Measuring Innovation in Multi-Component Engineering Systems

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Abstract: This paper presents formal criteria, called the Value and Component Distances, to measure innovation in multi-component engineering systems. A complementary visualization method, called the Design Solution Topography, is also presented. The criteria measure differences in configuration and attribute values in design concepts in an evolutionary computation construct to provide computational assessments of relative innovation, and are applicable to physical engineering systems.

Keywords: innovative design, evolutionary computation.

1 Introduction

The production of multi-component engineering systems is a challenging task in industry today. The authors have studied this issue for the application of space satellite systems, which are systems that are produced in predominately single-unit or at most single-digit production items [1,2]. They are typically very expensive to produce, and oftentimes have long design development and production timelines. Additionally, there may or may not exist comparable historical solutions providing the same or similar capabilities, and there may or may not be such solutions in the existing marketplace. The business environment in which these systems are manufactured is typically risk-adverse with constraints on manpower availability,

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schedule and cost. Thus, innovation is generally limited or very narrowly applied due to the limited alternative solution space explored.

To better enable innovation, the authors developed a conceptual designing method that integrates formal measurement criteria called the Value and Component Distances with an evolutionary computation procedure to generate large numbers of alternative design concepts [1-4]. The criteria assess two specific features of a population of design concepts – innovation and robustness to variances in design parameters. In doing so, the criteria are able to provide designers with risk-management-related assurance regarding system failure, while simultaneously providing insight into relative innovation characteristics of the alternative design concepts that are selected. A complementary visualization method called the Design Solution Topography was also developed.

A design concept is assessed in this paper to be innovative when it has variance from a designated reference point. In this construct, an innovative design concept is therefore a way to achieve the same types of performances that are different than other solutions. These variances are from two sources: (1) variance in same-type components between two design concepts arising from differences in both numerical and configuration specifications, and (2) variance in different-type components between two design concepts arising from component composition differences. It is assessed that the greater these variances are in specifications (numerical and configuration descriptions of a class of systems) or components (component composition descriptions of a class of systems), and the greater the diversity of these variances, then the greater the degree of relative innovation.

2 Assumptions

The proposed innovation criteria have been developed using an evolutionary computation construct. This approach uses a genome/allele structure to describe the components that comprise a design concept. A component is a fundamental part of the design that may be either a lowest physical decomposition (i.e. board / box-level) or a lowest functional / operational decomposition. Components are grouped by types, which are components that have the same symbolic attributes and functions. Components in a conceptual design may be of different types or may be of the same type but with different attribute values.

An attribute describes a physical characteristic or behavior of the system, and may be either static or variable in value throughout the design development process. In the evolutionary computing construct used in this paper, the attribute values are functions of the allele values that are grouped into genomes, which in turn are grouped to form the components. Attribute values can be quantitative or qualitative representations of design concept or component features. Quantitative features are typically numerically-based, such as weight, power, or bandwidth. Qualitative features describe characteristics of the design concept or component. For example, in Figure 1, a component of type “F”, being a bar assembly, is shown to illustrate how allele values can map to qualitative features (in this case, structural arrangement of bars), and quantitative attributes (here, mass and maximum tensile force). This example also shows how a particular allele value can map to both qualitative and quantitative characteristics simultaneously, although it is permissible that they map exclusively to one or the other kind of characteristic.

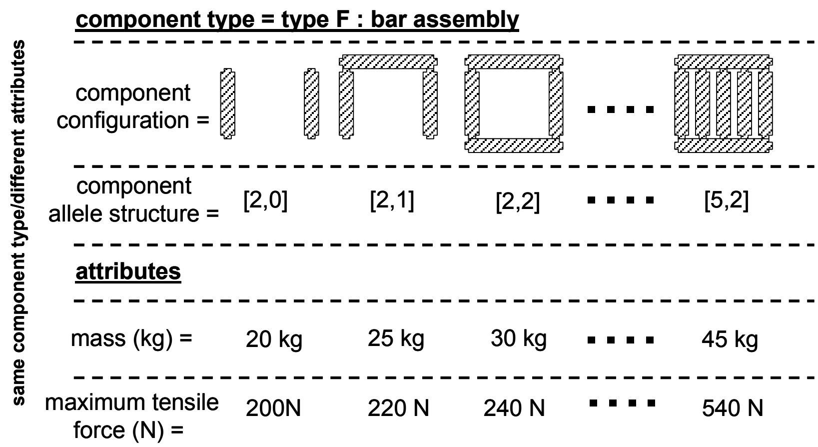

Fig. 1. Example of a component-allele description

3 Innovation Criteria and Their Visualization

The Value and Component Distances assess innovation in a population of design concepts by considering the differences between any two concepts. Similar to the Hamming Distance [5], the distances measure the variance between two design concepts, where (1) Value Distance measures variances in same-type components that are common to both design concepts (specification variance), and (2) Component Distance measures variances in different-type components that are not common to both design concepts (component composition variance). The algorithm for calculating these distances is described in detail in Shelton and Arciszewski [1]. The values of the criteria, like the Hamming Distance, are metrics – they are not something intrinsic that describe features of the design concepts themselves. As noted, they quantify the relative amount of variance, which is to say also the amount of diversity, between two design concepts. Analysis based on Value Distance assesses innovation from component attribute differences, while the Component Distance assesses innovation from component composition differences. The goal is to identify design concepts with comparatively larger distances that still provide acceptable performance – representing beneficial innovation.

4 Design Solution Topography

The "Design Solution Topography" modifies the Fitness Landscape [6,7]. Here, one horizontal axis represents variance in Component Distance and the other represents variance in Value Distance. As in the traditional Fitness Landscape, the vertical third axis represents performance for a given design concept considering a particular objective function. In this way, each coordinate indirectly represents an entire design concept instead of only a pair of attributes associated with a single design concept as is the case in a standard fitness landscape. In effect, this transforms the N-1 dimensions of the generalized fitness landscape (N-1 being the total number of discrete attributes that together define the performance function plotted as the Nth axis) into a 2-axis representation of a population of design concepts considering their specification and component characteristics. This is shown in Figure 2.

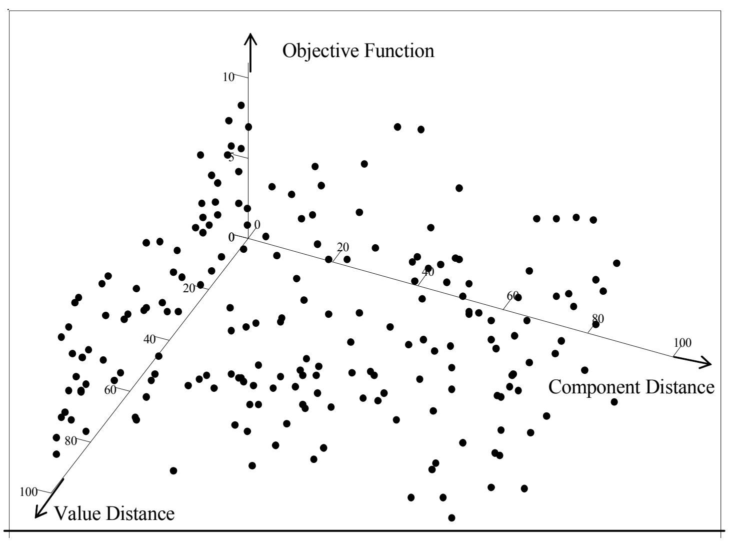

Fig. 2. General Form of Design Solution Topography

The third axis referred to as the performance is the value of the objective function. For a conceptual designing problem, there may be more than one objective function. In a classic evolutionary computing problem, there is only one, unified objective function that holistically represents the performance desired for the system. In the applications envisioned by this research, there will be several discrete objective functions, some of which are likely to be in conflict and competition with each other. Here, each population will have a collection of Design Solution Topographies, one for a different objective function. The population members that are selected as the best are those that have performance values across all the objectives in proportion to the weighted priorities of the objectives. This means that selection is based on a trade-off of objectives, given that it will not be likely that one design concept will be able to deliver optimal performance for all objectives simultaneously. Therefore, each objective has a priority relative to the other objectives, and the 'best' design concept is that which provides the best weighted performance, with the goal of having at least minimally acceptable performance for all performance objectives. The procedures for producing and evaluating the Design Solution Topography are provided in Shelton [2].

5 Example Problems

To illustrate the use of the proposed criteria, suppose that a customer desires the development of a satellite design concept to perform some particular set of performance objectives. The existing marketplace solution has a particular design concept, which may have some number of known minor variants that represent customization, alteration and feature modification of that basic design. Alternatives to it are desired to be developed and evaluated to advance the state-of-the-art. Using the criteria, the marketplace leader design concept could be taken as the base design. The minor variant designs would have comparatively small Value and Component Distances from the base design because they are simply small tailored alternatives of it. These could be plotted on the Design Solution Topography and would create a small distribution 'cloud' around the base design's location at (0,0,X) (where the Value and Component Distance of a design concept from itself is by definition zero as it does not have variance from itself). Innovative designs would be those designs that are found that have comparatively larger Value and Component Distances that put them outside the local region around the base design while still having comparable or superior performance.

The satellite design concepts in this example (taken from [8]) are composed of payload sensors performing data collection activities, with the customer performance objectives being defined in terms of the satellite's mass, power and data rate. The legal component types and their configuration specifications are shown in Table 1.

Using the conceptual designing method from Shelton [2], a population of alternative design concepts, with a target mass performance objective value of 1100 kg as one of the three performance objective values, are generated using evolutionary computation techniques. The results are shown in Figure 3. The industry standard is shown as the base design, as annotated on the figure. In this example, the population shows acceptable innovative options in both the Value Distance and Component Distance. This means that the population contains a significant number of alterative design options that vary from the industry standard in same-type component variances and different-type component variances while maintaining acceptable performance. Thus, innovation in this population has a rich diversity of options from which to choose.

Table 1. Payload Sensor Component Types

#	Payload Name	Acronym	Mass (kg)	Power (W)	Data Rate (Mbps)	Example Problem Mass	Example Problem Power	Example Problem Data Rate
1	Advanced Baseline Imager	ABI	220	410	21	$180 + 5(a_{11} - 1)$	1.85 * mass	$17 + 0.33(a_{11} - 1)$
2	Solar X-Ray Imager	SXI	50	200	2.8	$40 + (a_{12} - 1)$	4 * mass	$1 + 0.15(a_{12} - 1)$
3	Geostationary Microwave Sounder	GMS	300	300	0.5	$275 + 2(a_{13} - 1)$	1 * mass	$0.02 + 0.04(a_{13} - 1)$
4	Lightning Monitor	LM	37.5	144	0.2	$25 + (a_{14} - 1)$	4 * mass	0.2
5	Hyperspectral Environmental Suite	HES	157	527	65	$125 + 2(a_{22} - 1)$	3.35 * mass	$53 + (a_{22} - 1)$
6	Multi-function Sensor	MFS	80	100	1.4	$60 + 2(a_{23} - 1)$	1.25 * mass	1.4
7	Space Environment Monitor	SEM	54	94	0.00056	$45 + (a_{24} - 1)$	1.75 * mass	0.00056
8	Full Disk Sounder	FDS	180	190	1.2	$140 + 4(a_{31} - 1)$	1.05 * mass	1.2
9	Emmissive Hyperspectral Sounder	EHS	185	235	23	$140 + 4(a_{32} - 1)$	1.25 * mass	$17 + 2(a_{32} - 1)$
10	Data Collection System	DCS	17.9	29.7	0	$14 + 0.5(a_{33} - 1)$	1.65 * mass	0
11	Search and Rescue	SAR	8.6	22.4	0	$6 + 0.33(a_{41} - 1)$	2.6 * mass	0
12	Imaging Payload	IP	150	150	0.5	$120 + 5(a_{42} - 1)$	1 * mass	0.5
13	Additional Payload Mass and Power	A SAT ADD	61	100	0	$50 + 2(a_{43} - 1)$	1.65 * mass	0
14	Additional Payload Mass and Power	B SAT ADD	100	150	0	$75 + 2(a_{44} - 1)$	1.5 * mass	0
15	Enhanced Advanced Baseline Imager	Mod ABI	275	450	55	$250 + 3(a_{45} - 1)$	1.65 * mass	$31 + (a_{45} - 1)$
--	Enhanced Hyperspectral Environmental Suite	Mod HES	190	460	65	Not Used		

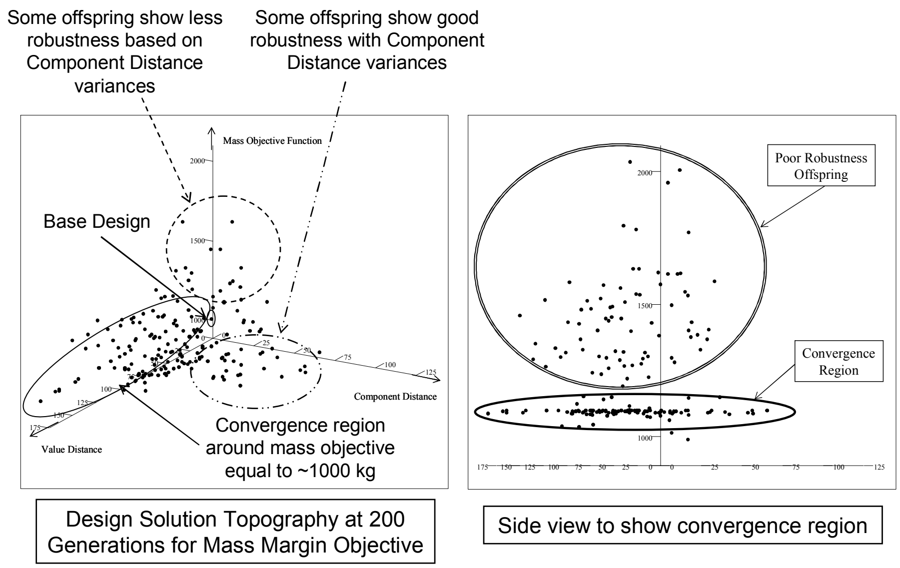

Fig. 3. Acceptable Innovation in Value Distance and Component Distance

Furthermore, the Design Solution Topography shows that these alternative design concepts are robust as well. The convergence region shows that large variances in Value Distance maintain acceptable objective performance. Therefore, an alternative design concept selected from that region can degrade or have manufacturing errors that result in different numerical or configuration specifications but still maintain acceptable performance. This can alleviate institutional concerns of failure in implementing innovative design concepts.

Similarly, numerous options with large variances in Component Distance are also able to maintain acceptable objective performance. Insight is also gained from the poor robustness offspring. These options identify which component types are ill-suited to produce robust solutions given the problem definition. Therefore, an alternative design concept selected from the robust regions can have component changes that arise for whatever reason – parts availability, part replacement, parts repair – and still maintain acceptable performance. Component types whose use should be avoided are also characterized. This also can reduce institutional fear of increased risk associated with innovation.

To contrast, suppose that a population of design concepts with a target mass performance objective value of 200 kg are produced with a Design Solution Topography as shown in Figure 4. The industry standard is shown as the base design, as annotated on the figure. In this example, the population shows acceptable innovative options in the Value Distance, although accommodating comparatively less variance than the previous example. In the Component Distance, though, "innovative" alternatives have significant changes in objective performance. This means that the population contains a number of alterative design options that vary from the industry standard in same-type component variances, although as noted in amounts that are less than the previous example. However, different-type component variances result in unacceptable changes in objective performance – namely, significant increases in mass above the target value. Thus, innovation in this population is significantly riskier when considering changes in component type composition, and is not as strong as the previous example for numerical and/or configuration changes as well.

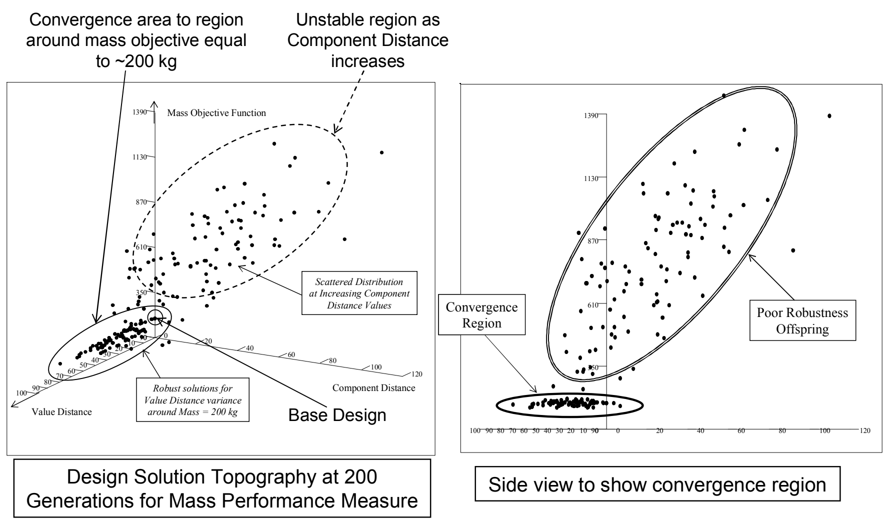

Fig. 4. Riskier Innovation in Value Distance and Component Distance

Consistent with this, the Design Solution Topography shows that these alternative design concepts have less robustness than the previous example. The convergence region shows that variances in Value Distance maintain acceptable objective performance, although at a comparatively lesser amount. Therefore, an alternative design concept selected from that region can degrade or have manufacturing errors that result in different numerical or configuration specifications but still maintain acceptable performance. This can alleviate some institutional concerns of failure in implementing innovative design concepts.

However, the options with large variances in Component Distance cannot maintain acceptable objective performance. Therefore, innovation from the base design that has component changes that arise for whatever reason – parts availability, part replacement, parts repair – will contain significant risk to maintaining acceptable performance. Interestingly, the Design Solution Topography shows that this condition is also true for the base design itself – which may well indicate a fundamental risk management concern with the problem definition wherein the stated objective performance goals have significant component-type selection limitations relative to the inventory of legal component type options that can be used to satisfy them. While it doesn't alleviate institutional concerns of risk associated with innovation, it can be beneficial by identifying and quantifying risk management issues that may not have been apparent otherwise.

6 Limitations of the Criteria

The proposed criteria require a particular representation structure for the problem definition, namely that the design concepts can be represented in an evolutionary computing format. The genome / allele representation of attributes, components and design concepts is necessary in order to implement the criteria. However, it is acknowledged that not all conceptual designing problems lend themselves to such a representation. If that is the case, then the designer will not be able to use these methods. For example, a satellite, building structure, antenna or other such systems lend themselves to evolutionary computing representation. They have discrete components that have characteristic attributes and perform various measurable functions, and these components interact to form design concepts that deliver some measurable desired performance objective.

Non-physical systems, such as software routines, do not lend themselves to this representation. They are lines of code that, in the aggregate, form a system whose performance tends to be difficult to represent as an objective function. As such, they are not well-suited for use of these methods.

Another limitation is that these concepts are more conducive to evaluating an innovative designing process vice an inventive designing process. The criteria currently require that in developing the problem definition, all objective functions, component types, their allowable configurations and attribute value ranges are established a priori. The criteria do not intrinsically add to the allowable inventory of component types, or modify the characteristics of those components. Completely new and unexpected applications of component types, legal attribute values, and design concept constructs will not be evaluated because the criteria do not create new first principle or problem definition information, but assess and evaluate differences in pre-defined allowable configurations. Thus, this limits the approach in two respects. First, the complete alternate solution space that can be evaluated is pre-defined. Secondly, the maximum range of innovation that can be evaluated is also pre-defined based on the maximum difference resulting from the various compositions of component types. These shortcomings are not necessarily present in other inventive approaches, such as TRIZ, Synectics, or Brainstorming [9-16]. However, the criteria do provide numerically-based evaluations capabilities that are not present in other approaches.

A potential enhancement to the criteria would be to merge them with an inventive design method like TRIZ or Morphological Analysis [9-16]. In doing so, the inventive method would drive modifications to the inventory of legal component types and objective functions, and the criteria would then assess the revised level of innovation based on the modified problem definition.

7 Conclusions

The criteria and associated Design Solution Topography provide a simple, easy-to-use capability to measure and assess the level of innovation present in a population of design concepts relative to a known base design reference point, such as the industry standard existing design concept. This innovation is characterized for robustness in order to address potential customer and designer concerns regarding failure as variances from known design specifications are introduced. This characterization can reduce institutional resistance and reluctance to embrace innovation in design concept development. If a population of design concepts contains members that show greater amounts of Value and Component Distance from the base design while maintaining acceptable performance, then they can be assessed as innovative. The criteria are also able to identify when design concepts are produced that, while having variance from the industry standard, only do so to a small degree and thus represent minor variants to the known solutions vice truly innovative alternatives.

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