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Author: Mr. Arman Asgharpoor
University of Tehran, Iran

Mr. Stefan Aleksa Djurdjevic
Deep Space Initiative, Serbia
Mr. Deepanshu Mathur
Deep Space Initiative, India

THE FUTURE OF IN-SPACE MANUFACTURING: A SYSTEMATIC REVIEW OF EMERGING TECHNOLOGIES, TRENDS, AND APPLICATIONS FOR SUSTAINABLE SPACE EXPLORATION AND OFF-EARTH COLONIZATION

Abstract

With the advancement of space exploration and technologies, long-duration and deep space missions are now possible, which require innovative approaches to sustaining habitation and managing resources. In-Space Manufacturing (ISM) emerges as a promising solution which has the potential to materialize the idea of such ambitious missions beyond Earth's orbit. This paper presents a comprehensive review of the potential applications of ISM technology for sustainable space exploration which explores the recently developed methods for in-space manufacturing, including additive and subtractive manufacturing, as well as in-space assembly techniques. The research scrutinizes ISM applications in diverse domains, leveraging the unique conditions of space, such as microgravity and vacuum, to present innovative solutions to longstanding challenges. It investigates the development of robust and sustainable manufacturing processes, utilizing lunar and Martian resources, and underscores the critical role of adaptive structures in microgravity environments. This paper aims to establish capabilities crucial for promoting sustainable space exploration, mitigating reliance on Earth-sourced materials and logistical issues associated with long-duration missions. It allows spacecraft components to be built, repaired, and upgraded directly in space, building shelter, or creating tools and electronic components. There has been emphasis on using robots and automation systems to increase scalability and possibility to manufacture and perform maintenance/replacement activities in outer space to reduce risk on human's life. Automations have shown promising results in drastically reducing errors and does not exhibit tiredness due to repeated tasks. Furthermore, it highlights ongoing projects such as the Vulcan Advanced Hybrid Manufacturing System and the Multi-Material Fabrication Laboratory, which aim to push the boundaries of ISM capabilities. And using the International Space Station as a testing ground to test feasibility of these technologies which can be used on deep space missions. Other methods like Einstein Elevator to test feasibility on earth by simulating conditions of microgravity are also included in this review. In conclusion, attention is given to identified gaps, current challenges, and a discussion on the path forward.