SPACE TRANSPORTATION NETWORK ANALYSIS FOR CISLUNAR SPACE ECONOMY WITH LUNAR RESOURCES. K. Ho[1] and H. Chen[1], [1]University of Illinois at Urbana-Champaign, (Talbot Laboratory, 104 South Wright Street, Urbana, IL, 61801, kokiho@illinois.edu, hchen132@illinois.edu).

Introduction: This work provides a transportation network analysis of lunar exploration architecture and cislunar mission design with lunar in-situ resource utilization (ISRU). This analysis is performed using a mathematical model for space transportation network analysis for cislunar resource economy. We propose a campaign-level integrated optimization framework that can (1) design a sequence of (potentially interdependent) missions concurrently with lunar resource as a potential propellant source; (2) select the ISRU architecture and/or technologies; (3) select the potential vehicles from a reslistic set; (4) provide an economic analysis of lunar resource. The proposed analysis method can be used to advance our quantitative and qualitative understanding about mission design for profitable cislunar space economy with lunar resource, and thus support design of a more self-sustained resource economy in cislunar space.

Methods: Our methods are based on the time-expanded mixed-integer generalized multi-commodity network flow (GMCNF) model [1-3]. In our model, space transportation map is converted into a network, where the nodes correspond to planets, celestial objects or orbits, and the arcs correspond to trajectories. With this conversion, space mission design problem can be considered as a mathematical network flow optimization problem. The formulation can take different objective functions; one example would be the campaign lifecycle cost including technology development, vehicle production, launch, and operations over all missions, while it can also include other metrics such as risk or robustness. In order to consider multiple missions concurrently, a time-expended network is considered that can effectively integrate the time dimensions into our analysis. By approximating the existing ISRU infrastructure design models, our method can also consider ISRU infrastructure sizing as part of the tradespace. With a set of vehicles we can use, we can optimize the routing of each vehicle trading off the associated cost and benefits in the campaign. The resulting model can be formulated as a mixed-integer linear programming (MILP) problem, which can be solved computationally efficiently with commercial software such as Gurobi or CPLEX.

In addition to optimizing the mission planning and vehicle design, the proposed method can also be used to evaluate the impact of different technologies to the systems architecture. For example, we can evaluate the pros and cons of lunar ISRU at a campaign level considering both its development/deployment cost and its benefits during the operation. Our past studies have shown an effective deployment plan of ISRU plants is critical to maximize the value of ISRU technologies [1-2]. This rigorous analysis method can fairly evaluate the value of ISRU technology and can be integrated into decision making for technology roadmapping.

Using the above methods, we introduce optimized transportation architectures for robotic and human lunar exploretaion missions and discuss the impact of lunar ISRU to various cislunar missions and campaigns. In addition, a preliminary analysis about propellant transportation after ISRU deployment is also introduced to provide an estimate of economic value of ISRU. The influences of mission scenarios, ISRU system architecture (i.e. concentrated ISRU system or distributed ISRU system), and launch vehicle capacity to the space transportation system are also analyzed.

Conclusions: With the proposed methods and the case study in lunar missions, we aim to demonstrate the capability of our method to analyze the cislunar space resource economy. We also aim to identify the bottleneck of the cislunar transportation network as well as the potential opportunities for commercialization and/or public-private partnerships.

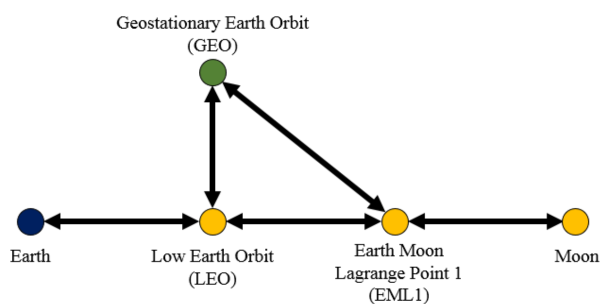

Figure. Example network for cislunar transportation.

References:

[1] Ho K. et al. (2014), *Acta Astronaut.*, 105(2), 428-443. [2] Ho K. et al. (2016), *Acta Astronaut.*, 123, 51-61. [3] Ishimatsu T et al. (2016), *J Spacecr Rockets.*, 53(1), 25-38.