Innovative Lander-Deployed Penetrator for Mars Subsurface Exploration Using Cold Gas Propulsion

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Exploring the Martian subsurface is crucial for understanding the planet's geological history, potential for past life, and in-situ resource utilization. However, past attempts to deploy penetrators on Mars, such as NASA's Deep Space 2 mission, have failed due to challenges in impact survivability, communication loss, and inadequate penetration depth. This paper presents a novel Mars lander-deployed penetrator system that overcomes these historical failures by utilizing cold gas thrusters for controlled subsurface insertion rather than relying on high-velocity impact. By eliminating the need for a ballistic approach, this system ensures greater structural integrity, precise depth control, and improved data retrieval. Designed to withstand Mars' extreme environmental conditions—low atmospheric pressure (~6 mbar), severe temperature fluctuations (-125°C to 20°C), and abrasive dust exposure—the penetrator is engineered with high-strength materials, active thermal regulation, and redundant communication systems. The propulsion system leverages low-thrust, high-efficiency cold gas jets, allowing gradual and adjustable penetration into diverse terrain types while preventing excessive deceleration forces that historically led to mission failures. The integrated scientific payload, including seismometers, spectrometers, and soil analysis sensors, enables real-time data collection and transmission, ensuring mission success where past designs failed. By combining autonomous navigation, advanced power management, and miniaturized yet robust instrumentation, this system represents a significant leap forward in planetary exploration technology, offering a viable solution for deep subsurface investigations in future Mars missions.

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I. Background

The exploration of Mars' subsurface is critical for understanding the planet's geological history, assessing its potential for past or present life, and identifying resources for future human missions. Subsurface investigations provide insights into planetary formation processes, past climatic conditions, and the presence of water ice or other volatiles that may be crucial for in-situ resource utilization (ISRU) [1]. However, penetrating the Martian surface presents significant technical challenges due to its regolith composition, extreme environmental conditions, and the difficulty of achieving sufficient depth while maintaining instrument integrity.

Previous attempts to deploy penetrators on Mars have encountered substantial failures. NASA's Deep Space 2 mission, part of the Mars Polar Lander in 1999, aimed to demonstrate impact-based penetration technology but was unsuccessful due to communication loss, structural damage upon impact, and an inability to verify subsurface deployment [2]. High-velocity impact designs, while effective in theory, have repeatedly faced limitations such as excessive mechanical stress, inadequate depth penetration, and data transmission issues [5]. These setbacks highlight the necessity for alternative approaches that ensure mission survivability and success [11].

This research proposes a novel lander-deployed penetrator system that overcomes historical challenges by utilizing cold gas thrusters for controlled subsurface insertion rather than relying on ballistic impact. This method allows for gradual and adjustable penetration, significantly reducing mechanical stresses while maintaining structural integrity and ensuring precise depth control. The penetrator is designed to function in Mars' harsh conditions, with high-strength materials, active thermal regulation, and a redundant communication system to prevent data loss.

By leveraging low-thrust, high-efficiency cold gas propulsion, this system enables entry into diverse terrain types without excessive impact forces, providing a more reliable means of conducting deep subsurface investigations. The onboard scientific payload—equipped with seismometers, spectrometers, and soil analysis sensors—facilitates real-time data collection and transmission, enabling high-resolution analysis of the Martian subsurface. This advancement represents a significant step forward in planetary exploration, offering a robust and innovative solution for future Mars missions.

II. Introduction

A. Objectives/ Mission Profile

Exploring the Martian subsurface is essential for understanding the planet's geological history, assessing its potential to have harbored life, and identifying resources that may support future human missions. The geological processes that have shaped Mars over billions of years are recorded beneath its surface, preserved from surface erosion and radiation exposure. Subsurface investigations provide critical insights into planetary formation, climate evolution, and the presence of volatiles such as water ice, which could be used for in-situ resource utilization (ISRU) to support long-term exploration efforts [1].

Most Mars missions, including Curiosity and Perseverance, focus on surface investigations using onboard instruments to analyze exposed rock formations and soil samples. However, the data gathered from surface exploration is limited due to long-term exposure to cosmic radiation, oxidation, and atmospheric weathering, which alter and degrade organic compounds over time [15]. A deeper subsurface probe would allow scientists to analyze pristine materials that have remained shielded from these destructive effects, increasing the likelihood of detecting preserved biosignatures or signs of past life [7]. Additionally, subsurface exploration enables the detection of buried water ice deposits, which are critical not only for understanding Mars' hydrological history but also for future crewed missions that may rely on local water sources [16].

A.2 Challenges in Previous Penetrator Missions

While the concept of deploying penetrators for subsurface exploration is not new, past missions have faced significant challenges that have led to partial or complete mission failures. NASA's Deep Space 2 mission, which aimed to demonstrate the feasibility of impact-driven penetration, ultimately failed due to communication loss and structural damage upon impact [2]. The high-velocity ballistic approach used in this mission subjected the penetrators to extreme mechanical stresses, resulting in either instrument failure or insufficient depth penetration [5]. One of the major limitations of traditional impact penetrators is their dependence on momentum to drive the probe into the ground. This method is highly sensitive to variations in surface composition; for example, softer regolith may absorb impact energy, leading to shallow penetration, while harder surfaces may cause excessive structural

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damage [11]. Additionally, impact-based systems often struggle with post-penetration functionality, as instruments and communication links must withstand extreme shock forces during deployment [9]. These technical shortcomings highlight the need for a more controlled approach that ensures the survival of scientific payloads while achieving deeper and more reliable penetration into Martian soil and ice layers.

A.3 Research Objectives

To address these challenges, this mission proposes the development of a novel lander-mounted penetrator system capable of controlled subsurface insertion using cold gas thrusters. Unlike traditional impact-based penetrators, this approach allows for gradual and adjustable penetration, significantly reducing mechanical stress and improving instrument survivability [14]. The primary objective of this mission is to advance the technology required for deep subsurface exploration, enabling the collection of high-resolution geological and chemical data that can further our understanding of Mars' composition, habitability, and resource potential.

The study aims to achieve several key goals. First, it seeks to develop a lander-deployed penetrator system that utilizes cold gas thrusters to achieve controlled insertion, eliminating the risks associated with high-impact deployment [4]. Second, it aims to enhance the structural integrity of the penetrator and ensure that onboard sensors remain fully functional after deployment. This will involve integrating shock-absorbing materials, high-strength casings, and redundant communication systems to improve mission reliability [8]. Finally, the system will be designed for autonomous operation and long-duration data collection, enabling continuous subsurface monitoring using scientific payloads such as seismometers, spectrometers, and temperature sensors [12].

By developing and validating this controlled penetration system, this research aims to lay the foundation for future planetary exploration missions, not only on Mars but also on other celestial bodies where subsurface analysis is critical, such as Europa or Enceladus. The implementation of a precise, thruster-assisted penetration mechanism represents a significant advancement in planetary science, ensuring that future missions can explore deeper layers of extraterrestrial terrains with higher reliability and data integrity.

B. Mission Profile

B.1 Problem Identification

Current robotic missions are significantly limited in their ability to explore deep subsurface layers of Mars, restricting our understanding of its geological history, potential biosignatures, and in situ resource availability [1]. Existing Mars rovers and landers, including Curiosity and Perseverance, are capable of drilling only to shallow depths, typically ranging from a few centimeters to about one meter beneath the surface [4], [7]. This limitation leaves the deeper Martian strata—where preserved evidence of past habitability, subsurface ice deposits, and potential microbial life may exist—largely unexplored [3], [13], [15].

Previous attempts to penetrate deeper into the Martian subsurface using high-velocity impact probes, such as NASA's Deep Space 2 mission, ended in failure due to excessive impact forces that led to mechanical destruction and loss of communication [2], [5]. The inability to control penetration depth and the extreme stresses on scientific instruments posed major challenges for deep-subsurface exploration. To address these issues, a more controlled approach is required to ensure the integrity of the payload while allowing for precise depth penetration.

The **PENNY penetrator system** is designed to overcome these challenges by employing cold gas thrusters to achieve a gradual and controlled descent into the Martian regolith. This approach minimizes mechanical stress, increases instrument survivability, and enhances terrain adaptability, thereby improving mission reliability and data accuracy. By achieving a penetration depth of up to **three meters**, PENNY will enable direct analysis of subsurface material,

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facilitate seismic activity detection, and provide detailed environmental measurements, offering new insights into Mars' climate history, hydrological processes, and potential Astro biological signatures [6], [9], [17].

B.2 Objective Goals

The primary goal of the PENNY system is to integrate a thruster-assisted penetration mechanism into a Mars lander, allowing for controlled insertion into the subsurface. Extending the penetration depth to three meters surpasses current rover drilling limits, enabling deeper geological and environmental studies [4], [9]. Equipped with seismometers, spectrometers, and temperature/moisture sensors, PENNY will analyze subsurface composition, detect seismic activity, and search for biosignatures [10], [12]. The system is designed for long-duration autonomous operation, utilizing lithium-ion batteries, RTGs, and a redundant UHF/X-band communication system to ensure continuous functionality in extreme Martian conditions [11], [14].

III. Design Innovations

PENNY represents a fundamental shift in planetary subsurface exploration by overcoming the limitations of previous impact-driven probes. Cold gas thrusters enable a controlled descent, significantly reducing the risk of instrument damage while improving depth precision [5]. Unlike high-velocity impactors that suffer from unpredictable penetration dynamics, PENNY allows for targeted depth control, ensuring optimized data collection [8]. The system is designed to operate across diverse Martian terrains, including loose regolith, compacted soil, and areas with potential subsurface ice deposits [16].

The harsh Martian environment, characterized by extreme temperatures, abrasive dust storms, and low atmospheric pressure, presents challenges for long-term functionality. PENNY incorporates high-strength materials, shock-absorbing structures, and an advanced thermal management system to withstand these conditions [6], [14]. By integrating thruster-assisted penetration with resilient engineering, PENNY provides a scalable and robust solution for deep subsurface exploration, advancing our ability to study Mars' geological and Astro biological history.

C. Controlled Penetration with Cold Gas Thrusters

A key innovation in PENNY is its thruster-assisted penetration mechanism, which replaces the conventional high-impact approach with a controlled and gradual insertion process. Cold gas jets provide precise depth modulation, allowing adaptation to various terrain types, including soft regolith, rocky surfaces, and icy layers. Unlike impact-driven designs that subject instruments to extreme mechanical stress, this method ensures higher survivability, preserving the functionality of onboard scientific instruments after deployment [5].

The thruster system also improves precision by allowing for adjustable penetration depth, reducing uncertainties caused by varying soil resistance [8]. Traditional ballistic penetrators often struggle with terrain adaptability, particularly on soft or icy surfaces where they may fail to achieve the necessary depth. PENNY's system optimizes

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penetration force based on regolith composition, enhancing mission reliability and enabling consistent data collection across diverse Martian landscapes [16].

By leveraging low-thrust, high-efficiency cold gas propulsion, PENNY provides a more durable and versatile solution for subsurface exploration. This method surpasses the limitations of past penetrators, ensuring deeper and more controlled access to the Martian subsurface while maintaining instrument integrity and data accuracy [6], [14].

D. Structural Enhancements for Impact Survival

To enhance durability and ensure mission success, PENNY integrates advanced materials and energy-absorbing structures designed to withstand the extreme environmental conditions and subsurface resistance of Mars. These enhancements protect the system during penetration and maintain instrument functionality throughout the mission.

D.1 Tungsten-Tipped Nose Cone for Enhanced Penetration

The tungsten-tipped nose cone provides efficient penetration through dense regolith, rock, or ice layers. Tungsten's high density and extreme hardness make it ideal for sustained subsurface insertion while minimizing resistance and ensuring greater depth precision [8]. Additionally, tungsten's superior shearing resistance allows the nose cone to maintain its structural integrity when encountering highly compacted soil or layered ice deposits, preventing deformation and ensuring continued effectiveness throughout the descent. Unlike conventional penetrators, which struggle with unpredictable soil compositions, this design allows PENNY to adapt to various geological conditions without compromising performance.

D.2 Aluminum Foam Shock Absorbers for Energy Dissipation

To safeguard delicate onboard systems, aluminum foam-filled shock absorbers are employed to dissipate residual impact energy. These absorbers prevent excessive force transmission to critical sensors and electronics, significantly improving system survivability [5]. Their lightweight yet durable structure ensures mass efficiency, keeping the penetrator within payload constraints while maintaining robustness. Additionally, aluminum foam exhibits high shear strength, allowing it to distribute impact forces evenly across the structure and reducing localized stress points that could otherwise compromise PENNY's functionality. Beyond impact protection, the aluminum foam also serves as thermal insulation, shielding instruments from Mars' extreme temperature fluctuations and preventing performance degradation due to the planet's harsh climate [6], [14].

E. Advanced Power and Communication Systems

Ensuring long-term functionality and reliable data transmission is essential for a successful penetrator mission. PENNY integrates an efficient power system and a dual-band communication network to overcome the challenges posed by subsurface deployment.

E.1 Hybrid Power System: Lithium-Ion Batteries + RTGs

The hybrid power system combines high-energy-density lithium-ion batteries with radioisotope thermoelectric generators (RTGs) to provide a continuous and robust energy supply. Lithium-ion batteries deliver the initial deployment energy and serve as a short-term power source, ensuring immediate functionality upon activation. Meanwhile, RTGs generate sustained power, allowing PENNY to operate through Martian nights and dust storms, when solar energy is unavailable [12]. Beyond power generation, RTGs also contribute to waste heat utilization, regulating onboard temperatures and preventing instrument freezing in extreme sub-zero conditions, which is crucial for long-term subsurface exploration [6]. This hybrid approach significantly extends operational longevity, ensuring mission continuity and sustained data collection throughout the penetrator's deployment.

E.2 Dual-Band UHF/X-Band Communication System

Reliable communication is critical for transmitting collected scientific data from beneath the Martian surface. PENNY utilizes a redundant UHF/X-band communication system to maintain a stable data flow. UHF antennas

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enable short-range communication with the lander, acting as an intermediary for relaying information, while X-band antennas support high-bandwidth transmissions to orbiters and ultimately to Earth [14]. This dual-band approach ensures robust signal integrity, reducing the risk of data loss due to subsurface interference or Martian atmospheric conditions. Additionally, backup transmission protocols provide data redundancy, preventing critical information gaps and ensuring the success of long-term scientific analysis [11].

IV. System Design

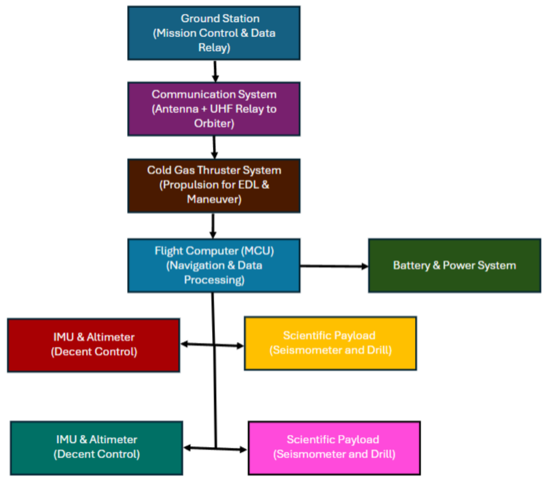

Figure 1. System Block Diagram for the lander and penetrator system. This figure depicts the interconnected parts of the Mars lander mission, tracing the path from mission control to scientific payload operations.

F. Environmental

To enhance durability in harsh Mars weather, the environmental subsystem includes radiation-hardened (Rad-hard) electronics covered with depleted boron. This coating acts as a powerful protection against high-energy particle destruction, increasing the durability and reliability of electronic components in space. For cryogenic applications, Aerospace Fabrications' Cryogenic Multilayer Superinsulator4 provides enhanced thermal protection, ensuring stable temperature conditions. This insulating system is especially important for ensuring the performance of temperature-sensitive subsystems. Furthermore, labyrinth seals are included in the design to reduce dust entry. These seals help to protect the integrity of important components by forming a complicated path that prevents particulate ingress, particularly in dusty extraterrestrial conditions on the Martian surface.

G. Lander

The lander incorporates advanced energy generation and dust mitigation systems to ensure efficient power management during planetary exploration. It utilizes UltraFlex Solar Arrays, which are flexible, lightweight, and specifically designed for space applications and have been used previously in the NASA InSight mission. These arrays have demonstrated durability, completing 2,000 geostationary orbit (GEO) and 17,000 low Earth orbit (LEO) thermal life cycles. With wing sizes scalable beyond 7 kW, and a specific power of 175 W/g–220 W/kg (beginning of life, BOL), the arrays maximize power efficiency while minimizing mass and storage requirements. Additionally, an electrostatic dust removal system is integrated to maintain optimal solar array performance in harsh wind conditions, which is something the NASA InSight mission struggled with.

For deployment and actuation, the lander employs MOOG HT1 Rotary Incremental Actuators, which provide precise motorized deployment for the solar arrays. These actuators operate at a maximum power of 10 W and weigh

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approximately 2.1 lbs per assembly. Onboard imaging and thermal monitoring systems include a GoPro MAX camera for general imaging and FLIR A40 Compact Thermal Smart Sensor Cameras for thermal mapping. The FLIR A40 model features a 51° field of view, allowing for effective environmental sensing and thermal analysis of planetary surfaces.

To enhance scientific exploration, the lander is equipped with a VibraTech seismometer for seismic activity detection, along with environmental monitoring sensors such as the BME280 for measuring temperature, humidity, barometric pressure, and volatile organic compounds (VOC) through a metal-oxide (MOx) sensor. The MLX90614 infrared temperature sensor provides non-contact temperature measurements by distinguishing between ambient and object temperatures. Additionally, a ground-penetrating radar (GPR) system, specifically the RIMFAX (Radar Imager for Mars Subsurface Experiment), enables subsurface analysis by penetrating up to 10 meters (33 feet) beneath the planetary surface, aiding in geological and resource assessments. These integrated systems collectively support the lander's mission by ensuring reliable power generation, precise environmental monitoring, and advanced scientific exploration.

V. Testing and Validation

To ensure the PENNY penetrator system is capable of withstanding the harsh Martian environment and effectively performing its mission objectives, rigorous testing and validation procedures must be conducted. These tests will assess the thermal resilience, mechanical durability, penetration capability, and communication reliability of the system under simulated Martian conditions. A combination of laboratory simulations and field tests will be used to verify the design, structural integrity, and scientific functionality of the penetrator before deployment.

H. **Thermal and Vacuum Testing**

Since PENNY will operate in low atmospheric pressure (~6 mbar) and extreme temperatures (-125°C to 20°C), thermal and vacuum testing is essential. Temperature cycling will subject PENNY to repeated heating and cooling cycles in a thermal chamber, ensuring that materials, electronics, and power systems remain functional despite Mars' harsh temperature fluctuations. To verify thruster efficiency and component performance in near-vacuum conditions, the penetrator will be tested in a low-pressure environment. Additionally, multi-layer insulation (MLI) and aerogel coatings will be assessed for heat retention, while the RTG system will be tested to ensure it maintains internal temperatures and prevents freezing in sub-zero conditions.

I. **Vibration and Impact Testing**

To ensure PENNY survives launch, landing, and penetration, mechanical stress testing will simulate the forces it will encounter. The penetrator will be placed on a multi-axis vibration table to mimic launch and entry forces, verifying that its structure and internal components can withstand the intense mechanical stresses. Shock and drop tests will evaluate impact resilience by releasing PENNY from various heights, testing the effectiveness of its aluminum foam shock absorbers and tungsten-tipped nose cone. Additionally, the cold gas thruster stability test will assess how well PENNY's propulsion system controls trajectory and penetration depth across different regolith compositions.

J. Field Deployment Simulations

Field tests in Mars analog environments will validate PENNY's penetration ability, sensor performance, and communication systems. Deployments in desert, permafrost, and volcanic regions will simulate Martian regolith conditions, assessing penetration depth and adaptability to varying substrates. Scientific instruments, including seismometers, spectrometers, and temperature sensors, will be tested in real-world conditions to ensure they collect and transmit accurate subsurface data. The UHF and X-band transmission systems will be assessed in remote locations to verify that PENNY can effectively relay scientific data over long distances without significant signal degradation. Through thermal, mechanical, and field tests, PENNY's resilience, efficiency, and reliability will be rigorously evaluated. These trials will confirm that the system is capable of operating in Mars' extreme environment, ensuring successful long-term scientific exploration and subsurface data collection.

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VI. Conclusion

The PENNY mission represents a substantial advancement in planetary subsurface exploration, addressing the limitations of previous impact-driven penetrators while introducing a more reliable, controlled method of subsurface insertion. By utilizing a cold gas propulsion system, the mission ensures a precise and controlled penetration depth, reducing mechanical stresses that historically led to mission failures such as those experienced by NASA's Deep Space 2 and ESA's Beagle 2. Unlike traditional high-velocity impact designs, which often resulted in communication loss, structural failure, and inadequate penetration depth, the PENNY system mitigates these risks by employing a thruster-assisted deployment, ensuring both scientific payload survivability and data transmission reliability. This fundamental shift in penetrator design enables a more consistent and adaptable approach to subsurface investigations across diverse planetary terrains.

The mission's technological innovations extend beyond its propulsion system. The integration of a tethered data transmission architecture ensures continuous communication with the lander, overcoming the common failure mode of lost telemetry in previous penetrator missions. Additionally, the inclusion of a high-strength, structurally reinforced penetrator casing allows the system to withstand the extreme environmental conditions of Mars, including drastic temperature fluctuations and low atmospheric pressure. Advanced onboard instrumentation, including spectrometers, seismometers, and ground-penetrating radar, enables real-time analysis of the Martian subsurface, providing critical insights into geological composition, potential biosignatures, and resource availability. The incorporation of a robust thermal management system, leveraging multi-layer insulation and aerogel-based thermal blankets, ensures long-term operational stability in Mars' harsh environment, further enhancing mission longevity.

Beyond Mars, the adaptability of the PENNY system establishes it as a versatile tool for planetary exploration. Its controlled penetration mechanism, autonomous operation, and durable structural framework make it a prime candidate for future missions targeting other celestial bodies with challenging surface and subsurface conditions. The same fundamental principles could be applied to exploring icy moons such as Europa or Enceladus, where a controlled penetration method would allow access to subsurface oceans beneath thick ice sheets. Additionally, the system's modular design allows for future modifications, enabling customization based on mission-specific requirements, whether for lunar exploration, asteroid prospecting, or deeper subsurface investigations on Mars itself.

By refining penetrator technology, improving data transmission capabilities, and ensuring long-term functionality, the PENNY mission sets a new standard for subsurface planetary exploration. Learning from past mission failures, this system not only enhances current exploration efforts but also lays the groundwork for future advancements in autonomous planetary science. As a robust, scalable, and adaptable platform, the PENNY mission represents a critical step forward in humanity's ability to explore and understand the hidden depths of extraterrestrial worlds.

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