Robotics and Autonomous Systems 94 (2017) 172–185

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

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

Tomás de J. Mateo Sanguino [1]

University of Huelva, Dep. Ingeniería Electrónica, Sistemas Informáticos y Automática, Ctra. Huelva-La Rábida S/N, 21819 Palos de la Frontera, Huelva, Spain

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.

ARTICLE INFO

Article history:
Received 29 September 2016
Received in revised form 4 April 2017
Accepted 28 April 2017
Available online 6 May 2017

Keywords:
Historical review
Mobile robotics
Planetary exploration
Rover
Space exploration
Updating

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

E-mail address: tomas.mateo@diesia.uhu.es.
[1] Fax: +34 959 217304.

http://dx.doi.org/10.1016/j.robot.2017.04.020
0921-8890/

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