ABSTRACT

DENHART, JASON DANIEL. Tradespace Exploration of Reconfigurable Systems with a Mars Rover Case Study. (Under the direction of Dr. Scott Ferguson).

Reconfigurable system design is a strategy that has shown promise for pushing the boundaries of performance of a variety of systems. Complex systems such as planetary exploration rovers and unmanned aerial vehicles seem to be prime candidates for reconfigurability as their performance demands are quite high. However, with the choice to add reconfigurability to a system comes the penalty of increased complexity. When this is done to a system that is already quiet complex, the result can be very difficult to manage. The primary motivation for this thesis is assessing the Transforming Rolling Roving Explorer (TRREx) architecture for Mars exploration. This case study is exacerbated by the challenges of performing on the chaotic and uncertain Martian terrain. This thesis poses two research questions. The first question is, "How can the performance of a reconfigurable rover be modeled with sufficient fidelity to assess the value of reconfigurability?" The question first required understanding the challenge caused by using the reconfigurable system in terms of its impact on the system architecture redesign. The concept sorting framework was created to perform this assessment. It recognizes that a trade-off is likely to exist between a concept's potential to revolutionize a system and its ease of adoption into the architecture of that system. It identifies the TRREx as a class 5 concept meaning it needs to show considerable performance advantage to offset the challenges of adopting it. To assess performance, a simulation environment was built to test both the TRREx architecture and the traditional rocker bogie architecture. An aggregate score was built up for 20 trial scenarios from three performance measures taken on three sizes of each rover. These trial scores were aggregated into mission scores to increase understanding of the rover's operation in a more realistic environment. The second question is, "How can reconfigurable systems be represented in a multidimensional tradespace, and how should Pareto dominance be assessed in such a representation?" To address this question, a methodology was developed for representing reconfigurable designs in a multi-attribute tradespace. Each static system and each configuration of each reconfigurable system is analyzed for a performance score for each operating condition the system will need to handle. The operating condition scores are used as the dimensions of the tradespace. By arranging the tradespace in this way, the surrogate point can be used to simplify the analysis of the reconfigurable systems. The reconfigurable system's surrogate point is defined as the location in the space with the best performance available to any of the system's configurations for each operating condition. The surrogate point is then used to present definitions of Pareto dominance between reconfigurable systems and for a reconfigurable system vs. a static system. This methodology is applied to the TRREx rover to show the TRREx architecture is non-dominated compared to the rocker bogie architecture of analogous sizes. While the tools developed in this thesis were motivated by the need to assess the TRREx concept, they are generalized for any reconfigurable system. For downhill travel, the TRREx significantly outperforms the rocker bogie. Several possible directions for future work are identified.

Tradespace Exploration of Reconfigurable Systems with a Mars Rover Case Study

by
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1. INTRODUCTION

1.1 Motivation

By definition, a system is said to be reconfigurable if it contains multiple operating configurations and can change between them repeatedly and reversibly [1]. Reconfigurable systems can potentially achieve several benefits that offer the opportunity for large improvements in system performance and robustness through multi-ability (operating at multiple performance points in the design space non-simultaneously), evolvability (changes to meet new demands), and survivability (changes to maintain functionality despite component failures). These benefits make reconfigurability particularly interesting to designers looking for solutions to very difficult problems in which performance advantages are highly valued. Such design tasks are often given the title "complex system design" because the solutions are typically characterized by having many parts, many objectives, multiple functions, large design teams, and/or intricate interactions between the system's pieces.

Reconfigurability has the potential to dramatically increase the effectiveness of a wide variety of complex systems. Planetary rovers have been considered as prime applications of reconfigurability. Research in this area has considered a wheel capable of changing width and diameter in response to different soil types [2]. Results from this study demonstrated that the optimal wheel configuration was dependent on the weighting parameter used in the objective function. Reconfigurability has also been studied when designing a fleet of Mars

Astronaut Transport Vehicles (ATVs) [3]. This work demonstrated that a team of five reconfigurable rovers could provide the same mission capability as six static rovers with a considerable savings in total system mass. Performance objectives in this work included vehicle range, speed, payload, and towing capacity. Another application of reconfigurability to Mars rovers motivated the investigation presented in this thesis. The Transforming Rolling Roving Explorer (TRREx) architecture is a rover concept with two distinct configurations. In the roving configuration, it travels on an active suspension with six wheels. It can reconfigure into a ball configuration for rapid downhill rolling travel. More information on rover architectures and the TRREx are included in Section 2.2.

Unmanned aerial vehicles (UAVs) have been another popular application of reconfigurability [4-6]. Research in this area has conducted sensitivity studies [7], explored concept embodiment [8], and developed analysis techniques capable of spanning multiple disciplines [4,8,9]. Reconfigurable UAVs have also been envisioned with offline reconfigurations where the UAV is changed between missions by swapping out wing and/or propulsion modules [10]. Along with rovers and UAVs, 90 reconfigurable products ranging from children's toys to airplanes have been identified [11].

Prior research in the design community has shown that reconfigurability has significant potential to improve system functionality. However, designing a system to be reconfigurable necessarily increases the complexity of that system. For systems that are already complex, this additional complexity can severely challenge the design team's ability to understand, analyze, and develop their system. In fact, Lewis states "researchers and practitioners are realizing that [reconfigurable systems] can be one of the most complex systems to model, design, and deploy" [12]. To manage this complexity, one goal for reconfigurable system design is to be able to apply the tools of engineering optimization to expedite the design process.

Multiobjective optimization finds design alternatives in a multi-dimensional performance space where each axis corresponds to an objective. Objectives are measurable preferences of the system, defined by the designer, that are to be minimized or maximized. The result of a multiobjective optimization is a collection of non-dominated solutions commonly referred to as the Pareto frontier. A non-dominated solution is one for which no alternative exists that is not worse in any objective and is better in at least one objective. A more formal discussion of domination is included in Section 2.7. Conducting a multiobjective optimization is valuable to the designer because it enables a design by shopping paradigm, where the designer can simplify his/her selection of alternatives to only those that are non-dominated (Pareto efficient) before considering the relative importance of each objective [13].

Engineering optimization has been used to provide insight into the design of several reconfigurable systems. In the UAV research, a vehicle was developed by selecting optimal wings and propulsion modules for each mission profile to meet the objectives of reducing fuel consumption, increasing loiter time, and increasing combat radius [5]. In another application, a reconfigurable racecar was designed by optimizing the airfoil and CG configuration for each segment of a racetrack [14]. The rover wheel shape was changed to optimize a performance objective consisting of drawbar force and wheel drive torque [2]. All of these systems possess performance objectives that can be calculated from analytical relationships. A complication for this thesis is handling rover performance which is difficult to describe analytically.

Tradespace exploration is an idea that closely parallels multiobjective optimization [15]. It is a tool for analyzing trade-offs inherent in system design using a more generalized multidimensional space. It differs from multiobjective optimization in that multiobjective optimization generally focusses on system performance whereas tradespace exploration allows any sort of data that is useful for assessing system tradeoffs. Furthermore, multi-objective optimization is generally focused on the act of computerized optimization (defining algorithms, modeling the system, and finding non-dominated solutions) whereas tradespace exploration is focused more on illustrating wide exploration of the design space for easier visualization of the alternatives that are available to the designers. Several specific methodologies for applying tradespace exploration have been used for various problems. These are further detailed in Section 2.6. Chapter 4 of this thesis provides a methodology for structuring a tradespace that simplifies the analysis of Pareto dominance for reconfigurable systems. This methodology will be particularly beneficial to the design community because many of the common multiobjective optimization strategies require assessing solution dominance [16].

The research described in this thesis was motivated by the challenges of assessing reconfigurable concepts for Mars rovers, especially assessing the value of the TRREx rover architecture. Designing for Mars missions is a novel challenge for reconfigurable systems as analytical representations of the performance objectives are not available due to the unpredictable nature of the chaotic terrain on Mars and the lack of information about the conditions that the rover could encounter. While the Mars rover case study drove the developments described in this thesis, the tools presented have been generalized for application to any reconfigurable system. The primary contributions of this thesis are the development of an environment for assessing rover architectures and a methodology for representing reconfigurable systems in multiobjective tradespace. The research questions that will lead to those contributions are presented in the next section.

1.2 Research Question #1

How can the performance of a reconfigurable rover be modeled with sufficient fidelity to assess the value of reconfigurability?

The rover problem does not have readily available analytical performance metrics that describe this system. This challenge is caused by the Martian terrain being chaotic and largely unknown. Building a model that can represent the performance of the rovers was, therefore, a non-trivial task. A fundamental challenge of answering this research question is understanding the assumptions and simplifications that can be made while still creating a simulation environment capable of performing the necessary analysis.

1.3 Research Question #2

How can reconfigurable systems be represented in a multidimensional tradespace, and how should Pareto dominance be assessed in such a representation?

With any complex system, a massive amount of data is available and the list of potential goals, constraints, and requirements is vast. Adding reconfigurability into the design of a system threatens to severely exacerbate this problem. There are many ways a designer might consider handling all of this information, but previous frameworks using tradespace exploration have done little to simplify the assessment of reconfigurable systems. By answering this question, a methodology that provides some organization and simplification of the data will be developed.

Once the reconfigurable systems are represented in the space, one of the critical comparisons in multi-objective optimization is the domination relationship between various designs. Many multiobjective schemes rely on Pareto rank as a primary input to their fitness evaluations. A common example is the NSGA-II algorithm upon which MATLAB's multiobjective genetic algorithm (MOGA) is based [16]. Pareto rank is a description of which Pareto frontier a concept falls on. That is, all of the non-dominated designs have rank 1. If these designs are ignored, the next remaining non-dominated designs have rank 2 and so forth. Assessing the Pareto dominance of reconfigurable systems will be specifically highlighted in the tradespace analysis in Chapters 4 and 5. The rover designs studied in Chapter 5 will be ordered according to domination rank.

1.4 Thesis Overview

The remainder of this thesis will be focused primarily on answering the research questions introduced in this chapter. The overall strategy came from investigating the idea of creating a reconfigurable Mars exploration rover. Chapter 2 focuses on the relevant technical background upon which the rest of this work is built. Chapter 3 discusses the creation, and sorting, of reconfigurable concepts, including the rover concept that will be the highlighted case study of the remainder of the thesis. Chapter 4 describes the methodology required to analyze concepts in the multiobjective tradespace and analyze their dominance. Chapter 5 describes the Mars exploration rover case study, specifically the analysis of the Transforming Rolling Roving Explorer (TRREx) architecture concept as compared to a more traditional rocker bogie rover architecture concept [17,18]. Chapter 6 is a discussion of the key findings of this research, and a list of suggestions for future work.

2. BACKGROUND

2.1 Chapter Overview

This chapter provides the technical background information required to frame the material that will be presented through the remainder of the thesis. It begins with discussions of Mars rover technology and reconfigurability research, the motivating topics of this thesis. It moves on to a review of system architecture and concept selection research. This is done to highlight the need for a concept sorting tool and present the background information required to answer the first research question. The chapter finishes with additional background on tradespace exploration and Pareto dominance since these topics are essential to the second research question.

2.2 Mars Rovers

Rover design is used as the motivating case study throughout this thesis. Extraterrestrial rover design has advanced from the NASA Jet Propulsion Laboratory's (JPL's) early work on lunar rovers in the 1960's to the landing of Curiosity on Mars in 2012. Rovers intended for use on Mars, and eventually on other planets, face significant engineering challenges when compared to those encountered when designing for the Earth or Moon. Mars rovers cannot practically be controlled in real time since there is a delay time ranging from about 7-30 minutes for radio communication. As a result, Mars rovers must have a fairly large degree of autonomy, with human controllers selecting major waypoints in the desired path and the on-board computer doing the actual maneuvering between them [19]. The large uncertainty in terrain details must be accounted for as well [20]. Information gathered from orbit can provide only the general features of the landing location, so the rovers must be designed to deal with a wide variety of terrain features. The need for autonomy even in the face of such uncertainty argues heavily in favor of high locomotive performance in Mars rovers.

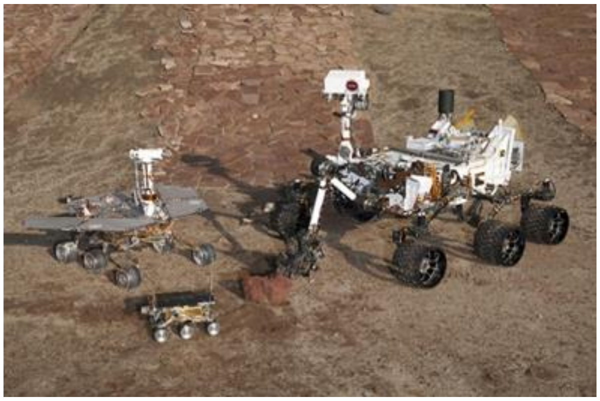


Figure 2.1. Earth Test Models of Successful Mars Rovers [21]

Sojourner (bottom) landed in 1997, Spirit/Opportunity (left) 2004, and Curiosity (right) 2012.

All successful Mars rovers have used a six-wheeled, rocker bogie suspension system as the sole method of locomotion. This suspension scheme was first used on the Sojourner micro-rover as part of the Mars Pathfinder mission [22]. It consists of a single axle differential interface (the rocker) with the main body of the rover connected directly to one front wheel and to two rear wheels through a bogie. This design allows the weight of the rover to remain distributed over all six wheels under any normally encountered situation, reducing the likelihood that any one wheel will sink into soft ground. The rocker bogie also facilitates a large amount of passive wheel articulation without the need for springs, allowing scientific instruments to remain relatively stable as the rover travels. Figure 2.2 shows a schematic of one half of the rocker bogie suspension from the Pathfinder rover.

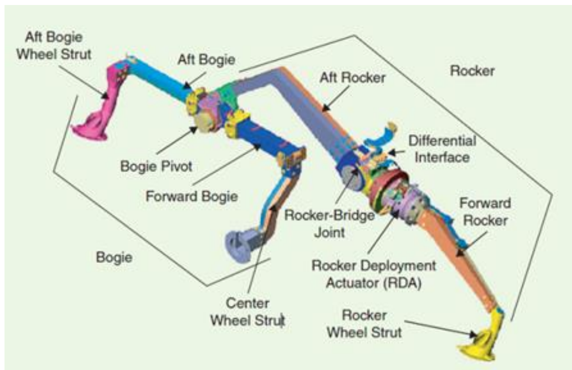


Figure 2.2. Left Side of The Mars Exploration Rover Rocker Bogie Suspension [17]

Several variations on the rocker bogie suspension have been proposed for various applications. Using a multistage bogie system provides even greater weight distribution over many wheels by connecting bogies together in series [23]. The shrimp rover suspension uses bogies and a single sprung wheel to achieve similar weight distribution characteristics to the rocker bogie [24]. The main limitation of these types of rigid suspensions is their low achievable speed. Dynamic jarring that begins to occur at speeds in excess of ~10 cm/s (depending on the overall rover size) causes a severe decrease in rover stability [17]. Increasing rover size has been the typical method of improving maneuverability. Eventually, this strategy will be limited by the tradeoff between increased performance and increased mass.

The Transforming Roving Rolling Explorer (TRREx) is a reconfigurable rover architecture currently in conceptual development [18]. It is fully reconfigurable between two separate locomotion configurations: roving and rolling. The bio-inspired design was derived from the golden wheel spider, which curls up its legs to roll down sand dunes and escape predators. The TRREx uses its six legs in its roving mode as an active suspension to maintain weight distribution as it travels the Martian terrain. When the rover encounters a decline, it reconfigures into a rolling mode by folding over and tucking its legs in. In this configuration it rolls downhill, covering distance quickly while using little power. The TRREx can maneuver in rolling mode, either to avoid obstacles or to move short distances, by controlled actuation of its legs to shift the location of its center of mass. Figure 2.3 shows the TRREx rover reconfiguring from its roving configuration to its rolling configuration.

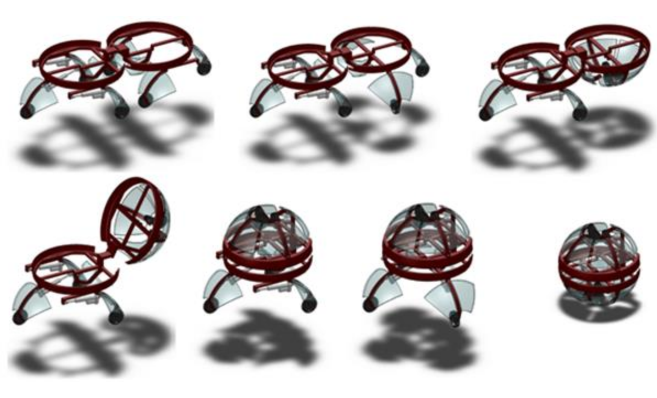


Figure 2.3. TRREx Rover Going Through a Reconfiguration [18]

This section provided background on current practices in Mars rovers and included additional information specifically on the TRREx reconfigurable rover concept, which motivated most of the work in this thesis. Section 2.3 provides some additional background into reconfigurability.

2.3 Reconfigurability

The introduction to this thesis demonstrated interest in including reconfigurability in complex system design. A few additional topics related to reconfigurability are discussed in this section. Several tools have been developed to assist a designer in envisioning reconfigurable systems. These tools include function sharing approaches for product combination [25] and the use of transformation principles [26]. In function sharing, functional models of separate products are observed for similarity. Reconfigurable products can then be made by mapping the common functions to shared components and the unique functions to interchangeable or parallel components. The transformation principles are tools to facilitate concept brainstorming for reconfigurable systems. The four transformation principals are expand/collapse, expose/cover, fuse/divide, and reorientation. These principles have been shown to describe a large number of reconfigurable systems [11, 26] and have been used successfully for concept generation [27]. Along with transformation principles, an extensive list of transformation facilitators has been created. Facilitators are generic ways of manifesting reconfigurations. For example, fuse/divide can be brought about using the nesting facilitator. Many concepts that leverage reconfigurability for Mars rovers were developed by several teams of undergraduates as part of the work that contributed to this thesis. The transformation principles were used extensively by all of these teams during their brainstorming sessions.

Research has characterized some of the complexity challenges of reconfigurable design. To support early design embodiment, Ferguson et al. have characterized the amount of allowable mass that could be added to a reconfigurable system [28]. This work recognizes that the ability to reconfigure requires changes to the system architecture and focusses specifically on the mass aspect of adding reconfigurability. In their case study (and many reconfigurable systems) additional mass degrades performance. Their work describes the maximum mass that can be added before the performance gains from increased reconfigurability are negated by the additional mass. Chapter 3 of this thesis develops a sorting framework that recognizes that introducing reconfigurability to a system can require substantial redesign of the system's architecture, adding another tool that helps characterize the challenges of creating a reconfigurable design. This framework was essential for sorting the concepts that were brainstormed using the transformation principles in [27]. Section 2.4 will address system architecture, one of the primary concerns of the sorting framework.

2.4 System Architecture

The concept sorting framework detailed in Chapter 3 is concerned with understanding the impact a reconfiguration concept will have on the system architecture. Reconfigurations can occur at many levels within a system. Using rovers, an example: a reconfigurable wheel can be added to a rover design by simply swapping it for the old wheel design. The wheel can reconfigure for the purpose of changing its ground interaction characteristics without much impact on the rest of the rover. Meanwhile, a rover that reconfigures into a ball to roll downhill, changes the spatial relationship between all of its components. Generically, these impacts can be thought of in terms of how heavily the architecture of the system is affected by incorporating a reconfiguration into the design of the system. This section defines product architecture and goes on to describe several tools for assessing the relationship between a product’s architecture and how a change to the system will propagate through that architecture.

A product’s architecture is the plan for how the products’ functions are mapped to physical entities. Complex system architectures can, in broad strokes, be classified as having varying degrees of modularity. Pahl and Beitz describe modular products as those that “fulfill various overall functions through a combination of distinct function units [which are called] modules" [29].

Suh argues that there are fundamental truths to effective design technique that he describes as design axioms [30]. Axioms are beliefs based on observations that have no apparent counter-examples. These axioms provide useful guidelines for the arrangement of a system, particularly, with the mapping of design parameters to functional requirements. The independence axiom states that a universal truth (axiom) is that designs that have been deemed “good” can all be shown to maintain independence of functional requirements. Likewise, the information axiom states that good designs minimize the information content of the design. Suh uses these axioms to argue that it is less important whether the physical components of a system are modular so long as the mapping between functions and design parameters remain uncoupled (one-to-one mapping) or decoupled (mapping that can be described by an upper triangular matrix.)

The opposite of a modular system is an integral system. Most systems possess some degree of modularity between purely integral and purely modular. Systems with high modularity are generally expected to be easier to change with less redesign time. However, modular designs usually have decreased performance in comparison to integrated systems because they often require more mass and because decoupling the module interfaces enforces more constraints on the design [29, 31]. Ulrich observes that integral systems optimize global performance objectives, vehicle mass for example, whereas modular systems optimize local performance objectives, engine power for example [32].

High performance, complex systems often exhibit a high degree of integration in their architectural layout as necessitated by the global performance demands. The interfaces between modules, components, and subsystems in these systems are complex and interrelated. The consequence of these interrelationships is that changing any part of the system can have a large impact on the schedule and/or cost of the design process. Any estimation of the impact of a change on the architecture of a system is valuable knowledge for a design team.

Change propagation analysis [33] provides rigor to the analysis of changing a system's design. However, formal change propagation analyses require models that map the relationships between design components in order to estimate the level of integration of a system and to approximate the amount of redesign a certain change will require. Common tools for this purpose include the design structure matrices (DSM) and functional models [29]. A similar tool to change propagation is the technology infusion framework, which is useful for understanding the cost of implementing a new technology into a product [34]. It builds a delta DSM representing the system change required to implement the new technology. Analyzing the delta DSM provides approximations of the design process implications of adding the new technology. Both of these methods require a detailed DSM, which may not have been created at the early concept sorting phase.

The concept sorting framework discussed in Chapter 3 specifically characterizes how the architectural impact of a reconfiguration concept should affect concept selection. Section 2.5 discusses concept selection.

2.5 Concept Selection

The topic of concept selection is not new in design literature, as it is one of the major steps of the conceptual design process [29]. The traditional challenge is that concept selection happens early in the design process when information about the concepts is scarcest but the financial impact of the designers' choices is highest. The Pugh Method of Complex Convergence, also known as a Pugh Decision Matrix, is a traditional tool for handling concept selection [35]. The designers enumerate the criteria they want to consider. Then, they assign one alternative as the datum and compare all other designs to it as better, worse, or the same with a plus, minus, or zero. Finally, the plusses and minuses are counted to determine favorable designs. When done iteratively and as intended, Pugh can be effective at eliminating weak alternatives and directing a team of experts to concepts that deserve additional investigation [36]. Literman et al. proposed a modification to Pugh's method to assist the designer of reconfigurable systems [37]. They argue for the inclusion of criteria that are present in reconfigurable systems, such as transformation time and ease of transformation. A major advantage of using a version of Pugh concept selection is that it does not require specifically precise quantitative evaluations of a concept's attributes. It only requires a qualitative comparison.

There are several accusations against Pugh's method, such as its susceptibility to irrelevant alternatives, the ability for the outcome to be influenced by the choice of datum, and its inability to address strength of preferences [38]. The use of utility theory in design is an alternative to Pugh proposed by Hazelrigg et al. It maps a decision maker's strength of preferences (SoPs) for each objective to a non-dimensional quantity called utility and combines the utilities in a weighted sum [38]. The utility equation describes this structure. Let U be the utility of a design with *j* objectives, w_i be the weight of the i^{th} objective, and let $u_i(x_i)$ describe the strength of preference mapping between the level of the i^{th} attribute, x_i and the utility in the i^{th} objective, u_i.

$$U = \sum_{i=1}^{j} w_i * u_i(x_i)$$

The strengths of preference are determined using a lottery question from traditional utility theory. The decision maker is presented with two options. The first option is certainty for getting the middle of the available range of an attribute. The second option is to gamble at some probability for the best possible attribute score with the consequence of losing being that they receive the worst possible attribute score. The decision maker is asked what the probability of winning would need to be for him/her to choose the gamble. Zero utility is assigned to the worst available attribute score, while one hundred is assigned to the best available attribute score. The answer to the lottery question determines the utility of the mid-point and a SoP curve is fit from the three points. This method assumes that the attribute ranges are known, and there is a decision maker available who is qualified to answer the lottery question. Traditionally, the weightings are assigned by an expert based on intuition, perception, or experience.

A technique known as the hierarchical equivalents and inequivalents method (HEIM) provides a way of measuring a decision maker's weights directly [39]. A series of hypothetical products are ranked by the decision maker. Assuming that the decision maker ranks the alternatives in order of his/her overall utility for each alternative, a set of inequalities describing his/her preferences are created by the ranking. A set of weights that satisfy the utility equation is solved from the inequalities defined by the ranking. By determining the SoPs and weightings of the decision maker, the designer has a model that can be used to assess any generated concept. A full utility analysis is quite difficult at the stage of the design process that the concept sorting framework (Chapter 3) is targeted because the models needed to assess the performance of the system are not yet derived. However, the rover performance models built in Section 5.3 are a direct application of utility theory techniques.

In complex system design, the challenges of conceptual design are exacerbated by reconfigurable and changeable concepts because they naturally lead to greater levels of system complexity. Mattson and Messac provide an optimization-oriented tool for concept selection by building s-Pareto frontiers of concepts for multi-objective optimization [41]. A global frontier is built from the concepts' individual frontiers. Different concepts are sorted by the level of participation their frontier has in the global frontier with fully dominated solutions being discarded and partially or fully dominant solutions surviving for more rigorous analysis. They use a truss case study to illustrate the methodology. Again, this methodology requires considerably more information than the sorting framework presented in Chapter 3. While this list of concept selection techniques is not exhaustive, its purpose is to demonstrate the various techniques used when selecting a concept. A thorough review of concept selection literature can be found in [42].

This section has reviewed research in concept selection. Section 2.6 will discuss tradespace exploration, a particular strategy for presenting design information when a large variety of concepts are to be considered. Tradespace exploration is a broad topic, but many of its uses require the application of utility theory and other concept evaluation methods.

2.6 Tradespace Exploration

The strategy used to answer this thesis's second research question is to define a particular type of tradespace that is particularly convenient for assessing reconfigurable designs. In this section, additional background on tradespace exploration and a review of its previous uses will be presented. A tradespace is any multidimensional space used by a designer to assist in analyzing trade-offs between potential solutions [40]. To define a particular tradespace, the designer must decide what information to assign to each dimension of the space. Generically, any information is permitted. In fact, the objective space used in multiobjective optimization could be thought of as a specific type of tradespace. Traditionally, designs are represented as points in the mulitdimensional space. This works very well for static designs but will be expanded to handle reconfigurable designs (see Section 4.6).

Ross and Hastings argue in favor of a tradespace for which the dimensions are the preferences of all of the stake-holders in a design project [43]. They advocate paying particular attention to the preferences of a special sub-set of stakeholders known as the decision makers. Decision makers are the stakeholders that provide the resources by which the goals of the stakeholders will be met. In this work, utility theory is the typical tool used to capture and model these preferences.

Much like many multiobjective optimization paradigms, tradespace exploration is often concerned with identifying non-dominated designs. Figure 2.4 shows an example of a two-attribute tradespace for a space tug satellite. The y-axis is the utility score of the combined attributes and the x-axis is the total lifecycle cost.

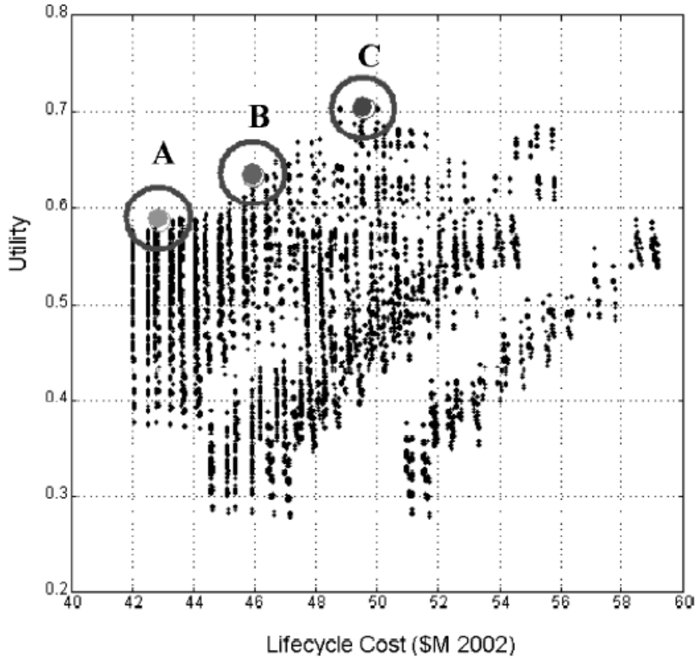


Figure 2.4. Example Tradespace Illustration [41]

In the tradespace depicted in Figure 2.4, the goal is to get the highest possible utility at the lowest cost. Thus the upper left corner is the ideal space, also known as the utopia point. A, B, and C are clearly designs on the Pareto frontier. Switching amongst these points produces an improvement in one attribute but a loss in the other.

The largest tradespace used in this thesis has three dimensions. It is used to demonstrate a procedure rather than to actually design a system. Even this relatively small tradespace is somewhat challenging to illustrate effectively. For a tradespace with many dimensions, several software environments have been developed. Amongst these are the ATSV software developed at Penn State University and RAVE, an open-source package developed at the

Georgia Institute of Technology [15, 43]. Both of these environments seek to provide a multitude of visualization techniques for illustrating multidimensional spaces.

Tradespace studies have been used to analyze the “illities” (reconfigurability, flexibility, durability, etc.) in an epoch-era framework. States of operating conditions (context, system, or needs) are described as epochs which are combined together into eras. The "illities" are then expressed as movements in the tradespace to react to the changes between epochs [45]. This framework has been shown to be useful in several projects for space system design [43,45]. One major challenge with this approach is that several characteristics may make up any particular operating condition and several conditions may be possible for each epoch. Analyzing all candidate designs for all possible eras is an excessively large computational task. Furthermore, if the number of candidate epochs is low but the number of epochs per era is high, it is likely that much of the computation effort will be evaluating very similar eras. Another challenge is that the epoch-era framework can illustrate discrete reconfigurations sufficiently but does not work for continuous, online transformations such as the reconfigurable wheel [3] or JPL’s reconfigurable rover for sample return [46]. In this case, a new epoch would be required at each small time step, so a mission of any length would have many epochs which would exacerbate the computational efficiency issue detailed above. In this thesis, a tradespace for handling reconfigurability will be defined where system performance under each set of operating conditions is a dimension in the space. In this way, the order that the operating conditions (Epochs) occur over the life of the system (Era) is unimportant and the enumeration of possible scenarios that need to be tested is substantially reduced.

This section has discussed tradespace exploration in detail. The topic of Pareto dominance is a common consideration in a tradespace. It is also a primary focus of the second research question in this thesis. For that reason, Section 2.7 presents a formal background on Pareto dominance.

2.7 Pareto Dominance

In a multidimensional tradespace, in which at least two objectives conflict, it is not possible to identify a single most-efficient design. Some subset of available designs will form the Pareto frontier of non-dominated solutions. The best definition of an efficient solution is one that is a member of this frontier. Such a design is called Pareto efficient. This section provides a formal definition of domination, by which designs can be sorted as non-dominated (Pareto efficient) or dominated status.

Zitler et al. provided rigorous definitions of Pareto dominance both between individual vectors in a performance space and between sets of vectors in the space [47]. The following definitions will be used any time a single point in the performance space is compared to another single point.

Definitions of dominance between single vectors (p_1) and (p_2) in the performance space [47]

- p_1 strictly dominates p_2 when p_1 is better in all objectives than p_2.
- p_1 dominates p_2 when p_1 is not worse than p_2 in any objective and is better than $p_2$in at least one objective.
- p_1 weakly dominates $p_2$when p_1 is not worse than p_2 in any objective.

- p_1 and p_2 are incomparable when neither p_1 weakly dominates p_2 nor $p_2$weakly dominates p_1.

Zitler et al. was primarily concerned with comparing the effectiveness of different optimization algorithms. To this end, they defined dominance between approximate sets. An approximate set is the estimation of the true Pareto frontier created by any particular algorithm.

Definitions of dominance between approximate sets [47]

- An approximate set of solutions, A, strictly dominates another approximate set, B, when every point in B is strictly dominated by at least one point in A.
- A dominates B when every point in B is dominated by at least one point in A.
- A is "better" than B when A weakly dominates B and A is not an identical set to B.
- A weakly dominates B when every point in B is weakly dominated by at least one point in A.
- A and B are incomparable when neither A weakly dominates B nor B weakly dominates B.

For the formal use of these definitions, it is important to note that the degrees of dominance are hierarchical. That is, if A strictly dominates B, it also dominates B, is better than B, and weakly dominates B. Figure 2.5 illustrates this relationship.

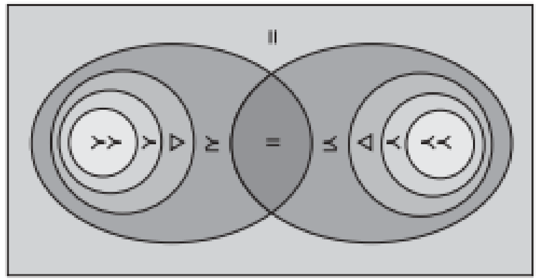


Figure 2.5. Hierarchy of Dominance [47]

By treating reconfigurable systems in this thesis as analogous to approximate sets, the definitions of dominance between approximate sets from Zitler et al. form the starting point for the dominance criteria that will be defined to characterize reconfigurable solutions.

2.8 Chapter 2 Summary

Section 2.2 reviewed Mars exploration rovers. The rocker bogie was identified as the traditional architecture for Mars rovers. It is characterized by passive suspension and has limitations on the sorts of missions it can undertake and the speed at which it can travel. The TRREx rover concept was described. It is a reconfigurable design for both downhill rolling and more traditional roving. Understanding the performance comparison between the reconfigurable TRREx and the more traditional rocker bogie is the primary case study of this thesis.

Section 2.3 provided additional background into reconfigurability. Notably, it discussed concept generation tools for reconfigurable systems such as the transformation principles and function sharing. It also identified research that has characterized the challenges of introducing reconfigurability to a system. The motivating case study for this thesis began with an extensive concept generation phase performed by application of the transformation principles.

Section 2.4 discussed system architecture. System architecture was defined as the plan for mapping a system's functional requirements to its physical manifestation. Section 2.4 also provided a review of the design community's current understanding of architecture. It recognized that reconfigurations can affect a system on a number of different architectural levels and that adopting reconfigurations can, therefore, have different degrees of impact on a design's architecture. Understanding these impacts is the primary purpose of the concept sorting framework developed in Chapter 3.

Section 2.5 reviewed concept selection techniques including quantitative frameworks such as Pugh and qualitative frameworks that apply utility theory. It also reviewed a work for comparing different architecture concepts using a multiobjective optimization scheme and comparing the Pareto frontiers of the various concepts. Section 2.5 concluded that the available concept selection techniques require a certain degree of knowledge about the concepts. There is a niche for very early concept sorting, particularly as it pertains to reconfigurability, to steer a design team toward concepts based on their programmatic goals before extensive modeling and investigation are done on the concepts. This niche is additional motivation for the concept sorting framework in Chapter 3. Additionally, the performance scores that are built up in section 5.3 are modeled similarly to decision based design. Section 2.6 described past work in tradespace exploration. The previous work in analyzing the “illities” (reconfigurability included) was the epoch-era framework. It is conceptually strong but in practice is likely to require extensive and redundant computation to create a full analysis. The tradespace that will be defined in Chapter 4 will provide a remedy to this problem.

Section 2.7 provided a formal definition of Pareto dominance, which is a theme that runs through much of the topics of this thesis including multiobjective optimization, assessment of reconfigurable systems as compared to static systems, and tradespace exploration. The definitions provided by Zitler et al. for point-to-point comparison are the formal definitions that are used throughout this thesis. Their definitions for comparison between approximate sets provide a formal definition for when one set of points dominates another set of points. These definitions are the foundation for the definitions developed in Chapter 4 of dominance as it relates to reconfigurable systems. Any new definitions of dominance should be consistent with those provided in this section.

Building upon the background developed in this chapter, Chapter 3 discusses the generation of reconfigurable concepts and introduces the reconfiguration concept sorting framework. This framework identifies one of the concepts, the rolling/roving concept that the TRREx is based on, as a good candidate for further investigation.

3. SORTING FRAMEWORK FOR EARLY CONCEPTUAL DESIGN OF RECONFIGURABLE SYSTEMS

3.1 Overview

A large number of concepts were developed while considering systems that leverage reconfigurability for Mars exploration. A strategy for early concept sorting was necessary to consider where to commit additional efforts. This chapter discusses a tool that was developed for the purpose of sorting reconfiguration concepts in the very early stages of conceptual design. Section 3.2 describes the framework, while Section 3.3 presents its use in sorting the rover concepts. From this effort, the TRREx concept is identified as a candidate requiring further investigation and is therefore used in Chapter 5 as the case study for the tools developed in Chapter 4.

The framework presented in this chapter is intended for use immediately following concept brainstorming. It requires that an assumed base architecture exists to trade concepts against. In considering the challenges associated with designing for reconfigurability, three questions were used to guide the sorting of reconfigurable concepts: “What is the architectural level of the concept?” “What architectural levels are impacted by the proposed concept?” and “How severe are the changes associated with this concept?” Exploring these questions allows a classification from one to five to be assigned to each concept. Class one concepts are components that can be accepted with minor or no impact on the rest of the system. Class five concepts are system level changes that have a major impact on all parts of the system’s design. The remaining classes fill in the continuum between these. This framework will not supplant the need to do full analysis of the effectiveness of a particular concept. Rather, it can steer the design team toward certain concepts based on its goals.

3.2 Framework Methodology

Overview:

This method is driven by three fundamental questions. First, at what level of the system design does the concept apply? Second, what level(s) of the system design does including the concept impact? Third, what is the severity (minor, moderate, or major) of the impact?

The procedure is broken into seven steps:

1. Define the baseline architecture that the design team will compare concepts to;
2. Define the levels of the system at which the concepts are to be considered;
3. Brainstorm a list of reconfigurable/changeable concepts, if needed;
4. Do initial filtering of ideas;
5. Define a set of criteria by which to classify the impact of a change as minor, major, or moderate;
6. Sort concepts based on the established definitions;
7. Choose concepts worthy of further investigation.

Procedure:

Step 1: Define the static system's "basic architecture".

The design team should consider what architectural concept they are starting with. Previous generations of the system, early prototyping, or historical examples might provide the assumption of the basic architecture. The assumption needs to be of the same resolution as the system that is being designed. For example, if the team is designing a vehicle, their baseline static architecture could be the previous generation of the vehicle. If they are designing a power train, the baseline assumption might be the previous generation of the power train. Concepts will score different classifications depending on what starting architecture they are compared against. This point will be illustrated in step 6 of Section 3.3.

Step 2: Define the architectural levels of the system for consideration.

The design team should break the design into three levels appropriate for the given design task, similar to the system breakdown advocated by the system engineering V [48]. At the top level is the entire system. The next level is sub-systems. At the bottom level is components and assemblies. Figure 3.1 provides an illustration of the V in this context. The design team can choose what levels of their system they wish to consider. Some firms may not be interested in full system design. A firm that is designing a vehicle might use vehicle-level, subsystem-level, and sub-assembly level. A firm designing a drive-train might use subsystem-level, subassembly-level, and component-level.

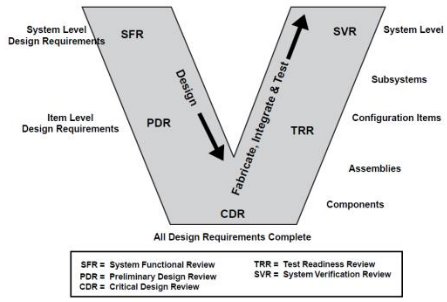


Figure 3.1. System Engineering V [48]

Step 3: Generate a list of reconfigurable/changeable concepts, if needed.

Generate a large list of concepts that leverage reconfigurability. Many techniques exist to augment concept generation including traditional techniques such as researching literature, analyzing natural or technical systems, drawing analogies, and brainstorming, as well as reconfigurability specific techniques such as the application of the transformation principles [26, 29 48, 49].

Step 4: Do initial filtering of ideas.

Designers should eliminate concepts that violate first principles or rely on technology that is not currently available. Also, they should consider using tools, such as allowable mass calculations [28], to eliminate infeasible and/or non-useful concepts. This step should not require extensive, detailed analysis of any concepts. In-depth analysis should be done after using this framework.

Step 5: Define a set of criteria by which to classify the impact of a change as minor, major, or moderate.

At the concept selection stage of the design, it may be undesirable to use rigid numerical criteria because the detailed analysis required to classify concepts probably does not exist. Instead, categorical estimates are used. This is similar to the logic behind physical programming in which categories are used in place of specific objective scores when the objectives are difficult to calculate [51]. Some guidelines are provided to assist this process:

Minor:

- These changes are what the designer expects would be absorbed if a full change propagation analysis were available. By definition, a change is absorbed if the component that it impacts can accommodate the change, and the propagation ends at that component. For example, a new component may require extra power, but the excess power available in the battery absorbs the impact at this level [52].
- These changes are isolated primarily to the design parameters affected by the concept. The architecture of the system will be mostly or completely unchanged. The original architecture will be recognizable after the change is included.

Moderate:

- Moderate changes are similar to what would be considered a passer if a full change propagation study were available [52]. A passer is a change that is passed down the line to some other aspect of the architecture, but does not carry on past that. If in the previous example, enough additional power is needed that the next size of battery is now required, it could be considered a moderate impact.

- A moderate impact may require changes to parts of the original architecture. Some aspects of the static architecture will remain intact after the change.

Major:

- Major changes will be similar to what change propagation research classifies as a multiplier [52]. A multiplier is a change that spreads out into multiple aspects of the system. Extending the battery example further, consider that a change requires so much additional power that the required battery is too heavy for the chassis. The frame, legs, body, etc. must all be redesigned.
- If most or the entire baseline architecture will be discarded and redesigned in order to facilitate a change, the impact is major. The initial static architecture will likely not be apparent in the final design.

Step 6: Sort concepts based on the established definitions.

Figure 3.2 shows the classification framework flowchart. In the flowchart, the first decision box is the answer to the question "What level of the system design does the concept apply?" This leads to one of the three decision blocks in the second row which ask the question "What level(s) of the system design does including the concept impact?" Following the appropriate answer to this question leads to the third row which asks the question "What is the severity (minor, moderate, or major) of the impact?"

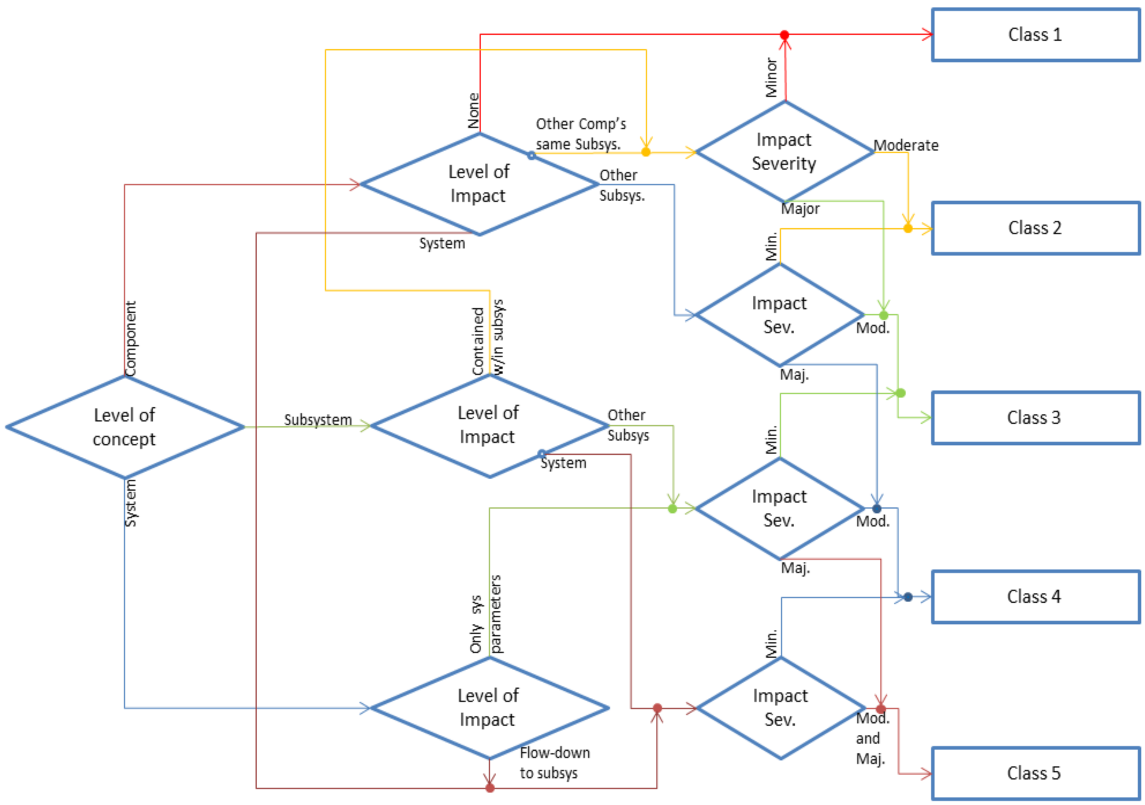


Figure 3.2. Classification Chart

Inspecting the various paths through this flowchart, a reconfiguration concept at the component or subsystem level can result in any classification as it is possible that any change can propagate to the high system levels. However, a reconfiguration concept at the architecture level of the system is limited to a classification of three or higher. This reflects the fact that a change to a high system level is certainly going to be somewhat challenging to handle.

Step 7: Choose concepts worthy of further investigation.

The classification framework describes the amount of difficulty a design team can expect to experience from including a specific concept. Obviously, low classification concepts that create high performance gains are highly desirable. High classification concepts that create small performance gains are undesirable. This principle is illustrated as a fever chart in Figure 3.3. This chapter has provided the tool required to place concepts on the x-axis of this figure. Several techniques exist to assess changeable concepts [43, 28]. Additional work in this area is the primary contribution of Chapters 4 and 5.

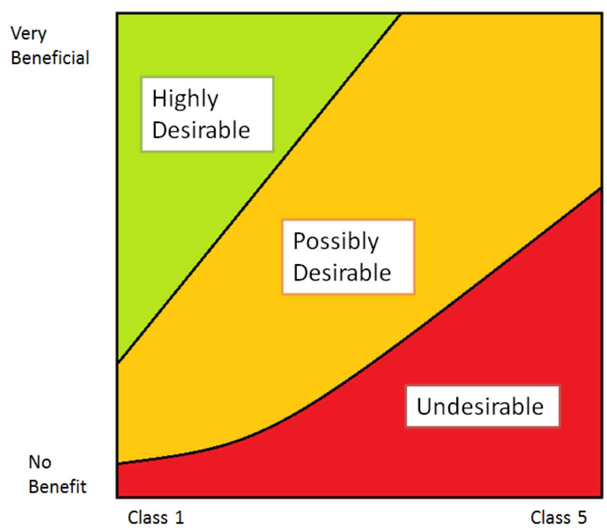


Figure 3.3. Fever Chart of Concept Selection by Classification and Potential Benefit

It should be noted that the decisions for concepts in the green and red areas are obvious. Therefore, the most interesting comparison is amongst concepts that fall somewhere in the yellow. Considering only concepts in the yellow band, Figure 3.3 can be roughly simplified to Figure 3.4. Class 1 designs will be relatively easy to incorporate into the system. These will be low level concepts that have no, or minor, impact for inclusion. The team can expect to be able to integrate these concepts with minimal engineering development effort. The team must have reasonable expectation regarding how much performance gain can be found from changeable concepts at this level. However, since the impact of integrating them is relatively low, a large performance increase may not be necessary to justify their inclusion. Class 5 designs, on the other hand, will require extensive effort to integrate into the system. These will be high level concepts with moderate or major impacts to the rest of the system architecture. Many aspects of the design will have to change to incorporate these concepts. They may be worth considering anyway because they may provide much more extensive opportunity for performance increase.

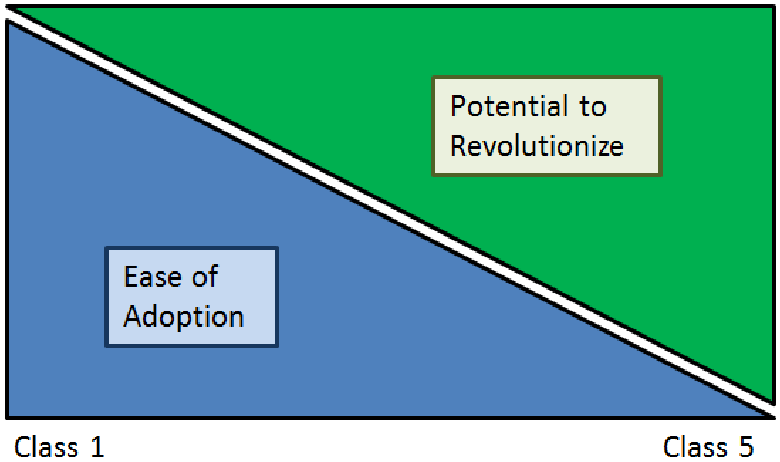


Figure 3.4. Illustration of Selection Trade-off Expected for Most Reconfigurable Concepts

When deciding which concepts to continue investigating, the design team might consider several additional factors. A team that has already partially embodied their concept, and/or is close to its deadline will stick to the lower classifications. A design team that has the time and budget to take some risks and is seeking more novel solutions may want to look more closely at its higher classification concepts.

Having described, the sorting framework for concepts that leverage reconfigurability, a case study will be presented that used the framework to assess 30 concepts for Mars rovers.

3.3 Case Study

In a project for the NASA institute for advanced concepts (NIAC) 30 total concepts were generated by four teams of undergraduate students and two graduate student teams for several different projects, all related to exploration vehicle travel on Mars. This step was reported in Ferguson and Mazzoleni [27]. The objective of this section is to explore the implementation of the classification scheme shown in Figure 3.2 using the concepts generated. By following the procedure outlined in the previous section, insights about the classification scheme and the implementation of reconfigurability into a planetary rover will be generated.

Step 1: Define the static system's "basic architecture".

The basic architecture for this case study will be a traditional "rocker bogie" rover with six wheels and a passive suspension. Historical Mars rovers such as Pathfinder, Spirit, Opportunity, and Curiosity are examples of this architecture [17]. Size, in terms of geometrical footprint, is not specified at this time. The concepts in the case study are locomotion/mobility concepts because the goal of the NIAC project was "Enabling All-Access Mobility" [27]. Therefore, this definition of the architecture is sufficient. If power concepts (for example) were included, the architecture definition would require some detail of the assumed power system.

Step 2: Define the levels of the system design for consideration.

The top level of the design is "system," which will be the level of the entire rover. System parameters would include size, layout, mass, subsystem organization and arrangement, etc. The middle level of the design is "subsystem." Subsystems are the locomotive subsystem, the power subsystem, the control subsystem, the scientific payload, etc. The low level of the design will be the component/subassembly level. This level will include wheels, legs, arms, sensors, wires, motors, batteries, etc.

Step 3: Brainstorm a list of reconfigurable/changeable concepts, if needed.

Thirty total concepts had been generated previously in [27]. Figure 3.5 shows sketches and pictures of the concepts. Eight examples were selected to illustrate a cross-section of the classifications and to generate specific insights for this case study. These examples are shown described in Tables 3.1-3.8.

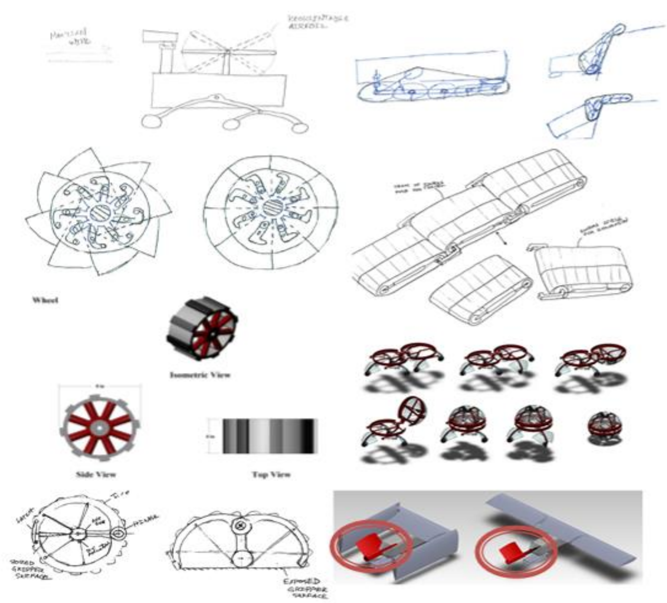


Figure 3.5. Concept Brainstorming Illustration

Table 3.1 Solar Panel Airfoil

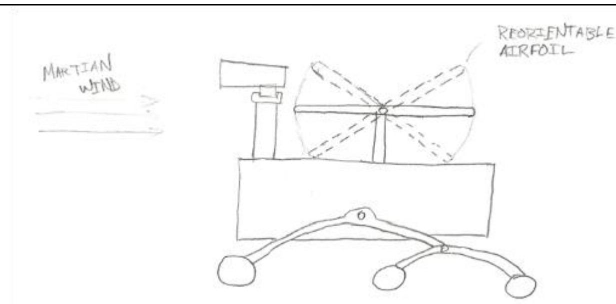
Description:	This concept would involve mounting an airfoil on top of the vehicle that could be reoriented to provide varying degrees of vertical force on the rover as the Martian wind interacted with it. If the vehicle needed extra traction or was stuck and needed a slight lift, the airfoil angle of attack could be altered to provide either.
Depiction:	
Advantages:	The advantage gained from this system would be that the rover could cope more easily with varying terrain conditions. The ability to alter the effective normal force supplied to the rover wheels could be of major assistance in situations such as the one Spirit was unable to recover from.
Dis-advantages:	A significant challenge to implementation would likely be rearranging scientific or functional instruments on the top of the rover to account for the fact that it would be under cover.

Table 3.2 Wedge Wheel

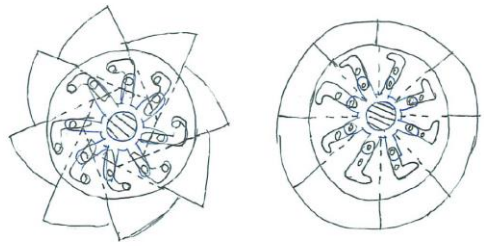
Description:	In this concept, a wheel made of wedges can be expanded into a pinwheel configuration.
Depiction:	
Advantages:	In the pinwheel formation, the wheel has additional surface area, which will help it float in loose terrain. The points of the pinwheel will also act like cleats generating more traction in soft terrain and perhaps allowing it to move forward in soil that would bury a traditional wheel.
Dis-advantages:	The mechanism to make the reconfiguration is necessarily complex as putting actuators in a wheel is a challenging design prospect. This complexity adds vulnerability that would need a mitigation strategy.

Table 3.3 Wheel Acting as Windmill

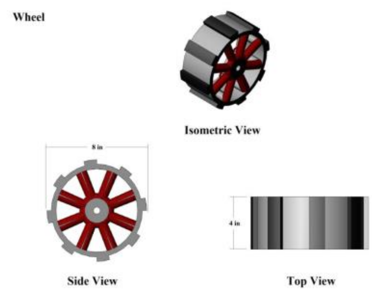
Description:	This concept would use the spokes of a wheel on the rover as vanes for a windmill to provide extra power for the rover. The wheel would be lifted off the ground and extended up into the air where the airfoil shaped spokes would generate power as the wind turns them.
Depiction:	
Advantages:	The advantage to this would be that the rover is essentially getting an extra power source for relatively little cost. The wheel is already necessary for the rover's locomotion and repurposing it during periods when the rover is not moving would allow the rover to extend its functionality.
Dis-advantages:	Not explored.

Table 3.4 5-Bar Robot Tracks

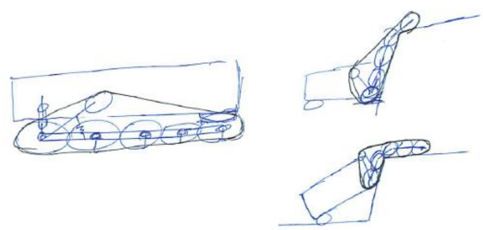
Description:	In this concept, the tracks are configured as a planar robotic arm. The arm can be reconfigured into different shapes to enable a wide variety of maneuvers.
Depiction:	
Advantages:	The flexibility provided by these tracks allows the ability to overcome a wide variety of obstacles. The rover can raise itself up to drive over high rocks. It could do this on one side only in order to maintain its balance when travelling cross-wise along an incline. It can climb small cliffs by placing the tips of its tracks atop the obstacle and progressively moving wheels up and over the cliff.
Dis-advantages:	The complex motion of this system requires sophisticated control and decision making to leverage its full potential. Many components in the tread likely add up to considerable extra mass.

Table 3.5 Combined Rover Concept

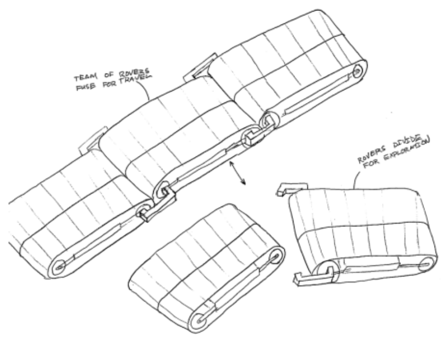
Description:	For this concept, several rovers would be produced such that they have an interface for connecting together into one larger vehicle.
Depiction:	
Advantages:	The combined rover would be advantageous for the travel phases of the mission. It could be designed such that it is more capable in chaotic terrain. That is, a vehicle consisting of three six-wheeled vehicles would have eighteen wheels and could survive much more in loose soil. There may be some energy or mass savings available with this arrangement. When the rovers reach a location of scientific interest, they would divide and perform their assigned tasks. Multiple rovers could explore an area more quickly than one big rover. Having the capability to divide into smaller fully-functional rovers mitigates mission risk. Multiple rovers create the possible risk mitigation strategy of rescue. That is, if one rover gets stuck, the others may have the capability of helping it get unstuck.

Table 3.5 (Continued)

Dis-advantages:	Less available payload for each individual rover means each small rover would have less scientific ability than one large rover of similar system mass. This disadvantage could be mitigated somewhat by distributing different sensors to different individual rovers although, that would have to be traded against the effectiveness of the risk mitigation proposed in the advantages.

Table 3.6 Roving-Rolling

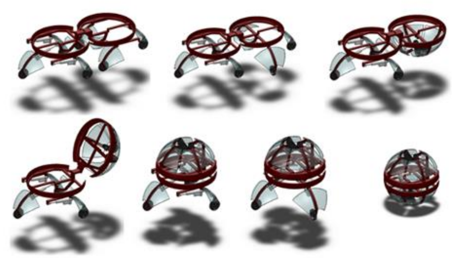
Description:	This concept is to combine a traditional wheeled architecture with a rolling mode of locomotion. This system has 6 wheeled legs in the roving mode which become body sections in the rolling mode. The transformation is achieved by hinging the chassis body at the center and folding in the legs. This concept as known as the Transforming Roving/Rolling Explorer (TRREx) and is under development at NC State University [26].
Depiction:	
Advantages:	The rover navigates flat and moderately rugged terrain while rolling. For downhill travel, the system can transform into a sphere. The rolling mode drastically increases rolling efficiency.
Dis-advantages:	To preserve the dynamic advantage of a sphere in free rolling, it is critical that the center of mass of the sphere be at the center of the sphere. In addition to the existing space constraints, this constrains the placement of various objects based on their weight and thus forces symmetric placement of components.

Table 3.7 Spine Foot

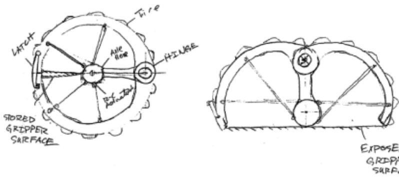
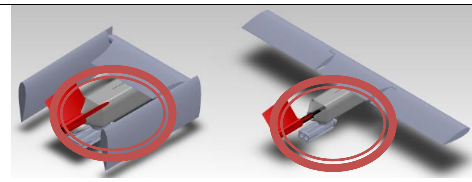
Description:	This concept is a wheel that opens like a clamshell to expose a microspine surface for climbing.
Depiction:	
Advantages:	In the foot configuration, the microspine surface is very useful for connecting to hard, rough rocky surfaces. This surface could be useful for a climbing rover to ascend a mountain or descend a canyon with a rocky wall. The wheel configuration would be for low energy travel over benign terrain.
Dis-advantages:	The foot configuration cannot share the rolling locomotion of the wheel. Therefore, the rover would need a walking locomotion mode to leverage the microspine feet. Also, some strategy for protecting the transformation mechanisms from dirt, dust, and debris would be needed to prevent degradation over the course of the mission.

Table 3.8 Deployable Gilder Tail

Description:	This concept is for the tail section of the glider. The tail boom compresses so the tail can be stored closer to the glider. When the glider is ready to deploy the tail boom extends into the flight configuration.
Depiction:	
Advantages:	The glider fits in an acceptable storage volume until the flight phase of the mission.
Dis-advantages:	The tail boom volume is not useful for other purposes.

Step 4: Do initial filtering of ideas.

This concept selection exercise was done at a very early development stage so no ideas were discarded. As part of this step, each concept was considered individually. A description and some initial thoughts about its advantages and disadvantages are enumerated for each of the concepts by the design teams that generated them with some supplemental analysis added by the author of this thesis. These initial reactions were described in Tables 3.1-3.8.

Step 5: Define a set of criteria by which to classify the impact of a change as minor, major, or moderate.

After brainstorming and examining the generated concepts at a high level, there is sufficient context to flesh out the impact classifications. The guidelines presented in Section 3.2 are intended for use as a starting point. More specific criteria were outlined with consideration of the concepts.

Minor:

- The change impacts the design's parameters 50% from the original parameter value or less. An example of a parameter might be kilowatts of required power, or the position of a component's attachment point.
- The concept has a small difference in mass or moment of inertia from the component/subsystem it replaces. For example, including reconfigurable wheels on a rover might add a few kilograms to the wheels. This may require a reconsideration of the legs' capabilities; but if it does, the impact will be easily handled by small parameter changes.
- A system-level concept that requires the addition of a component or small subsystem to enable the concept. For example, a team of rovers could be fused into a rover train for distance travel then divided for scientific exploration. This reconfiguration would require a component to couple the physical (and probably electronic) subsystems but this component would not have a substantial effect on the rest of the rover architecture.

Moderate:

- The change impacts the designs parameters by more than 50%. For example, the concept requires doubling the power usage of the system.
- The concept requires a modest change to the functional requirements of other parts. For example, a concept to move the center of gravity of a rover by repositioning its manipulator requires the manipulator to have a new function—balance the rover. However, the embodiment of the arm for its original function allows the new function to be added quite easily.
- A system level concept that propagates into one subsystem in a substantial way (requiring significant redesign) or into multiple subsystems.

Major:

- Including the concept requires the addition or removal of other subsystems. For example, separating an aerial explorer from a ballistic shell presumes a cannon exists to fire the ballistic shell. Since the base architecture doesn't have a cannon, this is a major impact.
- Including the concept requires significant changes to the functional requirements of other subsystems or the whole system. For example, including a wheel that turns into a foot requires adding walking functionality to the suspension. Otherwise the foot is of limited usefulness.

- The concept adds, removes, or significantly changes the primary system function. For example, the rolling/roving concept (Table 3.6) transforms into a ball for downhill travel. This is a change from a roving primary function to a rolling primary function.

Even with added specificity, these guidelines are still somewhat vague. This is typical of the fuzzy understanding a design team has when performing early conceptual design. As more decisions are made about the system and the design becomes clearer, later iterations of this procedure could increase specificity in these guidelines.

Step 6: Sort concepts based on the established definitions.

The framework was first tested by a two-designer team. It ranked the eight case study concepts according to the flowchart presented in Figure 3.2. The first concept was the solar panel airfoil (Table 3.1). This concept is for a reconfiguration at the component level. Presuming that the rocker bogie architecture has solar panels, this concept can probably be included with almost no impact to the rest of the system. Therefore, this concept is a class one concept.

The wedge wheel concept (Table 3.2) is also a concept for a reconfiguration at the component level. Unlike the airfoil solar panel, though, this concept probably impacts the rest of the locomotion system. Furthermore, it is likely to require changes in the controller to accommodate the new rolling characteristics of the rover and in the power supply both to actuate the wheel and to power the wheels in the wedge configuration. At this point in the development process, the design team expects this to be a minor impact because it is thought that the additional power and control can be provided without significant changes to the hardware of those systems so the change will be absorbed by the power and control subsystems. This makes the wedge wheels a class two concept.

The wheels acting as a windmill concept (Table 3.3) is a reconfiguration of a component, the wheel. It impacts the rest of the locomotion system because some device or process needs to be added that allows the middle wheel of the rover to be lifted into a position from which it can harvest wind energy. Furthermore, a change to the rocker bogie mechanism will be required to prevent the rocker from collapsing when the middle wheel is lifted. These are considered moderate impacts because part of the architecture of the locomotive subsystem needs to be redesigned but large portions of it can probably be kept in their original state. Therefore, the wheels as windmills concept is class two.

The 5-bar tracks concept (Table 3.4) is a reconfiguration concept at the subsystem level of the design. The locomotive subsystem would be replaced by this concept. The most important impacts from this concept will be contained within the subsystem. The impact of this change is considered to be moderate. This concept thereby receives classification three.

The combined rover concept (Table 3.5) is a system level reconfiguration. It will cause some flow down into the subsystems because a component will be necessary to handle the coupling and decoupling of the rovers. However, the designers think this concept will be minor because the necessary additional components will be a small item in comparison to the size of the system and because the original architecture will be almost entirely preserved after the change is implemented. Therefore, this concept scores classification four.

The Roving/Rolling concept (Table 3.6) is for the TRREx rover architecture [18]. This is a system level concept that completely diverges from the baseline architecture. It affects every subsystem. The severity is classified as major because the original architecture is discarded to implement this idea. This concept is therefore class five. It is particularly illustrative to contrast this concept with the previous one. In the combined rovers concept, large portions of the original architecture plan of a rocker bogie rover are still apparent while in the TRREx concept, the entire system is different architecturally and functionally.

The spine foot concept and the deployable glider tail concepts (Tables 3.7 and 3.8) are included to illustrate interesting observations of this framework. The spine foot concept shows the importance of defining the base architecture as it is of relatively little value for a rover that cannot walk. Therefore, when looked at from the rocker bogie baseline, a major change to the system—enabling a walking mode—is needed to include this concept, making it a class five concept. However, when compared to a baseline that already has walking locomotion, this concept is merely a component swap for the wheels or feet of that architecture and would score very similarly to the wedge wheel example (class two when compared to the rocker bogie architecture.) This is the justification for properly understanding the assumed baseline architecture before embarking on this exercise.

The glider tail concept, similarly, is not actually an idea for a rocker bogie rover. In order to utilize this concept, a glider is required and therefore this concept falls in class five. However, this concept can clearly illustrate that this framework implicitly accounts for the degree of system modularity. If the baseline architecture includes a glider, the tail deployment is a component level-change with little or no impact on the rest of the system. It would score class one or two. This lack of impact is because this particular aspect of this glider has been designed as a separate module. The tail's location is important to the glider but its interface with the rest of the components is very simple. It is connected and positioned by the boom. Changing the boom length before the glider flies does not impact the design of the rest of the system. If the glider concept were, for example, a flying wing architecture (which is inherently more integral) this concept would have considerably higher impact on the rest of the system. A summary of the classification steps for the eight illustrative examples is included in Table 3.9.

Table 3.9 Summary of Concept Classifications

Concept	Flowchart Path			Class
Solar Panel Airfoil	Component	None	N/A	1
Wedge Wheel	Component	Other Subsys	Minor	2
Wheel as Windmill	Component	Same Subsys	Mod.	2
5-bar Tracks	Subsystem	Contained	Mod.	3
Combined Rovers	System	Subsytem	Minor	4
Roving/ Rolling	System	Flow-down	Major	5
Spine Foot	Component	System	Major	5
Deployable Glider Tail	Subsystem	System	Major	5

In total, thirty designs were analyzed by the two-designer team, separately first and then with discussion. Both of these designers are graduate students in Aerospace Engineering that assisted the senior design teams who generated most of the concepts. A few of the concepts were generated by either of these designers. Both designers have studied Mars exploration systems, but neither has any professional experience in rover design. Table 3.10 shows the classifications after the initial rating. At this stage, one-third of the concepts were rated identically. The average rating difference was 1.0 class. The maximum disagreement was 2. The minimum disagreement was -3 (with negative denoting one designer classifying higher.)

As is typical in early conceptual design, some collaboration was needed to come to agreements on the classifications of the concepts. The designers spent approximately an hour discussing various concepts and detailing the assumptions they were using. The primary causes of the disagreements were found to be a different view of the baseline architecture assumption and some confusion about how to categorize the severity of some of the changes. Designer B was using three possible architectures when comparing concepts. He was choosing from a rocker bogie baseline, a tumbleweed baseline [53], or a generic launched flier concept depending on what made most sense for the concept under consideration. Therefore, his classifications were, on average, quite a bit lower than Designer A's. After discussing, the designers concluded that either perspective is valid for applying the framework and which one to use is dependent on how far along the design process the team is. The designers agreed to use the assumption of just a rocker bogie architecture for the purposes of this thesis to reduce unnecessary confusion in the case study.

The other point of debate was the definitions of minor, moderate, and major. Additional definitions were added to the methodology following this discussion. With improved agreement on the assumptions used for the analysis, the designers ran the concepts back through the framework. With the framework in its current form, they came to agreement within one classification on all of the concepts. They had identical classifications for 21 of the 30 concepts. Table 3.11 shows the results after the collaboration.

The results of the framework yield approximately the following distribution of ratings: one class one design, two class two designs, four class three designs, five class four designs, and eighteen class five designs. The large number of class five designs can be accounted for by two effects. First, the brainstorming activity was actually completed by several teams. They were not all focused on the rocker bogie architecture. The general focus of all of the groups was on reconfigurable concepts for Mars missions. Naturally, concepts that were brainstormed for architectures other than the rocker bogie will score very high when compared to the rocker bogie architecture. Second, the system under development is a complex system with many interacting influences to its design. Therefore, it is expected that most reconfigurable concepts will have a substantial impact on the system architecture.

Step 7: Choose concepts worthy of further investigation.

The Rolling/Roving concept is one of the essential innovations in the TRREx case study, which motivates this thesis. When it was analyzed using the concept sorting framework, it received classification 5. Therefore, it needs to show significant performance gains to offset the expected challenges of integrating the idea. Since the TRREx rover may have the potential to be revolutionary, it is worth continuing investigation. Chapter 5 will apply the analysis described in Chapter 4 to this architecture.

Table 3.10 Classifications Before Collaboration

Concept	Designer A	Designer B	Diff
Drill Anchors	5	2	-3
Deployable Legs	5	3	-2
Retractable Sails	5	3	-2
Boom Tumbleweed Deployment	5	3	-2
Umbrella	5	3	-2
Landing Bags as Hovercraft Skirt	4	2	-2
Folding Hoops	5	3	-2
Deployable Glider Tail	2	1	-1
Tracks protect rover	5	4	-1
Aerial Explorer from Shell	5	4	-1
Compressor for Projectile Loading	5	4	-1
Deployable Glider Wings	2	2	0
Enable Rolling	5	5	0
Spine Foot	4	4	0
Wheel and Skate/Ski	3	3	0
Roving/Rolling	5	5	0
Carrier Rover	5	5	0
Ballistic Aerial Explorer	5	5	0
Flying Scout	5	5	0
Crater Exploration	5	5	0
Track/Wheel/Ski	5	5	0
Solar Panel Airfoil	1	1	0
Walker Roller Hybrid	4	5	1
Wedge Wheel	2	3	1
Spine Wheel	2	3	1
Parafoil	4	5	1
Combined Rovers	4	5	1
5-bar Tracks	3	4	1
Wheel as Windmill	1	2	1
Reorienting Treads	1	3	2

Table 3.11 Classifications After Collaboration

Concept	Designer A	Designer B	Diff
Drill Anchors	5	4	-1
Deployable Legs	5	4	-1
Retractable Sails	5	5	0
Boom Tumbleweed Deployment	5	5	0
Umbrella	5	5	0
Folding Hoops	5	5	0
Deployable Glider Tail	5	5	0
Tracks protect rover	5	5	0
Aerial Explorer from Shell	5	5	0
Compressor for Projectile Loading	5	5	0
Deployable Glider Wings	5	5	0
Enable Rolling	5	5	0
Wheel and Skate/Ski	3	3	0
Roving/Rolling	5	5	0
Carrier Rover	4	4	0
Ballistic Aerial Explorer	5	5	0
Flying Scout	5	5	0
Crater Exploration	5	5	0
Track/Wheel/Ski	5	5	0
Solar Panel Airfoil	1	1	0
Combined Rovers	4	4	0
Wheel as Windmill	2	2	0
Reorienting Treads	3	3	0
Landing Bags as Hovercraft Skirt	4	5	1
Spine Foot	4	5	1
Walker Roller Hybrid	4	5	1
Wedge Wheel	2	3	1
Spine Wheel	2	3	1
Parafoil	4	5	1
5-bar Tracks	3	4	1

3.4 Analysis and Results

To further test the framework, an additional experiment was run with a four-designer team. These designers are graduate students in Mechanical or Aerospace engineering that primarily study design theory. Only one designer had experience with rovers. They were asked to use the framework to rank each of the designs individually. They then met to discuss their selections, clarify their assumptions, and agree on the definitions that comprise the classification. Finally, they updated their classifications based on their collaboration.

Table 3.12 compares the average classification in the two-designer test to the average classification in the four-designer test for each concept. The third column of Table 3.12 is the absolute value of the difference in rating. The difference between the average classifications for all designs was 0.27 higher for in the two-designer test. The highest difference for an individual concept between the two tests was 1.75. The average difference was 0.43. This suggests that the framework's outcome is reasonably repeatable.

Table 3.12 Summary of Concept Classifications

Concept Name	2-Designer Team AVG	4-Designer Team AVG	Absolute Difference
Deployable Legs	4.5	4.50	0
Deployable Glider Wings	5	4.75	0.25
Deployable Glider Tail	5	4.00	1
Drill Anchors	4.5	3.50	1
Walker Roller Hybrid	4.5	4.25	0.25
Wedge Wheel	2.5	1.75	0.75
Retractable Sails	5	3.25	1.75
Boom Deployment	5	5.00	0
Umbrella	5	5.00	0
Landing Bags as Hovercraft	4.5	4.50	0
Enable Rolling	5	5.00	0
Tracks protect rover	5	5.00	0
Spine Foot	4.5	3.50	1
Spine Wheel	2.5	2.25	0.25
Aerial Explorer from Shell	5	4.75	0.25
Wheel and Skate/Ski	3	3.25	0.25
Roving/Rolling	5	5.00	0
Parafoil	4.5	4.25	0.25
Combined Rovers	4	4.00	0
Carrier Rover	4	4.50	0.5
Ballsitic Aerial Explorer	5	4.75	0.25
Flying Scout	5	3.75	1.25
Crater Exploration	5	4.25	0.75
5-bar Tracks	3.5	4.25	0.75
Folding Hoops	5	5.00	0
Track/Wheel/Ski	5	3.75	1.25
Wheel as Windmill	2	2.00	0
Reorienting Treads	3	3.00	0
Solar Panel Airfoil	1	2.00	1
Compressor for Loading	5	4.75	0.25
AVERAGE	**4.25**	**3.98**	**0.43**

3.5 Chapter Summary

In this chapter, a framework for concept selection in reconfigurable system design was presented and tested. This framework can be used after brainstorming concepts for a reconfigurable system. The only prerequisite is an understanding of the baseline system that concepts are being traded against. Concepts are sorted into five classifications that relate to their relative ease of adoption and implementation with a classification of one being the simplest. The classifications are likely to relate directly to the potential a concept has to revolutionize the system. That is, class five concepts are more likely to provide opportunities for revolutionary improvement to the system.

The framework is useful at several different stages in early- to mid-conceptual design. As the designers come to higher levels of understanding about what their system architecture is, the framework can be repeated and concepts can be reclassified higher or lower depending on how they relate to the new understanding of the basic architecture. The framework was tested by a team of two designers during the development of the framework. Then it was tested for repeatability by a team of four designers. The results of this test show that a second group of designers came to similar classifications as the first group.

The rolling/roving architecture was identified as a high classification concept. In Section 3.2 (step 7) it was argued that high classification concepts need to show large performance gains to justify the significant architectural impact they have on the system's design. Therefore, assessment of the TRREx will continue with the understanding that it would need to be capable of significant gains in performance to warrant selection over a traditional, static architecture such as the rocker bogie. The TRREx will be the subject of a tradespace exploration case study in in Chapter 5. First, Chapter 4 will introduce the methodology of that case study.

4. METHODOLOGY FOR TRADESPACE EXPLORATION FOR RECONFIGURABLE SYSTEMS

4.1 Overview

In this chapter, a methodology is described for exploring reconfigurable systems in a multidimensional tradespace and assessing the systems for Pareto efficiency. Pareto domination rank is one possible metric that could be used on the y-axis of the fever chart presented in Chapter 3 (Figure 3.3). A methodology in is provided for representing reconfigurable solutions in a tradespace and for assessing dominance between systems in the tradespace. Chapter 5 will apply this framework to the TRREx rover case study to enable a comparison of its value to its sorting framework classification. Figure 4.1 shows an overview of the methodology.

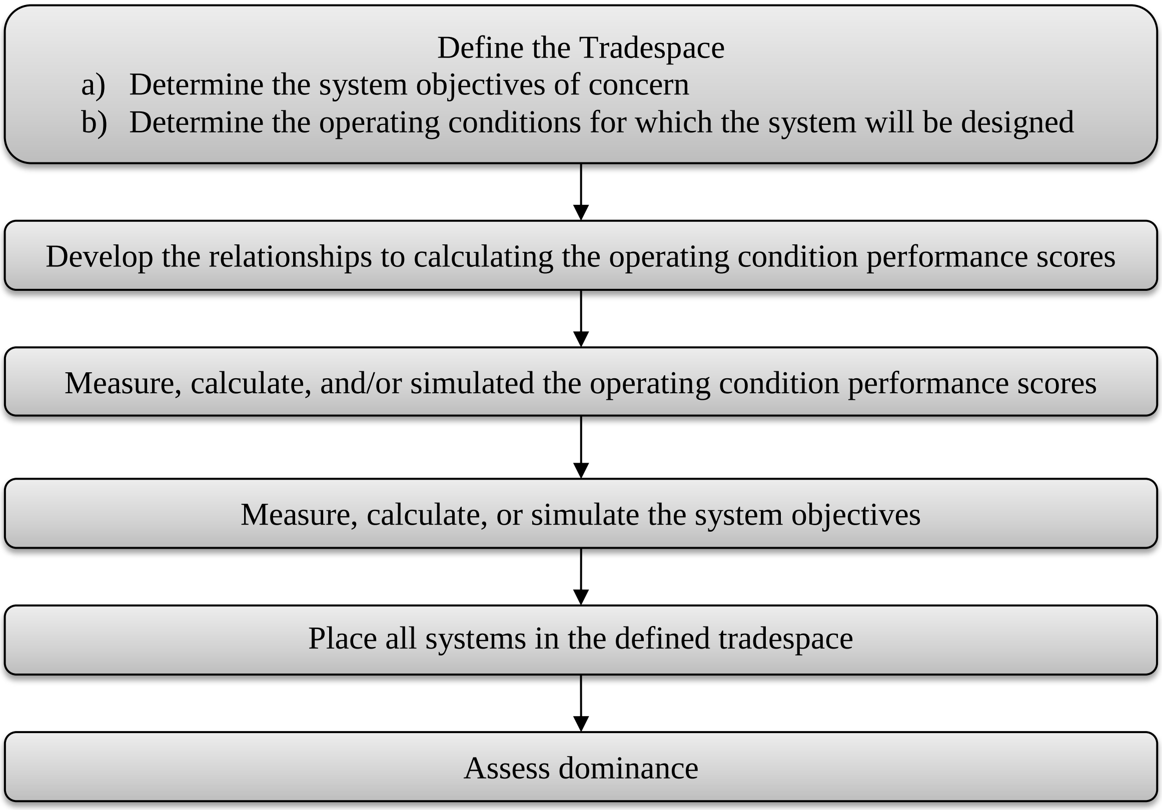


Figure 4.1. Flowchart of Tradespace Exploration Methodology

4.2 Step 1: Define the tradespace

Many possible objectives exist for any complex system design problem that could be included in the tradespace. As was argued in the introduction, a scheme for organizing the overwhelming amount of information that a designer might consider for a reconfigurable system is necessary. The first consideration for illustrating reconfigurable architectures in a tradespace is defining what information should be included on each axis. The relevant information can exist in many different spaces. The design space characterizes the parameters of the design. For simple systems, design variables can be directly mapped to the performance space once the system is analyzed. This performance space is typically characterized by objective functions that a designer wishes to maximize or minimize.

Complex systems, however, often require design variable information to be first aggregated into state variables. These state variables are then used to predict performance of a system – for example airfoil configuration (design variables) creates a coefficient of lift (state variable) which can then be used in estimates of range and endurance (performance objectives). Another particular challenge of representing a reconfigurable system in the tradespace is that the system operates in only one configuration at a time. To handle this problem, the axes of the tradespace should be assigned in such a way that they represent the demand on the system at different use instances. Guidelines are presented for selecting axes in the tradespace used to analyze reconfigurable systems.

1. *System objective axes*: Any property of the system that does not change as any system reconfigures can be included as an axis in the tradespace.
2. *Operating condition axes*: for properties that change with the reconfiguration of one or more concepts, a composite score must be created of the various objectives to represent the system's performance in each operating condition.

Using the TRREx rover example, the system objective axes might include measures such as cost, development time, total system mass, expected system lifespan, etc. The operating condition axes could include performance measures for the rover in downhill travel, flat travel, and uphill travel.

If this methodology were applied to a reconfigurable UAV design, for example, the operating condition axes might include a score for the cruise phase of the mission, a score for the loiter phase of the mission, and a score for the climb phase of the mission.

The operating condition axes are very similar to epochs from the Epoch-Era framework [54]. However, using them as axes in a tradespace allows the designer to ignore the order in which the epochs occur which creates a significant simplification to the amount of analysis required to understand the operation of the system through its life.

4.3 Step 2: Model the operating condition performance

For any system, there may be multiple measures of system performance. Since the tradespace allows only one score for each operating condition, the various objectives need to be mapped to an aggregate score for each objective. It is not necessary that the same framework is used to calculate each operating condition. There are several methodologies for mapping the scores of individual objectives into a composite score such as utility theory [38] and value theory [55].

Using the UAV example, each mission segment might have multiple system objectives such as “minimize fuel consumption,” or “minimize noise.” Additionally, the cruise phase may have an objective of “minimize travel time” while the loiter phase may have the objective of “minimize camera vibration.” However, this tradespace framework permits only one score for each operating condition so some model would be created to combine these various goals into one metric for each mission phase.

4.4 Step 3: Measure, calculate, and/or simulate the operating condition scores

With the tradespace defined, the system must be analyzed so that its score in each dimension can be determined. For some systems, analytical performance expressions will be available. For example, UAV cruise performance can be estimated based on its coefficients of lift and drag. In other cases, performance cannot be immediately calculated and simulations may be required to estimate the system performance as is the case in the TRREx rover assessment.

Using the model developed in step 2 (Section 4.3), calculate the performance score of each static system and each configuration of each reconfigurable system in each operating condition objective.

4.5 Step 4: Measure, calculate, or simulate the system objective scores

Each system (static or reconfigurable) must be evaluated for each system objective. By the definition of a system objective score, the reconfigurable systems will have the same performance in the system objectives at all times. For this reason, the performance of each configuration of a reconfigurable system in a system objective will be equal to the system objective score for the entire reconfigurable system. For example, if minimizing development time is a system objective, the system objective score for a UAV would be the time to develop the entire reconfigurable UAV system. It would not be the time required to develop the cruise configuration of the UAV.

4.6 Step 5: Place all systems in the defined tradespace

Once an appropriate tradespace has been defined and every point (static systems and configurations of reconfigurable systems) has been evaluated in each of the axes of the reconfiguration performance tradespace, the points can be located in the space. If a visual representation of the tradespace is created, the various configurations of any reconfigurable system should have a visual connection to show that they are the same system.

Figure 4.2 shows a theoretical two objective performance space. In this example, both objectives are to be minimized, meaning that the utopia point exists in the bottom left corner of the space. Here, the solid blue circles correspond to different possible static systems. The two yellow points correspond to a reconfigurable system capable of achieving two distinct configurations. The dashed line is used to denote that these are different configurations of the same system. The red line represents a continuously reconfigurable system, capable of achieving an "infinite" number of possible configurations with performance along this curve. This research focuses on discrete reconfigurations and leaves continuous reconfigurations to future investigations.

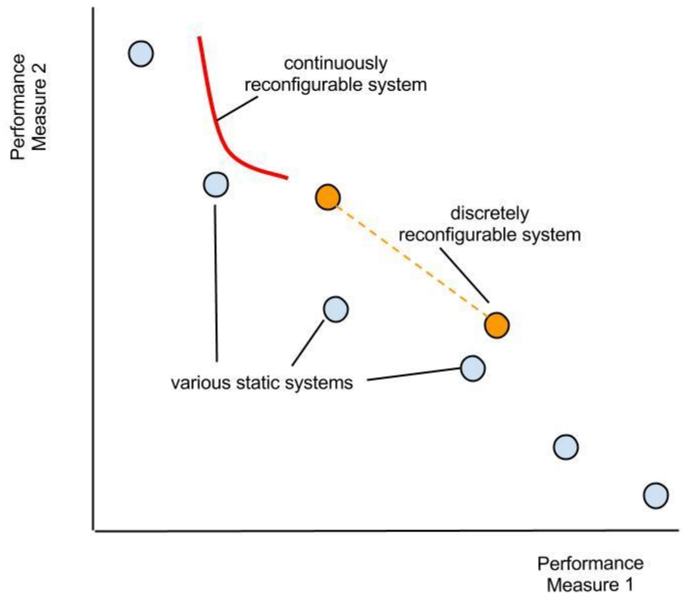


Figure 4.2. Reconfigurable Systems in a Two-Dimensional Performance Tradespace

The focus on tradespace exploration in this paper is limited to operating condition axes. However, the definitions that are presented in the next section are valid even if system objective axes are added to the space. Future work should add at least one such axis to the space to more accurately represent the trade-offs associated with reconfigurability.

4.7 Step 6: Assess dominance between the various systems

Having illustrated the reconfigurable systems in the performance tradespace alongside the static systems, the next task is to understand when each type of system can be considered dominant. In a study intended to compare approximations of Pareto frontiers generated by different optimization algorithms, Zitler et al. provided definitions of dominance both between individual vectors in an objective space and between sets of vectors in the space (see Section 2.7). To extend these definitions to reconfigurable systems, several complicating factors need to be considered. First, there exist three types of comparisons in a space containing static solutions and reconfigurable solutions. The first case is a static design vs. another static design. This case is fully handled by the definitions provided in Section 2.7. The second case is a static solution vs. a reconfigurable solution. The third case is comparison of two reconfigurable solutions. These will be handled by defining specific criteria for when a static system dominates a reconfigurable system, when a reconfigurable system dominates a static system, and when a reconfigurable system dominates a reconfigurable system.

The second complicating factor is that not every configuration of a reconfigurable system must be feasible for all operating conditions. Instead, the set of configurations must cover feasibility for all operating conditions. To handle this factor, it is assumed that the best configuration for each operating condition objective is feasible in that condition.

4.7.1 Definition of the surrogate point of a reconfigurable system (R_s)

The surrogate point is introduced to simplify the definitions and analysis of reconfigurable solutions. The surrogate point is defined as the location corresponding to the best performance in each objective available to the set of reconfigurable states. The surrogate thereby represents the best performance available to the reconfigurable system at any time. For m-dimensional minimization space (without loss of generality), the surrogate point (R_s) of a system containing k objectives is:

$$R_s = \{V_1^*, V_2^*, \dots V_m^*\}$$
$$V_n^* = \min\left(V_n^j\right)$$
$$n = 1,2, \dots m$$
$$j = 1,2, \dots k$$

Where V_n^j is the objective function score for the j^{th} configuration in the n^{th} objective. Using the concept of the surrogate point, new definitions can be created to define dominance as it relates to reconfigurable systems, starting with when a static solution dominates a reconfigurable solution.

4.7.2 Definitions for a static solution (S) dominating a reconfigurable solution (R)

- S strictly dominates R when S strictly dominates the surrogate point of R (R_s).
- S dominates R when S dominates R_s.
- S weakly dominates R when S weakly dominates R_s.
- S and R are incomparable when neither S weakly dominates R nor R weakly dominates S.

The definitions of dominance flow directly from the definition of the surrogate point and the dominance definitions in Zitler et al. If the surrogate point is the best possible performance at any time and the static design dominates this point, it also dominates all of the configurations of R and therefore dominates every point in R. This is true for strict, normal, and weak dominance.

4.7.3 Definitions for a reconfigurable solution (R) dominating a static solution (S)

- R strictly dominates S when R_s strictly dominate S.
- R dominates S when R_s dominates S.
- R weakly dominates S when R_s weakly dominates S.

It seems counter-intuitive to simplify these criteria down to just the surrogate points. However, the tradespace that has been defined for analyzing reconfigurable systems has the very specific property that the objective axes under consideration are not objectives that will be needed simultaneously. For example, a UAV does not cruise and loiter at the same time. If cruise performance and loiter performance are two objectives in the space, there is no benefit to being able to being able to do both simultaneously. Therefore, at no time is it desired to pick a static solution that represents a trade-off between two more specialized configurations presuming the objective space has been set-up correctly and the feasibility assumption holds.

Figure 4.3 illustrates dominance relationships between a static solution and a reconfigurable solution. In Figure 4.3, the reconfigurable design A dominates the static design B because A's surrogate point dominates B's. For either set of operating conditions, A has a configuration that outperforms B. The static design C dominates the reconfigurable design D because it dominates D's surrogate point. D cannot outperform C for any operating condition with any of its configurations. F weakly dominates E (and E weakly dominates F) because for either operating condition, they have equal performance. It is likely that E will be preferred to F since static systems are typically preferable in other objectives but this conclusion cannot be confirmed strictly from the information contained in the tradespace shown. Adding system objectives to this space could provide the information necessary to show this preference.

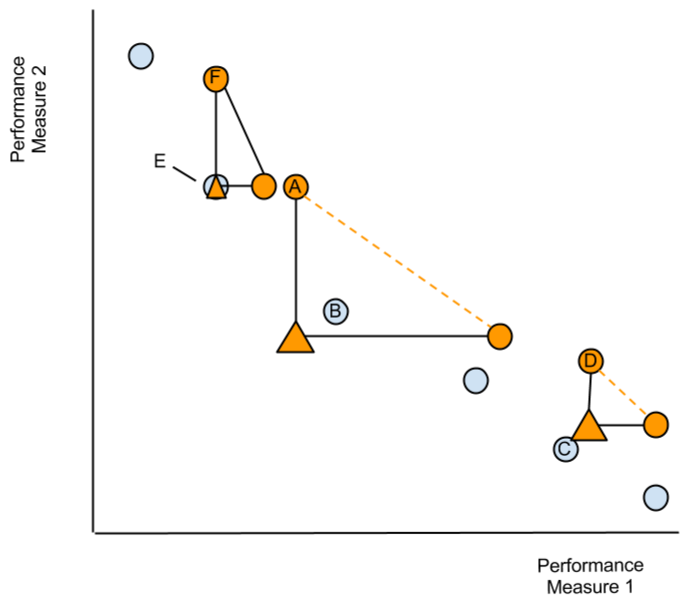


Figure 4.3. Dominance Between Reconfigurable Systems and Static Systems

4.7.4 Definitions of one reconfigurable design ($\boldsymbol{R_1}$) dominating another reconfigurable design ($\boldsymbol{R_2}$)

- R_1 strictly dominates R_2 when the surrogate point of R_1 (R_{1s}) strictly dominates the surrogate point of R_2 (R_{2s}).
- R_1 dominates R_2 when R_{1s} dominates R_{2s}.
- R_1 weakly dominates R_2 when R_{1s} weakly dominates R_{2s}.
- R_1 is incomparable to R_2 when neither R_1 dominates R_2 nor R_2 dominates R_1.

Figure 4.4 illustrates examples of various reconfigurable systems in a space with two operating condition objectives. System A dominates system B because in each operating condition, A has a configuration that outperforms the best configuration of B in that objective. System D and system C are mutually weakly dominant. In the objective space, D looks preferable because both of C's configurations are dominated by a configuration in D. However, when considering that the system only needs to meet one operating condition objective at a time, the benefit that D's top-left configuration has in performance measure 2 is not useful because when D needs to perform well in measure 2, it will use its bottom configuration. Therefore, without additional objectives, no preference can be assigned between C and D.

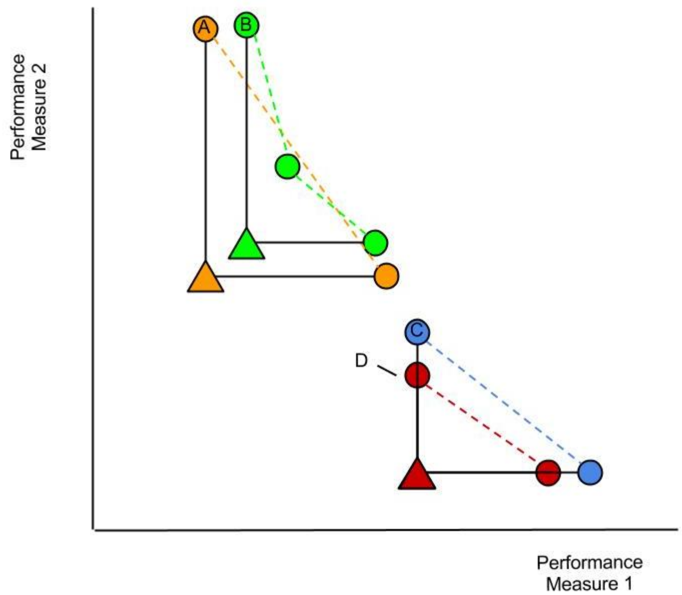


Figure 4.4. Dominance Between Reconfigurable Systems

Analyzing reconfigurable systems in using this methodology leads to some interesting and useful generalizations. First, if only the location of the surrogate point matters in the space and the surrogate's location is determined only by the best configuration for each objective, it is clear that a reconfigurable system should need no more configurations than there are conditions in which it is expected to operate. Therefore, the appropriate number of configurations depends upon the resolution with which the designer chooses to view the operation of the system. Design B in Figure 4.4 has three configurations. However, B will never use the middle configuration because for either operating condition objective, B has a better configuration available to it.

Based on these definitions, it seems that reconfigurable designs have a large advantage when compared to static designs. This is expected when only performance is considered. However, it is quite likely that reconfigurable designs will be more expensive, heavier, more complex, or more difficult to design. Therefore, in a tradespace that includes operating condition objectives and additional system objectives, static solutions should be competitive.

4.8 Chapter Summary

In Chapter 4, a methodology was presented for representing reconfigurable architectures in a tradespace and assessing dominance between architectures in such a space. The tradespace may contain two types of axes. The first type of axis is system objectives. To qualify as a system objective, the score in that objective must not change as any of the architectures reconfigures. The second type of axis is operating condition performance. These axes contain an aggregate score for the architectures operating under any set of operating conditions that the designers choose to analyze. There may be only one axis per operating condition so all of the parameters that the designers want to measure must be represented in the aggregate score for that axis.

Pareto dominance was defined between a static system and a reconfigurable system as well as between two reconfigurable systems. The surrogate point was introduced to simplify this sorting. The surrogate point is the location in the tradespace corresponding to the best performance available to a reconfigurable system under each operating condition. Because the space allows only one score for each operating condition, the designer need only consider domination of the surrogate point to understand domination of a reconfigurable system. In Chapter 5, a case study based on one of the concepts identified in Chapter 3 will be used to test this method.

5. CASE STUDY OF TRADESPACE EXPLORATION FOR RECONFIGURABLE SYSTEMS

5.1 Overview

In Chapter 3, the TRREx rover was shown to be a class 5 reconfigurable concept in the sorting framework. This identifies it as an idea that should have high potential to improve the performance of a rover. It also means that if the TRREx concept is to be adopted, it must show a fairly substantial performance advantage. This chapter will apply the methodology from Chapter 4 to the TRREx concept and compare it to a traditional rocker bogie type rover. For a more detailed description of the TRREx rover and a rocker bogie rover, see Table 3.6, background Section 2.2, and [18]. Three sizes of rover were tested for each architecture. The scaling parameter for comparing rovers was their minimum turning diameter, as it plays an important role in scaling the performance measurements taken in Section 5.4. The rover sizes are listed in Table 5.1.

Table 5.1 Rover architecture sizes

Architecture	Minimum turning diameter	Size designation
Rocker Bogie	5.7 m	Large
	2.8 m	Medium
	1.4 m	Small
TRREx	5.0 m	Large
	2.0 m	Medium
	1.0 m	Small

5.2 Step 1: Define the Tradespace

The tradespace for analyzing the rover architectures is defined by three operating condition axes. Operating conditions were defined in terms of three parameters: what sort of slopes the rover will encounter, what size obstacles the rover will encounter, and what the friction between the rover and the soil will be. The first operating condition is the baseline. It seeks to capture the rover's performance in benign terrain. This operating condition is characterized primarily by flat terrain with small obstacles and a small percentage of small hills, larger obstacles, and low friction areas. The second operating condition is downhill travel. This operating condition is characterized by descending slopes, mostly with small obstacles and a small percentage with larger obstacles. The third operating condition is uphill travel. This operating condition is characterized by ascending slopes, mostly with small obstacles and a small percentage with larger obstacles.

Using these three operating conditions, a large variety of actual Mars missions could be specified. For example, the first mission phase might be travel across flat ground from the landing site to a crater—the baseline condition. The second phase would be travel into the crater—the downhill condition. The third phase would be climbing back out of the crater—the uphill condition. Then the three phases could be repeated with additional craters for the duration of the mission.

5.3 Step 2: Model the operating condition performance

Simulation was identified as the appropriate tool to measure the rovers for a variety reasons. Each operating condition was defined as the weighted average score of the rover operating according in several specific trials. In total, two levels of obstacles, two levels of friction, and five levels of slope were considered. The levels of the three parameters are shown in Table 5.2.

Table 5.2 Terrain parameters

Level	Slope	Rock Field	Friction
1	30^0 Uphill	Sparse	High
2	15^0 Uphill	Dense	Low
3	0^0		
4	15^0 Downhill		
5	30^0 Downhill		

The distribution and size of the rocks in the terrain were controlled using Equation 5.1, as proposed by Golombeck and Rapp. *N* is the cumulative number of rocks per square meter with a diameter greater than or equal to a given diameter, D (in meters). F is the cumulative fractional area covered by rocks with a diameter greater than or equal D. L and s are constants that can be fit to the data of any particular rock field [20].

$$N(D) = Le^{-sD} \tag{5.1}$$

The diameter distribution is based on given input parameters L, s, the dimensions of the desired field, and the slope angle. The “sparse” field uses the fit for the Viking 2 lander site: (L=6.84, s=8.3). The “dense” field uses the fit for Mars Hill, a testing site in Death Valley, CA which is quite rugged in comparison (L = 4.78, s = 3.06). Sparse and dense are relative terms, as the Viking 2 Lander site is believed to be amongst the rockiest places on Mars. Mars Hill is most likely more rugged than any anticipated investigation site on Mars [20]. Such rugged fields were chosen to push the boundaries of the rover assessment.

Soil strength is often modeled starting with Equation 5.2 [56]:

$$\tau_{max} = c + \sigma \tan \phi \tag{5.2}$$

τ_{max} is the maximum shear stress the soil can sustain. c is the cohesitivity, σ is the normal stress on the soil, ϕ is the soil’s friction angle. Since sinking was not considered and Martian soil has very low cohesitivity, c was removed from the analysis. Rearranging the terms:

$$C_f = \frac{\tau}{\sigma} = \tan \phi \tag{5.3}$$

C_f is the friction coefficient. Two values of ϕ were chosen for the ground-wheel interaction. “Low” friction is modeled as $C_f = \tan(17^o)$. This is in the range given for dust deposits. “High” friction is modeled as $C_f = \tan(38^o)$ which is consistent with dust overlying rock [13].

Hill slope angles were chosen considering that while local anomalies may create small features with steeper than 30° slopes, according to several studies, the soil characteristics on Mars suggest that it is unlikely that large features with uniformly steeper slopes exist [56]. Since a fully capable robot could navigate around a localized trouble spot, this investigation was bounded to slopes within ±30°.

The twenty trials listed in Table 5.3 were created by enumerating the testing parameters shown in Table 5.2. While at least four of these scenarios are unlikely to occur, they were included for completeness. For example, soil with an internal friction angle of 17^o would never be expected to form a slope of 30^o.

Table 5.3 Trial specifications

Trial #	Slope	Rocks	Friction	**Trial #**	Slope	Rocks	Friction
1	30^0	Sparse	High	**11**	0^0	Dense	High
2	30^0	Sparse	Low	**12**	0^0	Dense	Low
3	30^0	Dense	High	**13**	-15^0	Sparse	High
4	30^0	Dense	Low	**14**	-15^0	Sparse	Low
5	15^0	Sparse	High	**15**	-15^0	Dense	High
6	15^0	Sparse	Low	**16**	-15^0	Dense	Low
7	15^0	Dense	High	**17**	-30^0	Sparse	High
8	15^0	Dense	Low	**18**	-30^0	Sparse	Low
9	0^0	Sparse	High	**19**	-30^0	Dense	High
10	0^0	Sparse	Low	**20**	-30^0	Dense	Low

A score for each trial was defined as an aggregate score based on three performance objectives: mean free path ratio (MFPR), normalized root mean distance from the path

(D^*_{rms}), and the average speed of the rover's progress through the trial (V_{avg}). The most basic description of performance is "How far did the rover go?" This is answered by the "first stop" metric. Mathematically, this is described as the straight line distance from the start point to the point that the first rover failure occurred. This metric is highly susceptible to a "luck" factor. While the distribution of the obstacles provides some expectation as to how far the rover should go, a large rock in front of a rover's start point can end a trial before much data is collected.

To overcome the limitations of the first stop metric, a rover encountering a failure, multiple trials can be done with different starting points. Mean free path (MFP) is defined as "expected distance that the vehicle can travel in a straight line before it encounters a non-traversable hazard [57]." Patel, N. et al have used this measure to classify the rover's intrinsic ability to overcome obstacles. In this thesis, mean free path was calculated as the average of several trials' FS measurements. This allows the terrain to determine what causes the stop, rather than an analytical failure model. The benefit is the arrangement of rocks sometimes allows the rover to overcome an obstacle that an analytical derivation would assume to cause a failure. The drawback is that with the limited number of simulations, the MFP measurements are susceptible to noise.

The mean free path ratio (MFPR) is the ratio of MFP to the diameter of the rover's minimum turning circle. It can assess how sophisticated the navigational control of a rover must be. If the MFPR is much bigger than one, the rover should need only occasional course corrections and high-level navigation inputs. If the MFPR is much smaller than one, the rover is incapable of navigating in the terrain under consideration. For a rover with MFPR near one, mobility is possible but requires detailed sensing and sophisticated navigational control [57].

In the case that the rover did not reach an obstacle that caused a failure, the MFP was assigned a default value of 20m. This is necessary because the simulation cannot run. The large rocker bogie rover has a turning diameter near 5.6m. So if it travels 20m without a failure, its MFPR is greater than 3.5. Thus, the rover is pretty capable compared to the terrain and running it further to get an exact number is a low value use of investigation time.

Another measure of the rover's performance was the Root Mean Square Distance from the Path (D_{rms}). It is calculated for each data point as follows:

$$D_{z,rms} = \sqrt{mean((z_{rover-}z_{path})^2)} \tag{5.4}$$

Where z_{rover} is the coordinate of the rover perpendicular to its intended travel direction and z_{path} is the location of the straight line from the start to the finish. D_{rms} provides a different measure of required control input. It characterizes how much the ground moves the rover away from its desired straight path. One problem arises with this measure for the case that the rover gets stopped. Each time the rover trial is restarted, the rover returns to the desired path. For that reason, this data is normalized against the MFP. Thus, D_{rms}^* becomes the ratio of how far the rover moves sideways to how far it moves forward. It is calculated according to Equation 5.5. The multiplied scalar sizes the measure to improve numerical conditioning.

$$D_{rms}^* = \frac{10 * \sqrt{mean((z_{rover-}z_{path})^2)}}{MFP} \tag{5.5}$$

Finally, average speed (v_{avg}) was calculated for the trial, as shown in Equation 5.6. The rovers were all set to run at the same speed in each trial, so this is a measure of how the rock field hinders the rover's forward progress. For each forward progress segment of the trial, the distance between start and end point is calculated. Because the data points were recorded at a regular interval, the elapsed time can be easily found.

$$V_{avg} = \frac{\sum D_{segment}}{\sum t_{elapsed}} \tag{5.6}$$

For each trial, the three performance measures were aggregated into a final score for that trial. Strength of preference (SoP) curves were used to map the performance objectives to a non-dimensional score. Then the various non-dimensionalized scores were added, with a weighting to determine an overall system score. In Equation 5.7, V_j is the score of the j^{th} alternative, w_i is the weight of the i^{th} performance characteristic, $x_{i,j}$ is the level of the i^{th} performance characteristic of the j^{th} alternative and $r_{i,j}$ is the non-dimensional score as a function of $x_{i,j}$.

$$V_j = \sum_i W_i r_{i,j}\left(x_{i,j}\right) \tag{5.7}$$

For this thesis, it was assumed that the designer's SoP curves were known. The three performance measures, MFPR, D_{RMS}^*, and v_{avg}, were mapped to non-dimensionalized scores according to the assumed SoP curves. The weightings for mapping the performance objectives to the trial utilities (for the purpose of calculating the operating condition performance scores) were 0.25 in MFPR, 0.25 in D^*_{rms} and 0.5 in V_{avg}.

With scores for each trial, determining an overall score for each operating condition axis was done by defining the operating conditions in terms of time percentage in the conditions of each trial. The baseline operating condition's profile is 60% trial 9 and 10% each of trials 5, 10, 11, and 13. The downhill operating condition's profile is 60% trial 13 and 20% each of trials 14 and 17. The uphill operating condition's profile is 60% trial 5 and 20% each of trials 1 and 6.

5.4 Step 3: Measure, calculate, and/or simulate the operating condition scores

The complex nature of rover dynamics and the uncertainty in predicting the exact parameters of the conditions that they will operate in eliminates the possibility of analytical performance calculations. Physical prototyping and testing is not only very expensive, it cannot mimic the Martian conditions very closely. Thus, simulation was chosen to create the data required to calculate the operating condition objective scores. The simulation environment, Webots was chosen for its ability to do terrain generation, rover modeling, and controller development in one place. Each architecture was modeled in the environment [58]. Figure 5.1 shows the TRREx rover configuration and the rocker bogie Webots models. The ball configuration of the TRREx was simply represented as a solid sphere with a diameter consistent with the body dimensions of the TRREx rover mode.

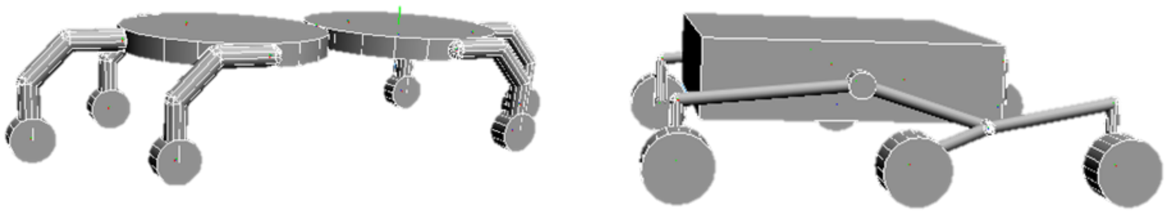


Figure 5.1. The TRREx Rover Mode Model and the Rocker Bogie Model Used in Webots

The terrains were generated using a Matlab code to populate rock fields corresponding to the parameters described above in 5.3. The size of each environment was 8m wide by 25m long. The rock fields were not randomized for each trial. One sparse rock field and one dense rock field was generated. This decision was made to avoid introducing error from the terrain randomization into the results. Figure 5.2 shows the top view of each rock field.

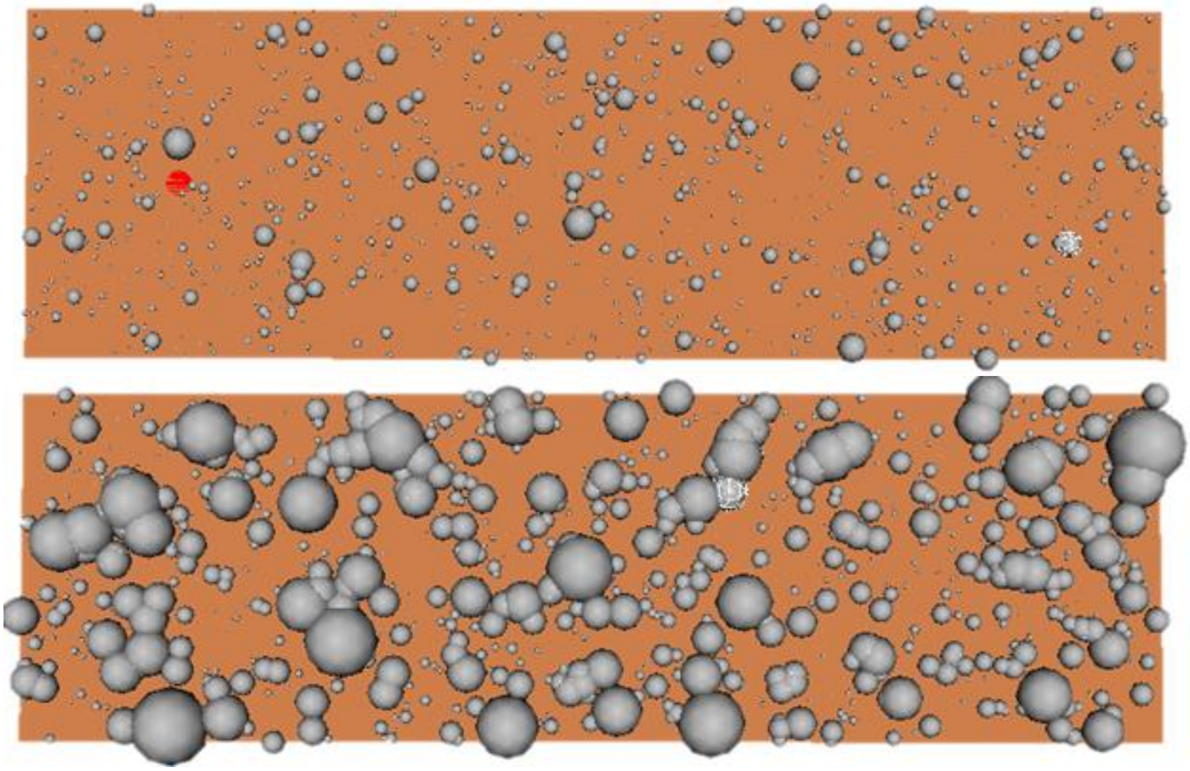
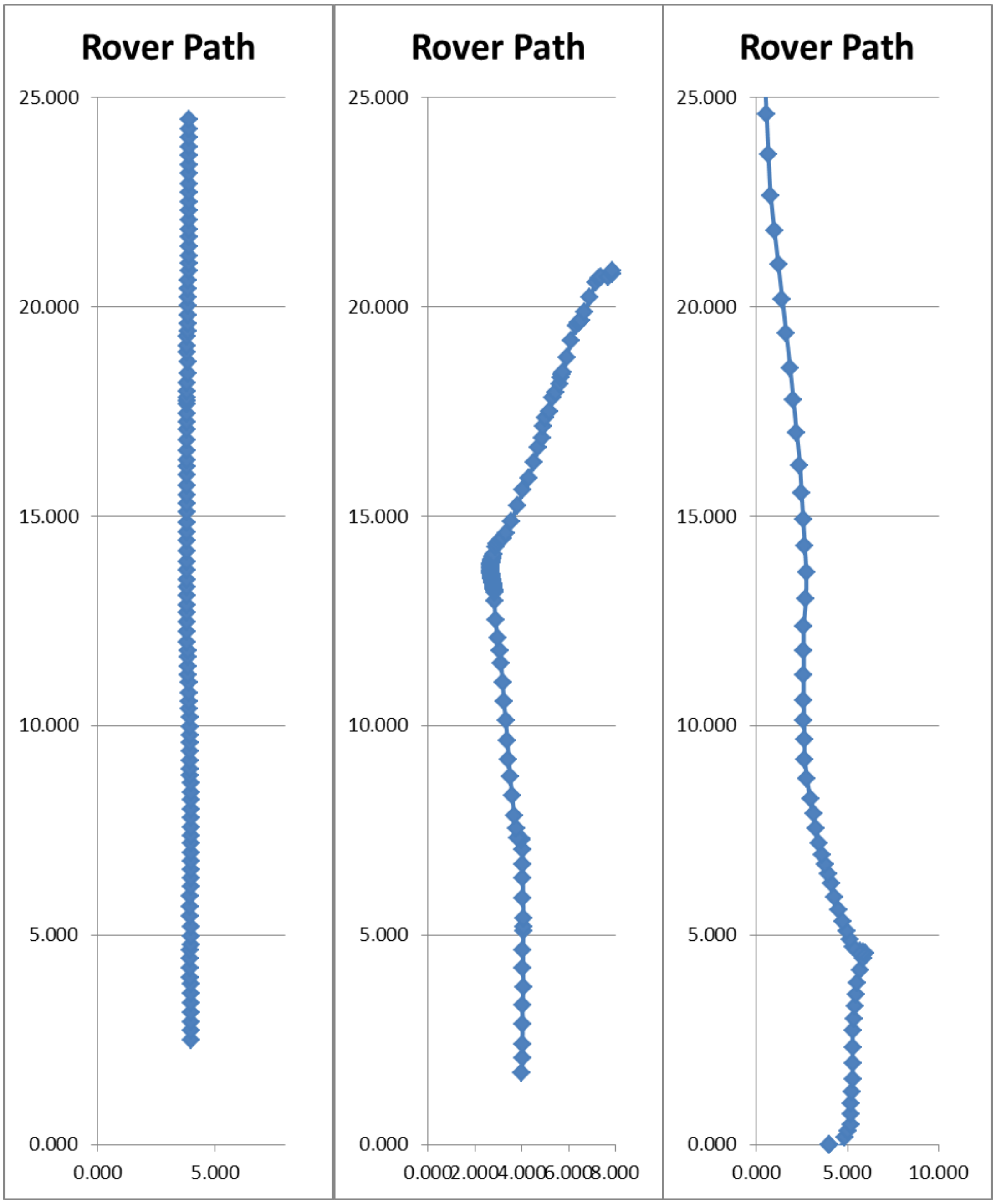


Figure 5.2. Illustrations of the Sparse (Above) and Dense (Below) Rock Fields

The rover was stared at a point 2.5m along the length of the trial and pointed at target 20m directly ahead. The rover's wheels were actuated such that the rovers would move on flat terrain at 2.5 cm/s. This is representative of a mid-range speed for Mars rovers, although they are usually operated closer to 1 cm/s since to facilitate long distance control. The simulation output provided the rover's location every 10 seconds. Figure 5.3 shows several examples of the data output for different trials.



A. **B.** **C.**

Figure 5.3. Sample Webots Data

for (A) Large Rocker Bogie, Trial 6 (B) Medium TRREx, Trial 10 and (C) Medium TRREx, Trial 13, Ball Mode

To test different rover sizes, it was easier to scale the environments than the rovers. The wheel speed was also adjusted on the rovers so they would move at analogous speeds after their positions were scaled during analysis. The data were all scaled down by the same factor that the environment and wheel speed were scaled up. Since the slow travel speed of the rovers means dynamic motion effects are negligible, the error introduced by this practice is expected to be negligible.

The simulation was performed on all three sizes of the rocker bogie architecture, all three sizes of the TRREx rover configuration, and all three sizes of the TRREx ball configuration in all of the trials that contributed to the operating condition sores (Trials 1, 5, 6, 9, 10, 11, 12, 13, 14, and 17.) The data were used to calculate the three mobility parameters, $MFPR$, D^*_{rms}, and V_{avg}, for each trial. The framework described in 5.2 was used to determine scores for each of the trials required to calculate each of the operating condition objective scores. Table 5.4 shows the three operating condition scores for each of the architectures' configurations.

Table 5.4 Score for Each Architecture in Each Operating Condition

Configuration	Operating Conditions Score		
	Baseline	Downhill	Uphill
Large RB	-85.33	-50.42	-29.44
Medium RB	-76.96	-49.95	-21.49
Small RB	-71.43	-47.11	0.00
Large TRREx	-56.58	-50.02	-19.76
Med. TRREx	-66.22	-39.62	-61.96
Small TRREx	-72.83	-49.88	-58.86
Large Ball	0.00	-123.10	0.00
Medium Ball	0.00	-67.49	0.00
Small Ball	0.00	-72.64	0.00

Two preliminary studies were done en route to the full understanding of this methodology. For these studies, there were only two architecture sizes. The results of these investigations are detailed in Sections 5.4.1 and 5.4.2.

5.4.1 Preliminary weighting sensitivity study

As part of the early investigation in developing the methodology in Chapter 4, a weighting study was done on the results from the twenty trials. It is important to note that at the time this study was conducted, there were only two rover sizes. The third size was added later. Table 5.5 shows the results of the best rover for each mission under varying performance weightings. The first column is treated as a baseline with equal weighting in all three categories. Variations from the baseline are highlighted. Clearly, no particular rover shows up as the best in all cases. The Large Rocker Bogie is consistently the best for flat ground. Small rovers are often preferred for hill climbing due to their short turning radiuses, giving them a boost in MFPR. In many of the uphill trials, only a few rovers could be considered viable candidates. The TRREx rovers demonstrate significant potential on the downhill portion, as the reconfiguration into ball mode allows a high performance in the v_{avg} category. Varying the weights has little effect on the outcomes except in the case that speed is neglected, which removes the advantage the TRREx rovers have on the downhill trials.

Table 5.5 Weighting Study Results

	Weighting					
w_{mfpr}	0.333	0.500	0.333	0.333	0.500	0.000
w_{drms}	0.333	0.167	0.167	0.500	0.500	0.000
w_{vavg}	0.333	0.333	0.500	0.167	0.000	1.000
Trial	Best Rover					
1	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx
2	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Sm. RB
3	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Sm. TRREx
4	None	None	None	None	None	None
5	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB
6	Sm. RB	Sm. RB	Sm. RB	Sm. RB	Lg. RB	Sm. RB
7	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx
8	None	None	None	None	None	None
9	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB
10	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. TRREx
11	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB
12	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB	Lg. RB
13	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Lg. RB	Sm. TRREx
14	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. RB	Lg. TRREx
15	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. RB	Lg. TRREx
16	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx
17	Sm. TRREx	Sm. TRREx	Sm. TRREx	Sm. TRREx	Lg. RB	Sm. TRREx
18	Sm. TRREx	Lg. TRREx	Lg. TRREx	Sm. TRREx	Sm. TRREx	Lg. TRREx
19	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. RB	Lg. TRREx
20	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. TRREx	Lg. RB	Lg. TRREx

5.4.2 Preliminary Mission Study

Initially the terrains were handled as having homogenous characteristics. In this study the various task scores were combined into missions comprised of a variety of terrain types. Four hypothetical missions were envisioned to demonstrate how task-wise data can be combined to provide an architecture selection for a more realistic rover mission. Here another set of weightings is assigned to represent the importance of a rover's performance in the various tasks to the performance in the overall mission. The score of the rover for the hypothetical mission is defined as the weighted sum of the task utilities. The four missions are described as follows:

Mission 1 "Basic": This mission is mostly flat sparse terrain with mildly varying slope, friction, and a small amount of rugged terrain.

- 50% task 9: flat, high friction, sparse rocks
- 10% task 5: 15^{o} uphill, high friction, sparse rocks
- 10% task 10: flat, low friction, sparse rocks
- 10% task 11: flat, high friction, rugged rocks
- 10% task 13: 15^{o} downhill, high friction, sparse rocks

Mission 2 "Hills": This mission is entirely hills with nearly equal amounts uphill and downhill. A sampling of rugged/sparse and high/low friction was chosen.

- 25% task 3: 30^{o} uphill, high friction, rugged rocks
- 15% task 5: 15^{o} uphill, high friction, sparse rocks
- 5% task 6: 15^{o} uphill, low friction, sparse rocks

- 15% task 13: 15^{o} downhill, high friction, sparse rocks
- 5% task 16: 15^{o} downhill, low friction, sparse rocks
- 25% task 17: 15^{o} downhill, high friction, rugged rocks
- 10% task 19: 30^{o} downhill, high friction, sparse rocks

Mission 3 “Rugged”: This mission is flat and mild slopes but with rugged rocks in all parts. It is mostly high friction but a few scenarios with low friction are mixed in.

- 30% task 7: 15^{o} uphill, high friction, rugged rocks
- 25% task 11: flat, high friction, rugged rocks
- 10% task 12: flat, low friction, rugged rocks
- 25% task 15: 15^{o} downhill, high friction, rugged rocks
- 10% task 16: 15^{o} downhill, low friction, rugged rocks

Mission 4 “Downhill”: This mission is a mix of downhill scenarios:

- 25% task 13: 15^{o} downhill, high friction, sparse rocks
- 25% task 15: 15^{o} downhill, high friction, rugged rocks
- 25% task 17: 30^{o} downhill, high friction, sparse rocks
- 25% task 19: 30^{o} downhill, high friction, rugged rocks

The performance weightings were set to the baseline of 1/3 for each of the three measures. The resulting scores are shown in Table 5.6 with the highest score highlighted for each mission.

Table 5.6 Hypothetical Missions

Mission 1 "Basic"	
Large RB	0.807
Large TRREx	0.674
Small RB	0.740
Small TRREx	0.730

Mission 2 "Hills"	
Large RB	0.551
Large TRREx	0.619
Small RB	0.716
Small TRREx	0.672

Mission 3 "Rugged"	
Large RB	Insuf
Large TRREx	Insuf
Small RB	Insuf
Small TRREx	0.511

Mission 4 "Downhill"	
Large RB	0.666
Large TRREx	0.830
Small RB	0.571
Small TRREx	0.776

The results of missions one, three, and four are obvious. Mission one is largely comprised of flat terrain where large rocker bogies demonstrated proficiency. The Small TRREx is the only viable solution to trial 7 which is one of the components of mission 3. Thus it is the only viable rover for mission 3. The TRREx rover is designed specifically to have an advantage going downhill. The weighting study validated that it is favorable for downhill travel. Thus it is obvious that the TRREx rovers should take the first and second spots in mission 4.

Mission two provides some deeper insights. The small rocker bogie is the ultimate winner. However, the TRREx architecture is better in the large category. This is useful information for a prospective designer. Furthermore, the small TRREx score is close to the small RB score. Therefore, mission two is a good candidate for another weighting sensitivity study. In Table 5.7, the weights were shifted toward speed (.333 MFPR, .167 D_{rms}^{*}, .5 v_{avg}). This switches the best choice from the small rocker bogie to the small TRREx.

Table 5.7 Mission Two Weighting Study

Mission 2 “Hills” Baseline	
Large RB	0.551
Large TRREx	0.619
Small RB	0.716
Small TRREx	0.672

Mission 2 "Hilly" Reweighted	
Large RB	0.453
Large TRREx	0.571
Small RB	0.589
Small TRREx	0.603

The first weighting study (Section 5.3.1) showed that the selection of a rover for a particular task is insensitive to the weighting structure used. However, the mission study demonstrated that when the tasks are combined into a more complex mission, a small change to the weighting structure may cause a change in architecture choice. Since the biggest advantage provided by the TRREx is its increase in downhill speed, certainly any mission in which it is preferred to a rocker bogie must include some opportunity for it to roll downhill. This analysis demonstrates that the designer must also care sufficiently about speed or the rocker bogie may still be preferred.

5.5 Step 4: Measure, calculate, or simulate the system objective scores

No system objective scores were considered in this study. This step is left for future work.

5.6 Step 5: Place all systems in the defined tradespace.

Figure 5.4 illustrates the architectures in the three dimensional performance tradespace. The top left, bottom left, and bottom right graphs are two-dimensional comparisons provided to assist visualizing the three-dimensional chart. The space is illustrated as minimization space, meaning the utopia is in the bottom-left of each 2D plot and the bottom-left-back of each 3D plot.

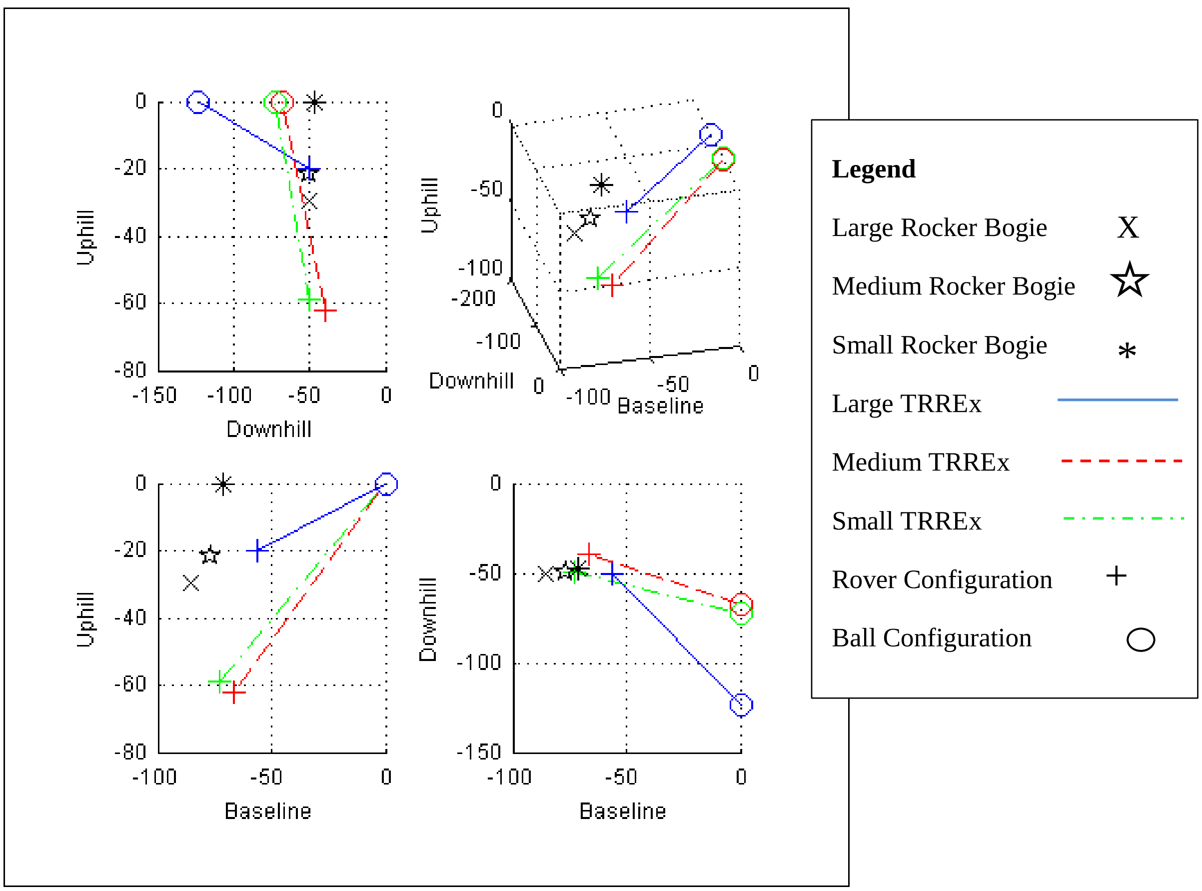


Figure 5.4. Three Reconfigurable and Three Static Designs in a 3-D Tradespace

Figure 5.5 illustrates the process of placing the reconfigurable designs' surrogate points in the space. Figure 5.6 shows the surrogate points in the space with the static points.

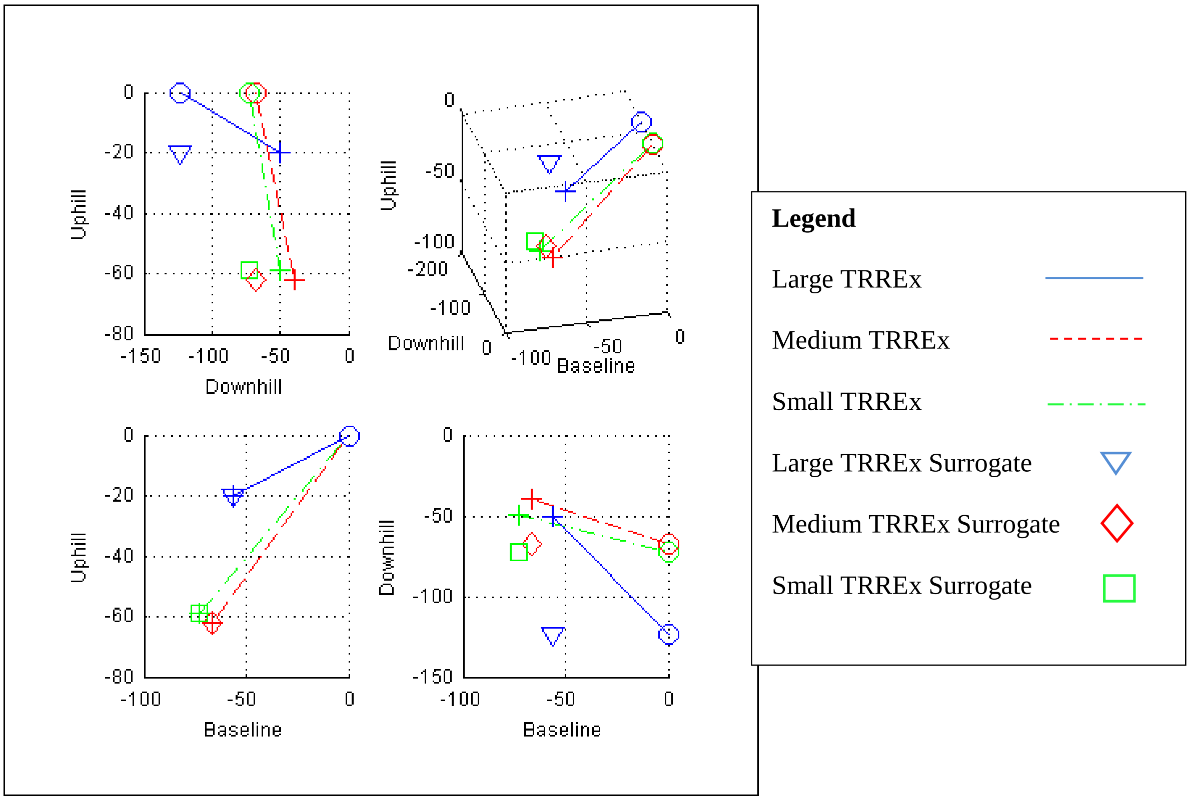


Figure 5.5. Placing the Reconfigurable Systems' Surrogate Points

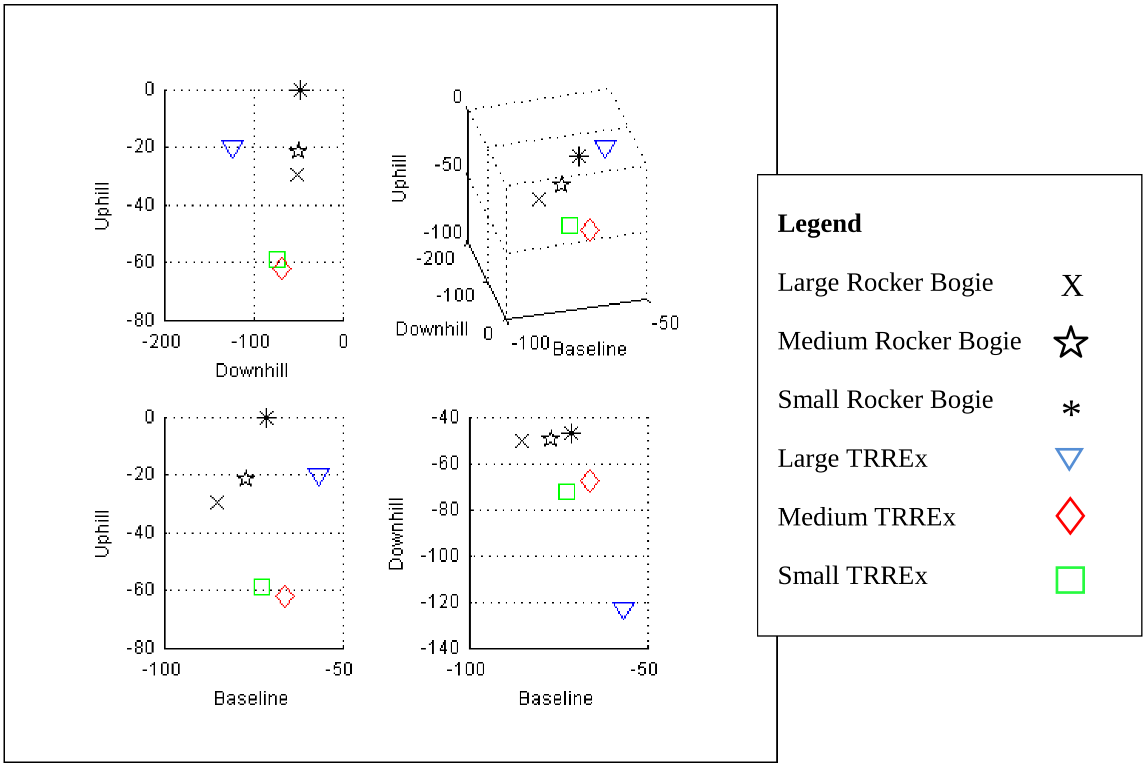


Figure 5.6. Static Systems and Reconfigurable Surrogate Points

5.7 Step 6: Assess dominance between the various systems.

All three TRREx architectures were non-dominated. The medium rocker bogie was strictly dominated by the large rocker bogie. The small rocker bogie was strictly dominated by the medium rocker bogie, the large rocker bogie, and the small TRREx. If this assessment was a phase in an optimization algorithm, the architectures would be preferred according to the following order: the three TRREx architectures and the large rocker bogie would be on the Pareto frontier (first rank.) The medium rocker bogie would be second rank and the small rocker bogie would be third rank.

Some additional illustration can be made by considering the two dimensional plots. This is analogous to pretending the mission planners decided that they are dropping a mission segment. For example, maybe they no longer feel the need to return from inside the crater, so only the baseline-downhill space is important. Or maybe they no longer want to explore craters. They want to go up the sides of a volcano instead. In this case, only the baseline-uphill space is important. In the baseline-uphill space, the surrogates for the TRREx rovers are in the same location as the roving modes for the TRREx rovers. This is an indication that incorporating the ball configuration is unnecessary since the ball mode will never be used in these segments; the designers would be better off omitting it to save the mass, cost, constraints, etc. In the downhill-baseline space, the surrogate for the small TRREx strictly dominates the surrogate for the medium TRREx (as seen in Figure 5.6), so the small TRREx strictly dominates the medium TRREx. In the uphill-downhill space, both the small and medium TRREx strictly dominate all rocker bogie sizes.

5.8 Chapter Summary

Chapter 5 presented a case study of the Method described in Chapter 4. It was used to assess the rolling/roving concept embodied as the TRREx architecture as it compares to a more traditional rocker bogie architecture. The tradespace was defined with three operating condition axes—one each for uphill travel, downhill travel, and a baseline with mostly flat travel. Three parameters were measured in a simulation environment to describe how each rover faired in 20 different trials. Strength of preference curves and weightings were assigned to each parameter to build a performance score for each trial. Operating conditions were then defined as a weighted average of different trials that described the operating condition under consideration. The architectures were illustrated in the tradespace and their dominance relationships were determined. Chapter 6 will present the conclusions of this thesis and will suggest venues for future research on these topics.

6. CONCLUSIONS AND FUTURE WORK

6.1 Thesis Summary

In Chapter 1, the benefits of reconfigurable design were demonstrated and the challenges of incorporating it in complex systems were detailed. Tradespace exploration was identified as a tool to help structure the massive amount of information that can be considered when designing these systems with the goal of moving toward an understanding of reconfigurable architectures that will allow designers to apply the tools of multi-objective optimization to their design. The first step to applying optimization techniques is understanding dominance. Two research questions were posed, "How can the performance of a reconfigurable rover be modeled with sufficient fidelity to assess the value of reconfigurability?" and "How can reconfigurable systems be represented in a multidimensional tradespace and how can Pareto dominance be assessed in such a representation?" Chapter 2 provided the background information that was necessary to begin addressing these questions.

Chapter 3 discussed an exercise that generated and sorted reconfiguration concepts for a Mars exploration mission. A sorting framework was created based on consideration of which level of the system design changed during a reconfiguration, which level(s) of the system design would have to change to accommodate the concept, and the severity at which those levels would be impacted. This exercise identified the TRREx architecture as a good candidate for further study so it became the case study for the rest of the investigation.

Chapter 4 presented a methodology in six steps that directly addresses the two research questions. The method is as follows; define the tradespace, develop the operating condition scores, perform the investigation required to calculate the operating condition scores, calculate the operating condition scores, perform the investigation required to calculate the system objective scores, place the systems in the tradespace, and assess dominance between systems.

Chapter 5 tested the methodology outlined in Chapter 4 using the reconfiguration concept identified in Chapter 3 as a case study. It assessed 6 rover architectures in a tradespace consisting of three operating condition objectives. It demonstrated that even for a chaotic objective such as assessing rover performance, the procedure is capable of providing an assessment of performance. The TRREx rover concepts were shown to be non-dominated when compared to any size rocker bogie architecture. This was largely because of their superior performance for downhill travel provided by the ball configuration. Therefore, it can be concluded that the TRREx architecture is a valuable concept provided that the mission calls for sufficient amounts of downhill travel. Next the research questions are revisited.

6.2 Research Question #1

How can the performance of a reconfigurable rover be modeled with sufficient fidelity to assess the value of reconfigurability?

A concept sorting framework identified the TRREx rover as a class five concept. Therefore, it can be expected to require considerable development work when compared to the static rocker bogie concept but that it should have good potential to demonstrate a performance advantage. The application of the concept sorting framework to the rover case study is detailed in Section 3.3.

Hi-fidelity simulation in Webots was identified as an effective means of handling the assessment of the TRREx and Rocker Bogie rovers. The rovers were simulated in 20 trials, each with a different combination of terrain challenges. Three parameters were measured from the position data in each trial.

A sensitivity study was done on the weights used to aggregate the trial scores (Section 5.3.1), The trial scores were combined into mission scores using weighted averages to describe non-homogenous terrain (Section 5.3.2.) Finally, in Section 5.7, the TRREx architectures were shown to be non-dominated by performing tradespace analysis on three operating conditions constructed in the same way as the mission scores from Section 5.3.2. The insights into tradespace exploration and dominance are handled more rigorously by the second research question.

6.3 Research Question #2

How can reconfigurable systems be represented in a multidimensional tradespace and how should Pareto dominance be assessed in such a representation?

The tradespace should be defined in terms of operating condition performance scores and system performance scores. The performance score for each operating condition must be a single aggregate objective function. Any number of system objectives may be considered so long as the score does not vary for any of the architectures amongst the various operating conditions. The tradespace must be defined in this way to enable the use of the surrogate point. Section 4.2 detailed the methodology of these representations while Sections 5.2-5.7 demonstrated its effectiveness in a case study.

The surrogate point of a reconfigurable design was introduced to simplify the dominance assessment between reconfigurable systems. The surrogate point is the location in the tradespace corresponding to the best performance available to a reconfigurable system under each operating condition. In a tradespace defined according to the rules provided in this thesis, the domination of a reconfigurable system is identical to the domination of the reconfigurable system's surrogate point. That is, if the surrogate point is dominated by another surrogate point or a static system, the reconfigurable system is dominated. If the surrogate point dominates another surrogate point or a static system, the other system is dominated. This is true for strict, normal, and weak dominance, as well as incomparability. Section 4.7 developed these definitions while Section 5.7 put them into practice.

6.4 Additional Observations

This section presents conclusions, observations, and generalizations that, while not directly applicable to the research questions, are worth noting.

- In Section 3.2, a fever chart (Figure 3.3) is presented for understanding the desirability of continuing investigation of a concept that leverages reconfiguration. One concept can now be placed on that chart. The rolling/roving concept was identified as class five in Chapter 3. In Chapter 5, it was shown to have considerable potential to outperform the rocker bogie under certain operating conditions. Therefore, this concept can be said to be in the top right corner, placing it in the "possibly desirable" region.

- In Chapter 3, of particular noteworthiness is the way the definition of initial system changes the classification of the concepts. This is demonstrated by the description of the collaborative use of the tool.
- Providing freedom for the designer to appoint the levels of the system creates the potential for the reconfigurable concept sorting framework to be applied to problems of many scales.
- By asking what levels of the design the concept impacts, the framework will automatically consider the degree of modularity in the baseline architecture. If the baseline architecture is highly modular, changing any one subsystem is less likely to have cascading effects. Thereby, similar concepts will receive lower classifications in a modular architecture than a highly integrated one.
- In Chapter 4 (Section 4.7) it is shown that only the surrogate point of a reconfigurable solution must be considered to determine dominance as it relates to that system. Furthermore, the surrogate point's location is determined by the location of the best configuration for each operating condition. Therefore, a reconfigurable system needs no more configurations than the number of operating conditions under consideration.
- Chapter 5 provides insight into the relative strengths of the six rover designs in a variety of scenarios. The TRREx rover generally underperforms the rocker bogie at traditional

rover tasks, probably because the rover's ability to reconfigure to ball mode imposes substantial constraints on the architecture of its rover mode.

- The ability to transform gives the TRREx a distinct and significant advantage over the rocker bogie rover when it is used for downhill travel. Thus, a decision to pick the rocker bogie or the TRREx for a given mission would have to be based on the mission profile, taking into account the likely terrain that would be encountered.

6.5 Future Work

Several avenues for future research have been identified to continue the research presented in this thesis including:

- Expand the dominance principals laid out in this paper to continuously reconfigurable solutions and understand under what operating conditions a continuously reconfigurable system may be desired.
- Investigate guidelines for the appropriate resolution into which the system's operating condition should be divided.
- Perform more case studies, include the addition of at least one system objective axis such as cost, control complexity, various risk measures, development time, mass, etc.
- Improve the sophistication of the rover simulation, possibly including the following:
    - Improve the active suspension controller for the TRREx.
    - Create rocks with varied geometries and heights above the plane.
    - Add a ground interaction model that includes sinking.

    - Increase the size of the trial (make the rovers travel farther).

- Improve the framework used to build up the operating condition scores by working with a subject matter expert to model real strength of preference curves and weights.

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