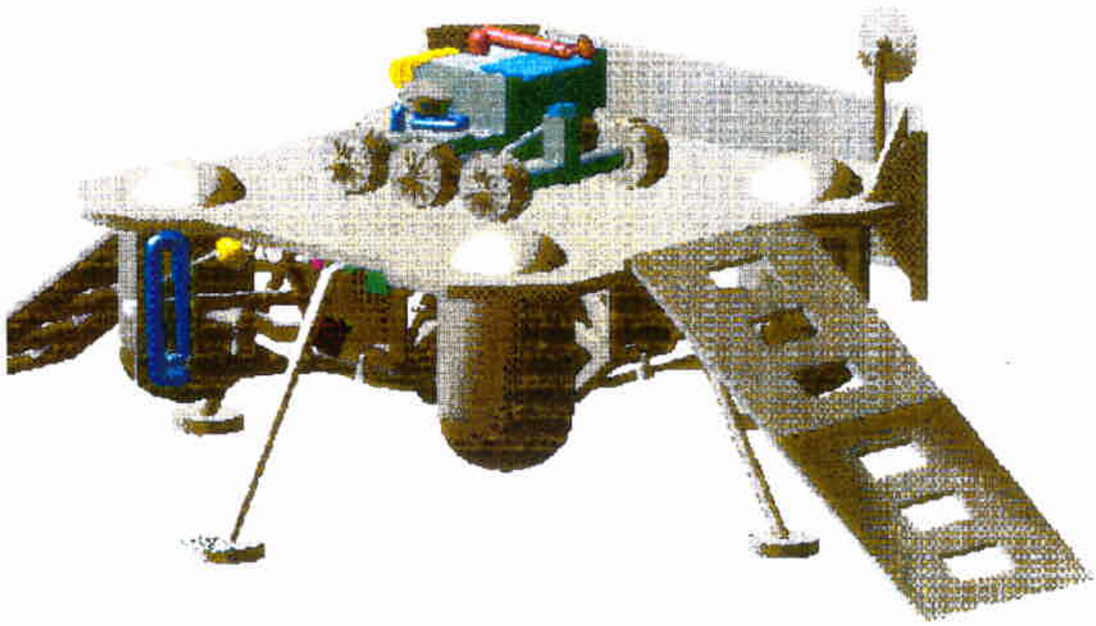
Tecnomare

Tecnospazio

RObotics for Lunar EXploration
ROLEX

Executive Summary



ESTEC Contract N. 11099-Work Order 4

Milan, 3rd of May 1996

ESA STUDY CONTRACT REPORT

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11099 Work Order 4	*RObotics for Lunar EXploration "ROLEX"*	*TECNOSPAZIO*

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ABSTRACT:

This document summarises the activity performed, by Tecnospazio as prime and Tecnomare as subcontractor, in the frame of RObotics for Lunar EXploration (ROLEX) program.

The objectives of ROLEX program are:

- identify and classify, for the future Lunar exploration scenario, the most qualifying potential applications for robotic manipulators (3 classes: small, medium and large) (activity performed by TM);
- finalise requirements on such robot manipulators (activity performed by TS);
- derive a proper demo experiment feasible under LEDA constraints and taking into account existing technologies and background (activity performed by TM);
- establish design concepts for the most critical issues of LEDA robots (small and medium classes) (activity performed by TS);
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LEDA (Lunar European Demonstration Approach) is the Lunar Lander mission currently considered as candidate for Phase 1 of ESA Moon Program.

The objectives of LEDA are:

- exploration;
- technology demonstration and assessment;
- media to enlisting public support for next phases.

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- Stationary part, permanently attached to the Lander, including scientific instruments, medium size robot arm and soil processing test facility.
- Mobile part, carried by a mini rover, including the rover itself, a set of instrument and a mini robot arm.

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Executive Summary

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Contract: ESTEC n. 11099/94/NL/JG

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REVISION INDEX OF SHEETS

Sheet	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Rev.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rev.	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Rev.	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sheet	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Rev.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rev.	A	A	A	A	A	A	A	A	A	A	A	A	A	A	
Rev.	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sheet	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Rev.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rev.	B	B	B	B											
Sheet	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Rev.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sheet	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
Rev.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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LIST OF CONTENTS

1. INTRODUCTION

This document summarises the activity performed, by Tecnospazio as prime and Tecnomare as subcontractors, in the frame of RObotics Lunar EXploration (ROLEX) program.

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- Mobile part, carried by a mini rover, including the rover itself, a set of instrument and a mini robot arm.

1.1. APPLICABLE DOCUMENTS

AD1 "Statement of Work: Robotics for Lunar Exploration (ROLEX)", P. Putz, ESTEC , May 1995

AD2 "A Moon Programme: The European View", ESA BR-101, May 1994

AD3 "Final Report of the LEDA Assessment Phase", ESA doc. nr. LEDA-RP-95-02, Rev. 0, May 1995

AD4 "LEDA Payload Requirement Document", P. Putz, LEDA-RQ-95-03 Rev. 0

1.2. REFERENCE DOCUMENTS

RD1 "Robotics for Lunar Exploration: Potential Applications, Requirements and Key Technologies", TS doc. n. ROLE-SA-TS-001, rev. B, dated 15.11.95.

RD2 "Robot technology demonstration experiment", TM doc. n. ROLE-SA-TM-002, rev. 1, dated 31.10.95.

RD3 "Requirements of the LEDA Lander Robotic Payload", TM doc. n. ROLE-SA-TM-003, rev. 1, dated 30.01.96.

RD4 "Requirements of the LEDA Rover Robotic Payload", TM doc. n. ROLE-SA-TM-004, rev. 1, dated 25.03.96.

RD5 "Critical Issues and Concepts in LEDA Robot Design", TS doc. n. ROLE-SA-TS-002, rev. B, dated 25.03.96.

RD6 "Preliminary Design Description of the LEDA Lander Robotic Payload", TM doc. n. ROLE-SA-TM-006, rev. 1, dated 25.03.96.

RD7 "Preliminary Design Description of the LEDA Rover Robotic Payload", TS doc. n. ROLE-SA-TM-003, rev. A, dated 25.03.96.

RD8 "LEDA Technical Information Exchange Meeting - Preliminary Rover Analyses", ESTEC 17.10.95, CNES

1.3. LIST OF ACRONYMS

AD	Applicable Document
APX	Alpha-Proton-X Ray Spectrometer
CAT	Computer Assisted Teleoperation
d.o.f.	degree of freedom
EE	End Effector
ESA	European Space Agency
ESTEC	European Space TEechnology and research Centre
F/T	Force/Torque
FTS	Force Torque Sensor
HD	Harmonic Drive
HW	Hardware
I/O	Input/Output
IA	Interactive Autonomy
IVA	Internal Vehicular Activity

LEDA	Lunar European Demonstration Approach
LRP	Lander Robotic Payload
MT	Manual Teleoperation
NED	NEutron Detector
RD	Reference Document
RDM	Radiation Dose Monitor
ROLEX	RObotics for Lunar Exploration
RP	Robotic Payload
RRP	Rover Robotic Payload
SEM	one/two/three-axis Seismometer
SPTF	Alpha-Proton-X Ray Spectrometer
SSA/DT	Small Sample Acquisition/Distribution Tool
SW	Software
TAP	Thermal Array Probe
TBC	To Be Confirmed
TBD	To Be Defined
TM	Tecnomare
TS	Tecnospazio
w.r.t.	with respect to

2. POTENTIAL APPLICATIONS

In this chapter the potential applications of robotic systems (mobile robots and manipulators) in the Moon Missions are assessed. These applications are defined to be compatible with the scope of the envisioned Moon programs, to be realistic in short and medium term and to be attractive w.r.t. terrestrial automation spin-in and spin-off.

According to the European proposed phased approach for the Moon missions [AD2] and considering the relevant potential robot applications, the possible scenarios for the Lunar exploration and exploitation missions are established with reference to the lunar robotic systems.

The four lunar approach phases described in [AD2] are:

- first phase: lunar environment exploration
- second phase: lunar base with permanent robotic presence
- third phase: first lunar resources exploitation and lunar base construction
- fourth phase: installation of the first lunar human outpost, featuring life-support and environmental control system

During the mission phases the following scenarios which involve robotic systems are established:

A. Exploration scenario and preparation for the scenario B (technical demonstration).

   In the exploration scenario Rover systems with robotic manipulation capability and sensing capability are involved.

   A manipulation system installed on the Lander is used for technological demonstration to assess the feasibility of robotic tasks in later missions and to service the Lander scientific instruments.

B. Lunar base construction and maintenance scenario and preparation for the scenario C (technical demonstration).

C. Human presence scenario with development of production facilities.

With reference to the envisioned Moon programs [AD2] and the possible scenarios for robotics in Moon programs, the following typical application classes are identified:

- exploration;
- construction of Lunar Bases;
- maintenance of Lunar Bases;
- production.

Assigned to the typical application classes, potential robot applications, foreseen for robot manipulator in lunar exploration/utilisation scenarios, have been identified.

Applications		Appl. Classes			
		Exploration	Lunar Base Construction	Lunar Base Maintenance	Production
a1	Burying scientific instruments or inserting instrument probes on the lunar surface	*			
a2	Changeout of the reconfiguration modules of an instrument	*		*	
a3	Coring lunar surface in order to take samples	*			
a4	Instrument mechanical regulation and command	*		*	
a5	Inspection of the Lunar structures external surface in order to assess damages caused by environment	*	*	*	*
a6	Pick and place lunar surface samples	*			
a7	Pick and place scientific instruments	*			
a8	Lunar surface exploration and elevation mapping	*			
a9	Repair damaged parts	*		*	
a10	Sampling of hard rocks with cutting tools	*			
a11	Assembling of shelter for equipment	*	*	*	*
a12	Antenna assembling, positioning and cleaning	*	*	*	
a13	Building a regolith dust shield/shelter	*	*		
a14	Solar panel assembling and maintenance	*	*	*	
a15	Visual inspection	*	*	*	*
a16	Unload of Lander and material transportation to the exploration site or to the lunar base	*	*	*	*
a17	Maintenance of energy production system	*		*	*
a18	Mechanical and electrical connection mating and un-mating	*	*	*	
a19	Mechanical device actuation (override, adjustment)	*	*	*	*
a20	Move, align, insert, connect and detach structure modules (assembling operations)	*	*	*	*
a21	Installation of a positioning reference net	*	*	*	
a22	Cleaning and flattening a lunar site		*		
a23	Heat rejection radiator assembling		*		

Applications		Appl. Classes			
		Exploration	**Lunar Base Construction**	**Lunar Base Maintenance**	**Production**
a24	Fuel transportation and distribution, tank refuelling		*	*	*
a25	Regolith and rock mining in order to extract material for construction and production facilities		*		*
a26	Regolith transportation for construction and to production facilities		*		*
a27	Truss structure construction (assembly)		*		
a28	Utility line connection, harness handling task and inspection		*	*	*
a29	Waste products transportation and stowage		*	*	*
a30	Cleaning lenses and other dust sensitive elements			*	
a31	Fetching tools and spare parts to crew's member and crew's member transportation			*	*
a32	IVA robotic operations (maintenance and inspection)			*	*
a33	Replaceable Unit changeout			*	*
a34	Replacing filters and consumable			*	
a35	Rescue and retrieval of stranded or incapacitated crew members			*	*
a36	Structure surface cleaning			*	
a37	Structure inspection in order to detect stress crack			*	*

The above applications were analysed in order to define the **utilisation criteria** and the **technological criteria**.

On the basis of these criteria, a possible demonstration experiment has been identified to verify robotic technology during LEDA mission.

3. ROBOT TECHNOLOGY DEMONSTRATION EXPERIMENT

This chapter provides the definition of the proposed robotic technology demonstration experiment for the LEDA mission (see RD2).

Some mission scenarios for the LEDA robotic systems have been introduced and analysed.

These scenarios include some basic component tasks for the robotic applications in the future Moon missions and fulfil the LEDA mission requirements on:

- technology demonstration;
- exploration;
- education and media coverage.

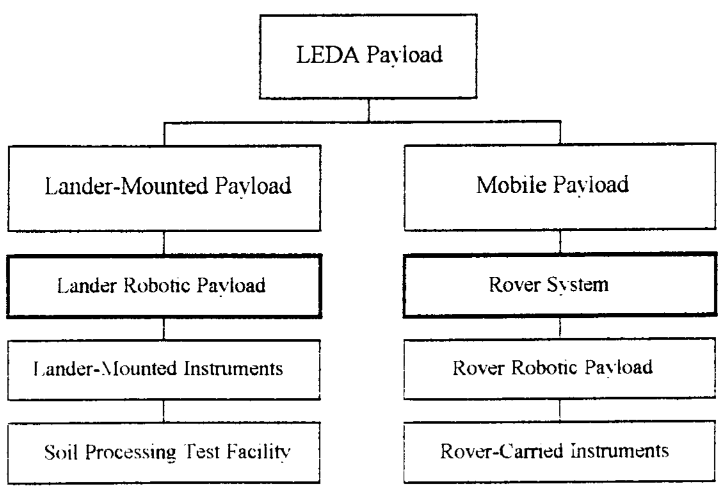
The basic tasks selected are principally meant to demonstrate the feasibility of robotic applications in the future Moon missions with the present technologic constraints.

The main LEDA constraints applying to the definition of the scenarios for the LEDA robotic technology demonstration are:

- environmental conditions;
- payload mass 200 kg;
- electrical power;
- communications with Earth.

The scenario for the LEDA robotic payloads involve two main systems:

- ***Lander Robotic Payload (LRP):*** a medium size manipulator permanently mounted on the Lander and an experiment kit with tools, instruments and devices for robotic applications.
- ***Rover Robotic Payload (RRP):*** a small and very light manipulator featuring few degrees of freedom and a set of tools, instruments and auxiliary devices;



The operations proposed in the following paragraphs have the purpose to fulfil the requirements on exploration, technology demonstration and information and education.

The two robotic systems are foreseen in order to test both operations which require manipulation with high dexterity and force control and operations which require to be done in a large area.

The Rover Robotics Payload features the possibility to explore a wide area around the Lander with instrumentation transported by the Rover, in order to support the exploration activity. Of high technological relevance, moreover is the effort to implement the robotic function in a simplified, small and lightweight robotic system.

Some coordination between the Rover and the Rover mounted arm is envisaged: the Rover carries the arm base to a suitable location and keeps it fixed while the arm EE reaches the target position.

The Lander Robotic Payload allows to perform the experimentation in space of new robotic technologies of manipulation, for instance the force/torque control. The new robotic technologies are used to perform operations otherwise impossible and necessary for the automation of a Lunar Base construction and maintenance: assembling/disassembling, connecting/disconnecting, installing/removing. Besides, the use of the Lander manipulator to install some instruments in order to measure geophysical parameters gives the possibility to compare the results with the measurements of the Rover instrumentation and provide a verification point for the measures.

The use of TV cameras to collect images of the performed tasks is important for the documentation and media coverage of the experiments. Some of the introduced tasks, address specifically the spectacularity aim.

3.1. LANDER ROBOTIC PAYLOAD (LRP)

The Lander Robotic Payload is part of the Lander-Mounted Payload and is composed of the following items (RD6):

- manipulator and controller;
- TV camera on manipulator wrist;
- tools: coring, cleaning and trowel tools and hole excavator;
- mounted instruments: Radiation Dose Monitor (RDM), Thermal Array Probe (TAP), Seismometer (SEM) and SPTF (Alpha-Proton-X-Ray Spectrometer);
- experiment kit: truss to be unfolded, power connector (male part deployable, female part fixed), signal connector (male part deployable, female part fixed), flag and sample container.

Tools and Experiment Kit items have been defined on the basis of the tasks selected for technological demonstration purpose (RD2):

m1 LRP arm motion in interactive autonomy command mode.

m2 LRP arm motion in teleoperation mode (manual or shared).

m3 Burying instrument. The arm performs a hole using the hole excavator tool and then inserts TAP or RDM into the hole.

m4 Unburying instrument.

m5 Inserting/extracting instrument probe.

m6 Replacing of consumable and changeout of reconfiguration modules.

m7 Chipping of Lunar surface material. The arm acquires rocky material samples using the coring tool and place them in the container.

m8 Mechanical device actuation.

m9 Inspection of the external surface of Lander structure.

m10 Collection of lunar soil sample. The arm acquires soil samples which are detached from the lunar soil or are of dust type and place them in the container.

m11 Feeding of SPTF with soil sample.

m12 Positioning of instrument at commanded location.

m13 Positioning of instrument in contact with soil.

m14 Close TV camera inspection of the lunar surface.

m15 Assembling of dummy truss structure.

m16 Mating/unmating of connector.

m17 Surface cleaning. The arm cleans sensors surface using the cleaning tool.

m18 Rover inspection/monitoring.

m19 Rover maintenance.

m20 Rover servicing.

m21 Static arm cooperation between LRP arm and RRP arm.

m22 Dynamic arm cooperation between LRP arm and RRP arm.

m23 Message writing.

m24 Planting of the flag in a hole made by the hole excavator.

Three main types of command modes are used for the execution of the above tasks:

- Manual mode: "manual teleoperation" (**MT**) foreseen to allow the Ground Operator to teleoperate on-line the manipulator.
- Shared mode: "computer assisted teleoperation" (**CAT**). Part of the kinematic parameters of the manipulator are controlled by the remote controller and part by the Operator, in shared way.

- Automatic mode: "interactive autonomy" (**IA**). A sequence of task macros is planned by the Operator on ground and the execution control is temporarily traded to the remote arm controller, with human supervision from ground.

3.2. ROVER ROBOTIC PAYLOAD (RRP)

The Rover Robotic Payload is part of the LEDA Mobile Payload and is composed of the following items (RD7):

- manipulator and controller;
- TV camera on manipulator wrist;
- mounted instruments: Thermal Array Probe (TAP), Neutron Detector (NED) and Alpha-Proton-X-Ray Spectrometer (APX);
- experiment kit: sample collection/containment.

Experiment Kit item has been defined on the basis of the tasks selected for technological demonstration purpose (RD2):

r1 RRP arm motion in interactive autonomy command mode.

r2 RRP arm motion in teleoperation mode (manual or shared).

r3 Inserting/extracting instrument probe.

r4 Collection of lunar soil sample.

r5 Positioning of instrument.

r6 Positioning of instrument in contact with soil.

r7 Close TV camera inspection.

r8 Lander inspection.

r9 Static arm cooperation between the RRP arm and the LRP arm.

r10 Dynamic arm cooperation between the RRP arm and the LRP arm.

The RRP has to perform also the task relevant to stowage in a volume saving pose, including latching, and deployment from that pose.

The same types of command modes introduced for LRP are used for the execution of the above tasks:

- Manual mode: "manual teleoperation" (**MT**).
- Shared mode: "computer assisted teleoperation" (**CAT**).
- Automatic mode: "interactive autonomy" (**IA**).

4. PROPOSED LANDER RP CONCEPT

In this chapter the concept for the LEDA Lander Robotic Payload is presented. In particular:

- para. 4.1 describes the constraints for the LRP in terms of accommodation and working environment;
- para. 4.2 describes the LRP design;
- para. 4.3 gives the LRP budget.

4.1. ACCOMMODATION AND WORKING ENVIRONMENT

The manipulator accommodation on the Lander is shown in fig. 4.1-1 [RD3].

The manipulator base is mounted on the Lander structure 800 mm over the soil [AD3].

The SPTF is mounted on the Lander structure above the manipulator and is at 0.5-1 m distance from the manipulator base [AD3].

The Lander Mounted Instruments TAP, RDM, SEM are installed at the outside of the Lander in a position reachable from the manipulator EE: 1-1.5 m distance.

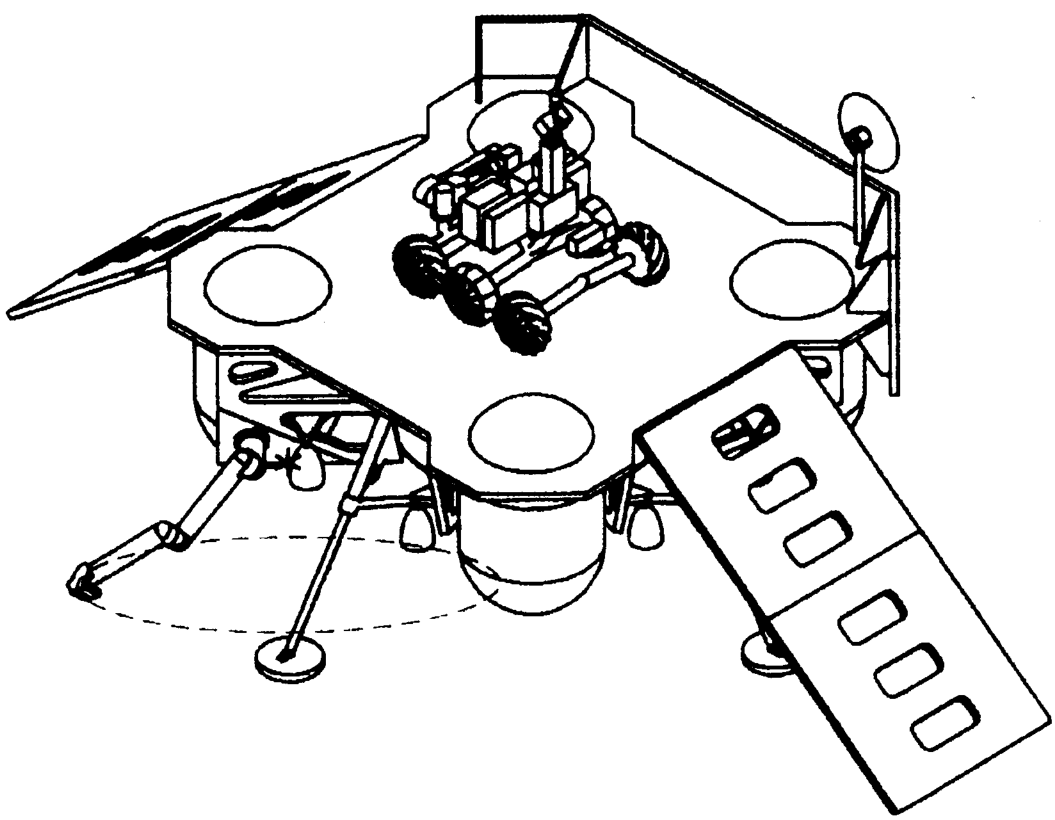


Fig. 4.1-1: Manipulator accommodation on Lander.

4.2. LANDER RP DESIGN

4.2.1. Arm

The arm configuration features 6 d.o.f. [RD5].

One TV camera is permanently mounted at the wrist [RD3].

One F/T sensor is fitted at the wrist in order to measure the interaction forces between the EE and the environment [RD3].

The fig. 4.2.1-1 shows the conceptual design of the robot. Main features are:

- max arm reach envelope: 1.5 m radius;
- max arm Cartesian speed at tool tip: 0.1 m/s;
- 6 rotational d.o.f.;
- position accuracy: 10 mm;
- orientation accuracy: 1 deg;
- max payload at EE (EE and wrist TV camera not included): 2.4 kg;
- max force at EE: 20 N;
- max torque at EE: 1 Nm;
- force/torque accuracy:
  - force accuracy: 1 N;
  - torque accuracy: 0.1 Nm.

The rotative joint design is based on the following concept [RD5]:

- DC brushless motor;
- harmonic drive reducer;
- joint out shaft fitted with position sensor, possibly requiring no contacts (resolver and inductosin);
- brake always on (metallic clutch like system);
- temperature sensor and heaters.

Cable passing at each joint is implemented by using external routing (with protective coverage). A number of conductors in the order of 100 are expected at the shoulder, including FTS and TV camera. Teflon covered cables are assumed.

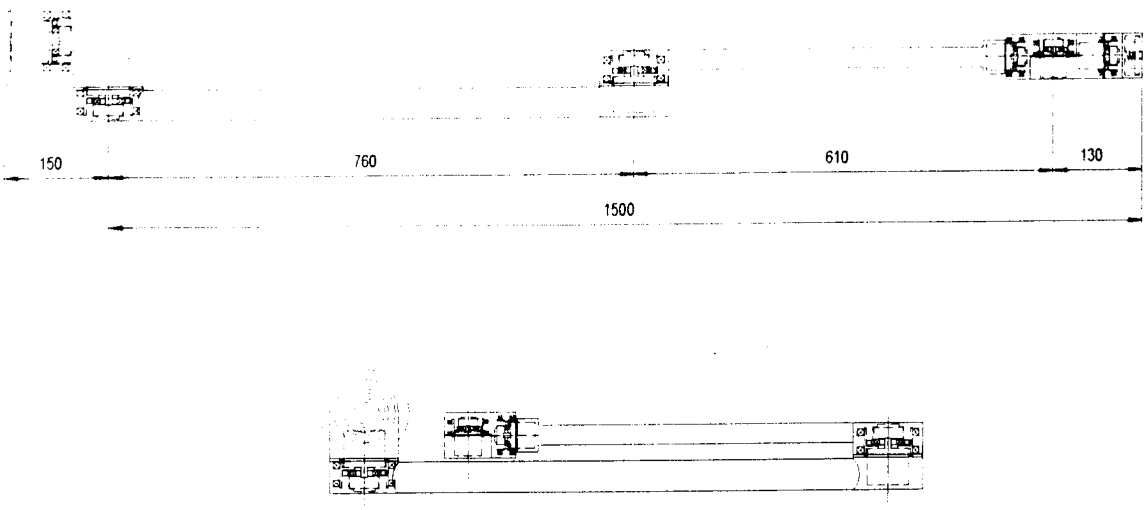


Fig. 4.2.1-1: Arm configuration (straight and folded).

4.2.2. End Effector

The End Effector is designed in order to provide a suitable interface between the arm and the tools and instruments.

The arm/tool interface is a bayonet type system that, with the relative rotation between radial plugs and dedicated grooves, fixes the tool to the arm using the rotative joint of the wrist (see fig. 4.2.2-2). In addition to mechanical connection, electrical connection could be required for the actuated tools, if any (TBC).

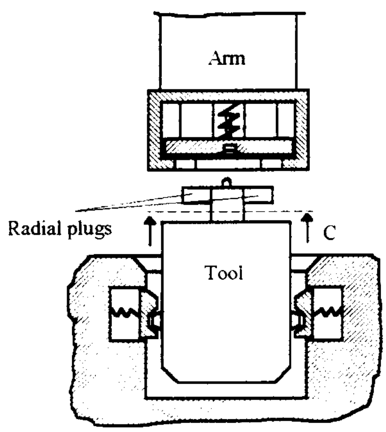


Figure 4.2.2-2: Arm/Tool Interface [RD5].

4.2.3. Tools

It is assumed that the Lander arm uses the following set of tools in order to interact with the soil:

- coring tool to core samples from rocks;
- hole excavator to dig a hole (depth 200 mm, Φ 50 mm) for the instruments;
- trowel tool to collect soil sample and transport it.

Another tool is used to interact with the Lander and sensor surface:

- cleaning tool (TBD) to clean sensor surface from dust.

Each tool is stowed in a container with the same shape of the tool, fixed to the Lander structure.

Coring tool (fig. 4.2.3-1) [RD5]

On top of the passive coring solution previously identified, an "active" solution derived from the preliminary results of on going activity SSA/DT for cometary sampling application can be considered:

This tool features a motor and of a solenoid that require electrical connection at the Arm/Tool interface. For all the other tools the passive solution is feasible.

The evaluated mass of the proposed tool is 0.5 kg.

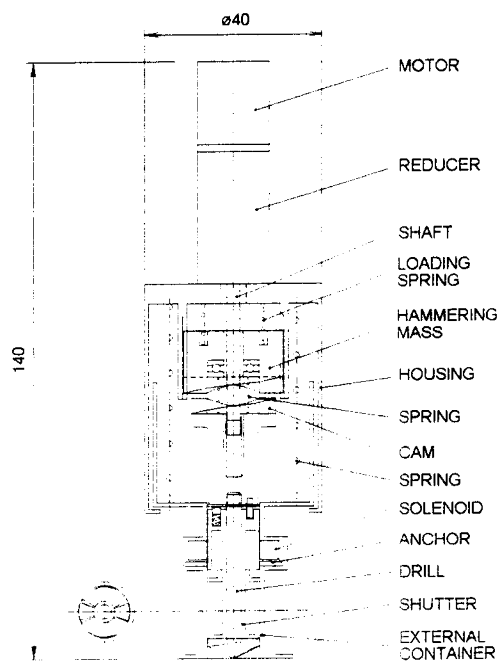


Fig. 4.2.3-1: Coring tool.

Hole excavator (fig. 4.2.3-2) [RD5]

The evaluated mass of the hole excavator is 0.5 kg.

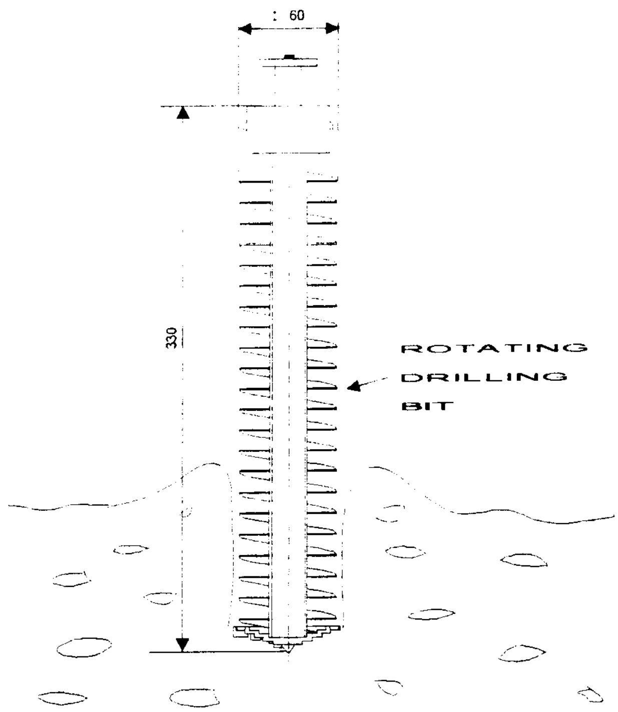


Fig. 4.2.3-2: Hole excavator.

Trowel tool (fig. 4.2.3-3)

The evaluated mass of the trowel tool is 0.2 kg.

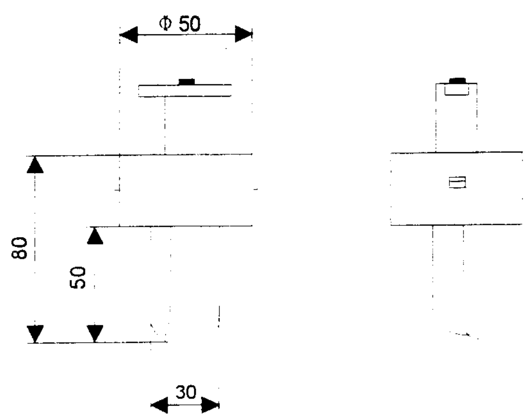


Fig. 4.2.3-3: Trowel tool.

4.2.4. Controller and Driver

The functional scheme of the Controller is described in figure 4.2.4-1. The following considerations apply [RD5]:

- the SW robotic functions of the control unit are implemented by the Lander control hardware;
- the I/O hardware and the motor drivers are implemented by dedicated hardware (six single Europe cards are preliminarily estimated);
- Cartesian and joint motion type with simultaneous acquisition of the output of all the position sensors and simultaneous control of all the joints;
- position control by using output shaft position sensor;
- DC motors used in synchronous mode, without closed loop commutation;
- control loop can run at frequencies lower than 250/500 Hz.

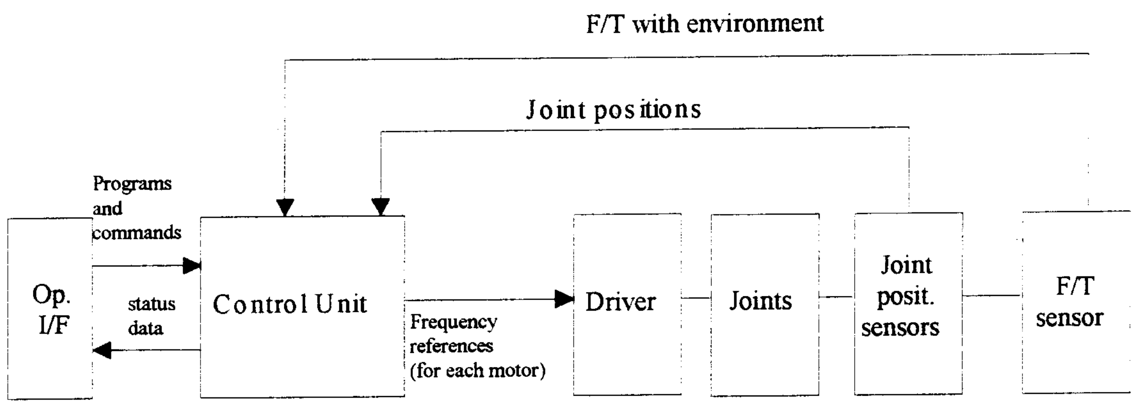


Fig. 4.2.4-1: Controller architecture.

The driver units are very simple and made of two main parts: wave generator (upon frequency command) and power bridges (fig. 4.2.4-2).

4.2.5. Latching devices

During launch, transfer and landing phases, the arm is folded and fixed to the Lander with suitable latching devices in order to withstand the acceleration loads.

Three latching points have been defined on the arm:

1. a pin at the shoulder, to block rotation of roll axis;
2. a clamp at the elbow;
3. at tight metal strip at the wrist.

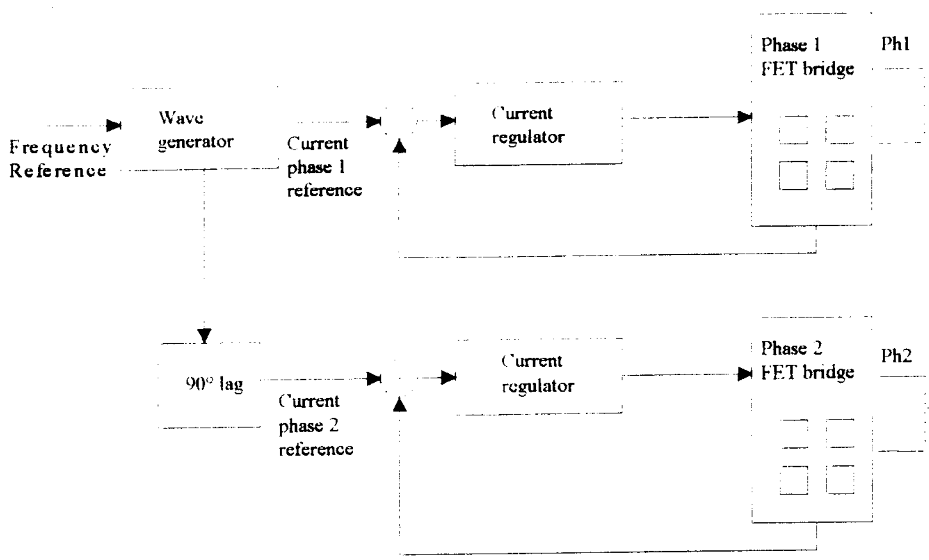


Fig. 4.2.4-2: Driver architecture.

For arm unlatching it is preliminarily assumed that:

- the pin is actuated, e.g. by a paraffin actuator;
- pyrotechnic devices are used for the clamp and the strip.

The tools and the mobile experiment kit items are latched by means of tight metal strips, pyrotechnic devices could be used to release the constraints.

4.2.6. Experiment Kit [RD2]

The experiment kit configuration is derived by [RD2].

In table the components which have to be moved by the arm and therefore require to have a connection interface with the arm are pointed out.

EXPERIMENT KIT COMPONENTS			
Components	**Dimension [mm]**	**Arm I/F**	**Mass (kg)**
Truss to be unfolded (16 elements)	140x280x35 (folded)	*	0.5
Power connector (male part, deployable)	H200xΦ50	*	0.2
Power connector (female part, fixed)	H200xΦ50		
Signal connector (male part, deployable)	20x50x30	*	0.3
Signal connector (female part, fixed)	10x50x30		
Flag	H500XΦ20	*	0.2
Sample container	100x150x150		0.3

4.3. MASS, POWER AND COMMUNICATION BUDGETS

It is assumed to exploit the Lander HW resources to implement the SW robotic functions in order to reduce the Control Unit mass and power requirements.

Communication budget

The preliminary evaluation of the overall data rate for communication of the LRP is:

- 2 kbit/s for LRP Controller in automatic mode;
- 3.2 kbit/s for LRP Controller in teleoperation mode;
- 512 kbit/image for the wrist TV camera.

Mass budget

The preliminary evaluation of the overall mass for the LRP is reported in the following table.

If the LRP hardware is not shared for the arm control, the evaluated mass of the Control Unit is 4 kg.

Item		**Mass (kg)**
Robotic Arm	Arm	10
	Latching Devices	1.6
End effector and tools	EE	1
	Tools	1.2
	Tool basket	0.2
Controller	Control unit	2.5
	Drive unit	3
Experiment Kit	Experiment kit components	1.5
	Restraining devices	0.2
Total		21.2
Margin (15%)		3.2
TOTAL		24.4

Power budget

The preliminary evaluation of the overall power consumption for the LRP is reported in the following table.

If the LRP hardware is not shared for the arm control, the evaluated power consumption of the Control Unit is 20 W.

Item		**Power consumption (W)**	
		Case 1	**Case 2**
Robotic Arm	Arm	35	6
	Latching Devices	N.A.	N.A.
End effector and tools	EE	N.A.	N.A.
	Tools (*)	5	5
	Tool basket	N.A.	N.A.
Controller	Control unit	10	10
	Drive unit	8	4
Experiment Kit	Experiment kit components	N.A.	N.A.
	Restraining devices	N.A.	N.A.
Total		58	25
Margin (15%)		9	4
TOTAL		67	29

Case 1: arm loaded with 25 N at wrist level, fully extended and operating at very low speed at all joints

Case 2: arm with no load but gravity, fully extended and operating at very low speed at all joints

(*) The evaluated power consumption for the tools applied to the power consumption of the coring tool.

5. PROPOSED ROVER RP CONCEPT

In this chapter the requirements on the LEDA Rover Robotic Payload are presented. In particular:

- para. 5.1 describes the constraints for the RRP in terms of accommodation and working environment;
- para. 5.2 describes the RRP design,
- para. 5.3 gives the RRP budget

5.1. ACCOMMODATION AND WORKING ENVIRONMENT

The manipulator accommodation on Rover is shown in fig. 5.1-1 [RD7].

The manipulator base is mounted on the Rover structure about 500 mm over the soil [RD8].

The Rover Mounted Instrument sensors TAP, NED and APX are installed inside the carousel permanently attached to the RRP arm [AD4], [RD2], [RD7]

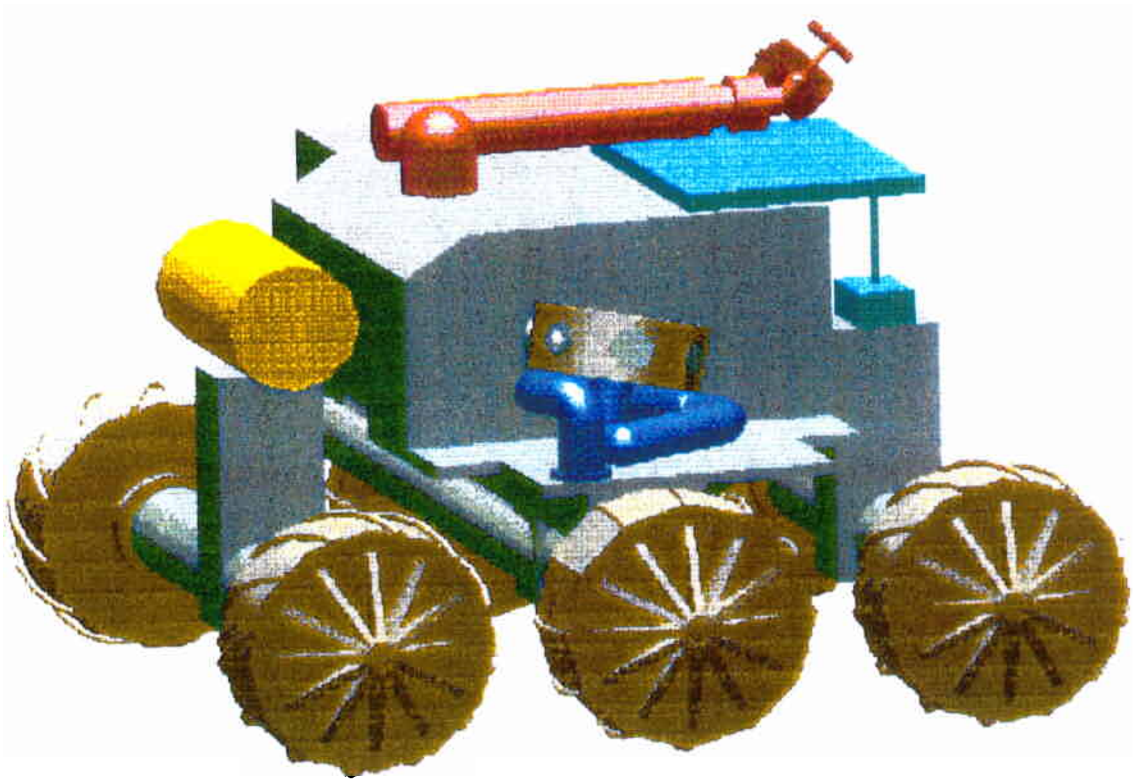


Fig. 5.1-1: Manipulator accommodation on Rover

5.2. ROVER RP DESIGN

5.2.1. Arm

The selected arm configuration [RD5] is a 5 rotative d.o.f. able to satisfy the following requirements:

- maximum force at tool level: 10 N;
- maximum torque at tool level: 0.5 Nm;
- maximum carrying load: 1.5 kg;
- maximum reach envelope: 0.5 m;
- position accuracy: < 20 mm;
- orientation accuracy: < 3 °.

The requirements of maximum force and carrying load at tool level have driven the dimensioning of the joints (RD2).

Table 5.2.1-1 summarises their main characteristics.

	Joint				
Characteristics	***#1***	***#2***	***#3***	***#4***	***#5***
Angular range (°)	300	300	300	200	360
Max torque (Nm)	6	6	6	2	2
Max output speed (rpm)	> 25	> 25	> 25	> 50	> 50
Mass (kg)	0.6	0.6	0.6	0.4	0.4

Table 5.2.1-1: Joints main characteristics.

All joints are equipped with:

- DC brushless motor;
- HD gearbox;
- position sensor on output shaft;
- low torque clutch like permanent brake on motor shaft.

In order to keep the dimensions and the mass as low as possible, cabling is accommodated externally to the arm.

Fig. 5.2.1-1 shows the arm reference concept.

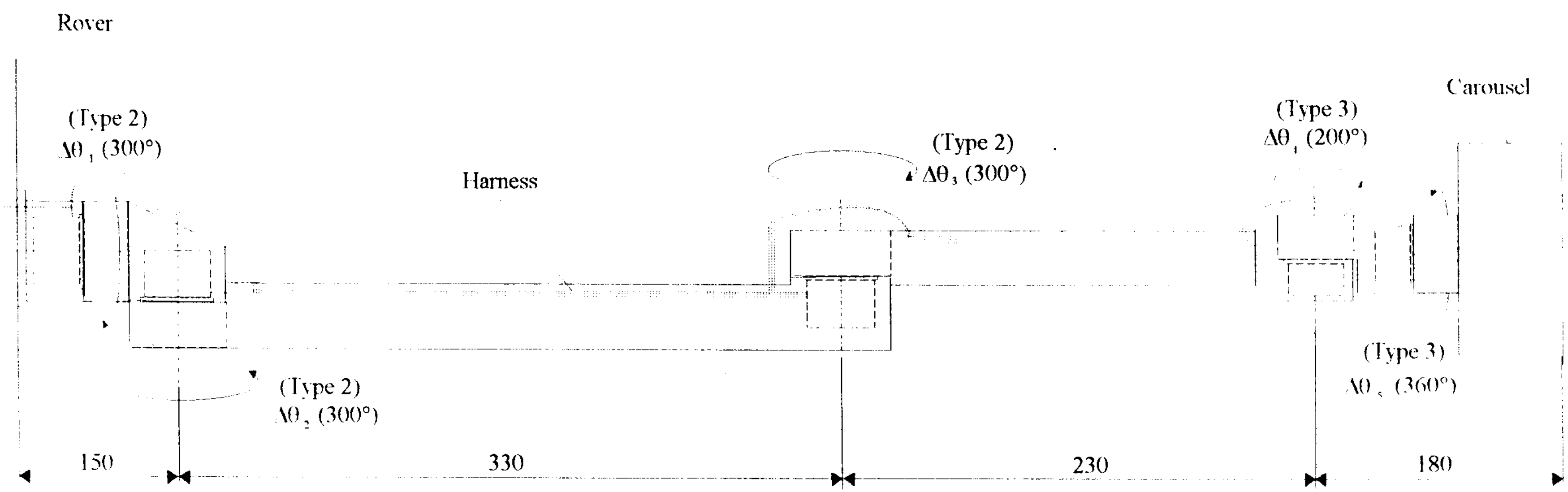


Fig. 5.2.1-1: RRP conceptual design.

5.2.2. End Effector

Instead of an End Effector, a carousel, permanently attached to the arm, has been selected.

On this carousel the following items are accommodated:

- one Thermal Array Probe (TAP) sensor;
- one Neutron Detector (NED) sensor;
- one Alpha-Proton-X-Ray Spectrometer (APX) sensor;
- one sample collection/containment.

The selection of the element to be operated is performed by means of the last degree of freedom of the arm. The insertion, without release, of the TAP is possible only into soft soil providing a linear displacement of the carousel by combined motion of the manipulator degrees of freedom.

The carousel (see fig. 5.2.2-1), of cylindrical shape, have the following dimensions:

- 250 mm diameter;
- 100 mm high.

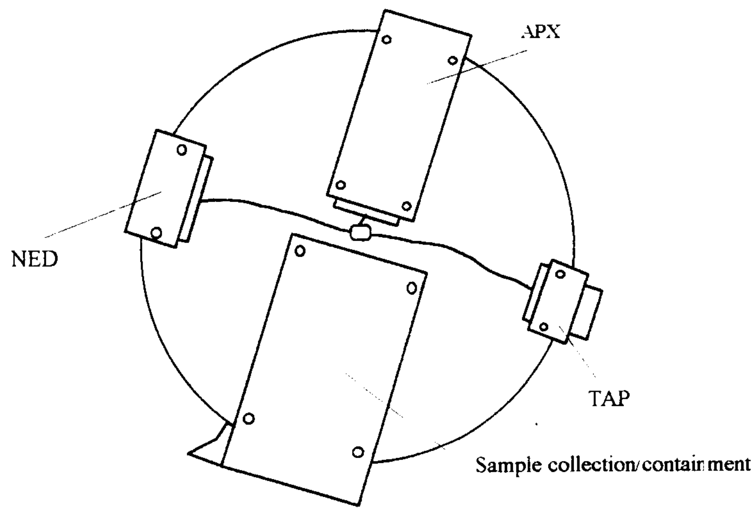


Fig. 5.2.2-1: Preliminary carousel layout.

5.2.3. Controller and Driver Reference design

The control schematic for a robot/manipulator depends on:

- arm kinematics complexity and layout;
- presence of gravity and brakes;
- number and type of sensors to be acquired;
- motor type and commutation.

The selected kinematic is a full 5 rotative d.o.f. manipulator. With this configuration, to achieve full performances, the joints should be operated simultaneously. Accepting some relaxation in performances, subsequent actuation of 1 d.o.f. at a time in certain phases and 2 to 4 d.o.f. at a time in others could be conceived.

A low torque clutch like permanent brake is installed on each joint. This solution improves the system operativity by guaranteeing proper functioning at reduced gravity without the need of brake on/off commands. Some more energy is required during motion.

The solution to equip the joint with only the position sensor on output shaft allows to get the information of prime interest from the task point of view (although does not allow to get maximum performances).

Finally, to reduce mass, cabling and electrical interfaces complexity, the solution to operate the DC brushless motor in synchronous mode (by renouncing to some performances) is considered.

Taking into account above considerations, the black box schematics for the overall control electronics is shown in fig. 5.2.3-2 and attain the main functions of:

- execution of programmed tasks or of teleoperation commands;
- Cartesian and joint motion type;
- control by using output shaft position sensor (assumed as baseline);
- DC motors used in synchronous mode.

It is assumed that the SW robotic functions of the control unit are implemented by the Rover control hardware.

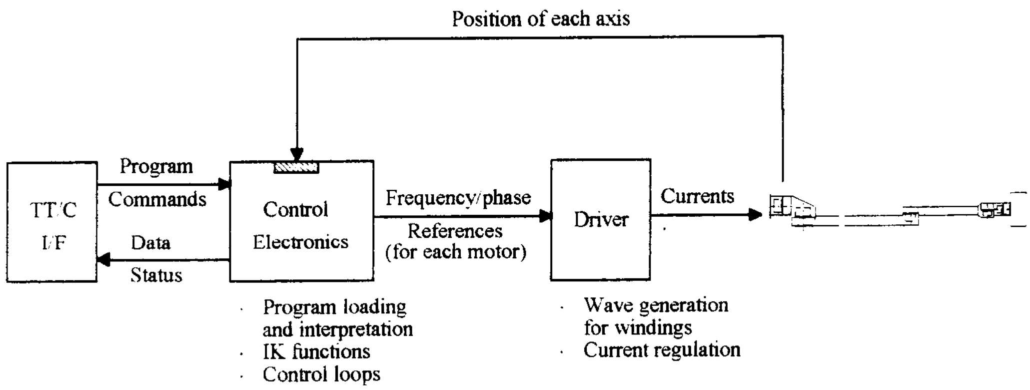


Fig. 5.2.3-2: Overall Control Electronics black box schematics.

5.2.4. Latching Device

A hold down mechanism is required to stow the arm during dormant or Rover motion period.

Two different solutions are proposed for this mechanism:

- a jaw like system (see schematics in fig. 5.2.4-1) able to fix the arm limbs using a rotative degree of freedom and the carousel using two supports on the two sides, moved by a rotative degree of freedom, which leave, when open, the space for limbs retraction (solution A).

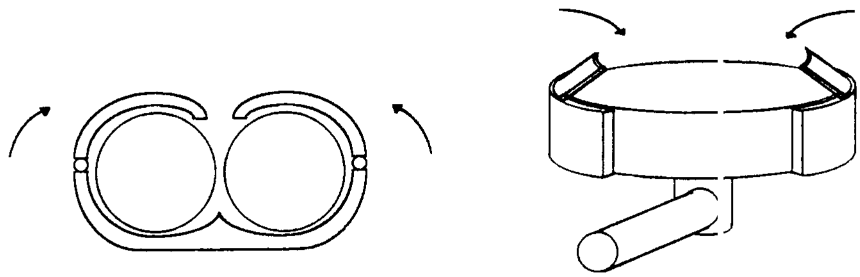


Fig. 5.2.4-1: Arm and Carousel latching mechanism (solution A)

- a combined system (see schematics in fig. 5.2.4-2) able to fix the arm limbs using a jaw like system moved by a rotative degree of freedom and the carousel using a bayonet system to be inserted inside the Rover base plate (solution B).

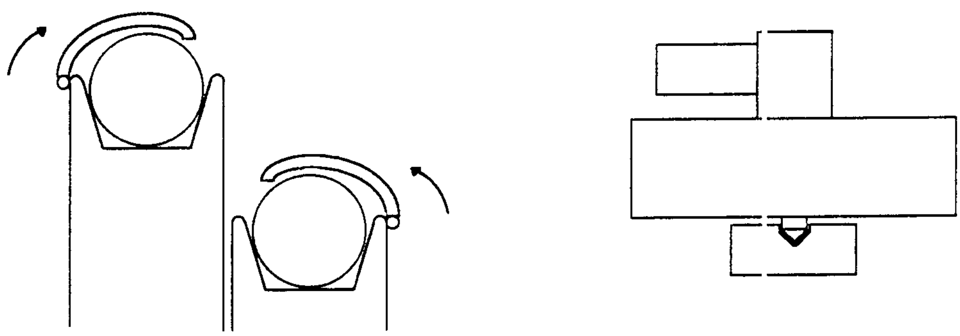


Fig. 5.2.4-2: Arm and Carousel latching mechanism (solution B).

The final decision between the two solutions will be taken considering the following elements:

- mass;
- accommodation volume;
- design complexity;
- workspace limitation.

5.2.5. Experiment Kit

Based on the tasks identified for the RRP (see RD1), the only item required is the sample collection/containment.

This item is accommodated, together with the instruments, inside the carousel (see fig. 5.2.2-1 for location).

It collects the samples grasping the Moon surface during carousel rotation and store them when a rotation of about 90 ° has been performed (see schematic on fig. 5.2.5-1).

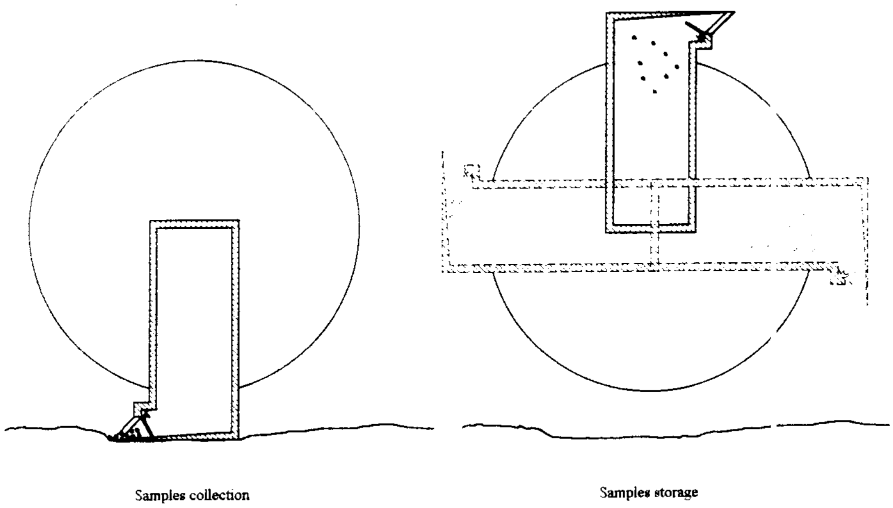


Fig. 5.2.5-1: Sample collection and storage principle.

5.3. MASS, POWER AND COMMUNICATION BUDGETS

Mass budget

The preliminary estimation of the overall mass of RRP is reported in table 5.3-1.

Item	*Mass (kg)*
Arm	7
End Effector (carousel)	0.4
Control Unit	1.5 (3)
Drive Unit	2.5
Stowage/Latching	0.5
Experiment kit	0.5
Instruments	0.6
Total	13 (14.5)
Margin (15%)	~ 2
Total	15 (16.5)

(): If control functions are not provided by the Rover.

Table 5.3-1: RRP mass budget.

Power budget

The preliminary estimation of the overall power consumption for the RRP is reported in table 5.3-2.

To this power budget, also the power consumption relevant to thermal control should be considered.

Item	***Power consumption (W)***	
	Case 1	Case 2
Arm	12	5
End Effector (carousel)	N.A.	N.A.
Control Unit	10 (20)	10 (20)
Drive Unit	5	4
Stowage/Latching (*)	10	10
Experiment kit	N.A.	N.A.
Instruments	1	1
Total	28 (38)	20 (30)
Margin (15%)	4.2 (5.7)	3 (4.5)
Total	32.2 (43.7)	23 (34.5)

Case 1: Arm loaded with 10 N at wrist level, fully extended and operating at very low speed at all joints.

Case 2: Arm with no load but gravity, fully extended and operating at very low speed at all joints.

(): If control functions are not provided by the Rover.

(*): This value is not part of the total being required when the other elements are not operating.

Table 5.3-2: RRP power budget.

Communication budget

The preliminary estimation of the overall data rate for RRP (see RD2) gives:

- < 0.4 kbit/s for overall Control Electronics when operating in teleoperated mode;
- 0.05 kbit/sample for Thermal Array Probe (TAP);
- 0.032 kbit/sample for Neutron Detector (NED);
- 32 kbit/sample for Alpha-Proton-X- Ray Spectrometer (APX).

6. CONCLUSIONS

First Moon explorations were done between beginning of sixties till the end of seventies. The advances of technology for spacecraft, instrument, detectors, processors, electronics, computers together with the availability of new technologies, have been so intense that one should expect a revolution in the renewed exploration of the Moon.

Among the new technologies, the one that can play a key role in this renewed Moon mission is the Robotic technology.

The present study has identified as Robotics can be extremely useful in all the Moon mission phases

- Exploration (e.g. burying scientific instruments, picking and placing lunar surface samples, exploring Lunar surface and elevation mapping, etc.)
- Base Construction (e.g. Antenna assembling, positioning and cleaning, Building a regolith dust shield/shelter, etc.)
- Base Maintenance (e.g. Solar panel assembling and maintenance, Installation of a positioning reference net, Structure surface cleaning, etc.)
- Production (e.g. Unload of Lander and material transportation to the exploration site or to the lunar base, Regolith and rock mining in order to extract material for construction and production facilities, etc.)

Based on the above, a potential LEDA Robotic Experiment has been defined and also a technical baseline has been selected.

Of this technical baseline some critical issues have been highlighted and are summarised in table 5-1.

The described critical technologies have been evaluated in terms of:

- importance/priority (for a preliminary mission);
- availability (of technology for ground applications);
- low development time, need and costs;
- cross fertilisation with terrestrial automation technology (reusability for ground applications).

As result of this evaluation, a breadboarding activity is suggested as next step in order to better analyse the behaviour of the system.

The following is proposed:

- Functional breadboard of the arm/tool interface to verify the design in terms of easy exchange operation, compliance capabilities and general behaviour under thermal and vacuum conditions.
- Functional breadboard of the joint to verify the behaviour also under thermal and vacuum conditions. The breadboarding of the joint implies the ad hoc development of the output shaft sensor (unless finally found on the market).

- Functional breadboard of the controller I/O and of the driver to verify the behaviour also under vibration and radiation.
- Breadboard of a system able to verify the cleaning action under thermal and vacuum conditions using a brush and the blowing action.
- Functional breadboard of drilling, chipping and sample collection/containment tools to verify their behaviour under thermal and vacuum conditions and under vibration.

Critical issues	*LRP*	*RRP*
Arm/tool interfaces: • Mechanical • Electrical	 • Bayonet type system • None	Not required: permanently attached carousel.
Kinematic configuration	6 rotative d.o.f.	5 rotative d.o.f.
Joint design: • Motor • Brake • Gearbox • Position sensor • Materials • Lubricant	 • DC brushless • Mechanical clutch system (always on) • Harmonic Drive • Resolver or Inductosin • Space compatibles • FOMBLIN grease or ANTISEIZE paste	 • DC brushless • Mechanical clutch system (always on) • Harmonic Drive • Resolver or Inductosin • Space compatibles • FOMBLIN grease or ANTISEIZE paste
Controller and drives design and strategies	• Utilisation of Lander resources for control actions (if possible) • Specific design for controller I/O and drivers • Not commutated system	• Utilisation of Rover resources for control actions (if possible) • Specific design for controller I/O and drivers • Not commutated system
Sample handling in reduced g	Feasible	Feasible
Soil interaction	• Drilling action • Chipping action	Surface grasping
Thermal control	• Heaters • Temperature measurement • Protective layers I/F	• Heaters • Temperature measurement • Protective layers I/F
Dust protection: • Mechanical parts • Interfaces • Optical parts	 • Compressed gasket plus collar (teflon) • Elastic membrane and brushes • Wiping, blowing and/or protective covers	 • Compressed gasket plus collar (teflon) • Wiping, blowing and/or protective covers
Operator interface	Advanced interfaces for command/displays	Advanced interfaces for command/displays

Table 5-1 Summary of critical issues identified solutions