ROBOTIC LUNAR LANDERS IN THE CONTEXT OF THE VISION FOR SPACE EXPLORATION – USE CASES AND COMMONALITY OPTIONS

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Abstract

This paper presents an analysis of mission objectives, system architectures, and options for technical commonality for robotic lunar lander precursors for the human return to the Moon by 2020. Commonality with LSAM offers opportunities for cost and risk reduction of the overall lunar exploration program; these advantages have to be weighted against potential up-front cost and risk penalties that the robotic lunar program would have to carry. A systematic process for the assessment of commonality options in a portfolio of complex systems is outlined and applied, including the analysis of mission objectives, robotic lander architecture analysis, identification, and the identification and assessment of commonality options on a technical basis. Primary mission objectives for the first robotic lunar lander mission should include the characterization of a lunar surface environment not previously visited (preferably one of the lunar poles), and mission operations and maneuvers similar to those planned for LSAM in order to gain operational experience relevant to human lunar landing. Four families of interesting lander architectures were identified, including concepts with staging during lunar descent. Depending on the propellant combination for the lunar lander and the launch vehicle used, payload masses between 100-2300 kg can be delivered to the lunar surface with current US launch vehicles and technology. Major opportunities for commonality with LSAM exist in the operational domain (similar trajectories and maneuvers), RCS propulsion, and GN&C; the primary benefit from this type of commonality is the reduction of developmental cost and risk, and operational risk for LSAM.

Introduction

Robotic lunar missions are an integral part of the lunar exploration program outlined in the US Vision for Space Exploration (VSE) [1], primarily intended as precursors to and trailblazers for the planned human return to the Moon by the year 2020. Currently, a robotic lunar orbiter mission called Lunar Reconnaissance Orbiter (LRO) is under development and scheduled for launch in 2008, a robotic lunar lander mission is in the planning stages for the post-2010 timeframe, and subsequent robotic landing missions are under consideration by NASA's Lunar Precursor and Robotics Program (LPRP) [3]. The work presented in this paper was focused on the first lander mission, but the results apply more generally to all robotic lunar lander precursor missions in the context of the VSE.

Commonality in portfolios of complex systems (such as the set of systems planned for Project Constellation) has long been recognized as a potential way to significantly reduce overall lifecycle cost and risk of the portfolio [7,8,9,10,11,12]. In the context of space systems architecture, commonality can be defined as the "usage of common programmatic and technical items at all levels of system and component design and development" [7].

Specific advantages of commonality in space system portfolios may include:
- Reduced lifecycle DDT&E (Design, Development, Test & Evaluation) cost and risk due to a reduced number of individual development projects that need to be carried out
- Reduced lifecycle recurring cost due to a reduced number of customized design which results in fewer production lines and reduced number of specialized skills required ("standing army")
- Reduced lifecycle operational risk due to increased operational experience with fewer customized designs and due to operational similarities (even without common design)
- Accelerated development schedule for later developments in the portfolio due to the availability of previously developed common components
- Reduced need for sparing and re-supply due to component interchangeability (more relevant for the long-term ongoing operation of a set of space systems)

Potential drawbacks of common designs are:
- Increased up-front DDT&E cost and risk for the first element of the common system family mainly due to additional requirements and complexity due to commonality
- Increased operational risk for the first element of the family of common systems, also due to additional complexity related to commonality
- Potential performance sub-optimality of all designs in the family of common systems

Given that the advantages are accrued over the entire life-cycle, and the penalties occur mostly up-front, a repeatable process is required for the identification and assessment of commonality options. Due to the strong dependence of commonality options on the architecture and technologies chosen for the individual systems in the portfolio, this process must include the architecting phase itself. Figure 1 outlines the high-level process that was developed to address this need; for purposes of simplification, a portfolio consisting of only two systems is considered (System 1 and System 2).

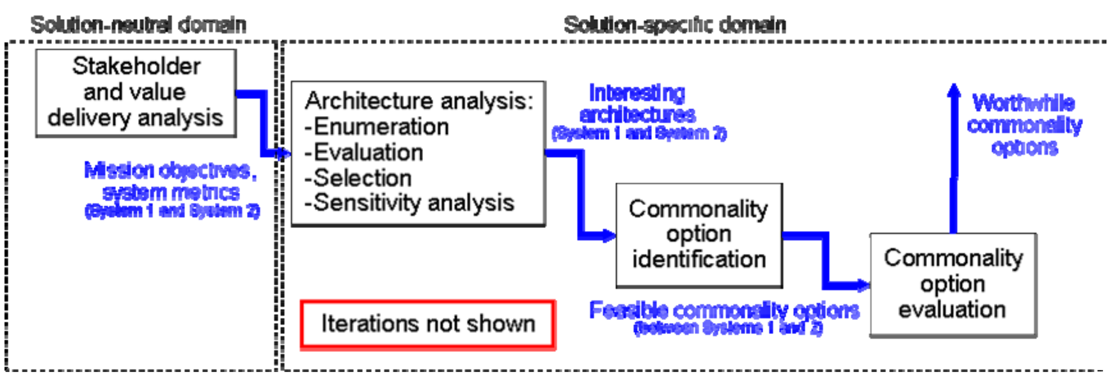


Figure 1: Generic architecting and commonality analysis process for a portfolio of systems

The following is a description of the individual steps of this generic process:
- First, an analysis of stakeholder objectives, and of the value delivery mechanism for each system in the portfolio; this is an expanded version of what is traditionally called requirements analysis
- Analysis of point-design architectures for each system in the portfolio, based on the enumeration and evaluation of a large number of feasible concepts with regard to cost, risk, and performance metrics, and the subsequent selection of a set of preferred architectures. A

sensitivity analysis is sometimes included in order to investigate changes in architecture selection due to changes in requirements and assumptions [4,5,6].
- Identification of technically feasible commonality options through systematic comparison of functionality, technologies, and operations between portfolios of preferred architectures
- Evaluation of the economic and organizational feasibility of the commonality options

The work presented in this paper is focused on the first three steps of this process, which are covered in the remaining sections below.

Analysis of Robotic Lunar Lander Mission Objectives

An analysis of possible mission objectives was carried out based on the overall lunar robotic exploration program purpose outlined in the VSE and the ESAS report [2], and important stakeholders for the lunar robotic exploration program such as Project Constellation, the science community, and the public. The following primary and secondary objectives were derived in this analysis [13]:

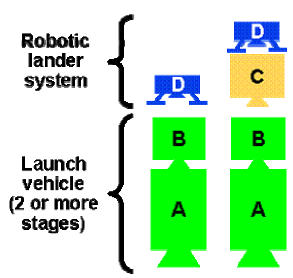
Primary mission objectives for the first robotic lunar landing mission:
- Characterize surface environment at one of the lunar poles (could also provide “ground truth” / calibration for LRO data)
- Provide operational experience, demonstrate automatic / semi-automatic landing capability
- Test of innovative lander architectures and design concepts to establish feasibility for LSAM
- Provide a high-profile programmatic milestone for Project Constellation and show progress towards human lunar return

Secondary mission objectives:
- Pursue science objectives on an opportunistic basis
- Pre-deployment of communications and navigation assets for human lunar exploration
- Determine distribution of obstacles smaller than resolvable with radar / LIDAR mapping
- Demonstrate regolith-based oxygen production
- Test for water in vicinity of landing site (no dedicated search for water because utility of potentially existing water is doubtful when compared to regolith-based ISRU)

Given the data and the amount of samples available from the Surveyor and Apollo programs, objectives such as characterization of equatorial sites, investigation of lunar soil properties, or analysis of effects of lunar dust on mechanisms do not seem to justify lunar robotic precursor missions.

Robotic Lunar Lander Architecture Analysis

The second step of the process outlined in Figure 1 is the quantitative analysis of architectures for each system in the portfolio, and the subsequent selection of a set of preferred architectures. In this context, only an analysis of robotic lunar lander architectures was required, because an architecture analysis for human lunar landers was available from [6].



Maneuver Allocation Options

LEO	TLI	LOI	Descent	Landing
AB	D	D	D	D
AB	AB	D	D	D
AB	AB	AB	D	D
AB	AB	AB	AB	D
AB	C	D	D	D
AB	C	C	D	D
AB	C	C	C	D
AB	AB	C	D	D
AB	AB	C	C	D
AB	AB	AB	C	D

Figure 2: Enumeration of maneuver allocations to propulsion stages for lunar landing

A large number of robotic lunar lander architectures were enumerated based on:

- The number of propulsion stages, and the allocation of maneuvers to the stages (see Figure 2); stage D is the lunar lander itself, stage C is a kick stage, and stages A and B are a placeholder for the launch vehicle (which may have a different configuration than two stages in tandem)
- The propellant combination of the lander (stage D)
- The launch vehicle (constrained to existing US launch vehicles, i.e. legacy launch vehicles)
- The kick-stage type (constrained to existing liquid or solid propellant upper stages, i.e. legacy upper stages)

A comprehensive quantitative analysis of the performance capabilities was carried out for each of these robotic lander concepts, including variations in the delta-v split between the different stages [14]. Figure 3 shows on the left side a table with payload capabilities to the lunar surface for the subset of preferred lander architectures that were selected on the basis of the results from the quantitative analysis. The payload capabilities range from ~100 kg for use of a Delta-II-type launch vehicle and storable propellants to ~2300 kg for launch on a Delta IV heavy launch vehicle and use of a Centaur V1 as additional kick-stage [14,16,17]. This upper limit of performance capability in conjunction with general US launch vehicle prices [15] indicates that it will not be economical to supply a lunar man-tended outpost with smaller robotic lander once the Ares V and LSAM capabilities are available. Robotic landers could, however, play an interesting role in commercial and international partnerships.

The operational configurations of the preferred architectures are shown on the right-hand side of Figure 3 for Trans-Lunar Injection (TLI), trans-lunar coast, Lunar Orbit Insertion (LOI), and descent and landing (a distinction is made between direct descent to the lunar surface vs. prior capture into lunar orbit). There are 4 major families:

- #1: the launch vehicle provides TLI, and the lander stage carries out all remaining maneuvers
- #2: the launch vehicle provides TLI, but a kick stage provides midcourse corrections and LOI
- #3: same as #2, but with staging of the kick-stage during direct descent
- #4: the lander stage provides all maneuvers including TLI

Lunar Robotic Lander Capabilities
(credit: Alexandre Herkenhoff Gama, Wilfried Hofstetter)

Launch vehicle	TLI	Kick-stage	Lander propellants	Lunar surface payload [kg]
Delta II 7925 H 10L	With launch vehicle	None	MMH/N2O4	100
Delta II 7925 H 10L	With launch vehicle	STAR 37 XFP	RP-1/LOX	302
Delta II 7925 H 10L	With launch vehicle	STAR 37 XFP	MMH/N2O4	301
Delta II 7925 H 10L	With launch vehicle	STAR 37 XFP	LOX/LH2	295
Delta II 7925 H 10L	With launch vehicle	STAR 37 XFP	N2H4	275
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Delta IV H	With launch vehicle	STAR 63F	RP-1/LOX	1949
Delta IV H	With launch vehicle	STAR 63F	MMH/N2O4	1948
Delta IV H	With launch vehicle	STAR 63F	LOX/LH2	1826
Delta IV H	With launch vehicle	STAR 63F	N2H4	1619
Atlas V 552	Lander / Centaur V1	None	LOX/LH2	2000
Delta IV H	Centaur V1	Centaur V1	N2H4	2332
Delta IV H	Centaur V1	Centaur V1	RP-1/LOX	2294
Delta IV H	Centaur V1	Centaur V1	MMH/N2O4	2294

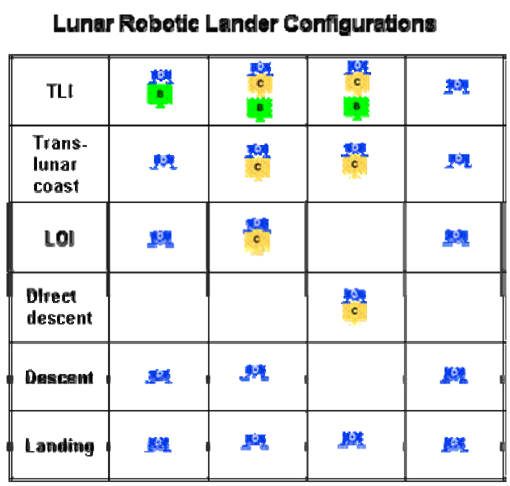


Figure 3: Performance capabilities and operational characteristics / configurations of interesting robotic lunar lander architectures

Robotic Lunar Lander Commonality Analysis

Based on the preferred robotic lunar lander concepts identified in the architecture analysis step, a high-level screening for options for commonality between robotic landers and LSAM was carried out. Two principal tools were used:

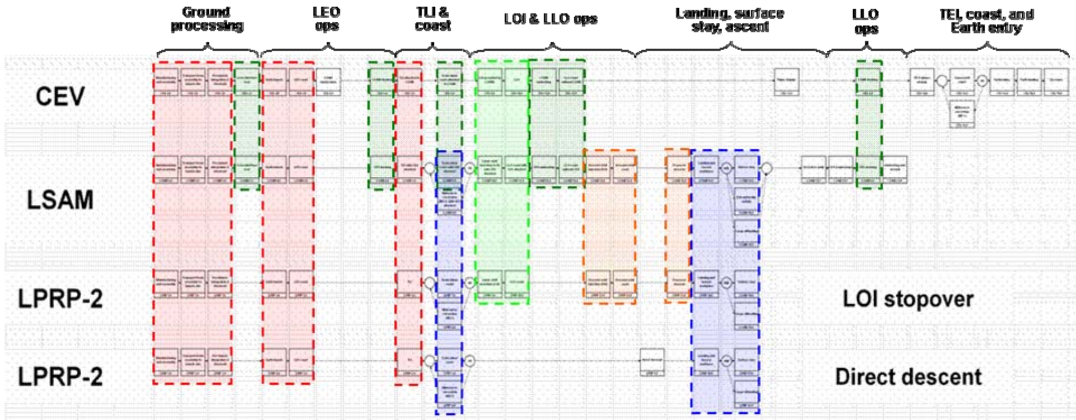


Figure 4: Operational commonality between CEV, LSAM, and two robotic lunar lander concepts

Functional Flow Block Diagrams (FFBDs, Figure 4): for each system in the portfolio, a FFBD was constructed and operationally similar building blocks were placed in the same column. This allowed for the graphical identification of operational similarities and differences, as indicated by the colored blocks in Figure 4. Opportunities for operational commonality between the LSAM and robotic landers exist during trans-lunar coast and final landing (blue marker), and also during ground processing, LEO operations, and TLI (red marker). For a robotic lander that performs LOI, operational commonality is also conceivable for this mission phase.

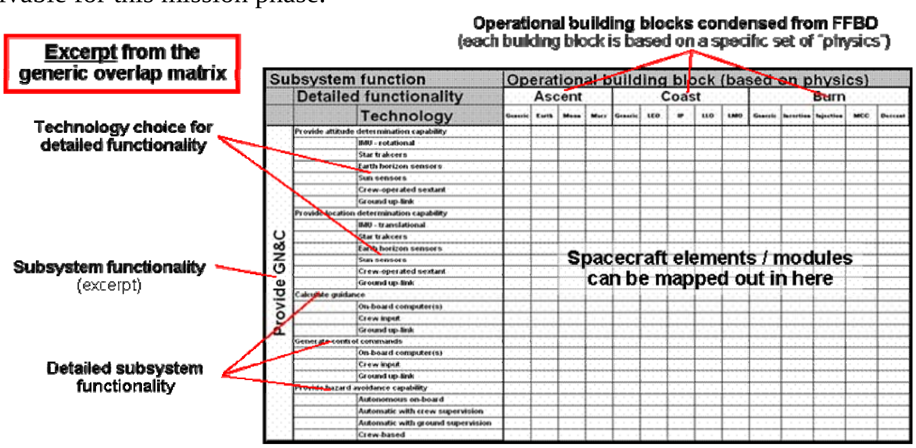


Figure 5: Excerpt of the generic overlap matrix for characterization of systems or system elements in the functional, technology, and operational domains

The system overlap matrix (see Figure 5): the overlap matrix is a concept that captures functionality, technology choices, and operational building blocks for a system concept. On the left-hand side of the matrix, detailed functions are listed, and immediately below the technology choices that exist for fulfilling this function. The detailed functions group into high-level functionality such as "provide GN&C". Along the top of the matrix, the operational building blocks from the FFBD are listed; each operational building block is characterized by its unique physical laws and environmental conditions. By creating one matrix that covers all functions, technology choices, and operational building blocks encountered in all of the concepts for each system in the portfolio (i.e. the matrix contains the union of all sets of functions, technologies, and operational building blocks), one can capture any concept for every system in the portfolio. By arithmetically "overlaying" matrices of two concepts, it is possible to identify similarities ("overlap") between systems, which represent options for commonality. In Figure 6 in the Appendix, such an analysis is carried out between the LSAM descent stage and a robotic lunar lander concept that features stop-over in lunar orbit. The fields marked in red indicate direct overlap, green, blue, and yellow markings highlight operational building blocks, functions, and technologies that have any overlap at all in the matrix. The analysis indicates that options for commonality exist primarily in the GN&C and RCS propulsion domains.

Conclusions

In this paper, results from an analysis of robotic lunar lander architectures as part of the Project Constellation system portfolio and associated options for commonality are presented. To carry out this analysis, a repeatable process was developed that includes analysis of value delivery and stakeholder objectives, architecting and conceptual design of the individual systems in the portfolio, identification of technically feasible options for commonality, and evaluation of the commonality options with regard to their economic and organizational feasibility. The work presented focuses on the first three steps for landers intended to go to one of the lunar poles. 4 families of interesting concepts for robotic lunar landers were identified; their payload performance ranges from ~100 **-** ~2300 kg depending on launch vehicle, kick-stage, and lander propellant selection. For the identification of commonality options, FFBDs and a novel tool called system overlap matrix were utilized to identify options for commonality in the propulsion and GN&C domains during various lunar mission phases. Opportunities for future work include the further development and application of the commonality screening tools to robotic lunar lander and other systems, and the detailed economic and organizational analysis of the commonality options identified through screening.

Acknowledgements

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Appendix

High-level function			Operational building blocks and environments																
	Detailed functionality		Coast					Burn					Surface stay			Landing			
		Technology	Generic	LEO	IP	LLO	LMO	Generic	Insertion	Injection	MCC	Descent	Generic	Lunar surface	Mars surface	Generic	Earth	Moon	Mars
Provide GN&C	Provide attitude determination capability		0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
		IMU - rotational	0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
		Star trakcers	0	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0
		Earth horizon sensors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Sun sensors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Crew-operated sextant	0	1	1	1	0	0	1	0	1	1	0	0	0	0	0	0	0
		Ground up-link	0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
	Provide location determination capability		0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
		IMU - translational	0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
		Star trakcers	0	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0
		Earth horizon sensors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Sun sensors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Crew-operated sextant	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
		Ground up-link	0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
	Calculate guidance		0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
		On-board computer(s)	0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
		Crew input	0	1	1	1	0	0	1	0	1	1	0	0	0	0	0	1	0
		Ground up-link	0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
	Generate control commands		0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
		On-board computer(s)	0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
		Crew input	0	1	1	1	0	0	1	0	1	1	0	0	0	0	0	1	0
		Ground up-link	0	1	2	2	0	0	2	0	2	2	0	0	0	0	0	2	0
	Provide hazard avoidance capability		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
		Autonomous on-board	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Automatic with crew supervision	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
		Automatic with ground supervision	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
		Crew-based	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide Main Propulsion	Provide propellant storage		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Separate fuel and oxidizer tanks	2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Common bulkhead tanks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Provide fuel and oxidizer		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		LOX / LH2	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
		LOX / LCH4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		LOX / RP-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		N2O4 / MMH	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
		N2O4 / Aerozine-50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Provide propellant feed		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Pressurization	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
		Pumps	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
	Provide thrust generation		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Gas generator cycle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Expander cycle	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
		Staged combustion cycle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Pressure-fed cycle	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
	Provide throttling capability		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		With main propulsion	1	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		With RCS pulsing	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		With main propulsion pulsing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Provide RCS Propulsion	Provide RCS propellant storage		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Separate fuel and oxidizer tanks	2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Common bulkhead tanks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		With main propellants	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Provide RCS fuel and oxidizer		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		LOX / LH2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		LOX / LCH4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		LOX / Ethanol	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		N2O4 / MMH	2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		N2O4 / Aerozine-50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Provide RCS propellant feed		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Pressurization	2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Pumps	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Main propulsion system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Provide RCS thrust generation		2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0
		Gas generator cycle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Expander cycle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Staged combustion cycle	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Pressure-fed cycle	2	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0

Figure 6: Assessment of system overlap between LSAM descent stage and a robotic lunar lander concept in the propulsion and GN&C domains