Acta Astronautica 123 (2016) 51–61

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Campaign-level dynamic network modelling for spaceflight logistics for the flexible path concept

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ARTICLE INFO

Article history:
Received 26 November 2015
Accepted 2 March 2016
Available online 8 March 2016

Keywords:
Space systems
Space logistics
NEO exploration
Mars exploration
Network optimization

ABSTRACT

This paper develops a network optimization formulation for dynamic campaign-level space mission planning. Although many past space missions have been designed mainly from a mission-level perspective, a campaign-level perspective will be important for future space exploration. In order to find the optimal campaign-level space transportation architecture, a mixed-integer linear programming (MILP) formulation with a generalized multi-commodity flow and a time-expanded network is developed. Particularly, a new heuristics-based method, a partially static time-expanded network, is developed to provide a solution quickly. The developed method is applied to a case study containing human exploration of a near-Earth object (NEO) and Mars, related to the concept of the Flexible Path. The numerical results show that using the specific combinations of propulsion technologies, in-situ resource utilization (ISRU), and other space infrastructure elements can reduce the initial mass in low-Earth orbit (IMLEO) significantly. In addition, the case study results also show that we can achieve large IMLEO reduction by designing NEO and Mars missions together as a campaign compared with designing them separately owing to their common space infrastructure pre-deployment. This research will be an important step toward efficient and flexible campaign-level space mission planning.

1. Introduction

As space becomes more and more accessible through technology development, space systems design has also become increasingly complex. Thus, we need a campaign-level perspective for space systems design in addition to the conventional mission-level perspective. A campaign contains multiple missions that may or may not be for the same destinations. A design method taking the whole campaign into consideration can enable efficient and flexible space systems.

We can see a transition from mission-level design into campaign-level design in our history of space exploration. In the Apollo project, all missions used a carry-along strategy, where they transported everything they needed by themselves. This was possible due to their short mission durations (e.g., 2 weeks) and small demands in consumables and equipment. However, that type of mission-level strategy is not necessarily desirable for long-term missions. For example, the International Space Station (ISS) programme could not use a mission-level strategy because it aimed to have a human presence in space over the long term. Instead, it used a campaign-level resupply strategy, where the vehicles are launched regularly to resupply the hardware and consumables and even replace the crew.

The campaign-level strategies include uses of technologies and infrastructure considering the whole campaign. Particularly, a combination of pre-deployment, carry-along, and resupply strategies will be very important for interplanetary missions over the long term. In addition, effective uses of different technologies and infrastructures such as advanced propulsion system [1,2], propellant depot [3–6], and in-situ resource utilization (ISRU) [7–11] have also been proposed to be useful.

Given that background, we aim to find an efficient optimization framework to consider a campaign-level mission planning for future human and robotic space exploration. This paper particularly intends to improve and extend the most advanced work we recognize in space logistics optimization literature, which uses time-expanded generalized multi-commodity network flow (GMCNF) approach for space logistics modelling [12–15]. In the previous work, dynamic linear programming (LP) based network optimization approach has been proposed to be effective [12–15].

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http://dx.doi.org/10.1016/j.actaastro.2016.03.006
0094-5765/

However, using continuous variables for all flows might not provide a realistic solution. For example, a crew member can be split into multiple pieces in the optimal solution. In order to avoid that situation, this paper proposes a mixed-integer linear programming (MILP) formulation. A more important contribution of this paper is about the time-expanded network. The previous work used a bi-scale time-expanded network for dynamic optimization [14,15]. This method was useful in providing a logistics flow over time and provided a more realistic solution than static optimization, but it required a large computational resources. In this paper, a new efficient approximate method, a partially static time-expanded network, is proposed. This method combines the ideas from both static and bi-scale time-expanded network approaches, which enables significant improvement in computational effort.

The resulting efficient dynamic optimization formulation is proposed and applied to a case study containing human exploration of a near-Earth object (NEO) and Mars, related to the concept of the Flexible Path. This case study shows that a design from a campaign-level perspective would significantly improve the performance. This is the very reason why we need to pursue campaign-level space mission planning, and the proposed method can be a very strong support and evaluation tool for that purpose.

The rest of the paper is organized in the following: Section 2 shows the past research in space logistics modelling, and Section 3 shows the detailed method. Section 4 applies the proposed method to the case study. Section 5 concludes the discussions.

2. Literature review

Space logistics has been studied recently in the context of the efficient human exploration of Mars. A detailed literature review and motivation behind space logistics research can be found in the past papers [14,15], but a few important studies are shown here.

Network modelling has been proposed to be an effective technique for efficient optimization of space logistics. It converts the space logistics map into a mathematical graph as shown in Fig. 1. Here, the nodes correspond to physical destinations or potential locations for staging or mass transfer in space, whereas the arcs connect pairs of nodes. In the graph, the following nodes are considered: Kennedy Space Centre (KSC) for launches, a Pacific Ocean splashdown zone (PAC) for return, a 300-km low-Earth orbit (LEO), a 35,786-km geostationary Earth orbit (GEO), a geostationary transfer orbit (GTO), the lunar south pole (LSP), a lunar transfer orbit (LTO), a low-lunar orbit (LLO), Earth–Moon Lagrangian points (EML1, EML2, EML 4/5), a low-Phobos orbit (LPO), Phobos transfer orbit (PTO), a low-Deimos orbit (LDO), Deimos transfer orbit (DTO), a low-Mars orbit (LMO), Gale Crater (GC) on the Martian surface, and a representative NEO. The arcs connect each pair of these nodes where transportation is allowed. With this graph, we can apply a mathematical network simulation or optimization technique to space logistics design.

The pioneer in the field of network modelling of space logistics is SpaceNet, a space logistics modelling software developed by Massachusetts Institute of Technology [16]. With SpaceNet, one can simulate and evaluate a space logistics campaign easily and intuitively. SpaceNet has been used for simulation of logistics for various projects including ISS, lunar expedition, and Mars exploration [17–19].

One problem of SpaceNet is that it does not have an optimization function to find the most appropriate scenario, although that is one of the important purposes in space logistics design. In order to achieve that optimization function, multiple studies have been conducted in order to optimize space logistics effectively. Taylor et al. proposed a heuristic optimization algorithm based on multi-commodity combinatorial optimization [20,21]. However, this method is computationally heavy and also cannot be applied to the cases with ISRU or other resource generation mechanisms.

Recently, there has been a proposal to use a graph-theoretic approach to perform space architecture tradespace exploration [22]. This approach is similar as the network modelling of space logistics reviewed above, but it also considers the order of system sizing, or the system hierarchy, using topological sorting. The resulting method is powerful in rapid tradespace exploration, but it explores only a limited tradespace due to its lack of feedback in its system hierarchy.

In order to deal with these difficulties, Ishimatsu proposed a generalized multi-commodity network flow (GMCNF) formulation

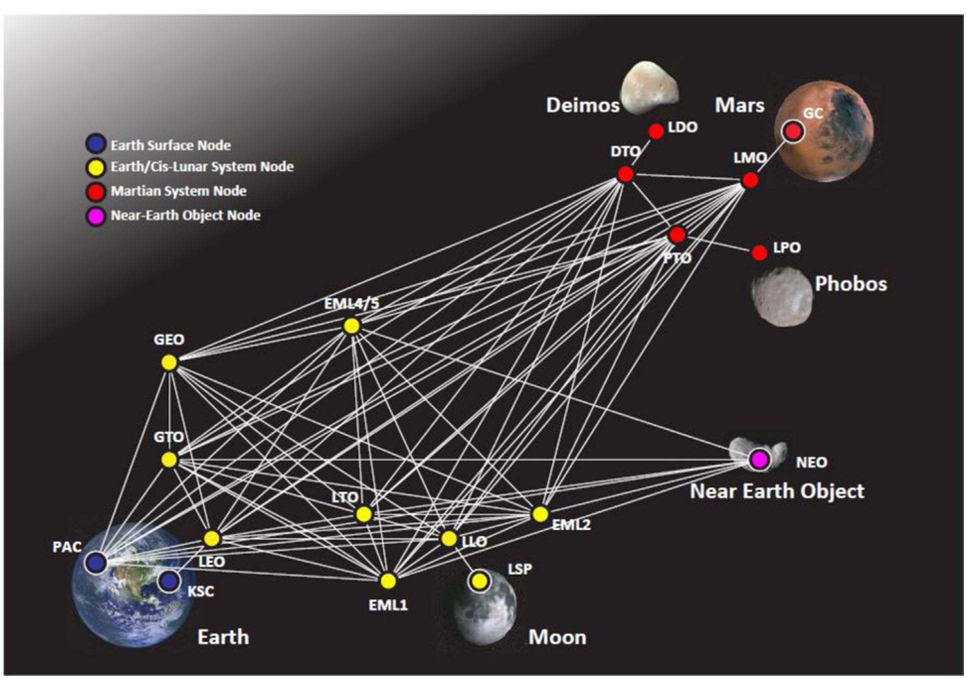

Fig. 1. Earth–Moon–Mars–NEO logistics network graph based on the figure by Ishimatsu [12]. The acronyms are listed in the text.