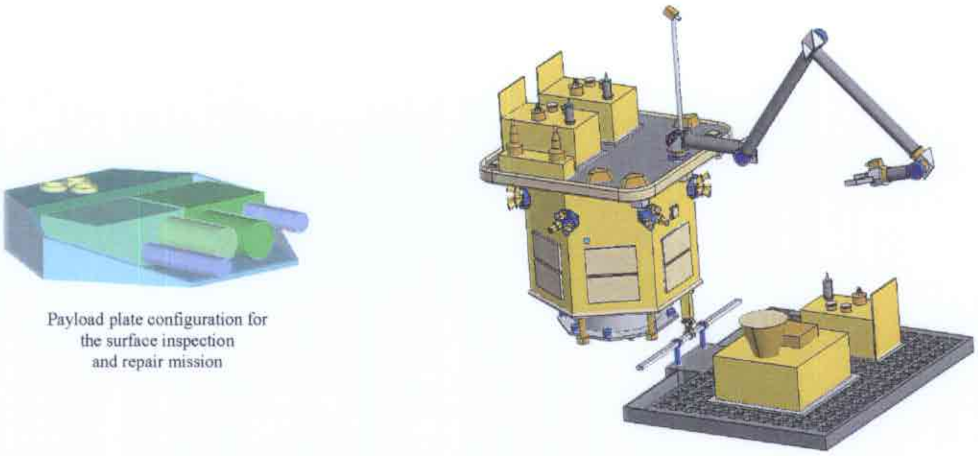


Figure 5.3/4: GNC sensors and propulsion configuration

4.4-Instrumentation for the missions

The robotic system necessary for the servicing mission includes a robotic arm, a robotic electronic unit for the control of the system, tools, cameras and a light source mounted on a boom with one camera. To reach any location on a Pallet the robotic arm has a maximum length of 1.6m. The servicing operations, performed when SERVISS is attached on the working site, are teleoperated by the ISS crew. The servicing configuration is illustrated on figure 5.3/5.

The instrumentation for the surface inspection and repair mission include a video camera with high magnification lenses, a laser beam to sweep the inspection path highlighting cracks, holes, etc, a laser filter to see flaws in detail, inspection tools such as eddy-current, a scanning electron microscope, X-ray and lighting devices. The payload module shall also be equipped with some special repair units or actuators like sealant and adhesive dispensers, patching devices, etc.



Payload plate configuration for
the surface inspection
and repair mission

Figure 5.3/5: SERVISS working site configuration

4.5-Programmatic

The implementation plan of the SERVISS system includes the pre-development phase, the development phase and the utilisation phase.

Pre-development phase

It covers the system activities (identification of required technologies, phase 0 and phase A), the R&D activities related to the identified technologies and to be started as soon as possible, and some pre development activities necessary for critical items or for adaptation of already existing items.

Development phase

The development phase covers the phases B, C and D of the SERVISS system. The technology R&D activities will continue in parallel and in coherence, the objective being to have the new technologies integrated in the design with a good level of confidence at the PDR, that means at the end of phase B. The field of R&D activities is the one described in section 6.

The approach proposed for the development phase (figure 5.5/1) aims to minimise the risks. It is based on the use of mathematical models, simulations and a few breadboards in phase B, before the PDR, and in three types of models in phase C/D: Structure and Thermal Model (STM), Engineering Model (EM) and ProtoFlight Model (PFM).

The STM, fully representative in term of structure and equipped with equipment dummies and a mechanical model of the robotic system, allows to validate the vehicle structure sizing and the thermal model. Associated with a mechanical model of the Adapter, it will be used to verify the docking mechanism concept and sizing.

The EM will include the avionics equipment engineering models (without redundancy), a propulsion chain, the planned harness and connectors, all equipment being integrated in a vehicle structure mock up. Coupled to an avionics test bench, the EM aims to perform a functional verification of the vehicle, including verification of the control command interfaces with crew or ground station, of the integration procedures and of the harness. EMC tests and verification of the propulsion chain will also be carried out. An adapter EM (mainly electrical equipment) is necessary to perform the functional verification of the system in docked mode.

A GNC bench, including a few boards of the central management unit (the processor and those boards related to the sensors electronics), engineering models of sensors and a first version of the flight software, is used to validate the SERVISS vehicle performances in the different phases. GNC bench and avionics test bench definitions will maximise the use of common elements.

The protoflight model will be subject to functional tests, vibrations, thermal vacuum solar, EMC and workmanship. Additional functional tests, integration tests and leakage tests will be performed on the system PFM, once the vehicle PFM with its instrumentation is integrated on the adapter PFM.

The development plan (figure 5.5/2), is derived from the development approach. The phase B, concluded by the PDR, lasts 12 months. The phase C/D has a duration of 3 years. It includes a CDR, about 18 months after the PDR, to verify the design of the vehicle.

Operations

A new SERVISS vehicle is launched every two years, the same STS flight recovering the previous vehicle down to Earth. A spare vehicle is manufactured after the launch of the protoflight and is stored on ground to be used in case of failure of any of the operational vehicles.

The life cycle of both servicing and surface inspection with repair missions assumes a 10 years lifetime of the system, 5 vehicles launched in orbit (1 every 2 years) and one spare on ground, 12 missions per vehicle, and starts with the development phase.

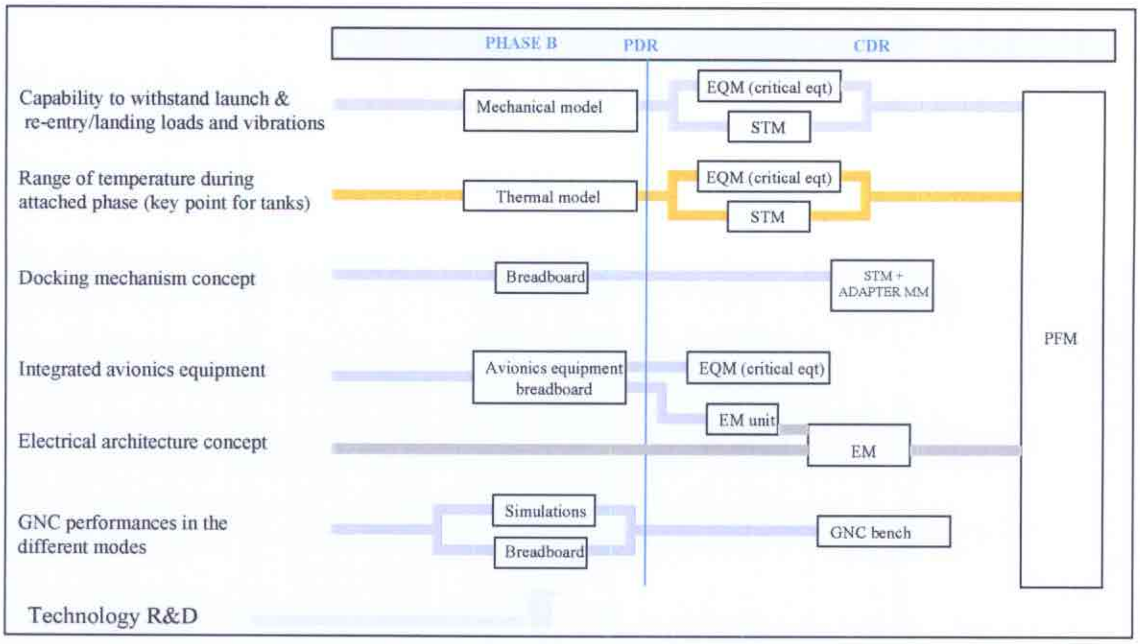


Figure 5.5/1: Verification/validation philosophy

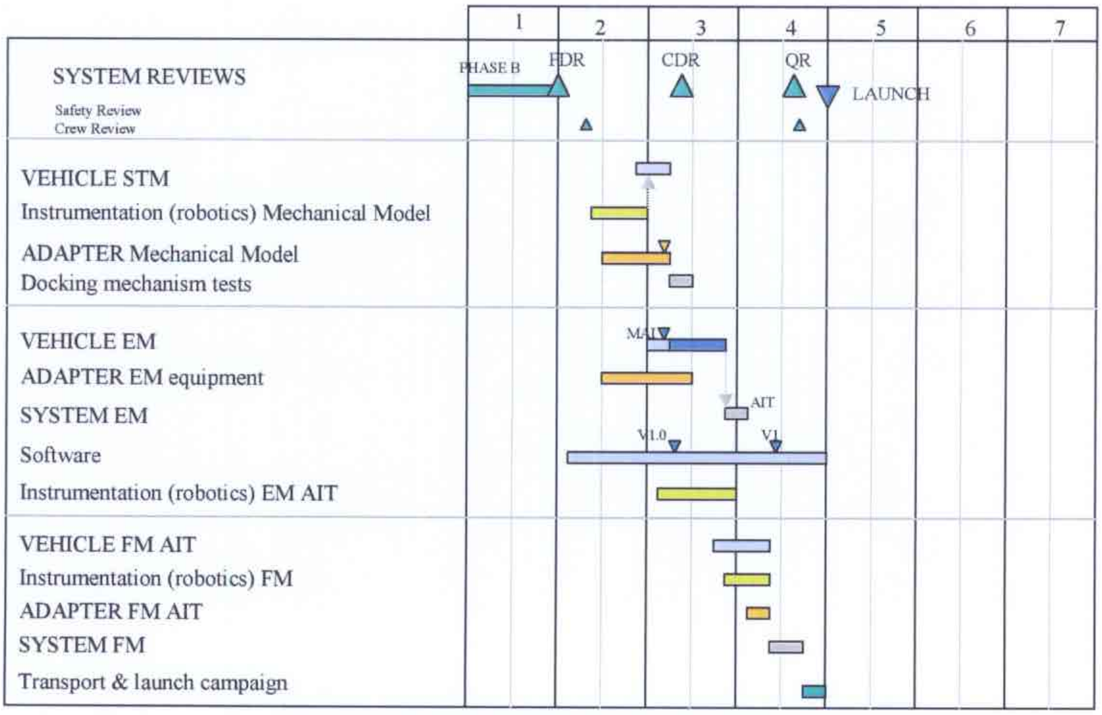


Figure 5.5/2: SERVISS development plan

5. TECHNOLOGIES

The design of the proposed FFMO vehicles relies on the development of new technologies, and in particular on the use of miniaturisation and micro technologies in areas like avionics, sensors, propulsion and instrumentation.

The main axes of micro-technology R&D are summarised in the table 6/1. They are related to:

- Sensors: optical sensors (cameras and star trackers), rendezvous sensors, gyros, GPS receivers,
- Micro propulsion: micro thrusters (ACR has developed micro thrusters for GOCE and IMM has proposed a concept for Micros), micro valves, micro pressure regulator.
- Avionics system: road maps have been established to go to a "system on board" first, as proposed on SERVISS, and later to "system on chip". Development or improvement of different technologies (such as fine ceramic substrate, high density PCB, dual cavity MCM, micro connectors, etc) is necessary. Another axis is the development of low voltage component for digital electronics.
- Instrumentation: the instrumentation necessary to fulfil the FFMO mission shall also take benefit of the micro technologies: optical spectroscopy, partial and total pressure measurement, endoscopy, micro cameras.

The development of the micro technologies should involve Labs, SME and also companies with strong background in development of Space equipment. The packaging and reliability should be looked at carefully for implementation on Space vehicles, in order to assess mass, size and power.

The micro technologies will probably be introduced progressively on the FFMO vehicles. A certain number of these technologies could be available for the first FFMO development provided the relevant activities are initiated from now. Besides, FFMO design improvements including micro technologies will be implemented in parallel with on going operational missions.

Other axes of R&D technologies have also to be undertaken. They concern the GNC (vision based navigation, obstacles avoidance system), the propulsion (high efficient cold gas), the power generation (improvement of rechargeable batteries performances, research of new type of batteries), the vehicle autonomy.

All these technologies, necessary for the FFMO, are also applicable to other missions, like telecom satellites, micro satellites, planetary vehicles (probes, small vehicle, landers, vehicles returning from planet to Orbiter, future reusable launchers, etc).

TECHNOLOGY	*AXES OF DEVELOPMENT*	*APPLICABILITY*
Optical sensors (cameras, star trackers)	- development of new technologies (APS, etc) - optical head with minimum proximity electronics (ASIC, etc), sensors electronics in avionics box - objective: optical head mass < 0.5 Kg	- Micro satellites - Planetary vehicles
RV sensors	- development of micro telemeters for obstacle detection. It can be based on the development for commercial applications (LETI, LAAS) - cameras sensors: interest of common development with optical sensors	- Vehicle returning from planet to Orbiter - Landers
Gyros	- to continue the current R&D on micro gyros. - objective: drift < 1°/h, integrable on a chip - FOG technology to achieve the objective by 2002 - MEMS technology is an axis of R&D	- Telecom satellites - Micro satellites - Planetary vehicles
GPS	-to develop a micro GPS for Space based on technology developed for commercial applications -objective: to have RF, clock and signal processing integrated on a small board	- Micro satellites - Future reusable launchers
GNC	- vision based navigation - obstacles avoidance system	- planetary vehicles - landers
Avionics packaging	- Objective: "system on board" by 2002, "on chip" by 2005 - R&D on very fine ceramic substrate (VFL), High density PCB, dual cavity MCM, micro connectors	- Future reusable launchers - Telecom satellite - Micro satellites - Planetary vehicles, landers
Power	-High density DC/DC converter in hybrid technology -Mixed ASIC for power control function -Low voltage for digital electronics : 1.8v by 2002, 1.2v by 2004 - high efficiency rechargeable batteries	- Future reusable launchers - Telecom satellite - Micro satellites - Planetary vehicles - Landers
Propulsion	- Micro thrusters (0.1 N) for proportional thrust - Micro valves in the range 0-5 bars, and for 50 bars - Micro pressure regulators for 1- 50 bars - Micro pressure sensor	- Micro satellites - Small vehicles to planets - Vehicles returning from planet to Orbiter
Instrumentation	- Micro cameras: common development and technology with optical sensors. - Micro spectrometers - Micro tools to be assessed - Effort measurement sensors	- Micro satellites - Planetary vehicles

Table 6/1: Summary of main axes of technology R&D

6. CONCLUSIONS

Missions and users exist for free flying micro operators based at ISS. Some attractive missions have been identified, such as:

- Inspection, in support to the Station (monitoring, operations) or other (education, media, etc)
- Servicing of ISS or external payloads
- Support to free flying payloads
- Relay satellite between ISS and EVA or incoming vehicles, etc

Two complementary concepts of vehicles have been studied, which both can be part of the FFMO system:

- A mono-task concept for inspection, internally stored (MICROS concept)
- A modular concept, externally mounted on an Express Pallet adapter (SERVISS concept)

Both concepts rely on miniaturisation and micro technologies, and both vehicles have a low mass (<10 Kg for MICROS, <50 Kg for SERVISS)

The FFMO programme is a technological driver for the development of miniaturisation techniques and micro technology, which will benefit to other applications, such as planetary missions.

The FFMO system reuses and extends the development already undertaken by Europe in the frame of ISS utilisation:

- Automatic rendezvous and docking capabilities
- Express Pallet adapter payload analysis and integration
- JERICO manipulator system

The implementation plan of the two vehicles shows a short development plan (3 years for MICROS, 4 years for SERVISS), a low development and life cycle cost and the need for a technology R&D programme.

The two vehicles are complementary in term of missions: MICROS is adapted to missions with payload integrated in the vehicle while SERVISS is adapted to missions with payload plate and /or contact with ISS. The FFMO system could take advantage of this complementarity with a progressive implementation of the system relying on a stepped approach, and a common technology programme. That would allow the validation of technologies capability of the vehicle in development by the vehicle in operations. Such a stepped approach allows to propose an attractive FFMO family covering a wide range of missions while being a main factor of cost reduction.

7. STUDY DOCUMENTATION

The following documents have been issued during the study and are part of the final report:

1. FFMO TN1, "FFMO Mission Definition", FFMO/MMT/TN/1, iss.1, rev.0, dated 09.06.98
2. FFMO TN2, "FFMO Mission Characteristics", FFMO/MMT/TN/2, iss.1, rev.0, dated 09.06.98
3. FFMO TN3a, "FFMO Preliminary Conceptual Design", FFMO/MMT/TN/3, iss.1, rev.0, dated 20.11.98
4. FFMO TN 3b, "Life Cycle Cost Model", FFMO/MMT/TN/5, iss.1, rev.0, dated 30.11.98
5. FFMO TN4, "FFMO Missions trade-off analysis", FFMO/MMT/TN/6, iss.1, rev.0, dated 30.11.98
6. FFMO TN5, "FFMO System Requirements for the Reference Missions", FFMO/MMT/TN/7, iss.1, rev.0, dated 31.01.99
7. FFMO TN6, "FFMO Preliminary conceptual design ", FFMO/MMT/TN/8, iss.1, rev.0, dated 20.03.99
8. FFMO TN7, "FFMO Programmatic assessment and technology requirements", FFMO/MMT/TN/9, iss. 1, rev.0, dated 15.06.99
9. FFMO Final Presentation Hand-out, MMS/DTH/GL/FFMO/002.99, dated 18.05.99

8. ACRONYMS

APS	Adaptive Pixel Sensor
ASE	Airborne Support Equipment
CDR	Critical Design Review
EM	Engineering Model
EMC	ElectroMagnetic Compatibility
EPA	Express Pallet Adapter
EVA	Extra Vehicular Activity
FFMO	Free-Flying Micro-Operator
FT	Fault Tolerant
GEO	Geostationary Orbit
GNC	Guidance, Navigation and Control
GPS	Global Positioning System
GSE	Ground Support Equipment
IR	InfraRed
ISS	International Space Station
IVA	Intra-Vehicular Activity
LEO	Low Earth Orbit
MCM	Multi Chip Module
MCS	Monitoring & Control Station
ORU	Orbital Replaceable Unit
PCB	Printed Circuit Board
PDR	Preliminary Design Review

PFM	ProtoFlight Model
P/L	Payload
R&D	Research & Development
ROM	Random Of Magnitude
SSRMS	Space Station Remote Manipulator System
STM	Structure and Thermal Model