Executive Summary of Master's Thesis
MIT Systems Engineering Advancement Research Initiative

Quantifying Flexibility in the Operationally Responsive Space Paradigm

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Abstract

Designing complex space systems that will deliver value in the presence of an uncertain future is difficult. As space system lifetimes are now measured in decades, the systems face increased risk from uncertain future contexts. Tradespace exploration increases the designer's system knowledge during conceptual design and with dynamic analysis can predict the system's behavior in many possible future contexts. Designing flexible systems will allow mitigation of risk from uncertain future contexts and the opportunity to deliver more value than anticipated by the designers.

Flexibility is a dynamic property of a system that allows it to take advantage of emergent opportunity and to mitigate risk by enabling the system to respond to changing contexts in order to retain or increase usefulness to system stakeholders over time. *Value Weighted Filtered Outdegree* is introduced as a metric for identifying valuably flexible systems in tradespace studies in order to improve decision making during the conceptual design phase. Dynamic Multi-Attribute Tradespace Exploration (Dynamic MATE) is used as the basic tradespace exploration method for Value Weighted Filtered Outdegree, and applies decision theory to computer simulation of thousands of system designs, across hundreds of unique future contexts. Epoch-Era Analysis is used to parameterize future contexts for dynamic analysis of the designs' performance. Although dominated in static analysis, flexible designs are valuable in the presence of changing contexts.

Keywords: flexibility, tradespace exploration, engineering systems, operationally responsive space

1. Introduction

Since the launch of the first artificial satellite, Sputnik, on October 4, 1957 the uses and applications of satellites have become entwined in national security, commercial ventures, and everyday households. Timing signals from Global Positioning Systems constellations enable ATM transactions, voice and telecommunications are transmitted almost instantly around the world, and military operations in far-flung Areas of Interest (AOIs) are supported in real time from locations within the nation. Satellites have become an accepted and essential component of doing business in the modern world, and as engineers look to the future the demand for space-based capability is likely to increase.

2. Problem Formulation

As the expected lifetime of a satellite system increased from years to decades, the need to keep the system relevant became more pronounced. Flexibility is a dynamic property of a system that allows the system to take advantage of emergent opportunity and to mitigate risk by enabling the system to respond to changing contexts in order to retain or increase usefulness to system stakeholders over time (Ross et al., 2008; Viscito and Ross, 2009). A space system that is flexible will deliver more value over these changes than a non-flexible

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system. Increasing system costs and operational lifetimes have driven research in recent years to develop understanding of how flexibility can be incorporated into systems in the conceptual design phase (Saleh et al., 2008). However, the concept of flexibility is still not mature, and designing for flexibility would be aided by a way to compare the flexibility of systems during conceptual design.

2.A. Problem Statement

Space systems are essential to the national security of the United States of America and many other nations. Typically, designers would consider objectives such as cost, mass, volume, and capability, and the satellite that minimized mass, volume and cost at the greatest capability would be the optimal design. However, the lifetime of the system can often be measured in decades. Over that period of time, the likelihood of the environment and user requirements changing is very high. If the context does change, it is possible the system will no longer deliver acceptable levels of value. Value is a subjective measure of benefit from a bundle of consequences that is specified by a stakeholder (Keeney and Raiffa, 1993).

2.B. Research Questions

This research seeks to answer two questions.

1. What is an objective, repeatable metric that incorporates design utility and flexibility?
2. Does a modular architecture have more flexibility than a legacy architecture for an electro-optical imaging Operationally Responsive Space mission with changing user preferences?

In answering the first question, the process of developing the metric will be described, and then the metric is demonstrated in a case application. Dynamic MATE (Ross, 2003, 2006), and Epoch-Era Analysis (Roberts et al., 2009), are explained within the implementation framework Responsive Systems Comparison (RSC) (Ross et al., 2008). The extensions for calculating the metric are described using the information generated during RSC.

The second question deals with applying the new metric to a current topic and exercising the new metric. A case application about Operationally Responsive Space (ORS) (Cerbowski and Raymond, 2005; Department of Defense, 2007; Fram, 2007) will compare the flexibility of two architectures for ORS: legacy or ‘custom’, and modular.

3. Value Weighted Filtered Outdegree

Because the value of flexibility is only realized in the presence of uncertainty, the designer needs to have a possible future era in which to asses the design in the tradespace. Value Weighted Filtered Outdegree is defined as:

$$VWFO_i^k = \frac{1}{N-1}\sum_{j=1}^{N-1}[sign(u_j^{k+1} - u_i^{k+1}) * Arc_{i,j}^k] \tag{1}$$

where
N is the number of designs considered
k is the current epoch
$k+1$ is the next epoch in the era
i is the design under consideration
j is the design to be transitioned to
u_i^{k+1} is the utility of design i in the $k+1$ epoch
u_j^{k+1} is the utility of the design j in the $k+1$ epoch
$Arc_{i,j}^k$ is the logical value indicating the presence of a transition arc from design i to design j

$VWFO_i^k$ is dependent on the choice of N, the subset of designs from the design space. The analyst can choose to look at the VWFO of an entire design space, in which case N is the same as the total number of designs in a the tradespace study. Alternatively, a smaller subset of designs can be chosen, and examined in great detail. VWFO uses the direction change in utility to determine if a particular transition is 'good', which occurs when the design transitions to a design of higher utility. By summing both the positive and negative transitions, the designer can see designs that are valuably flexible, (the design with positive VWFO), and the designs that are changeable but are carrying 'dead weight' (the design with negative VWFO).

3.A. Satellite Radar System Case Application

The Satellite Radar System is an extensive modeling effort performed by several students. The model follows the RSC processes, which are described in Ross et al. (2008).

This metric captures the utility difference in the destination designs and is dependent on how many transitions are available. The intent of the metric is to act as a screening heuristic, and it is left to the decision maker to make a final call on the value of the design.

Designs with high magnitudes of VWFO may be more valuably flexible than others. Designs that have positive VWFO are able to transition to destination designs that have higher net utility. Unlike choosing designs based solely on high NPT or high FOD, VWFO can identify designs that are valuable and flexible. VWFO takes into account the value of the change (the utility change direction), the changeability of the design (transition arcs), and the context changes (era progression).

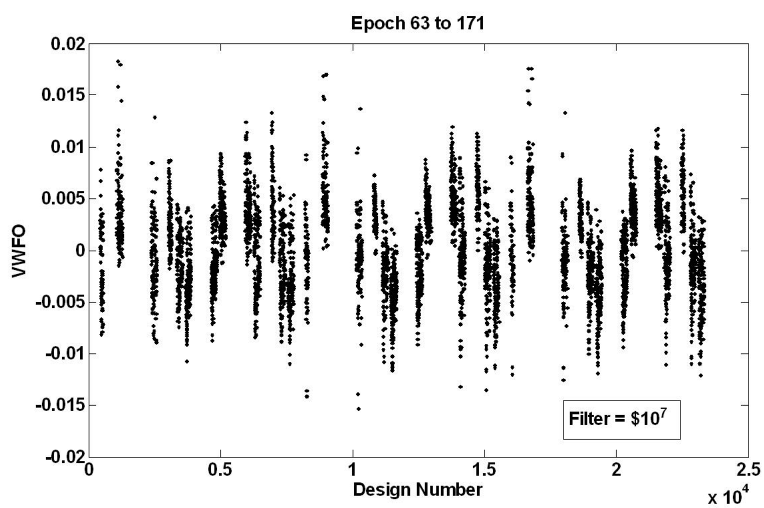

Figure 1: Value Weighted Filtered Outdegree for Epoch 63-171

Figure 1 plots the VWFO for an entire tradespace by design number. The striations in the space are caused by the discrete enumeration of the design space.

The SRS case application revealed several interesting aspects of VWFO. Several designs had high VWFO, and one way for a designer to determine which design to analyze further is to use Figure 2, which indicates designs with high VWFO and high origin design utility. By having positive VWFO and high starting utility, these designs have more transitions to other high utility designs.

There are several limitations to VWFO. The first is that the results obtained from any study of this nature will depend on the transition rules chosen. If the designers do not specify transition rules that are useful during context changes, no designs will be identified. In addition, it is also dependent on the order of epochs in the era, which determines which designs are valid for transition. Essentially, if a design in invalid in either epoch, it appears as invalid in both. Another problem with the metric occurs when the VWFO of a design is zero. The designer does not know, without further analysis, if that design has zero VWFO

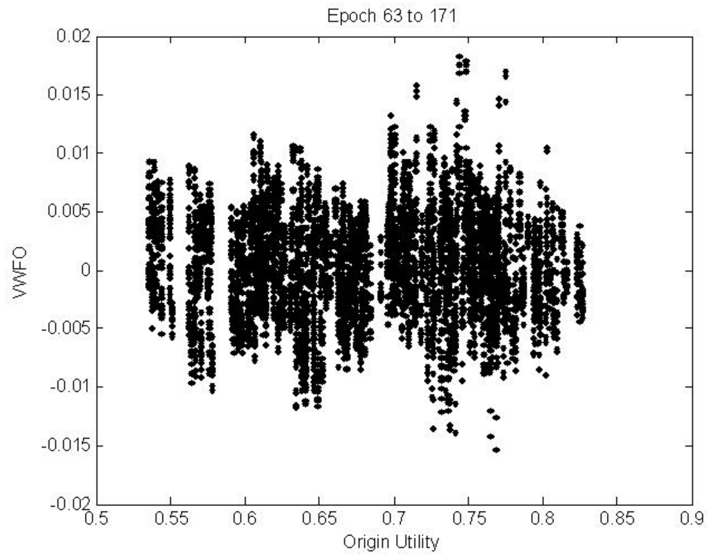

Figure 2: Total Utility of Origin Design with VWFO to Check for Linear Correlation

because it is an invalid design in one of the epochs, or because the net utility change is zero. The metric is also dependant on the tradespace sampling strategy used by the designer. If the design space has many designs in one area of the design space, which causes the FOD of those designs to increase, it is likely that the VWFO of the design will increase disproportionately as well.

3.B. Operationally Responsive Space Case Application

The ORS case application modeled a small electro-optical imaging spacecraft (Richards et al., 2008; Viscito et al., 2009), constructing a legacy or modular spacecraft system for the designs. The modular designs had an expansion option available in the event that changes were required during the early phases of the spacecraft. Figure 3 shows VWFO plotted by design number for each of the epoch transitions.

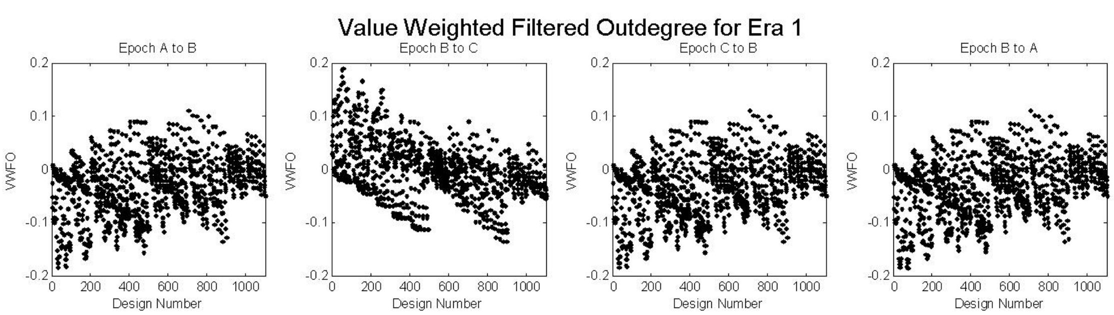

Figure 3: Value Weighted Filtered Outdegree for ORS Era 1

The designs with the highest VWFO are the modular architecture designs. Interestingly, these designs are not the highest utility designs, as indicated by the Pareto sets , nor the highest Filtered Outdegree designs, reinforcing the intuition gained from the previous case study that there is a sweet spot for flexibility somewhere off the Pareto Front. Modular designs are not required to be on the Pareto Front, as the value of the architecture manifests when stakeholders' needs change. The ease with which a modular spacecraft can be built to meet these new needs is more than that of the legacy systems. While the legacy systems may be more optimal in the traditional sense, under the paradigm shift where responsiveness is more important than perfection, a modular architecture may be beneficial.

The differences between legacy and modular architectures, as modeled, are shown in the static tradespace and in the VWFO analysis. While traditional metrics such as Pareto Trace and Filtered Outdegree identified two sets of designs, VWFO indicated a design set separate from those identified earlier. As the choice for ORS systems, a modular architecture looks like a good choice. Designs with modular architectures have higher VWFO than many of the legacy architectures.

A note of caution, however, as the result will be very sensitive to the actual ability of the modular architecture to achieve the schedules and costs estimated in this model. If the modular architecture is used to advantage, meaning that many spacecraft are built taking advantage of the economies of scale available, then the results may hold true. However, the experimental nature of the ORS paradigm should signal that many of the assumptions made in this model may prove to be invalid.

4. Conclusions

While previous metrics measured the passive value robustness of a design (Normalized Pareto Trace) or the changeability of a design (Filtered Outdegree), neither has addressed the how to identify valuable changes. Flexibility, much like optimization, is only optimal with respect to a defined objective, and therefore saying a design is flexible begs the question of what contexts it is flexible to. Changeable designs have many ways to transition to other designs, but these designs are only valuable if the transition can mitigate utility loss, either in the near or long term. Interest in flexibility as a risk mitigation strategy has increased, so it has become necessary to create a metric for identifying valuably flexible designs. The operationalization of valuable flexibility from a general concept to a tradespace system property will aid decision makers and increase their ability to make the business case for including flexibility.

Flexibility is the dynamic property of a system that allows it to take advantage of emergent opportunity and to mitigate risk, by enabling the system to respond to changing contexts, in order to retain or increase usefulness to system stakeholders over time. As the lifetime of a system approaches decades long, the likelihood of encountering changing contexts increases, leading to the risk that the system will not be able to deliver enough value in the new context. This risk, along with the desire to take advantage of opportunities also presented by the changing contexts, has increased the desire to include flexible systems in conceptual design trade studies. However, identifying these flexible systems has often been a subjective and haphazard endeavor.

Dynamic MATE, a method using utility theory and computer simulation to aid decision making during front-end conceptual design, was used as the framework for developing a flexibility metric. Several existing MATE metrics, *Normalized Pareto Trace* and *Filtered Outdegree*, informed the new metric for flexibility: *Value Weighted Filtered Outdegree*. VWFO is objective and repeatable; it identifies the valuably flexible designs by combining changeability with the value as operationalized by utility changes. To incorporate the dimension of time, which is necessary for flexibility to be valuable, future scenarios were parameterized with Epoch-Era Analysis.

VWFO acts as a screening heuristic on a design space, identifying designs that are valuably flexible. This gives a decision maker several designs with which to focus the search for flexibility. When presented with the thousands of designs that may be generated in a front-end tradespace study, any decision maker may be quickly overwhelmed with the amount of data that is presented. As designers, distilling this much data looking for the 'best' designs can be a daunting task. By operationalizing the 'ility' of flexibility, the designers have been given a starting point.

VWFO is a good metric for capturing flexibility for three reasons.

1. It is objective and repeatable.

2. The assumptions and biases in the metric can be understood by examining the transition rules, the epochs and eras chosen, and the model assumptions.
3. It identifies a subset of designs that are highly changeable and valuably flexible.

Static analysis of the ORS tradespaces revealed that in general, the modular architectures had more utility than the legacy architectures, for a higher cost in the short term, or for a constant utility, higher cost. While the legacy architectures had lower initial costs and tended to have higher Filtered Outdegree, many modular designs had higher VWFO. This would suggest that the modular architecture, for the given transition rules and modeling assumptions, does have more flexibility than the legacy architecture. Given the low confidence in the modular cost estimation models, a sensitivity analysis is necessary to see if this is actually the case, however this was outside the scope of the case application.

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