SPACE TRANSPORTATION NETWORK MODEL FOR RAPID LUNAR ARCHITECTURES EXPLORATION

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ABSTRACT

The challenge of space exploration is to do technologically and cost efficient short and long-term missions. With uncertainty in funding, political and public support, mission design and planning needs to forward sustainable architecture decisions. We develop a rapid evaluation tool for lunar architectures, which allows analysis of many mission and technological options simultaneously. This paper explains the modeling approach, and gives a flavor of the results. This tool provides potential for powerful analysis for campaign planning, long-term strategy and asset development.

NOMENCLATURE

CTVa – Crew Transportation Vehicle A
CTVb – Crew Transportation Vehicle B
tHABem – Transfer habitat from Earth to Moon/Mars
tHABme – Transfer habitat from Moon/Mars to Earth
sHAB – Surface habitat
dHAB – Descent habitat
aHAB – Ascent habitat
TMI – Trans-lunar stage
AS – Ascent stage
DS – Descent stage
TEI – Trans-Earth injection stage
EO – Earth orbit
MO – Moon/Mars orbit
M orbit, M surface – refers to either Moon or Mars
ESL1 – Earth-Sun L1
ESL2 – Earth-Sun L2
EML1 – Earth-Moon L1
EML2 – Earth-Moon L2

INTRODUCTION

The goal of paper is to present a rapid-evaluation, moderate-detail space transportation architectures tool for lunar missions. The tool should allow testing the conceivable space of transportation architectures via a set of generic vehicle models.

The challenge of space exploration is to plan technologically and cost efficient short and long-term missions. With uncertainty in funding and public support, countries with space programs strive to ensure program sustainability, especially for landing on the Moon by 2018. The next challenge is integrating new technologies in a traditionally slow development and testing industry. It is difficult and expensive to test and validate new technologies independently in a remote space environment. Often design decisions are made early and critical options are missed. To aid the early design process, a systems engineering mathematical approach is proposed to explore rapidly all architectures with various technology switches to a moderate level of engineering detail.

The space transportation network model consists of abstract spacecraft states during a lunar mission, such as planetary surfaces (Earth, lunar), orbits (Low Earth Orbit, cislunar, Low Lunar Orbit, around a Lagrange point) and operational-sequence states like descent and ascent, launch and re-entry. The latter are modeled as discrete states with timelines similar to the Apollo and Soyuz descent/ascent profiles.

In a state, the spacecraft expends fuel for attitude control, stationkeeping or trajectory correction burns and has power-related activities. States are modeled as continuous-discrete blocks with varying discretized time steps. For example, launch and ascent/descent take on order of 10 minutes to 60 minutes, whereas orbiting takes order of hours, and surface exploration - order of days. State transitions are usually related to an instantaneous fuel burn. Surface operations are not modeled in detail except for considering science and mobility payload and ISRU (In-Situ Resource Utilization) fractions. A surface habitat is designed at the same level as other in-space, descend, ascent and (combinations of) habitats.

Architectures are generated by considering all possible paths from node to node and then assigning all combinations of vehicle fleets that satisfy the mission requirements. Around 20000 architectures, of varying degrees of similarity, feasibility and interest, are generated. The number is high because of the Lagrange point analysis and the numerous vehicle options. Rankings of vehicle mass breakdowns, vehicle types, mission launch weight and other data is available. This model enables analysis of key technologies such as propulsion types, engine types, materials and in general transportation scenarios and vehicle combinations. Multiple stakeholder value and technology trade-off analysis is also possible. The network description allows to identify key staging locations in space and select enabling technologies for investment.

MOTIVATION

System design is traditionally tailored to a particular mission and fixed architecture. Detailed engineering models are usually built to address specific requirements. Recently, more holistic approaches have been employed to understand system design, including using concurrent engineering models and building general rapid evaluation models [1].

Space exploration is a complex topic with various levels of modeling, analysis and engineering decisions. It is challenging to look at the entire problem, and decide upfront which options are favorable in the long-term. The purpose of this study is to develop the entire tradespace of architectures for lunar exploration and provide a tool for relatively rapid moderate-fidelity evaluation of a single architecture.

The value of exploring the entire tradespace has many aspects. It allows identifying missed opportunities, in logistical, technological or modeling sense. Understanding the problem holistically helps to classify architectures, including past experience in human space exploration. Another benefit is that looking at the big picture helps understand parts of the problem better. For example, some vehicles or stacks or specific technologies might appear more robust across architectures, or disable/enable architectures. Such insight will stimulate goals for further development. Finally, a holistic approach enables the implementation of various metrics, some of which might not necessarily be easily quantifiable. Examples are scientific goals, stakeholder value, cost, risk, complexity and robustness. Ranking architectures or options with various metrics might be much more insightful compared to simple launch mass ranking. This provides a powerful analysis capability to do campaign planning and think about assets in space and long-term strategy.

ARCHITECTURE GENERATION

In the context of space exploration, the definition of *architecture* used is a *set of vehicles and their operations during the mission*. More precisely, this means deciding which elements are needed to fulfill a particular mission and how they transfer, separately or together, how they are pre-deployed and which trajectories they traverse.

CTV-centric Approach

There are many ways to enumerate options, depending on the model. Our approach is based on the operations of the Crew Transportation Vehicle. The CTV is a central vehicle to any architecture. It is the module in which the crew is launched and maybe re-enters with. We call this a CTV-centric approach.

A Crew Transportation Vehicle can have levels of functionality. It can be a light module which only goes to Earth orbit, and remains there, waiting for the crew's return to rendezvous and re-enter. Second, a CTV can launch and transfer with the crew to Moon/Mars orbit, and remain there, waiting for rendezvous and return trajectory and re-entry. Finally, a CTV can go all the way to the surface and either function as a habitat or await ascent. These options are illustrated in Figure 1.

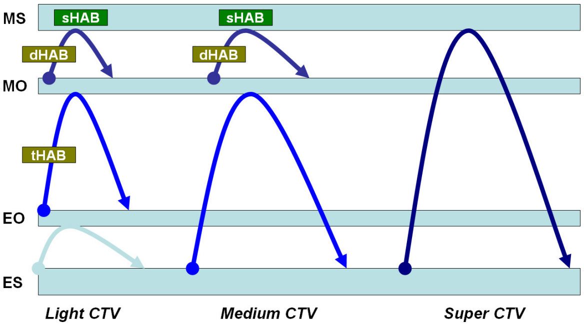

Figure 1: CTV functionality in three levels, *light*, *medium* and *super*-CTV. All three architectures are symmetric with respect to the CTV destination. Additional habitats where needed are also shown.

For each of the architectures outlined in Figure 1, it can be deduced in what other mission phase additional life support is needed. For example in the medium-CTV case, descent, ascent and surface habitation need habitat modules. In the light-CTV case, transfer habitats also have to be included. Using simple logic, the architecture generation code assigns relevant habitats and propulsion stages needed, based on the functionality of the CTV.

All architectures discussed so far are *symmetric* with respect to the CTV destination. Suppose a non-symmetric case, in which the CTV again has three levels of functionality, to EO, MO and MS (Moon surface) respectively, but does not return. In that case, we consider two CTVs, CTVa and CTVb, where CTVb is designed to always re-enter and at a maximum ascend from the surface. Then for each CTVa option there are three CTVb options. Some examples of these architectures are given in Figure 2.

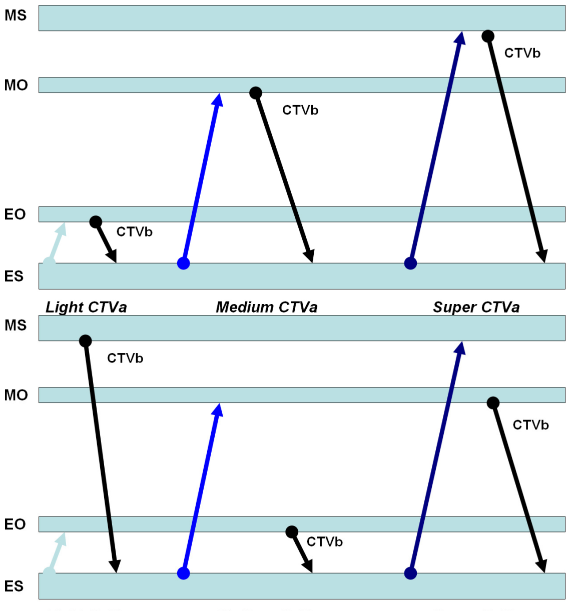

Figure 2: CTVa and CTVb options for non-symmetric architectures.

Considering all CTV-generated options and filling in the additional life support is documented in incidence matrices. A vehicle is present in an architecture and active during a particular phase if its corresponding cell is set to 1. Figure 3 shows an example of a light CTVa. CTVa stays in Earth orbit, therefore the matrix shows the incidence of transfer, surface and descent/ascent habitats.

Phases	CTVa	CTVb	tHABem	tHABme	sHAB	dHAB	aHAB
E Sub Orb	1	0	0	0	0	0	0
E Orb Inj	1	0	0	0	0	0	0
EO	1	0	0	0	0	0	0
TMI Burn	0	0	1	0	0	0	0
TO	0	0	1	0	0	0	0
LOI Burn	0	0	1	0	0	0	0
MO	0	0	0	0	0	1	0
M Deorbit	0	0	0	0	0	1	0
M Descent	0	0	0	0	0	1	0
M Surface	0	0	0	0	1	0	0
M Ascent	0	0	0	0	0	0	1
MO	0	0	0	0	0	0	1
TEI Burn	0	0	0	1	0	0	0
TO	0	0	0	1	0	0	0
Dir. descent	1	0	0	0	0	0	0
E EDL	1	0	0	0	0	0	0

Figure 3: Habitat incidence matrix. If an entry is set to 1, the corresponding habitat is active (crewed) during the corresponding phase or at least some fraction of it.[1]

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[1] Detailed mission description is given in the Appendix.

Vehicle combinatorics

The next step in defining the architecture after establishing the life support requirements is deciding the vehicle operations. For example, if a surface habitat is needed, how exactly is it pre-positioned to the surface. Does it arrive with the crew or a separate direct-to-surface flight?
To address this question, consider the nomenclature of flights visualized in Figure 4 and summarized in Table 1.

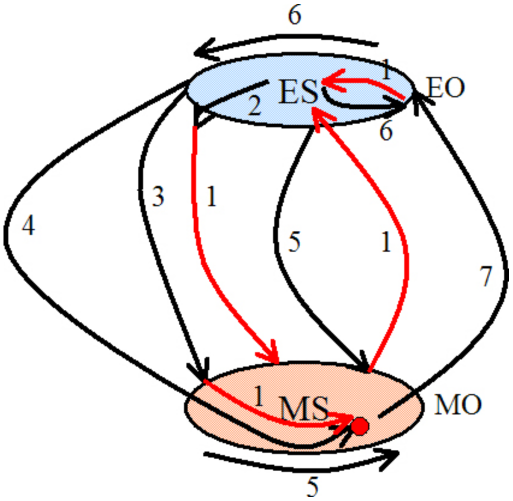

Figure 4: Flights definition illustration

There is one crewed flight: flight 1, all vehicles or modules transferring with the crew are said to be on flight 1. Essentially, flights are an abstract concept, defined by purpose. Modules can transfer from one flight to another in different phases. Non-crewed flights are usually pre-positioned, awaiting to be used (crewed) during the mission.

Pre-positioned flights can be i/ pre-positioning assets in near-Earth orbits: EO, ISS or other LEO orbits; ii/ pre-positioning in near-M (Moon/Mars) orbits: MO; iii/ pre-positioning in Lagrange points (ESL1, ESL2, EML1, EML2); iv/ pre-positioning in transfer orbit: TO and v/ pre-positioning on a planetary surface: Moon, Mars.

Table 1: Flights definition

Flight 1	wherever the crew is at all times; this is the only crewed flight, and it goes from E surface to M surface and back
Flight 3	pre-deployed assets in M orbit for descent, a non-crewed flight from E surface to M orbit
Flight 4	assets pre-positioned directly to M surface; a non-crewed flight which goes from E surface to M surface direct
Flight 5	pre-deployed to M orbit for return; a non-crewed flight from E surface to M orbit
Flight 6	Pre-positioned (waiting) in E orbit for re-entry; this is a non-crewed orbiting flight

This flight nomenclature allows describing vehicle operations during any mission phase. Figure 5 shows an augmented architecture description. This is a symmetric architecture (no CTVb) with a light-CTVa which stays in Earth orbit (on flight 5) waiting for the crew to return. The return transfer habitat tHABme is pre-deployed in M orbit on flight 5. The ascent and surface habitats are pre-positioned directly to the surface (on flight 4). The transfer habitat to M and the descent habitat are always with the crewed flight.

Phases	CTVa	CTVb	tHABem	tHABme	sHAB	dHAB	aHAB
E Sub Orbital	1	0	1	5	4	1	4
E Orb Inj	1	0	1	5	4	1	4
EO	1	0	1	5	4	1	4
TMI Burn	6	0	1	5	4	1	4
TO	6	0	1	5	4	1	4
LOI Burn	6	0	1	5	4	1	4
MO	6	0	0	5	4	1	4
M Deorbit	6	0	0	5	4	1	4
M Descent	6	0	0	5	4	1	4
M Surface	6	0	0	5	1	0	4
M Ascent	6	0	0	5	0	0	1
MO	6	0	0	5	0	0	1
TEI Burn	6	0	0	1	0	0	0
TO	6	0	0	1	0	0	0
TO to E direct	1	0	0	0	0	0	0
E EDL	1	0	0	0	0	0	0

Figure 5: Full description architecture matrix

Using this matrix representation, 27707 architectures were generated. A small number of those are interesting for further study. Further logic, constraints and requirements can be implemented to classify, group or downselect architectures. The architectures set can also be narrowed by mission requirements, such as direct descent, minimizing the number of rendezvous, the use of a Lagrange point, aerobraking and so on.

TRANSPORTATION NETWORK MODEL

In order to evaluate many architectures, a flexible space transportation model is necessary. A general transportation network model is developed, which covers all spacecraft states during a mission with relevant state transitions. This model captures the physics and implements a physical simulation of a single architecture, given any mission sequence. A mission sequence, or set of mission phases, is a sequence of states and the transitions between them.

A general model can tie network algorithms from operations research and graph theory with physical and engineering principles from aerospace engineering to describe a complete network of space trajectories with vehicle and module flow through them. The network representation also suggests that route optimization for payload flights is possible, if cheaper and slower transfer is desired.

Network model principle

There are states in space which a spacecraft can exist in with minimal energy (eg. orbiting). State transitions require energy leaps, in the form of fuel burns, provided by the vehicle itself or an external force (another vehicle, by-passing planet etc). Naturally, states can be modeled as nodes and transitions as links, so that mission time or value is concentrated in the nodes, while mission cost or energy spent is contained mainly in the links. This is not a perfect assumption, because transitions are not instantaneous and states are not cost-free (eg: stationkeeping and correction maneuvers). A visualization of the network model is shown in Figure 6.

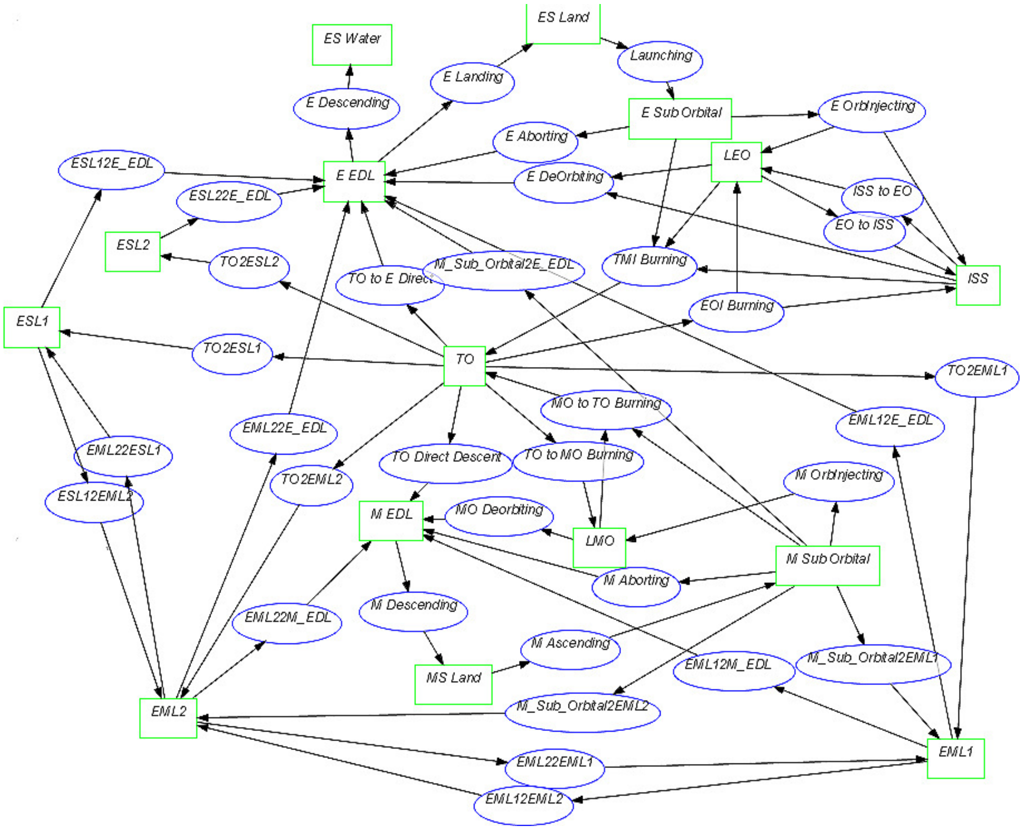

Figure 6: Complete Space Exploration Network Model

States and links, transition rules

A *node* or *state* is a physical state in which the spacecraft needs to spend a considerable amount of energy to leave. The exception to this rule are descent and ascent states. There are three types of nodes: orbits, surfaces and operational sequences. Earth orbit, M orbit, transfer orbit, orbits around Lagrange points are all considered orbits and physically described with 6 orbital elements in an Earth-centric reference frame. There are two surface nodes in this model (Earth and Moon) though for a Mars network trajectory model, other lunar surfaces like Phobos may be considered. Operational sequences are represented by 4 nodes, E_Sub_Orbital (Earth launch), E_EDL (Earth entry, descent and landing), M_Sub_Orbital (ascent from lunar surface) and M_EDL (descent onto lunar surface). These states are modeled with fixed delta Vs and durations regardless of the architecture. Reference numbers are taken from Apollo and Soyuz descent, ascent and entry, descent and landing data.

All nodes are saved in a list data structure, as described in Figure 7. For example, the transfer orbit node is type orbit, it has 6 orbital elements, from which only the true anomaly changes. Other information stored is mission time, duration which the spacecraft spends in that state, original and destination states.

```
node(TO).name = 'TO';
node(TO).type = orbit;
node(TO).origin = EO;
node(TO).dest = MO;
node(TO).start = 0;
node(TO).status.a = TO_semimajor_axis;
node(TO).status.i = TO_inclination*Constant('deg to rad');
node(TO).status.W = 0;
node(TO).status.w = 0;
node(TO).status.e = 1-node(EO).status.a/node(TO).status.a;
node(TO).status.M = 0;
node(TO).fin = Period(node(TO).status.a,Constant('muE'));
node(TO).time = node(TO).start;
node(TO).x = [r_to;v_to];
node(TO).stationkeep = TO_stkeep; % traj. corr.
node(TO).fe = 0;                  % eclipse fraction
```

Figure 7: Example of the mathematical description of the *transfer orbit* node. The information which changes with mission time is highlighted in red, including true anomaly and spacecraft position and velocity.

A *link* is a transition from one state to another. This is most often a fuel burn. Sometimes the delta V for transitions is zero, in cases like direct entry. Link values are set to 1, if they exist. Their value in terms of delta V is also saved, together with semantic description (name) and type. Type of links can be orbit to orbit (Hohmann transfer), surface to sequence (launch), orbit to sequence (deorbit burn) and so on. An example is given in Figure 8.

```
adj(EO,TO).name = 'TMI Burning';
adj(EO,TO).type = orb2orb;
adj(EO,TO).val = 1;
adj(EO,TO).dT = 800;
adj(EO,TO).fe = node(EO).fe;
```

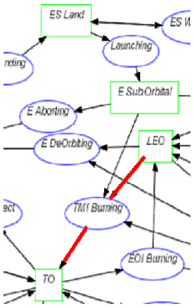

Figure 8: TMI link example

The exploration network is a directed graph which means that not all transitions between nodes are possible, or not all are considered in the model. For example, there is no direct link between the earth surface and the lunar surface because at least a transfer orbit is needed as an intermediary step. Each node has parents (set of nodes which have directed links pointing to this node) and children (set of nodes at which directed links arrive from the chosen node). Ideally, any transition from parents to children should be possible, unless there are mission requirements which specify certain trajectories or node sequences. There could also be physical constraints for certain vehicles which could enable or disable certain links. A change of state or a link transition causes a change of location ($\vec{x}$) and energy level ($\vec{v}$). The position and velocity vector are enough to describe the state of the spacecraft in some reference frame (ECI or with respect to the Sun). In terms of the vehicle, the wet mass usually decreases with the amount of used up propellant, while the structure could also suffer some changes, like radioactive and thermal effects.

Transition rules are based primarily on what transitions are possible, described by directed links in the network model and by the pre-specified mission sequence. Delta Vs and times of flight are calculated for a link only if the link exists during the simulation.

Path generation

The resulting network contains many loops so for the purposes of path optimization assume that going through the same state is not optimal in the energy sense unless mission requirements dictate so, and unless this is on a return trajectory. The connectivity of the trajectory graph reduces the number of possible paths from node to node. For example, to get to any node far from the vicinity of the Earth, the node TO (transfer orbit) is needed. Paths leading outside of Earth orbit can be partially optimized already up to transfer orbit (TO). The following example shows all possible ways to get to transfer orbit from the Earth surface, given this network. Transitions are shown in brackets.

```
ES_Land → TO
ES_Land (Launching) → E_Sub_Orbital
    (TMI_Burning) → TO
ES_Land (Launching) → E_Sub_Orbital
    (E_OrbInjecting) → EO (TMI_Burning)
    → TO
ES_Land (Launching) → E_Sub_Orbital
    (E_OrbInjecting) →ISS (TMI_Burning)
    → TO
ES_Land (Launching) → E_Sub_Orbital
    (E_OrbInjecting) → EO (EO_to_ISS) →
    ISS (TMI_Burning) → TO
ES_Land (Launching) → E_Sub_Orbital
    (E_OrbInjecting) → ISS (ISS_to_EO) →
    EO (TMI_Burning) → TO
```

Delta Vs and times of flight are calculated or assigned during the simulation. Hohmann transfer from Earth to the Moon and back is also modeled. Standard Hohmann transfer is used, which is designed so that the spacecraft meets the Moon at a preset date. Both the lunar orbit and the ISS orbit are simulated using an orbit propagation algorithm and Julian dates.

SAMPLE RESULTS AND CONCLUSION

In this section, the results of the light-CTV and super-CTV cases are shown. Masses per subsystem for the various vehicles are presented in table format.

Light CTV

In this architecture, as seen in the matrix below, CTVa stays in Earth orbit, the crew transfers in a separate habitat, descends and ascends to and from surface with dedicated habitats. A dedicated surface habitat is pre-positioned directly to the surface. The architecture matrix is shown below, which is an instance of the matrix in Figure 5. The rows correspond to mission phases, indexed in the first column (see Appendix for indexing), the columns correspond to the following vehicles: CTVa CTVb tHABem tHABme sHAB dHAB aHAB TEI1 AS1 DSc DS4, in that order.

```
arch_mat = [ 1  1  0  1  5  4  1  4  1  4  1  4;
             4  1  0  1  5  4  1  4  1  4  1  4;
             5  1  0  1  5  4  1  4  1  4  1  4;
            10  6  0  1  5  4  1  4  1  4  1  4;
            11  6  0  1  5  4  1  4  1  4  1  4;
            16  6  0  1  5  4  1  4  1  4  1  4;
            18  6  0  0  5  4  1  4  1  4  1  4;
            19  6  0  0  5  4  1  4  1  4  1  4;
            20  6  0  0  5  1  0  4  4  4  0  0;
            21  6  0  0  5  0  0  1  1  1  0  0;
            23  6  0  0  5  0  0  1  1  1  0  0;
            16  6  0  0  1  0  0  0  1  0  0  0;
            17  6  0  0  1  0  0  0  1  0  0  0;
            11  6  0  0  1  0  0  0  1  0  0  0;
            13  1  0  0  0  0  0  0  0  0  0  0;
             3  1  0  0  0  0  0  0  0  0  0  0];
```

A key thing to notice about this architecture is that the TEI stage goes to the surface (this can happen for abort options), which results in very high propulsion masses for descent/ascent stages and further on TMI stages. Masses, per subsystem for the CTV are shown in Table 2.

Table 2. Mass breakdown for a light-CTV mission.

CTVa	**Mass [kg]**	**Margin [%]**	**Mass incl. Margin [kg]**	**% of Dry Mass [%]**
AOCS	25.8	5.0	27.1	1.0
Propulsion	0.0	10.0	0.0	0.0
Instruments	220.0	0.0	220.0	7.8
Power	125.4	7.1	134.2	4.8
Communication	35.3	9.2	38.6	1.4
Data Handling	109.0	10.9	120.9	4.3
Structures	698.2	20.0	837.8	29.9
Mechanisms	224.4	10.0	246.8	8.8
Thermal	555.8	10.0	611.4	21.8
Life Support	566.0	0.1	566.4	20.2
Total Dry Mass	**2559.9**	**9.51**	**2803.3**	**100**
System Margin		***10.00***	***280.3***	
Total Dry Mass with Margin			**3083.6**	
Total Dry Mass Margin		***20.46***		
AOCS Propellant	16.1	50.00	24.2	
Propulsion Propellant	0.0	0.00	0.0	
Total Propellant			**24.2**	
Total Module Mass at Launch			***3107.8***	

Super CTV

In this architecture, CTV performs the life support function during the entire mission. There is only one non-crewed flight, 4, which pre-positions the ascent stage on the surface. The architecture matrix follows and the mass breakdown for the CTV is presented in Table 3.

```
arch_mat = [ 1 1  0  0  0  0  0  0  1  4  1  4;
              4  1  0  0  0  0  0  0  1  4  1  4;
              5  1  0  0  0  0  0  0  1  4  1  4;
             10  1  0  0  0  0  0  0  1  4  1  4;
             11  1  0  0  0  0  0  0  1  4  1  4;
             15  1  0  0  0  0  0  0  1  4  1  4;
             16  1  0  0  0  0  0  0  1  4  1  4;
             18  1  0  0  0  0  0  0  1  4  1  4;
             19  1  0  0  0  0  0  0  1  4  1  4;
             20  1  0  0  0  0  0  0  4  4  0  0;
             21  1  0  0  0  0  0  0  1  1  0  0;
             23  1  0  0  0  0  0  0  1  1  0  0;
             16  1  0  0  0  0  0  0  1  0  0  0;
             17  1  0  0  0  0  0  0  1  0  0  0;
             11  1  0  0  0  0  0  0  1  0  0  0;
             13  1  0  0  0  0  0  0  0  0  0  0;
              3  1  0  0  0  0  0  0  0  0  0  0];
```

Table 3. Mass breakdown for a heavy-CTV.

CTVa	Mass [kg]	Margin [%]	Mass incl. Margin [kg]	% of Dry Mass [%]
AOCS	25.8	5.0	27.1	0.4
Propulsion	0.0	10.0	0.0	0.0
Instruments	220.0	0.0	220.0	2.9
Power	3665.1	6.7	3910.2	51.4
Communication	35.3	9.2	38.6	0.5
Data Handling	109.0	10.9	120.9	1.6
Structures	803.6	20.0	964.3	12.7
Mechanisms	224.4	10.0	246.8	3.2
Thermal	555.8	10.0	611.4	8.0
Life Support	1461.3	0.1	1462.3	19.2
Total Dry Mass	**7100.3**	**7.06**	**7601.7**	**100**
System Margin		***10.00***	***760.2***	
Total Dry Mass with Margin			**8361.8**	
Total Dry Mass Margin		***17.77***		
AOCS	16.1	50.00	24.2	
Propellant				
Propulsion Propellant	0.0	0.00	0.0	
Total Propellant			**24.2**	
Total Module Mass at Launch			***8386.0***	

These numbers indicate that from a very rough estimate a light CTV without propellant (except for attitude control) weighs about 3 tons at launch, while a heavy CTV weighs about 8.4 tons at launch. These numbers should be taken with a grain of salt, especially because the fuel weight is not included, but they give a sense of the type of analysis possible.

In this paper, we presented a general, rapid evaluation tool for lunar architectures, with all the modeling and algorithm principles, and a sample of the results. We believe that such modeling techniques can stimulate and accelerate detailed design studies and overall be a useful tool for a lunar or Mars mission architects.

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APPENDIX

Table 2: Table of mission phases, their description, active habitat modules and flights (as defined in Table 1). Note: Flight 7 is reserved for returning scientific payload from M surface on a non-crewed flight.

index	Phase Name	Phase Description	Flights	Active Habitats
1	**E Sub Orbital**	Suborbital launch sequence	1,2,3,4,5,6	CTVa
2	**E Aborting**	Aborting to descent before third stage insertion	1	CTVa
3	**E EDL**	Entry, descent and landing sequence	1,7	CTVa, CTVb
4	**E OrbInjecting**	Third stage injection to a LEO orbit (+ISS)	1,2,3,4,5,6	CTVa
5	**EO**	Earth Orbit	1,2,3,4,5,6	CTVa, tHABem
6	**ISS**	ISS orbit	1,2,3,4,5,6	CTVa, tHABem
7	**EO to ISS**	Earth orbit to ISS orbit burn	1,2,3,4,5,6	CTVa, tHABem
8	**ISS to EO**	ISS orbit to another EO orbit burn	1,2,3,4,5,6	CTVa, tHABem
9	**E DeOrbiting**	Deorbit burn for EDL sequence	1	CTVa
10	**TMI Burning**	Trans-Lunar injection burn	1,3,4,5	CTVa, tHABem
11	**TO**	Transfer Orbit to the Moon	1,3,4,5,7	CTVa, CTVb, tHABem, tHABme
12	**EOI Burning**	Earth orbit injection burn from TO	1	CTVa, CTVb, tHABme
13	**TO to E Direct**	Direct Descent to Earth from TO	1,7	CTVa, CTVb
14	**TO Direct Descent**	Direct descent to lunar surface from TO	1,4	CTVa, tHABem
15	**TO to MO Burning**	Injection burn to low lunar orbit	1,3,4,5	CTVa, tHABem
16	**MO**	Low lunar orbit	1,3,4,5,7	CTVa, CTVb, tHABem, tHABme
17	**MO to TO Burning**	Trans-Earth injection burn	1,7	CTVa, CTVb, tHABme
18	**MO Deorbiting**	Deorbit burn from LLO to lunar descent sequence	1	CTVa, dHAB
19	**M EDL**	Lunar descent sequence	1,4	CTVa, dHAB
20	**MS Land**	Lunar surface	1,4	CTVa, sHAB
21	**M Sub Orbital**	Ascent sequence from lunar surface	1,7	CTVa, CTVb, aHAB
22	**M Aborting**	Abort ascent to low lunar orbit	1	CTVa, CTVb, aHAB
23	**M OrbInjecting**	Inject into low lunar orbit from M_Sub_Orbital	1,7	CTVa, CTVb, aHAB
24	**EO2ESL1**	Earth orbit to ESL1 transfer	3,4,5	-
25	**ESL1**	Earth-Sun-L1 Lagrange point	3,4,5,7	-
26	**ESL12E_EDL**	ESL1 to Earth surface transfer	7	-
27	**EO2ESL2**	Earth orbit to ESL2 transfer	3,4,5	-
28	**ESL2**	Earth-Sun-L2 Lagrange point	3,4,5,7	-
29	**ESL22E_EDL**	ESL2 to Earth surface direct transfer	7	-
30	**EO2EML1**	Earth orbit to EML1 transfer	3,4,5	-
31	**EML1**	Earth-Moon-L1 Lagrange point	3,4,5,7	-
32	**EML12E_EDL**	EML1 direct transfer to Earth surface	7	-
33	**EML12M_EDL**	EML1 direct transfer to Lunar surface	3,4,5	-
34	**M_Sub_Orbital2EML1**	Lunar surface direct to EML1	7	-
35	**EO2EML2**	Earth orbit to EML2 transfer	3,4,5	-
36	**EML2**	Earh-Moon-L2 Lagrange point	3,4,5,7	-
37	**EML22E_EDL**	EML2 direct transfer to Earth surface	7	-
38	**EML22M_EDL**	EML2 direct transfer to lunar surface	3,4,5	-
39	**M_Sub_Orbital2EML2**	Lunar surface direct to EML2	7	-
40	**ESL12EML2**	ESL1 transfer to EML2	3,4,5,7	-
41	**EML22ESL1**	EML2 transfer to ESL1	3,4,5,7	-
42	**EML12EML2**	EML1 transfer to EML2	3,4,5,7	-
43	**EML22EML1**	EML2 transfer to EML1	3,4,5,7	-
44	**M_Sub_Orbtial2E_EDL**	Lunar surface direct to Earth surface	7	-