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PIONEERING MARS EXPLORATION: A COMPREHENSIVE STUDY ON THE ECONOMIC AND STRATEGIC BENEFITS OF CONTINUOUS TRANSFER STRATEGIES

Abstract

Crewed Mars missions represent the pinnacle of space exploration ambitions, facing challenges in technical, logistical, and economic areas. The journey to Mars requires significant investments in propulsion and life-support systems, thereby increasing mass and cost. The planet's thin atmosphere and diverse terrain complicate entry, descent, and landing (EDL), further challenging the delivery of crew and equipment. Additionally, the need to launch during specific Earth-Mars alignments adds operational constraints, complicating mission planning.

This paper examines the economic viability and strategic advantages of establishing continuous robotic and crewed Earth-to-Mars transfers, incorporating innovative logistic strategies such as asteroid refueling via In-Situ Resource Utilization (ISRU) and the development of a Mars Base Camp (MBC). The Lunar Gateway plays a crucial role in Mars exploration, notably due to its proximal orbital energy relationship with Mars compared to Earth, thereby enhancing the feasibility of sustained Martian exploration. This strategic positioning not only facilitates more regular missions but also offers a pragmatic solution for emergency rendezvous en-route to Mars with a station significantly closer than Earth, thus supporting risk management efforts in Martian endeavors by mitigating potential hazards. By assessing the cost-effectiveness of utilizing asteroids as intermediate refueling points, this study shows how overall mission costs can be reduced and how sustainability of prolonged crewed Mars missions can be enhanced. Our analysis further investigates the economic threshold at which continuous transfer methodologies surpass traditional, episodic mission architectures in terms of cost-efficiency and strategic feasibility.

This study evaluates NASA's Space Launch System, Orion crew capsule, and SpaceX's Starship as key launch vehicles, and explores In-Situ Resource Utilization (ISRU) across potential sites. Lockheed Martin's Mars Base Camp, positioned in a Mars-Phobos Distant Retrograde Orbit, offers strategic benefits for efficient Phobos operations with minimal propellant use, around $\sim$30 m/s per maneuver. Additionally, asteroid 2009-OS5 significantly reduces Earth-Mars Δv by 27%, enhancing continuous transfer viability. The primary goal is to identify the optimal strategy for achieving cost and logistical efficiency in space exploration.

Employing a multidisciplinary approach that merges advanced propulsion technologies, ISRU, and comprehensive economic modeling, our research shows that a permanent human settlement on Mars can be achieved with current technology by 2050. Furthermore, this paper dives into the logistical and economic considerations essential for the sustained exploration and habitation of Mars, offering insights into the implementation of a continuous transfer strategy.