SYMPOSIUM ON BUILDING BLOCKS FOR FUTURE SPACE EXPLORATION AND DEVELOPMENT (D3)
Strategies & Architectures as the Framework for Future Building Blocks in Space Exploration and Development (1)

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DYNAMIC MODELING AND OPTIMIZATION FOR SPACE LOGISTICS USING TIME-EXPANDED NETWORKS

Abstract

As human and robotic space exploration projects become increasingly complex, logistics considerations become crucial. Although past missions have used simple strategies such as carry-along or resupply, these strategies are no longer practical; instead the logistics system requires a network perspective. Also, as various space infrastructure technologies such as propellant depot and In-Situ Resource Utilization (ISRU) have been proposed, we need to consider how to use these technologies through space resource flow modeling and optimization.

One of the most powerful techniques for such analysis is the Generalized Multi-Commodity Network Flow (GMCNF) formulation. This formulation utilizes graph-theoretic approach to formulate space logistics as a Linear Programming (LP) problem. All events including ISRU resource generation, crew consumption, and propulsive burns are modeled as commodity transformations.

Unfortunately, GMCNF has critical drawbacks due to its static nature. For example, GMCNF does not consider the time ordering of events and the dependence among missions. This can result in optimization results containing “time paradoxes.”

In response to this background, we introduce a dynamic version of GMCNF formulation. A time-expanded network is used for multi-period simulation. This does not only remove “time paradoxes,” but also consider the infrastructure deployment phase as part of its optimization.

In order to solve the dynamic GMCNF efficiently, two ideas are proposed in this paper. First, uneven time step resolutions are used that correspond to different time scales in space exploration. The idea is that only the critical time windows matter for the optimization results, and therefore the time steps that do not directly affect the time windows can be eliminated for “good enough” results. In addition, an approximation algorithm based on Dynamic Programming (DP) is proposed. With this approximation, the space logistics problem can be decomposed into ISRU deployment problem and depot allocation problem, the former of which can be solved efficiently using DP-based algorithms.

Preliminary analysis is performed for the Mars exploration case in the paper and the resulting strategy is proposed. The results show the effectiveness of space infrastructure such as depot and ISRU in various architectures.

This work contributes to high-level architecture and logistics design of future human/robotic exploration of the Moon, Mars, asteroids, and beyond. The proposed framework can find the strategies that are

optimal over the whole campaign including the infrastructure deployment. The contribution includes proposal of an optimal set of space infrastructure that can be commonly used across space players including national organizations and private companies.