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Introduction

Yang Gao, Elie Allouis, Peter Iles, Gerhard Paar, and José de Gea Fernández

Planetary robotics is an emerging multidisciplinary field that builds on knowledge of astronautics, terrestrial robotics, computer science, and engineering. This book offers a comprehensive introduction to major research and development efforts for planetary robotics, with a particular focus on autonomous space systems, which will enable cost-effective, high-performing, planetary missions. Topics covered in this book include techniques and technologies enabling planetary robotic vision processing, surface navigation, manipulation, mission operations, and autonomy. Each topic or technological area is explained in a dedicated chapter using a typical space system design approach whereby design considerations and requirements are first discussed and followed by descriptions of relevant techniques and principles. Most chapters contain design examples or use cases that help demonstrate how techniques or theoretical principles can be implemented in real missions. Since any space engineering design or development is a system engineering process, this book also dedicates one chapter to planetary robotic system design – from mission concepts to baseline designs. As a result, this book can be used as a text or reference book for relevant engineering or science courses at the undergraduate and postgraduate level, or a handbook for industrial professionals in the space sector.

This chapter introduces the book by offering a chronicle on how planetary exploration and robotics have evolved to date, a systematic overview of planetary robotics, as well as an explanation on the organization and scope of the book.

1.1
Evolution of Extraterrestrial Exploration and Robotics

The need for humans to explore beyond the realm of Earth is driven by our inherent curiosity. Throughout our history, new worlds have been discovered by daring explorers who set out to discover new lands, find riches, or better understand these little-known territories. These journeys were fueled by the technological advances of the times such as the compass, maritime maps, or plane, and in return contributed tremendously to the scientific knowledge of humankind. For all

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the good provided by these exploratory endeavors, history also reveals that *exploration* is difficult, perilous, and can be fraught with unforeseeable consequences. For examples, within early maritime exploration, only a fraction of all the ships that aimed for the new worlds eventually achieved their goals. There have also been countless instances where the discovery of the new lands was detrimental to the indigenous populations. The past and lessons learned serve as a stark reminder to all new exploration endeavors.

Outer space has provided real, new exploration frontiers for mankind since the 1950s. With the capability and the irresistible attraction to go beyond our planet Earth, minimizing the impact of mankind on other extraterrestrial bodies (be it a planet, a moon, a comet, or an asteroid) is paramount. Strong with the hindsight and knowledge provided by humans' own history, we are continuously learning about these new space frontiers and taking precautions to avoid repeating mistakes learned from the past exploration activities.

The onset of space exploration in the late 1950s to early 1960s focused on sending humans into space and the Moon, a key priority for the two main adversaries of the Cold War. However, it was true then as it is now, in parallel to the expensive development of manned space programs, the use of cheaper robotic proxies was deemed important for understanding the space environment where the astronauts will be operating. The USSR had the first set of robotics missions, successfully launching a series of Luna probes starting from 1959. Within a year, the Luna 1 managed a flyby of the Moon, Luna 2 crash landed on the Moon, and Luna 3 took pictures of the Moon's far side. It took another 7 years before both the USSR and the United States, within a few months from each other, performed soft landing on the Moon with their respective probes, Luna 9 and Surveyor 1. These missions paved the way for the first human landing on the Moon in 1969 by the United States. Building on these earlier successes, robotic exploration missions have extended their reach to Mercury, Venus, Mars (known as the *inner solar system*), and subsequently the *outer solar system* where tantalizing glimpses of the volcanic Io, the frozen Europa, or the methane rains of Titan have been obtained.

Planetary missions can use various ways to explore an extraterrestrial body, often starting with reconnaissance or remote sensing using orbiting satellites. More advanced approaches (such as landing, surface operation, and sample return) enabled by sophisticated robotic systems represent a giant leap in terms of mission complexity and risk, but more importantly scientific return. Not surprisingly, advanced extraterrestrial exploration is littered with unsuccessful missions bearing witness to serious technical challenges of such endeavors. Table 1.1 presents statistics of successful surface missions aimed for the solar system (excluding manned missions). The relatively low success rate is a clear reflection on the technical difficulties involved in designing, building, and operating the required robotic spacecraft. It is worth noting that space engineers and scientists have created the landscape of what we know today. With sheer determination, they continue to address countless challenges, failing often, but regrouping until they succeed.

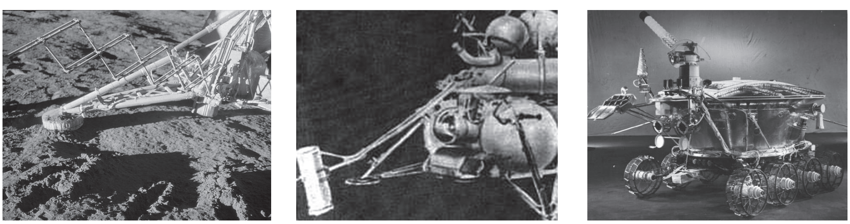
Within the existing successful unmanned missions, various types of robotic systems have played significant roles, including **robotic platforms** (such as the

Table 1.1 Statistics on planetary unmanned landing missions as of 2015.

	Venus	Moon	Mars	Titan	Asteroids/comets
Total landing missions launched	19	35	16	1	6
Successful surface operation	9	13	9	1	1
Successful sample return	0	3	0	0	1

Table 1.2 Successfully flown robots on Mars, the Moon, and small bodies as of 2015.

Mission	Country	Target	Rover	Arm	Sampler	Drill
Surveyor 3	United States	Moon			×	
Luna 16/20/24	USSR	Moon		×	×	×
Luna 17/21	USSR	Moon	×			
Viking	United States	Mars		×	×	
Mars Path Finder	United States	Mars	×			
Hayabusa (or Muses-C)	Japan	Asteroid			×	
Mars Exploration Rovers	United States	Mars	×	×	×	
Phoenix	United States	Mars		×	×	
Mars Science Laboratory	United States	Mars	×	×	×	
Chang'E 3	China	Moon	×			
Rosetta	Europe	Comet		×	×	×



(a) (b) (c)

Figure 1.1 First successfully flown planetary robotic systems. (a) Surveyor 3 scoop, (b) Luna 16 arm-mounted drill, (c) Luna 17 rover (Lunokhod 1). (Credits NASA, Lavochkin Association).

surface rovers) or **robotic payloads** (such as the manipulators or robotic arms, subsurface samplers, and drills). Table 1.2 summarizes those successfully flown robots found on the Moon, Mars, and small bodies. The first genuine robotic payload successfully operated on an extraterrestrial body was a scoop (i.e., a manipulation cum sampling device) onboard the Surveyor 3 lander launched in 1967 to the Moon (as shown in Figure 1.1a). Following that, Luna 16 succeeded with the first planetary robotic arm-mounted drill in 1970 (as shown in Figure 1.1b), and Luna 17 succeeded with the first planetary rover called Lunokhod 1 in 1970 (as shown in Figure 1.1c).

There is no denying that these “firsts” led to incredible mission successes and science discoveries as a result of unabated and relentless launch attempts during the *space race* between the superpowers. Building on these foundations, the new generation of planetary exploration has since the 1990s not only traveled further into the solar system but also studied deeper fundamental scientific questions. The desire to go and explore is as strong as ever. Past space powers have been gradually joined by a flurry of new nations eager to test and demonstrate their technologies and contribute to an increasing body of knowledge. Commercial endeavors also have eyes on space and actively promote the Moon and Mars as possible destinations for long-term human presence or habitation. Shall the future exploration missions be manned or unmanned, planetary robots are always desired to deliver the robotic “avatars” and perform *in situ* tasks to proxy or assist through their “eyes,” “ears,” and “hands.”

1.2
Planetary Robotics Overview

A typical robot on Earth is an unmanned electromechanical machine controlled by a set of automatic or semi-autonomous functions. Industrial standard robots are typically used to address the “3D” activities: Dirty, Dull, and Dangerous. This notion was created in reference to the Japanese concept of “3K” (kitanai, kiken, and kitsui) describing the major areas where the robots should be used to effectively relieve human workers from working environments such as with the construction industry. Therefore, robotic systems are envisaged to work on repetitive, long-duration or high-precision operations in the environment where humans are expected to perform poorly or where it is impractical for human presence.

Robotics, as an engineering or scientific subject, emerges from a number of traditional disciplines such as electronics, mechanics, control, and software, as illustrated in Figure 1.2. Designing a robotic system, therefore, involves the design of hardware subsystems (e.g., sensors, electronics, mechanisms, and materials) and software subsystems (such as perception, control, and autonomy). A planetary robotic system is functionally similar to a terrestrial robotic system, with different performance characteristics to cope with things such as stringent space mission requirements (often in aspects such as radiation hardness to survive the space environment), scarce power and computational resources, and high autonomy demanded due to communication latency.

A robotic system is not required to possess a fixed level of automation or autonomy. In fact, it can employ a wide range of control modes from remote or teleoperation, semi-autonomous to fully autonomous operation as appropriate to its mission goal, location, and operational constraints. Fundamental differences between the *automatic* and the *autonomous* control mode relates to the level of judgment or self-direction in the action performed. An autonomic response or control is associated to a reflex, an involuntary behavior that is “hard-wired” into the robot with no decision making involved. An autonomous behavior on the

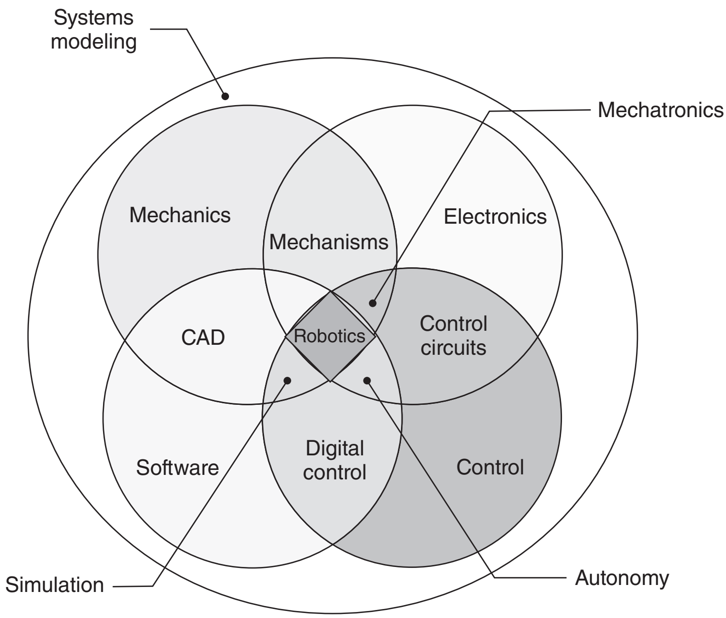


Figure 1.2 Robotics: a multidisciplinary subject.

other hand represents a complex independent response not controlled by others (meaning there is decision making involved). An analogy can be drawn from the nature that evolved from the monocellular organisms behaving similar to an automatic system reacting to external stimuli to complex organisms such as mammals and birds that exhibit significantly more advanced independent logical behaviors.

According to the European Cooperation for Space Standardization (ECSS), a spacecraft (or a planetary robotic system in this case) is standardized to work on four different levels of autonomy or control modes as follows:

- Level E1: execution mainly under real-time ground control, that is, remote or teleoperation;
- Level E2: execution of preplanned mission operations onboard, that is, automatic operation;
- Level E3: execution of adaptive mission operations onboard, that is, semi-autonomous operation;
- Level E4: execution of goal-oriented mission operations onboard, that is, fully autonomous operation.

Planetary robots can also be classified into three groups depending on their capabilities of achieving different ECSS levels of autonomy:

- **Robotic agents** that act as human proxies in space to perform exploration, assembly, maintenance, and production tasks in the level E1–E3 operations.

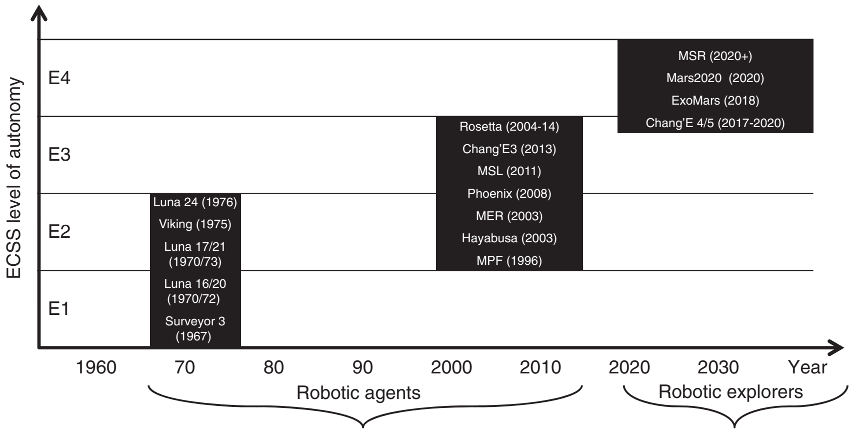


Figure 1.3 ECSS defined Level of autonomy for existing and planned planetary robotic systems.

- **Robotic assistants** that help human astronauts to perform tasks quickly and safely, with higher quality and cost efficiency using the level E3 or potentially E4 operation.
- **Robotic explorers** that explore the extraterrestrial targets using the level E4 operation.

Figure 1.3 presents the timeline of existing and foreseen planetary robotic systems with respect to the ECSS levels E1 – E4. Existing, successfully flown planetary robots are all within the robotic agent category. It is evident that as time proceeds, modern planetary missions with increasingly challenging goals require increased level of autonomy within the robotics systems, hence a shift from robotic agents to robotic explorers.

1.3 Scope and Organization of the Book

The book focuses on R&D topics that directly influence the onboard software and control capabilities of a planetary robot in achieving greater level of autonomy. It does not aim to cover design issues of any hardware subsystems such as sensors, mechanisms, electronics, or materials. However, discussions on hardware-related issues can be provided whereby they influence the design of required functions, or to provide a wider context of the robotic system design. The rest of the book is organized in such a way that each chapter focuses on a specific technical topic so that it can be read or used without much dependency on other chapters. At the same time, the technical chapters are cross-referenced among each other when there are crossovers between their subjects to help the readers establish an understanding of the system engineering philosophy that is fundamental to any space system design and development.

The design of a planetary robotic mission is complex. Past and current missions have shown how the endeavor can be treacherous and fraught with design, implementation and operational challenges. From the impact of the environment, the management of resources, to the operational concept, the system design and development must be approached as a whole rather than the sum of discrete elements. Chapter 2 conveys that a top-level view of mission-driven considerations should be established at the early stage of the robotic system design assessment, and hence introduces the space system design methodology and tools. Following the introduction Section 2.1, Section 2.2 presents a system engineering approach required to design the planetary robotic systems. Section 2.3 introduces a range of planetary robotic systems used as part of past and present exploration missions, as well as how they can address specific mission challenges and contribute to the return of the valuable science data. This section also looks ahead at future robotic systems that are currently being investigated to implement more adventurous mission concepts and operational scenarios. Section 2.4 reviews a range of planetary environmental factors that are driven by mission targets and at the same time drive designs of various robotic systems and subsystems. Section 2.5 demonstrates using a case study how to define system-level design drivers and perform subsystem design trade-offs. Finally in this chapter, Sections 2.6 and 2.7 provides insightful design options for key system operations and subsystems that have major influence to the overall system design.

A planetary robot is expected to interact with the environment and other assets of a mission, and perceive information. Similar to humans, visual sensing to the robot is the most effective and powerful way for collecting information in an unknown environment and situation. Chapter 3 addresses the vision aspects as being a prerequisite for navigation, autonomy, manipulation, and scientific decision-making. The introduction Sections 3.1 and 3.2 presents the scope, aims, terms, and most important requirements as well as constraints for robotic vision in the planetary context. Vision sensors and sensing are addressed in Section 3.3 including representative examples. Section 3.4 describes the radiometric and geometric sensor calibration that is the key to objective and meaningful sensor data interpretation and exploitation with important error influences listed as well. The following sections cover the complementary approaches of ground-based vision processing (Section 3.5) and onboard vision processing (Section 3.6) offering complementary material to the surface navigation and localization in Chapter 4. Section 3.7 presents past and present mission approaches exploiting robotic vision techniques and highlights the vision processing mechanisms used in Mars missions MER, MSL, and ExoMars. The chapter closes with a set of advanced concepts in Section 3.8.

Planetary surface navigation is among the key technologies in any robotic exploration missions, particularly involving mobile robotic platforms such as the rovers. Navigation technologies allow the rover (and hence the ground operators) to know where the robot is, where the robot should go next, and to guide the robot along a selected path. In the presence of obstacles, the navigation system enables safe and efficient exploration of its environment. Chapter 4 investigates all aspects of the rover navigation system. Following the introduction Section 4.1, Section 4.2 presents challenges of navigating on different extraterrestrial bodies and describes relevant flight rover systems including the Apollo LRV, the Russian Lunokhods, the Mars Exploration Rovers, and Curiosity. Section 4.3 presents the navigation system design process through a discussion of requirements and major design concepts. A thorough description of localization technologies is given in Section 4.4, including orientation estimation, relative localization, absolute localization, and fusion of localization sources. This is followed by Section 4.5 with a discussion of all the steps necessary to achieve autonomous navigation, from sensing to control. Finally, in Section 4.6 of the chapter, the prospect of planetary robotic navigation is presented, with a review of planned flight rovers, missions, and as enabling future technologies.

As evident from existing planetary robotic missions, robotic manipulators have played an important role, such as serving scientific experiments by grabbing samples or delivering the drills to access rocks or soil. The first part of Chapter 5 reviews past manipulators and their technical characteristics (see Section 5.1). Section 5.2 provides an overview of design criteria, specifications, and requirements for constructing a planetary manipulator, a lot of which have synergies to constructing a rover. Section 5.3 discusses control algorithms, from the low-level control of an actuator to high-level motion planning for the arm including trajectory generation, teleoperation, and possible autonomous mode. Section 5.4 further discusses testing and validation procedures for a planetary robotic arm system. Future planetary robots are envisaged to possess not only sophisticated manipulation skills and the ability to reuse these skills for different tasks but also a high level of autonomy to cope with complex mission scenarios (such as building lunar outpost). Hence, the last section (Section 5.5) of the chapter investigates various novel capabilities of planetary manipulators in the long term, for example, the use of two arms, the use of whole-body control algorithms, which considers the mobile platform as part of the manipulation system, or the ability to act in dynamically changing environments.

There is no doubt that future planetary robotic missions aim for high operational autonomy and improved onboard software capabilities. Chapter 6 offers a systematic, thorough discussion on mission operations and autonomy. Section 6.1 introduces the background and Section 6.2 sets the context of the topic by introducing the basic concepts of mission operations, processes and procedures, and typical operation modes of planetary robotic systems. Section 6.3 discusses the first step in developing the mission operation software, that is, how to establish the software architecture (both onboard and on ground) for a given mission operation. The following three sections investigate the main design aspects or core technologies in mission operations: Section 6.4 discusses the planning and scheduling (P&S) techniques and representative design solutions that can enable high level of autonomy; Section 6.5 presents the technology that allows reconfiguration of autonomous software within mission operation; and Section 6.6 covers various tools and techniques for validation and verification of autonomous software. To demonstrate the practicality of the theoretical principles, Section 6.7 presents a design example of mission operation software for Mars rovers. The last Section 6.8 of the chapter outlines some over-the-horizon R&D ideas in achieving autonomous operations and systems for future planetary robotic missions.

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