Rover Routing Problems and Distributed Life Support Systems Analysis for Lunar Surface Exploration

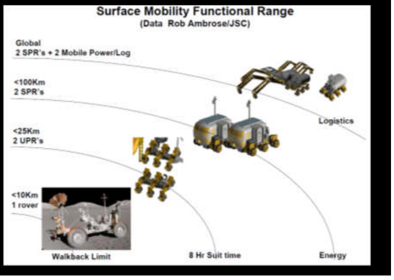
42nd International Conference on Environmental Systems (ICES)
15 - 19 Jul 2012
Hilton San Diego, San Diego, California

Hiroyuki Miyajima
Tokyo Jogakkan College
Space Systems Development Corporation

Table of contents

High-Mobility Exploration on Lunar Surface

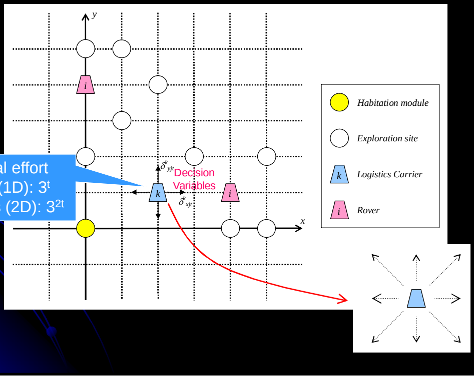
- One of the lasting lessons of the Apollo project is over the idea that surface mobility is key to improving the efficiency of manned exploration on the lunar surface. (Robert M. Bagdigian, SAE 2009-01-2481).
- Explore the lunar surface at a range stretching beyond a hundred kilometers from outpost with the use of a logistics carrier and pressurized rovers.
- Life support systems as well as supplies for life support may be used at individual points within the range.



Objective

- The purpose of this research is to provide a method for logistics carriers to make dynamic resource allocations and to design distributed life support system configurations by computer simulation.
  - The previous paper described an analysis of the logistics carrier operations using a two-dimensional model on the lunar surface. (H. Miyajima AIAA 2011-5233)
  - The capability of the method was confirmed by numerical simulations with regard to the expansion of operation time and range of movement.
- In this paper, life support system designs and operations are studied using an expedition route from the Shackleton crater to Malapert based on topographic data provided by the SELenological and ENgineering Explorer (SELENE) of JAXA.

Formulation of a logistics carrier and rover movement in a logistics network



Computational effort
1 Dimension (1D): 3^t
2 Dimensions (2D): 3^{2t}

Lagrangian decomposition and coordination (LDC) procedure

1. Formulation of the problem (Original problem)
2. Decomposition to partial problems (Decomposability)
3. Optimal solution of the relaxed partial problems through the use of Dynamic Programming (DP)
   - 2-dimensional DP method was developed to obtain exact solutions of partial problems
4. If there is any competition, it provides a feasible solution for the original problem based on optimized solutions of the partial problems

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

Cost of Logistics Carrier's movements

Supply cost to Rovers

Supply cost to Logistics Carriers

Terrain effect

$$min \quad \sum_{t=1}^{T}\sum_{k=1}^{K}\left[\sum_{j=1}^{J} c_k \sqrt{(\delta_{xjt}^{k})^2+(\delta_{yjt}^{k})^2}\right.$$

$$+\sum_{i}^{I} h_i A_{ik}\sqrt{(((dr_{xit}-d_{xh})/D_{xU})^2+((dr_{yit}-d_{yh})/D \quad)}\left((M_{Ui}-m_{it})/M_{Ui}\right)$$

$$\left.+h_k\sqrt{(((dc_{xkt}-d_{xh})/D_{xU})^2+((dc_{ykt}-d_{yh})/D_{yU})^2)}\left((M_{Uk}-m_{kt})/M_{Uk}\right)+te\cdot G\left(dc_{xkt},dc_{ykt}\right)\right]$$

$subject \quad to \quad dc_{(x,y)k,t+1}=dc_{(x,y)kt}+\delta_{(x,y)jt}^{k}\cdot v^{k}{}_{(x,y)jt} \quad \forall j,k,t$	Logistics Carrier (LC) position
$dc_{(x,y)kt}\ge D_{(x,y)L} \quad \forall k,t$	Lower bound of LC's position
$dc_{(x,y)kt}\le D_{(x,y)U} \quad \forall k,t$	Upper bound of LC's position
$m_{i,t+1}=m_{it}+\Delta m_{it} \quad \forall i,t$	Stored mass on Rover
$m_{k,t+1}=m_{kt}+\Delta m_{kt} \quad \forall k,t$	Stored mass on LC
$\sum_{j}^{J}\delta_{(x,y)jt}^{k}B_{(x,y)jk}\le 1 \quad \forall k,t$	Competition on LC

Lagrangian relaxation

$$min \quad l=\sum_{t=1}^{T}\sum_{k=1}^{K}\left[\sum_{j=1}^{J} c_k \sqrt{(\delta_{xjt}^{k})^2+(\delta_{yjt}^{k})^2}\right.$$

$$+\sum_{i}^{I} h_i A_{ik}\sqrt{(((dr_{xit}-d_{xh})/D_{xU})^2+((dr_{yit}-d_{yh})/D_{yU})^2)}\left((M_{Ui}-m_{it})/M_{Ui}\right)$$

$$\left.+h_k\sqrt{(((dc_{xkt}-d_{xh})/D_{xU})^2+((dc_{ykt}-d_{yh})/D_{yU})^2)}\left((M_{Uk}-m_{kt})/M_{Uk}\right)+te\cdot G\left(dc_{xkt},dc_{ykt}\right)\right]$$

$$+\sum_{t=1}^{T}\lambda_t\sum_{k=1}^{K}\sum_{j}^{J}\delta_{(x,y)jt}^{k}B_{(x,y)jk}$$

Decomposition to partial problems

$$min \quad l_k=\sum_{t=1}^{T}\left[\sum_{j=1}^{J} c_k \sqrt{(\delta_{xjt}^{k})^2+(\delta_{yjt}^{k})^2}\right.$$

$$+\sum_{i}^{I} h_i A_{ik}\sqrt{(((dr_{xit}-d_{xh})/D_{xU})^2+((dr_{yit}-d_{yh})/D_{yU})^2)}\left((M_{Ui}-m_{it})/M_{Ui}\right)$$

$$\left.+h_k\sqrt{(((dc_{xkt}-d_{xh})/D_{xU})^2+((dc_{ykt}-d_{yh})/D_{yU})^2)}\left((M_{Uk}-m_{kt})/M_{Uk}\right)+te\cdot G\left(dc_{xkt},dc_{ykt}\right)\right]$$

$$+\sum_{t=1}^{T}\lambda_t\sum_{j}^{J}\delta_{(x,y)jt}^{k}B_{(x,y)jk}$$

Initial Condition

Transportation Capacity

- ➢Six crewmembers can stay in the Habitation Module
- ➢Two groups, each consisting of two crewmembers, can explore at the same time.
- ➢Rover has sufficient supplies to sustain two persons for 14 days (+ 2 days).
- ➢Initial stored oxygen: Rovers 1 & 2 : 32CM-days : Logistics Carrier : 56 CM-days

1 CM-day is equivalent to the amount of oxygen consumed by one crewmember in one day.

Production and recycling of material

	Habitation Module	Rovers
O_2 Generation	Yes	No
CO_2 Removal and Reduction	Yes and Yes	Yes and No
Waste Waster is collected	Yes	Yes
Water Recovery	Yes	No

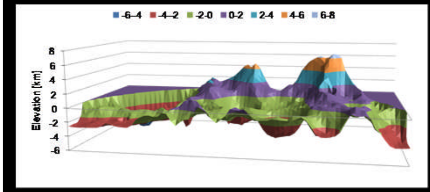
NASA Constellation Architecture Team-Lunar Scenario 12.0

Planning Problem

- ➢28 day operation (twice of 14 day) schedules of Rovers 1 & 2 are given in advance for expedition to Cabeus and Malapert and the operation schedule of the Logistics Carrier is determined by the calculation.
- ➢This schedule has to keep the stored oxygen of Rovers 1 & 2 and the Logistics Carrier within a specific range. And also keep stored water and waste water levels within a specific range.

Lunar Terrain Map around South Pole

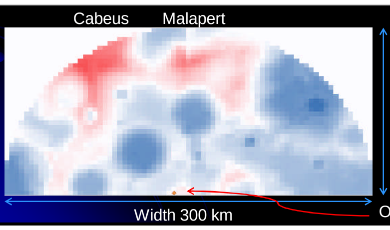
Topographic data provided by JAXA/SELENE



Latitude: 85 S ~ 90 S degrees
Longitude: 90 W ~ 90 E degrees

Center of the front side: South Pole
Backside: Earth's view

Cabeus Malapert



Earth's View

Depth 150 km

Width 300 km

Outpost at Shackleton crater

Mass Balance

Consumption increases 16.7 % after 8 hours of EVA

Crewmember Life Support Input and Output

Input	Without EVA kg/CM-day	With EVA kg/CM-day	Output	Without EVA kg/CM-day	With EVA kg/CM-day
Oxygen	0.835	0.974	Carbon dioxide	0.998	1.165
Dry food solids	0.617	0.720	Urine solids	0.059	0.069
Food rehydration water, and water in food	1.424	1.662	Fecal solids	0.032	0.037
Drinking water	2.100	2.451	Sweat solids	0.018	0.021
			Respiration and perspiration water	2.277	2.657
			Urine water	1.501	1.752
			Fecal water	0.091	0.106
Hygiene water	0.560	0.560	Water used for hygiene	0.560	0.560
Urine flush water	0.300	0.300	Water used for urine flush	0.300	0.300
Total intake water	**3.524**	**4.113**	**Total elimination water**	**3.869**	**4.515**
Total water	**4.384**	**4.973**	**Total water**	**4.729**	**5.375**
Total	**5.836**	**6.667**	**Total**	**5.836**	**6.667**

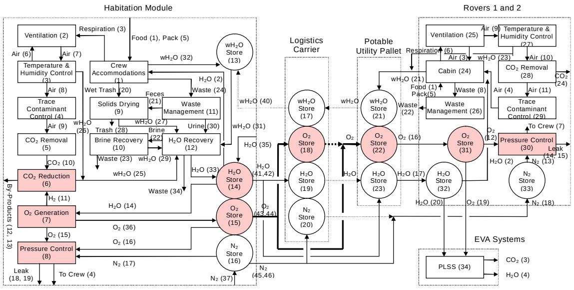
In HM: 1.096 – 0.953 = 0.143 kg
In Rovers :1.096 kg

Water Balance of CO_2 Reduction and O_2 Generation

Input	Without EVA kg/CM-day	With EVA kg/CM-day	Output	Without EVA kg/CM-day	With EVA kg/CM-day
CO_2	0.998	1.165	$2H_2O$	0.817	0.953
$2H_2$	0.091	0.106	C	0.272	0.318
CO_2 reduction total	**1.089**	**1.271**	**CO_2 reduction total**	**1.089**	**1.271**
$2H_2O$	0.939	1.096	O_2	0.835	0.974
			$2H_2$	0.104	0.122
O_2 generation total	**0.939**	**1.096**	**O_2 generation total**	**0.939**	**1.096**

The EVA uses 2 kg/CM-day surplus suit cooling water which is not reusable.
6 cycles/week x 4 crewmembers

Life Support Systems in the Lunar Outpost



Solved oxygen, water and waste water allocation problems using oxygen supply as the driving factor

Oxygen supply system

Oxygen tank models

$$Ta_{M1O2}(t+1) = Ta_{M1O2}(t) + pO_{2Sa}(t) + pO_{2El}(t) - rO_{2M1}(t) - sw_1 - sw_2 - sw_3$$ Habitation Module

$$Ta_{L1O2}(t+1) = Ta_{L1O2}(t) + sw_1 - sw_4 - sw_5$$ Logistics Carrier

$$Ta_{R1O2}(t+1) = Ta_{R1O2}(t) - rO_{2R1}(t) + sw_2 + sw_4$$ Rover 1

$$Ta_{R2O2}(t+1) = Ta_{R2O2}(t) - rO_{2R2}(t) + sw_3 + sw_5$$ Rover 2

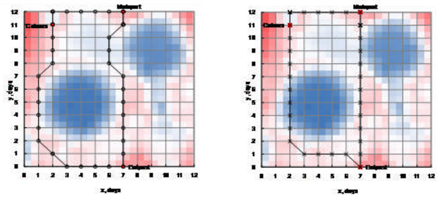
Oxygen supply models

$$sw_j = \begin{cases} if\,(dc_1 = 0) & sw_1 = Ta_{L1O2\max} - Ta_{L1O2}(t) \\ if\,(dr_2 = 0) & sw_2 = Ta_{R1O2\max} - Ta_{R1O2}(t) \\ if\,(dr_3 = 0) & sw_3 = Ta_{R2O2\max} - Ta_{R2O2}(t) \\ if\,(dc_1 = dr_2) & sw_4 = Ta_{R1O2\max} - Ta_{R1O2}(t) \\ if\,(dc_1 = dr_3) & sw_5 = Ta_{R2O2\max} - Ta_{R2O2}(t) \end{cases}$$

LC ＝ HM
Rover 1 ＝ HM
Rover 2 ＝ HM
LC ＝ Rover 1
LC ＝ Rover 2

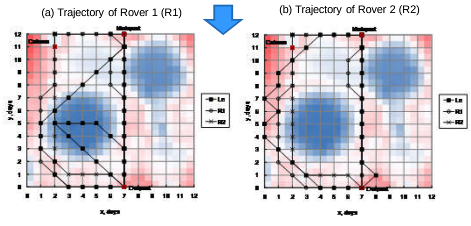
Same equations of water and waste water are also modeled

Trajectory of Rover 1 (R1), Rover2 (R2) and Logistics Carrier (Lc) in a 28 day operation



(a) Trajectory of Rover 1 (R1)

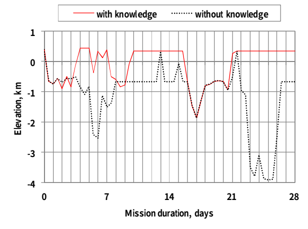
(b) Trajectory of Rover 2 (R2)



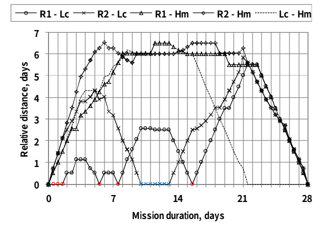
Trajectory of Logistics Carrier (Lc) without knowledge of difficult terrain

(d) Trajectory of Logistics Carrier (Lc) with knowledge of difficult terrain

Elevation changes and Relative distance



Elevation changes of Logistics Carrier



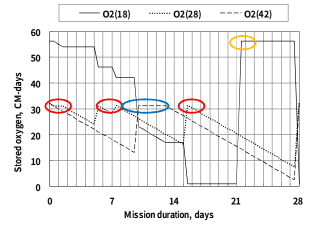
Relative distance between Rover 1 (R1), Rover 2 (R2), Logistics Carrier (Lc) and Habitation Module (Hm)

Ranges in elevation
With terrain effect: 2.3km
Without terrain effect: 4.3km

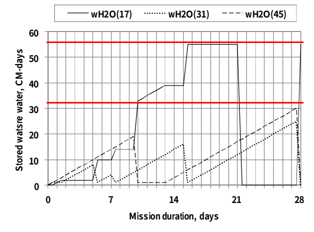
Lc -> R1: Days 1,2,6,8 and 16
Lc -> R2: Days 10-13
Lc -> Hm : Day 21

Stored oxygen and waste water changes

Steps of stored oxygen, water and waste water changes are defined: 1 CM-day is 0.974 kg, 4.973 kg + 2kg(EVA), and 5.375 kg, respectively.



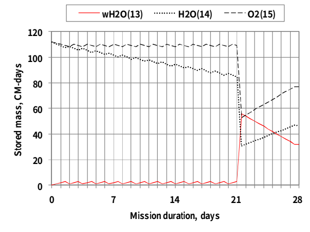
Stored oxygen changes in Logistics Carrier (18), Rover 1 (28) and Rover 2 (42)



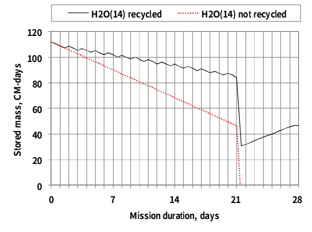
Stored waste water changes in Logistics Carrier (17), Rover 1 (31) and Rover 2 (45)

Rover 1 on days 1, 2, 6, 8 and 16
Rover 2 from days 10 to 13.

Stored mass changes in Habitation Module



Stored mass changes of waste water (13), water (14) and oxygen (15) in HM when waste water is recycled



Comparison of stored water (14) changes when waste water is recycled and not recycled.

Summary

- This work has examined an operations planning method for a Logistics Carrier using Lagrangian Decomposition and Coordination (LDC) to study high-mobility exploration on the lunar surface.
- In a previous paper the capability of the 2DP method was confirmed by numerical simulations in which operation time and movement were expanded.
- In this paper, the Logistics Carrier's operation route is enhanced by the addition of terrain effect based on actual lunar surface topography taken near the South Pole by SELENE/JAXA.
- The 2DP method yielded a successful operation plan for the Logistics Carrier to supply oxygen and water to the two Rovers and to bring waste water back to the Habitation Module while avoiding mountains and craters during a 28-day expedition to Cabeus and Malapert.
- It was confirmed that the distributed life support systems in the Logistics Carrier and Rovers can operate within acceptable supplies of oxygen, water, and waste water capacities.