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ON THE TECHNOLOGICAL AND ECONOMIC FEASIBILITY OF SUSTAINABLE MISSION EXTENSION AND CONSTRUCTION VEHICLES: A SWARM OF MODULAR FREE-FLYING AUTONOMOUS REPAIR AND CONSTRUCTION ROBOTS

Abstract

With widespread ideas ranging from SpaceX CEO Elon Musk's aspirations for Mars colonization, Blue Origin founder Jeff Bezos' ideas for constructing O'Neill cylinders, and recent progress with NASA and ICON's partnership for lunar habitation; the pursuit of enabling sustainable, long-term extraterrestrial habitation is becoming a serious consideration among academics, governments, and industry. More recently in April 2024, NASA published a document identifying 187 technological shortfalls that require further development to support future space exploration, science, and mission operations. Among these, the need for autonomous robotics for sustained in-space manufacturing, intelligent servicing robots, and in-space and on-surface manufacturing capabilities emerged as central themes. Future missions, whether in orbit or on extraterrestrial surfaces such as the Moon and Mars, will require modular, adaptable, and autonomous solutions to extend mission lifetimes, reduce reliance on Earth-based resupply, and facilitate large-scale infrastructure development.

To address these challenges, this paper explores the feasibility, viability, and potential design methodologies for Mission Extension and Construction Vehicles (MECVs), a class of modular, self-flying robotic platforms capable of faciliting in-orbit manufacturing, habitat construction, and mission repair. These MECVs would integrate free-flying robotic mobility, autonomous assembly and maintenance, and resource-efficient manufacturing techniques to create a sustainable and scalable solution for long-duration space operations.

Our preliminary research examines propulsion, autonomy, and swarm coordination strategies, leveraging existing work on small spacecraft propulsion, energy-efficient LLMs for high-level swarm control, dynamic SLAM for situational awareness, and free-flying robotic inspection and servicing systems. The feasibility of utilizing fuelless welding, in-situ resource utilization (ISRU), material recycling, and low-power AI-driven onboard computing is also considered in the context of maintaining operational efficiency while reducing energy consumption. Additionally, we investigate potential economic and logistical impacts, such as cost efficiency, material sourcing, and infrastructure scalability, to determine the viability of these systems in future space operations.

This paper presents an initial assessment of the feasibility of MECVs as a key enabler of autonomous, scalable construction and servicing capabilities in space. By addressing critical gaps in NASA's roadmap, MECVs have the potential to enhance mission flexibility, reduce costs, and support the expansion of human and robotic activities beyond Earth. Our findings provide a foundation for further research and prototyping efforts, contributing to the advancement of autonomous servicing and construction technologies essential for the next generation of space exploration.