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50 years of rovers for planetary exploration: A retrospective review for future directions

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HIGHLIGHTS

- Extensive review of history and innovative technical contents from former robotics to present robotic exploration vehicles.
- Comprehensive study with collection of 100 mobile robots along history.
- Robot's statistical profile on weight, size, number of wheels, and speed of movement.
- Exhaustive bibliometric analysis over 8,120 contributions between 1963 and 2015.
- Continuity of mobile robotics due to advanced science development at the expense of forthcoming space exploration missions.

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ABSTRACT

This paper contributes an extensive review of the history from the former robotics to the present providing a particular emphasis on innovative technical contents of robotic exploration vehicles. To this end, a comprehensive study with a representative collection of 100 mobile robots along the history was performed for which a robot's statistical profile was obtained considering aspects such as weight, size, number of wheels, and speed of movement. In addition, an exhaustive bibliometric analysis has been conducted over 8120 contributions between 1963 and 2015. The study on the scientific literature found that, thought mobile robotics is a research field being displaced by other disciplines of higher scientific return (e.g., humanoid robots, unmanned aircraft systems or intelligent autonomous vehicles), it is nevertheless confirmed the continuity of mobile robotics with the aim of developing advanced science at the expense of forthcoming space exploration missions. Therefore, this paper attempts to address what is the current state-of-the-art and what are the future challenges set in mobile robotics.

1. Introduction

Since its inception, space exploration has flag among its goals different targets such as finding evidence of life in the present or the past, the understanding of the climate for the development of life on other planets or testing technologies aimed at preparing future space missions [1]. The slowdown of the Russian space race after the fall of the Soviet curtain first and the reduction of the NASA budget in second place – whose state funding decreased from 4.4% in the sixties to the current 0.5% – have made that interest turns into other research fields with faster and more profitable scientific return such as the humanoid robots, the unmanned aerial vehicles (UAV) or the autonomous cars [2,3]. That is the example of the Moon, whose surface has not been officially explored again over four decades since the Soviet Luna-24 mission in 1976.

However, the latest achievements of NASA as the discovery of the most Earth-like planet so far (i.e., Proxima b) and the arrival of the New Horizons probe to Pluto have returned the sight into space exploration. The importance of these scientific successes along with a brilliant media campaign through the social networks with the aim of providing marketable results – not only to the scientific community or politicians but also to the general public opinion – have returned a positive image and prominence to the US space agency not enjoyed for decades [4]. These achievements along with the successful Mars rovers of JPL or the China's Yutu lunar rover plus the impending Chandrayaan-2, ExoMars, Mobile MAV and MELOS missions demonstrate the current interest of the scientific community for the space exploration, thus prolonging the research and development of robotic exploration vehicles [5].

State-of-the-art overviews published in scientific journals include a very rich literature but mostly oriented to cover specific aspects of planetary robotics. For instance, a summary of wind-driven rovers for planetary exploration [6], an outline on the best

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design methodologies for hypermobile robots [7], a review on the major European rovers and development programs in different space application scenarios [8], an analysis on ground mobility systems for space exploration [9], a study on control systems and communication methods for wheeled mobile rovers [1], a survey on control architectures for autonomous vehicles [10], a review on visual navigation systems for mobile robots [11], or an examination on computer processing capabilities for increasing the autonomy in Mars rovers [12], among others. Other research papers on service robotics for planetary exploration deal with more general aspects closer to this work. For example, an introduction on exploration rover concepts and development challenges [13], a taxonomic study based on performance metrics for planetary rovers [14], and a summary on possible areas of application in space such as robotic mobility and exploration [15].

References to existing books with similar state-of-the-art overviews on planetary robots include remarkable works. For instance, a wide coverage on space exploration missions evolving from planetary flybys and orbiters towards *in situ* surface missions is provided in [16]. In this line, the latest results and findings on the hot field of planetary exploration – with special focus on geophysics – as well as next-generation planetary science are offered in [17]. Similarly, a set of technology roadmaps for NASA during the 2011–2021 decade – based in a report from the US National Research Council – to select a list of objectives and high-priority technologies in the area of autonomous systems (i.e., guidance, navigation and control) is presented in [18]. More specifically, a summary on mobility technology of already accomplished and ongoing research with the aim of achieving lighter, cheaper and faster space missions is provided in [19]. Also, several realizations of wheeled mobile robots to analyze and compare commonly encountered designs are introduced in [20]. Finally, R&D topics with the aim of providing greater level of autonomy to planetary robots but without covering design issues of any hardware subsystems (e.g., sensors, mechanisms, electronics or materials) are described in [21].

More oriented to a wider audience, the design, development and deployment of the Lunar Roving Vehicle (LRV) as part of the Apollo 15, 16, and 17 Moon missions is covered in [22]. Also, the development, design and engineering of three generations of Mars rovers (i.e., Sojourner, Spirit & Opportunity, and Curiosity) is faced in [23]. In this line, [24] offers a detailed look at the technical, programmatic and challenges faced by the second wave of NASA Mars missions starting after Viking until Mars Science Laboratory (MSL) and Curiosity. As well, a day-by-day recounting of what went through to build the Spirit & Opportunity rovers and then operate them on Mars is presented in [25]. Likewise, a personal story to guide readers through the many setbacks, victories and difficult decisions that came with planning the Curiosity mission is edited in [26].

In general, the above mentioned papers, chapters and books do not always emphasize about the historical evolution, cover a statistical profile either conduct a bibliometric study in robotics with a broad perspective over time. Besides, their scope is frequently limited to specific aspects and/or contemporary robots, thus demanding a wider focus and obligated update. For this reason, the research question this paper aimed to examine was: which is the past, current and future interest on mobile exploration robots? It had four main objectives: (1) to undertake a comprehensive bibliography update on mobile robots, especially in rovers, (2) to situate the scientific impact through the examination of who, when and about what has been made the research, (3) to review what technological milestones over the last five decades led rovers to more powerful machines, and (4) to set a baseline design for planetary exploration rovers as a representative example of typical practices and future trends. To this end, this paper is structured as follows. The following section describes the presence of ancient vehicles in antiquity and lays the foundation for current and future mobile robots in land research missions. Then an analysis about the profile of mobile robots is performed. Next section provides a study on the scientific evolution of robotic exploration vehicles. Finally, the paper presents the conclusions.

Fig. 1. The autonomous vehicle of Leonardo da Vinci. *[Credit: Léonard de Serres.]*

2. State of the art

The purpose of this section is to present the history of robotic vehicles across the time, from the mechanical designs of the antiquity to the next generation of rovers going through the robotic exploration missions nowadays.

2.1. From ancient to the modern era

Machine manufacturing has fascinated humans for over 4000 years and the world of automata is as large as its definition. One of the earliest propelled vehicles documented in the history was a wind-driven wagon designed by Guido da Vigevano in 1335 A.D. Although never built, an analysis conducted by the University of Stuttgart estimated a total size of 6–8 m with wheels of 2.4 m in diameter able to drive up to $\sim$50 km/h into the wind direction [6]. However, there is evidence of the construction of several automata and mechanical robots by Leonardo da Vinci in the late 15th century (Fig. 1). The 812r sheet from the Codex Atlanticus showed an outline of a tricycle vehicle equipped with gears and springs – in its upper part – to perform the function of autonomous movement [27]. The Institute and Museum of the History of Science in Florence, Italy ordered to build – to engineers C. Pedretti and M. Rosheim – three scale models showing the complex mechanism of spirals devised by Leonardo. This used the same system than the old toys before the arrival of the batteries, thus allowing to move a few meters by itself. According to statements by Dr. P. Galluzzi, director of the museum, it was the first autonomous vehicle in the world.

In the modern era, mobile robots own their origin to the electromechanical systems in the thirties – as the so called micro-mouse – created to independently discover paths in mazes with the aim of developing intelligent functions [28]. Later Dr. W.G. Walter was known in 1948 for the construction of the first electronic autonomous vehicle (Fig. 2(a)). Such a robot – dubbed *Walter's turtle* due to its shape and slow motion — was initially dubbed *Machina Speculatrix* in order to see how a small number of neural connections could lead to complex behaviors. The robotic vehicle – endowed with a locomotion system of three wheels — was able to move in response to light stimuli (i.e., phototaxis), overcome obstacles and recharge its 45 V batteries before being depleted. This

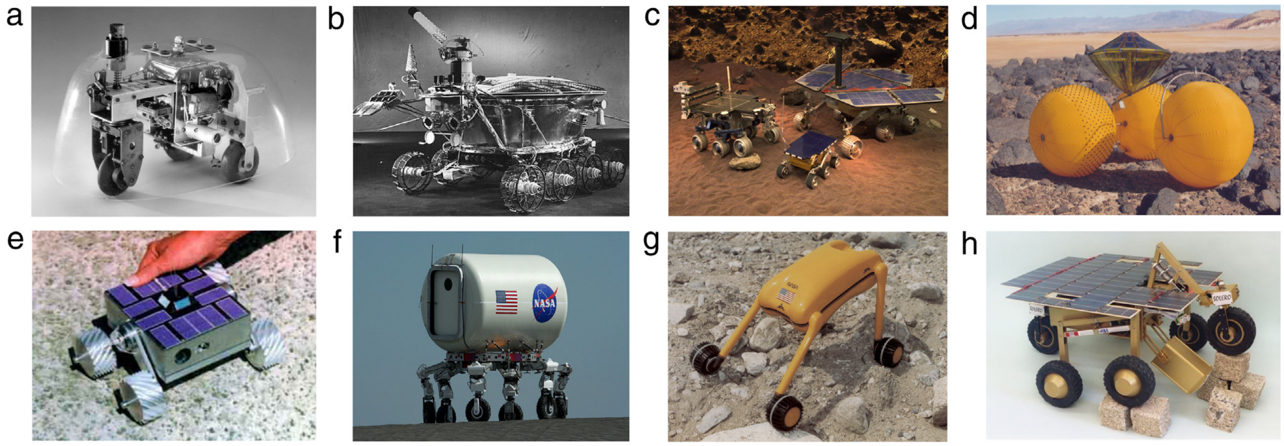

Fig. 2. Example of different designs of robotic exploration vehicles: (a) Walter's turtle, (b) Lunokhod 1, (c) Sojourner, FIDO and Opportunity rovers, (d) Big Wheels Inflatable Rover, (e) Muses-C, (f) ATHLETE, (g) GoFor, and (h) SOLERO. *[Credits: Smithsonian Institution, Wikimedia Commons, JPL/NASA, ESA.]*

made it a potentially autonomous and independent system from its creator [29]. This prototype inspired other following designs as *Tinius* in 1950, an autonomous vehicle also attracted by light sources; *Docilis Machina* in 1951, a version of the Walter's turtle that included sound detector, anti-shock system and additional capabilities that allowed it to memorize obstacles; *Vienna Turtle* in 1954, designed by E. Eichler in base to the conditioned reflex behavior; *Machina Versatilis* in 1956, named for its modular design based on transistorized electronic cards [30]; *Ladybird*, a beetle built by D. Muszka and L. Kalmár equipped with microphone, light sensors, seven touchpoints on the skin, capacitive memory and two electric motors powered with 220 V AC; or the *Yellow Turtle* in 1969, the first robotic vehicle physically connected to a computer via wired lines and programmed with LOGO language [31].

Other examples of autonomous vehicles with diverse designs were *Creep Mk-2* in 1962, a programmable radio-controlled robot with triangular structure equipped with arm and clamp [32]; *Hexy* in 1965, a simple autonomous light-seeking hexagonal robot that scanned when the drive motor was reversed [33]; *Fred and James* robots in 1967, a set of robotic systems created to design the home of the future through mobile rooms; *JASON* in 1971, a robot equipped with a robotic arm, IR proximity sensors, radio link between onboard microprocessor – devoted to data collection, communication and low level behavior – and remote computer dedicated to perform top level calculations for navigation and planning [34]; *Flakey* in 1972, a robotic hexagonal platform of 90 cm tall and 60 cm in diameter equipped with three-wheeled differential system, maximum speed of 30 cm/s, 12 sonar rangefinders and video camera used – in combination with a laser – to provide depth information [35]; *Microtron* in 1976, an octagonal robot with aluminum chassis of 180 cm width and 30 Kg weight carrying a 12 V battery car which was able to interpret up to 10 voice commands [36]; *Newt* in 1977, an intelligent vehicle with tower-type structure equipped with vision sensors and a manipulator arm [37]; *HILAIRE* in 1977, an autonomous robot vehicle of $1.10 \times 1.10 \times 0.70$ cm^3 and 400 kg with a maximum speed of 1 m/s equipped with ultrasonic sensors and a laser rangefinder [38]; *Toddler Tee* in 1978, an autonomous medium size vehicle with speed up to 1.6 km/h equipped with 12 V rechargeable battery, rotating sensor to search for light, shock sensor, sound system and Z-80 microprocessor [39]; or the *Electromechanical Servant* in 1979, an intelligent home robotic vehicle with four-wheel structure equipped with manipulator arm, tweezers and proximity sensor based on a 16-bit microprocessor [40].

In the 80s, *Unicorn-1* stands out as a fully mobile robot that reminded the R2-D2 prototype from the Star Wars film saga with the ability to use its hands and arms through a wired link console or a radio controlled computer [41]; *Pluto CMU Rover*, a cylindrical autonomous vehicle with two-wheeled differential system assisted by a caster wheel, television camera with pan, tilt & slide mount, and a MC68000 processor designed to test a wide range of control and perception techniques [42]; *ROBART-I*, a robot of 1.5 m height equipped with sonar, IR proximity scanner, anti-shock sensor and tactile elements designed with the goal of patrolling domestic environments [43]; or *Herbert*, a fully autonomous mobile robot with onboard parallel processor, integrated manipulator, and laser scanner capable of performing 3D real-time vision while performing simultaneous navigation and manipulation tasks [44].

More recently, an outstanding mobile robot with the aim of developing basic science in the areas of personal and professional use was *Xavier* in 1995, a robot vehicle accessible from the Internet originally created at Carnegie Mellon University (CMU) for three months with the idea of trying a new autonomous navigation algorithm for indoors [45]. It received during its lifetime more than 30,000 applications for connection. The main achievement of this project – with respect to others – was the implementation of remote interactions on a mobile and autonomous vehicle since the wireless bandwidth was quite limited until recently, thus affecting significantly the control and visual feedback in real time. As another example, *TALON* is a next-generation vehicle in the field of military applications belonging to the family of robotic caterpillars. Its modular components consist of a manipulator arm, multi-view cameras, tele-operated control and dual RF communications system. Since the year 2000, it has been involved in military operations such as Bosnia or Afghanistan. Also, the company BlueBotics has successfully carried out in 2013 a robot for the guidance and assistance of passengers at the Geneva airport, Switzerland [46]. The robot, called *Robbi*, is the first android robot in the world designed to guide newcomer passengers to certain places of interest (e.g., ATMs, toilets or baggage counters). Robbi has great autonomy – up to 11 h – and returns by its own initiative to the place that has been assigned to wait for new customers. Although it has not been yet programmed to return to a recharge station without human assistance – which limits its functionality – its concept is a starting point for the development of new projects. In this sense, the *Robotino*® vehicle by Festo was successfully used to assist dependent people in navigation tasks of robots through an augmented virtuality telepresence system [47]. Some other recent examples in the field of personal applications are the famous *Roomba*®, a mobile robot able to assist people with the potential to provide a high degree of independence in activities of daily living [48]; *Urbie*, a robotic platform designed for urban environments based on the *Packbot* of iRobot with two processors, wireless Ethernet, differential GPS/IMU, digital compass, LIDAR unit, omnidirectional camera and binocular stereo camera to perform a wide range of tasks including self-localization by EKF, stairs climbing, obstacle avoidance, etc. [49]; *SAFIR*, a rescue robot designed to be used for technical assistance and the first explorations of hazardous scenarios [50]; *COBRA*, a high mobility rescue robot equipped with four caterpillar tracks [50]; *telerobot*, a robotic vehicle for home care [51]; *Spy-cye*, a robotic surveillance vehicle for home and office [52]; *EGIS-SR*, yet another home surveillance robot; *Care-O-Bot II*, an assistant robot to actively assist humans [53]; *CareBot*, a personal robot useful for the care of children and elderly [54]; *RP-VITA*, a system for telemedicine which includes a telepresence robot for use in hospitals, homes and residences [55]; *MantaroBot*, a telepresence robot to facilitate the communication between patients, families and doctors [56]; *Beam RPD*, a tele-controlled robot aided at increasing the perception in remote environments [57], and *Quillo!*, *LudoSys*, *Pololu*, *e-puck*, *Khepera*, *mOway*, *Mini-Z* or *Iwaver 01*, another robotic systems focused on clinical and educational sectors [58–61].

2.2. Robotic vehicles for space exploration missions

In the last 50 years substantial research effort has been directed towards the development of concepts and working prototypes for lunar exploration vehicles. Perhaps, the first Moon exploration vehicle used in an experimental phase was an unmanned roving vehicle for the JPL/NASA Surveyor Spacecraft program in 1963 [62]. This consisted of a six-wheeled articulated vehicle powered with Ag-Cd batteries with 3.66 m long by 1.52 m wide and a weight of 30 kg on Earth. At the same time, the Soviet Union developed *Ш*-1 in 1965, a self-propelled mockup aimed at checking technical decisions, debugging of control systems and investigating the interaction of the chassis with lunar soil [63]. This led – after years of secret engineering development and training – to the first robotic space exploration vehicle called *Lunokhod 1* (Fig. 2(b)), a mobile robot carried by the Luna-17 probe, one of the great successes of the old Soviet's lunar exploration program which landed on November 17, 1970 on the selenite surface. This vehicle along with the *Lunokhod 2* robot – submitted three years later – have been the only two automatic mobile laboratories guided by remote control in 40 years with the aim of exploring and sending images of the lunar surface.

Lunokhod 1 was a large-sized remote vehicle that traveled about 10.5 km during its lunar journey along eleven months, thus exceeding the 90 days of life for which was expected. The wheels were not designed to turn, so that the turn of the vehicle was achieved by varying the rotation speed of the wheels in the left and right trains. It transmitted more than 20,000 television images and 200 high-resolution panoramic views of an area around 80,000 m^2. It accomplished nearly 500 experimental tests consisted in analyzing the chemical and physical properties of lunar soil in 25 and 500 points, respectively. Unexpectedly, the main technological milestone has been to continue working after 40 years of silence on the lunar surface. In 2010, the Lunar Reconnaissance Orbiter (LRO) from NASA detected Lunokhod 1 at 2.3 km north of its landing point, which allowed to obtain the coordinates of its position. Following the rediscovery, two scientific teams – American and French – pointed their scientific equipment and laser instruments at Apache Point and Côte d'Azur observatories toward the Lunokhod 1 reflector, after which they received signals for more than three nights with around 2000 readings in one of the attempts [64,65].

Lunokhod 2 was profoundly remodeled and improved over its predecessor for a mission of four months in which provided 86 panoramic and over 80,000 TV image views. A third vehicle of the series – *Lunokhod 3* – was designed and built, although the mission was terminated before its launch so it never became employed. It is currently exhibited in the Russian museum of Lavochkin Research and Production Association. Other robotic vehicles with different fate were *Lunokhod 1A*, a mission destroyed during its launch in 1969; *PROP-M*, a mini vehicle of 4.5 kg and 215 × 160 × 60 mm^3 aboard the Mars-3 mission reported missing in 1971 [66]; and *Marsokhod*, a vehicle with six bevel-gear wheels and a mass of 70–75 kg on board the Mars 4NM mission projected for the year 1973 [67].

A derivation of the meaning of robotic vehicle – coined by NASA – was the term rover, also known as *Lunar Roving Vehicle* (LRV). This locution – first used in the Apollo XV mission – served to designate an all-terrain, bogie-type, vehicle used by the astronauts on their move on the lunar surface after conducting the first lunar mobility studies during the 1960s (i.e., the Mobility Laboratory, the Lunar Scientific Survey Module and the Mobility Test Article). The term was extended later to the concept of remotely operated vehicle for emplacement and reconnaissance when the *Sojourner* robot was used in the Mars Pathfinder mission of NASA in 1997. This term has been transformed nowadays into the acronym MER – Mars Exploration Rover – to designate the *Spirit* and *Opportunity* rovers deployed since 2004. Following the Apollo XV mission, Apollo XVI and XVII series continued. The electric vehicles were powered by non-rechargeable batteries based on the design of Pratt & Whitney Aircraft. The four-wheel off-road traction system – built by Boeing and General Motors – was designed to operate in low gravity on the Moon dust and could reach an average speed between 13–18 km/h. For that, the rovers were equipped with aluminum tires coated with wire mesh. In total, the three Apollo missions made a tour of 90.64 km over the lunar surface around a safety radius of 9.6 km from the lander [68].

By contrast, Sojourner was a small-sized vehicle capable of moving only about 500 m around the Mars Pathfinder platform (Fig. 2(c)). Its weight on the Earth was 11 kg while on Mars only weighed the equivalent to 4.1 kg [69]. During its 83 days operating on the surface, Sojourner sent to the Earth about 550 pictures and chemical analysis conducted in 16 different locations. The way to drive the rover represented a hybrid method between the real-time telecommand and the total autonomy. On the one hand, a program developed in Java™ for an SGI Onyx2™ display by Silicon Graphics was used to remotely control the robotic vehicle. With this assistance system, a NASA team generated scripts to guide the rover using a sophisticated graphical interface. This contained the complicated commands and consisted of working timetables accessible via the mouse. Through it, the driver – Brian K. Cooper – first selected the command and then introduced the parameters. A second screen collected the images taken by the Mars Pathfinder platform through a special stereoscopic camera. Once the data was received, a processing software allowed to generate a 3D virtual space where both the platform and the robotic vehicle were. On the other hand, the NASA team used a mouse – through giant darts within images — indicating the waypoints that the rover should follow. After marking a set of targets – along with the experiments and the operations to conduct — the information was sent from the Earth to the Mars Pathfinder platform through an X-band datalink. Subsequently, the platform relayed this information to the Sojourner vehicle. Thus, the work for each Martian day of the mission (i.e., sol) was scheduled avoiding to send regular information every few minutes [70].

The Sojourner's successor was *Rocky 7* both designed with a six-wheeled rocker-bogie suspension, a successfully proven technology. Rocky was extremely stable, had a sophisticated computer brain and was designed to explore a planet never seen before. Its main mechanical characteristics were 11.5 kg, 48 W of consumption and maximum speed of 30 cm/s. Sojourner was basically controlled by the lander, so it could not move beyond the limits of its line of sight (LOS), meaning that it could not go more than

30 m from the platform. However, all Mars explorers must be autonomous because the time needed to get a signal from Earth to Mars is too long. Typically, orders are sent in the morning and the robot works all day autonomously. Rocky 7 was designed to operate alone for long periods of time and had the ability of self-situation – even far from the LOS of the mothership – by means of Sun sensors. So Rocky 7 could be smart enough to carry out an expedition without direct control from the Earth and get something that made sense [71].

In January 2004 the pair of rovers, Spirit and Opportunity officially labeled as *MER-A* and *MER-B*, arrived at the Mars surface in a new research mission on Victoria Crater at Meridiani Planum (Fig. 2(c)). These medium-sized vehicles differ from the Sojourner rover in size and capability, whose total payload cost about $400 million. The MERs are more autonomous, each one carrying its own telecommunications equipment, cameras and computers on board. However, the Sojourner rover was controlled by operators from the Earth – whose signal typically takes between 15 and 20 min to arrive – and most of its equipment was at the base landing platform. Each MER is equipped with a 5 DOF robotic arm carrying a turret with a digital microscope, a rock abrasion tool (RAT), an X-ray spectrometer and a solid Mössbauer spectrometer. The contact with the Spirit rover was lost in 2010 whilst Opportunity is still operating today and exploring all kind of craters, formations and stones. A review of the MER mission has allowed to know a list of incidents, among which there are a Spirit's computer memory saturation, wheel stranding in the sand or worn parts.

2.3. Terramechanical vehicles for planetary science

Other efforts made by public research institutions, universities and/or companies with the aim of testing robotic vehicles for possible exploration missions have been *Clifford*, an all-terrain four-wheel robot – based on ATRV-II – designed to test collision detection and route planning algorithms on planetary surfaces [72]; *LSR*, a lightweight vehicle with a six-wheeled rocker-bogie suspension designed to reduce its volume by 25% for transport operations [73]; *Nomad*, a lunar exploration large vehicle with independent four-wheel drive (4WD) developed for long journey missions [74]; *Big Wheels Inflatable Rover* (Fig. 2(d)), a large but light vehicle devised to overcome high rocks on the Martian surface [75]; *Muses-C* (Fig. 2(e)), a four-wheeled miniaturized rover initially designed to explore and take pictures on an asteroid surface [76]; *Rocky 1* to *Rocky 8*, a series of prototypes built prior to the Mars Pathfinder mission to prove that a small rover could maneuver in rough terrain, take payload and operate autonomously [77]; *FIDO* (Fig. 2(c)), a six-wheeled prototype equipped with autonomous navigation technology to make planetary science before the MER mission [78]; *Zöe*, a vehicle capable of performing precise movements, climbing slopes, maximizing energy and transporting scientific payload to investigate the Atacama Desert [79]; *Athena SDM*; a six-wheeled platform to test the mobility and surface navigation capabilities through onboard software previous to the MER mission [80]; *K9*, a scientific exploration rover for remote and autonomous operation [81]; *Micro5*, a series of robotic vehicles designed for lunar exploration [82]; *PLuto*, a vehicle designed with programmable logic used for the development of planetary exploration technology mechanically similar to FIDO [83]; *ATHLETE* (Fig. 2(f)), a vehicle capable of moving over moderate terrain and walk on extreme lands by means of six legs with independent wheels [84]; *GoFor* (Fig. 2(g)), a high mobility robot vehicle developed with wheels-on-legs configuration able to climb vertical steps of height 70% of the maximum stowed vehicle dimension [85]; *LAGR*, a vehicle with two differential wheels equipped with stereo cameras and GPS/IMU used autonomously or remotely as a platform for data collection on sandy soil [86]; *K10*, a rover participated by students with four wheels and remotely controlled to carry out systematic journeys on simulated lunar points [87]; *Zaurus*, a small mobile robot with six wheels connected by an active mechanism of high maneuverability provided with three joints [88]; and *K11*, a prototype of four wheels used as a platform to investigate mechanical, electrical and power subsystems under realistic scenarios [89], among others [90].

Finally, other outstanding examples of experimental autonomous vehicles for general-purpose science are *SpaceCat*, a micro-rover of 2 kg with 30 × 20 × 20 cm^3 consisting of an innovative mobility solution based on six independent wheels arranged in a triangular structure [91]; *Nanokhod*, a miniaturized caterpillar vehicle with 1.450 kg based on Russian designs [92]; *SOLERO* (Fig. 2(h)), a vehicle designed for optimal energy consumption thanks to an intelligent power management system combined with an efficient locomotion [93]; *Hyperion* (Fig. 3(a)), an experimental articulated four-wheel vehicle designed to increase solar energy catchment using photovoltaic panels facing the Sun [94]; *Cool Robot* (Fig. 3(b)), a robot-cube prototype used in polar exploration missions [95]; *PER*, a personal exploration vehicle with a more educational approach [96]; *VANTER* a specialized reconnaissance exploration vehicle of 0.35 × 0.75 × 0.3 m^3 and 12 kg with independent four-wheel rotation, speed up to 0.60 m/s, 5 DOF robot arm, wireless system and micro camera [97]; *MPE*, a concept study of small fetching rover of ∼10 kg for future ESA' sample return missions [98]; *Light Crawler*, a lunar vehicle aimed at achieving greater mobility by reducing contact pressure with four independent and steered caterpillar tracks [99]; *Scarab*, a demonstration of a medium-sized lunar rover design to explore polar cold traps for water ice as a potential resource [100]; *Tri-ATHLETE*, a fully independent three-limbed robot developed to support the return of humans to the lunar surface [101]; *Axel*, a tethered system which was developed to provide mobility in steep rugged gradients up to 90° and to be able to transit from overhangs to sloped or flat terrain [102]; *Tressa/Cliffbot*, a rappelling robot aimed at demonstrating semi-autonomous science investigation and sample collection in cliff sites [102]; *SR-II*, a four-wheeled solar rover capable of traversing rough terrain using an efficient high degree of mobility suspension system [103]; *CESAR*, a lightweight mobile robot with a hybrid wheel/leg locomotion concept that combines the benefits of wheeled and walking systems while keeping simplicity [104]; *MoonHound*, a 4WD rover for research on mobility and perception with special focus on SLAM algorithms [104]; *Mörri*, a six-wheeled solid base robot designed to operate in extreme weather conditions and heavy load [104]; *Rugbot*, a tracked robot devoted to safety, security and rescue tasks tested in the ESA Lunar Robotics Challenge [104]; *DAVID*, a rough-terrain casting robot developed for the ESA's Lunar Robotics Challenge [105]; *SherpaTT*, a versatile hybrid wheeled-leg rover with autonomous active ground adaption [106]; *RATLER II*, an all-terrain lunar exploration rover currently being used as 4WD platform for tasks such as surveillance, localization of chemical sources, and search and rescue missions [107]; *Hercules*, a medium-class rover prototype for lunar science and resource prospecting [108]; *Nexus 6*, a small-sized test bed for planetary exploration with articulated body [109]; *Hylos*, an experimental prototype of hybrid wheel-leg locomotion system aimed at optimizing movements in natural terrains under criteria of stability and energy consumption [110]; and *Micro-rover*, a two-wheeled self-righting robot for inspection and reconnaissance in extraterrestrial environments [111].

2.4. Recent missions for robotic space exploration

In mid-2012, after 36 weeks of travel from Earth, the *Curiosity* robot successfully landed on the Gale Crater on Mars as part of the NASA's MSL mission. The one-ton car-sized vehicle with ten scientific instruments costs $2.5 billion due to the increase of complex

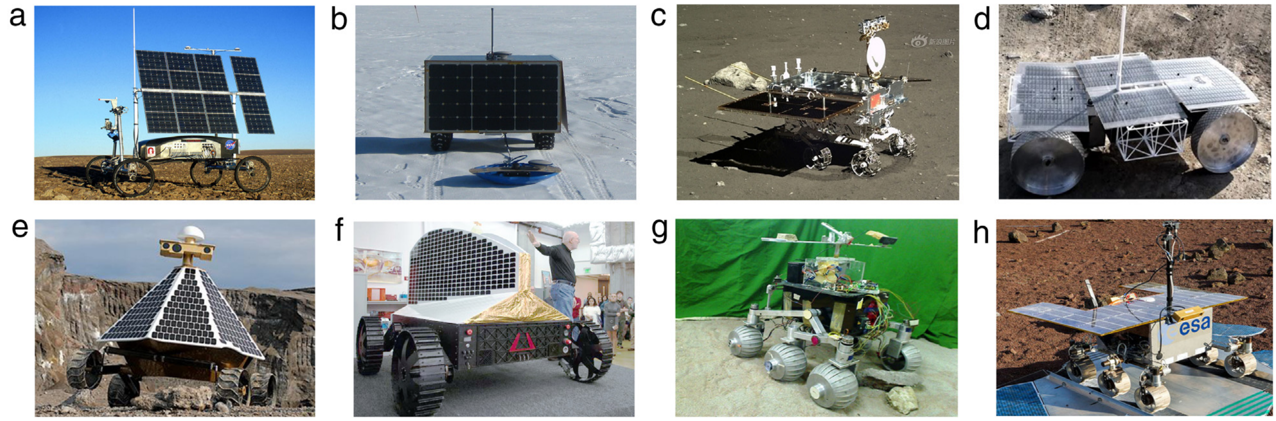

Fig. 3. Example of different designs of robotic exploration vehicles: (a) Hyperion, (b) Cool robot, (c) Yutu, (d) Barcelona Moon Team, (e) Red Rover, (f) Polaris, (g) Chandrayaan-2, and (h) ExoMars. *[Credits: CMU, J. Lever, CASC/China Ministry of Defense, Barcelona Moon Team, Astrobotic Technology, IIT-Kanpur, ESA.]*

experiments and sensing systems, which are all still working fine to date and reporting data. Among the innovative technical aspects, Curiosity has a rover environmental monitoring station (REMS), which comprises a meteorological package aimed at helping in future human surface habitability on Mars through the study of the ground-atmosphere interaction in long-term (i.e., humidity, pressure, temperature, wind speed and ultraviolet radiation). Another novelty is Chemistry & Camera (ChemCam), a scientific package that consists of a laser that remotely collects data to study the elemental composition of rocks and soil at the sub millimeter scale. This instrument presented a challenge in terms of how to analyze material with respect to other gadgets (e.g., the Alpha Particle X-ray Spectrometer (AXPS) used since Sojourner) by not requiring to deploy a robotic arm. As an advantage, the ChemCam does not need to scratch, dig and drill to collect information (i.e., just drive, stop and zap things), thus avoiding to slow down the rover in the search for new targets [112]. Regarding the communication system, Curiosity also carries a high-gain antenna (HGA) that allows adjusting its tilt and position so that data can be directly sent at 32 kbps in X-band between robot and Earth through the Deep Space Network (DSN) in ∼14 min. Furthermore, the Curiosity robot used – for the first time in a rover – a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) capable of producing 2.5 kWh/day with 4.8 kg of Plutonium-238 dioxide. This is combined in addition to rechargeable lithium batteries for power peak demands with a life between 15–20 years. Unlike MERs – which landed folded within a capsule wrapped in airbags – the Curiosity mission set a radical change in the strategy of the descending system. Called sky-crane, this revolutionary approach was based on an automated falling maneuver during seven minutes in which eight PWM leveling retro-rockets were used to fly a major mass component suspended from a variable length trapeze [113]. As main benefit, the sky-crane minimized the mass of the landing stage, thus maximizing the size of the payload within a given total weight.

Despite of the current Curiosity's popularity – more than 3.6M followers on Twitter – its mission received the worst rating among seven space projects from NASA in a report commissioned from a group of scientists by the US Congress because of the poor scientific return obtained after the first years of research. Nonetheless, Curiosity recently discovered that there was not only nitrogen in the Mars atmosphere but also nitrates on the surface. This confirmed the initial hypothesis that Mars may have supported microbial life at some point in its history before becoming dry and barren [114].

At the end of 2013, China successfully managed to deposit an exploration vehicle on the Moon's Mare Imbrium region thanks to the soft landing – in a controlled way – of the unmanned Chang'e-3 probe [115]. The medium-sized robotic vehicle, dubbed *Yutu*, featured among other scientific payload a high-gain communication antenna over a mast of ∼1.5 m tall, a front robotic arm with an AXPS and a hybrid power system consisting of solar panels and Radioisotope Heat Unit (RHU) to keep internal electronics warm. While its look reminded NASA's designs (Fig. 3(c)), one of its innovative instruments was a ground-penetrating radar (GPR), the first instrument of its type to fly to the Moon (channels at 60–500 MHz; resolution of 1–0.3 m; depth of 100–30 m). As the main scientific result, this tool allowed to discover a new type of basaltic rock different than the samples returned by Apollo and the Soviet-era Luna programs, thus giving a deep look into the magma formation about the Moon's past [116].

The Yutu robot – for about $500 million – was designed to operate for three months in lunar soil and travel about 10 km on an area of 3 km^2 with slopes up to 30°. Given the difficulty of remotely driving the rover, Yutu featured several panoramic and UV cameras used by a Delaunay algorithm to analyze onboard stereo imagery in real-time. This way, the robot was capable of autonomously navigating around, recognizing obstacles and hazards automatically avoided, identifying driving targets and locations, determining its own attitude and relative position through sensors and imagery, and then selecting the most optimized routes for exploration activities. Its main mission ended after month and a half of operation due to a mechanical failure during its second period of hibernation [117]. However it was partially reanimated after a month and, despite being unable to move, it collected scientific data, communicated signals and recorded video images until mid-2016 (maybe due to cold temperatures of about minus 180 °C during a two-week lunar night). Thus, Yutu broke the record for eleven months of permanence on the Moon's surface owned by the Soviet Lunokhod-1 robot. Although both landing and surface operations were controlled from two Chinese stations (Kashi and Jiamusi), its launch was covered with the support of the ESA space tracking network (ESTRACK) – such as in Kourou, French Guiana or Cebreros, Spain – by radio signals that take a bit more than a second to travel the distance between the Earth and the Moon. Afterwards, the operations were broadcasted live via Sina Weibo, a Chinese social network whose Yutu's account had nearly 600,000 followers. As the main achievement, scientists have publicly released all processed data from Yutu, whose mission has returned 7 terabytes of data.

2.5. *Next generation of planetary rovers*

In 2007 was announced The Google Lunar X PRIZE® (GLXP), an international competition organized by the X Prize Foundation and sponsored by Google in order to successfully launch a low-cost robotic system that could land, travel for 500 m through the

Moon surface, and send high-definition images and videos back to the Earth. Planned by the end of 2017, only 5 teams out of 29 have currently passed to the final stage of the GLXP competition endowed with $30 million. Among those which have come to make remarkable progress is Moon Express, an US company that is implementing an unmanned mobile robot – designated *MX-1* – with hydrogen peroxide (H_2O_2) and solar energy that can navigate by itself on the lunar surface, make plant cultivation and exploitation of mineral resources thanks to its capacity of carrying up to 60 kg; Synergy Moon, an international collaboration that has designed two rovers – a spherical vehicle called *Tesla Surveyor* and a four-wheeled rover called *Tesla Prospector* – equipped with HD cameras for stereoscopic vision, a NVIDIA Tegra 3 processor based on the CUDA programming language for autonomous operation and remote control via the Web to bring the space to mankind through events and educational campaigns [118]; Team Indus, an Indian taskforce planning to place a 4WD rover controlled from Earth – in ∼4 s — codenamed ECA for *Ek Choti si Asha* (a small dream) with an all-aluminum chassis (i.e., no rubber) of around 10 kg and a fixed top solar panel powering a variety of scientific equipment including two cameras supported by the French Space Agency CNES and the winning experiment of the international Lab2Moon challenge; Hakuto or formerly White Label Space, an expert Japanese space science team that has developed a unique dual approach consisting of a four-wheeled rover – called *Moonraker* – and a two-wheeled rover – called *Tetris* – linked by a tether that would allow exploring volcanic geological formations to study the Moon's past and search for candidate sites for long-term habitats. These two vehicles of about 4 kg have been developed after many iterations of prototyping and testing with configurations from 2 to 6 wheels, solar panels and dimensions of about $48 \times 60 \times 54$ cm^3 (e.g., *CM-1*, *CM-2*, *PM-1*, *PM-2*, *PM-3*, *EM*, *PFM* and *Mini*). Among its main innovative technical developments and ideas are a hyperbolic mirror omnidirectional vision system to capture 360° images for SLAM and wheels made with thermal insulation material to prevent from harsh temperatures that could be conducted from the Moon surface to a strong and lightweight body molded with carbon fiber reinforced polymer.

Other notable teams participating in previous phases of the competition – only failing to secure a contract to launch their spacecraft – were Part-Time Scientists, a German team with collaboration of Deutsches Zentrum fur Luft- Und Raumfahrt (DLR) officially created to address the first private lunar mission with a rover – initially dubbed *Asimov Jr. R3* and later called *Audi Lunar Quattro* after the support of the automobile company – with 35 kg of weight, dimensions of $60 \times 40 \times 50$ cm^3, solar panel, Li-Ion battery, cameras capable of capturing 3D images, semi-autonomous navigation and four-wheel system at a maximum speed of 3.6 km/h; Barcelona Moon Team, a Spanish team with participation of the National Institute for Aerospace Technology (INTA) and the China Great Wall Industry Corporation (CGWIC) which is developing a vehicle for scientific and commercial exploration with four wheels, three-piece articulated body and solar panels (Fig. 3(d)); and Astrobotic Technology, a privately held company founded in 2008 by CMU which is building *Red Rover*, a vehicle of $1.4 \times 1.4 \times 1.7$ m^3 and drive speed of 10 cm/s suitable for equatorial destinations. The rover is equipped with solar panels fixed to a light and rigid vertical structure, two engines mounted on a chassis of ∼80 kg and tele-camera capable of capturing images and 3D video maps (Fig. 3(e)). This spinoff is also building the *Polaris* rover, a medium-sized robotic vehicle that has won several contracts with NASA for the Moon prospecting (Fig. 3(f)). Also, the consortium formed by the scientist team from CMU and Astrobotic Technology is working with SpaceX – a private company for the space exploration – to build a lunar telepresence robot. *Andy*, as the vehicle is known, has been designed to improve the remote control user's experience through a virtual reality headset based on Oculus Rift. The project, whose mission was originally scheduled by 2016, was also competing in GLXP [119].

On the other hand, ISRO plans to launch in 2017 its second lunar exploration mission for which is including this time a rover named *Chandrayaan-2* (Fig. 3(g)). This vehicle – designed by India with the Russian assistance – is aimed at finding water ice on the south pole of the Moon. The rover will be equipped with a solar power source and possibly nuclear power, laser and X-ray spectrometers, 3D camera view as well as kinematic and dynamic control for a six-wheeled traction [5]. Also, the first of the two ExoMars missions – a joint project between ESA and the Russian Federal Space Agency, Roscosmos – is scheduled to be launched in 2018 when a rover will explore the red planet (Fig. 3(h)). The vehicle – based on an earlier prototype called *IARES* [120] – will be significantly smaller than Curiosity but higher than Spirit and Opportunity. The software – developed by the French Centre National d'Etudes Spatiales (CNES) and the Space Research Group (SRG), University of Alcala de Henares, Spain – confers the vehicle a high autonomous capability. The rover – equipped with panoramic cameras and a tool capable to drill up to 2 m deep – will use the sunlight to generate the electrical power required to travel up to 100 m a day and a RTG unit which keep it warm during the night [121].

As a backup to Chang'e-3, China is also preparing the Chang'e-4 mission to land its second lunar lander and rover – on the far side of the Moon – by the end of 2018. The aim is to test equipment in advance of the future Chang'e-5 mission for which CNSA will first launch a communication satellite to relay the signals between the lander/rover and the earth station. This technology will serve as know-how to prepare the future Chinese mission to Mars by 2020. Its rover – with a weight about 200 kg – will carry four solar panels, six wheels and 13 scientific instruments including cameras, RADAR and a laser to study both the subsoil and its chemical composition during at least three months. These plans will be completed along with a sample return mission in 2030 [122].

Also, the Japan's aerospace agency (JAXA) is working on several exploration missions with the goal of landing two rovers on the Moon and Mars' surfaces. In 2018, a robotic spacecraft that will include an orbiter, a lander and a small-sized rover of about 100 kg – called SELenological and ENgineering Explorer (*SELENE-2)* – is expected to be launched for a mission lasting two weeks. The second rover, called *MELOS* (Mars Exploration of Life-Organism Search), is a robotic vehicle smaller than the MERs whose primary mission would last 68 days in which it would travel up to 50 km. For it, MELOS will be able to travel up to 500 m/sol, to face slopes up to 15°of inclination and will use a sky-crane precision descent system, color cameras, a visible and IR mapping spectrometer, a RADAR, a weather station and a life detection module (LDM) which includes a microscope to search for possible bio-signatures left by Martian microorganisms. Optionally, MELOS would include a methane detector, a sound recorder, an atmospheric dust sensor and a LIDAR [122]. Meanwhile, the South Korean space agency – known as KARI – would launch by 2025 a space probe including a small-sized rover of about 68 kg able to run up to 40 km over the Moon' surface. This vehicle, dubbed *Boreum*, would be powered – probably for heating – with 500 g of Strontium-90 for a mission lasting one month [123].

According to plans, the private Dutch television project called Mars One would send two rovers to Mars – after its first demonstrating mission – in 2018 and 2021, respectively. These rovers, with non-scientific purposes, are designed to fit up on board a multipurpose arm, transport vital modules and conduct the optimal location of settlements to house a future human colony by 2025. The rovers, whose initial design is based on a large but simple platform with four wheels and solar panels, will be able to make trips up to 80 km at a maximum speed of 10 km/h [124].

On the other hand, NASA is currently in the final stage of planning for the M2020 mission officially called Mars Sample Return (MSR). For it, NASA preselected 58 proposals from researchers and engineers from around the world, twice the usual number received in such calls. This represents an indicator of the extraordinary interest of the scientific community for exploring Mars. The expected rover will help to advance knowledge on how future human explorers could use the natural resources available on the red planet' surface. Thus, one of the most interesting instruments – called MOXIE – aims at producing oxygen from Martian atmospheric carbon dioxide [125]. The design of the rover – dubbed *Mobile MAV*, meaning Mars Ascent Vehicle – is based on the Curiosity robot but with more sophisticated hardware and instruments. The still conceptual design includes circular photovoltaic panels of 2.2 m in diameter and the successful rocker-bogie suspension with capability for journeys up to 10 km, to climb slopes up to 15^{o} and high obstacles as the diameter of a wheel (i.e., 50 cm). It will also be fitted with a weather station (MEDA), a three axes stereoscopic camera at 1.8 m above the ground (Mastcam-Z), radar to reach up to 500 m depth with a resolution between 5 and 20 cm (RIMFAX), and ultraviolet (SHERLOC), IR/visible (SuperCam) and X-ray fluorescence laser spectrometers. The chemical analysis will be performed using a 5 DOF robotic arm equipped with an abrasion tool with a total length of 2 m in size and 40 N of force. The communication system will be based on an UHF-band antenna with capacity between 2 Mbps and 64 kbps for transmission and reception, and two antennas in the X-band (i.e., a low gain one for emergency and other high gain antenna) with capacity between 438 and 1120 bps and 2 kbps for transmission and reception, respectively. One of the novelties of the mission is that the rover will carry built-in microphones to hear both the descent maneuver through the atmosphere of the red planet and the natural sounds of the Mars' surface [121].

Within the collaboration framework between ESA and NASA is also expected potential space missions to Mars. Thus, ESA would contribute a European rover capable of carrying 156 kg around 290 m per sol and collect samples to return them to the Earth. The project – called MarsFast – would be a pre-trial before the MSR mission, so that its viability would depend on the collaboration between the agencies and, in particular, the degree of development of the MSR mission. Also, between 2026 and 2028, the Precision Mars Lander (MPL) mission would have the task of sending a space probe to the red planet's surface to collect samples and return them to the Earth. Although little has become known to date, it is expected to achieve greater drop accuracy than 10 km, land and deploy a small rover of 100 kg able to travel more than 170 m per sol [126].

Finally, Roscosmos has launched the first preparedness plans to return to the Moon – after its last Luna-24 mission in 1976 – with the Lunokhod 3 and Lunokhod 4 rovers between 2020 and 2023 as stated by the head of the nuclear planetology office at the Institute of Space Studies of the Academy of Sciences, Igor Mitrofanov. The aim would be to determine a permanent landing station by 2024 with the idea of taking the first steps to form a future habited base [127].

2.6. Innovations and technological milestones

Tables 1 and 2 show the main features and capabilities of the rovers designed for outer-planet exploration. Some of these missions achieved considerable technological milestones over the last five decades that led to more powerful machines, whose methodology has been to increase exploration capabilities to meet their scientific objectives. As a rule, the number of scientific instruments is generally found proportional to the mass and dimensions of the rover whose higher requirements must be supported with higher CPUs and power resources. For instance, small-sized rovers (up to 50 kg) typically carry up to 2 scientific instruments, medium-sized rovers (between 50 and 100 kg) carry between 4 and 9 scientific instruments, and large-sized rovers (higher than 100 kg) vary between 6 and 9 scientific instruments for the early missions and 10–16 for the most modern missions.

Regarding the control of the scientific payload, the Apollo LRVs were the first vehicles to use a digital/analogical signal processing unit (SPU) – which was essentially a small solid-state computer made by Boeing Co. for guidance calculations – on the contrary to the remotely manned Lunokhod missions. Although many CPUs have been used thenceforth, engineers do not always use the latest and greatest microprocessors since they must be highly reliable and durable. In this sense, current designs with 32-bit CPUs are evolving in upcoming missions to 64-bit cores in line with progress as chips become tried and well known (e.g., NVIDIA Tegra in Tesla Surveyor, Tesla Prospector or Polaris). In addition, designs include redundancy and radiation hardened memory to tolerate extreme radiation from space as for the Curiosity rover.

CPUs – and electronics in general – can end up being damaged due to wide variations of temperature in space. As a solution, Lunokhod 1 introduced a RTG unit for the first time in a rover – since its invention in 1954 by K. Jordan and J. Birden and after the successful Transit 4A spacecraft in 1961 – to convert the heat from radioactive material into electricity. Similarly, the more light-weight RHUs were used to heat critical components on the first two generations of Mars rovers whose electrical power was supplemented by solar panels. These facilities have transitioned to higher end and more efficient designs – up to 25% more – as the MMRTG for the Curiosity and Mobile MAV rovers, which even still generates less power than the Lunokhod's entire solar panel dish. However, the disadvantages of generating nuclear power is challenging governments and companies to develop new materials and technologies only sustained by heaters as in the Polaris, Chandrayaan-2 or MELOS rovers [128].

Increasing the heater power also leads to increasing the mass of batteries, thus breaking the balance in the cost per kilogram of space journeys. The battery capacities have changed over time – since the first non-rechargeable batteries in the Apollo LRVs – as did the power consumption, albeit the discrepancy has only gone higher rather than lower. In this area, lithium-based technology has contributed significantly to the success of robotic exploration vehicles since the Sojourner mission, so the methodology is being focused on integrating fast recharging batteries – as the promising Li-S cells, Li-air cells with oxygen-based oxidizer or the graphene-based supercapacitors – aimed at increasing the power density ratio (Wh/kg) while maintaining the safety characteristics. Meanwhile, current approaches have their major challenge in extending exceptionally the battery life beyond 1000 cycles for more than 10 years, whose amount of energy storage is being almost doubled every $\sim$5 years [129]. In the other hand, photovoltaic systems have been used as sole or complementary power sources in the $\sim$70% of the rovers. Low temperatures and low irradiance suppose the main challenges for outer-planet missions, which milestone has been to go from 11% of efficiency for rigid polycrystalline silicon cells (e.g., Lunokhod 1) to 29% for flexible multi-junction solar cells in the upcoming rovers. In this sense, current technology from industry projects to reach 33% to 36% of efficiency with qualification by 2017 [130].

Attending to the mechanical standpoint, the wheel-on-leg system was designed as a means of lifting each wheel independently off the ground to provide greater stability by lowering the center of mass (e.g., ATHLETE, Tri-ATHLETE, GoFor, CESAR or SherpaTT). However, it requires higher complexity due to the large number of actuators needed by a multi-legged rover, thus presenting greater potential for mission failure. In this sense, Sojourner introduced the rocker-bogie suspension that is currently being used

Table 1
Comparison of basic features and capabilities for various rovers designed for planetary exploration.

Name	Institution	Size (m^3)	Weight (kg)	Wheels	System	Speed (cm/s)	Distance (km)	Year
Lunokhod 1	NPO Lavochkin	1.6 × 2.22 × 1.35	756	8	Differential	55	10.5	1970
Apollo XV	NASA	3.1 × 2.3 × 1.1	210	4	Ackerman	330	27.8	1971
Apollo XVI/XVII	NASA	3.1 × 2.3 × 1.1	210	4	Ackerman	330	27.1/35.74	1972
Lunokhod 2	NPO Lavochkin	1.7 × 2.15 × 1.35	840	8	Differential	55	37	1973
Sojourner	JPL (NASA)	0.65 × 0.48 × 0.3	11	6	RB	1	0.1	1997
Spirit/Opportunity	JPL (NASA)	2.3 × 1.6 × 1.5	174	6	RB	1	7.7/43.44[a]	2004
Curiosity	JPL (NASA)	2.9 × 2.7 × 2.2	900	6	RB	5	14.4[a]	2012
Yutu	CNSA	1.5 × 1.0 × 1.1	136	6	RB	5.5	0.1 out of 10	2013
Polaris	Astrobotic Technology/NASA	1.67 × 2.13 × 2.43	150	4	Differential	30	0.5 projected	2015
Chandrayaan-2	ISRO/Roscosmos	0.6 × 0.5 × 0.4	20	6	RB	10	150 projected	2017
ExoMars	ESA/Roscosmos	1.2 × 1.1 × 2.0	219	6	3B	1	–	2018
Mobile MAV	NASA	2.7 × 3.0 × 2.2	1050	6	RB	TBD	–	2020
MELOS	JAXA	1.2 × 1.0 × 0.5	150	6	3B	0.75	50	2020

RB = Rocker-Bogie; 3B = Three-Bogie; TBD = To be determined.
[a] = Ongoing

Table 2
Comparison of advanced features and capabilities for various rovers designed for planetary exploration.

Name	Tools	CPU	Radioisotope	Heat	Power/Solar Panel	Battery System
Lunokhod 1	6	Remotely controlled	RTG (^{210}Po)	1 × 1020 W_{th}	20 W_e+1× Si cells (4 m^2, 11%, 180 W_e)	AgCd (250 Wh)
Apollo XV	1/7[a]	SPU	RTG (^{238}PuO)	1 × 1480 W_{th}	73 W_e/None	2× non-recharg. Ag-Zn/KOH (4356 Wh)
Apollo XVI/XVII	1/7[a]	SPU	RTG (^{238}PuO)	1 × 1480 W_{th}	73 W_e/None	2× non-recharg. Ag-Zn/KOH (4356 Wh)
Lunokhod 2	9	Remotely controlled	RTG (^{210}Po)	1 × 1020 W_{th}	20 W_e+1× GaAs cells (4 m^2, 18%, 180 W_e)	AgCd (250 Wh)
Sojourner	2	Intel80C85 (2 MHz, 512 KB RAM, 176 KB Flash)	RHU (^{238}Pu)	3 × 1 W_{th}	1 × 18 GaAs/Ge cells (0.22 m^2, 18.2%, 15.3 W_e)	3× $LiSoC_{12}$ (12.4 kg/u, 150 Wh)
Spirit/ Opportunity	5	BAE Systems Inc. RAD6000 (20 MHz, 128 MB RAM, 256 MB Flash, 3 MB EEPROM)	RHU (^{238}Pu)	8 × 1 W_{th}	GaInP/GaAs/Ge cells (1.2 m^2, 23.8%, 100 W_e)	2× Carbon-$LiNiCoO_2$ (7.15 Kg/u, 600 Wh)
Curiosity	10	BAE Systems Inc. RAD750 (132 MHz, 256 MB RAM, 2 GB Flash, 256 MB EEPROM)	MMRTG ($^{238}PuO_2$)	1 × 2000 W_{th}	125 W_e/None	2× Carbon-$LiNiCoO_2$ (8.30 kg/u, 1200 Wh)
Yutu	4	n/a	RHU (^{238}Pu)	1 × 4 W_{th}	2 × 0.8 − 1 m^2	1× Li-Ion
Polaris	TBD	NVIDIATegra K1 (2.3–2.5 GHz, 8 GB DDR)	None	TMU	3× vertical panels (250 W_e)	$LiFePO_4$(1000 Wh)
Chandrayaan-2	2	TBD	TBD	2 TMUs ×8 W_{th}	1× double-sided panel (0.28 m^2)	1× Li-Ion
ExoMars	9	2× LEON processors & 1× FPGA co-processor	RHU (^{238}Pu)	2 × 8.5 W_{th}	5× GaAs cells (1.45 m^2, 19%, 120 W_e)	2× Li-Ion (9.25 kg/u, 1250 Wh)
Mobile MAV	16	SPARC V8 & Xilinx 5QV FPGA	MMRTG ($^{238}PuO_2$)	1 × 2000 W_{th}	125 W_e/2× circular panels (3.8 m^2)	2× Li-Ion (1257 Wh)
MELOS	5–9	TBD	None	TMU	2× inflatable paddles +1× fixed (1.5 m^2)	Li-Ion (720 Wh)

SPU = Signal Processing Unit; TMU = Thermal Management Unit.
[a] =Scientific instruments at the Apollo landing site.

after 20 years as the rovers' favored design. As advantage, the rocker-bogie allows to climb over obstacles that are up to twice the wheel's diameter in size while keeping all six wheels on the ground. However, this structure is limited to be used at slow speed and shallow-sloped terrains unlike other locomotion systems. This configuration has currently evolved for ExoMars and MELOS into a three-bogie suspension to remove the need for implement a differential linkage either internally or externally [21].

Meanwhile, the strategy for rovers' landers is aimed at significantly reducing the landing ellipse – the margin of error around the targeted landing location – by improving the systems' ability with surface terrain recognition as the novel camera-based navigation system built by Masten Space Systems in Mojave, California for M2020. In this sense, Pathfinder/Sojourner introduced for the first time in Mars a set of airbags – to supplement rockets – combined with a parachute to reduce the supersonic speeds achieved during landing. On the contrary, the strategy for greater weight and sized rovers – as Curiosity – required to introduce innovative descent techniques as the one based on the sky-crane structure. Due to the success of this system – which eliminates the undercarriage and airbags thus reducing weight – it will be used with almost no mechanical changes on the M2020 mission and possibly in MELOS. However, planetary rovers have been mostly designed to operate on relatively flat and low-sloped regions (i.e., not for caves, deep craters, canyons, mountains, etc.). So extreme terrains stand for a unique set of challenges and requirements for a robotic vehicle whose conventional designs must be re-evaluated (e.g., considering aerial approaches such as balloons, zeppelins, drones or UAVs) in order to face future high-risk terrain missions [131].

3. Analysis on the profile of robotic vehicles

A complete accounting and systematic comparison of all the robotic vehicles is clearly impossible within the confines of a paper, not only by the number of available publications – 51,660 records between 1959 and 2016 were found in Elsevier Scopus® with the keyword *mobile robot* – but also by the scope of robotics as a discipline. For this reason, a representative study including the robotic vehicles mentioned in this paper has been conducted, which comprises a collection of 100 mobile robots. They have been classified

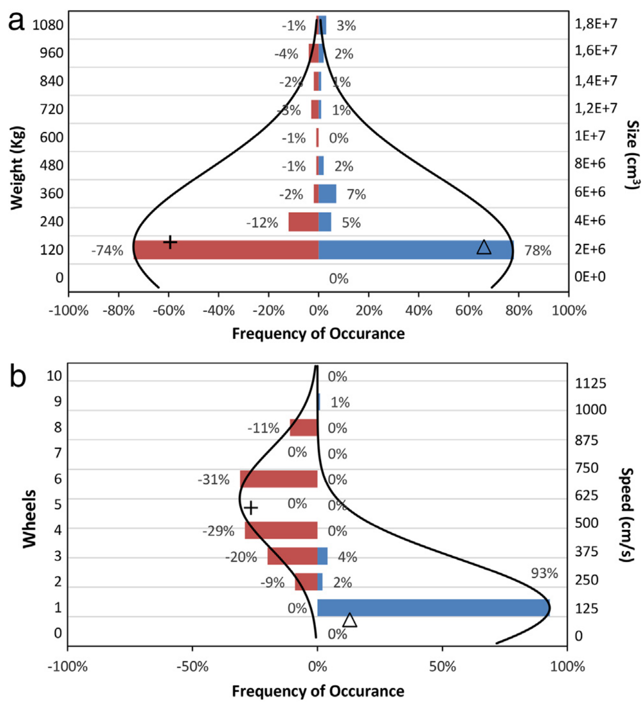

Fig. 4. Analysis on the features and capabilities for a sample of 100 mobile robots: (a) weight and size, and (b) number of wheels and speed.

through histograms considering aspects such as the weight, size, number of wheels, and speed of movement (Fig. 4(a)–(b)). A Spearman rank analysis tested a correlation between weight, size and wheels. The t-statistic values were $p \ll 0.01$ and $\rho = 0.848$, $p \ll 0.01$ and $\rho = 0.339$, $p = 0.004$ and $\rho = 0.280$ for weight *vs* size, weight *vs* wheels and wheels *vs* size, respectively. This means that the relationship between the measurement variables of the mobile robots – as expected when following a design methodology – is significant. However, no strong association was found between speed and weight, size or number of wheels ($0.01 < p \leq 0.05$), which suggests that the robots' speed may depend on further factors (e.g., type of terrain, mission goal or power requirements).

Specifically attending to the weight (Fig. 4(a)), the histogram shows a distribution with 74% of the mobile robots weighting between 0 and 120 kg (average value is 140.33 ±123.87 kg), which suggests that most of the robots were middle class vehicles. The analysis found that Mobile MAV (1050 kg) was the heaviest of them followed by Curiosity (900 kg) and Hercules (870 kg), whilst mOway (50 g) was the lighter followed by Khepera (80 g) and ePuck (200 g). Considering the size (Fig. 4(a)), the histogram indicates that 78% of the robots are low-sized vehicles between 0 and 2×10^6 cm^3 (average value is $2.11 \times 10^6 \pm 2.23 \times 10^6$ cm^3). The analysis similarly found that the Big Wheels Inflatable Rover ($300 \times 350 \times 200$ cm^3) was the largest of them followed by Mobile MAV ($270 \times 300 \times 220$ cm^3) and Curiosity ($290 \times 270 \times 220$ cm^3), while Khepera ($5.5 \times 5.5 \times 3$ cm^3) was the smaller robot followed by ePuck ($7 \times 7 \times 5$ cm^3) and mOway ($10 \times 5 \times 5$ cm^3).

Attending to the number of wheels (Fig. 4(b)), the histogram determined that 31% of the mobile robots consists of six-wheeled structures. This is closely followed by four-wheeled (29%), three-wheeled (20%), eight or tracked-wheeled vehicles (11%), and two-wheeled vehicles (9%). Considering the robot's mobility, the analysis encountered the following taxonomy: two wheel differential system (19%), tricycle system (7%), four wheel skid system (25%), front/rear wheel steering system (7%), four wheel steering system (23%), six wheel steering system (6%), and other special (13%) as the rail system of Fred & James, the sliding system of PROP-M, the circulating wheels of SpaceCat, the omni-wheels of Robotino®, the wheel-on-leg of ATHLETE and Tri-ATHLETE, the four track steering system of Light Crawler, or the articulated systems of Ш-1, Marsokhod, Zöe and Hyperion. As for the mechanical system, 76% of the robots have a basic suspension system, whilst 19% of them implement the successful rocker-bogie system and 5% present other models like the Micro5's Pegasus system, the SOLERO's shrimp system or the three-bogie system of ExoMars and MELOS.

Considering the speed (Fig. 4(b)), the histogram found that 93% of the vehicles operate at low velocity between 0 and 125 cm/s (average value is 50.88 ±61.82cm/s). The results reveal that PROP-M and Nanokhod are the slowest mobile robots (0.14 cm/s) followed by Herbert and Pluto CMU Rover (0.2 cm/s), and SpaceCat (0.22 cm/s). On the contrary, Mörri was the fastest mobile robot (1110 m/s) followed by the Apollo XV to XVII vehicles (330 cm/s), and ATHLETE, Tri-ATHELETE and Hercules (280 cm/s).

4. Study on the evolution of robotic exploration vehicles

A comprehensive and systematic bibliometric analysis has been conducted considering the online abstract and indexing service provided by Scopus® through Elsevier. The reason for its choice – versus others as the IEEE Xplore® digital library, Google Scholar or DBLP – is that Scopus® is the largest scientific database that provides with all of the content and bibliographic information also commonly included in the other recording services. To make this task manageable, a number of restrictions has been used to limit the search spectrum to a representative subset. The contributions published in conferences, journals, reviews, notes, books, letters, business articles, and reports between 1963 and 2015 were analyzed, for which several keywords were used to filter the following categories: *rovers* (8120 publications), *humanoid robots* (8881 publications), *aerial robots* (25,907 publications), *underwater robots* (3767 publications), and *robotic arms* (21,056 publications).

4.1. Analysis on scientific databases

The survey shows that despite the long history of research on robotic exploration vehicles – first record dated in 1963 [132] – there are other disciplines in robotics that have irrupted with great force (Fig. 5). The results suggest that the interest of the scientific community has changed or has been mainly attracted to other research fields that have recently evolved faster such as aerial robotics (first record in 1957), robotic manipulators (first record in 1967) or humanoid robots (first record in 1980). Specifically, in the field of rovers, the constant appearance of publications in conferences is equally followed by a growing activity on scientific journals but no so strong in books (Fig. 6). The results reveal that a maturation period after ∼35 years of the space exploration career resulted in a burst of publications, first with Sojourner and more significantly afterwards with the MER mission.

The analysis on the publications per territory shows a significant activity in the Americas led by the US and Canada with 46.29% and 5.52% of the total publications, respectively (Fig. 7). The main activity shown between 1995 and 2013 indicates that this research field has been strongly influenced as a result of the different periods of preparation, development and/or operation carried out by NASA for the Sojourner, MER and Curiosity missions. The analysis shows that such activity has been also reflected in the research conducted by Europe and Asia, which has been mainly led by China (10.15%), the UK (6.35%), Germany (5.41%), France (4.47%), Japan (4.20%), and Italy (3.72%). Specifically considering Asia, its maximum peak after 2013 coincides with the exploitation phase of the Yutu rover by China. From the analysis, a high scientific impact was found after the successful missions of Sojourner, MER

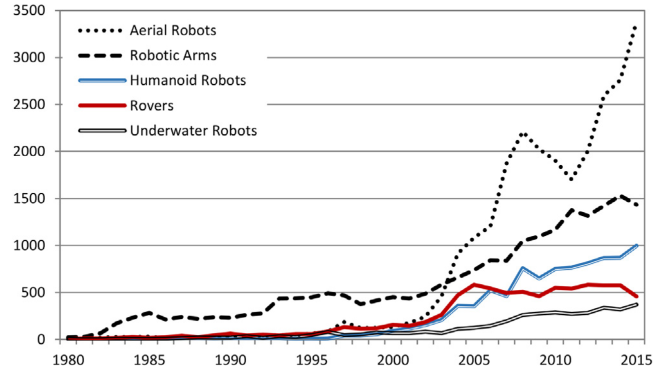

Fig. 5. Detail of the bibliographic evolution in different fields of robotics.

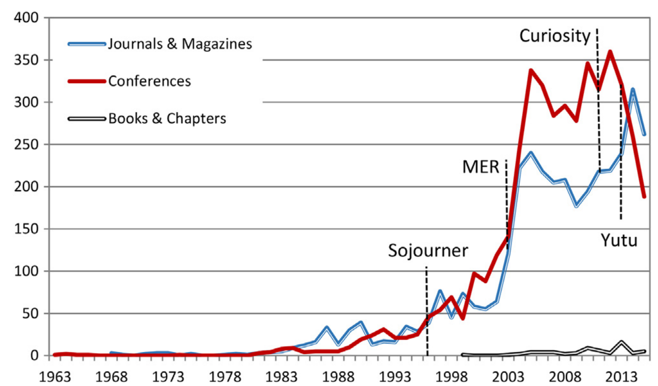

Fig. 6. Evolution of the contributions on robotic exploration vehicles per communication media.

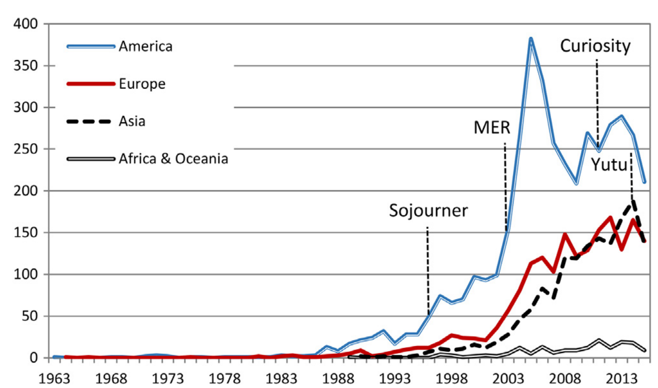

Fig. 7. Evolution of the contributions on robotic exploration vehicles per territory.

and Curiosity *vs* the low scientific return achieved after the less successful Yutu mission. Moreover, a lower activity after the Curiosity mission compared with the MER mission was found, which suggests a less scientific performance considering the cost of \$2.5 billion *vs* \$820 million of its rovers, respectively. In addition, the results show that the contributions have decreased in general after the period 2013–2015, suggesting that the activity of the scientific community has been reduced at the expectation of future space exploration missions.

A study of the publications about the design and implementation of rovers per affiliation shows the leadership of NASA over other entities (27% of the total), for which JPL, the Ames Research Center, and the Johnson Space Center have mainly supported the

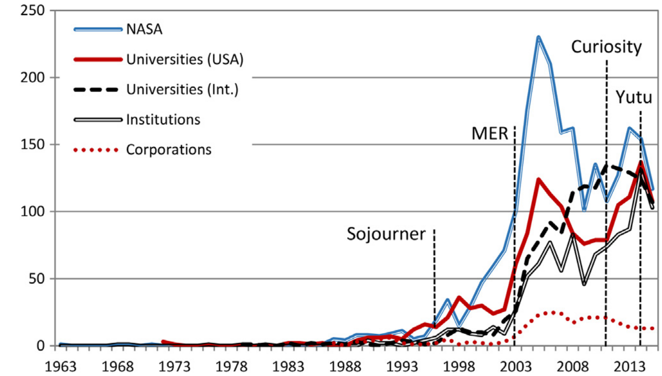

Fig. 8. Evolution of the contributions on robotic exploration vehicles per organization.

scientific research in USA with 53.37%, 17.51% and 11.64%, respectively (Fig. 8). It is observed that the trend of the NASA's activity has been also followed by the scientific research conducted in US universities (18.28% of the total). In particular, no significant differences were found between their trends (for Student's *t*-test, $p \gg 0.05$), which suggests a strong collaboration between NASA and the US universities. This has been mainly carried out in USA by the Cornell University, Arizona State University and CMU with 12.43%, 12.36% and 12.30%, respectively. The results from the analysis show that the contribution of other international universities stand for the 17.13% of the total, whose ranking is led by Harbin Institute of Technology in China (12.84%), University of Toronto in Canada (5.29%), and Johannes Gutenberg Universitat Mainz in Germany (5.08%). Regarding the contributions made by governmental and non-profit institutions (12.54% of the total), they have been mainly led by United States Geological Survey (14.75%), DLR in Germany (10.7%), and Planetary Science Institute in USA (9.73%), respectively. Finally, the analysis found several publications with direct participation of industries since the year 1987 (3.28% of the total), which suggests an incipient collaboration through private funding especially in the period between the MER and Curiosity missions. The top three is led by Lockheed Martin (33.45%), Malin Space Science Systems (17.27%), and Honeybee Robotics Spacecraft Mechanisms Corp. (15.07%) in USA, among others.

5. Conclusions

The search for evidence of life on other planets, the understanding of the physical and atmospheric phenomena or the testing of systems to prepare for future missions have fascinated humans to undertake the career of space exploration. However, the lack of motivation and competitiveness after the fall of the Soviet Union, the reduction of the US funding because of the high cost of space missions and the low media impact due to a little scientific return have weighed down the missions for land exploration using robotic vehicles.

The paper conducted a representative study including a collection of 100 mobile robots over a period of time ranging from 1959 to 2016. It found that 78% of the robots are low-sized vehicles between 0 and 2×10^6 cm^3, 74% of the mobile robots weight between 0 and 120 kg, 93% of the vehicles operate at low speeds between 0 and 125 cm/s, 31% of the mobile robots consist of structures with six wheels, 25% are based on a four wheel skid system, and 76% of the robots have a basic suspension system. Although this analysis could be completed considering a wider spectrum, the typical profile obtained is intended to be a baseline design for current practices and future trends in mobile robotics. As a result, actions should be focused in meeting a balance between more powerful machines – to increase the scientific return – and the rover's constrains (i.e., size, computation, power source, locomotion, missions). In this sense, the innovative technical aspects and challenges found were: (i) CPU designs evolving to redundant and hardened 64-bit cores in consonance with progress; (ii) higher-end and more efficient MMRTGs which are being replaced by safer and cheaper solutions (e.g., smart materials or heater-based technology); (iii) fast recharging batteries with higher density ratio, life cycle and safety (e.g., Li-S, Li-air or graphene supercapacitors); (iv) more efficient photovoltaic systems based in multi-junction solar cells (33%–36% of efficiency); (v) more simple and efficient locomotion systems to reduce potential mission failures (e.g., three-bogie); (vi) more precise landing systems with improved abilities to reduce error on target areas (e.g., sky-crane with terrain visual recognition); and (vii) new approaches with the aim of exploring extreme terrains and carrying high-risk missions (e.g., balloons, zeppelins, drones or UAVs).

Finally, with idea of taking the pulse of the current state-of-the-art, a comprehensive analysis on the history and the scientific contributions published since 1963 to the present about robotic exploration vehicles has obtained the following conclusions: (i) research interest on robotic exploration overtaken by other disciplines with higher scientific return such as robotic manipulators, UAVs or humanoid robots; (ii) increase of scientific publications about mobile robots strongly influenced in the past thanks to the activity of the Sojourner, MER and Curiosity missions; (iii) research on robotic exploration primarily conducted by the US, Canada, China, the UK, Germany, France, Japan, and Italy; (iv) greater collaboration of non-profit organizations and industries with universities and governmental organizations to reduce costs and address purposes not only scientific but also commercial as space tourism or securing resources (e.g., Helium-3, Platinum and other rare earth elements from the Moon); and (v) introduction of social networks with the aim of providing marketable results and a positive image (e.g., Yutu on Sina Weibo, New Horizons, MERs and Curiosity on Twitter, and Synergy Moon as the first Moon based Internet web server).

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