New Robot Concept for Mars Soil Exploration: mechanics and functionality

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INTRODUCTION

The exploration of Mars on 2004 by robots Spirit and Opportunity represents a step towards the use of the Mars planet by the man, in a future. The robots made an excellent job and their exploration was finally a description of the characters of the Mars soil. The European Exomars satellite could detect parameters of the composition of the soil and their exam supported the conviction of the presence of water, and in the same time the possible existence of life. More than a special idea of a project, now it is necessary to perform like a universal idea, which will be the consequence of the results obtained up to now by robotics. The concept of colony of many robots for exploration, able to perform actions on Moon or on Mars is here presented, like a step for new concepts in space robotic design.

DESIGN CONCEPTS FOR SPACE ROBOTICS

Concurrent engineering as official necessity of a total cooperation in the design is a duty for people working with ESA (European Space Agency). The diagram shows that the action of the mind, of the experience, of the intuition, of the knowledge of everyone must be offered to the other members of the team, to increase the total efficiency and the adjoined value of the design results. Very small action, up to 2000, was in fact dedicated to the interrelation with the active designers in the world in similar projects. Now it is very easy to recognize that teams in strong competition sometimes share information on experiments and theories, like a peaceful territory, to save time and resources. They implicitly suppose that creativity and personal skills are the real jolly in the design competition. Everyone knows the exchange of designers in the car industry, as a key point. Today, share of knowledge plus communication and digital exchange of data are richness.

Figure 1: Actual design in ESA (European Space Agency)
The examples of robot for the exploration are inside a large category of possible designs from ideas. Here is reported a representation of flying insect robots, robot with wheels and legs, robot with wheels, robot with wings, robot like snake, hopping robots, swarm robots, beagle robots.

The design of every kind of robots will follow different procedures, and the goal of the new design is to be able to integrate all robots inside a general, universal scheme of logics and of creativity.

The design of space robots is here presented as a result of cooperative work and of communication. Every researcher and every designer must participate of the whole project. This participation was infrequent in mechanical engineering, in past years, but now the large quantity of data and the information is so effective that the amount of notions must be substituted by the short and clear activity of the creative brain. The detailed engineering analysis is needed in the phase of technical description and of definition of the values for the specific acquisition of the components. But in upper position there is the design phase which contains the main part of the project for space robotics. This is a specific necessity for robotics in unconventional environments, and we need to take care of the necessity to produce the design of a new system, and not only of an assembly of components.

**CONCEPTUAL DESIGN FOR A SPACE ROBOT**

Inside European projects and Italian projects for space exploration, robotic is inspiring new solutions and applications. Call for ideas from European Space Agency ESA and Italian Space Agency ASI are soliciting researchers and industries to perform robots suitable for future tasks in space, above all for planetary exploration.

Ladyfly, which is the ancient English name of ladybird and ladybug, is a design concept, one with new and different characteristics. It consists of a robotic system usable for Mars soil exploration. It is therefore compatible with the technologies relevant to the European Aurora programme goals and scenarios. The design consists of a colony of five robots (one main and four smaller ones), deployed from a lander, to explore the Mars soil in preparation of a human mission to the red planet. The main robot, also called the scientific robot, carries the scientific detection instruments, whilst the four smaller ones have the capability of scanning the area to be explored and creating a map. Mapping data and soil features are then collected by the main robot and passed to the lander and from this relayed to the earth. The main robot is able to detect the nature of the materials of which the soil is constituted by means of a very efficient X-ray spectrometer. The robots have a double transmission system: on wheels, for plane motion, and on legs to overtake small obstacles. The wheels are mounted at the lower end of six legs. The motion is telecontrolled with independent autonomous movements in its working activities. All the robots are equipped with micro- and nanosensors, embedded in their body. The detection system is positioned at the centre of the main robot. The control software of the Ladyfly robots is similar to the neuromotor control of a human body, as concerns the integration of sensors and decisions on actions to be taken.

It is assumed that the Ladyfly colony will fly on a satellite which will reach a low Martian orbit. The satellite could be launched for example on an Ariane V rocket during one of the launch windows created by Mars opposition. Once the satellite has reached the Martian orbit, a descent module (lander) will be detached. The descent module will land on the chosen area of the Martian surface by means of a parachute and an airbag. The robots colony will then be deployed
from the lander and start at a proper time the planned activity. The data concerning the Martian environment must be taken into account for the design and the definition of the mission.

DESIGN METHODOLOGIES AND SOME ADVANTAGES OF THE DESIGN CONCEPT

The following methodology has been applied for the design of the Ladyfly colony. It is necessary to start initially from the external shape of the robots and their basic layout, utilising simulation software and generating rendering images to give an immediate perception of the vehicles. The simulation software could reproduce the characteristics of the Martian soil, thus offering a realistic environment. The position of the main components, i.e. legs and wheels must be determined. Cinematic and dynamic simulations are performed with a simplified model, utilising Adams software package. Finally all the subsystems and the instruments of which the robots are composed are studied in detail.

Owing to the multidisciplinary nature of this project, a traditional approach with a centralised design would be ineffective. It must be adopted a concurrent design methodology, based on workbooks realised with MS Excel sheets containing input and output data, exchange data, results and database tables. Each workgroup has its own workbook which must be uploaded in a Ladyfly ftp site. The Ladyfly design concept would offer the following advantages:

a) The tasks to be performed, i.e. exploration of the soil and detection of its nature, are executed respectively by the four minor robots and by the main one. This separation of tasks allows a smaller size for the robots, therefore lower weight, swifter motion and lower energy consumption. In addition, the four minor robots operate as a team, thus reducing the time needed to explore the chosen areas.

b) So far the rovers utilised for Mars soil exploration did not offer any element of redundancy and there were no possibility of any maintenance intervention. Therefore their reliability throughout the whole duration of a mission was inevitably limited. Having a colony of five robots is automatically an element of redundancy.

c) Each of the robots can be utilised to monitor the status of the other ones and some maintenance interventions could be performed. For example, it would be conceivable to replace the solar cells when their efficiency is degraded, thus increasing the duration of a mission.

d) The Ladyfly concept is very flexible. Each robot of the colony is completely autonomous and can communicate with the main one enabling the execution of predetermined strategies which can include contingency manoeuvres in case of unforeseen problems. For problems other than the Martian soil exploration, a colony of Ladyfly robots could be used to communicate with a central unit, not necessarily a robot itself.

MECHANICS OF ROBOT

Motion system

The structure foreseen for the Ladyfly robots is composed of a base-frame on which the legs are hinged. The robots can move using wheels or legs or a combination of both. In the mechanic legs chosen for this project six main parts can be distinguished: Shoulder – Arm – Elbow – Forearm – Wrist – Wheel. Because of the wheels at the end of each leg, the shoulders must be positioned outside the robot surface, to permit legs and wheels to rotate around the vertical direction with an angle $\alpha \geq 180^\circ$ ($\approx 194^\circ$). Thus, the robot surface can be completely closed allowing for a better mechanical and thermal protection of the electronic components. Arm and forearm are designed trying to reduce the total volume of the robot and to confer to it a compact shape that prevents damages. They have been designed paying a particular attention to the material strength by using the finite elements method. There is no real wrist because there are no relative movements between forearm and wheel, excepting for the wheel rotation. Particular attention is required in designing this connection in order to reduce frictions during wheels movement of the robot. The inner stresses and the possible deformations of the arm are estimated through a finite elements analysis, a 3D model of the arm.
The design foresees six wheels positioned at the end of each leg. Each of the wheels has an internal motor to drive it. The robot in this condition is capable of moving on irregular terrain such as the Martian soil.

The drive motors must be relatively high torque motors. High torque to enable the robot to cross impervious terrain is needed, because each motor should be able to theoretically lift the weight on its portion of the body. On the outer surface of the wheels there is some helicoid shaped knurling to improve the grip on the sandy soil. The wheels could be made of titanium alloys or steel alloy.

Shell, Inner distribution of the components

The robots are covered with a hemispheric shell. The legs which are hinged at the base of the chassis remain outside the hemisphere. With this solution all the vital components of the robots are inside the shell and therefore well protected from the atmospheric agents and dust the solar cells can be arranged in an optimal way all around the hemisphere. In order to optimise the utilisation of the inner space of the hemisphere and to facilitate maintenance operations, the different components are subdivided in modules. Four modules are foreseen for the batteries, the electronic circuits, the telecommunications sub-system and the instruments.

The batteries module is the heaviest one and for stability reasons it is preferable to put it in the lower position over the base-frame in order to have a low centre of gravity. The batteries inside the module are located in radius direction. The masses are therefore optimally distributed in order to avoid laterally unbalanced position.

The telecommunication module is located over the batteries module. The telecommunication cards will have a semi-annular shape in order to be adapted to the module.

The next module from the bottom is the control module, which contains all the electronic circuits.

In order to dissipate the heating created by the various processors, it is foreseen to install a small fan near a little window.

At the centre of the hemisphere there is a cylinder-shape module. On the top of the cylinder is mounted a mast supporting the camera and its mechanical and electronic mechanisms. The camera can pop off the top of the hemisphere. It is protected from dust by a transparent cover. When not in use, the shell protects it from low temperatures. In the main robot, the cylindrical module contains also at the bottom the X-ray spectrometer. Each module is insulated from the external world, in particular from dust, and from the other modules. The modules are connected through the electrical cables.

ENERGY COLLECTION, STORAGE AND DISTRIBUTION

Each activity of Ladyfly robot on Mars soil depends from the availability of electric power. The best solutions are based on the new technology TEC 3i. This kind of solar cells is made with 3 junctions deposited on a Germanium substrate. Each cell has a 26.5 cm² surface and its weight is 2.4 g. It is necessary to add a protective layer to repair the panel; the weight will slightly increase. Cells are applied on the hemispherical surface with the following configuration. Cells can produce a power of 43 W at noon on Mars. However it is necessary to consider that a strong efficiency reduction will occur because of different causes: sand deposited on the surface and panel degradation due to solar radiation. The total weight is about 1,35 kg.

The final proposal for this first step in the project development is to use commercial lithium batteries.

INTERNAL AND EXTERNAL ROBOT SENSOR

The robots have several sensors in order to monitor their motion, to operate correctly and also to execute all the functions they are supposed to perform. In particular, there will be the following type of sensors:

- **internal position sensors**, like nano-hollow shaft incremental encoders, to monitor and to control the position of each mechanical component of the robot;
- **distance measurement system**, consisting of four parts:
  a) six ultrasonic proximity micro-sensors collocated near each micro-camera sensors in the lower part of the hemisphere;
b) three convergent laser collimators for precise distance measurement to evaluate the position of the Ladyfly base with respect to the ground;

c) two others convergent laser collimators for precise distance measurement to evaluate the distance of the X-ray spectrometer work point from Ladyfly;

d) one other convergent laser collimator for precise distance measurement to evaluate the position of X-ray spectrometer (work position or stand-by);

- *forces sensors*, such as strain gauges, to monitor the forces which operates on the mechanical components and to detect/prevent collisions with external objects;

- *environmental sensors* to measure physical parameters, such as atmospheric temperature, atmospheric pressure and wind speed to evaluate climatic and meteorological conditions of the Martian atmosphere. These sensors, resistance thermometers Pt-100, capacitance manometer and thermal anemometry, are positioned in the top of the hemisphere.

END-EFFECTOR

An alternative is to provide the colony with tools for cutting, drilling and scraping. Being the Ladyfly provided with robotic arms, the simplest solution is to equip the end part of one of those with end-effectors inclusive of the tools for samples preparation. As concerns the choice of the rover where to fix the end-effector, two possibilities are available: the scientific or the explorer rovers.

MODELLING OF ROBOT

The following modelling has to be performed to study cinematic, dynamic and programming aspects. Ladyfly robots are moving only two legs at a time and these legs are at 180°. Kinematics and dynamic simulations must be performed using ADAMS software with the objective of:

- implementation of the kinematic laws necessary to move the robot;

- calculation of the links in order to have a useful control system for the choice and the dimensioning of actuators and transmissions;

- demonstration of Ladyfly capabilities.

Special focus is put on the following points:

- raising from ground with 6 legs;

- first step fig 7;

- ability of Ladyfly to go back to normal operational conditions after anomalous situations.

![Fig. 7: This simulation at the first step](image)

Fig. 8 shows the simulation in Martian atmosphere of the motion using six legs. The study has been focused on the implementation of motion laws that reduced the braces due to hit with land. Moreover Ladyfly is raised without having to dig in the ground. Braces and the laws of motion are shown in the diagrams.

In this case the study has been focused to obtain a constant distance from the base to the ground and a constant speed motion. In order to avoid an abrupt acceleration and an unexpected stop, a trapezoidal law for the base has been studied.
CONTROL AND COMMUNICATION SYSTEM

The robots will communicate by means of an UHF radio frequency modem. This has already been tested on Mars and may be preferred also for availability and reliability of commercial components. There are two ways for communication: one is through the scientific robot, that co-ordinates data exchange between the explorers and the Lander, the other is an emergency mode. In normal communication mode, four channels are used by the explorers and one by the main rover. In case of failure of any of these, the small robots can send an interrupt signal to the Lander to gain the capability of up-linking data, and inform that the data link with the main robot is not available. On the other end, if the link between the Lander and the scientific rover is not active, due to an obstacle or other difficulties, the explorers can serve as a radio relay enabling the data stream to continue. Instructions are provided from earth to the main robot at a macro level, simplifying the human control. The rover then organises itself and the Explorers for the execution of the task. It is assumed that the X-band system will be of the standard type used by ESA and use a ground station able to communicate with the Mars orbiter (e.g. the ESA New Norcia 35 m. ground station). As concerns the UHF systems the BiM modules from Radiometrix are proposed. These modules are of very small size and able to support a half-duplex transmission at 40 Kbit/sec. The specific modules to be utilized will be chosen according to maximum operative distance to be reached between the lander and the Ladyfly colony.

MOTION STRATEGY IN THE OPERATIONAL SCENARIO

The following points offer an overview of the possible position the robots can take in relation to the terrain conditions and the task assigned to it.

Dormant state. (Fig.9) When the robots are not working, (i.e. during the winter, when communication with earth are interrupted) they take this position and can maintain it also for long periods. In the closing position the wheels are set out radially on the base, as the legs, with the rotation axis tangent to the circumference of the shell. In case of storms it is possible to extend the legs, in order to get the maximum stability of the body.

Swift motion. In order to move it is necessary that the robot moves all the wheels in the same direction. It is possible to maintain this position when the conditions of the Mars terrain allows it. It is not necessary to have all the six motors working together: the control system can evaluate which to activate by evaluating speed and power required and adherence conditions. In order to steer, the robot must simply turn the shoulder.
Active motion: leg and wheel together. (Fig. 10) In case of uneven terrain conditions the robot can benefit from this cinematic configuration. The control uses the legs as active suspensions adapting them to the terrain conditions, constantly monitored by the proximity sensors that intervene in the lower level of the control loop. The decision about the direction and speed of the entire system are taken at high level, exploiting the information coming from sensors and other robots.

Stepping motion. This configuration is suitable when the robot moves on difficult terrain and the size of the obstacles prevent the active motion, or when the main robot need to position itself accurately over the surface, where the analyses are to be conducted. In this case the wheels are stopped and the robot can practically walk.

360° Rotation. In a narrow area the robot can rotate 360°, orienting its legs 90° compared to the closing position. In this way the rolling direction of the wheels is tangent to circumference of the shell and the robot is able to rotate on its own vertical axis.

Analysis operation. (Fig.11) After identifying an interesting spot for scientific analysis, the robot overcomes it by means of the robotic legs avoiding contaminations between wheels and soil. Once this operation is done the survey begins with the calibration of the spectrometer, then the door of the base opens and the analysis conducted with the X-Ray spectrometer can take place. Furthermore the robotic legs allow the correct positioning of the robot during the survey avoiding collisions with stones, in particular with the samples under examination.

The Ladyfly concept for Mars soil exploration (Fig.12) is innovative and, among other peculiarities, presents the idea of having a colony of interactive robots instead of a single robot linked to a fixed station as in the Pathfinder mission. Therefore an accurate study of the motion strategy and the control logic is of primary importance.

Before proceeding to the analysis of the soil components it is necessary to create a map of the surface as accurate as possible. The mapping activity is performed by the smaller robots or explorers, as their main activity is to explore and create a map of the chosen areas.

The limits of this activity is created by the autonomy of the robots. The motion strategy should therefore be optimised in order to minimise the periods of inactivity.

The main task is however executed by the main robot, which performs the spectral analysis of the interesting areas. The activities of the small robots are to be synchronised with those of main robot. For example, when the small robots are transmitting the soil maps to the main robot, the latter cannot perform the soil analysis. Similarly, when the main robot itself is moving to the selected areas, it cannot execute the soil analysis. The main robot by means of the data received from the small robots, builds two distinct maps, one with the geographical characteristics of the area and the nature of the obstacles and the other with the areas of scientific interest. Overlapping these maps is possible to derive the area having the peculiarity of being both accessible and of scientific interest.

CONCLUSIONS

The Ladyfly project represents a concept which could fulfil the aim of the Martian soil exploration foreseen in the context of the ESA Aurora programme. The Ladyfly robots could also host other type of instruments and be used for
example to collect samples of the soil and bring them to the lander. Furthermore the Ladyfly concept could be used to explore other planets of the solar system.

The Ladyfly concept could obviously be utilised also outside the space environment. Whenever a complex task is to be performed, the related activities can be split among a team of robots, each carrying only a limited set of instruments, thus simplifying the design and the manufacturing of each robot and warranting some elements of redundancy, useful for back-up and maintenance purposes.

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