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論文内容要約

From multidisciplinary labs orbiting Earth’s lowermost orbit to robotic probes photographing the edge of our solar system, space has served as the greenhouse from where intense experimentation and technological innovation sprouted.

A new stream of unanswered questions and pressing industry needs demand robotic technology with increasing levels of dexterity. The robots that once gently roamed the deserted lands of the Moon or Mars are being now required to delve into the darkness of the lunar poles, to scout below the surface into lunar caves, or to make decisions as to what samples to collect before light irreversibly sets beneath the Moon’s subdued horizon. In all of these conceptual scenarios, ground mobility systems—the technology that provides robots the capacity to traverse over what was, once, uncharted territory—take on an unprecedented role. Increasing not only the capacity to operate on a myriad of terrains but the actual speed at which planetary robots negotiate these environments are becoming the enablers for a number of different missions.

A set of conceptual missions recently being discussed among space agencies and private corporations for the exploration of particular regions within the lunar poles demands robots capable of traveling faster. The poles of the Moon harbor some of the most precious resources currently sought in space—water ice and other volatile compounds—both for their scientific and commercial value. This is due to the lack of atmosphere, low obliquity, and low temperatures of the Moon, which creates in the poles a unique set of environmental conditions under which these resources are trapped. The polar regions are also characterized, however, by some of the most extreme elevation

profiles of the Moon, permanently shadowed areas, and the lack of on-site characterization data, which make navigating through these regions particularly challenging.

Off-road locomotion is primarily affected by two aspects: the wheel-soil interaction, or the capacity to generate enough traction when operating over particulate matter, and the degree of performance of the suspension in providing stability, isolating the chassis, and mitigating impact loads and vibrations. How increasing speed under reduced gravity fields and over the type of terrains characteristic of planetary environments affects either or both of these aspects was, at the onset of this project, unknown or, at most, poorly understood. The research unfolded in these pages contains one of the most extensive and rigorous looks at the current state of the technology for extraterrestrial wheeled locomotion, uncovering the unknowns and addressing the needs associated with traveling speeds 20 to 100 times faster than current rovers; i.e, speeds in the order of 1 m/s.

The tone is initially set by outlining the limitations and obstacles that confront engineers and scientists when addressing the subject of robotic mobility. Highlighting the risks associated with extraterrestrial surface exploration and outlining the constraints involved in the design, testing, and verification of locomotion systems prior to the launch of a new mission help us understand the underlying challenge prompted by the need to drive faster.

In an attempt to understand the theoretical framework governing traction, I examine in Chapter 2 the foundation of Bekker’s classic terramechanic equations—the most frequently used semi-empirical model to predict mobile robots off-road performance. A precise understanding of the assumptions in which Bekker’s ideas are founded allows me to highlight its limitations, and consequently those of the works that succeeded it. These asumptions are often overlooked, mainly in the field of off-road mobile robotics, in favor of the simplicity and ease of application of Bekker-based models. This chapter ends with a review of the efforts that have been made by other authors to expand the range of application of Bekker’s postulates to dynamic wheel-soil interactions—i.e., interactions in which the effect of wheel rotational speed is accounted for—, their benefits, and limitations.

Valuable lessons are extracted at the end of Chapter 2 by analyzing existing experimental evidence on fast off-road mobility, both in the military and agricultural domains. Additionally I review in detail previous experiences on the lunar surface looking for pontential clues and lessons to be learned with respect to the effects of speed on reduced-gravity, off-road locomotion. This is approached through the study of the existing footage and post-mission reports from the Luna 17, Luna 21, and the last three Apollo missions—the set of five missions that witnessed the fastest ground vehicles ever used in the history of space exploration to date: the lunokhod and the Lunar Roving Vehicle.

In light of the lack of conclusive evidence on the effects of speed, we conducted a series of velocity-dependent single-wheel characterization tests in cooperation with the Institute of System Dynamics and Control of the German Aerospace Center, where a testing facility called the Terramechanics Robotics Locomotion Lab (TROLL) had been recently built. Unlike conventional single-wheel testbeds, the TROLL facility makes use of an industrial robotic arm and preprogrammed trajectories and routines to operate the wheel and to condition the ground before every new experiment. About 500 forced-slip tests were conducted using different wheel designs and soil constituents. Speeds tested went from 0.01 to 1 m/s at slip ratios up to 90%. A description of the facility, the experimental process, the measurements collected, and the insights learned from these wheel-soil characterization tests are reported in Chapter 3.

It is in Chapter 4 where building upon the lessons learned through the experience of the Apollo and Luna missions, I delve deeper into the evaluation of the performance of passive suspension configurations when subjected to the adversity of fast lunar locomotion, looking directly for the first time at the effects of gravity, or lack thereof. Due to the impossibility to simultaneously test on Earth every environmental aspect influencing the performance of a rover, I developed a series of multibody dynamic simulation modules to virtually simulate extreme conditions a lunar rover would face during a mission. Hypothesizing on the need for energy dissipation devices, and understanding the benefits deriving from traditional free-balancing suspensions, I devise a new configuration called a mechanically-hybrid suspension or MHS, whose functional principles are put to the test and compared against two of the most widely used passive suspension configurations: the independent double-wishbone and the free-balancing rocker suspensions. The individual features of the virtual environments developed, the different suspension configurations evaluated, and the results obtained from the full-vehicle dynamic simulations are uncovered through Chapter 4.

Finally, the knowledge gathered through the evaluation of existing evidence, the insights amassed during the single-wheel test campaign, and the principles characterizing the simplified dynamic model of the MHS are implemented into a new rover prototype specifically designed and developed for fast lunar locomotion and mobility related studies, a prototype we named Explorer-1. It consists of a 23.8-kg teleoperated rover with a 4x4x4 chassis configuration (4 rigid wheels, all-wheel-drive, 4-wheel-steering) and capable of being driven at a maximum speed of 1 m/s. The schematics of the mechanical design of the rover locomotion system are presented in Chapter 5, along with a static and dynamic stability evaluation and an in-depth discussion of its capabilities and potential for high-speed, off-road locomotion. Additionally, the design of this new rover is put to the test during an 18-meter virtually simulated lunar mission formed by four stages: 1) egress from the lander, 2) acceleration and initial climb, 3) brake and turn, and 4) acceleration and final climb. To further analyze the potential application of the mechanically-hybrid configuration in real mission architectures, Chapter 5 ends with two additional studies: an analysis of the potential benefits and limitations of combining flexible metallic wheels with the MHS, and a breakdown of possible approaches to the gravity scaling problem faced when testing and validating on Earth the design and operations of a fast-moving rover before the launch of a mission.

It is with hope that I have written this dissertation. Hope that others will find value and inspiration in the work myself and many others have done over the past three years. Hope that the effort and the time we devoted to the study of fast lunar locomotion will sow the seed for a number of robotic missions to places yet to be explored. Hope that other’s work will confirm or refute, expand or improve the theories and hypotheses formed in the course of this study.