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EVALUATING FUNCTIONAL COMMONALITY OF SYSTEM USE-CASE SCENARIOS
CASE STUDY: PLANETARY LANDING ATTENUATION SYSTEM

Stephen Bathurst
sbathurst@gmail.com
Massachusetts Institute of Technology
Cambridge, USA

Peter Jeziorek
Massachusetts Institute of Technology
Cambridge, USA

Taesik Lee
tslee@mit.edu
Massachusetts Institute of Technology
Cambridge, USA

AJ Schrauth
Massachusetts Institute of Technology
Cambridge, USA

Nam P. Suh
npsuh@mit.edu
Massachusetts Institute of Technology
Cambridge, USA

ABSTRACT

While the concept of "functional requirements should drive the design process" is not novel, it is not uncommon to find other considerations, such as system level constraints/objectives and pre-conceived physical solutions that overwhelm the entire design process of a subsystem enough to obscure this basic rationale. That is particularly likely in a large, complex system development project. This paper presents a case study conducted by MIT's Park Center for Complex Systems in cooperation with Draper Laboratories to establish a way of evaluating the use of common hardware, which was a high-level design driver in developing a space exploration system architecture. This study examines the level of functional commonality that exists between different use cases for a planetary landing attenuation system. The goal was to determine the extent to which a common landing system could be used for various future space exploration missions. In order to achieve this, it was necessary to systematically determine how the functional requirements change between use cases. Rigorous characterization of the use cases was accomplished through the introduction of a new use case parameter design domain containing a set of metrics that characterize each use case scenario. Once the use case parameter domain was established, interactions were traced between the use case parameters and the systems functional requirements. With traceability established it became clear how changes in each use case parameter value affect the design ranges of the associated functional requirements. Careful attention was also paid to use case parameter changes that introduce or eliminate functional requirements. The linking of use case parameters to functional requirements allowed for detailed comparison of the functional requirements between use cases. We observed that two conditions must be satisfied for use cases to be considered common and eligible for a common design solution. First, the sets of functional requirements must be compatible. The changes in the functional requirements and their design ranges must not introduce coupling in either use case. Second, the design ranges required for each use case must be compatible. For each functional requirement there must exist a design parameter with a system range that is within the design ranges of the functional requirements associated with both use cases. If the required changes to the design ranges decrease system performance to an unacceptable level, or introduce coupling, then the use cases are considered to be uncommon and will require independent design solutions. Further applications of this method might include evaluating the ability of a preexisting system to satisfy an unanticipated use case scenario, or any other situation in which it is desirable to know the effects of system use on the systems functional requirements.

Keywords: Use Case Parameter, Functional Commonality, Landing Attenuation, Use case Parameter Mapping, Coupling Terms and Commonality

1 INTRODUCTION

Use case scenarios are tools used to conceptually model how end users may expect a system to respond to a certain set of inputs. They can be used to gain insight into a systems' functional requirements, or to provide information about the design ranges for those requirements. Often engineers are asked to design products which perform well under use cases that appear to be similar. A few inputs may change between cases but a large portion of the system response remains unaffected. This can be seen in many systems, including products designed to be interchangeable between larger systems and products intended for human use. When presented with a problem that involves similar use case scenarios the designer must decide if the use cases are functionally different enough to warrant physically separate systems, or if an integrated system will be lest costly. If physically different systems are used for similar use cases then the overlap in functionality of these systems, the extent to which the two systems share common functions, represents redundant effort during the design phase and missed opportunities to lower costs through economies of scale during manufacturing. In order to facilitate the making of these decisions, this paper presents a structured way to use an Axiomatic Design decomposition to determine the level of functional commonality that exists between two use case scenarios.

In his vision for the future of American space travel presented on January 14, 2004 President Bush announced that

United States should pursue a sustained human presence on the moon. The moon could provide a testing ground for the new technologies and systems that would be required for future missions to mars[1]. As a result NASA contracted concept exploration and refinement (CE&R) studies to investigate what systems might look like that could carry out manned missions to the moon and mars. In our study we focused on the mission to mars in order to determine what systems would benefit from testing on the moon. One of our tasks was to evaluate if the same planetary landing system could be used on the moon as on mars. The method presented here of use case parameterization and evaluation of functional commonality was created in order to determine if the intended use cases for the planetary landing system were functionally similar enough to warrant using common landing system hardware for all missions.

2 USE CASE PARAMTERIZATION

The first step in determining the amount commonality between two use cases for a system is defining the parameters that characterize each use case scenario. Use case parameters can be determine from analysis of the design equations. We know that each element in the FR-DP design matrix represents a functional dependency[2] that can be expressed as:

$$\{FR\} = [A]\{DP\}$$

For a linear design with two FRs and DPs the design equations may be written as:

$$FR_1 = A_{11}DP_1 + A_{12}DP_2$$

$$FR_2 = A_{21}DP_1 + A_{22}DP_2$$

The constants that make up the elements of the design matrix contain information that relates the value of each DP to the value of each FR, and they include, as much as possible, all variables that may affect those values. These constants can contain data on physical environment, interfaces with other systems, safety requirements or any parameter that affects the values of the FRs. Use case parameters should be taken from the set of variables that make up these constants and should include all elements in the design equations that will affect a large change in the design range of functional requirements between use cases.

In order to determine the correct use case parameters for the landing system, we first analyzed and decomposed its functional requirements. The functional requirements for the landing gear system were derived from the use case scenarios that were part of the baseline Lunar and Martian mission architectures that were established by the Draper Laboratory, Arch. 1 and Arch 969. Within these architectures there are four use cases that involve the functionality of a landing system. For the case of the moon, the two vehicles that must land on the surface in Arch. 1 are the crew exploration vehicle (CEV) (Use Case #1) and the uncrewed Habitat (Use Case #2), as seen in Figure 1. Only the CEV ascends from the Lunar surface and returns to Earth. Additionally, there is a use case for delivering cargo to the Lunar surface (Cargo Use Case), but this use case was not considered for the design of the landing gear system.

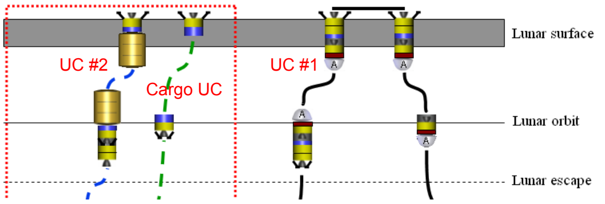


Figure 1 - Arch. 1: CEV, Habitat and Cargo are sent to the Lunar surface, and the CEV returns directly to Earth

For Mars mission architecture, the MIT-Draper team recommended that a Mars Ascent Vehicle (MAV) and Earth Return Vehicle (ERV) be pre-deployed on the Martian surface and in Mars orbit, respectively. The crewed Transfer and Surface Habitat (TSH) lands on the surface. Once the mission has been completed, the crew transfers from the TSH into the MAV, ascends to orbit, rendezvous and transfers to the ERV, and returns to Earth (Arch. 969, seen in Figure 2). The two vehicles that must land on the surface of Mars in Arch. 969 are the uncrewed MAV (Use Case #3) and the crewed TSH (Use Case #4).

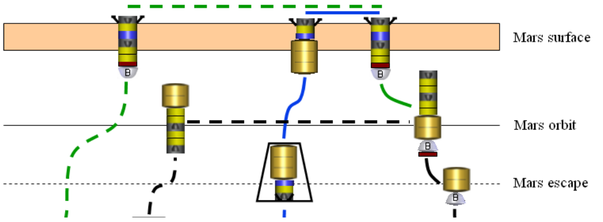


Figure 2 - Arch. 969: Mars Ascent Vehicle (MAV) is predeployed on the Mars surface, crewed Transfer and Surface Habitat (TSH) sent to the surface, and Earth Return Vehicle (ERV) deployed in Mars orbit. After the mission on the surface is complete, crew enter the MAV, ascent to orbit, dock and transfer into the ERV in orbit, and then return to Earth in the ERV.

The baseline functional requirement decomposition was derived from use case #1 (Lunar CEV landing) as a reference. The highest-level functional requirement was “FR0: Safely support the spacecraft during impact, surface operations, and ascent”. The spacecraft is, in the context of our design task, all of the subsystems with certain mass properties that need to be supported by the landing gear system. For example, in use case 1 (Crew Transportation System landing), the spacecraft includes CEV, IPU, Ascent stage, and Descent stage. For use case 2 (HAB landing), it includes Lunar habitat and Descent stage. Operation phases in which a landing gear system should provide supporting function are at touchdown and settling (impact), while the vehicle is on the surface (surface operations), and at take-off for CEV case.

These top-level functional requirements are decomposed to nine sub-level functional requirements:

- FR1: *Monitor the state of the landing gear throughout all phases* – Landing gear system must provide means to monitor its own health and state, and communicate the information to relevant control system.
- FR2: *Provide autonomous isolation and recovery from conditions which could result in loss of human life or loss of vehicle* – The

landing gear system must provide an appropriate level of redundancy and contingency plans to protect the crew and vehicle. This includes sub-system safety features and coordination with its super system.

- FR3: *Provide secure final position* – Once the spacecraft is settled down from touchdown event, the landing gear system must provide means to secure its final position to support the spacecraft in its stable position throughout its lifecycle.
- FR4: *Control touchdown event* – One of the primary functional requirements of the landing gear system is to support the spacecraft during touchdown. This involves impact energy absorption and preventing tipping due to touchdown dynamics.
- FR5: *Support maximum loading scenario* – All the members of the landing gear system must be strong enough to endure maximum loading they are exposed at any given moment.
- FR6: *Allow crew access to surface* – The landing gear system is the interface between the spacecraft and the lunar surface, and thus it must incorporate a function to provide crew with access to and from the surface.
- FR7: *Bring the spacecraft to vertical within acceptable tolerances* – Given a possibility that the spacecraft may land on a sloped surface or that the surface is uneven, the landing gear system must provide means to level the spacecraft with respect to the gravitational field for two purposes: 1) ascent propulsion requires to be in reasonable vertical direction, and 2) habitable environment for crew requires reasonable leveling.
- FR8: *Allow for ascent stage launch* – The landing gear system must provide support until the moment the ascent stage is successfully launched from the surface. It may require special consideration for a loading condition in the case of an abrupt engine-cutoff during ascent abort. This requirement is relevant only to the CTS landing use case.
- FR9: *Integrate the landing gear with other subsystems* – The landing gear must be integrated with other subsystems, e.g. exoskeleton, and be packaged into an acceptable envelope.

Once the decomposition was carried to a sufficient level of detail, it was possible to analyze how the values of the functional requirements change between each of the use cases. It became clear that all uses cases shared a certain set of characteristics, though perhaps with different values. Each must land a vehicle with a specific amount of mass, center of gravity height, and moment of inertia. These mass properties affect landing gear functions like absorbing impact energy, supporting maximum load, and preventing tipping. The surfaces that these vehicles must land on can be described by the magnitude and direction of gravity, surface properties including relevant statistics of craters, rocks, and soil properties, and the presence of an atmosphere. The surface properties affect landing gear functions like supporting the maximum load, tipping prevention, and providing a secure final position. Each vehicle may or may not contain crew and may or may not ascend from the surface. The presence of a human crew requires specific constraints on failure tolerances and acceleration limits which restrict the rate of energy dissipation. Finally, each of these vehicles and their landing gears will be under specific packaging constraints, depending on the launch vehicle and/or use of a heat shield. These packaging constraints will require the landing gear to have two configurations: packed and unpacked. This may put additional constraints on how large the members of the gear mechanisms can be. These nine characteristic parameters (mass, center of gravity height, moment of inertia, gravity, surface properties, atmosphere, crew, ascent and packaging) define each use case and are the use case parameters. Estimated values of the use case parameters can be determined for each use case as defined by the Draper-MIT CE&R design. Figure 3 and Figure 4 summarize the results of the evaluation for the four use cases.

Arch. 1: Lunar Direct Return	Lunar Crew Transfer System	Lunar Long-Duration Surface Habitat
	UC1	UC2
$M_{touchdown}$ (mT)	37	34
H_{cg} (m)	6.3	6.9
I [1000 kg m2]	367	414
Gravity (m/s2)	1.635	1.635
Surface	Lunar	Lunar
Atmosphere	No	No
Crewed	Yes	No
Ascent	Yes	No
Packaging (m)	6.8 – 7.5	6.8 – 7.5

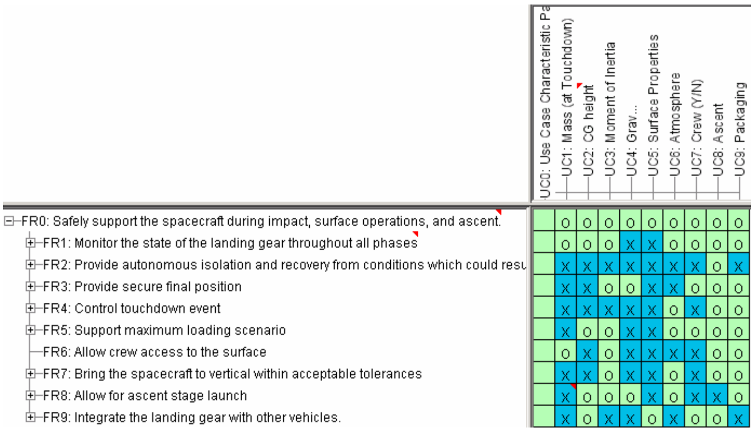
Figure 3 – Use case parameters for Lunar landing use cases

Arch. 969: Mars Orbit Rendezvous: Combined Trans. and Surf. Habs	Mars Ascent Vehicle & Return CEV	Mars Surface Habitat
	UC3	UC4
$M_{touchdown}$ (mT)	49	56
H_{cg} (m)	6.3	7.3
I [1000 kg m2]	n/a	n/a
Gravity (m/s2)	3.71	3.71
Surface	Martian	Martian
Atmosphere	Yes	Yes
Crewed	No	Yes
Ascent	Yes	No
Packaging (m)	Heat Shield	Heat Shield

Figure 4 – Use case parameters for Mars landing use cases

3 MAPPING USE CASE PARAMTERS TO FUNCTIONAL REQUIRMENTS

Once each use case has been characterized in terms of the key parameters that will affect the landing gear design, the effect of those parameters on the functional requirements of the landing gear system can be determined. In order to accomplish this, traceability was established between the use case parameters and the complete set of baseline functional requirements that the landing gear must satisfy. Ultimately, this clear link between each use case parameter and the FRs will help in determining how much hardware commonality is possible among different use cases. This traceability was established using the Acclaro Designer™ software, and a summary of the traceability from the use case parameters to the top-level FRs is presented in Figure 6.



	UC0: Use Case Characteristic Pa	UC1: Mass (at Touchdown)	UC2: CG height	UC3: Moment of Inertia	UC4: Grav...	UC5: Surface Properties	UC6: Atmosphere	UC7: Crew (Y/N)	UC8: Ascent	UC9: Packaging
FR0: Safely support the spacecraft during impact, surface operations, and ascent.		O	O	O	O	O	O	O	O	O
FR1: Monitor the state of the landing gear throughout all phases		O	O	O	X	X	O	O	O	O
FR2: Provide autonomous isolation and recovery from conditions which could resu		X	X	X	X	X	X	X	O	X
FR3: Provide secure final position		X	X	O	O	X	X	O	O	O
FR4: Control touchdown event		X	X	X	X	X	O	X	O	O
FR5: Support maximum loading scenario		X	O	O	X	X	O	O	O	O
FR6: Allow crew access to the surface		O	X	O	X	X	X	X	O	O
FR7: Bring the spacecraft to vertical within acceptable tolerances		X	X	O	X	X	O	X	O	O
FR8: Allow for ascent stage launch		X	O	O	O	X	O	X	X	O
FR9: Integrate the landing gear with other vehicles.		X	O	X	X	O	X	O	O	X

Figure 6 - Mapping from Use Case Parameters to Functional Requirements

By analyzing which use case parameters have similar values, and estimating the effect the differences will have on the values of the functional requirements, it can be determined if it is possible to satisfy those FRs with common a common solution. The touchdown mass difference between the two Lunar vehicles is less than 10%, and for the Martian vehicles it is about 12%. Between Lunar and Martian use cases, however, the difference in touchdown mass is at least 30% and can be as high as 50%, with Martian vehicles heavier than the Lunar vehicles. In addition, the gravity on Mars is more than twice in strength when compared to the Moon's gravity. Also noteworthy is that the Martian vehicles must be packaged within a heat shield, having implications on both landing gear packaging and deployment timing. These values in the use case parameters indicate that the functional requirements for the landing gear to be used on vehicles landing on the Moon and Mars will be very different. Specifically, they will require more capability to absorb impact energy, late deployment of the landing gear (with respect to the landing), different packaging constraints, harsher maximum loading scenario, and different abort scenarios. For example, the landing gear for the Mars surface habitat would need to support 208 kN of force over a duration of two years in a more temperate climate, while a long-duration Lunar surface habitat would need to support 56 kN of force over a duration of a few months in both hot Lunar days and frigid Lunar nights. Another stringent requirement is the fact that a heat shield will be used while entering the Martian atmosphere, until a certain height above the surface. If, after the heat shield is dumped, the landing gear do not deploy, then there is very short time before impact in order to implement contingencies. Whereas for Lunar missions, the landing gear will be deployed at the earliest possible opportunity, perhaps in Lunar orbit. This allows for a long duration of time to implement contingencies. Martian landing gear contingencies will require fast action, while Lunar landing gear might only need an astronaut EVA for repairs. These factors all contribute to Martian requirements that show significant differences from the Lunar requirements.

On the other hand, the requirements between the two Lunar use cases are similar enough, allowing for commonality. The difference in mass between the use cases is only 3 mT. A single landing gear can be designed to absorb the maximum energy and support the maximum loads of the most severe of the two Lunar use cases. The same can be said about the center of gravity height. The habitat's CG height is higher by 0.6m, which will require the use of a somewhat larger landing gear footprint in order to prevent tipping. There will be a mass penalty when landing the CEV, which has a lower CG and mass than the habitat, but this can also be considered as an additional factor of safety. This is a benefit when considering that the CEV will be a crewed landing. Another difference is that the Habitat's landing gear will not be required to allow for an ascent stage launch. However, the design parameter which allows for an ascent stage launch is not coupled to any other requirement. This indicates that ascent system is independent and allows for an overall common Lunar landing gear to be designed.

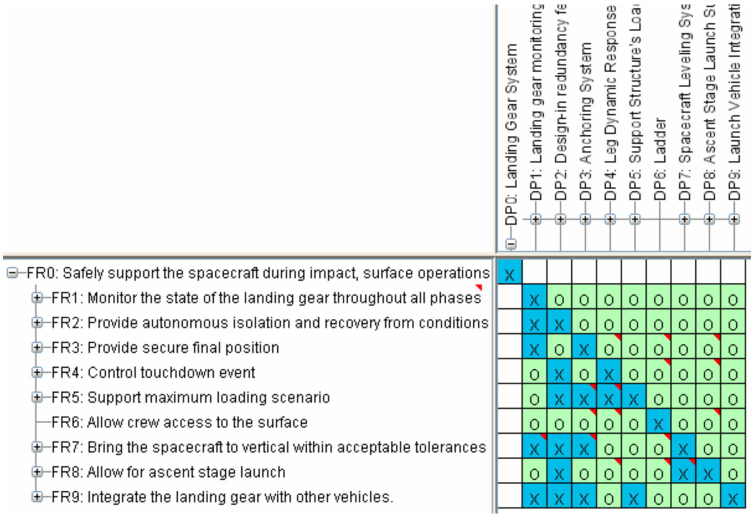
Our study ultimately concluded that commonality in functional requirements does exist between the mars and moon use cases for functions such as monitoring, allowing crew access, leveling, and ascent stage launch as difference in use case values do not affect those functional requirements. However, there seems to be significant differences in the functions of providing a safe final position, absorbing landing impact energy, supporting maximum load scenario, and satisfying packaging constraints. This is summarized in Figure 7.

		Use Cases			
		UC1	UC2	UC3	UC4
Functional Requirements	Monitor the state of the landing gear throughout all phases	Commonality among all use cases possible			
	Allow crew access to the surface				
	Bring the spacecraft to vertical within acceptable tolerances				
	Allow for ascent stage launch		n/a		n/a
	Provide autonomous isolation and recovery from conditions which could result in loss of human life or loss of vehicle.	Commonality among Lunar use cases possible		Commonality among Martian use cases possible	
	Provide secure final position				
	Control touchdown event				
	Support maximum loading scenario				
	Integrate the landing gear with other vehicles.				

Figure 7- Commonality in functional requirements for different use cases

4 THE EFFECT OF COUPLING TERMS ON USE CASE COMMONALITY

The evaluation of the effects of use case parameter changes on the functionality of system further confirmed the need to eliminate off diagonal terms in the design matrix, especially at the highest levels of decomposition. While the full decomposition and design matrix cannot be presented here, it is interesting to note some of the effects that the high level coupling terms have on the possibility of using common system hardware. Figure 5 shows the top level design matrix.



	DP0: Landing Gear System	DP1: Landing gear monitoring	DP2: Design-in redundancy fe	DP3: Anchoring System	DP4: Leg Dynamic Response	DP5: Support Structure's Loa	DP6: Ladder	DP7: Spacecraft Leveling Sys	DP8: Ascent Stage Launch St	DP9: Launch Vehicle Integrati
FR0: Safely support the spacecraft during impact, surface operations	X									
FR1: Monitor the state of the landing gear throughout all phases		X	O	O	O	O	O	O	O	O
FR2: Provide autonomous isolation and recovery from conditions		X	X	O	O	O	O	O	O	O
FR3: Provide secure final position		X	O	X	O	O	O	O	O	O
FR4: Control touchdown event		O	X	O	X	O	O	O	O	O
FR5: Support maximum loading scenario		O	X	X	X	X	O	O	O	O
FR6: Allow crew access to the surface		O	O	O	O	O	X	O	O	O
FR7: Bring the spacecraft to vertical within acceptable tolerances		X	X	X	O	O	O	X	O	O
FR8: Allow for ascent stage launch		O	X	O	O	O	O	X	X	O
FR9: Integrate the landing gear with other vehicles.		X	X	X	O	X	O	O	O	X

Figure 5 - Top level design matrix for use case 1

What became apparent during the commonality analysis was that if a design parameter affects multiple FRs then the possibility of a common hardware solution is reduces significantly. For example, if the design parameter which allows for an ascent stage launch affected other FRs, then the extent to which those FRs change between use case is increased significantly. This is an another argument for analyzing and eliminating all unnecessary design interactions in the baseline design. By minimizing off-diagonal terms in the design matrix, the possibility for commonality, or at least modularity, is increased.

5 CONCLUSION

NASA will be landing multiple types of vehicles in a variety of conditions that affect the design of the landing gear. This provides them with an opportunity to increase performance and reduce cost if the level of functional commonality can be established. This problem is one shared by engineers world wide and is especially critical in large, complex systems like those in the aerospace and defense industries. The common characteristics of all use cases that affected the landing gear design were determined by the parameter values of mass, center of gravity height, moment of inertia, gravity, surface properties, atmosphere, crew, ascent and packaging constraints. For other systems these parameters could be as diverse and numerous as the use cases require. The values for each of these use case parameters were determined for each of the use case scenarios. In addition, traceability between the use case parameters and functional requirements was established. The ability to estimate a value and establish this traceability are the most basic requirements for the selection of use case parameters, and provide a general structure that can be applied to other systems. In the future this flexibility may allow for the application of this method in a number of different ways. This includes the possibility of determining if a vehicle or system is acceptable for a specific use case that may not have been considered during the design stage. By analyzing the similarity between use case parameters, it was determined how similar the functional requirements would be and if a common physical solution is cost effective. It was shown how landing gear functional requirements for the two Martian use cases will be significantly different from the Lunar use cases. However, the general structure provided a way to link the functionality of a system to the way it which that system is used. This method can be applied, not only to determine when integration of two systems is possible, but also to discover how a system will perform for other use case scenarios.

6 REFERENCES

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