An Operations Management Method for a Logistics Network of Distributed Life Support Systems on the Lunar Surface

Hiroyuki Miyajima
Tokyo Jogakkan College
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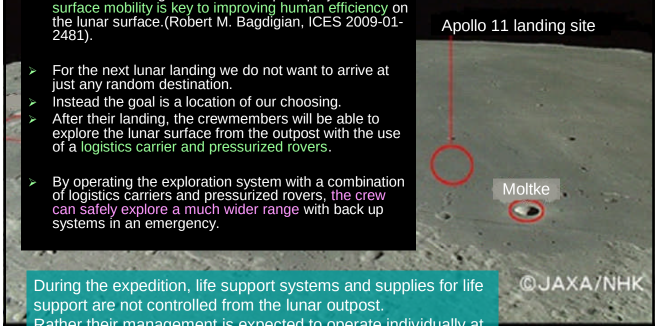
Landing points of the Apollo Project

- Lunar roving vehicles were carried to the lunar surface on Apollo flights 15, 16, and 17.
- In Apollo 15 the astronauts drove the vehicle for 27.6km.

NASA's Goddard Space Flight Center Scientific Visualization Studio.

Expedition from outpost

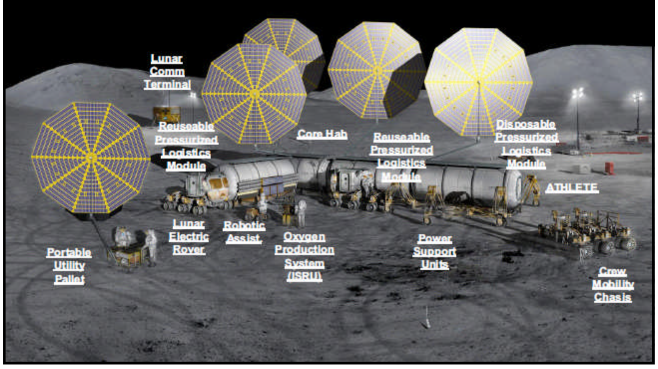
- One of the lasting lessons of the Apollo project is that surface mobility is key to improving human efficiency on the lunar surface.(Robert M. Bagdigian, ICES 2009-01-2481).
- For the next lunar landing we do not want to arrive at just any random destination.
- Instead the goal is a location of our choosing.
- After their landing, the crewmembers will be able to explore the lunar surface from the outpost with the use of a logistics carrier and pressurized rovers.
- By operating the exploration system with a combination of logistics carriers and pressurized rovers, the crew can safely explore a much wider range with back up systems in an emergency.



During the expedition, life support systems and supplies for life support are not controlled from the lunar outpost.
Rather their management is expected to operate individually at multiple points within the network.

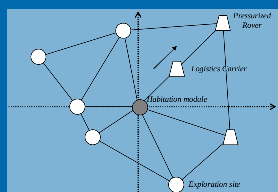
Lunar outpost with high degrees of mobility

presented by Robert M. Bagdigian, at ICES 2009-01-2481
Constellation Lunar Surface System Project @NASA MSFC



Logistics network for wide area movement on the lunar surface

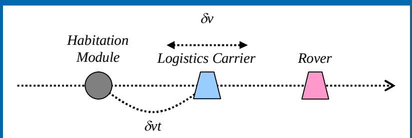
- With such distributed life support system operations, we have to decide where, when, how much, and what types of supplies are going to be stored in order to meet the expedition needs and those needs can vary with each operation.
- If the supplies are inappropriately stored at any site, regardless of whether or not there is a sufficient amount of supplies on the lunar surface, this inappropriate storage will inevitably lead to a lack of supplies.
- It is very important to develop a logistics network for the lunar surface and operation method for the distributed life support systems.



- The purpose of this research is to provide a method for making such dynamic resource allocations in a logistics network.
- The Lagrangian Decomposition and Coordination (LDC) method, which was developed for Advanced Life Support Systems (ALSS), is here applied to the study of logistics carrier operations planning in the logistics network.

Formulation of logistics carrier movement in logistics network

Position model of a Logistics Carrier in limited axial movement



$$d_i = \delta_i v_i t_i$$
$$\delta_i = \{-1, 0, 1\}$$

Each requirement for supply by the rover places a demand on the logistics carrier's activity and each such demand constitutes a job in this scheduling.

Formulation of logistics carrier operations by using Lagrangian decomposition and coordination (LDC)

Distance the logistics carrier moves

Amount of deviation from the rover target position

Product of the distance from the habitation module and the exhaustion rate of the required supplies

$$\min \sum_{t=1}^{T}\sum_{j=1}^{J}\left[c_{1j}\left|\delta_{jt}\right| + c_{2j}\left(d_{ij,obj}-d_{ij}\right)/d_{ij,obj} + h_i\left(B_{ji}\, d_{ij}/D_{i\max}\right)\left(x_{i\max}-x_{it}\right)/x_{i\max}\right]$$

subject to $d_{it+1} = d_{it} + \sum_{j=1}^{J}\delta_{jt}v_{ijt}t \quad \forall i,t$ — Logistics carrier position

$d_{it} \ge D_{Li} \quad \forall i,t$ — Lower bound of position

$d_{it} \le D_{Ui} \quad \forall i,t$ — Upper bound of position

$\sum_{j}^{J}\delta_{jt}B_{ji} \le 1 \quad \forall i,t$ — Competition on a logistics carrier

Lagrangian relaxation

$$\min \sum_{t=1}^{T}\sum_{j=1}^{J}\left[c_{1j}\left|\delta_{jt}\right| + c_{2j}\left(d_{ij,obj}-d_{ij}\right)/d_{ij,obj} + h_i\left(B_{ji}\, d_i/D_{i\max}\right)\left(x_{i\max}-x_{it}\right)/x_{i\max}\right] + \sum_{t=1}^{T}\sum_{i}^{I}\lambda_{it}\left(\sum_{j=1}^{J}\delta_{jt}B_{ji}-1\right)$$

subject to $d_{it+1} = d_{it} + \sum_{j=1}^{J}\delta_{jt}v_{ijt}t \quad \forall i,t$

$d_{it} \ge D_{Li} \quad \forall i,t$

$d_{it} \le D_{Ui} \quad \forall i,t$

Decomposition to partial problems

$$\min\ l_j = \sum_{t=1}^{T}\left[c_{1j}\left|\delta_{jt}\right| + c_{2j}\left(d_{ij,obj}-d_{ij}\right)/d_{j,obj} + h_i\left(B_{ji}\, d_{ij}/D_{i\max}\right)\left(x_{i\max}-x_{it}\right)/x_{i\max}\right] + \sum_{t=1}^{T}\sum_{i}^{I}\lambda_{it}\delta_{jt}B_{ji}$$

subject to $d_{it+1} = d_{it} + \delta_{jt}v_{ijt}t \quad \forall i,t$

$d_{it} \ge D_{Li} \quad \forall i,t$

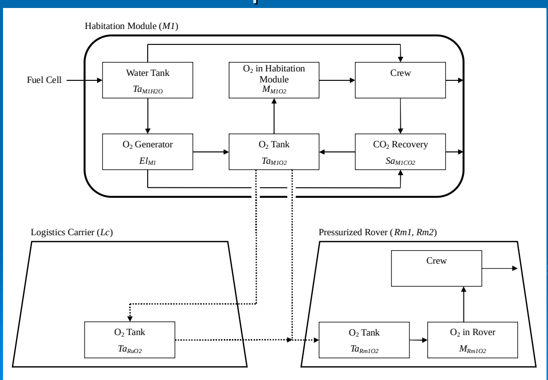
$d_{it} \le D_{Ui} \quad \forall i,t$

Lagrangian decomposition and coordination (LDC) procedure

1. A formulation of the problem (Original problem)
2. Decomposition to partial problems (Decomposability)
3. Solution of the relaxed partial problems optimally by using Dynamic Programming (DP)
   - If there are any competitions in solving partial problems, the procedure moves on to the next step.
4. Provides a feasible solution for the original problem based on optimized solutions of the partial problems

This method does not suffer from the usual exponential increase in computational complexity in proportion to size of the problem.

Oxygen supply systems in the lunar outpost



Oxygen supply system models

Oxygen tank model

$$Ta_{M1O2}(t+1) = Ta_{M1O2}(t) + pO_{2Sa}(t) + pO_{2El}(t) - rO_{2M1}(t) - sw_1 - sw_2 - sw_3$$
$$Ta_{LcO2}(t+1) = Ta_{LcO2}(t) + sw_1 - sw_4 - sw_5$$
$$Ta_{Rm1O2}(t+1) = Ta_{Rm1O2}(t) - rO_{2Rm1}(t) + sw_2 + sw_4$$
$$Ta_{Rm2O2}(t+1) = Ta_{Rm2O2}(t) - rO_{2Rm2}(t) + sw_3 + sw_5$$

Position model

$$d_i = \delta_i v_i t_i$$
$$\delta_i = \{-1, 0, 1\}$$

Oxygen supply model

$$sw_j = \begin{cases} if\,(d_1=0) & sw_1 = Ta_{LcO2\max} - Ta_{LcO2}(t) \\ if\,(d_2=0) & sw_2 = Ta_{Rm1O2\max} - Ta_{Rm1O2}(t) \\ if\,(d_3=0) & sw_3 = Ta_{Rm2O2\max} - Ta_{Rm2O2}(t) \\ if\,(d_1=d_2) & sw_4 = Ta_{Rm1O2\max} - Ta_{Rm1O2}(t) \\ if\,(d_1=d_3) & sw_5 = Ta_{Rm2O2\max} - Ta_{Rm2O2}(t) \end{cases}$$

The operation schedule of the Logistics Carrier is calculated considering both the rover positions and supply possibilities.

Initial condition for two operation schedules

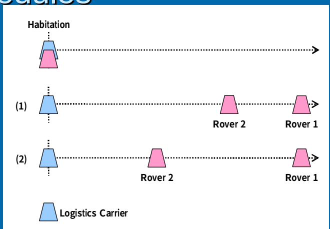
1. Rover 1 and Rover 2 are used at a short separation distance
2. Rover 1 and Rover 2 are used at a long separation distance

- Given positions of Rover 1 and Rover 2 for their two-week explorations

Rover 1 = {0,1,2,3,4,5,6,7,6,5,4,3,2,1,0}

Rover 2 = {0,0,1,2,3,4,5,5,5,4,3,2,1,0,0}

Rover 2 = {0,0,1,2,3,3,3,3,3,3,3,2,1,0,0}



Amounts of initial oxygen storage

Logistics Carrier: 28 CM-days

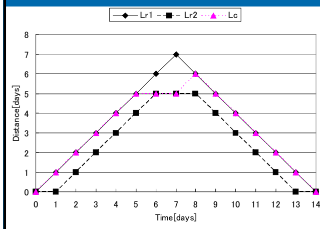
Rover 1 and Rover 2: 14 CM-days

which is a half requirement for two weeks

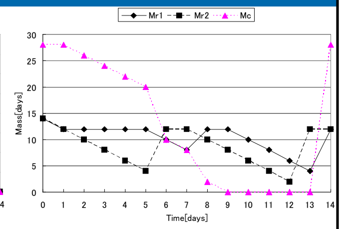
The units of the position and the amount of oxygen are defined:
1 [day] is the distance of 1 day's movement,
and 1 [CM-day] is the amount of oxygen consumed per crewmember in 1 day.

Rover 1 and Rover 2 are used at a short separation distance

Positions of the vehicles



Amounts of oxygen

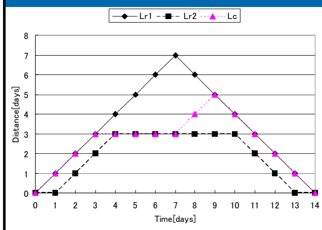


Horizontal axis : Time [days]
Vertical axis : Distance [days]

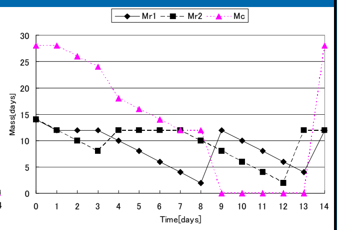
Horizontal axis : Time [days]
Vertical axis : Amounts of oxygen [CM-days]

Rover 1 and Rover 2 are used at a long separation distance

Positions of the vehicles



Amounts of oxygen



Horizontal axis : Time [days]
Vertical axis : Distance [days]

Horizontal axis : Time [days]
Vertical axis : Amounts of oxygen [CM-days]

Summary

- The proposed logistics network for manned wide-area exploration on the lunar surface was formulated by means of a Logistics Carrier operation problem using LDC.
- The results demonstrate that this method can solve operation schedule problems that consist of two rovers and a Logistics Carrier all modeled in limited axial movement.
- The method benefits from the computational accuracy of partial problems because of the use of Dynamic Programming (DP) to solve them.
- Because this is a decomposition method, it can be applied to large-scale problems. As the evaluation function of this method can be expanded to include movement in a network, the plan is to extend the application to large-scale problems in complex networks in the future.

This method is applicable to resource allocation problems which consist of distributed subsystems in a wide area such as the lunar surface, Mars, and deep space explorations.