SPACE ROBOTIC SYSTEM FOR PROXIMITY OPERATIONS

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Abstract

Space stations will be built, maintened and upgraded (servicing) in space over a period of several years. Key to an efficient accomplishment of servicing operations is the development of a scenario where the presence of man in space is well integrated with the capability of teleoperated and automatic robot system outside the stations. In this context, Tecnospazio is performing, on behalf of the Italian Space Agency (ASI), a feasibility study on a space robotic vehicle (SPIDER) capable of inspection and repair activities around and on Space Platforms.

The paper illustrates the results up to now obtained and, in particular, will focus on mission requirements, trajectory sequences, propulsion S/S features and manipulative kit characteristics relevant to the MTFF-RM proximity servicing mission (Robotic Mission). Nevertheless, the type of vehicle here considered can operate in different scenarios, e.g. in Space Station close proximity, provided that the overall energy budget is maintened.

1. Introduction

A generic on orbit servicing mission is schematically represented in **Figure 1-1**. Such a mission is formed by two main portions, functionally separated:

- the Logistic Mission
- the Robotic Mission

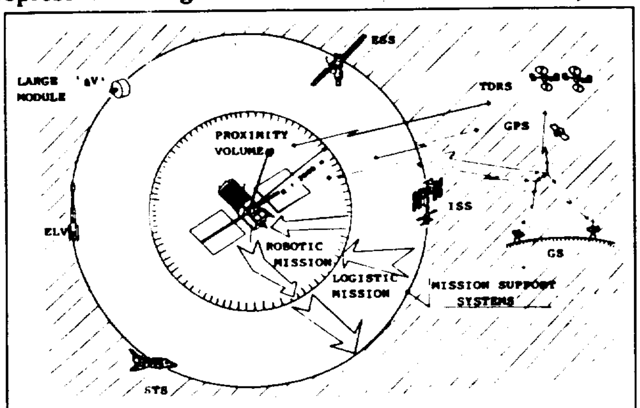

Fig. 1-1: On Orbit Servicing Mission

The Serviced System (the MTFF-RM) is considered included in a "Proximity Volume" (for example a 2000 m. diameter sphere) inside which the cold gas propulsion is advisable. The Mission Support Systems are constituted by large platforms and/or structures allowing proper interfaces with the Telerobot.

The Logistic Mission takes care of the Telerobot phisical transfer between the Mission Support Systems and the Proximity Volume. The transfer, normally performed by large ΔV modules, is controlled through high level requirements such as: mission synchronism, orbital parameters, energy, etc.

The Robotic Mission is intended to be constituted of all the activities to be performed by the Telerobot inside the "Proximity Volume".

Tecnospazio on going activity is related to a feasibility study of a Telerobot capable to perform the Robotic Mission. The activities performed are in line with general "feasibility aspects" rather than optimization or detailed technological considerations except for "technological risks".

2. Robotic Mission Requirements

The starting mission condition (see **Figure 2-1**) is assumed to be the following:

- the Telerobot is docked to a large ΔV transfer module and parked (on the surface of the proximity volume) at x = +2000 (m) along the +VBAR.

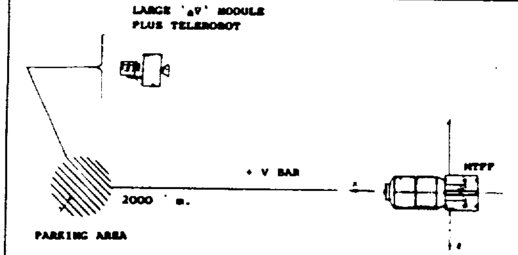

Fig. 2-1: Starting/Ending Conditions

The ending mission condition is assumed to be the same as the starting one.
The activities to be performed during the Robotic Mission and which constitute the Telerobot requirements, are shown in **Table 2-1.**
It must be pointed out that the identified requirements are derived from a MTFF configuration still provisional and with the specific servicing requirements not yet fully defined. Therefore, some of the requirements are necessarily in a qualitative form though allowing a range of possibilities.
Based on activities already performed, and anticipating some outputs, the candidate Telerobot concept, presently under investigation, is represented in **Figure 2-2.**

It is formed by the following main subsystems (S/Ss):

- cold gas propulsion
- manipulative (arms + rigidizer)
- storage area
- sensors
- electronics (computing, processing, Man Machine Interface (MMI), Telemetry, Tracking & Command (TTC), etc)
- mechanical body

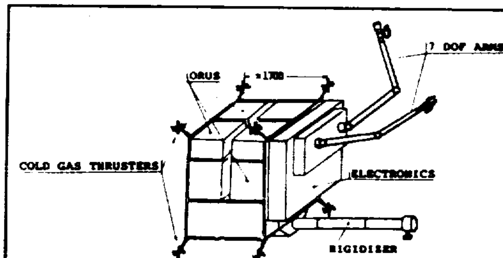

Fig. 2-2: Candidate Telerobot Concept

The "size" of the investigated concept is maintened in a reduced envelope based on three main assumptions:

- a small and dexterous robot can include and cover the gap between the work space envelopes typical of human EVA and of the manipulators in the 10 - 15 m. class
- a small robot needs support system with "limited capabilities"
- the Italian Space Agency (ASI) is oriented in the development of this class of Telerobot (SPIDER).

<u>Prox Navigation Requirements</u>

- Telerobot transfer from parking zone to MTFF and return
- Telerobot to MTFF closed (1 - 20(m)) proximity motion
- Approach/Docking capability
- Attainment of safety criteria

<u>Inspection Requirement</u>

- In "prox" condition (100 - 2000 (m))
  - visual (definition in the order of 1 - 10 (mm)
  - I/R (thermal mapping)
- In "closed prox" condition (1 - 20 (m))
  - visual (TBD)
  - I/R (TBD)
- In "docked" condition
  - temperature (contact)
  - leak detection
  - detailed optical

<u>Manipulative (arms + rigidizer) Requirements</u>

- Exchange of 5 ORU (0.7 x 0.7 x 0.5 (m) 70 (Kg)) each in RM Main Body
- Opening/Closing of thermal covers in RM Main Body and Super ORU section
- Telerobot transfer between two docking ports (in continuous mechanical contact)
- Alternative possibility of exchanging 1 non standard ORU (assumed features: 0.9 x 0.9 x 1 (m). 350 (Kg)) located in the super ORU section.

Tab. 2-1: Robotic Mission Requirements

3. Propulsion S/S Evaluation

The propulsion S/S considered is a cold-gas low-thrust type capable of smooth, non polluting proximity motion.
Three types of missions (see **Figure 3.1** for a general schema) have been considered in order to derive the S/S features:

- Fly-by
- Docking
- Closed inspection.

The fly-by and docking are two basic and fully dedicated missions. The closed inspection mission is a variant that can be added to each of the previous ones. The computed ΔV requirements include:

- full thrusters misalignement effects
- margin for attitude stabilization
- margin for dispersion recovery
- safety margin.

Safety Criteria

The safety criteria utilized in order to derive the specific trajectory features is herebelow described, with respect to "off-type" thrusters failure (see **Figure 3-2**):

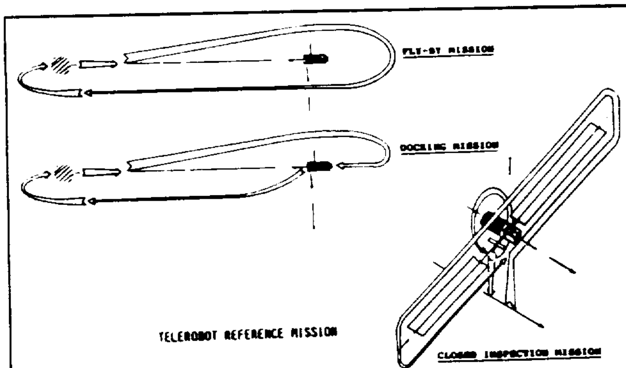

Fig. 3-1: Telerobot Reference Mission

any manoeuvre $X(\tau)$ in the Σ_2 space is considered "safe" if a complete "off-type" thrusters failure at time $\tau = t_i$ will leave the telerobot in a drift orbit that exclude the regions Σ_1 and Σ_3 or enter these regions with a speed < 0.01 m/s for any time $\tau > t_i$.
The speed of 0.01 (m/s) is chosen in order to guarantee a "non-damaging telerobot/stations collision". The free drift trajectories following an "off failure" are represented, in the next figures, by dotted lines.

Fly-by Mission

The Fly-by mission has the objective of performing MTFF external inspection in "far" conditions (90 ÷ 600 m. range). The mission is made up by three main trajectories (**Figure 3-3**) hereafter summarized:

- Trajectory A: it consists of two impulsive and one continuous steps
- Trajectory B: it consists of four impulsive steps and two coasting phases
- Trajectory C: it consists of three impulsive and one continuous steps and one coasting phase.

The requirements for this mission result in the following:

$\Delta V = 2.78$ (m/s)
$T_m = 50{,}619$ (s)

where T_m is the manoeuvre time. In strict proximity the manouevres are performed at $Vm = 0.01$ (m/s) for safety reasons.

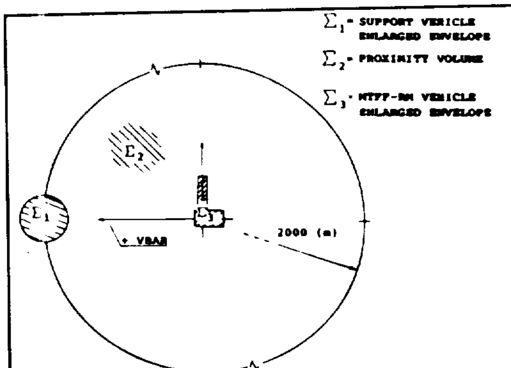

Fig. 3-2: Regions Definition for Safety

Docking Mission

The Docking mission has the objective of performing MTFF-RM external servicing in docked conditions.
The mission is made-up by four main trajectories (**Figure 3-4**) hereafter summarized:

- Trajectory A: it consists of two impulsive and one continuous steps
- Trajectory B: it consists of eight impulsive and one continuous steps and three coasting phases
- Trajectory C: it consist of four impulsive and one continuous steps and two coasting phases.
- Trajectory D: it consists of three impulsive and one continuous steps and one coasting phase.

The requirements for this mission result in the following:

$\Delta V = 5.86$ (m/s)
$T_m = 79{,}852$ (s).

The time required for the manipulator tasks has to be added to the computed time manoeuvre Tm.
The continuous strict proximity manoeuvres are performed at $Vm = 0.01$ (m/s) for safety reasons.

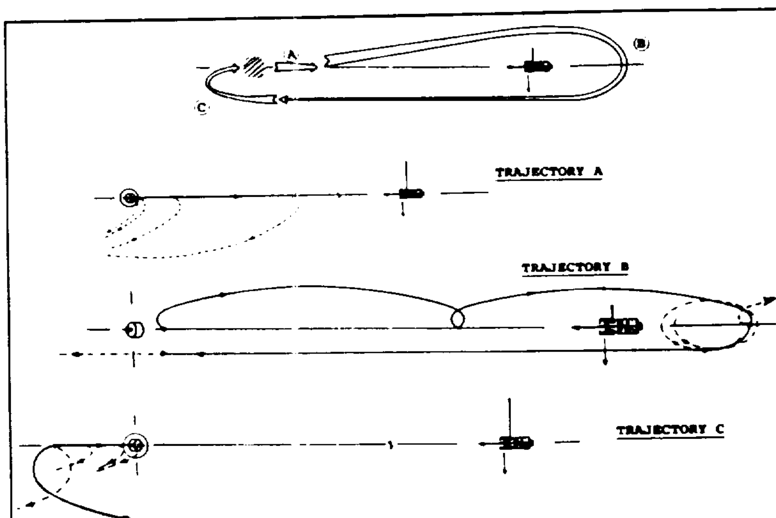

Fig. 3-3: Fly-by Mission

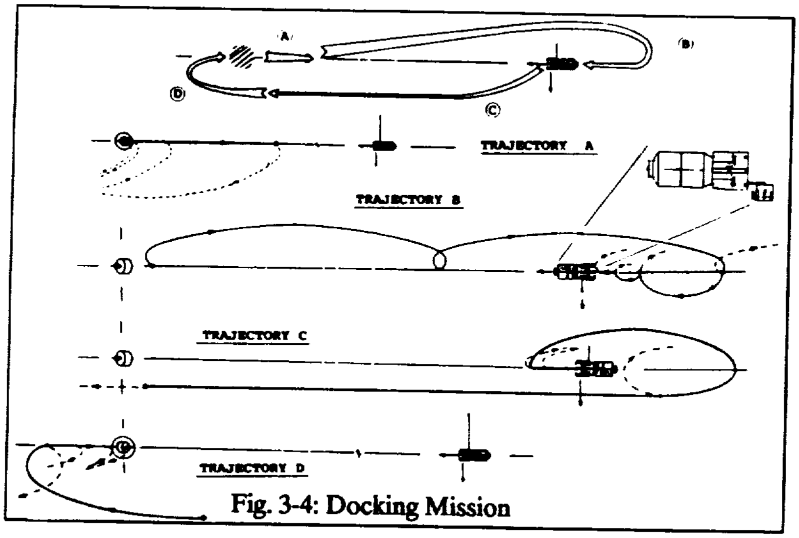

Fig. 3-4: Docking Mission

Closed Inspection Mission

The Closed Inspection Mission has the objective of performing MTFF closed inspection (few meters) and is made-up by a number of trajectories (**Figure 3-5**) including impulsive and continuous steps. This is a kind of Δ mission and could be added to both the Fly-by and Docking ones: the injection point is in the return phase at the coordinates X = 0 (m); Z = 90 ÷ 100 (m). This is a non-safe mission unless the manoeuver speed is kept below 0.01 (m/s). Unfortunately, the ΔV requirement is a function of the manoeuver speed and presents a minimum of ΔV min = 7.45 (m/s) for V_m = 0.05 (m/s).

Maintaining the manoeuvre speed within the safety level, the mission requirements are the following:

V_m = 0.01 (m/s)
ΔV = 16.6 (m/s)
T_m = 39,142 (s).

Reference Overall Mission

The evaluations summarized in the previous points allow the definition of the following reference mission:

Reference mission = Docking mission + Closed Inspection Mission

ΔV_{Ref} = 22.4 (m/s)
T_{mRef} = 119,100 + TBD (s)

where TBD refers to the time required for operation in docked configuration.

Ejected and Stored Fuel Requirements

The propellent utilized is constituted of GN_2 nitrogen initially stored at 3000 (psia) pressure, while the thrusters considered for this type of application allow a specific impulse in the 65 ÷ 70 (s) range depending on the actual tank pressure.

The overall ejected fuel is then computed through the rocket equation. The stored fuel mass is computed through a 15% increase of the ejected fuel mass to account for a residual 250 psia tank pressure. The results illustrated in **Figure 3-6** are summarized as:

M_{EF} (Ejected) = 51 (Kg.)
M_{SF} (Stored) = 58 (Kg.).

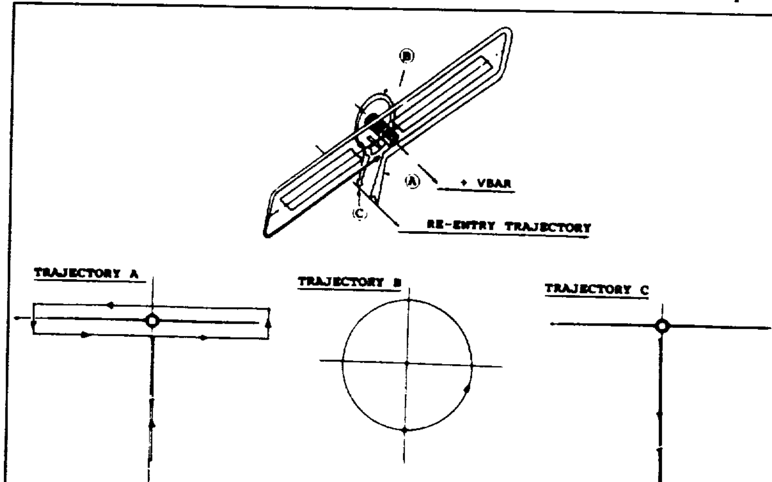

Fig. 3-5: Closed Inspection Mission

Propulsion S/S main features

The propulsion S/S is schematized in **Figure 3-7** and is fully redundant as far as thrusters, piping and valves are concerned.

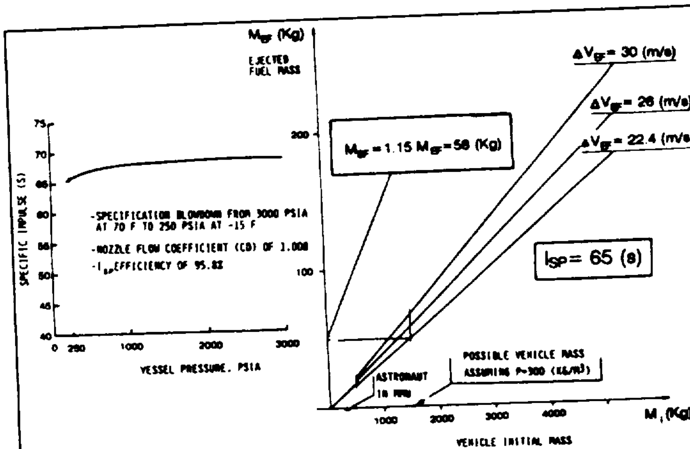

Fig. 3-6: Fuel Requirement

It consists of the following main components:

- 24 (eight triad) fixed position nitrogen (GN_2) /thrusters
- 2 tanks for nitrogen
- piping and valving connections
- Thrusters and Drive Electronics
- (Prox Nav Computer)
- (Nav Sensors).

Figure 3-8 illustrates the main component features.

Thruster triads.

Each triad module contains three identical 10 N class thrusters; each of them can be independently activated through an elctrically operated solenoid. A number of cold thrusters is already available on the market.

Nitrogen Tanks.

Two tanks, each one with 133 (liters) volume and 26 (kg.) nitrogen loading, will be utilized. They can be manufactured following a composite design. No special technological difficulties are foreseen.

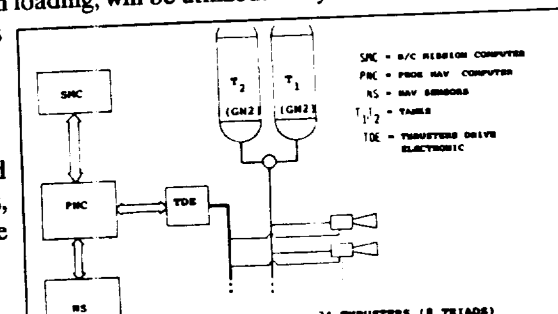

Fig. 3-7: Propulsion S/S Configuration

Piping and valving system.

The piping and valving system is duplicated for the primary and redunded thrusters and it is formed by a number of connectors, valves, regulators and pipes. No technological difficulties are foreseen.

Thrusters Drive and Electronic Unit (TDEU).

The TDEU converts the command signals, coming from the Prox Nav Computer, into currents to thruster windings and consists of three main sections: Power and Data Interface (I/F), Driver Selector, Command (CMD) generators. No technological difficulties are foreseen.

(Proximity Navigation Computer and Navigation Sensors).

These items will be considered in the prosecution of the activity.

Propulsion S/S Overall Budget.

The propulsion S/S overall budget is summarized in **Table 3-1** with respect to mass, volume, energy requirements and expected technological criticalities.

4. Manipulative S/S Evaluation

The manipulative S/S considered is formed by a bi-arm system, with two identical 7 d.o.f. arms, and a rigidizer mechanism which is a 3 d.o.f. device.
The arms are in the 2 - 3 meters class according to the general requirement of dimension reduction.
For this reason, it is necessary to identify on the serviced vehicle a number of different docking points which allow, through a combined arms/rigidizer action, the displacements of the servicing system on the surface of the serviced vehicle.

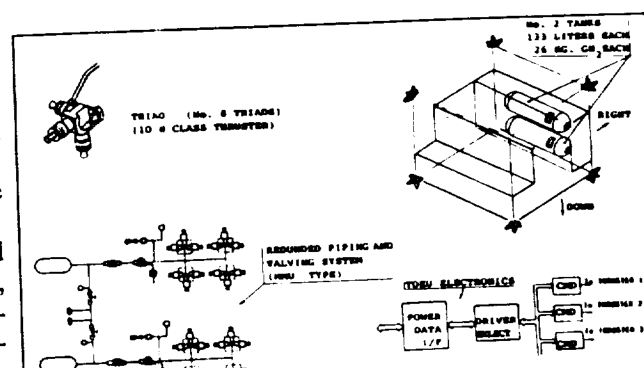

Fig. 3-8: Propulsion S/S Components

FEATURE / ITEM	MASS (Kg)	VOLUME (CM)	ENERGY (Joule)	SINGLE ITEM TECHNOLOGICAL RISKS
THRUSTER TRIADS	15	"SPECIAL LOCATION"	200,000	OFF THE SHELF
ON BOARD GN_2	58	"LOCATED INSIDE TANKS"	N.A.	NONE
TANKS	42	0.27	N.A.	NONE
PIPING AND VALVING SYSTEM	15	INCLUDED IN THE TOTAL THROUGH MARGIN	LIMITED INCLUDED IN THE TOTAL THROUGH MARGIN	NONE
TDE	5	0.008	40,000	NONE
TOTAL (Including +5% margin)	~142	~0.28	255,000	

Tab. 3-1: Propulsion S/S Overall Budget

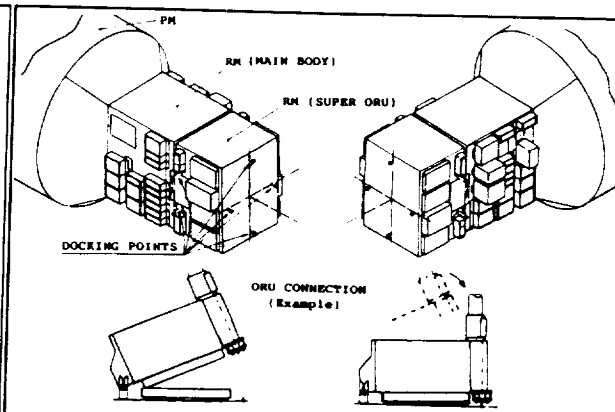

Fig. 4-1: MTFF-RM ORUs Layout

The rigidizer is basically an extendable boom (1 translational d.o.f.) with 2 additional rotational d.o.f. near the End Effector. Its length in extended position will be about 2 meters.
The manipulative S/S has then three basic goals:

- Orbital Replaceable Units (ORUs) exchange
- Displacements of servicing system around the serviced vehicle (with continuos mechanical contact)
- On orbit repair and smart manipulative actions (which can be accomplished in future evolutions).

Reference Servicing Mission and Requirements.

The development of MTFF design has pointed out the necessity of changing 8 - 10 external ORUs every year. For this purpose, 2 Hermes missions are foreseen, one every 180 days. Furthermore, an extraordinary servicing mission every three- four years is planned in order to change the SUPER-ORU: the MTFF will dock to the International Space Station (ISS) where the Remote Manipulator System (RMS) will perform the operations.
The dimensions of the standard ORUs are limited by the dimensions of Hermes, while the dimensions of the SUPER-ORU depend on those of the U.S. Space Shuttle. Actually, there are different sizes of standard ORUs, while not definitive information are available with regard to the dimensions of the non standard ORUs in the SUPER-ORU area.
The dimensions of the largest size standard ORU can be so given: this ORU, with all its equipment and frames, is contained in a volume of 700x700x520 (mm) size with a mass limited to 70 Kg. The manipulative mission taken as reference for the Telerobot is related to the MTFF-RM external servicing with a capability to exchange up to 5 max size standard ORUs. The ORUs will be fixed to the RM with a standard interface (independently on their size) through a latching/delatching mechanism. The body of the servicing veichle will contain 6 interfaces: 5 standard ORUs can be fixed to it with 1 spare location necessary for the change operations.
All these requirements lead to define the servicing vehicle body as a 1.7 meter side cube.
The MTFF-RM configuration is shown in **Figure 4-1**. Comparing these dimensions with those given in the previuos paragraph, it can be assumed to have 8 docking points, 4 on the RM back, near its propulsion system, the others in the two sides of the SUPER-ORU area.
Due to the presence of thermal covers, the four docking points located in the SUPER-ORU area, can be reached only after the opening of the covers.
It is then possible to split the reference mission into 5 phases :

- 1) Opening of covers
- 2) Change of docking point (maintaining mechanical contact)
- 3) Standard ORUs exchange
- 4) Return to original docking point (maintaining mechanical contact)
- 5) Closure of covers.

If both sides of the RM have to be serviced during the mission, the above phases will be repeated twice, of course between the two cycles a further exchange of docking points is necessary.
For sake of completion, it has been also evaluated the possibility of a non standard ORU exchange (in the SUPER-ORU area). In general the arms and rigidizer trajectories are not laid in a plane. Nevertheless, the considerations here

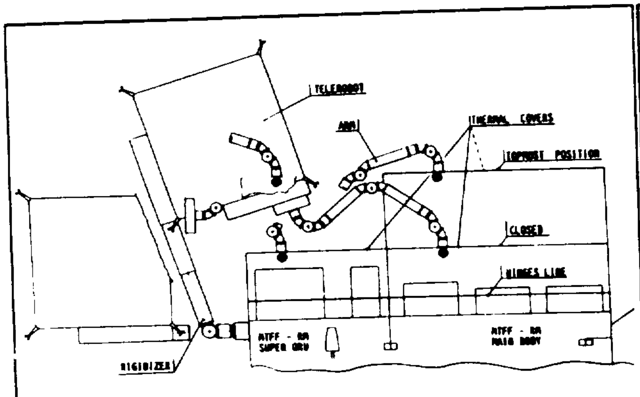

Fig. 4-2: Opening and Closure of Covers

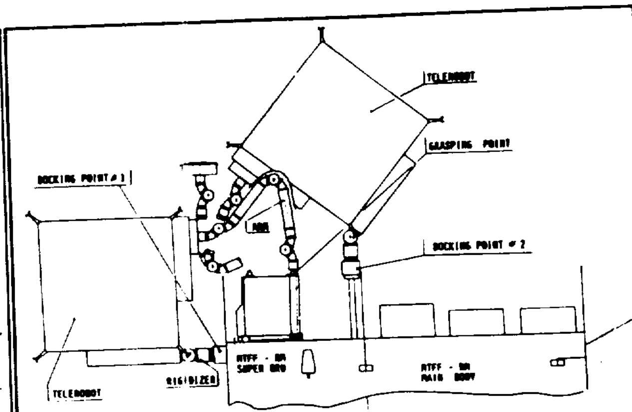

Fig.4-3: Exchange of Docking Points

developed are also applicable to skewed configuration; this fact can be stressed considering that the exact definition of the type and of the d.o.f number is well beyond the scope of this activity.

Phases 1 and 5: Opening and Closure of Covers.

These phases are summarized in **Figure 4-2.** and two different sequencies are foreseen:

- Opening and closure of SUPER-ORU area covers: in this case the rigidizer is only partially extracted.
- Opening and closure of standard ORU area (Main Body) covers: the rigidizer has its maximum length (2 m.) and its rotation allows one arm to reach the cover handles.

In the figure are shown the starting and the topmost positions (of the opening sequence).

Phases 2 and 4: Exchange of Docking Points.

These phases are summarized in **Figure 4-3.** One arm grasps a proper ORU grapple fixture, which becomes the pivot for the vehicle displacement. It has be noted that all the twist joints except for the one nearest to the grapple fixture, must have a rotation of 180° to complete the operation. At the end, the vehicle has a specular configuration with respect to the starting condition.
A rotation of the rigidizer twist joint around the axes of the new docking point can enable the system to service standard ORUs.

Phase 3: Standard ORUs Exchange.

The main features of this phase are summarized in **Figure 4-4** and it is possible to distinguish two different steps:

- To reach the ORUs and to extract them from RM
- To insert the ORUs in the body of the servicing vehicle in its own interfaces.

For the first step it is necessary to foresee two different arm positions (depending on ORUs distance). Anyway, there is just only one final position for the first step that is the starting position for the second one.
The second step is the most critical one, because of the arm dimensions: the arms length must be in the order of 2.5 (m).

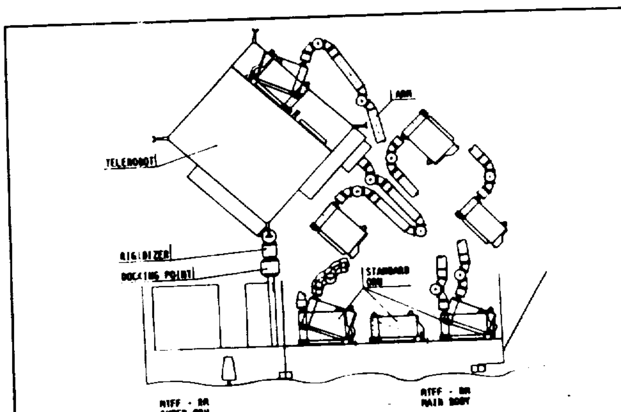

Fig. 4-4: Standard ORUs Exchange

Extraordinary Mission: Non Standard-ORU Exchange (in SUPER- ORU area).

This mission is summarized in **Figure 4-5** , except for the opening/clousure of covers. A final decision about non standard-ORUs shapes, dimensions and masses has not been yet estabilished.

For this reason this figure must be seen in a general sense: it has been considered one non standard ORU of 350 Kg. (5 times the maximum standard ORU mass), with a height which does not interfere with the cover, and with the other dimensions proportional to the standard ORU ones. Within this data range it is possible to get a reasonable feeling of mission feasibility.

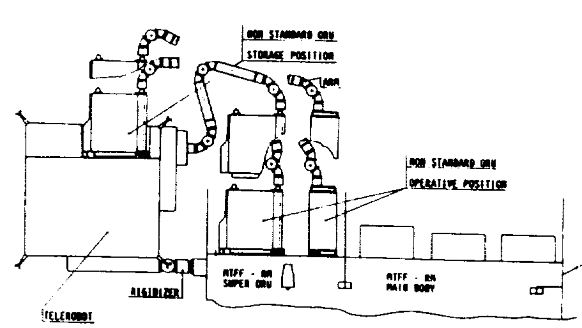

Fig. 4-5: Non Standard ORU Exchange

Manipulative S/S main features:

The manipulative S/S is schematized in **Figure 4-6**; it consists of the following main components:

- 2 arms (7 d.o.f. each)
- 1 rigidizer (3 d.o.f.)
- Drive Electronics Units
- (Robot Computer)
- (Robotic Sensors).

Figure 4-7 illustrates the main components features.

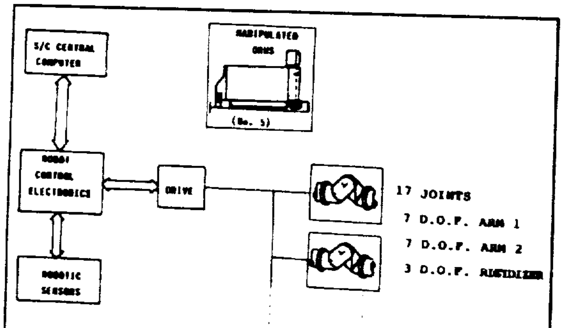

Fig. 4-6: Manipulative S/S Schematization

Arms

A number of possible arm configurations can be taken as valid. The one considered has been investigated in different activities and presents interesting features as far as workspace envelop is concerned. The joint torque level is in the 20-100 (Nm) range. The final articulation architecture, including joint selection, will be object of a dedicated technological activity.
Some technological difficulties are expected for the joint compactness requirements.

Rigidizer

The same considerations done for the arms apply to the rigidizer. It does not need a sophisticated control because its main scope is to position in relative way the Telerobot body and the ORUs layout. The joint torque level is 100 (Nm).

Drive Electronics.

It converts the command signals coming from the Robot Control Electronics into input currents to all the joint motors. It consists of two main sections: Power and Data I/F, and drive. No technological difficulties are foreseen except for problems related to dimension reduction (for example if the electronic is placed inside limbs).

Robotic Electronics and Robotic Sensors.

These items will be considered in the prosecution of the activity.

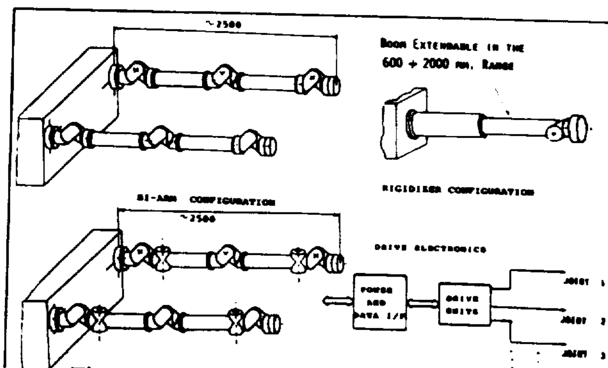

Fig. 4-7: Manipulative S/S Main Components

Manipulative S/S Overall Budget:

The manipulative S/S overall budget is summarized in **Table 4-1** with respect to mass, volume, energy requirements and expected technological risks.
The energy budget has been developed considering reference worst cases, with proper margins included during the process.
Assuming an EE/Spacecraft relative velocity in the order of 0.01 (m/s) and accounting the torque deliverable by

FEATURE / ITEM	MASS (Kg)	VOLUME (CM)	ENERGY (Joule)	SINGLE ITEM TECHNOLOGICAL RISKS
ARM 1	40	"SPECIAL LOCATION"	83.000 (ARM 1 + ARM 2)	LIMITED TO JOINT COMPACTNESS
ARM 2	40	"SPECIAL LOCATION"		LIMITED TO JOINT COMPACTNESS
RIGIDIZER	30	"SPECIAL LOCATION"	32.000	LIMITED TO JOINT COMPACTNESS
MANIPULATED ORUS	350	1.6	TBD	N.A.
DRIVE	10	0.015	20.000	LIMITED TO COMPACTNESS (IN CASE OF SPECIAL LOCATION)
TOTAL (including +5% margin)	~ 492	~ 1.7	~ 120.000	

Tab. 4-1: Manipulative S/S Overall Budget

	MASS (Kg)	VOLUME (CM)	ENERGY (Joule)
COMPUTED PROPULSION PLUS MANIPULATIVE S/Ss FEATURES (INCLUDING FUEL AND 350 Kg OF ORUs)	634	2	375,000
ASSUMED REFERENCE TELEROBOT FEATURES (INCLUDING FUEL AND 350 Kg OF ORUs)	1,500 (ASSUMING ρ = 300 Kg/m³)	4.9	TBD
AVAILABILITY FOR REMAINING S/Ss (COMPUTING, SENSORS, BATTERIES, TTC, THERMAL, STRUCTURE, ETC..)	866	2.9	TBD

Tab. 5-1: Propulsion and Manipulative S/S Overall Features

joints as well as the full geometric sequence, the overall time required to fulfill the complete manipulative mission is in the order of 15,000 sec.
The 0.01 (m/s) relative velocity has been assumed based on the necessity to avoid any collision, case of failures, between whatsoever structure and the moving parts, with a velocity which can constitute a serious hazard.

5. CONCLUSIONS

A preliminary evaluation of the results obtained with respect to the propulsion and manipulative subsystems, indicates that Mass, Volume and Energy requirements, are in line with the general feature assumed for the Telerobot vehicle (see **Table 5-1**).
Moreover, from the technological risk point of view it seems that no special problems should arise, apart some electromechanical compactness requirements on typical space robotic components (joints, drivers).
Nevertheless, the confirmation on feasibility can be obtained only after completion of the remaining activities and,in this respect, particular importance will be given to the computing and TTC aspects.

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