Campaign-Level Dynamic Network Modelling for Spaceflight Logistics for the Flexible Path Concept

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[Part of the presented work was performed with Prof. Olivier de Weck at MIT]

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Outline

• Introduction
• Space Logistics Network Modeling
• Case Study: Impact Evaluation of ISRU for Mars Exploration
• Conclusion and Ongoing Research
Background

• Logistics network becomes increasingly complex for future space exploration
  ➢ Pure carry-along or resupply does not work efficiently any more

• New strategic logistics paradigm is required
  ➢ Combination of Prepositioning, Carry-along, and/or Resupply?
  ➢ Effective use of logistics infrastructure such as In-situ Resource Utilization (ISRU) and propellant depot.
    ▪ Propellant is the largest mass fraction for rockets (e.g. >90%).
Space Logistics Infrastructure

- **In-Situ Resource Utilization (ISRU)**
  - “Oil field” in space
  - Generate resource from the in-situ environment
    - E.g. Propellant, water, gas...
  - Location: Moon, Mars, ...
  - Limitations: long construction period, large plant mass

- **Propellant depot**
  - “Gas station” in orbit
  - Store propellant/structure in space
  - Location: Lagrangian points, Low-Lunar Orbit, ...
  - Limitations: Refilled by tanker from the Earth or ISRU, boiloff

Are they effective and efficient at the campaign level?
Research Objective

**Objective: A campaign-level architecture/design optimization tool**

- Optimize multiple missions and their technology uses concurrently
- Capture trades for multiple technology options
  - ISRU (lunar, Martian), Propulsion (chemical, NTR, SEP), 3D-printing, etc...
- Applicable for various destinations:
  - NEO, Mars, Moon, etc...

This presentation will show **one scenario for Mars exploration**

- **Why Dynamic?**
  - Not much emphasis on system deployment phase, which is non-negligible in space exploration.
  - Interdependency between missions are also non-negligible

- **Why Network Modeling?**
  - LP-based Broad Tradespace Exploration
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Space Logistics

• **Space Logistics:**
  - The theory and practice of driving space system design for **operability** and managing the **flows of materiel, services, and information** needed throughout the **system lifecycle** (AIAA Space Logistics Committee)

• **MIT Space Logistics Project:**
  - Terrestrial supply chain **analyses**
  - Space Logistics **network** analysis
  - Exploration demand-supply modeling with uncertainties
  - Interplanetary Supply Chain Architecture: **Trade Studies**
SpaceNet

- **SpaceNet 2.5r2 (de Weck et al.)**
  - A software modeling the space exploration logistics within a discrete event simulation environment
  - Perform demand analysis using a dynamic logistics model of a given mission sequence.
  - Simulate the full campaign to quantify Measures of Effectiveness (MOE)

http://strategic.mit.edu/spacenet/
## Literature on Space Architecture Optimization

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Generalized Multi-Commodity Network Flow (GMCNF)

• Space logistics modeling by Static Generalized Multi-Commodity Flow (GMCNF) (Ishimatsu et al.)
  ➢ Generalized flow: Network with arcs that involve gain/loss.
  ➢ Multi-commodity flow: Network with multiple commodities.
  ➢ Generalized multi-commodity flow: Multi-commodity network with arcs that involve gain/loss, commodity type conversion, or both of them.

• Commodity: [payload, vehicle, propellant, food, water, waste, structure, crew, …]

E.g. ISRU propellant generation

E.g. Propellant consumption

E.g. Food -> Waste

Multi-Graph for multiple transportation options (e.g. Nuclear Thermal Rocket vs. Chemical Rocket; Pareto optimal trajectories along TOF - ΔV trade)

Self-loops: Resource generation/consumption at nodes
GMCNF Formulation (Ishimatsu et al.)

Minimize:

\[ J = \sum_{(i,j) \in \mathcal{A}} c_{ij}^+ x_{ij}^+ \]

subject to:

\[ \sum_{j : (i,j) \in \mathcal{A}} x_{ij}^+ - \sum_{j : (j,i) \in \mathcal{A}} x_{ji}^- \leq b_i \quad \forall i \in \mathcal{N} \]

\[ x_{ij}^- = B_{ij} x_{ij}^+ \quad \forall (i,j) \in \mathcal{A} \]

\[ C_{ij}^+ x_{ij}^+ \leq p_{ij}^+ \quad \forall (i,j) \in \mathcal{A} \]

\[ x_{ij}^+ \geq 0_{K \times 1} \quad \forall (i,j) \in \mathcal{A} \]

\[ x_{ij}^\pm = \begin{bmatrix} x_{ij1}^+ \\ \vdots \\ x_{ijK}^+ \end{bmatrix} \]: Commodity in/outflow

Mass balance

Flow Transformation

Flow Concurrency

Flow bound

Linear Programming formulation -> Computationally efficient!
Examples of B-matrix and C-matrix

\( B^{(1)}_{ij} \): Propulsive Burn (propellant mass fraction \( \phi_{ij} \))

\[
\mathbf{x}_{ij}^- = \begin{bmatrix}
\text{payload} \\
\text{crew} \\
\text{propellant} \\
\text{consumables} \\
\text{waste}
\end{bmatrix}_{ij} = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}_{ij}
\]

\[
\mathbf{B}_{ij} = \begin{bmatrix}
\text{payload} \\
\text{crew} \\
\text{propellant} \\
\text{consumables} \\
\text{waste}
\end{bmatrix}_{ij}^+
\]

\[
\mathbf{B}_{ij} \mathbf{x}_{ij}^+ = \mathbf{x}_{ij}^-
\]

\( B^{(2)}_{ij} \): Consumables (at a rate of \( c \)) into Waste (a rate of \( w \))

\[
\mathbf{x}_{ij}^- = \begin{bmatrix}
\text{payload} \\
\text{crew} \\
\text{propellant} \\
\text{consumables} \\
\text{waste}
\end{bmatrix}_{ij} = \exp\left(\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & -c & 0 & 0 & 0 \\
0 & w & 0 & 0 & 0
\end{bmatrix}_{ij}\Delta t_{ij}\right)
\]

\[
\mathbf{B}_{ij} = \begin{bmatrix}
\text{payload} \\
\text{crew} \\
\text{propellant} \\
\text{consumables} \\
\text{waste}
\end{bmatrix}_{ij}^+
\]

\[
\mathbf{B}_{ij} \mathbf{x}_{ij}^+ = \mathbf{x}_{ij}^-
\]

\( C^{+}_{ij} \): Structure Mass (inert mass fraction \( f_{\text{inert}} \))

\[
\eta \equiv \frac{f_{\text{inert}}}{1-f_{\text{inert}}}
\]

\[
C^{+}_{ij} \mathbf{x}_{ij}^+ = [0 \ \eta \ -1]_{ij}^+ \begin{bmatrix}
\text{payload} \\
\text{propellant} \\
\text{structure}
\end{bmatrix}^+_{ij} \leq 0
\]
Time-Expanded Network

• Limitation of **Static** modeling: No time dimension
  ▶ Not considering **time ordering** of events
  ▶ Not considering **time windows** for transportation/supply/demand
  ▶ Not considering **interdependencies** between the missions
  ⇒ Can provide unrealistic solutions

• **Dynamic Generalized Multi-commodity Flow**
  ▶ **Time-expanded network**: Expanding nodes to time dimension
  ▶ Static network is an **lower and overoptimistic bound** of full time-expanded network

What is a good time step?
Proposed Cluster-Based Time-Expanded Network

**Basic Ideas:** Only “important” timings matter in time-window critical systems!

1. Divide nodes into clusters depending on the time windows of arcs

---

**Clusters:**
- Earth Surface Clusters
- Earth/ Cislunar Cluster
- Martian Cluster
- NEO Cluster
- NEO Cluster

**Launch Windows:**
- Launch Window (Astrodynamics)

**Orbits and Terms:**
- KSC: Kennedy Space Center
- PAC: Pacific Ocean
- LEO: Low-Earth Orbit
- GEO: Geostationary Earth Orbit
- GTO: Geostationary Transfer Orbit
- LSP: Lunar South Pole
- LLO: Low-Lunar Orbit
- EML: Earth-Moon Lagrangian Points
- LDO: Low Deimos Orbit
- DTO: Deimos Transfer Orbit
- PTO: Phobos Transfer Orbit
- LMO: Low Mars Orbit
- GC: Gale Crater
- NEO: Near Earth Object
Proposed Cluster-Based Time-Expanded Network

1. Divide nodes into clusters depending on the time windows of arcs
2. Draw cluster-scale time-expanded network for clusters only at open windows
3. Allow a round trip within the cluster at each time window

- Useful for time window critical system.
- Computationally efficient and provides a good approximation of a realistic solution.
Dynamic GMCNF formulation

\[
\begin{align*}
\text{Minimize:} & \quad J = \sum_{(i,j) \in \mathcal{A}} \sum_{t \in \{0 \dots T-1\}} c_{ij}^T x_{ijt}^+ \\
\text{subject to:} & \quad \sum_{j : (i,j) \in \mathcal{A}} x_{ijt}^+ - \sum_{j : (j,i) \in \mathcal{A}} x_{ji(t-\Delta t_{ji})}^- \leq b_i t \quad \forall t \in \{0 \dots T-1\} \quad \forall i \in \mathcal{N} \\
& \quad x_{ijt}^- = B_{ij} x_{ijt}^+ \quad \forall t \in W_{ij} \quad \forall (i,j) \in \mathcal{A} \\
& \quad c_{ij}^+ x_{ijt}^+ \leq p_{ij}^+ \quad \forall t \in W_{ij} \quad \forall (i,j) \in \mathcal{A} \\
& \begin{cases} 
x_{ijt}^+ \geq \mathbf{0}_{K \times 1} & \text{if } t \in W_{ij} \\
x_{ijt}^+ = \mathbf{0}_{K \times 1} & \text{otherwise} \end{cases} \quad \forall t \in \{0 \dots T-1\} \quad \forall (i,j) \in \mathcal{A}
\end{align*}
\]
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Assumptions for Case Study

• **Objective:** Minimize Initial Mass to Low-Earth-Orbit (IMLEO)
• **Variables:** 21 types of commodities over each arc
  - **Payload:** Equipment/Habitat; Samples
  - **Human:** Crew; Returning Crew
  - **Consumables:** Hydrogen; Oxygen; Methane; Water; Food; Waste
  - **Tanks:** Hydrogen Tank; Oxygen Tank; Methane Tank; Water Tank
  - **Other Inert Mass (excluding Tank):** Crew Vehicle; LOX/LH2 Inert; Nuclear Thermal Rockets (NTR) Inert; LOX/LCH4 Inert
  - **Entry Structure:** Aeroshell/TPS
  - **ISRU:** Oxygen ISRU; Water ISRU; Methane ISRU
• **Propulsion Options:**
  - LOX/LH2; NTR; LOX/LCH4 for Mars ascent/descent
  - All with aerocapture option when applicable
• **Boil-Off:**
  - LH2: 0.127%/day; LOX: 0.016%/day
• **Lunar and Martian ISRU:**
  - 10 [kg/plant kg/year] for soil-based ISRU (Hydrogen Reduction/Molten Regolith Electrolysis/Water Ice Extraction)
  - 10 [kg/plant kg/year] for atmosphere-based ISRU (Sabatier Reaction)
Concept of Bootstrapping ISRU deployment

- **Bootstrapping ISRU deployment**: developed by Koki Ho’s PhD thesis at MIT; research continues at UIUC.
  - Deploy ISRU in stages with frequent cis-lunar missions
  - Utilize propellant generated by ISRU for further ISRU deployment

Each cis-lunar mission is a **round trip between Moon and Earth orbits**.
- **Frequency of the cis-lunar missions** is a key parameter.
Results

Analysis
• 3 cases are considered depending on the frequency of cis-lunar missions

<table>
<thead>
<tr>
<th>Cis-lunar missions freq</th>
<th>IMF=0.1 IMLEO</th>
<th>IMF=0.2 IMLEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 780 days (all-up)</td>
<td>813 MT (no ISRU)</td>
<td>1180 MT (no ISRU)</td>
</tr>
<tr>
<td>(2) 390 days (bootstrapping)</td>
<td>769 MT</td>
<td>1050 MT</td>
</tr>
<tr>
<td>(3) 195 days (bootstrapping)</td>
<td>662 MT</td>
<td>861 MT</td>
</tr>
</tbody>
</table>

Findings
• With all-up strategy, lunar ISRU does NOT pay off.
• With bootstrapping strategy, lunar ISRU does pay off.
• More frequent cis-lunar missions (i.e. more reuses of vehicles) => lower IMLEO.
• The quantitative results depend on various assumptions (e.g. ISRU productivity, IMF).
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Conclusion and Ongoing Research

Objective: A campaign-level architecture/design optimization tool

Strength
• Architecture-level global optimization and sensitivity analysis
  • Provide technology investment portfolio over time
• General methodology applicable for different missions/campaigns
• Low computational effort (~1 min for Mars case on a desktop computer)

Limitation
• Linearization effects can result in a relatively low fidelity reusable vehicle/ISRU model (e.g. vehicle as a “flow”)

Ongoing Research at UIUC: 3 presentations for AIAA Space 2016:
• SEP trajectory design and its campaign-level trade with chemical rockets/ISRU/depot uses
• Integration with higher-fidelity vehicle model using mixed-integer nonlinear programming
• Design and Optimization for on-orbit repair/refuel system with 3D printing using stochastic model and queueing theory

⇒ Towards Campaign-Level Astrodynamics and Mission Design
How can low-thrust technologies (like SEP) best aid beyond-LEO space operations that involve multi-mission campaigns?

- Inner loop will provide solutions to the low-thrust and impulsive high-thrust trajectory problem, providing a value of the objective function (usually, mass or time): *cost of travelling on an arc using provided thruster type*
- Outer loop will perturb the state vector that is input to the inner loop: *parameters of each arc*