Proceedings of IDETC/CIE 2007
ASME 2007 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
September 4-7, 2007, Las Vegas, Nevada, USA

DETC2007/DAC-35745

FLEXIBLE AND RECONFIGURABLE SYSTEMS: NOMENCLATURE AND REVIEW

Scott Ferguson
Graduate Research Assistant
Department of Mechanical and Aerospace Engineering
University at Buffalo, Buffalo, NY

Afreen Siddiqi
Post-Doctoral Research Associate
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139

Kemper Lewis
Professor
Department of Mechanical and Aerospace Engineering
University at Buffalo, Buffalo, NY
Corresponding Author: kelewis@eng.buffalo.edu
(716) 645-2685

Oliver L. de Weck
Associate Professor
Department of Aeronautics & Astronautics, Engineering
Systems Division
MIT, Cambridge MA 02139
deweck@mit.edu

ABSTRACT

The demands on today's products have become increasingly complex as customers expect enhanced performance across a variety of diverse and changing system operating conditions. Reconfigurable systems are capable of undergoing changes in order to meet new objectives, function effectively in varying operating environments, and deliver value in dynamic market conditions. Research in the design of such responsive and changeable systems, however, currently faces impediments in effective and clear discourse due to ambiguity in terminology. Definitions of the terms flexibility and reconfigurability, two related concepts in reconfigurable system design, are explored based on their original lexical meanings and current understanding in design literature. Design techniques that incorporate flexibility both in the design (form) and performance (function) space are presented. Based upon this literature survey, a classification scheme for flexibility is proposed, and its application to reconfigurable system design is explored. This paper also presents recent methodologies for reconfigurable system design and poses important research questions that remain to be investigated.

1.0 INTRODUCTION

The requirements of product design in the 21st century present an ever-increasing challenge. Consumers now demand products that suit their specific, yet constantly changing, needs. Pine et al. have stated that merely including additional improved features to a product does not guarantee the customer will receive exactly what they want [1]. There also has been increased economic and political pressure to develop systems capable of performing multiple roles, or to be "jack-of-all-trades" [2]. Designers are therefore beginning to shift focus from a single product design to a realm of designs that are expected to evolve, perform multiple tasks, and operate under changing operating conditions. One approach to meet this demand is mass customization: offering many variants of a product at very low cost so a customer can buy multiple products, each tailored to a unique purpose [1,3-7]. Another potential solution to this increased demand for enhanced performance is reconfigurable systems.

Reconfigurable systems are designed to maintain a high level of performance by changing their configuration to meet multiple functional requirements or a change in operating conditions [8]. Siddiqi elaborates upon this definition by adding that reconfigurable systems achieve a desired outcome within acceptable reconfiguration time and cost [9]. Motivation for this type of system comes from the inherent tradeoffs incorporated in an effort to resolve issues when involving conflicting objectives.

Figure 1 shows a classification of reasons why reconfigurability is being pursued. The three main needs addressed by reconfigurability are: multi-ability (the ability of a system to perform multiple functions over time but not concurrently), evolution (the ability to morph the system into future planned or unplanned configurations), and thirdly survivability which ensures that a system can still operate partially despite the presence of failures in some of its components or subsystems.

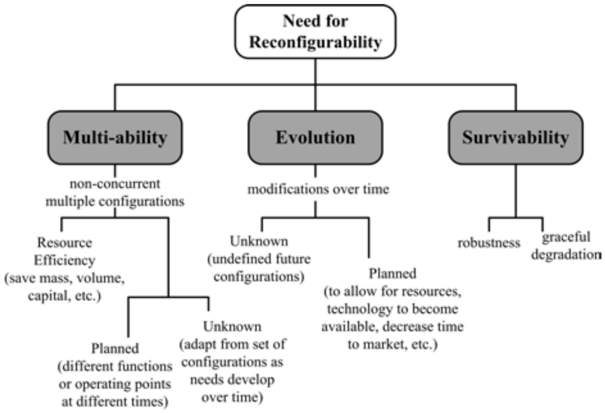

Figure 1. Need for Reconfigurability, Source: [9]

Reconfigurable system research is at an early stage in engineering design, and many research questions remain. The purpose of this paper is to first investigate flexibility, a fundamental principle and enabler of reconfigurable systems. Following this, the state-of-the-art research in the field of reconfigurable system design will be discussed, and necessary research questions that remain to be investigated are posed. To accomplish this, this paper first examines the definitions of two main concepts associated with reconfigurable system design: flexibility and reconfigurability. The terms are examined in detail in an effort to guide future reconfigurable system research. Section 2.0 demonstrates the interest and theoretical background in changeable systems, systems whose design variables change after deployment. Reconfigurable systems are a subset of this family of systems. A study of current engineering design techniques that incorporate the principle of flexibility is presented in Section 3.1. Section 3.2 discusses a classification scheme proposed by the authors that describes flexibility in both the performance and design spaces. In Section 4, attention will return to the current state of reconfigurable system research where current advances and future areas of research will be presented.

2.0 CHANGEABLE SYSTEMS

Changeable systems are those systems whose configurations can be changed, altered, or modified, with or without external influence after the system has been deployed. Reconfigurable systems, therefore, are a subset of changeable systems. The field of design research in changeable and reconfigurable systems, however, currently faces impediments in effective and clear discourse due to ambiguity in terminology. The nomenclature related to these systems, such as reconfigurability and flexibility, has increasingly appeared over the last decade. However, despite the increased usage of these terms, as demonstrated in Figure 2, they remain abstract concepts and owners of various definitions. In the literature, these terms are often used interchangeably and in an ad hoc manner. For reconfigurable system research to mature and progress, these concepts must be explored, well defined, and differentiated.

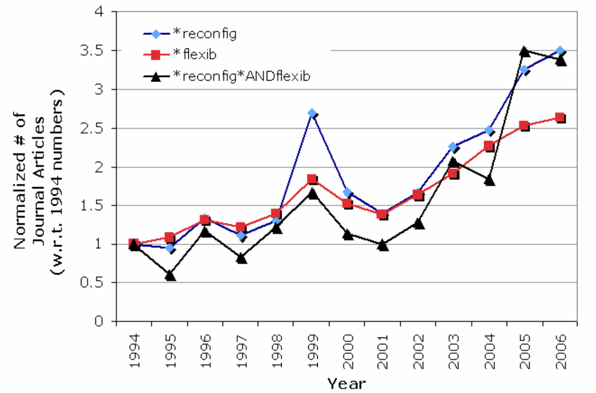

Figure 2. Papers with the keyword "reconfig*" and/or "flexib*" in the title or abstract, Source: [10]

Inconsistent usage of a word can lead to confusion and hamper effective communication. This paper therefore attempts to provide definitions, relevant to the domain of design and engineering, in order to facilitate uniformity and understanding. Section 3.0 elaborates on flexibility while Section 4.0 will discuss reconfigurability in detail.

Traditional engineering design has focused on the optimization of systems with fixed design variables, while accounting for the operating environment and system objectives. A typical problem formulation is:

$$\begin{aligned} &\min f(x) \\ &st. g(x) \le 0 \\ &\quad h(x) = 0 \\ &\quad x_{LB} \le x \le x_{UB} \end{aligned} \tag{1}$$

Where f is an objective function (e.g. minimize lap time for a race car, minimize the likelihood of getting stuck in soft terrain), x is the vector of design variables, g(x) are general inequality constraints, and h(x) are general equality constraints.

Engineers work in the design space x. This is where the designer establishes the settings of the system, establishing geometric shape, adding or removing modules, defining possible platforms, and receiving variable values from other designers. Each point in the design space is equivalent to a unique design. The performance space *f(x)* quantifies the value of a system with respect to each system objective for a set of design variable values. Fixed design variables (such as wheel diameters on cars) are generally not allowed to change once the system has been deployed, preventing changes in the system's state. Systems with fixed design variables are represented by the rear face of the dashed box in Figure 3.

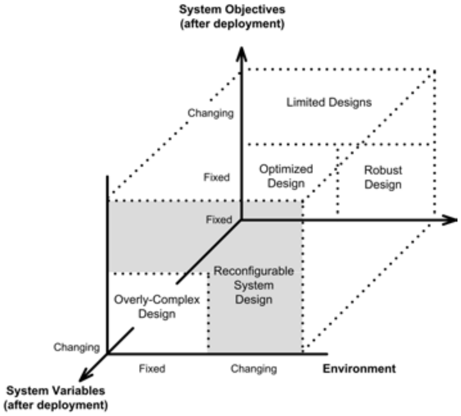

Figure 3. Core Concept Relationships

Three resultant design types are possible when designing a system with fixed design variables: optimized, robust, and limited designs. *Optimized* designs can be achieved when the configuration of a system is set to achieve maximum performance under fixed operating conditions (environment). To be optimal, however, both the operating environment and the system objectives must be fixed (or non-changing) after deployment. *Robust* design [11] has been introduced as a means to allow a system to satisfy a fixed set of system requirements despite stochastic changes to the operating environment, by designing the system to be insensitive to such possible disturbances. The expectation in robust design however, is that once decided upon, the design will not change as it is operated. Systems with fixed design variables have no means of responding to changes in system objectives after they have been deployed to maintain an optimal performance. In such situations, the presence of multiple objectives demands that tradeoffs are incorporated into the final design. *Limited* designs are therefore those systems with an inability to attain optimality across multiple operating conditions.

Changes to system objectives and operating conditions within the operating environment can create designs that do not perform as well as originally intended. Adapted from Saleh [12], Figure 3 has been extended in the third dimension, allowing for design variables to change after system deployment. This ability to change is a fundamental concept of both reconfigurable and flexible system design. However, having the ability for design variables to change is not always easy to achieve. In order to achieve some degree of reconfigurability, systems often become more complex due to the addition of sensors, actuators and controllers beyond those that would be present in a single configuration system. Therefore, having the ability for design variables to change is not always beneficial. In cases where the operating environment and the system objectives remain fixed, there is no need to design a system that is capable of changing configuration after deployment. Systems designed to be reconfigurable in such a scenario can be classified as *overly-complex* designs. The shaded region on the front face of the rectangle designates the influence of reconfigurable systems. Reconfigurable systems accommodate potential changes in both the operating environment and system objectives, creating designs with enhanced performance and eliminating the need for limited designs.

To understand reconfigurable system design, we must first understand the property that allows system design variables to change after initial deployment. We propose that *flexibility* is the property that facilitates such changes in the system, both in the design and performance spaces. The following section examines the various uses of flexibility in engineering design literature. Section 3.2 then proposes a classification scheme for flexibility in both the design and performance spaces

3.0 FLEXIBILITY

The word ‘flexible’ comes from the Latin language, meaning ‘to bend’. Another lexical meaning is ‘ready and able to change so as to adapt to different circumstances [13]. In the context of reconfigurable system design, he latter meaning is the most relevant and applicable.

Defining flexibility is an important undertaking towards the conceptual understanding of reconfigurable system design.. In the early 1990’s, Sethi and Sethi identified over fifty definitions of flexibility within the manufacturing domain [14]. Saleh, examining aerospace systems from the life-cycle perspective, defines flexibility as “the property of a system that allows it to respond to changes in its initial objectives and requirements – both in terms of capabilities and attributes – occurring after the system has been fielded, i.e. as in operation, in a timely and cost-effective way” [12]. Gupta and Goyal, similarly, have determined that an inherent aspect of flexibility is the ability to change and adapt to a range of states [15]. Within the design community, the proposed definitions for flexibility encompass both design and performance spaces. Overall, flexibility is viewed as a property, a result of design decisions that can be expressed as a set of principles [16]. This property allows a system to undergo changes in state to promote new, or enhanced, functionality [17]. Fricke and Moses independently elaborate on these definitions, adding that flexibility is a property characterizing a system’s ability to be changed easily [18,19] We find that the latter definition is now generally well accepted, i.e. that flexibility is the property of a system that allows it to be changed easily. Having discussed how flexibility is defined, Section 3.1 investigates how different design techniques apply the concept of flexibility.

3.1 FLEXIBLE SYSTEMS DESIGN

The following sub-sections review engineering design techniques, introduced in the last decade, that develop and apply techniques to handle and quantify flexibility in a tangible way. The goal of such a study is to develop an understanding of how flexibility has been and can be leveraged in the design and performance spaces. A classification scheme for flexibility is introduced in Section 3.2 based upon the insight gathered from these design techniques.

3.1.1 TRANSFORMER DESIGN THEORY

In transformer design theory, flexibility describes changes in form, allowing a design to perform separate functions or improve its original function [17]. Such systems exhibit increased performance profiles and efficiencies when compared to a collection of single-function, or single-state multi-function, systems [20]. Product flexibility is facilitated by three main directives that bring about changes in state:

- Expand / Collapse
- Fuse / Divide
- Expose / Cover [17].

Determining the directives that need to be applied in a system is aided by designer constructed model. These models describe the interactions and the resultant performance at each state. However, the designer must also be aware of the negative impacts, namely increases in weight and volume, of incorporating transforming principles [20].

3.1.2 CHANGE MODE EFFECTS ANALYSIS (CMEA)

CMEA research views product flexibility as a degree of responsiveness to outside factors [21]. Such flexibility minimizes the amount of redesign time required, increasing responsiveness to changing market demands [21]. Rather than examining state changes, CMEA is intended to allow for future unknown and unplanned changes in a current product design [22]. Flexibility is measured by the number of parts, functions, modules, interfaces, and types of interfaces [21]. Modifying the number of parts in a module has shown negligible effect on flexibility due to external interfaces on most module designs [21]. In light of this, seventeen principles of flexibility have been identified, permitting the development of a Change Potential Number. This number is capable of describing how readily a product is able to accommodate change resulting from product evolution [16].

3.1.3 CHANGE PROPAGATION ANALYSIS (CPA)

Change propagation is the process by which a change to one part or element of an existing system configuration results in one or more additional changes to the system. CPA is key to understanding and implementing flexibility. Impacts of change propagation are clearly occurring daily, see [23] as well as [24].

The majority of the work to date has been to define and begin to characterize engineering change propagation as in Eckert, Clarkson and Zanker [25-28]. In harmony with Terwiesch and Loch's [29] findings, they observed that the higher the level of connectivity between components (subsystems, systems), the more likely that one change would cause others. Following analysis of their data, Eckert, Clarkson and Zanker [25] defined different components with regard to change propagation as falling into several categories, paraphrased here:

- Constants: components unaffected by change, these neither absorb nor cause changes to other components
- Absorbers: absorb more changes than they cause
- Carriers: absorb / cause a similar number of changes
- Multipliers: generate more changes than they absorb

As follow-on, Clarkson and Eckert went on to team with Simons [30] to describe a method for predicting change propagation using Design Structure Matrices (DSMs). Building on previous work, de Weck and Suh [31] address the area of system design for flexibility with the specific goal of minimizing change propagation through preventative measures (e.g. splitting multipliers into sub-components). By modeling the propagation of changes in functional requirements to system variable changes and physical components, those parts of the system can be identified that could benefit from flexibility.

3.1.4 COMPLIANT MECHANISMS

Compliant mechanisms use physical changes to achieve performance changes, using a combination of actuators and sensors. Synthesizing structural topology optimization and actuation allows for maximized energy efficiency while concurrently satisfying various weight, loading, and performance constraints [32-37]. In most studies, however, only single target profiles that are selected a priori are considered. Furthermore, most architecture problems fail to address how the actuator relates to the rest of the physical system [34].

3.1.5 RANGED SETS / FLEXIBLE TARGETS

Chen has defined flexibility as the ability to obtain a ranged set of solutions, rather than a single solution, allowing the accommodation of uncertainty and possible design changes [38,39]. Flexibility is addressed in both the specification of design requirements and the design solutions, and change can be enhanced by allowing for changes to top-level specifications with the development of probabilistic-based models [38]. Flexibility is measured and assessed by calculating the size of the region and the performance information of the proposed designs. This metric can then be used to select the most desired region of the design space [39]. Heterogeneous knowledge of the attribute space can be captured, allowing expected design changes to promote design evolution [39]. Flexibility is measured as the potential of achieving solutions in the target region when considering the uncertainty associated with the design. Flexibility can also be increased when design requirements are allocated into sets of varying desirability, and the Compromise Decision Support Problem is applied to achieve a final design. Chen and Lewis [40] demonstrated increased designer freedom when flexibility was harnessed by combining robust design and game theoretic approaches in the optimization of a passenger aircraft.

3.1.6 PRODUCT PLATFORMS

Product platform research has traditionally focused on creating product variety while reducing development time and manufacturing cost [41-44]. However, most research in this area has focused on architecture design that creates predetermined variants under the theme of cost optimization [18]. Haubelt and his coauthors have expanded on this idea, showing that flexibility in product platform design entails the implementation of alternative behaviors and the construction of interfaces in platform design allows the degree of flexibility to be specifically tailored [45]. Hierarchical graph modeling is introduced as a method for the efficient exploration of the flexibility / cost tradeoff curve [45]. Suh and de Weck approach flexibility as a real option value to handle market uncertainties [31]. Here, flexibility allows management to respond to changes in the marketplace by altering the direction, or scope, of the product. Achieving flexibility in this context generally requires an initial increase in investment, but can potentially suppress change propagation and lower switching costs [31]. They show the increased value of flexibility in cases of uncertainty, lowering the expected costs of future redesign. Overall, work in this field has shown that the increased product functionality gained through flexibility allows for extended product life and additional functional upgradeability [46].

3.1.7 RECONFIGURALBE MACHINE TOOLS

Reconfigurable manufacturing systems [47,48], can exist in different configurations, or layouts; such that they are neither dedicated to a single task or as general as CNC mills [49]. Such abilities allow reconfigurable machining tools to provide exactly the necessary capabilities and flexibility [48]. Much like product platforms, reconfigurable machining tools are constructed from different modules, allowing for rapid configuration change. Such tools allow for mass customization [50,51], yet the effective design of such tools requires thorough analysis of each component [50].

3.1.8 CONFIGURABLE ENTERPRISE SYSTEMS

Enterprise systems increase their flexibility through semantic representations, promoting rapid tailoring to the needs of different consumers [52]. This model-driven system minimizes redesign and redevelopment times. To accommodate daily work, the software tools can be tailored to meet the individual needs and tasks of each user [53].

3.1.9 PROCESS FLEXIBILITY INDEX

From a manufacturing standpoint, flexibility implies producing a variety of products efficiently and effectively in response to market changes [54]. Identification of which factors, or design variables, are most suitable for modification is given by the process flexibility index [55]. When the actual performance of a design is not matched by the predicted performance, such changes become necessary [56]. The Process Flexibility Index serves as a metric to quantify the ability of a manufacturing system to avoid unwanted redesign yet meet required attributes.

While traditional robust design approaches focus on reducing the risk of a redesign, adaptive robust design is introduced as accepting this risk and striving to minimize the negative effects [56]. A flexible design methodology is introduced which implements both passive and adaptive robust design. Parkinson and Chase [57] define passive adaptive robust design as requiring external adjustments to cancel out unwanted variations. Adaptive robust design is the addition of supplementary features that allow the automatic cancellation of such unforeseen effects, and are not required for the original function of the system [57]. The increase in cost can be managed by calculating change probabilities, leveraged to understand the tradeoffs between flexibility and cost [58].

Based on the preceding review of how flexibility is viewed and used in engineering design research, it can be summarized that: **Flexibility is a property that promotes change in both the design and performance spaces.** This is evident from the survey of several design methodologies presented. The next section builds upon the insights gained from this literature review and proposes a classification scheme for flexibility.

3.2 FLEXIBILITY CLASSIFICATIONS

Understanding how to measure, or even classify, flexibility has been a constant challenge. Past efforts have mainly focused on manufacturing, rather than examining the designed system itself [21]. The need for an encompassing classification and measurement schema for flexibility has been recognized for quite some time [15,54]. A method for measuring flexibility of a system has been proposed by Shewchuk, who created a generalized metric based upon each designer's view of flexibility [59]. Many other measures of flexibility in engineering design are based on redesign effort, time, or cost

[22]. However, a standardized approach to classify, or even discuss, flexibility has not yet been settled upon.

As seen in the previous section, flexibility is a property that exists in the design and performance spaces. This can be used as a basis for classifying system flexibility. The following sub-sections propose such a scheme and use an example of a flexible/reconfigurable racecar for illustration. Such a vehicle is able to optimize its performance as a function of the current track conditions, ignoring possible racing restrictions. As in Figure 4, whether on a straightaway, a large turn, or a hairpin turn, the car could adjust variables like the center of gravity, roll stiffness, and aerodynamic downforce to maximize performance.

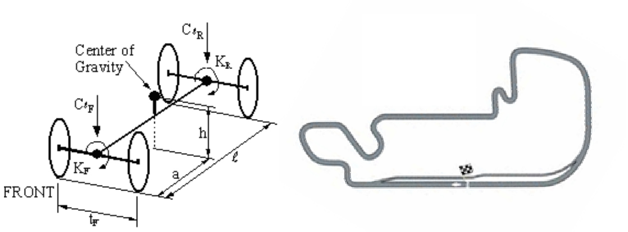

Figure 4. Race Car Design and Indianapolis Road Course

3.2.1 DESIGN SPACE (x) FLEXIBILITY

The design space comprises the set of possible designs and design parameters that satisfy a problem's constraints. This is where designs physically take form, allowing for performance assessment of the system to become possible (either through simulation or physical testing). A dimension, as defined by [60], "is a physical variable that is used to describe or specify the nature of a measurable quantity." Furthermore, base, or fundamental, dimensions, "are those dimensions that's cannot be broken down or subdivided into other dimensions or those that have been internationally accepted as the most basic dimension of a physical quantity" [60]. Seven base dimensions have been defined for use in the engineering and physics community.

As base dimensions have been defined to provide a comprehensive list of fundamental quantities, we propose that this classification scheme can be extended to classify flexibility in the design space. Hereby referred to as *dimensional flexibility*, this classification is suitably generic to encompass hardware, software, and human and/or robotic operators/agents. While this section discusses mechanical systems, it is important to note that this classification scheme can be extended to electrical and chemical systems using the remaining base dimensions.

Analysis of the design techniques in Section 3.1 show that three of these base dimensions are primarily leveraged: length, mass, and time. Identification of these three base dimensions allows for the manner in which these design techniques utilize flexibility in the design space to be both categorized and quantified. A brief description of each is presented.

Mass – Design techniques such as CMEA, product platforms, and reconfigurable machining tools achieve flexibility through the removal and addition of parts and modules. It has been shown that functionality and features added in this manner come without major changes to the core architecture of the system. Similarly, configurable enterprise systems are capable of adding or removing computer code (in the form of functions, classes, etc.) to the core architecture to suit the individual needs of the consumer. Functional changes to software, generally the prime motivation for flexibility, occur when the base code is modified. However, the addition of specific software could also be gained through consultants, increasing mass both in terms of computer code, and personnel. Quantifying the flexibility in something as non-physical as computer code requires a definition that is not limited to solid matter alone. Therefore, *mass dimensional flexibility* can be defined as the flexibility to allow the addition or removal of elements in the form of hardware, personnel, or software. Referring back to our example of a reconfigurable race car, mass dimensional flexibility would allow components such as the front wing or the vehicle's engine – in an extreme situation - to be changed easily without the need for massive redesign.

Length – Changes in physical dimension make permissible the ability for a design to perform separate functions or to improve its original function. In transformer design theory, three directives were identified to bring about changes in state. Actuators are used in combination with sensors in compliant mechanisms to achieve physical changes, commonly used in morphing airfoil design. Pins within reconfigurable mold cavities are moved to create necessary part geometries, permitting rapid part construction. *Length dimensional flexibility* refers to the flexibility to allow geometric changes within the system after the system has been fielded. Such geometrical changes include, but are not limited to, changes in length, width, height, volume, surface area, etc. In a reconfigurable race car, length dimensional flexibility could describe the ability to change the location of the center of gravity, or the position of a control point on the front wing.

Time – Unlike *mass* and *length dimensional flexibilities*, this flexibility measure does not relate to the physical nature of the system. Instead, *time dimensional flexibility* provides flexibility in making decisions about the values of the design (i.e. ranged sets), and reducing the time required for redesign by utilizing an easily modified architecture (i.e CMEA and product platforming). In our working example, time dimensional flexibility provides a racing team the ability to introduce technological breakthroughs into the architecture of the vehicle with only minor changes to the core architecture of the vehicle.

The chart in Figure 5 explains the hierarchical breakdown proposed for dimensional flexibility and shows how the various design techniques can be categorized. Note, that it is possible for a design technique to fall under two categories. For example, CMEA provides *mass* flexibility through the ability to change modules, while also providing *time* flexibility in reducing required redesign time.

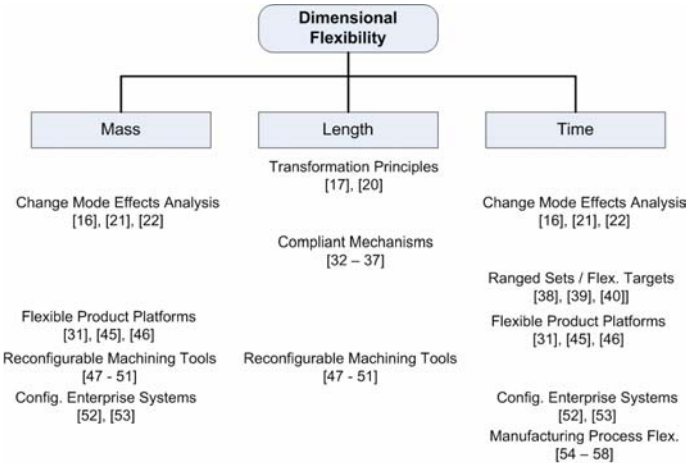

Figure 5. Dimensional Flexibility

3.2.2 PERFOMANCE SPACE (f) FLEXIBILITY

Performance can be affected by a variety of factors including changing operating conditions, numerous functional requirements, and changing customer needs. Many of the design techniques studied in Section 3.1 attempt to address these factors by leveraging flexibility. Its manifestation can be through multi-ability, evolvability or robustness. In the performance space, the three proposed flexibility properties are shown in Figure 6. Again, the appropriate design techniques are placed into the corresponding type of flexibility in the performance space. Each of these performance flexibilities is briefly discussed.

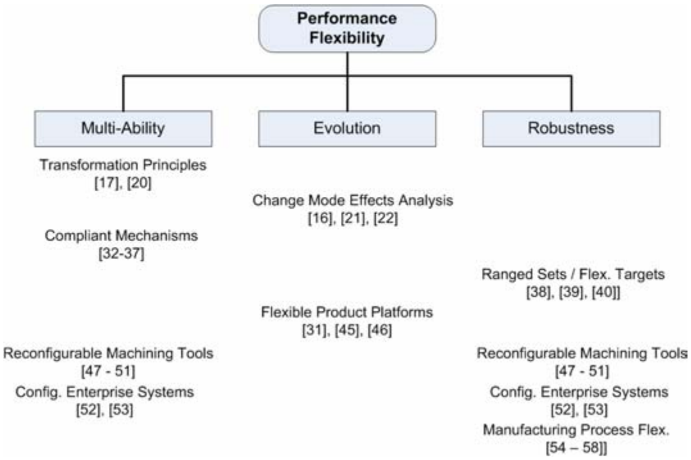

Figure 6. Performance Space Flexibilities

<u>Multi-ability</u> – Systems with multi-ability can fulfill multiple objectives (albeit not simultaneously), from a fixed set of resources. The need to satisfy multiple objectives may arise from the demands of varying operating conditions, or the need to fulfill new roles over time. Some relevant examples include unmanned aerial vehicles (UAVs) with morphing wings that can carry out both attack and reconnaissance missions [61], variable motion engines [62], etc.

A key aspect of multi-ability is that the modified functions are a part of the initial functional requirements, allowing the system design to be crafted to accommodate them. In our working example, Formula One racetracks are designed to have a variety of turns with different radii to test the performance of a vehicle. A reconfigurable race car, whether on a straightaway, a large turn, or a hairpin turn, would be able to minimize the time required to traverse each section of the track.

<u>Evolution</u> – Flexibility in this context refers to the ability for a system to be readily redesigned to meet changes in technology or customer demands. In many cases, these future needs and demands are unpredictable and the exact course of product evolution is not planned. Evolution performance flexibility can be extended to the reconfigurable race car example by allowing the vehicle's architecture to be open to advances in powertrain development or to meet future power sources.

<u>Robustness</u> – In product design there are a multitude of important factors that cannot be predicted. For example, in a racecar, factors such as temperature, wind, and rain, can have a significant effect on the performance. Flexible systems can actively respond to changing conditions. By undergoing some kind of change, these systems can either maintain their optimal performance or keep some level of functionality which otherwise would not have been possible in a traditionally designed, fixed system. Robustness performance flexibility in a reconfigurable race car can be extended to both the environment and the vehicle itself. In the case of the operating environment, track temperature affects the performance of the tires, directly influencing the performance of the vehicle. Fuel consumption changes the weight distribution and overall mass of the vehicle, also altering expected performance. A reconfigurable vehicle, instead of minimizing the effects of these possibilities, would instead change its configuration to obtain an optimal performance.

The challenge in practice is to first define the type and amount of flexibility that is desired in the functional performance space and to determine how this can best be achieved physically in the design space.

The proposed classification in the design and performance space provides groundwork towards measuring and quantifying flexibility. Previously, flexibility has been defined, and quantified, within the scope of the product being designed.

Under this classification, the definitions of dimensional and performance flexibility are independent of the system being designed or the design technique being used. This independence permits the quantification and comparison of flexibility across potential designs and between design techniques.

The focus of this section with its definition and classification of flexibility provides the necessary background for a discussion on reconfigurability. The remainder of this paper investigates and develops a definition of reconfigurability, provides an overview of some of the most recent design methodologies formulated for reconfigurable systems, and highlights future research topics in this area.

4.0 RECONFIGURABILITY

The term 'configure' is a combination of the Latin words 'con' (together), and figurare (to shape). The meaning of configure is 'to shape or put together in a particular form or configuration' [13]. The word 're-configure' follows from this definition and means 'to configure again or differently' [13]. A new, simpler definition is now proposed by building upon the ones described above: reconfigurability allows a system to attain different configurations (or states) as desired. The prefix 're' should be specifically accounted for in the definition and understanding of reconfigurability. **A *re*configurable system is therefore one in which the configurations can be changed repeatedly and reversibly.** It is thus not limited to only one-time changes. The specific states/configurations that the system attains can either be unique every time, or the system may achieve states that are limited to a fixed set. Such usage of this definition in engineering literature has already occurred, with reconfigurable systems being described as "those systems that can reversibly achieve distinct physical configurations (or states), through alteration of system form or function, in order to achieve a desired outcome within acceptable reconfiguration time and cost" [9]. Thus reconfigurability can be interpreted as a subset of flexibility.

4.1 RECONFIGURABLE SYSTEM DESIGN

In traditional design problems, the designer is faced with the challenge of choosing a single point, preferably Pareto optimal, as a final design. The design variables in a reconfigurable system, however, can change their physical values. Revisiting Figure 3, Figure 7 depicts how reconfigurable system design can be further understood with the addition of dimensional and performance flexibility. After the system has been deployed, dimensional flexibility allows the design variables to change their physical values, permitting the design to move from the rear face, to the shaded front face. Leveraging performance flexibility, along with dimensional flexibility, allows the system to respond to changing operating conditions or system objectives.

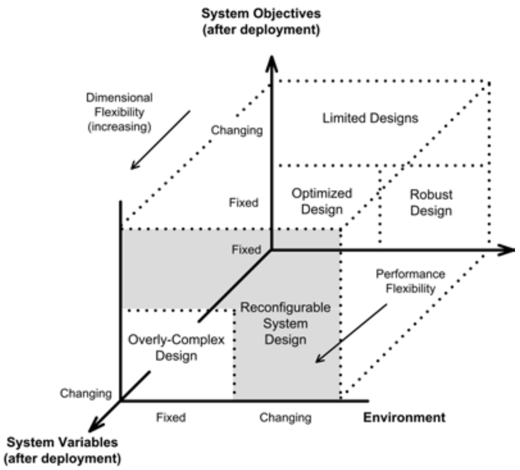

Figure 7. Core Concept Relationships

Figure 8 elaborates upon the usages of dimensional and performance flexibility within reconfigurable system design. Here, mass dimensional flexibility and length dimensional flexibility are primary agents used to promote change amongst the system's design variables. *Modularity* provides an effective means toward achieving mass dimensional flexibility, in that modules can be replaced and updated. As defined by Eppinger, a truly modular architecture is one in which each module of the overall system accomplishes one specific function and the interfaces are well defined [63].

Adaptability has been defined as characterizing a system's ability to adapt itself to deliver intended functionality under varying conditions through the design variables changing their physical values [18,19]. Dimensional flexibility permits the physical changing of the system through active (on-line), or passive (off-line), configuration changes.

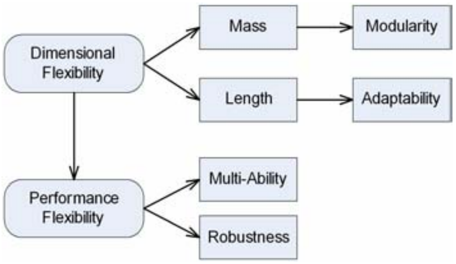

Figure 8. Flexibility Applied in Reconfigurable System Design

Utilizing the ability to change design variable values to achieve multi-ability allows a reconfigurable system to respond to changes in system objectives after the design has been deployed. A reconfigurable system is also able to respond to changes in the operating environment by leveraging the concept of robustness performance flexibility. However, it is important to note that this robustness is different than traditional robust design. Robust design selects values for design variables that minimize the performance degradation when the operating environment changes. Robustness performance flexibility, in the context of reconfigurable system design, accepts changes in the operating environment, and determines the appropriate adaptation needed to obtain an optimal design.

Applications of dimensional flexibility to attain performance flexibility have been studied in reconfigurable system design research. The next section of this paper highlights recent work that has been conducted within the design community.

4.2 RECENT RESEARCH IN RECONFIGURABLE DESIGN

Recent research in reconfigurable system design has mainly focused on three specific areas: costing, design variable selection, and transitioning with control theory. Costing studies have resulted from the conclusion that in order to design a system whose design variables change during operation will result in increased cost. This cost can occur from both a monetary and a resource perspective. Design variable selection research studied which design variables should be allowed to change, while the interest in controls comes from the need to understand the dynamics and choices in designing a changing system. This section provides a brief literature of reconfigurable system research advances in these three areas.

4.2.1 COSTING

Introductory reconfigurable system design research first focused on utilizing Decision-Based Design (DBD) to determine the increased costs of increased reconfigurability and other operating issues. The original DBD framework, presented by Hazelrigg [64], was adapted to provide a decision support tool that incorporated all the major parts of any corporation. Optimization was used to select the optimal design variable ranges that produced the best reconfigurable system performance. The target range of the system was classified by the endpoints of the Pareto frontier, with a penalty term reflecting the inability of the design to achieve the full boundaries of this target range [65].

Olewnik built upon this model by using conjoint analysis to assess the component ‘part-worth’ for each attribute comprising a product, making it possible to calculate the product’s total utility. An iterative optimization approach was applied where dimensional flexibility in a system was reduced to improve the overall utility of the system. The cost of dimensional flexibility was handled as a one-time cost and a per-unit cost of changing each design variable. This research demonstrated that consumer choice theory allows a designer to understand how design variable choices affect the utility of a product. By accounting for a corporate attitude toward risk, the use of corporate utility affects the end product.

4.2.2 DESIGN VARIABLE SELECTION

In the design of Unmanned Aerial Vehicles, Martin and Crossley studied the design variable variation to determine which variables would be the best candidates for morphing actuation [66]. Roth and Crossley treated morphing as an “independent variable” in determining which design variables should be changed, and by what magnitude [67]. This work focused on reconfiguration represented as occurring via an instantaneous shape change between mission segments. Other work has developed missions specifically to capitalize on advantages of morphing aircraft, or methods for assessing the capability of such aircraft [61,68].

Khire and Messac [69] integrated two key processes of reconfigurable system design: the selection of adaptive and fixed design variables, and the optimization of the reconfigurable system. Stating the discreteness involved in the selection of which design variables should be made adaptable, the Variable-Segregating Mapping-Function (VSMF) was introduced. The VSMF supplies a continuous function that progressively approximates this discontinuous mapping. Selection of fixed and adaptive design variables was completed based on the tradeoff between penalty and performance. The penalty of allowing a system to reconfigure was measured by factors such as the increased cost and the complexity of operation. A penalty function was defined as an increasing function based upon the change in the design variable values. Design alternatives differed in the number of adaptable design variables, and the penalty associated with each alternative.

4.2.3 MARKOV AND CONTROL THEORY

Reconfigurable systems change over time by attaining different states during their operational life. This property sets them apart from traditional fixed/single state systems. Siddiqi [9] introduced a methodology based on Non-Homogeneous Markov Models and developed a meta-controls framework particularly suited for studying the time aspects of such systems. Analysis is performed by assuming that the probability of a reconfigurable system transitioning from one state to another is conditioned on some external process. The system behavior and performance is simulated after formulating an appropriate objective function and the transition probability function. This method allows designers to identify ‘good’ configurations for the system that it should be able to adopt over the course of its operations. The meta-controls framework uses concepts of classical control theory to model the system as comprising of two control loops. An outer control loop represents off-line reconfiguration, and an inner control loop models the on-line reconfiguration process of the system. This modeling allows designers to study effects of reconfiguration time and different allowable states on the output (effectiveness) of the system. Ferguson [70] presented a method to determine how the design variables of a system should change when made adaptable, as well as investigating the stability of a reconfigurable system through the application of a state-feedback controller. The optimal trajectory of the design variable changes is determined based on the performance of the system and stability conditions. After the required changes in design variables are identified, a controller is developed that will allow for effective trajectory tracking. This controller accomplishes two tasks: ensuring proper behavior of the system within a changing environment and verifying that the changes in the design variables over time are appropriate for the system considered. The controller solution is based upon a linear quadratic regulator (LQR) approach by generalizing the process for a linear regulator problem to a linear tracking problem. Simulations then serve as the analytical feasibility assessment.

4.2.4 MODULAR RECONFIGURABLE ROBOTS

Outside the design community, there has also been increased research in the area of self-reconfigurable robots. These systems are a class of robotic systems capable of changing shape and functionality without external help [71,72]. The idea behind such robotic systems is the capability of performing multiple, complex tasks while being composed of thousands of connected modules [73]. Individually, these modules are extremely limited in their capabilities. Each module is generally equipped with computational and communication capability, sensors and actuators [71]. As the numbers of modules in the system increase, research has shown that the system's behavior range grows exponentially [74]. A modular-based approach allows a wide variety of robot configurations to be achieved from the same set of modules [75], while also providing opportunities for self-repair by replacing damaged modules with spare modules [71]. Designing for self-reconfigurability requires researchers of these robotic systems to leverage the same design and performance flexibilities defined earlier in this paper. These systems are capable of serving many different functions [75], obtaining multi-ability performance flexibility through length and mass dimensional flexibility, and high levels of redundancy and self-repair [76], in the form of robustness performance flexibility through mass and time dimensional flexibility. A survey of self-reconfigurable robot research demonstrates that researchers in this field have focused their efforts in the same areas as the design community.

Designing self-reconfigurable robots from a modular approach allows for potential cost savings at both the factory and supply level. Comprised of a few standardized components, economies of scale can be utilized at a factory level, while supply depots are required to stock only the number of different modules composing the robotic system [75,77,78]. The structure of the module, meanwhile, determines the overall system performance, especially when considering the allocation of actuated degrees of freedom [71]. As an example, the Telecube modules have the ability to independently extend each face of the module [74]. To understand the required module changes, the systems must be capable of recognizing that a given operating environment requires a new configuration and what new configuration is required [76]. Researchers in this field are interested in developing software capable of verifying that two arbitrary configurations are possible and to calculate the reconfiguration path between these configurations [71]. An advantage of module homogeneity from a control standpoint is a reduced concern regarding which physical modules end up at which location [74]. However, as the number of modules increase the possible sequence of connections grows exponentially, making the reconfiguration sequence quite complex [76].

4.3 CURRENT RESEARCH QUESTIONS

The methodologies presented above only begin to answer some of the many questions associated with reconfigurable system design. Some additional important questions, essential to the future development of reconfigurable system design, are summarized here.

How can reconfigurable system research be influenced by the implementation of the design techniques studied within the systematic design process?

The synthesis of various existing methods creates a set of interesting challenges. For instance, Transformation principles can naturally be implemented into the early stages of a systematic design process, while CMEA would naturally be used later in the process. Common characteristics of these existing methods could be merged into a support infrastructure for the design of reconfigurable systems. Research into whether the sets of operating assumptions are congruous in these methods may provide critical understanding towards providing more comprehensive decision support in the design of reconfigurable systems.

Which design variables and associated elements of form should be made adaptable when designing a reconfigurable system?

While reconfigurable systems eliminates the need to tradeoff performance on conflicting operating objectives, it creates another set of tradeoffs between the level of reconfigurability and the associated increase in some costs. Studying the relationship between the cost of reconfigurability and the value of reconfigurability to a customer would help companies position themselves strategically in a growing reconfigurable systems marketplace. Associated with this is studying how to determine which system design variables to make adaptable (driven by flexibility) and which ones to make static (driven by robustness). There may be multiple different combinations of adaptable and static variables that give similar flexible performance and developing formal methods to evaluate these configurations is essential.

How can reconfigurable system design be enhanced with the integration of cyberinfrastructure?

With the continued growth of cyberinfrastructure (CI) developments, it will become increasingly important to establish the foundations for auto-reconfigurable systems that integrate CI tools and techniques to enable systems to interact with their environment to sense, adapt, and respond. Valuable research issues exist in the integration and deployment of various types of onboard and outboard sensors, developing control algorithms both at the local system level and at the system-user level, and addressing ontological challenges in the information and knowledge infrastructures.

How can product family design be leveraged to make reconfigurable systems more effective?

Systems that have complete adaptability are capable of satisfying the entire market, as they achieve optimal performance for each objective. The need for product platforming becomes clear when considering reconfigurable systems that are not entirely adaptable. Intelligent design of such systems will allow for broader applications when technical and economic constraints are present. While aggressive platforming can lead to the development of sub-optimal designs, this can be avoided given the nature and focus of reconfigurable systems. However, the question of how to utilize the strengths of reconfigurable systems and product platforming to reduce the need for customer sacrifice when designing for a broad application range remains.

5.0 CONCLUSIONS

The demands for increased performance have made the ability to change a system a necessity. As shown in Section 3.1, flexibility is the property that allows a system or product to be changed easily, and such modifications come in response to changes in operating environment or system objectives. Changes to a system are made in the design space (elements of form, design variables) in order to affect the range of behaviors in the performance space. However, measuring or classifying flexibility has remained a constant challenge.

In Section 6.0, the proposed definitions for nomenclature associated with reconfigurable system design are complied for easy reference. This paper leverages flexibility as a property in the design and performance spaces as a basis for a classification scheme. *Dimensional flexibility* is introduced as a measure of effecting changes in the (7) basic fundamental dimensions of a system. For the design of mechanical systems, three of these fundamental dimensions are studied: mass, length, and time. Leveraging dimensional flexibility in system design allows for changes in performance, especially after the system has been deployed. Changes in performance can manifest themselves through the proposed *performance flexibilities*: multi-ability, evolvability and robustness. This classification scheme provides the groundwork towards measuring and quantifying flexibility, independent of the design technique being used. A challenge that still remains is how to identify the type, and amount of flexibility desired, as the set of uncertainties that drive the need for flexibility, or set of future states that the system will take, might not be known a priori.

Reconfigurable systems leverage both dimensional and performance flexibility in their design, and act as a subset of changeable systems. A distinguishing characteristic of reconfigurability compared to flexibility is that changes in state are reversible, whereas reversibility is not necessary in the broader context of system flexibility. The set of configurations, or states, that a system can take is influenced by the dimensional flexibility leveraged, as the design variables in a reconfigurable system can change their physical values. The transitions between states are made to require the minimum amount of time and resources as is appropriate to the situation at hand. Research into reconfigurable system design has focused on this issue, studying the cost of reconfigurability, design variable selection, and transitioning with control theory. However, these works only answer a few of the many questions associated with reconfigurable system design, and remaining research questions are posed to promote reconfigurable system maturity.

6.0 NOMENCLATURE

This section compiles the terminology and definitions proposed in this paper for easy reference. As discussed in Section 2.0, there exists the need for clear and unambiguous nomenclature to allow research in changeable and reconfigurable systems to mature. Based upon their usage and current understanding in design literature, definitions for terms associated with flexibility and reconfigurability are presented. A classification scheme for the property of flexibility in the design (form) and performance (function) space is proposed as dimensional flexibility and performance flexibility, respectively. The manners in which dimensional and performance flexibility are leveraged in system design (i.e. mass dimensional flexibility) are also defined. Finally, definitions for reconfigurability, adaptability, and modularity within the context of reconfigurable system design are also supplied.

Flexibility	The property of a system that promotes change in both the design and performance space.
Dimensional flexibility	A classification scheme, built around the concept of base dimensions, describing

	flexibility in terms of configuration changes in the design space.
Mass dimensional flexibility	A form of dimensional flexibility allowing for the addition, or removal, of elements in the form of hardware, personnel, or software.
Length dimensional flexibility	A form of dimensional flexibility allowing for geometric changes within the system after fielding.
Time dimensional flexibility	A form of dimensional flexibility that provides both increased freedom when making decisions about the values of the design and reduces the time required for redesign by utilizing easily modified architectures.
Performance flexibility	Alterations in system performance manifested by configuration changes in the design space in response to varying operating conditions, functional requirements, and changing consumer needs.
Multi-ability performance flexibility	A mode of performance flexibility that provides a system the capability to fulfill multiple non-simultaneous objectives from a fixed set of resources.
Evolution performance flexibility	A mode of performance flexibility that provides a system the ability to be readily redesigned to meet changes in technology or consumer demands.
Robustness performance flexibility	A mode of performance flexibility in which system changes are dictated to maintain an optimal performance, or maintain a required level of functionality, in response to unpredicted factors.
Reconfigurability	A subset of flexibility in which system configurations can be changed repeatedly and reversibly.
Modularity	An approach towards achieving mass dimensional flexibility, in that those modules comprising a system can be replaced and updated.
Adaptability	An approach towards achieving length dimensional flexibility by characterizing a system's ability to deliver intended functionality under varying conditions through the design variables changing their physical values.

ACKNOWLEDGMENTS

We gratefully acknowledge the National Science Foundation, grant DMII-0322783, and the National Aeronautics and Space Administration, contract NNK050A50c, for their support of this work.

REFERENCES

[1] Pine, J. B., and Gilmore J. H., 2000, Markets of One:: Creating Customer-Unique Value Through Mass-Customization. Harvard Business School Press, Boston, MA, pp. xxiii.

[2] Bowman, J., Weisshaar, T., and Sanders, B., 2002, "Evaluating the Impact of Morphing Technologies on Aircraft Performance," 43rd AIAA/ASME/ASCE/AHA/ACS Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, AIAA 2002-1631.

[3] Pine, J. B., 1993, Mass Customization: The New Frontier in Business Competition, Harvard Business School Press, Boston, MA.

[4] Tseng, M., and Piller, F., eds, 2003, The Customer Centric Enterprise: Advances in Mass Customization and Personalization, Springer, New York.

[5] Roach, g. M., Cox, J. J., and Sorensen, C. D., 2005, "The Product Design Generator: A System for Producing Design Variants," *International Journal of Mass Customization*, 1(1): 83-106.

[6] Moser, K., Muller, M., and Piller, F., 2006, "Transforming Mass Customization From a Marketing Intrument to a Sustainable Business Model at Adidas," *International Journal of Mass Customization*, 1(4): 463-479.

[7] Blecker, T., and Friedrich, G., eds, 2006, Mass Customization: Challenges and Solutions, Springer, New York.

[8] Olewnik, A., Brauen, T., Ferguson, S., and Lewis, K., 2004, "A Framework For Flexible Systems And Its Implementation In Multiattribute Decision Making," *ASME Journal of Mechanical Design*, 126(3): 412-419.

[9] Siddiqi, A., de Weck, O. L., and Iagnemma, K., 2006, "Reconfigurability in Planetary Surface Vehicles: Modeling Approaches and Case Study," *Journal of the British Interplanetary Society*, 59.

[10] Compendex, http://www.engineeringvillage2.org

[11] Phadke, M. S., 1989, Quality Engineering Using Robust Design. Prentice-Hall, Englewood Cliffs, NJ.

[12] Saleh, J.H., Hastings, D.E., and Newman, D.J., 2003, "Flexibility in System Design and Implications for Aerospace Systems," *Acta Astronautica,* 53(12): 927-944

[13] Oxford University Press, 2005, Oxford American Dictionary: 2nd edition.

[14] Sethi, A. K., and Sethi, S. P., 1990, "Flexibility in Manufacturing, A Survey," *International Journal of Flexible Manufacturing Systems,* 2(4): 289-328.

[15] Gupta Y. P., and Goyal, S., 1990, "Flexibility of Manufacturing Systems: Concepts and Measurements," *European Journal of Operational Research*, 43(2): 119-135.

[16] Qureshi, A., Murphy, J. T., Kuchinsky, B., Seepersad, C., Wood, K., and Jensen, D., 2006, "Principles of Product Flexibility," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, PA., DETC-99583.

[17] Skiles, S. M., Singh, V., Krager J., Wood, K., Jensen, D., and Szmerekovsky, A., 2006, "Adapted Concept Generation and Computation Techniques for the Application of a Transformer Design Theory," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, PA, DETC2006-99584.

[18] Fricke, E., and Schulz, A.P., 2005, "Design for Changeability (DfC): Principles to Enable Changes in Systems Throughout Their Entire Lifecycle," *Systems Engineering*, 8(4): 342-359.

[19] Moses, J., et al. 2002, ESD Symposium Committee Overview, The ESD Internal Symposium, MIT, Cambridge, MA.

[20] Singh, V., Skiles, S. M., Krager, J., Wood, K., Jensen, D., and Szmerekovsky, A., 2006, "Innovations in Design through Transformation: A Fundamental Study of tRaNsFoRmAtIoN Principles," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, PA, DETC2006-99575.

[21] Rajan P.K, Wie, M. V., Campbell, M. I., Wood, K. L., and Otto, K. N., 2005, "An Empirical Foundation for Product Flexibility," *Design Studies*, 26(4): 405-438.

[22] Keese, D. A., Takawale, N. P., Seepersad, C., and Wood, K., 2006, "An Enhanced Change Modes and Effects Analysis (CMEA) Tool for Measuring Product Flexibility with Applications to Consumer Products," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conferences, Philadelphia, PA, DETC2006-99478.

[23] Wright, I. C., 1997, "A Review of Research into Engineering Change Management: Implications for Product Design," *Design Studies,* 18: 33-42.

[24] Pikosz, and Malmqvist, 1998, "A Comparative Study of Engineering Change Management in Three Swedish Engineering Companies," Proceedings of the ASME Design Engineering Technical Conference, DETC98/EIM-5684.

[25] Eckert, Clarkson, and Zanker, 2004, "Change and Customization in Complex Engineering Domains," *Research in Engineering Design*, 15: 1-21.

[26] Cohen, and Fulton, 1998, "A Data Approach to Tracking and Evaluating Engineering Changes," Proceedings of the DETC ASME Design Engineering Technical Conference, DETC98/EIM5682.

[27] Jarratt, Eckert, and Clarkson, 2005, "Pitfalls of Engineering Change: Change Practice During Complex Product Design," *Advances in Design*, 413-424.

[28] Huang, and Mak, 1999, "Current Practices of Engineering Change Management in UK Manufacturing Industries," *International Journal of Operations & Product Management* 19(1): 21-37.

[29] Terwiesch, and Loch, 1999, "Managing the Process of Engineering Change Orders: the Case of the Climate Control System in Automobile Development," *Journal of Production Innovation and Management*, 16: 160-172.

[30] Clarkson, P. J., Simons, C. S., and Eckert, C. M., 2004, "Predicting Change Propagation in Complex Design," *ASME Journal of Mechanical Design,* 126(5): 788-797.

[31] de Weck, O., and Suh E. S., 2006, "Flexible Product Platforms: Framework and Case Study," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, PA., DETC2006-99163.

[32] Trease, B. P., and Kota, S., 2006, "Synthesis of Adaptive and Controllable Compliant Systems with Embedded Actuators and Sensors," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, PA., DETC2006-99266.

[33] Wang, H. V., and Rosen, D., 2006, "An Automated Design Synthesis Method for Compliant Mechanisms with Application to Morphing Wings," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, PA., DETC2006-99661.

[34] Lu, K.J. and Kota, S., 2003, "Design of Compliant Mechanisms for Morphing Structural Shapes," *Journal of Intelligent Material Systems and Structures*, 14(6): 379-391.

[35] Trease, B., Moon, Y., and Kota S., 2005, "Design Of Large-Displacement Compliant Joints," *ASME Journal of Mechanical Design,* 127(4).

[36] Maddisetty, H., and Frecker, M., 2004, "Dynamic Topology Optimization of Compliant Mechanisms and Piezoceramic Actuators," *ASME Journal of Mechanical Design.* 126(6): 975-983.

[37] Ramrakhyani, D., Lesieutre, G., Bharti, S., and Frecker, M., 2005, "Aircraft Structural Morphing using Tendon Actuated Compliant Cellular Trusses," *Journal of Aircraft*, 42(6): 1615-1621.

[38] Chen, W., and Yuan, C., 1999, "A Probabilistic Design Model for Achieving Flexibility in Design," *ASME Journal of Mechanical Design,* 121(1): 77-83.

[39] Liu, H., Chen, W., Qureshi, K., and Scott, M., 2006, "Determination of Ranged Sets of Design Specifications

by Incorporating Heterogeneous Design Capability Information," ASME IDETC Conferences, Philadelphia, PA., DETC-99494.

[40] Chen, W., and Lewis, K., 1999, "A Robust Design Approach for Achieving Flexibility in Multidisciplinary Design," *AIAA Journal*, 7(8): 982-989.

[41] Meyer, M. H., and Lehnerd, A. P., 1997, the Power of Product Platforms: Building Value and Cost Leadership, New York: Free Press.

[42] Simpson, T. W., Maier, J. R. A, and Mistree, F., 2001, "Product Platform Design: Method and Application," *Research in Engineering Design*, 13(1): 2-22.

[43] Martin, and Ishii, 2002, "Design for Variety: Developing Standardized and Modularized Product Platform Architectures," *Research in Engineering Design*, 13: 213-235.

[44] Simpson, T.W., Siddique, Z., and Jiao, J., eds, 2006, Product Platform and Product Family Design: Methods and Applications, Springer, New York, pp. 157-185.

[45] Haubelt, C., Telch, J., and Richter, K., 2002, "System Design for Flexibility," Design, Automation and Test in Europe Conference and Exhibition, Paris, France.

[46] Umeda, Y., Shimomura, Y., Ishigami, Y., Yagi, H., Kondoh, S., and Yoshioka, M., 2005, "Development of Design Methodology for Upgradeable Products Based on Function-Behavior-State Modeling," *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 19:161-182.

[47] Kota, S., and Moon, Y., 2002, "Generalized Kinematic Modeling of Reconfigurable Machine Tools," *Journal of Mechanical Design,* 124(1): 47-51

[48] Gopalakrishnan, V., and Kota, S., 1998, "A Parallel Actuated Work Support Module for Reconfigurable Machining Systems," ASME Design Engineering Technical Conferences, Atlanta, Georgia, DETC98/MECH-5959.

[49] Chen, L., Xi, F., and Macwan, A., 2005, "Optimal Module Selection for Preliminary Design of Reconfigurable Machine Tools," *Journal of Manufacturing Science and Engineering*, 127(1): 104-115.

[50] Kelkar, A., Nagi, R., and Koc, B., 2005, "Geometric Algorithms for Rapidly Reconfigurable Mold Manufacturing of Free-Form Objects," *Computer-Aided Design*, 37(1): 1-16.

[51] Tokunaga, H., Matsuki, N., Imamura, S., Tanaka, F., and Kishinami, T., 2002, "Reconfiguration of Kinematic Structure for Changing Motion Requirement Based On Reusability Evaluation in Lie Algebra," ASME 2002 Design Engineering Technical Conferences and Computer and Information in Engineering Conferences, Montreal, Canada, DETC2002/DAC-34052.

[52] Ni, Q., Yarlagadda, P. K., Lu, and W. F., 2006, "Semantic Representation for Configurable Enterprise Systems," ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, PA., DETC-99032.

[53] Tegel, O., 1999, "Flexible Computer Support of Systematic Design Processes - A View Back," 1999 ASME Design Engineering Technical Conferences, Las Vegas, Nevada. DETC99/EIM-9011.

[54] De Toni, A., and Tonchia, S., 1998, "Manufacturing Flexibility: A Literature Review," *International Journal of Production Research,* 36(6): 1587-1617.

[55] Kapoor,, D., and Kazmer, D., 1997, "The Definition and Use of the Process Flexibility Index," 1997 ASME Design Engineering Technical Conference, Sacramento, California., DETC97/DFM-4476.

[56] Kazmer, D. O., and Roser, C., 1999, "Evaluation of Product and Process Design Robustness," *Research in Engineering Design*, 11(1): 21-30.

[57] Parkinson, A. R., and Chase, K. W., 2000, "An Introduction to Adaptive Robust Design for Mechanical Assemblies," ASME Design Engineering Technical Conferences, Baltimore, Maryland, DETC2000/DAC-14241.

[58] Roser, C. and Kazmer, D., 2000, "Flexible Design Methodology," 2000 ASME Design Engineering Technical Conferences, Baltimore, Maryland, DETC2000/DFM-14016.

[59] Shewchuk, J. P., 1999, "A Set of Generic Flexibility Measures for Manufacturing Applications," *International Journal of Production Research,* 37(13): 3017-42.

[60] Hagen, K. D., 2005, Introduction to Engineering Analysis 2e, Prentice Hall, New Jersey.

[61] Peters, C., Roth, B., Crosslet, W., and Weisshaar, T., 2002, "Use of Design Methods to Generate and Develop Missions for Morphing Aircraft," AIAA Paper 2002-5468.

[62] Webb, A., 2002, "A Piston Revolution," *Engineering Management Journal*, 12(2): 29-30.

[63] Ulrich, K., and Eppinger, S., 1995, Product Design and Development, McGraw-Hill, Inc., New York.

[64] Hazelrigg, G. A., 1998, "A Framework for Decision-Based Engineering Design," *ASME Journal of Mechanical Design*, 120: 653-658.

[65] Olewnik, A., and Lewis, K., 2006, "A Decision Support Framework for Flexible System Design," *Journal of Engineering Design,* 17(1): 75-97.

[66] Martin, E., and Crossley, W., 2002, "Multiobjective Aircraft Design to Investigate Potential Geometric Morphing Features," AIAA 2002-5859.

[67] Roth, B., and Crossley, W., 2003, "Application of Optimization Techniques in the Conceptual Design of Morphing Aircraft," AIAA 2003-6733.

[68] Cesnik, C., Last, H., and Martin, C., 2004, "A Framework for Morphing Capability Assessment," AIAA 2004-1654.

[69] Khire, R., and Messac, A., 2006, "Selection-Integrated Optimization (SIO) Methodology for Optimal Design of Adaptive Systems," ASME Design Engineering Technical Conferences, Philadelphia, PA., DETC2006-99322.

[70] Ferguson, S., and Lewis, K., 2006, "Effective Development of Reconfigurable Systems Using Linear State-Feedback Control," *AIAA Journal*, 44(4): 868-878.

[71] Murata, S., Yoshida, E., Kamimura, A., Kurokawa, H., Tomita, K., and Kokaji, S., 2002, "M-TRAN: Self-Reconfigurable Modular Robotic System," *IEEE/ASME Transactions on Mechatronics*, 7(4): 431-441.

[72] Gross, R., Bonani, M., Mondada, F., and Dorigo, M., 2006, "Autonomous Self-Assembly in Swarm-Bots," *IEEE Transactions on Robotics*, 22(6): 1115-1130.

[73] Suh, J. W., Homans, S. B., and Yim, M. H., 2002, "Telecubes: Mechanical Design of a Module for Self-Reconfigurable Robots," IEEE International Conference on Robotics and Automation, Washington, D. C., 4095-4101.

[74] Vassilvitskii, S., Kubica, J., Rieffel, E., Yim, M. H., and Suh, J. W., 2002, "On the General Reconfiguration Problem for Expanding Cube Style Modular Robots," IEEE International Conference on Robotics and Automation, Washington, D. C., 801-808.

[75] Eldershaw, C., Yim, M. H., Duff, D. G., Roufas, K. D., and Zhang, Y., 2002, "Modular Self-Reconfigurable Robots", Robotics for Future Land Warfare Seminar and Workshop, Defence Science Technology Organization, Australia.

[76] Yim, M., Roufas, K., Duff, D., Zhang, Y., Eldershaw, C., and Homans, S., 2003, "Modular Reconfigurable Robots in Space Applications, *Autonomous Robots*, 14(2-3): 225-237.

[77] Globus, A., Hornby, G., Larchev, G., Hancher, M., Cannon, H., and Lohn, C., 2004, "Teleoperated Modular Robots for Lunar Operations," AIAA 1st Intelligent Systems Technical Conference, Chicago, Illinois, AIAA-2004-6435.

[78] Akin, D., Roberts, B., Roderick, S., Smith, W., and Henriette, J-M., 2006, "MORPHbots: Lightweight Modular Self-Reconfigurable Robotics for Space Assembly, Inspection, and Servicing," Space 2006, San Jose, California, AIAA-2006-7408.