

Abstract

The space economy is undergoing a major transformation, evolving from a government-driven sector to a rapidly growing commercial industry. Within this broader domain, the lunar economy is emerging as a distinct and highly promising segment, driven by increased private sector involvement and ambitious institutional space programs. In March 2025 alone, two private companies, Firefly Aerospace and Intuitive Machines, landed on the Moon with two commercial landers. In June, the Japanese ispace performed its second attempt at achieving a soft landing. The year 2025 will also see the launch of the second commercial lander developed by Astrobotic. For the first time in history, these private companies are providing stable and commercial access to the lunar surface. Alongside these private initiatives, numerous institutional missions are underway, including the U.S. return to the Moon with the Artemis program and China's lunar exploration efforts. Europe will also play a major role with Argonaut LDE, the lunar lander developed by the European Space Agency (ESA).

According to ESA, more than 400 missions are forecast to launch to the Moon in the next decade. The long-term goals include the establishment of a permanent human presence, the development of infrastructure, and the extraction of resources for in-situ utilization. According to the agency, the very first step is to *find*, to locate water ice, map the lunar terrain, study the harsh lunar environment and more. However, lunar satellites are unable to acquire sufficiently detailed measurements, making in-situ exploration necessary. Conventional rovers represent a viable option for such investigations, but their mobility is inherently inadequate for accessing complex and hazardous terrains.

This is where the need for extreme-mobility vehicles emerges, and Evolunar, a spin-off of the Polytechnic University of Turin, aims to meet this need with LuNaDrone, a small lunar hopper capable of performing rocket-propelled flights over the lunar surface. The extreme mobility capabilities of this vehicle allow for the exploration of otherwise inaccessible locations, enabling the exploitation of strategic sites for the future of humans on the Moon. It also reduces the risks for future lunar missions by providing critical data for efficient mission planning, collected by LuNaDrone in low-cost precursor missions. Finally, this hopper provides a last-mile delivery solution, allowing payloads and scientific instruments to be transported to the most valuable locations, even far from the lander's touchdown site.

This dissertation investigates one of the most demanding mission scenarios for LuNaDrone: the exploration of a lunar pit in search of a potential entrance to an underground lava tube. The research first establishes the mission definition, identifying objectives, high-level requirements, and a reference concept of operations. Analytical and numerical tools were then developed to model LuNaDrone's flight dynamics and evaluate mission-critical parameters. The core of the dissertation is dedicated to the Propulsion System, considered the main enabling technology for this class of vehicles. The study includes the selection of the main engines, the sizing of the tanks, and the comparative assessment of different propellant feeding architectures. Complementary analyses were carried out for other key elements, including Guidance, Navigation and Control, Thermal Control, Communication, and Electrical Power systems. The outcomes of these studies enabled the derivation of the spacecraft's mass budget and the assessment of its geometry.

Overall, this dissertation provides a comprehensive system-level assessment of LuNaDrone in the framework of a challenging lunar exploration scenario. The developed methodologies and design tools constitute a solid foundation for future developments, representing a critical step toward the realization of LuNaDrone's first lunar mission and, more broadly, toward the development of extreme-mobility platforms for planetary exploration.