Progress in Aerospace Sciences 97 (2018) 61–105

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

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

Evolution of space drones for planetary exploration: A review

M. Hassanalian, D. Rice, A. Abdelkefi *

Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM 88003, USA

ARTICLE INFO

Keywords:
Solar body
Space drones
Planetary exploration
Design
Challenges

ABSTRACT

In the past decade, there has been a tendency to design and fabricate drones which can perform planetary exploration. Generally, there are various ways to study space objects, such as the application of telescopes and satellites, launching robots and rovers, and sending astronauts to the targeted solar bodies. However, due to the advantages of drones compared to other approaches in planetary exploration, ample research has been carried out by different space agencies in the world, including NASA to apply drones in other solar bodies. In this review paper, several studies which have been performed on space drones for planetary exploration are consolidated and discussed. Design and fabrication challenges of space drones, existing methods for their flight tests, different methods for deployment and planet entry, and various navigation and control approaches are reviewed and discussed elaborately. Limitations of applying space drones, proposed solutions for future space drones, and recommendations are also presented and discussed.

1. Introduction

From the last century, space agencies in the world have increased their presence in space. During this period, lots of planetary bodies have been discovered [1,2]. Exploration and discovery is defined as observation, visitation, and increased knowledge of the cosmic neighborhood [3]. Our solar system, including the sun and everything that orbits it (planets, asteroids, moons, comets, and meteoroids), has attracted more attention from various space agencies compared to other cosmological systems [4]. The solar system starts from the sun, and is orbited by the four inner planets: Mercury, Earth, Venus, Mars and also the four gas giants including Jupiter and Saturn. The inner planets were found with the unaided eye in ancient times, and then with the invention of the telescope added the far giant planets, such as Uranus, Neptune, Pluto, and many of the moons. There are 66 moons in our solar body system, where one of them has atmosphere, 16 of them have water, ice or ocean, and 5 with both atmosphere and water or ice [5].

In order to expand planetary exploration, there are spectrums of approaches which are being developed. Generally, these approaches are classified into seven groups including earth-based observations, airborne and orbital telescopes, probes and fly-by spacecraft, orbiters, Landers, rovers, and sample return [6]. In Fig. 1, a view of the discussed approaches and methods for planetary exploration is shown.

In Earth-based observations, usually telescopes, radar astronomy, and radio astronomy are applied for exploration [6,7]. In airborne and orbital telescopes, the telescope can be carried by an aircraft or can be launched into space, such as the Hubble space telescope [6,8,9]. Spacecraft application can be considered as one of the approaches that can be used for planetary exploration. For instance, Luna 3 was applied to view the far side of the Moon [10], and Rangers VI and IX spacecraft were used to take close-up photographs of the lunar surface [11]. Mariner 4 was launched to Mars to take the first close-up observation of the planet [12]. Pioneer and Voyager spacecraft were the first probes designed to study the gas giants, such as Jupiter, Saturn, Neptune, and Uranus [13]. Space exploration by orbiters is considered as one of the most efficient methods with more benefits as compared to others. With applying this method, the entire surface of a planet can be observed and the orbiting spacecraft may make repeated observations of the same area, therefore, they can record any changes that may have taken place on the planet [6]. Mariner 9 and the Viking 1 and 2 orbiters were launched into the orbit of Mars, and the Galileo orbiter was used to study Jupiter and its moons [14,15]. Even though a lot of information can be found about the surface of a studied planet from an orbiting spacecraft, detailed observations should be made on the surface [6]. Sending Landers to the planet and targeted solar bodies could provide more information about the planet. The Surveyors Landers were used to study the mechanical, electrical, and thermal properties of the lunar surface [16]. Two Viking spacecraft's and the Mars Pathfinder landed on the surface of Mars in order to perform several analyses such as for the detection of life, meteorological, chemical analysis, and seismography [17]. Landers can provide detailed

* Corresponding author.
E-mail address: abdu@nmsu.edu (A. Abdelkefi).

https://doi.org/10.1016/j.paerosci.2018.01.003
Received 12 October 2017; Received in revised form 29 January 2018; Accepted 30 January 2018
Available online 9 February 2018

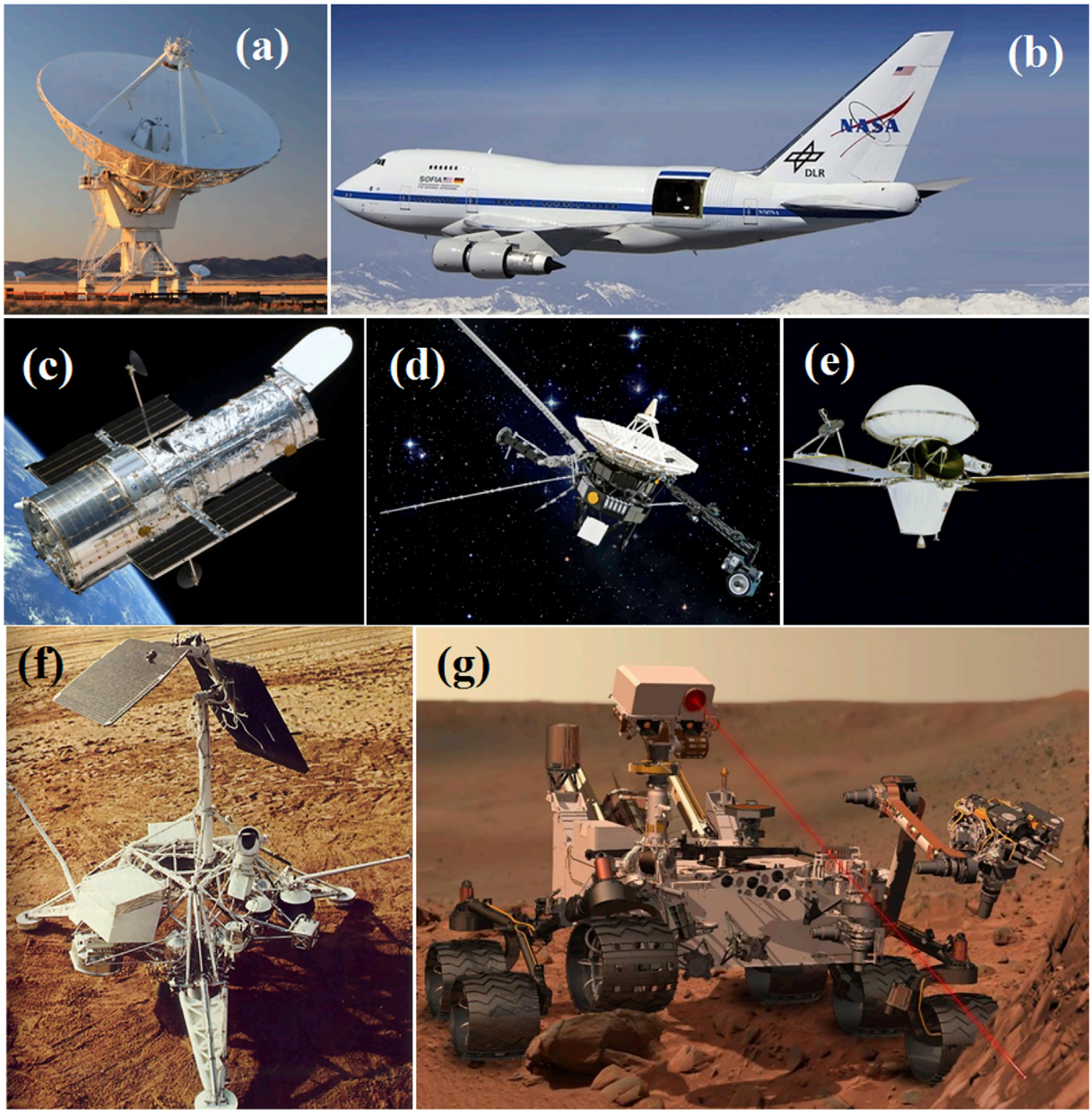

Fig. 1. View of various approaches for planetary exploration, (a) radio astronomy, (b) telescope on airplane, (c) Hubble space telescope, (d) Voyager 2 spacecraft, (e) Viking 1 orbiter, (f) Surveyor Lander, and (g) Curiosity [6].

observations of a planet's surface, but generally these observations are restricted to a small area [6]. To cover a wider area of the planet, spacecrafts can carry some robots which are able to move over the surface and collect information [18]. Lunokhod and Apollo 15 were two rovers which were used in lunar surface and Curiosity was the robot which has been used recently to study the Martian surface [19,20]. The last common way to study the rocks and soils of planets is sample return. In this way, the samples are taken by astronauts or robots and brought back to Earth for analysis [6].

There are some advantages and disadvantages for all of the applied methods for planetary exploration, but as discussed above, the ability for surface mobility should be maximized in order to enhance the cost effectiveness and efficiency of the planetary explorations and missions [21]. Recently, in order to explore in a cost efficient manner, new types of planetary exploration vehicles, such as aerobots and hydrobots are defined and designed to explore atmospheres, oceans, and surfaces of the targeted planets [22]. Aerobots include robotic atmospheric vehicles, such as drones, lighter-than-atmosphere vehicles, and suborbital ballistic hoppers which are applied for exploration of planetary atmospheres. Hydrobots include gravity-melt lander vehicles, submersible hydrodynamic robotic vehicles, and submersible probes which are applied for planetary ocean explorations [22]. These two robotic systems can be powered by different ways, including fuel cells, batteries, radioisotope thermoelectric generators, solar photovoltaics, nuclear reactors, and chemical combustion engines [22].

Progress in recent technologies has enabled space drones to be considered as valuable platforms for planetary exploration [23]. Thus, drones and especially Unmanned Aerial Vehicles (UAVs) have had extremely high progress to be applied for planetary science missions [24]. Usually drones have greater ranges for exploration than other surface platform explorers, such as rovers. Also, these flying vehicles due to their proximity to the planet's surface could provide more high resolution information compared to the orbiters [25]. These drones are able to correct atmospheric entry errors, and they can provide a fundamental