FRACTIONATED ROBOTIC ARCHITECTURES FOR PLANETARY SURFACE MOBILITY SYSTEMS

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Planetary surface exploration missions are becoming increasingly complex and future missions promise to be even more ambitious than those that have occurred thus far. To deal with this complexity, this paper proposes a fractionated approach to planetary surface exploration. Fractionation involves splitting up large vehicles into several smaller ones that work together in order to achieve the science goals. It is believed that fractionation of rovers can lead to increased value delivery and productivity, as well as helping manage complexity. A science goal-driven methodology for generating a tradespace of multi-vehicle architectures in the early stages of mission design is detailed. A set of carefully designed metrics are then put forward as a way to help compare multi-vehicle architectures to each other and to the single vehicle (monolithic) equivalent. These include science value delivery, productivity, system- and vehicle-level complexity, and mass metrics. Through two Mars-based case studies, the advantages and limitations of fractionation are demonstrated. Fractionation is found to be particularly advantageous when the science goals are broad, when there are competing requirements between goals, and when the exploration environment is particularly treacherous. Additionally, multi-vehicle systems entail simpler vehicles with lower vehicle-level complexity, lower mission risk and higher productivity over the mission duration, as well as being more easily upgradeable. On the other hand, they lead to higher system-level complexity, and can somewhat increase the overall mass of the system. This means that mass is traded for higher science return and lower risk during the mission, and complexity is shifted from design complexity to operational complexity. Multi-vehicle systems involve more testing and on-board automation than single vehicles, but they also lend themselves more easily to collaboration between different agencies, and can benefit from several emergent properties that increase the overall functionality of the system.

I. INTRODUCTION

The traditional approach to planetary surface exploration is to use a single planetary surface vehicle and consists of a point design with limited exploration of the multi-vehicle architecture trade space. While this has led to many successful missions, with the growing complexity emerging from increasingly ambitious mission objectives, the accomplishment of future missions will likely require a change in paradigm in order to achieve these goals. Looking at the history of the Mars rovers: the Mars Science Laboratory[1] (MSL) was an order of magnitude heavier, more complex and more expensive than the Mars Exploration Rovers[2] (MERs), which in turn were an order of magnitude larger that Sojourner.[3] It could also be argued that it is MSL's excessive complexity that led to the mission being late and significantly over budget.

In order to continue achieving ever-increasing science goals while managing this complexity issue, this paper puts forward a *fractionated* approach to the design of planetary surface mobility systems, as a way to increase scientific return and robustness, as well as to decrease vehicle level complexity, compared with the monolithic. Fractionated mobility systems are composed of physically independent vehicles that can collaborate to provide additional benefit or value to the beneficiaries. Separately, each vehicle may have limited functionality, but together, they have at least as much, and often more, functionality than their monolithic counterpart. In the aerospace domain, fractionation is currently being investigated under the DARPA F6 program,[4,5] whose goal is to replace traditional, highly-integrated, monolithic satellites with wirelessly-networked clusters of heterogeneous modules incorporating the various payload and infrastructure functions. The key finding of this program is that such fractionated architectures can deliver a comparable or greater mission capability than monolithic satellites, as well as significantly enhanced flexibility and robustness with respect to environmental events and changes in needs and requirements.

Notionally, fractionation for satellites and fractionation for planetary surface vehicles are similar concepts. However, the implementation of fractionation on mobility systems as compared to satellites is inherently different, as it presents several novel and unique opportunities for the following subsystems:

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- *Communication*: The communication systems can be shared across vehicles in areas with limited visibility (when exploring lava tubes or the lunar poles, for example) or multiple vehicles can carry different long-range communication systems to increase the redundancy & data transmission rate;
- *Navigation*: The path planning and sample taking activities can be separated to increase overall mission speed by allowing key activities to occur concurrently (in a manner similar to that used for de-mining activities);
- *Power Generation and Thermal Protection*: Fractionation can lead to a concept with a larger "mothership" vehicle providing thermal energy and power to smaller vehicles. Alternatively, one vehicle can generate energy using solar panels in a highly illuminated area while another travels in areas with low illumination (again for the exploration of lava tubes, craters or the lunar poles, for example);
- *Payload*: Fractionation of planetary surface vehicles allows for the spreading and/or duplication of scientific instruments across several vehicles to increase the rate at which scientific activities are being performed and the coverage area, while also increasing the robustness of the system.

The idea of multi-vehicle robotic systems for planetary surface exploration is not a new one. In the field of controls, a significant amount of work has been undertaken in function allocation and to demonstrate the advantages of multi-agent mapping of unknown areas.[6,7,8] Furthermore, the field of collaborative robotics for planetary surfaces is also rapidly growing, in an attempt to enable the exploration of particularly treacherous environments.[9,10,11] Finally, multi-rover architectures have also emerged in recent early mission concepts. For example, one of the architectures that was proposed for a potential Mars 2018 mission included a 2-rover system, working collaboratively on the surface of Mars.[12]

Despite this increased interest in multi-rover exploration in the recent years, there has never been an attempt to systematically explore the tradespace of multi-vehicle architectures during early system design. Furthermore, the evaluation of a tradespace of fractionated multi-vehicle architectures is non-trivial. It requires non-traditional metrics that highlight the trades between single vehicle and multi-vehicle architectures. These include science value return, productivity or robustness to failure, complexity, system mass and more specific mission properties such as the speed at which the mission goals can be achieved or the terrain slope of the areas that are accessible by the system.

This paper describes a methodology for generating and exploring a tradespace of fractionated robotic architectures that may be able to achieve greater science value return than the monolithic baseline, as applied to the exploration of the Martian surface. The approach starts by identifying the mission goals. A functional decomposition is then performed to identify the functions required to achieve a particular mission. As explained in Section II, once these functions have been identified and labeled, the architecture space can be generated. A set of constraints can also be applied to limit the size of the tradespace. Following this, the tradespace is evaluated using carefully designed metrics. Finally, the space can be visualized and explored through the tool described in Section IV of this paper, and interesting architectures can be down-selected.

This paper explores the trades that exist between monolithic and fractionated architectures, through two case studies. The first is based on the fractionation of an ExoMars-type rover,[13] and is described throughout this paper to illustrate the methodology. ExoMars is a rover design from the European Space Agency (ESA) that was originally part of a 2-vehicle joint mission with NASA, as the first part of the Mars Sample Return (MSR) mission. It is now a single-vehicle joint mission between ESA and the Russian Space Agency, due to land on Mars by the end of the Decade. The second case study undertakes a redesign of the MSL[1] to demonstrate the possible advantages of fractionated systems.

II. ARCHITECTURE GENERATION

The first step in generating a tradespace of architectures is the identification of the science objectives. The science goals for ExoMars have evolved significantly over the past few years and are still being revisited at the time of writing. For the purposes of this case study, the following goals,[13] in order of importance, were assumed:

1) To search for signs of past and present life on Mars.
2) To characterize the water/geochemical distribution as a function of depth in the shallow subsurface.

Once the science goals have been identified, the *functions* required to fulfill these science goals need to be identified. Functions are the activities, operations and transformations that cause, create or contribute to performance (i.e. to meeting goals). Functions can then be mapped to forms, which are the physical embodiment of that function on a vehicle.

These functions can be separated into two distinct types: Value Delivery (VD) functions, that provide the primary values associated with the science objectives, and supporting functions. The forms associated with VD functions are mostly science instruments. Supporting functions are functions that do not directly provide value, but are needed for value to emerge. Examples of supporting functions are "long-range traversing" and "generating energy". The difference between these two types of functions is shown in the Object-Process Diagram[14] (OPD) shown in Figure 1.

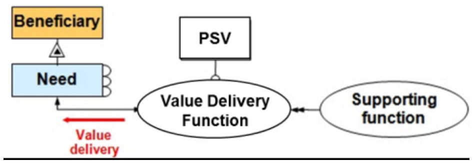


Fig. 1: OPD showing the difference between value delivery and supporting functions. PSV stands for Planetary Surface Vehicle.

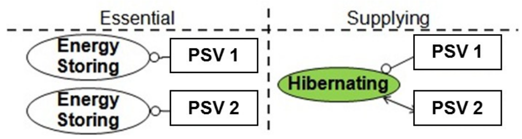


Fig. 2: OPD showing the difference between ES and SS functions. PSV stands for Planetary Surface Vehicle.

Supporting functions can be further separated into Essential Supporting (ES) functions, which every vehicle has to have in order to operate, and Supplying Supporting (SS) functions, which one vehicle can theoretically provide to another. In other words, SS functions can be fractionated, and ES ones cannot. Whether a function is essential or not is dependent on the technology available. Moreover, fractionating functions often leads to losses in efficiency in achieving that particular function, but can increase the overall system efficiency. For example, generating energy could be a Supplying Supporting function. It would rely on energy beaming technology being available. Energy beaming has low efficiency, but if one rover were to beam energy to another, the latter would not need to carry an on-board source of power. It would be lighter and could travel at higher speed, thus possibly leading to a more efficient overall system. The difference between these two categorizations is shown in Figure 2.

The functions derived for the ExoMars rover and their categories are shown in Table 1.

After the functions have been derived and categorized, the architecture tradespace can be generated. Only SS and VD functions can be split across vehicles (i.e. fractionated), ES functions must be present on each vehicle. The space is generated by setting a minimum and maximum number of vehicles (set as 1 and 3 respectively for the ExoMars-type rover case study), and generating the possible combinations of functions. In order to limit the size of the space, some constraints can be imposed in addition to completeness and uniqueness. In the case study at hand, the number of communication systems was limited to one per vehicle and all the SS and VD functions were fractionated except the path planning function. Moreover, there could not be more than two of a given instrument in each architecture, and instruments were not allowed to be duplicated on a given vehicle. This generated 18195 possible architectures.

Upon the completion of the architecture tradespace generation, the architectures need to be evaluated against each other, to understand the trades that occur when replacing single vehicle systems with multi-vehicle ones. This evaluation process is described in the next section.

III. ARCHITECTURE EVALUATION METRICS

A set of metrics was developed to evaluate the multi-vehicle architectures to each other and to the monolithic equivalent. These metrics are presented here and include: value delivery, productivity, system- and vehicle-level complexity and system mass.

Function	Form	Category
Imaging	Panoramic camera (PanCam)	VD
Detecting and identifying molecular species	Organic molecule analyzer (MicrOmega)	VD
Characterizing the structure and composition of samples	Imaging IR spectrometer (MOMA)	VD
Irradiating powdered rock and measuring diffracted protons	X-ray diffractometer (Mars-XRD)	VD
Identifying and characterizing minerals and compounds	Raman spectrometer	VD
Analyzing shallow interior	Shallow ground-penetrating radar (WISDOM)	VD
	IR borehole spectrometer	VD
Detecting biomarkers	Life Marker Chip (LMC)	VD
Traversing	Mobility System	ES
Energy generating	Solar panels	SS
Energy storing	Batteries, power management system	ES
Payload carrying	Vehicle	ES
Thermal protecting	Thermal system	ES
Transmitting data	Rover-to-rover communication system	ES
	UHF communication to an orbiter	SS
	Direct to Earth communication	SS
Navigating	Path-planning system	SS

Table 1: Functions and their associated forms and categories for the ExoMars-type vehicle; in the form column, examples of instruments specific to the ExoMars vehicle are given in brackets.

III.I Value Delivery

The value delivery metric identifies the ability of each architecture to meet the missions' science goals. For a given cost, a higher value delivery leads to a higher science return per dollar. The metric is defined in Eq. 1.

$$Value\ Delivery = \sum_{all\ s/c} \left(\sum_{j=1}^{m} \left(W_j \sum_{i=1}^{n} V_i \right) \right) \quad [1]$$

V_i is the value of instrument i, for a given science objective j, based on the scale given in Table 2.

Weighting	Meaning
0	Does not address science investigation
1	Touches on science investigation
2	Partially addresses science investigation
3	Addresses most of the science investigation
4	Fully addresses the science investigation
5	Exceeds the science investigation

Table 2: Value weightings scale

W_j is the weighting given to the science objective j. Each W is a number between 0 and 1 and the sum of all W_j is 1. W_j values can be varied during the tradespace exploration to understand the effect of the prioritization of mission objectives on the relative value of the architectures.[15] This aspect of the metric directly allows the user to understand how the value assigned to an objective affects the optimality of the architectures. For simplicity, in the case study at hand, the first goal was assumed to be 50% more important than the second goal.

The value of each instrument and thus its ability to achieve the mission objectives was derived using the information available on each of the instruments.[13] In an early mission design scenario, the values would be derived directly from the science traceability matrix and/or through a discussion with the science definition team of the mission. The V_i values can be modified as part of the science definition process to help identify candidate architectures.

III.II Productivity

One of the advantages of fractionated systems is that they have the opportunity to increase the mission reliability through the duplication of subsystems. In turn, this increases the productivity of the mission, since a more reliable system can operate for longer without failure. Reliability is defined as the probability that a system will be in a functional state at the end of the nominal mission. There are two distinct ways to increase a system's reliability: the component reliability can be increased, or redundancy can be added. In complex systems, reliability is therefore achieved by carefully trading component reliability with redundancy. Fractionated systems intrinsically lend themselves to increased redundancy, which means that higher risks can be taken in terms of component reliability to achieve the same system reliability.

Although reliability is a key factor when designing a system, the ability of this system to continue to function in the event of a failure is also an important. In order to design a system that has as high a productivity as possible, the system must be modeled and productivity must be analyzed in each possible state. A state is defined as the functional system that remains in the event of failure. Modeling the productivity of a system in each state requires two aspects: a method to model the productivity of a system given the system parameters, and a Markov, or state-transition, model of the initial system. In this paper the productivity is defined as the number of hours a particular payload is operated. The Markov model analyzes transition rates from one state to another. It assumes that the probability of being in the initial state at the beginning of the simulation is one, and that the system transitions from one state to another at rates equal to the failure rate of the subsystems. If the probability of being in each state throughout time is known, and since the productivity in each state can be modeled, a total estimated productivity in the event of failures can be calculated and used in comparisons between architectures. The comparison of curves of productivity over time between different architectures, for fixed reliability values, can also help demonstrate the advantages of fractionated systems with redundancy. Another option would be to vary the component reliability to achieve the same productivity as the monolithic. In that case, reliability is traded for redundancy.

The productivity of a fleet of rovers can be defined as the number of hours each piece of payload is operating. This means that the system becomes degraded when a particular *value delivery* function is lost. The loss of ability of the system to provide a particular value delivery function 'X' can be due to any combination of the following events:

- Loss of the payload providing 'X' in the system
- Loss of communication on a vehicle providing the 'X' function
- Loss of mobility of a vehicle providing the 'X' function (only if mobility is required for that function to be performed)
- Loss of power on a vehicle providing the 'X' function
- Total loss of long-range communication of the system

In a Markov model, the possible states of the system and the rate at which the system transitions from one state to another is defined using a state-transition matrix, also called the *A* matrix. Each state is defined by the number of *different* value delivery functions that are operational. The state of the system changes whenever a combination of the abovementioned failures causes the system not to be able to provide a given value-delivery function at all. If P is defined as the vector of probabilities of being in each state of the system at any time, the definition of the A matrix is given in Eq. 2.

$$\frac{dP(t)}{dt} = AP(t) \quad [2]$$

The state-transition matrix is essential in calculating the probability of being in each state of the system. It can be built automatically for each architecture in order to rapidly explore the tradespace.[16] The state-transition matrix is not only dependent on how many functions exist within the system, but also on how they are distributed across the system. For given levels of reliability, this metric thus enables the comparison of architectures to each other.

A 2-vehicle architecture with the same value delivery and in the same mission class as the single vehicle baseline (i.e. whose mass falls within 30% of the baseline) was chosen from the tradespace of vehicles in the ExoMars-type vehicle case study. Its productivity curves and that of the single rover are shown in Figures 3 and 4 respectively.

In both of these plots, the blue line dropping from 1 to 0 represents the first state, where all value delivery functions are working. The green line going from 0 to 1 represents the last state, where all the functions have failed. All the other curves represent intermediate states.

In this case, the 2-rover fractionated system has a 50% higher productivity than the monolithic system for given reliability values. It can also be seen that the 2-rover system degrades more gracefully over the mission lifetime (the blue curve is more shallow and the system spends more time in the intermediary states). This could be leveraged by performing tasks with instruments that have high failure rates first, and undertaking the subsequent tasks once the system has degraded.

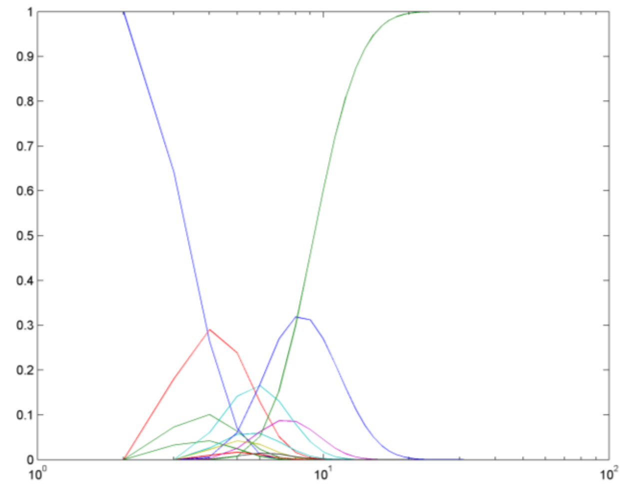


Fig. 3: State transition curves for the 2-rover architecture. The y-axis gives the probability of being in a given state, and the x-axis is normalized mission time.

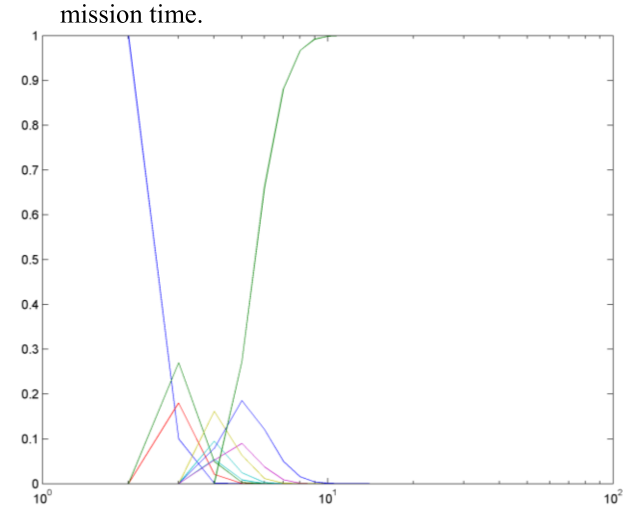


Fig. 4: State transition curves for the single-rover architecture. The y-axis gives the probability of being in a given state, and the x-axis is normalized mission time.

III.III Vehicle-level Complexity

The vehicle-level complexity metric evaluates the design complexity of each individual vehicle in an architecture. This metric is based on the complexity metric developed by Sinha[17] and is defined in Eqs. 3 and 4.

$$vehicle\ complexity = \alpha = E * \sum (w_f * n_f)\ for\ all\ f \quad [3]$$

$$average\ vehicle\ level\ complexity = \sum_{i=1}^{m} \frac{\alpha_i}{m} \quad [4]$$

In these equations, m is the total number of vehicles, and n_f is the number of times a particular function appears on a vehicle (typically 1). The variable w_f is a weighting allocated each function (and its associated form) on each vehicle. This weighting is derived from the concept of cost-risk subfactors[18] and assigns a penalty for some of the vehicle properties that are believed to drive complexity and cost. The weighting allocation scheme is shown in Table 3. Finally, E is a weighted upper-triangular matrix that accounts for conflicting requirements between functions.

Category	Levels	Weighting
TRL	Low (1-3)	+2
	Mid (4-6)	+1
	High (7-9)	0
Level of integration/interaction	High	+1
	Low	0
S/w complexity	High	+1
	Low	0
Power level required	High	+1
	Low	0

Table 3: Complexity weighting allocation

III.IV System-level Complexity

Because fractionated vehicles explore the same site at the same time and collaborate to accomplish the mission goals, the vehicle interactions cannot be ignored. Even if the vehicles do not interact in any way (e.g. if they do not share samples, or share power to name but a few), the vehicles have to interact with each other in order to avoid collisions since they are exploring the same site. The system-level complexity metric illustrates the added system complexity that arises from this interaction and is defined in Eq. 5.

$$system\ level\ complexity = \frac{\left(\sum_{i=1}^{n}\sum_{j=1}^{m}\beta_{ij}A_{ij}\right)\varepsilon}{n} \qquad [5]$$

In this equation, n is the number of vehicles, m is the number of functions on vehicle n, and β_{ij} $*A_{ij}$ is the weighted connectivity matrix that describes the interactions between each vehicle and ε is the graph energy, which is defined as the sum of the eigenvalues of the connectivity matrix A_{ij}. The weighting β_{ij} is allocated to each incoming and outgoing link between two vehicles (directionality is important in cases where one vehicle provides a functionality to another) based on the types of interactions between the two vehicles, as commonly identified in a Design Structure Matrix (DSM).[19] These interactions are shown in Table 4. The weighting of a connection from one vehicle to another is the number of types of interactions there are between two vehicles.

Label	Type of interaction
A	Mechanical Contact
B	Information Transfer
C	Mass Transfer
D	Energy Transfer

Table 4: Types of interactions between vehicles

The 3-vehicle architecture described in Table 5 illustrates the trade between vehicle-level and system-level complexity. The interactions between each of the vehicles are shown in Figure 5.

	3-rover architecture			1-rover arch.
Payload	WISDOM LMC Ma_MISS (+drill)	Raman MOMA Mars-XRD	MicrOmega PanCam (+mast)	(ALL)
Fractionated Functions	Provides Energy DTE Link	UHF Link	Receives Energy	N/A
Vehicle-Level Complexity	25	30	18	43
System-Level Complexity	2.67			0

Table 5: Example of a 3-rover architecture, as compared to the monolithic

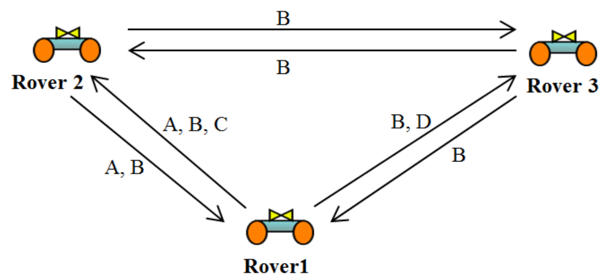


Fig. 5: Interactions between rovers in the 3-rover system example

In this example, it can be seen that each vehicle is individually much less complex than the monolithic vehicle. However, due to the interactions between the vehicles, the system complexity is significantly increased. It can therefore be said that, in fractionated systems, there is a shift from *design* complexity to *operational* complexity and this shift must be carefully weighed when choosing architectures. For example, architectures where the analysis instruments and the drill are on the same vehicle are clearly more advantageous because there is no need to transfer a sample from one vehicle to another, thus reducing the system-level complexity. Furthermore, fractionating the energy generation system is a careful trade. On one hand, the vehicle with no energy generation system (i.e. with no solar panels) is now much less complex, and it does not need to be in sunlight to operate. This is advantageous when exploring craters and lava-tubes for example. On the other hand, fractionating this function causes the system-level complexity to increase as well as the complexity of the vehicle providing power. The power subsystem should therefore only be fractionated if there is a need to explore areas with low illumination. In those circumstances, complexity is traded for additional functionality.

III.V System Mass

One of the key ways to differentiate architectures from each other is their overall mass, due to the direct correlation between mass and launch vehicle cost. To this end, a rover mass-modeling tool was developed to estimate the total mass of each architecture. The model consists of nine sub-systems, along with a payload system, which are then called by a master script in an iterative manner to obtain a model which meets the input requirements. The interactions between the subsystems in the modeling tool are shown in Table 6 and its inputs and outputs are detailed in Table 7.

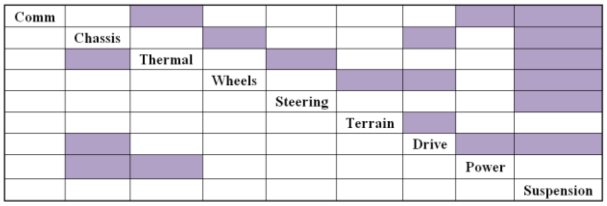


Table 6: Connection between each subsystem

Input	Output
No of Sortie Days	Navigation System Mass
Planet	Comm System Mass
Bandwidth	Comm System Power
Data Rate Needed	Structure Mass
No of Wheels	Wheel size & mass
Chassis Material	Thermal System Mass
Sinkage	Wheel Load
% time spent on slope	Sprung Mass
Max slope angle	Steering Mass
Wheel Slip	Turning Radius
Drive Type	Level Power
Motor Type	Slope Power
Power Source	Power Mass
Payload Mass	Solar Array Size
Payload Power	Total Power

Table 7: Inputs and outputs to the rover modeling tool

Details of the modeling tool can be found in Ref. 20 and a brief overview of the modeling assumptions for each subsystem is shown in Table 8. The modeling tool was validated against existing rover designs and was found to have estimates within 10% of the actual masses of these rovers.

Since the evaluation of the architecture space occurs in the early stages of the design process, the system mass is used to categorize the architecture. Any architecture having a mass within ±30% of the mass of the monolithic vehicle is assumed to be part of the same *class* of architectures (30% is a standard margin in Pre-Phase A design). The assumption is that systems of the same class can be launched on the same launch vehicle and can be landed with the same Entry Descent and Landing (EDL) system. Architectures of the same class can therefore directly be traded against each other. The rest of the architecture tradespace can also be divided up into classes, in order to evaluate the potential science return per dollar.[15]

Sub-System	**Assumption**
Payload	Mass, power and duty cycle for all instruments given as an input by the user
Communications	Mass and power calculated using the link budget equation and mass correlations[11]
Chassis	Modeled as a simple ladder frame
Thermal	Thermal balance equation evaluated, heat is rejected using radiations and is input using radioisotope heater units (RHU)
Wheels	The diameter and width of the wheels are sized for a specified sinkage and soil bearing pressure
Steering	Assumes Ackerman steering (models the mass of a steering motor required for each set of wheels that are steerable), a steer-by-wire system, and some additional mass for mechanisms.
Terrain	Terrain properties are used to measure the driving resistances
Drive	Resistances are used to measure torque and motor power
Power	Power of other subsystems are used to measure energy requirements and size the power system
Suspension	Assumed to be 12% of the rover mass, from historical data[12]

Table 8: Overview of the assumptions used for the design of each sub-system

IV. TRADESPACE EXPLORATION

Once the architectures have been generated and the metrics described in Section III have been calculated, the architecture space must be visualized in order to allow the user to iteratively explore the tradespace and to choose interesting architectures for further study. A software tool was developed to accomplish this. The user simply has to: input the monolithic vehicle's payload, functionality and the associated weightings; identify the SS functions; and decide on the maximum and minimum number of vehicles. The tool then generates the tradespace of possible architectures and calculates the aforementioned metrics for each architecture. The results are displayed on an interactive screen, as shown in Figure 6 using the ExoMars-type rover tradespace described thus far as an example. On this screen, any metric can be plotted against any other. The user can downsize the space using the down-selection option. This allows the user to interactively explore the tradespace. Once the final few architectures have been chosen, the tool can display the composition and the productivity plots for each of the final architectures (examples of which are given in Figures 3 and 4). Two of the most interesting architectures, along with the monolithic architecture, from this example tradespace are shown in Table 9.

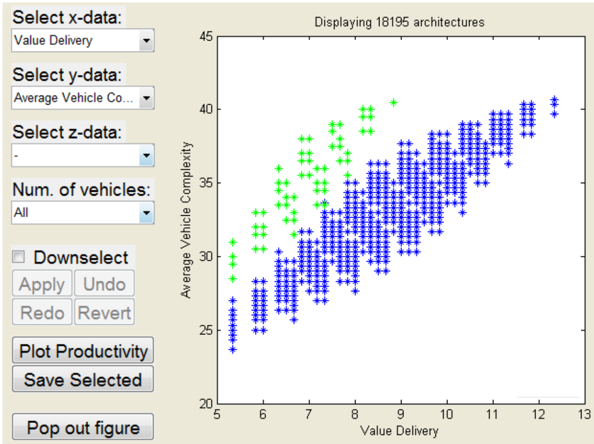


Fig. 6: Example of a display of the tradespace

	Monolithic	2 rovers		3 rovers		
Payload	All	LMC, WISDOM, MOMA, Raman, Ma_MISS, (+ deep drill)	WISDOM, PanCam, MicrOmega, MARS-XRD, (+short drill, mast)	WISDOM, LMC	LMC, MOMA, Raman, Ma_MISS, (+ deep drill)	WISDOM, PanCam, MicrOmega, MARS-XRD, (+short drill, mast)
Comm	UHF + DTE	UHF	DTE	Short-range only	UHF	DTE
Total Mass (kg)	330	409		560		
Value	1	1.63		1.83		
Productivity	1	2.21		3.16		
Vehicle-Level Complexity	43	27	32	12	26	24
System-Level Complexity	0	1		1.4		

Table 9: Details of the down-selected architectures, with value and productivity normalized

In Table 9, the 2-rover architecture falls well within 30% of the mass of the monolithic. Its vehicles are approximately 30% less complex and provide 60% more value than the monolithic. They are also more than twice as productive, due to the increased redundancy and the fact that both vehicles can operate at the same time. There is some system-level complexity cost, but it is quite low since vehicles do not have to directly interact much (they only have to avoid colliding, and communicate to each other). The main penalty comes in the slight mass increase. There are two reasons for this increase. First, any rover, even if not carrying payload or a communication sub-system, has a minimum mass due to its chassis and wheels. Secondly, the main penalty in this case is from the fact that both vehicles must have a drill in order to avoid having to transfer samples from one vehicle to another. Enhanced productivity and reduced system-level complexity are therefore traded for added mass. The same occurs in the 3-vehicle scenario. However, one notable aspect of the 3-vehicle architecture shown in Table 9 is that all three rovers have nearly the same mass, and are all approximately the size of one MER. This means that there are potential savings that could be made from learning curve effects by using this architecture.

V. CASE STUDY: MSL REDESIGN

In this case study, the design of the Mars Science Laboratory (MSL) was used as the baseline monolithic system. The aim was to use the methodology described in this paper to identify some multi-vehicle alternatives to the monolithic system. As mentioned at the beginning of the paper, MSL is a highly integrated and complex 930kg rover. After a 2-year delay and significant budget overruns, it successfully landed on the surface of Mars on August 6th 2012. Even though the design of the rover can be deemed to be successful, this case study attempted to uncover where the trade between a multi-vehicle architecture and a monolithic system lies in the case if MSL.

The overarching science goal for MSL was to explore and quantitatively assess a local region on Mars' surface as a potential habitat for life, past or present.[1] The four primary science objectives were to:

1) Assess the biological potential of at least one target environment
2) Characterize the geology of the landing region at all appropriate spatial scales
3) Investigate planetary processes of relevance to past habitability
4) Characterize the broad spectrum of surface radiation

The functions for MSL were derived and classified based on these goals. The list of functions generated was similar to that in Table 1, with MSL's instruments (shown in Table 10) instead of those considered in the first case study. The main difference was the method for energy generation. In this case study, energy generation was classified as ES (and thus was not fractionated) and it was assumed that MMRTGs provided power if the rover required more than 100W of power from its payload (if it required less than 100W, solar panels were assumed). Some restrictions were imposed for the instrumentation. For example, the MastCam had to be accompanied by the ChemCam. Additionally, the APXS and MAHLI had to be on the same vehicle, to avoid duplication of the robotic arm. Similarly, CheMin and SAM were made to be on the same vehicle, to contain the analysis of samples to one vehicle. Finally, the fractionation of the path planning system was allowed between vehicles, but each vehicle had to have at least one stereo camera. This led to the 7 groups of instrument shown in Table 10.

Instrument	Acronym	Group
Mast Camera	MastCam	1
Chemistry & Camera	ChemCam	1 & 6
Alpha-Particle X-Ray Spectrometer	APXS	1
Mars Hand Lens Imager	MAHLI	1
Chemistry & Mineralogy	CheMin	2
Sample Analysis at Mars	SAM	2
Radiation Assessment Detector	RAD	3
Rover Environmental Monitoring Station	REMS	4
Dynamic Albedo of Neutrons	DAN	5
Hazard Camera (stereo)	HazCam	1 & 7
Navigation Camera (panoramic)	NavCam	2 & 7

Table 10: Instruments onboard MSL used in the case study

A very large tradespace of architectures was generated (>100,000 architectures) but patterns were rapidly identified in the architecture set to help downsize it. Twelve architectures that are representative of the trade space were found and evaluated, as shown in Figure 7. The two best performing architectures in this subset (apart from the monolithic) are circled. Note that all the values shown in Figure 7 are normalized by the value for MSL.

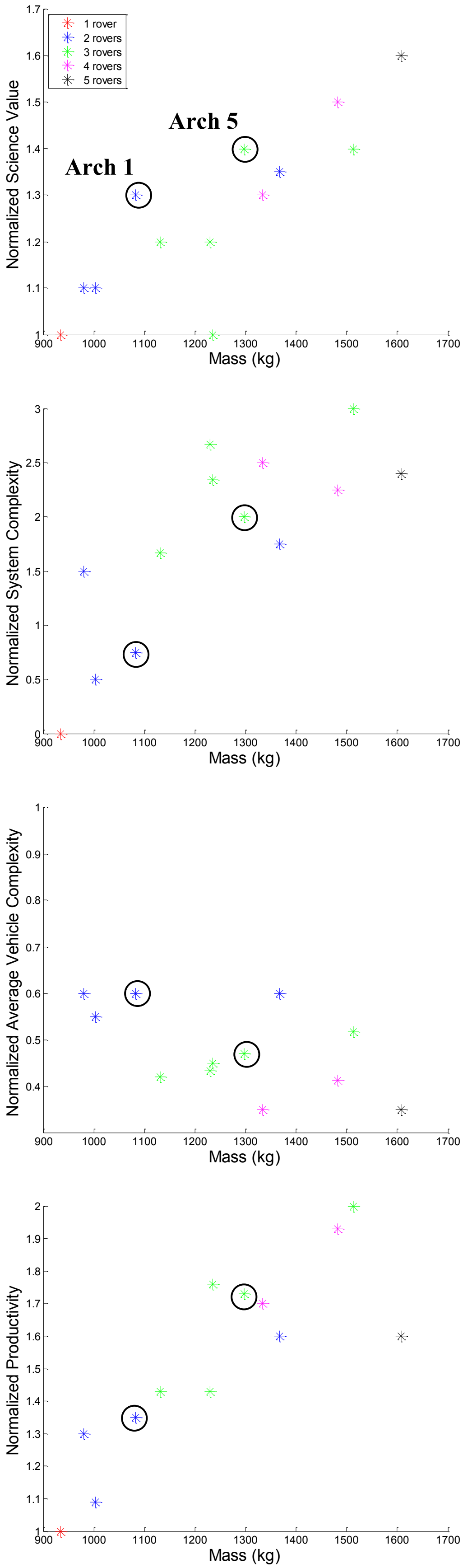
A few general observations can be derived from the results. First, it can be seen that architectures with more vehicles have higher productivity, higher value and lower average vehicle-level complexity, but they generally have higher mass and higher system-level complexity. This is due to several factors. First, multi-vehicle architectures can cover a larger area during the mission duration, which leads to higher science return. Additionally, the inherent redundancy present in multi-vehicle systems leads to greater robustness to failure and thus to longer mission durations. Each vehicle in the system carries a smaller amount of payload, which means that many of them can operate on solar power. This in turn leads to a lower vehicle mass, and a higher power-to-weight ratio. These vehicles can thus travel at a higher speed and cover more terrain than their heavier counterpart.

Furthermore, in many of these architectures, the path planning occurs on the smaller, lighter vehicle. Since the vehicle carrying CheMin and SAM cannot travel whilst performing analysis (due to power restrictions), having a smaller vehicle perform some of the path planning and explore the area ahead of the larger vehicle allows the latter to traverse the surface more efficiently. In particular, architectures that possess an additional ChemCam on a lighter vehicle (i.e. the architectures that possess payload group 6) have higher productivity than others. This is because the ChemCam is particularly important in the process of finding sites of interest for sample extraction. If a vehicle can travel ahead to perform some of this initial analysis while the larger "laboratory" vehicle analyzes a sample, the number of samples analyzed over the mission duration can be dramatically increased. This does come at a cost however, since the ChemCam must be mounted on a mast. This leads to both increased mass and increased vehicle-level complexity in an architecture.

In the architectures in Figure 7, it can be seen that if instrument groups 1 and 2 are on different vehicles, the productivity increases but the system-level complexity also increases dramatically. This is because the instruments in group 1 are used to collect a sample, and those in group 2 analyze the sample. If they are on different vehicles, mass transfer must occur between the vehicles. This leads to this increased system-level complexity. The increased productivity occurs from the fact that, if on a single vehicle, group 1 and group 2 instruments must operate at different times due to power limitations. If they are on different vehicles, collection and analysis can occur concurrently, thus increasing productivity.

Despite the increase in mass described earlier, there are a number of architectures that fall within 30% of the mass of MSL, and can be assumed to be part of the same mission class. In particular, architectures 1 and 5 performed very well. One interesting point about architecture 5 is that two of the rovers are very alike (both have solar panels and approximately the same mass). In the same way as the 3-rover architecture in the last case study, this makes the vehicle design simpler than if both vehicles were significantly different and could lead to potential economies of scale.

In this case study, the monolithic vehicle still performs very well in most metrics, and has the lightest total mass. This is due to the fact that many of the MSL instruments were designed to be highly integrated with each other and the vehicle. This is particularly true of the instruments in groups 1 and 2, and therefore limits the amount of VD functions that can be fractionated. Because of the choice of instruments, there are no architectures composed of several very light (<100kg) vehicles that can perform the same task as the monolithic, and at least one larger (>500kg) vehicle is needed in each architecture. If this analysis had been done in the early stages of the mission design, there would have been a trade between instrument complexity, science value and productivity. A more fractionated system would have been able to meet the mission goals with different instruments (e.g. with multiple smaller drills and more surface samples) and with a higher productivity, while potentially sacrificing some of the quality of the measurements.



Arch ID	Rover ID	Payload Groups	Mass (kg)
0	1	1, 2, 3, 4, 5, 7	935
1	1	1, 2	790
	2	3, 4, 5, 6, 7	293
2	1	1, 2	790
	2	3, 4, 5, 7	213
3	1	1, 3, 4	745
	2	2, 4, 6, 7	622
4	1	1, 3, 4	745
	2	2, 4, 7	235
5	1	1, 2	790
	2	3, 4, 7	266
	3	5, 6, 7	241
6	1	1, 2	790
	2	3, 4, 7	186
	3	5, 7	156
7	1	1, 3, 4	745
	2	2, 5, 7	540
	3	6, 7	228
8	1	1, 3, 4	745
	2	2, 7	300
	3	4, 7	190
9	1	1, 2	790
	2	3, 7	172
	3	4, 7	190
	4	5, 7	182
	5	6, 7	273
10	1	1, 2	790
	2	3, 7	172
	3	4, 7	190
	4	5, 7	182
11	1	1, 2	790
	2	5, 7	202
	3	6, 7	282
	4	3, 4, 7	208
12	1	1, 2	790
	2	5, 7	202
	3	3, 4, 7	238

Fig. 7: Details and evaluation of twelve representative architectures.

VI. OPPORTUNITIES AND LIMITATIONS OF MULTI-VEHICLE SYSTEMS

Through the case studies presented in this paper, and others undertaken by the authors, a more general understanding of the opportunities and limitations that arise from fractionating planetary surface vehicles has been achieved. These patterns are presented in this section.

First and foremost, multi-vehicle architectures have been found to be valuable in missions with conflicting science goals.[15] Having different vehicles to deal with each of the mission goals leads to reduced vehicle-level complexity and increased productivity, since different goals can be addressed at the same time.

Moreover, fractionated multi-vehicle systems can make use of a number of emergent properties that have not yet been discussed in this paper. For example, the rover-to-rover communication systems could be used for navigation and triangulation or, if a rover was to get stuck, another could be used to try to tow it. Additionally, the inherent redundancy in these systems can lead to higher productivity. Alternatively, the same productivity as that of the monolithic system could be achieved with less reliable sub-systems. This could in turn lead to reduced costs. A multi-vehicle system leads to lower mission risk: if one vehicle fails, some of the mission goals can still be achieved. A high risk component can also easily be added to a fractionated system without risking the achievement of the main science goals. For example, small "micro-rovers" could be added to these systems to increase ground coverage at a very low cost[21] or one of the rovers as part of a suite could be used to explore a more dangerous terrain without risking the whole mission.

Fractionated systems are also more upgradeable and fit better within a "campaign" approach to planetary surface exploration: new vehicles can be sent to the surface to enhance an existing system, or can make use of some of the pre-deployed functionality. The tool described in this paper can easily be adapted to deal with this kind of scenario.[15]

Having multiple moving assets on the surface of a planet leads to more ground being covered, although this could also lead to increased operations costs depending on how the vehicles are commanded. Furthermore, fractionating certain functions can allow for a more efficient exploration of treacherous environments.[22] For example, fractionating the energy generating function (via solar panels) can enable the exploration of craters or lava-tube: a vehicle without an energy generation system could undertake the exploration of low illumination areas, while another traverses in an illuminated area to generate enough energy for both vehicles.

Finally, architectures with several similar vehicles, such as the 3-vehicle architecture presented in the ExoMars-type rover case study and architecture 5 in the MSL case study, could make use of learning curve effects, or of previous designs such as MER, to reduce design and development costs.

On the other hand, fractionated systems also have their limitations. Operating a multi-vehicle systems would require a change in the way operations are currently undertaken and an increase in the levels of autonomy onboard the vehicles. In turn, this would lead to increased testing time and cost. In general, fractionated systems also increase the overall mass of the system due to the inherent mass associated with the chassis and wheels of a rover. Since the rovers in fractionated systems are most often simpler than the monolithic, it is not clear whether this increased mass would affect the design and build cost of the systems.

Finally, depending on the science goals, fractionated systems are not always advantageous. For example, when the goals are closely knit and the science package is highly integrated, as was the case for MSL, the potential benefits of fractionated systems become somewhat limited because separating payload can lead to the duplication of more complex assets such as drills and masts to avoid excessive interactions between vehicles.

VII. CONCLUSION

This paper has presented a methodology for the generation of fractionated multi-vehicle systems for planetary surface exploration. A set of metrics was presented to evaluate these architectures and help identify interesting architectures for more detailed evaluation. Two redesigns of existing rover concepts were undertaken to demonstrate the potential of the methodology. However, the methodology is designed for use in early mission design, before the instrumentation has been packaged, to demonstrate opportunities and trades involved in multi-mission architectures. Undertaking this analysis early on in the design process may even help design instrument packages that lend themselves better to fractionation or it may help trade different instruments against each other. Overall, fractionation was found to be particularly advantageous for missions with ambitious and/or conflicting science goals, in risky environments or when productivity and evolvability are important.

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