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A Multi-Stage Sample Return Architecture for Interplanetary Exploration with Planetary Protection Measures

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Abstract: This study proposes a novel multi-stage sample return architecture for missions to near-Earth objects and other planetary bodies. Our approach prioritizes scientific return while minimizing mission complexity and adhering to planetary protection protocols. Traditional sample return directly to Earth presents logistical challenges and back contamination risks. This architecture proposes intermediary destinations, such as the International Space Station (ISS) or lunar laboratories, for initial sample screening and containment. Following these initial analyses, only demonstrably safe samples would be transferred to Earth for in-depth investigation. This multi-stage approach leverages existing technologies and promotes responsible planetary exploration. The paper concludes with a discussion of the mission's feasibility and its potential impact on future interplanetary sample return endeavors. A schematic of the proposed architecture is included.

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1. Introduction

The return of extraterrestrial samples has long been a cornerstone of space exploration, offering invaluable scientific insights at a relatively low cost compared to crewed missions. Sample return missions allow for detailed analysis in sophisticated Earth-based laboratories, far exceeding the capabilities of in-situ instrumentation on planetary surfaces. These analyses have revolutionized our understanding of the solar system, providing data on the formation and evolution of celestial bodies, the potential for extraterrestrial life, and the composition of asteroids and comets that pose a threat to Earth. Despite its undeniable importance, sample return missions have faced significant challenges. Only a handful of missions, such as NASA's OSIRIS-REx and JAXA's Hayabusa2, have successfully retrieved samples from other solar system bodies. One major obstacle is the complexity and expense of designing spacecraft capable of both outbound and return journeys. Additionally, the potential for back contamination – the inadvertent transfer of extraterrestrial microorganisms to Earth – necessitates strict planetary protection protocols that add further complexity to mission planning. This paper proposes a novel multi-stage sample return architecture that addresses these challenges. By leveraging existing infrastructure and prioritizing planetary protection, this architecture facilitates a more cost-effective and responsible approach to interplanetary sample return.

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2. Challenges of Traditional Sample Return Architecture

Direct return of samples from celestial bodies to Earth presents several challenges:

- ***Mission Complexity:*** Designing spacecraft capable of both outbound and return journeys requires sophisticated propulsion systems, heat shields for re-entry, and robust biological containment measures. This complexity drives up mission costs and development timelines.
- ***Planetary Protection Concerns:*** The potential for back contamination necessitates rigorous sample containment throughout the mission. This includes stringent sterilization procedures for outbound spacecraft and robust containment measures during the return journey to prevent potentially harmful extraterrestrial organisms from reaching Earth.
- ***Logistical Challenges:*** Direct return missions require dedicated quarantine facilities on Earth to handle potentially hazardous samples upon arrival. These facilities necessitate additional safety protocols and infrastructure.

3. A Multi-Stage Sample Return Architecture

This study proposes a multi-stage sample return architecture that mitigates the challenges associated with traditional approaches. The key concept involves utilizing intermediary destinations within our solar system for initial sample processing and containment prior to transport to Earth. This approach offers several advantages:

- ***Reduced Mission Complexity:*** The architecture allows for simpler spacecraft designs. Instead of a single spacecraft for the entire journey, missions could employ a dedicated lander for sample collection and a separate return vehicle specifically designed for the leg from the intermediary destination to Earth. This modular approach reduces complexity and potentially lowers mission costs.
- ***Enhanced Planetary Protection:*** Intermediary destinations, such as the International Space Station (ISS) or a dedicated lunar laboratory, could provide advanced containment facilities for initial sample processing. These facilities would be specifically designed to handle potentially hazardous materials, minimizing the risk of back contamination during the return journey to Earth.
- ***Streamlined Earth-based Operations:*** By pre-screening samples at intermediary destinations, only demonstrably safe materials would be transferred to Earth for further analysis. This reduces the need for extensive quarantine facilities on Earth, simplifying logistical considerations

4. Potential Intermediary Destination

Two primary options are envisioned for intermediary destinations:

International Space Station (ISS): The ISS offers a readily available platform equipped with laboratories and experienced personnel for initial sample handling and analysis. However, the size and capabilities of the ISS may limit the scope of such operations.

Lunar Laboratories: Establishing dedicated lunar laboratories specifically designed for sample processing offers greater flexibility and control. The Moon's proximity to Earth facilitates rapid transport, while the lunar environment provides natural isolation, reducing back contamination risks. This option requires additional investment in lunar infrastructure but could provide a long-term solution for interplanetary sample return missions.

5. Mission Feasibility and Future Prospects

The proposed architecture leverages existing technologies like those employed in the OSIRIS-REx and Hayabusa2 missions. The development of robust containment facilities for intermediary destinations presents an engineering challenge, but advancements in biocontainment technology offer promising solutions. The feasibility of lunar laboratories is dependent on ongoing lunar exploration efforts.

This multi-stage architecture has the potential to significantly enhance the effectiveness and affordability of future interplanetary sample return missions. By prioritizing planetary protection and leveraging existing and near-future infrastructure, this approach can pave the way for a new era of scientific discovery, furthering our understanding of our solar system and the potential for life beyond Earth.

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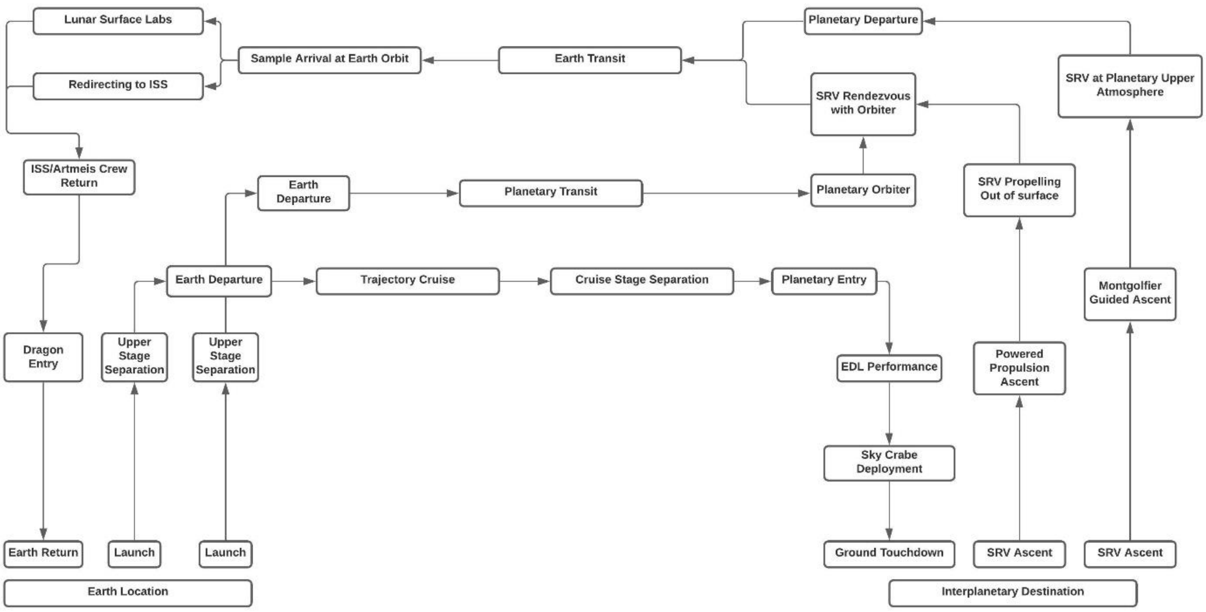
6. Conclusion

Sample return missions have played a pivotal role in space exploration, providing crucial data for scientific advancement. The proposed multi-stage sample return architecture addresses the challenges associated with traditional approaches by utilizing intermediary destinations for initial sample processing and containment. This approach offers a more cost-effective, efficient, and responsible method for retrieving. The mission architecture depicted in the figure below represents the typical plan for this project. However, it is important to note that the mission architecture is currently under study at Acceleron Aerospace Sciences Private Limited. We anticipate publishing a follow-up paper detailing the comprehensive architecture and design study in the coming years.

Figure-1 Schematic Map of Sample Return Architecture (Considering Planetary Protection Policy)



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8. Biography

Malaya Kumar Biswal M: Malaya Kumar Biswal is the Founder & CEO of Acceleron Aerospace in Bangalore, India. He is a renowned entrepreneur and scientist in aerospace engineering, specializing in space exploration. After earning his bachelor's degree in Aerospace Engineering, he worked as a Senior Research Scientist at Grahaa Space, focusing on satellite reliability, aerospace design, and space science research. With a visionary mindset, Biswal founded Acceleron Aerospace and now leads the company in revolutionizing the aerospace industry. He is particularly interested in human Mars exploration and envisions ambitious missions to Mars and Ceres. Biswal's achievements have earned him respect in the scientific community, and he actively mentors aspiring scientists, inspiring future space pioneers.

9. Conflict of Interest & Funding

The author have no conflict of interest to report. No external funding was received to support this study.