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SUSTAINABILITY IN SYSTEM ARCHITECTURES THROUGH RECONFIGURABILITY: A CASE STUDY OF PLANETARY SURFACE VEHICLES

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ABSTRACT

Traditionally, space systems have been built for pre-defined missions, fixed requirements, and optimized for highest performance. Sustainable system architectures however need to be affordable, ensure delivery of value, minimize failure risk, and adapt to new requirements. Reconfigurability in systems can be a means for achieving these desirable characteristics. Currently, there is no formal methodology for studying reconfigurability issues in system architecture and design. This paper presents such a methodology and investigates how reconfigurability can be a means for reducing cost and mitigating risk. As a specific case study, reconfigurable planetary surface vehicles for human exploration of Moon and Mars are analyzed. It is assumed that reconfigurability is primarily desired in the system to maximize value through multi-functionality (and thereby reduce total mass required to be transported to planetary surface). It is found that for the specific case study analyzed, the mass savings due to reconfigurability in a fleet of vehicles can be on the order of 35% while risk of non-performance can be reduced to 1%. The cost of reconfiguration however goes up with increasing reconfigurability in the system.

1.0 INTRODUCTION

The history of space exploration has highlighted the need for sustainable system architectures. The Apollo program was cut short due to budget constraints [1]. Skylab burnt up in the atmosphere long before it had completed its intended service time due to unexpected increased solar activity [2]. Several robotic missions to Mars failed due to a variety of reasons (*e.g.* Mars Polar Lander [3], Beagle II [4]). As the individual systems, and the larger System of Systems (SoS) of which they are a part of increase in size and complexity, the frequency of these failures will increase unless their architecture is properly chosen. One of the underlying principles for good architecture of these kinds of SoS is *Sustainability*. Sustainable systems are defined to be those that ensure delivery of value, are affordable, minimize risk, and are robust to policy changes [5]. There are several potential means through which sustainable architectures may be achieved, one of which is *Reconfigurability*. It can allow for reduction in costs, flexibility in system capabilities and functions, and adaptability towards new needs.

This study explores how reconfigurability maybe studied in a systematic way in order to assess its effects on a system of interest. A formal definition is introduced along with a discussion on its classification and quantification. A method to determine an optimal reconfigurable design is also proposed. As a specific case study, the various concepts and methods are applied in analyzing reconfigurable planetary surface vehicles (PSV). A comparison between non-reconfigurable versus reconfigurable vehicles is made to systematically assess the effects on value delivery, cost, and risk of a planetary mobility system architecture.

1.1 Literature Review

In recent years there have been increasing attempts at formalizing the analysis of various qualities of a system such as its flexibility, adaptability, supportability *etc.* Reconfigurability has received special attention since it can potentially provide the means for meeting the modern challenges involved in the development and operation of large systems. Researchers have explored the economic benefits of reconfigurable manufacturing systems (RMS) [6], performance improvements in reconfigurable race cars [7], implementation issues for reconfigurable satellite constellations [8], and design concepts for reconfigurable communication satellites [9].

This work attempts to provide a *comprehensive* approach towards studying reconfigurability issues in a system. It proposes definitions, concepts and tools that can aid in a systematic study of the effects and value of reconfigurability. A case study of PSVs is used to illustrate some of these ideas and methods.

2.0 SYSTEM RECONFIGURABILITY

In order to study reconfigurability some key definitions and concepts were first developed. The following sections provide a detailed discussion.

2.1 Definition

There are several notions that exist in various engineering domains, with no common definition of *what* reconfigurability really means. It is thus essential to first establish a base definition.

> Reconfigurable systems may be defined as those that can *reversibly achieve distinct configurations (or states), in order to affect system form and/or function to achieve desired outcomes, within bounded reconfiguration time and cost.*

Systems whose configurations can undergo only a one-time change will therefore not be considered as reconfigurable in this study (*e.g.* spring-loaded or pyrotechnic mechanisms for one-time deployment). The notion of a bounded reconfiguration time and cost is also important to note. Many systems given an infinite amount of time and resources may be able to undergo changes in their configurations (by themselves or through an agent acting upon the system). However, for a system to be considered as a truly 'reconfigurable' one, its reconfiguration time and cost, which is the time and cost respectively that it takes to change from one configuration to another, must be within certain limits. The cost includes monetary, energy, and other types of expenditures. The extent of the bounds will depend on the type of the system. An RMS for instance will have reconfiguration times and costs that are markedly different from perhaps Field Programmable Gate Arrays (FPGAs). Figure 1 shows an Object-Process Diagram (OPD) [10] of a reconfigurable system as defined above. It is shown that in a reconfigurable system:

- the attributes of the system form
- the externally delivered function itself
- the attributes of the function

are affected by a process of reconfiguration.

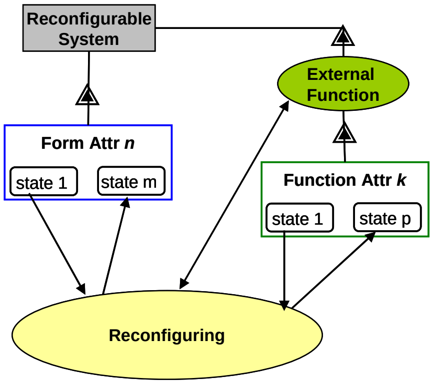

Figure 1: Object-Process Diagram of a Reconfigurable System

For instance, a mini-van, or a car with reconfigurable seating can change its seating capacity. This is illustrated through an OPD in Figure 2.

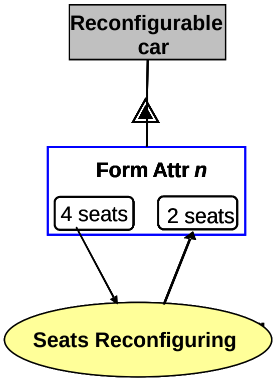

Figure 2: OPD of a Car with Reconfigurable Seating

2.2 Need Assessment

Determining *why* a system may need reconfigurability can be a fundamental question in an architecting effort. In general, four different categories can be defined for which reconfigurability maybe needed.

1. Uncertainty Management: Systems that encounter various kinds of uncertainties can benefit from reconfigurability. For instance, consumer goods that need to be customized to match changing styling demands, large capital intensive systems with uncertain demand forecasts *etc.* [11]

2. System Evolution: Reconfigurability is needed for evolving some systems over time through expansion, upgrades *etc.*

3. Multi-Functionality: Systems that need to fulfill different functions at different times from a fixed set of resources may need to be reconfigurable. For instance, an aircraft with reconfigurable wings is required if it needs to carry out both reconnaissance and attack missions [12]. Similarly, in a space exploration program where there are severe mass and volume constraints on the amount of payload that can be delivered to a planetary surface, the ability to reconfigure a fixed set of hardware for different functions can be greatly beneficial.

4. Graceful Degradation: Reconfigurability maybe needed for certain systems that need to be able to function on a limited scale in order to avoid ‘sudden death’ in the event of partial failure. High cost, large systems in particular often have such requirements.

2.3 Stage of Occurrence

One of the key things about reconfigurability is *when* it happens in the system, *i.e.* at what stage in the life cycle of a system is it reconfigurable. It can be reconfigurable during:

- development
- manufacturing
- initial deployment, or
- operation.

Depending on ‘when’ the reconfigurations can take place, there can be direct effects on the reconfiguration time and cost, system value, risk and a host of other relevant characteristics.

In many cases it maybe obvious as to when the system should be reconfigurable. Often the *need-category* in which a system is classified will drive to a certain extent the life cycle stage in which the system has to be reconfigurable. For instance, systems that require reconfigurability in order to achieve graceful degradation (category 4 discussed above) will need to be able to undergo their reconfigurations after they have been deployed and are either in or between operational states. In other situations, however, it may not be immediately clear. For instance, consider the case in which there are to be future exploration missions to Moon and Mars in which the number of missions for each of the two planets is highly uncertain. It is not immediately obvious if it is better to have a design of planetary surface vehicles whose manufacturing can be reconfigured so that the production of the specific instances is customized for separate use on Moon and Mars (development time reconfiguration), or is it better to only produce one standard vehicle in larger quantity and reconfigure it as the need arises for use on Moon and Mars (*i.e.* deployment reconfiguration).

2.4 Processes

Fundamentally, there are three high-level processes that can be used in describing *how* a particular reconfiguration takes place. Each of these processes change matter, energy, and/or information of the system in some fashion. These *primitive* processes for discrete and continuous changes are:

- addition (extension),
- subtraction (reduction), and
- transposition (transformation)

For example, adding new components, or increasing the dimensions of a room involve addition and extension respectively. Removing parts or scaling down the size of an inflatable structure involves subtraction and reduction respectively. Similarly, re-arranging components or changing the shape of a wing are examples of transposition and transformation. A car in which the seats can be reconfigured by stowing away to make room for cargo is also an example of transposition. Figure 3 depicts these primitive processes for a generic system.

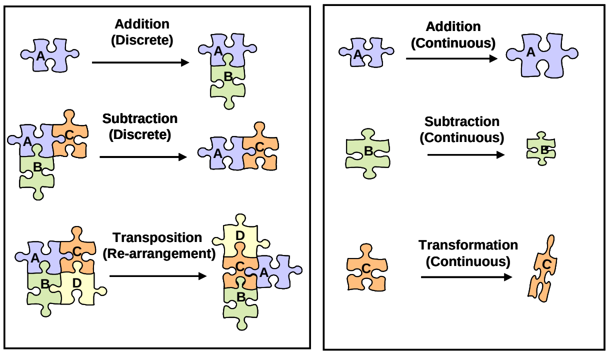

Figure 3: Processes of Reconfiguration

The determination of these processes for a particular reconfigurable system can be obvious in some cases and not clear in others. For instance, suppose that it is desired to have planetary surface vehicles that can undergo a reconfiguration in their locomotive system such that they are capable of traversing terrain of widely varying conditions ranging from dry sand, to hard compacted surfaces to soft ice. It is not obvious if the design should be such that the appropriate sub-systems can be substituted (which involves removal and then addition of components) or simply have an innovative technological solution that can allow for transformation of the locomotive sub-system characteristics. The cost and complexity of the processes, and other constraints (such as required reliability) will eventually drive the decision.

2.5 Quantification

It is very challenging to have a meaningful quantitative description of *how much* of a particular quality is exhibited by a system. However it is highly desirable to have such means since they would allow for easy comparison between various architectures. Reconfigurability can potentially be measured both in the performance (objective) and design space. For each of these cases, the quantification methods will require different types and amount of information about the system. The following section presents four metrics that can be used:

2.5.1. Reconfigurability Index: In case of the performance space, it is proposed that *the extent of reconfigurability of a system can be measured by the maximum amount of change in the system's capability among all of its viable configurations.* In other words, the capability 'bandwidth' of a reconfigurable system can be used as a measure of the extent its of reconfigurability.

The capability can be quantified through metrics that are based on the high level performance parameters related to the value delivering function of a system. For example, for transportation systems the Transport Capability metric [13] can be utilized. This will be discussed further in section 3.5.

In general, a reconfigurable system will have capability C_i when it is in its configuration *i*. For a total of *n* possible configurations (or viable states) a set **C** can be defined for the system as:

$$\mathbf{C} = \left[C_1 \quad \cdots \quad C_i \quad \cdots \quad C_n \right] \qquad (1)$$

A reconfigurability index, *RI*, for the system is then:

$$RI = \max(\mathbf{C}) - \min(\mathbf{C}) \qquad (2)$$

2.5.2. Coefficient of Variation: This metric is similar to *RI*, however it is more applicable to situations where there is a nominal point of operation. It can therefore be best used at the component/sub-system level rather than at a system level. It is defined as the ratio between the range of operation, σ, and the nominal (or mean) operating point, μ.

$$c_v = \frac{\sigma}{\mu} \qquad (3)$$

The reconfigurability of wings, antennas *etc.* can be described with this metric.

2.5.3. Combinatorial Efficiency: It is the ratio of number of distinct configurations, n_c, of the system and the total number of modules, N_m [14].

$$\eta_c = \frac{n_c}{N_m} \qquad (4)$$

It is called 'combinatorial efficiency' since it provides a measure of how many configurations can be achieved (which can be thought of as the output) through a given 'input' set of modules.

2.5.4. Coefficient of Connectivity: It is defined as the ratio of the number of links changed, l_c, to the total number of links in the initial and final configurations, l_t.

$$\lambda = \frac{l_c}{l_t} \quad (5)$$

The links can be physical, informational *etc.* In order to make use of this metric, detailed information about the system connectivity relationships (such as through Design Structure Matrices) will be required. It is thus only applicable for cases where enough information about the system design is available.

In general, it can be expected that the reconfiguration cost will be directly related to the λ. Reversibility of the reconfiguration relates primarily to whether the link changes, l_c, can be reversed.

2.6 Optimal Reconfigurable Designs

In addition to having definitions and metrics for formally studying reconfigurability, various tools and methodologies are also needed for determining the design of such systems. One particular problem in this context is the issue of finding an optimal reconfigurable design. This section presents a methodology that can be employed to address this problem for a certain class of systems that need to reconfigure between a small set of discrete configurations (or states). It is thus applicable, for instance, in cases where a system may require reconfigurability for multi-functionality so that it can reconfigure between its various states and can carry out different functions as needed. The details of the method are as follows.

Consider a system defined by a design vector, **x,** with *n* elements. Let the i^{th} configuration, in which the system can exist, be denoted as $\mathbf{x_i}$ where it is given as:

$$\mathbf{x}_i^T = \begin{bmatrix} x_{1i} & x_{2i} & x_{3i} & \cdots & x_{ni} \end{bmatrix} \qquad (6)$$

If a total of *p* configurations are possible, then a larger vector **X** can be defined as:

$$\mathbf{X}^T = \begin{bmatrix} \mathbf{x}_1^T & \cdots & \mathbf{x}_i^T & \cdots & \mathbf{x}_p^T \end{bmatrix} \quad (7)$$

where $\mathbf{X} \in \Re^{np \text{ x } 1}$.

An optimization problem can now be formulated in which the goal is to find **X** such that some optimality criterion, ***J***, is satisfied subject to certain constraints **g(x)**. If it is desired to find a design such that the reconfiguration cost is minimized over the system life cycle then the problem can be formulated as:

$$\begin{aligned} &\min \mathbf{J} = \sum_{j=1}^{p}\sum_{k=1}^{p} m_{jk} z_{jk} \\ &s.t. \qquad\qquad\qquad\qquad (8) \\ &\mathbf{g}_i(\mathbf{x}_i) \le 0 \end{aligned}$$

where z_{jk} is the reconfiguration cost and m_{jk} is the total number of reconfigurations between state *j* and *k*. In most practical situations, m_{jk} may not be known accurately, and the designer may only have a probability distribution for its estimate. In that case the expected value can be used to obtain results.

It should be noted that this method is suitable only when *np* is small. Thus, either both the number of elements in a design vector and the number of configurations should be small or at least one of them should be small. Otherwise the computational expense for the optimization will quickly get prohibitive (since the dimensions of **X** will be large for large *np*).

A case study of planetary surface vehicles was employed to demonstrate how such an evaluation can be carried out. The following section provides a detailed discussion of this analysis.

3.0 CASE STUDY: PLANETARY SURFACE VEHICLES

In a space exploration enterprise that is geared towards human exploration of Moon and Mars, a fundamental and arguably perhaps the most important component will be the surface exploration system. This is because one of the principal benefits from an exploration program is *knowledge* or *information*. In the case of planetary exploration, this knowledge will primarily be produced as a result of traversing a large and varied area of interest. A sustainable architecture of the mobility system is thus essential. This case study explores the role of reconfigurability in the sustainability of a mobility system by analyzing its effects on value, cost and risk.

3.1 Description

For long- term missions to Moon and Mars a number of researchers have analyzed the types of vehicles that will potentially be needed for surface operations and exploration [15-17]. The various types include survey vehicles, science vehicles, site preparation vehicles, transport and assembly vehicles, astronaut transport vehicles, service and maintenance vehicles, and mining vehicles [16]. Each type is based on the primary function performed by the vehicle.

For simplicity, in this case study we consider a surface operations scenario in which five crew members land on a planetary surface and use a vehicle for setting up some basic infrastructure. The tasks in that operation will include moving and placing large equipment and modules (such as the lander, a habitat *etc.*) in a desired location so as to set up a long term base. The towing and cargo carrying capacity of such a vehicle will thus have to be large. However, its speed can be expected to be fairly slow since its operations will be performed with utmost care and may also require a reasonable degree of accuracy (especially if various modules need to be interfaced together). Its total range (the distance it can traverse before it needs to be refueled) will also be small since it is expected that the modules will be delivered to the planetary surface in close proximity (a few hundred meters apart).

Once the base set up operations are over, the astronauts will start the exploration phase of the mission in which they will make both short and long range sorties from the main base. The short range sorties (that do not require an over-night stay away from the base) can be conceived to be carried out by vehicles that can transport one crew member and basic field equipment and tools. The cargo carrying capacity will not need to be large; however its top speed and range should ideally be higher.

For long range excursions that will require the crew to be away for several days from the base, a *planetary camper* will be used. The camper would essentially be a vehicle that provides a pressurized, habitable volume to a crew of 2 for a few days. This camper will be hauled by an un-pressurized vehicle with sufficient towing capacity.

For the scenario described above, there can be two options in the context of reconfigurability for architecting the mobility system. In the first option, the different operations are carried out by a fleet of vehicles in which each performs a dedicated task. The fleet will consist of the following three types of vehicles:

- Site Preparation Vehicle (SPV) for transporting and placing modules, shelters, and lander to desired locations.
- Long Haul Vehicle (LHV) for towing a camper to various planetary sites for over-night excursions.
- Astronaut Transport Vehicle (ATV), to be used for high speed, long range, traverses for exploration.

The desired specifications of range, tow capacity, cargo capacity, and speed for each type are shown in Table 1.

Table 1: Specifications for Dedicated Vehicles

	SPV	LHV	ATV
Range [km]	5	50	100
Speed [km/hr]	3	8	12
Tow Capacity [kg]	5000	2500	5
Cargo Capacity [kg]	500	200	50

It is assumed that the exploration operations consist of two teams of two people each that explore the surface at a given time. Each team brings a camper, and two LHVs for the trip. One person stays on the base for maintenance and support and uses an ATV. Based on these assumptions, the mobility fleet will consist of one SPV, four LHVs, and one ATV.

In the second option, a set of identical reconfigurable vehicles is used. The reconfigurable vehicles can undergo changes in their capabilities so that any one vehicle can be configured to carry out any of the three types of tasks at a given time. This will thus be a case in which the system needs to be reconfigurable in order to have multi-functionality. Furthermore, the reconfigurability is required after it has been deployed, and is between various operational states. For the exploration operations scenario described above, this would require 5 reconfigurable vehicles.

One vehicle will be used by the person at base, and the two teams out on exploration will use two vehicles each.

In order to determine which option should be pursued, various trades between the two types of systems were carried out from a sustainability perspective. The following sections discuss the modeling and analysis.

3.2 PSV Modeling Framework

A tool was developed in MATLAB to model various kinds of concept vehicles. The model is based on physics of off-road vehicle motion and terrain interaction [13], and uses parametric models of component masses (such as wheels, motors *etc.*) to get mass estimates. The inputs to the tool are various specifications such as range, speed, tow and cargo capacity, vehicle type (pressurized or un-pressurized), number of passengers *etc.* The outputs include estimates of mass, power, torque, energy, wheel base, track *etc.* of the vehicle. Figure 4 shows a generic PSV that the tool can model.

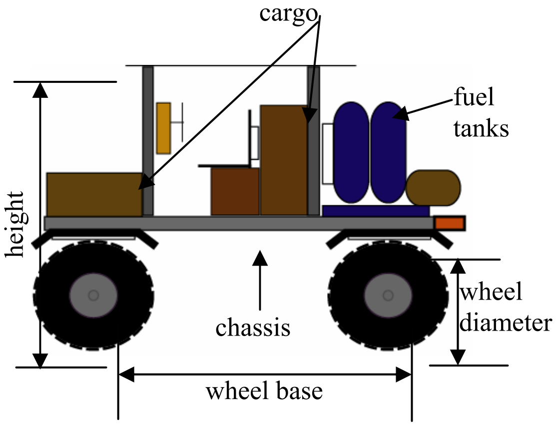

Figure 4: Planetary Surface Vehicle Concept

In order to assess the reliability of the estimates, the Lunar Roving Vehicle (LRV) [18] that was used in Apollo 15-17, and Northrop's concept vehicle, the Lunar Surface Vehicle (LSV) [19] were used for benchmarking. Table 2 shows the data for the LRV comparison.

Table 2: Comparison of Actual and Estimated Data for Apollo LRV

	Actual	Estimate
Wheel Diameter [m]	0.82	0.7
Wheel Width [m]	0.23	0.18
Wheel Base [m]	2.29	2.64
Track [m]	1.83	1.7
Length [m]	3.1	3.34
Width [m]	2.06	1.8
Height [m]	1.14	1.7
Battery Capacity [W-hr	8280	7400
Drive Motor Power [W]	191.5	193
Gradeability [deg]	23	15
Total Mass [kg]	210	226

It can be observed that the model estimates and actual data are in fairly good agreement. Once the tool had been validated, it was used to model various vehicles. Table 3 shows the details of the SPV, LHV, and ATV that were described in the previous section, and designed for minimum mass. The vehicles are modeled to be used on Mars (0.38g), with four independently driven wheels using harmonic drives of gear ratio 1:30, and having one crew seating capacity.

Table 3: Design Details of Fixed Vehicles

	SPV	LHV	ATV
Total Power [kW]	2.68	3.47	0.94
Fuel [kg]	2.7	11.4	4.1
Wheel Base [m]	2.54	2.54	2.54
Track [m]	1.52	1.52	1.52
Wheel Diameter [m]	1.13	1.12	1.09
Wheel Width [m]	0.34	0.28	0.27
Max Torque [Nm]	34.6	16.65	2.7
Traction Drive Power [W	646	842	211
Total Mass [kg]	358	401	245

3.3 Reconfigurable Vehicle Design

A 'good' reconfigurable vehicle design was obtained by using the methodology presented in section 2.6. In this problem, the vector that described the i^{th} configuration (or state) was defined as:

$$\mathbf{x}_i^T = \left[r_i \quad V_i \quad T_i \quad M_i \right] \tag{9}$$

where r is the range [kg], V is the speed [km/hr], T [kg] is the mass the vehicle can tow, and M [kg] is the mass the vehicle can carry as payload. It was assumed that the reconfigurable vehicle needs to exist in three different configurations, A, B, and C, in order to carry out the three types of tasks discussed earlier. The full design vector that needed to be determined through optimization was thus:

$$\mathbf{X}^T = \left[\mathbf{x}_A^T \quad \mathbf{x}_B^T \quad \mathbf{x}_C^T \right] \tag{10}$$

consisting of 12 variables. The problem was formulated as:

$$\min \mathbf{J} = z_{AB} + z_{BC} \quad (11)$$

s.t.

$$\begin{array}{lll} 0.5 \le r_A \le 8 & 60 \le r_B \le 80 & 50 \le r_C \le 100 \\ 0.5 \le V_A \le 5 & 4 \le V_B \le 10 & 6 \le V_C \le 15 \\ 4000 \le T_A \le 7000 & 2500 \le T_B \le 4000 & 5 \le T_C \le 50 \\ 500 \le M_A \le 800 & 100 \le M_B \le 200 & 30 \le M_C \le 180 \end{array}$$

where the objective function ***J***, was simply the sum of reconfiguration costs in changing from state A to B, z_{AB}, and in changing from state B to C, z_{BC}. It was assumed that $z_{AB} = z_{BA}$ and $z_{BC} = z_{CB}$.

3.3.1 Reconfiguration Cost: The reconfiguration costs, z_{ij}, were computed on the simplifying assumption that the cost is directly related to the amount of mass that is interchanged during a reconfiguration process. Thus, greater the mass of the components that need to be substituted, higher will be the costs. In reality, other costs such as energy crew time *etc.* will also be involved.

The determination of which components are substituted and which are transformed was based on the type of the component. It was assumed that the chassis frame, fuel tanks, and thermal system could only be altered through discrete addition and removal. The wheels and traction drives were considered to have the additional capability of undergoing *transformation*. For the case of transformation, the coefficient of variation, c_v, was set to 10% for both the wheels and drives. This effectively meant that the wheel diameter and width could vary by 10%, and the max power level of the traction drives could be altered by 10% (perhaps by channeling extra-power from non-essential devices when needed). If the required change in the component characteristics in configuring from one state to another was greater than what could be achieved with the given c_v, then substitution (*i.e.* a sequence of subtraction and addition) would be carried out. The mass of the component removed and that of the one installed are both summed up to get the total mass that is 'inter-changed'. In case a component was found to be reconfigurable through transformation, then no additional mass was added. The reconfiguration cost is therefore a lower bound on the actual costs that may be incurred.

3.3.2 Optimal Reconfigurable Vehicle

The optimization was carried out by using a heuristic method, Simulated Annealing [20], which is suitable for problems with both continuous and discrete variables. Although in this specific analysis only continuous variables were involved, in other more general analyses discrete variables are also involved such as number of wheels, power source type, drive type *etc*. Hence simulated annealing instead of a gradient based algorithm has been implemented in this MATLAB framework for studying PSVs.

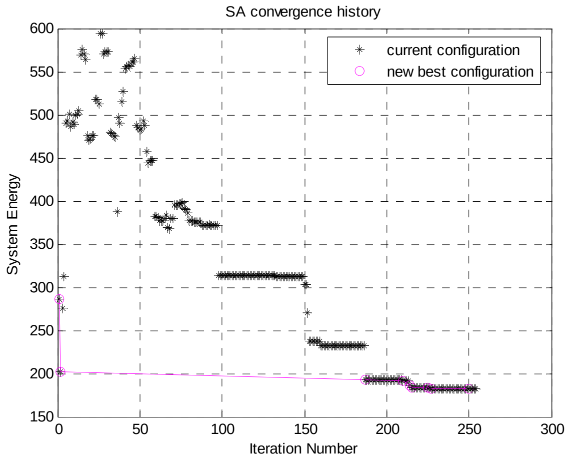

Figure 5: Convergence History of Optimization

The initial condition used for the optimization was $\mathbf{X_o}^T$ =[5, 2, 5000, 500, 50,5,2000,300, 80,15,100,50]. Figure 5 shows the convergence history of the algorithm. The optimal solution found for the given objective function and constraints (as shown in Equation 11) was: $\boldsymbol{J}^*$ = 182 kg, and $\mathbf{X}^*$ = [8, 0.67, 5527, 501, 60, 4.5, 2522, 118, 95.7,12.5, 42.2, 171]^T. The total mass of the reconfigurable vehicle was computed to be 330 kg. Table 4 shows this solution.

Table 4: Optimal Configurations for Reconfigurable Vehicle

	A	B	C
Range [km]	8	60	95.7
Speed [km/hr]	0.67	4.5	12.5
Tow Capacity [kg]	5527	2522	42.2
Cargo Capacity [kg]	501	118	171

Each configuration was modeled with the same number of passengers (*i.e.* one), drive system *etc.* as the fixed case. The detailed design specifications for each of these configurations are given in Table 5 below.

Table 5: Design Details of Reconfigurable Vehicles

	A	B	C
Total Power [kW]	0.73	1.92	1.36
Fuel [kg]	4.48	13.1	5.4
Wheel Base [m]	2.54	2.48	2.48
Track [m]	1.52	1.52	1.48
Wheel Diameter [m]	1.13	1.11	1.11
Wheel Width [m]	0.32	0.27	0.28
Max Torque [Nm]	37.5	15.7	3.9
Traction Drive Power [W]	156.8	455.6	315.3
Total Mass [kg]	245	311	270

It is observed that the fuel tank sizes need adjustment in changing from configuration A to B and B to C. The changes are needed in order to reduce the mass of the vehicles. In calculating the mass of the power subsystem of each configuration it was assumed that the tank size and other hardware elements are sized according to its maximum fuel capacity. Thus, if the largest tank size (which is used in B) is used on other configurations as well with partially filled fuel, the mass of configuration A (245 kg) and for C (270 kg) in that case will be higher. The traction drive powers are markedly different in all the three states so they are also changed. The wheel diameters and widths do not undergo a change larger than their c_v so they can simply be reconfigured through transformation. These results can aid in making architectural decisions about the interface designs between the sub-systems that would allow for installations, removals, and transformations.

3.4 Reconfigurability and Cost

The cost of any particular architecture was assumed to be the total mass of the mobility system that needs to be delivered to the planetary surface. Mass was used as a surrogate for cost, since the cost in dollars of any space exploration mission is strongly related with the amount of mass that needs to be transported.

The total dry mass for the non-reconfigurable (or fixed) vehicles fleet, which consists of 1 ATV, 4 LHVs, and 1 SPV, is 2154 kg. For the reconfigurable case, 5 identical vehicles were to be shipped to the planet with a total dry mass of 1393 kg. There can thus be potentially a saving of 35% in total mass. It should be noted that the masses of the reconfigurable system give a lower bound since any mass penalty of having components that can transform, or be installed and removed easily has not been factored in. The difference of 761 kg thus provides the limiting value of reconfigurability, *i.e.* the reconfigurable option is better strictly in terms of mass if the mass penalties are lower than 761 kg. However, even if all the 761 kg mass difference were consumed by the heavier reconfigurable components, there still is a benefit to the reconfigurable fleet because as failures occur components can be swapped out more easily and multi-functionality is retained longer at the fleet level.

The trade can be further refined by incorporating the difference in fuel consumption of the two fleets. The vehicles have been modeled to use H_2-O_2 fuel cells, both of which are not found in free states on Moon or Mars. In the event that the total fuel for the mission has to be transported, then the total mass associated with the mobility system will be the mass of the vehicles plus the fuel they will use over the course of the entire mission.

Figure 6 shows how the two options compare. It was assumed that a total of 50 km is traversed during the course of base set up operations, *i.e.* the SPV for the fixed case, and configuration A for reconfigurable case travel a total of 50 km. The distance covered by the LHVs (and configuration Bs), and the ATV (and configuration C) however can be quite varied depending on a how surface operations and exploration sorties are carried out. These distances were therefore allowed to vary, and the corresponding total mass of the entire mobility system (which includes the mass of the vehicles and that of the total fuel consumed) was plotted in Figure 6.

It is clear that the reconfigurable case and the fixed case are suitable for different usage levels of the vehicles. For smaller traverse distances the reconfigurable system is lower in mass. The deciding factor is the usage level of configuration B. After 16000 km of total traverse, the mass of the reconfigurable system becomes larger in mass. Thus, if a reconfigurable fleet is used in which two vehicles will be in state B at a time, each can have a maximum traverse of 8000 km. If the average round trip distance on an excursion is 200 km, then a total of 40 sorties by each of the two vehicles is the break even point. In a 600-day mission to Mars it is unlikely that this many sorties will be carried out. However, if the vehicles are to be used in subsequent missions (that maybe part of a long exploration campaign) then it is preferable to use fixed vehicles since over the course of only two missions (considering each will involve over 20 long range excursions) their cost will come out lower.

A reconfigurable fleet, however, is better if the vehicles will be used in only one mission (which maybe the case if the exploration campaign involves missions that land on different locations on the planet each time such that the previous assets on prior bases are inaccessible).

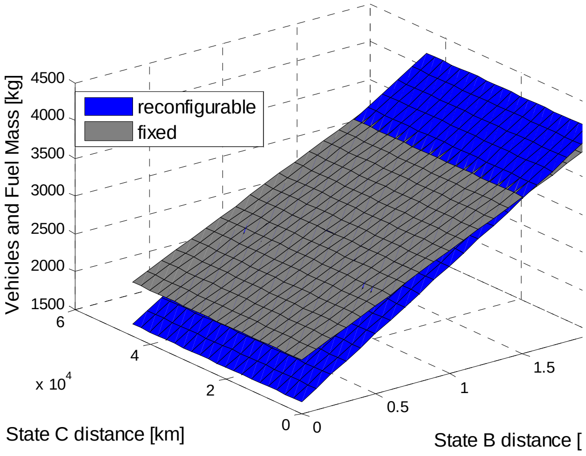

Figure 6: Mobility Mass Comparison with out ISRU

In the event that In-Situ Resource Utilization (ISRU) plants are available to produce O_2 from the CO_2 atmosphere on Mars, or from the regolith on the Moon, then only H_2 will have to be brought to the planetary surface. In that case the results are as shown in Figure 7.

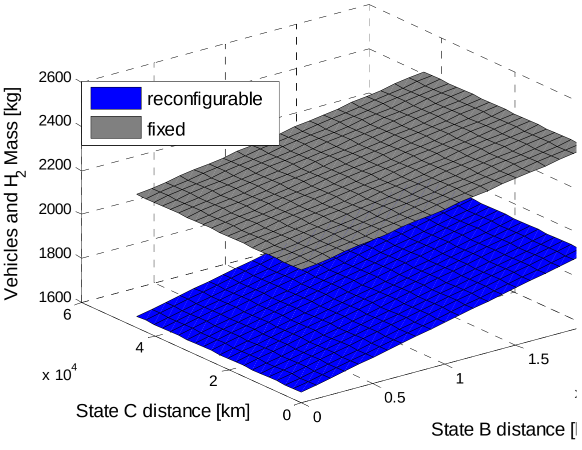

Figure 7: Mobility Mass Comparison with ISRU

In this situation the reconfigurable option always seems better in terms of the cost (*i.e.* mass) of the architectures. Thus if the exploration missions make use of ISRU plants for generating fuel for mobility operations, then reconfigurable vehicles can offer significant mass and therefore cost savings.

3.5 Reconfigurability and Risk

There are two kinds of risks that are associated with a reconfigurable architecture. The first is on a lower level, which is the risk of reconfiguration, and the other is on a higher level, which is the risk of non-performance. Both of these types are discussed in this section.

3.5.1 Reconfiguration Risk: To study this, it was assumed that the risk of reconfiguration is directly associated with the costs of reconfiguration. Thus, reconfiguration cost (which was described in 3.3.1) can be used as a surrogate.

The *reconfigurability* of a given vehicle architecture was computed by determining its reconfigurability index, RI, in which the capability of each configuration was computed from its Transport Capability metric. The Transport Capability of a vehicle is defined as [13]:

$$v = V(T + M) \quad (12)$$

where V is the average speed, T and M are the mass transported by the vehicle through towing and carrying respectively. For each architecture, a set $\mathbf{v}$ was formed in which the elements v_i were the transport capability for the i^{th} configuration. The RI for that architecture was then:

$$RI = \max(\mathbf{v}) - \min(\mathbf{v}) \qquad (13)$$

For instance, the RI_{fleet} of the optimal reconfigurable fleet design determined in section 3.3.2 will be computed as follows:

$$\mathbf{v} = [v_1 \quad v_2 \quad v_3]$$

$$\begin{aligned} v_1 &= 0.66(5526.8 + 501) = 4028.7 \\ v_2 &= 4.25(2522 + 118) = 12003 \\ v_3 &= 12.48(42.2 + 170.6) = 2656 \\ RI_{fleet} &= (12003 - 2656) = 9347 \end{aligned}$$

To determine the relationship between RI_{fleet} and reconfiguration risk (for which reconfiguration cost was used as a surrogate), a set of reconfigurable designs (that can exist in three distinct configurations) with varying RI_{fleet} was generated. The ratio of RI_{fleet} with total mass of each fleet was then plotted versus its reconfiguration cost. Three different values for the coefficient of variation, c_v of wheels and motors were used to get three plots. Figure 8 shows the results.

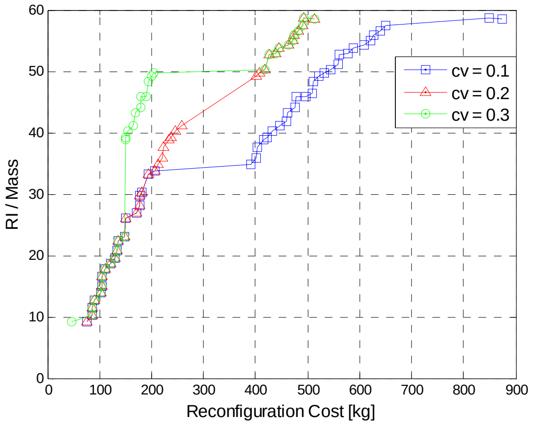

Figure 8: Reconfigurability vs Reconfiguration Cost

It is clear that with increasing reconfigurability per unit mass, the reconfiguration cost and therefore the reconfiguration risk also increase. It can also be seen that with increasing c_v, the plots are shifted to the left. Thus for the same level of reconfigurability per unit mass, the cost is lowered. The large discontinuities in the plots are due to the way the reconfiguration costs have been computed. As described in section 3.3.1, if a component is substituted its mass is added in the cost, but if it is transformed then no addition is made to the cost. Thus for varying designs, as the component characteristics pass the threshold defined by the c_v, there is a sudden jump in the value for the cost since the reconfiguration operation changes from *transformation* to substitution (*i.e.* a sequence of *addition* and *subtraction*).

3.5.2 Non-Performance Risk: On a higher level for any system, the risk can be that the system fails to successfully carry out the functions/tasks that were required from it. A detailed assessment of the effects of reconfigurable vehicles on this type of risk will be made in future studies. From a very basic perspective however, it is clear that a reconfigurable architecture can help in mitigating this risk when compared to a fixed case. If a fleet of fixed vehicles is employed, then the failure of any one vehicle will reduce the productivity of the fleet and may even cause serious issues. If the SPV fails, then the large towing and hauling tasks will either be impossible to perform, or will be carried out with great difficulty in a degraded way (through using several of the remaining vehicles). In case of the reconfigurable system however, if one vehicle fails, the other two can be reconfigured to carry out the desired function. The number of available 'spares' for a particular configuration essentially goes up when a reconfigurable fleet is used. There are thus essentially three A configurations, or B or C. Where as in the fixed case there is only one SPV and one ATV. This can be illustrated by considering the simple case in which it is assumed that the probability of failure of a fixed vehicle , P_{fxFail} is 0.2, where as that of a reconfigurable vehicle P_{RFail} is 0.4. Suppose the number of SPVs is N_{SPV}, the number of LHVs is N_{LHV}, and the number of ATVs is N_{ATV}. The probability that all three functions will be available for the entire mission in the fixed fleet scenario considered in the case study will then be:

$$\begin{aligned} P &= \left(1 - P_{fxFail}^{N_{SPV}}\right)\left(1 - P_{fxFail}^{N_{LHV}}\right)\left(1 - P_{fxFail}^{N_{ATV}}\right) \\ &= \left(1 - 0.2^{1}\right)\left(1 - 0.2^{4}\right)\left(1 - 0.2^{1}\right) \\ &= 0.639 \end{aligned}$$

In the reconfigurable fleet case, the three functions can potentially be performed till the last vehicle remains in working order. Thus, only in the event that all of the N_{Rcfg} vehicles in a fleet fail will the mission lose its capability of performing the three types of tasks. For the case study of five reconfigurable vehicles, the probability of availability of the three functions is therefore:

$$\begin{aligned} P &= \left(1 - P_{RFail}^{N_{Rcfg}}\right) \\ &= \left(1 - 0.4^{5}\right) \\ &= 0.989 \end{aligned}$$

The risk of non-performance thus reduces to almost 1% in the reconfigurable case.

3.6 Reconfigurability and Value

The *value* from a system is defined as some benefit at cost. In this case the benefit is essentially the transportation of crew and cargo, while the total mass of the transportation system (that needs to be delivered to the surface) can be treated as a surrogate for its cost.

The *benefit* from a particular architecture was quantified by again using the Transport Capability metric. The total value for a mobility system consisting of three vehicles with a certain range, speed, and tow and cargo capacities was then computed as:

$$Value = \frac{\sum_{k=1}^{3} v_k}{TotalMass}$$

where v_k is the transport capability of the k^{th} vehicle or configuration. For the first option in which a fleet of dedicated vehicles was considered the *TotalMass* was simply $\sum_{k=1}^{3} M_k$ where M_k is the mass of the k^{th} vehicle. For the reconfigurable case however, the calculation of the TotalMass of the system was done by summing up the vehicle mass along with the set of all the components that are removed and installed during various reconfigurations. Figure 9 shows how Value varies with increasing reconfigurability. It can be seen that with increasing RI per unit mass, the value also goes up.

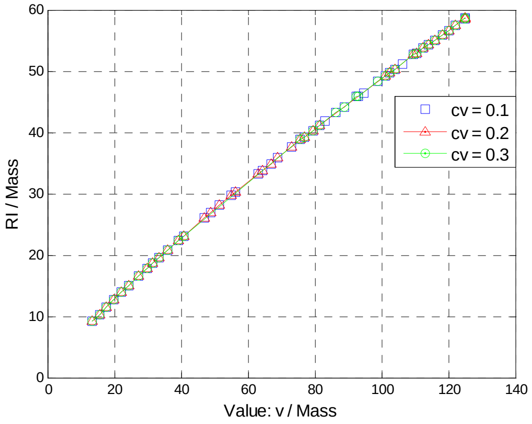

Figure 9: Reconfigurability vs Value

4.0 CONCLUSIONS

A comprehensive analysis of the effects of reconfigurability on system architecture was presented. This paper introduces definitions, concepts, and methods that can be formally employed to analyze reconfigurability issues in systems.

Through a case study of planetary surface vehicles, it was shown that reconfigurability can be beneficial in reducing cost by lowering the total mass required for a mobility system for surface operations where ISRU plants are available for producing fuel. Reconfigurable vehicles are also better in the absence of ISRU if their usage will be low (few thousand kilometers of total traverse). The relationships between increasing reconfigurability, reconfiguration cost, and value showed that value from an architecture can increase with increasing reconfigurability, however the reconfiguration cost at the same time also increases.

In future studies, methods for determining the bounds on reconfiguration time and cost will be explored on a general level. The effect of reconfigurable systems on spares and broader supply chain impacts will also be analyzed. Additionally, for the PSV case study, concepts for reconfigurable vehicle designs and technologies (such as smart materials, drive-by-wire *etc.*) that can enable transformation and easy substitution will be investigated

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