

# The State-of-the-art in Space Robotics

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**Abstract.** This paper deals with the space robotics and associate space applications. An overview of the space era and the robotic space probes is presented to contextualize the space robotics in the space exploration scenario. Concepts, classification and key-questions associated with robotics for space applications are presented and discussed. Safety-critical aspects of the space robotics are discussed as well the human limitation to operate in the hostile space environment and long time duration missions. The paper also focuses on the state-of-the-art of robotics for the International Space Station EVA operations, for the planetary exploration such as the ongoing Mars exploration, Hayabusa rendezvous and landing in asteroids and the robotic probe Rosetta landed in a comet recently. The paper also includes a discussion of the applications of new concepts like the robonauts, the space tugs applications and robots for future planetary exploration.

## 1. Introduction

The space robotics [1] deeply marked the beginning and the evolution of the space age with the spaceships and probes placed around the Earth and in an amazing evolution to the Moon, other planets and their moons, the Sun and finally asteroids and comets. Remarkably, the space journey reached the interstellar region with Voyager 1 and the most distant planets with Voyager 2. The robots are appropriate machines to substitute the astronauts in risky activities in the hostile space environment. The integration of artificial intelligence [2] to the robot design and development is getting more and more importance and will be a key issue for the future of the space exploration. The orbital robotics requires special attention to problems of radiation, strong temperature variation, micro-gravity environment, and magnetic fields associated to some celestial bodies. Specifically, for planetary exploration one special aspect of the robotics applications include surface exploration where the local gravity, soil characteristics, local pressure, and atmosphere must be taken into account.

Some fields of space applications require robot and astronaut to work in a micro-gravity environment where man experiences the apparent absence of weight and fluctuates. This means that any work platform is a non fixed base sustaining the man and machines while in activities in orbit. The apparent absence of weight represents a key issue to be analyzed in order to assure good and safe performance of on orbit operations, be it done by astronauts or mobile robots. Presently the International Space Station labs are playing a very important role for tests in micro-gravity environment [3-4].



The space conquer has been evolved in the scenario of the cold war having the US and the former Soviet Union as the main parts of a strong competition characterizing the space exploration as a space race. The parties did their best to prove that their political and economic regimes were the best for the world (Democracy and Capitalism & Communism and Socialism). In such scenario the Earth orbital missions, followed by missions to the Moon, Venus and Mars were developed in parallel by both the US and the former URSS, with all sort of secrets, misinformation, and spying technique. For years both countries persuaded the firsts aiming to beat each other. The first satellite, the first man in space, the first woman in space and even the first animal in orbit, the first walk in space, and so on. The results of the competition are the space exploration as we have today, characterized by the landing of man in the moon, landing o robotic spacecraft, probes, and rovers on the Moon, Venus, Mars, asteroids and comet. Scientific missions have been sent to outer space covering all distant planets and their moons. It is worth to point out the incredible missions of the Voyager 1 and 2, with the first reaching the interstellar region of space, resulting in the discovery of teens of moons in Jupiter and Saturn, new knowledge about the atmosphere and soil composition of the planets. It is worth to point the discovery of the exoplanets and so many galaxies thanks to the space telescopes (Kepler and Hubble). The Mars exploration is another extraordinary accomplishment of the man toward the planetary exploration [6-9].

The very first space robots were spacecraft and probes and the main goal of those machines was the study of the Moon surface aiming manned missions to the Earth natural satellite. The capability of those robotic spacecraft included photographing and recording the surface and sending television images to the Earth. The first spacecraft sent to the Moon had not even the capability to land in the surface. They were lunar impact spacecraft. Television images were obtained and send to the Earth while falling down on the moon. Other robotic space achievements by using probes were directed to Venus, Mars, and Mercury, Jupiter and Saturn.

## **2. An overview on Robotic Functionality for Space Applications**

The main space robot functionalities can be classified into two categories, planetary surface exploration and in-space exploration [10]. The planetary surface operations involve surface mobility, science planning and perception [11], instrument, deployment and sample manipulation. Exploration of asteroids and comets also belongs to this category.

In-space operations involve operations functionalities like in-space assembly, in-space inspection in-space maintenance, EVA (Extra-Vehicular Activities), and in-orbit scientific experiment manipulation.

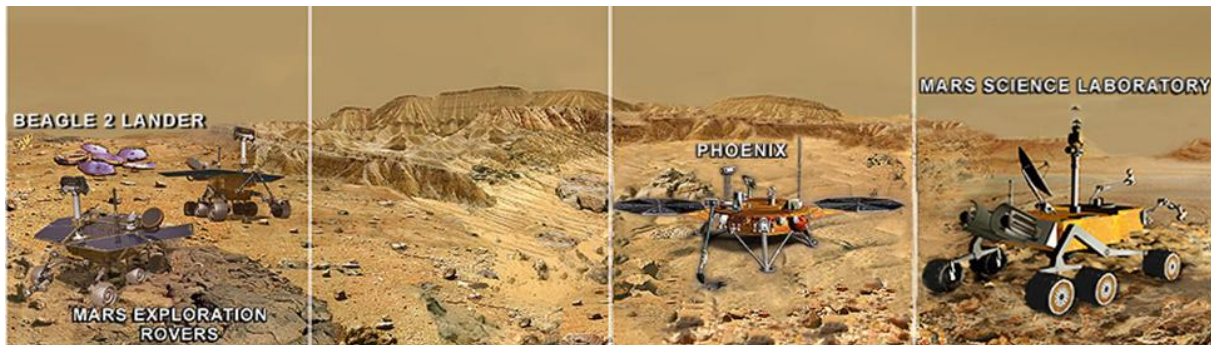
### *2.1. Planetary Exploration*

Planetary exploration robotics applications are remarkably operating on Mars surface. Robotic space probes also have reached a comet (Rosetta, mission, ESA) and asteroids Hayabusa mission (JAXA) and Dawn spacecraft in mission at the asteroid belt (NASA) to study protoplanets Vesta and Ceres.

The state-of-the-art for deployed planetary surface exploration robots remounts the Sojourner [5], the Pathfinder Mars rover that landed on o Mars on July 4, 1997 and explored Mars for around three months. It has been followed by the Mars exploration rovers (MER), and the Martian Scientific Laboratory (MSL) Curiosity rover. The MER launched in 2003 (Opportunity and Spirit) [10] and the MSL Curiosity rover (2012) [12], are the best and most complex space robots (or a space robot system) ever constructed and in operation. Opportunity and Spirit are the NASA's twin robot geologists. Table 1 shows the scientific Spirit rover instruments and functionalities carried by both rovers [4].

**Table 1.** Opportunity and Spirit rover Instruments/Functionalities [10]

Scientific Instrument	Functionality
Pancam (Panoramic camera)	For determining the mineralogy, texture and structure of the local terrain
Mini-TES (Miniature Thermal Emission Spectrometer)	For identifying promising rocks and soils for closer examination and for determining the processes that formed Martian rocks.
MB (Mössbauer Spectrometer)	For close-up investigations of the mineralogy of iron-bearing rocks and soils
APXS (Alpha Particle X-ray Spectrometer )	For close-up analysis of the abundances of elements that make up rocks and soils.
Magnet	For collecting magnetic dust particles to be analyzed by MB and APXS
MI (Microscopic Imager)	For obtaining close-up, high resolution images of rocks and soils
RAT (Rock Abrasion Tool)	For removing dust and weathered rock surfaces and exposing fresh material for examination by instruments onboard



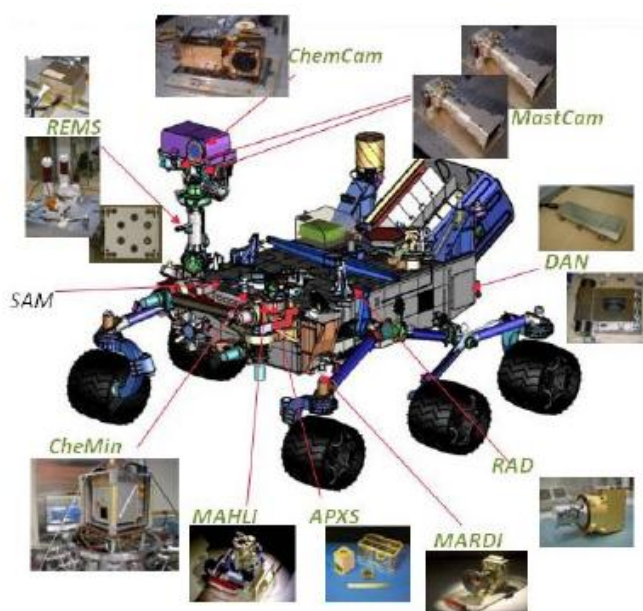
**Figure 1.** Mars rovers and spacecraft landed on Mars

The Curiosity is the Mars Science Laboratory (MSL) rover, the most technologically challenging interplanetary rover ever designed. To accomplish the science objectives of the Mars Scientific Laboratory mission, the rover carries a set of payloads with instruments that are shown in table 1. The set of instruments and associate functionalities pictures the complexity of the space robot and also the high level of technology ever used before in planetary exploration. Curiosity really represents the stat-of-the-art of space robotic applications for surface exploration. Figure 2 shows the MSL and associated robotic subsystems. Table 2 shows the Curiosity rover instruments by categories and functionalities.

**Table 2** Curiosity Instruments/categories and functionalities [12]

Instrument	categories	functionalities
Mast Camera (MastCam)	Remote Sensing	The MastCam takes color images and color videos of the Martian terrain. The objectives are to study of the Martian landscape, rocks and soil, to view frost and weather phenomena and to support the driving and sampling operations of the rover.
Chemistry and Camera (ChemCam)	Remote Sensing	ChemCam fires a laser and analyzes the elemental composition of vaporized materials from areas smaller than 1 millimeter on the surface of Martian rocks and soil.
Mars Hand Lens Imager (MAHLI)	In-Situ	This system is equivalent to a geologist's hand lens. It provides the earthbound scientists with close-up views of the minerals, textures, and structure in Martian rocks and surface layers of rocky debris and dust.
Alpha-Particle X-ray Spectrometer (APXS)	In-Situ	APXS measure the chemical elements in rocks and soils.
Chemistry and Mineralogy Instrument (CheMin)	Analytical	CheMin identifies and measures various mineral on Mars. The search for minerals may lead scientists to get indication of the past Martian environment that might have supported life.
Sample Analysis at Mars (SAM)	Analytical	SAM searches for compounds of elements carbon, including methane. This element is associated with life and explores ways in which they are generated and destroyed in the Martian ecosphere.
Radiation Assessment Detector (RAD)	Environmental	RAD is one of the first instruments sent to Mars specifically to prepare for future human exploration. RAD measures and identifies all high-energy radiation on the Martian surface, such as protons, energetic ions of various elements, neutrons, and gamma rays. Also RAD includes the capability to investigate how radiation affects the chemical and isotopic composition of the Martian rocks and soil.
Mars Decent Imager (MARDI)	Environmental	The system was used to take color video during the rover descent toward the Martian surface, providing a view of the local environment as a view of an on-board astronaut. Also it includes the capability to help Earthbound planners select an optimum path of exploration and capability to provide information about the larger ecologic context surrounding the landing site.

Dynamics Albedo of Neutrons, DAN	Environmental	Cosmic rays constantly bombard the Mars surface. In this scenario if liquid or frozen water happens to be present, hydrogen atoms slow the neutrons down. The rover pulsating neutron generator called DAN that is sensitive enough to detect water content as low as one-tenth of 1 percent resolves layers of water and ice beneath the surface.
Rover Environmental Monitoring Station (REMS)	Environmental	REMS measures and provides daily and seasonal reports on atmospheric pressure, humidity, ultraviolet radiation at the Mars surface. Also it provides the wind speed and direction, air temperature and ground temperature around the rover. In addition its infrared sensors measures the infrared radiation emitted by ground.



**Figure 2.** Curiosity Scientific Instruments

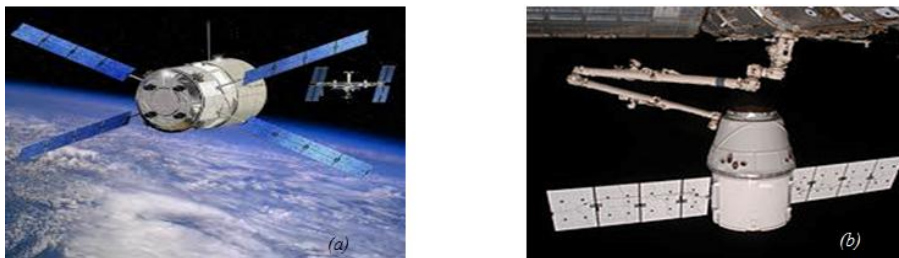
In the next 10 years it is expected that the space robots for surface exploration be not constrained anymore by navigation and mobility. Long traverses and access to most locations on a planetary surface will be possible [13]. On the other side it is expected that ground based planning and visualization tools enable scientists from ground station to interact straightforward with the robots in the surface of celestial bodies. However, robotic performance at the level of a space suited human scientist is and will continue to be a major challenge.

## 2.2. In-Space Operations

The automation by using robots in space operation got new impulse with advent of space stations and the space tugs concepts for orbital servicing. One of the most important accomplishment with an extraordinary advance in robotic was the space shuttle series of spacecraft. Space shuttle can be considered the first space tug in that it really implemented orbital servicing of grasping satellite for maintenance, maintenance and assembly for the International Space Station (ISS), and inserting new satellites into Low Earth Orbit (LEO). In 1993 astronauts based on the space shuttle grasped and

repaired the mirrors of the Hubble Telescope. In-space operations and orbital servicing require rendezvous & docking and berthing operations [14,15].

The Space Shuttle was replaced by the ATV, the automated transfer vehicle (a robotic space tug) that executed several rendezvous & docking operation with the ISS for maintenance and scientific purposes. Presently the SpaceX Dragon spacecraft is replacing the ATV. Dragon is a partially reusable spacecraft developed by SpaceX, an American private space transportation company. Figure 3 (a) and (b) shows the ATV and Dragon spacecraft, respectively. The space shuttle cannot be considered as a robotic spacecraft as his successors. However, it carried a long robotic manipulator capable to grasp satellites to provide OOS. ATV and Dragon were/are spacecraft with large autonomy. Again, most operations include some level of teleoperation and straightforward commands from ground based control station. The teleoperation is still part of the Space Station Remote Manipulator System from the ISS, currently in orbit.



**Figure 3.** (a) and (b) showing the ATV and Dragon, respectively

The robonauts [16, 17] represent another state-of-the-art in the space robotics area. They resemble a human in shape and size. The hands are like human hands capable to operation the same tools human operates. Some robonauts versions include the capability to climb on the external surfaces of ISS like a spider. Some other activities are being planned to the robonauts so that it can help astronauts by manipulating task such as turn on/off systems and helping with scientific experiment manipulation. The robonauts also is being trained to execute medical task for future support to astronauts. Leap motion technology is being used to train the robonauts to grasp and hold tools and instruments.

The in-orbit inspection aims to use robots for external inspection of the space station. However, so far this kind of robotic operation has not been implemented. A test of a free-flying camera, AERCam Sprint was conducted during the STS-87 in 1997. The robot was purely teleoperated. In same line the Germans designed a robot called Inspector to implement inspection operation at MIR space station but it failed in flight. Presently tests are being conducted in the ISS with free-flying smart spheres. In a near future the in-orbit operations will be part of the space operations. The microgravity environment at ISS is appropriate to conduct the test of this kind of robots.

In-space maintenance refers to the so called OOS and the services include refueling, repairing satellites, replacing pieces, providing food and water to astronauts, correcting orbits, and in a near future, towing a spacecraft to the a space station for repairing and fixing problems and then, take it back to its orbit.

### 3. Conclusion

This paper presented the state-of-the art of space robots with focus on spacecraft and probes like robots, in-orbit robotic applications, and planetary surface robotic applications. It was placed more emphasis on the robotic applications for planetary exploration for it represents currently the most risky type of exploration for humans. The risky is not associated only with the hostile environment of planets like Mars, Venus, and other but also with the long duration of the space trips that involves



aspects that may impact the human health to deaf and not ready investigated and clarified by the scientists. The robots represent the only alternative for those long trips and risky activities in the space environment. The space robots are designed by using ultimate technology aiming performance and autonomy. However, in terms of intelligence much is still to be done. Activities where decision taking is required, mainly those in dangerous and risky situations require still the presence of humans. The progress reached in space area is remarkable considering the beginning to space era by 1957 with the launching of the Sputnik.

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