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Complex Systems Architecting Using Design Primitives, Comparative Analysis and Fuzzy Analytical Feedback

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Abstract — Modern systems are increasing in complexity. It is advantageous to understand and control this complexity as early in the design lifecycle as possible. The system architecting community must reconcile the inherent ambiguity in a system description with the need for analytical assessments of system attributes so as to increase the likelihood of developmental success. Presently, it is commonplace to decompose systems and subsystems using assumptions of idealized severability and reliance on superposition to estimate composite performance. It is suggested that these assumptions can result in errant oversimplification and represent an opportunity for new systems engineering research. This paper introduces a new methodology for assessing system architectures — one that leverages tools and expertise commonly found in the specialty domains of detailed engineering disciplines. The foundational elements and concepts behind the Canonical Decomposition Fuzzy Comparative assessment method are presented herein. The intent of this research is to better illuminate the characteristics of inter- and intra-system dynamics for programs that warrant the increased rigor of this method.

Keywords—architecture; extensible; canonical design primitive; comparative analysis; fuzzy assessment

I. INTRODUCTION

As systems evolve with increasing complexity, the methods, processes, and tools (MPTs) used to develop them must similarly evolve. Initial system architecture concepts are inherently ambiguous, but the sooner an architecture can be characterized and understood, the better it can be planned, managed and controlled. Systems architecting is a search process whose goal is to efficiently navigate a near infinite combination space in pursuit of a solution that is best able to satisfy a multitude of competing system goals. While performing this search, the architecting process yields a hierarchical reduction in ambiguity as system concepts move from the fuzzy word-based descriptions of customer needs to the crisp quantitative descriptions of the detailed design community.

The selection of a system architecture plays a critical role in the eventual success or failure of any program. Contained within the chosen architecture are hidden dependencies, coupling variables, and unforeseen details that will emerge as the system design moves forward. Improper architecture selection can disadvantage or condemn a system from the outset. Thus, there is an intrinsic dilemma in systems architecting: to remain tolerant of ambiguous system descriptions while trying to objectively and realistically assess architecture candidates.

The architecting process is iterative — each time striving to produce an architecture that satisfies competing measures of success. The process begins at the functional architecture level, progresses through more detail to the system architecture, and finally yields a physical architecture description. The physical architecture may identify technologies to incorporate, but is still ambiguous since the detailed design work for the physical artifact has yet to begin. Thus the dilemma identified above is present in all levels of the architecting process.

In response to this dilemma, and the need for new MPTs, this paper describes the results of ongoing research to develop an architecture assessment method that improves fidelity and objectivity while remaining tolerant of design ambiguities. The Canonical Decomposition Fuzzy Comparative (CDFC) method is an analytically rigorous assessment method that is currently being studied at the physical architecture level. The principle reason for focusing on the physical architecture level is the computational complexity of the CDFC method. This complexity makes the assessment lengthy and thus some means to reduce the input search space is needed. Smart Systems Architecting methods, such as those presented in [1], can be used to provide the CDFC method with a subset of the strongest system architectures for consideration at the physical architecture level. The details of the CDFC method are addressed in each of the following sections.

II. THE CANONICAL DECOMPOSITION FUZZY COMPARATIVE METHOD

The most rigorous assessment takes place at the physical architecture level. It is commonplace to decompose systems by assuming perfect severability between components and assigning them nominal performance values. Furthermore, system architects frequently rely upon superposition of the
nominal subsystem performance estimates to predict net system responses. However, [2-4] suggests that these assumptions may result in errant oversimplification. The practices just described are usually employed due to the absence of reliable analytical predictions of integrated system performance. Ref [5] asserts that “meaningful measurements may be impossible or impractical” for complex systems that do not yet exit. It is the goal of this research to develop an architecture assessment methodology that better illuminates the nature of inter- and intra-system dynamics thereby offering a more realistic assessment of system performance and improving the systems architecting/engineering process.

The Canonical Decomposition Fuzzy Comparative architecture assessment method consists of four elements:

- **Extensible modeling** – The extensible modeling concept facilitates the exchange of data between model resolution levels. By understanding the equations and algorithms used at each level of system modeling, one can decompose an analysis to examine the validity of the input parameters. Similarly, by specifying the output of low level model data, analysts can integrate basic physical quantities into larger system models without recalculating them.

- **Canonical design primitives** – Canonical design primitives are basic representations of classes or genres of system components. They do not represent actual physical artifacts, but are instead the inspiration from which many eventual designs originate. They contain enough specificity to support computational analysis, while retaining the ambiguity still present in candidate architectures.

- **Comparative analysis** – A comparative analysis approach further supports the ambiguity of candidate architectures. Given that physical system architectures are decomposed into canonical substructures, the assessment performed cannot be overly specific. Instead, conclusions are reached based on comparative measures between baseline assumptions and canonical embodiments or between physical architecture alternatives.

- **Fuzzy inference** – The data that is generated via comparative analysis must be interpreted with the same appreciation for ambiguity that is given during decomposition into canonical substructures. Fuzzy inference systems provide a mathematically rigorous and repeatable way to map system response features to fuzzy sets describing the overall architecture assessment.

Figure 1 illustrates the composition of the CDFC method. Each of the four elements is discussed in detail in subsequent sections.

III. EXTENSIBLE MODELING

Multi-resolution modeling is the ability to conduct analyses at different levels of detail depending upon the number of actors involved and the required level of fidelity. Extensible modeling joins modeling activities by enabling the exchange of model data via interfaces between the resolution levels. In this way, the information produced in one model environment can benefit from, and offer support to, interfacing model environments.

Consider a large campaign or system of systems operational model. Numerous independent actors are involved and each is typically described in terms of general system attributes or overall strength/weakness metrics. To justify these values, underlying measures of effectiveness can be calculated from system functional models. As described in [6], measures of effectiveness are decomposed into, or are supported by, system measures of performance. Finally, the measure of performance associated with a system model can be justified based on technical performance measures calculated at the subsystem model level. The interactions in this hierarchy are shown in Figure 2 below.
As an example, consider a large campaign model predicting the outcome of military operations when provided with supporting airborne radar jamming. This type of modeling is commonly statistical in nature, employing a Monte Carlo or other multiple random trial approach. An assumption about the jamming platform may suggest that it is x% effective against a particular radar. To support this macro-level assumption, one should decompose the jammer and the radar into system functional models and predict their effective radiated power and receiver sensitivity. These quantities can be linked via an RF path loss model to determine signal power levels and determine the J/S ratio. Taking this one step further, one will find that predictors for effective radiated power require estimates of antenna gain. The antenna gain is a technical performance measure that can be estimated at the subsystem model level. A different level of resolution is required to estimate each of the quantities described in this example. The extensible modeling concept connects these resolution levels and links the assumptions or dependencies in each performance indicator. A more detailed treatment of extensible and multi-resolution modeling is available in [2-4].

IV. CANONICAL DESIGN PRIMITIVES

One benefit of extensible modeling is that it allows system architects to leverage the tools and expertise of the detailed design community. Computational techniques such as finite element analysis, finite difference time domain, method of moments, finite integration technique, and others offer very powerful means to analyze the performance of a component or subsystem. The primary obstacle to using this level of analysis is the fundamental reality that a system architecture is still ambiguous as to its final physical form. Indeed, the techniques mentioned are usually used to optimize the final physical artifacts whose performance specifications have been decomposed from higher level architectural performance measures during system development. Without these detailed design specifications, one might wonder how these tools can be used and what value they provide.

At the physical architecture level, one may not have insight into the details of the final embodiment of a system, but the architecting team has generally narrowed the list of candidate technologies. In fact, many architectural alternatives at this level are simply permutations of the same set of technologies. A technology in this context refers to a class, or genre, of physical artifact. For example, candidate technologies for moving a large industrial vehicle include tires, tracks, or walkers. While technology descriptions at this level sound vague, one finds that a technology genre has several basic design equations governing its inherent attributes. These basic design equations describe a canonical form of the technology. Final designs often draw their inspiration and represent optimized departures from canonical forms. In this way, the canonical form is representative of the technology while remaining tolerant of design ambiguity by not over specifying the design details.

One is able to employ the computational analysis described earlier by decomposing a candidate physical architecture into its canonical substructures. In doing so, architecture assessments become more realistic. Natural coupling between system components can be exposed and estimations of system sensitivities can be made.

The type of canonical primitives used is highly dependent on the system under study and the desired level of detail in the analysis. Figure 3 illustrates some canonical design primitives. Each primitive facilitates a computational model that contains the important attributes of a particular technology. The dipole antenna in Figure 3a represents a fundamental resonant E-field antenna exhibiting omnidirectional radiation in the plane perpendicular to its axis. The horn antenna in Figure 3b represents a canonical structure exhibiting directional radiation. The loop antenna in Figure 3c is a fundamental H-field antenna. The ram air turbine (RAT) in Figure 3d facilitates analyses of point of use power designs based on different airflow configurations, blade diameter, and revolutions per minute. The airborne pod structure in Figure 3e allows for the calculations of system volume, center of mass, and aerodynamic drag.

It must be noted that performance assessments derived from analysis on canonical structures is only accurate for that particular physical form. Final system hardware will have different levels of performance and system analysts must be careful in the conclusions they draw from canonical analysis. To ensure the legitimacy of canonical analysis, one should consider a comparative analysis approach.
V. COMPARATIVE ANALYSIS

A comparative, or differential, analysis identifies the contrasting features between two items whose configurations are carefully manipulated. By identifying and controlling key configuration parameters, the impacts of single or multivariate changes can be assessed. In empirical settings where samples of measured quantities are the subject of investigation, many statistical techniques can be employed to facilitate the design of experiments, determine the size of a response, and produce confidence intervals with respect to those estimations. In an ambiguous setting such as architecture assessment, it may not be possible to precisely estimate the magnitude of a response. However, it is generally possible to identify trends in output performance as a result of changes in input parameters. It is also possible to generate an ordinal ranking of architecture configurations based on estimated response levels, trends in performance and sensitivity, and comparison between integrated canonical models and baseline assumptions.

As mentioned, the calculated performance of a canonical design primitive is inextricably linked to its physical representation. However, if a single canonical structure is chosen as a baseline for comparison, analysts can perform a comparative assessment between different configurations employing the same structure. For example, the canonical RAT shown in Figure 3d can be used to compare the AC power production potential in free stream versus internally ducted air for airborne point of use power scenarios. Similarly, the canonical antenna structures can be used to compare the placement alternatives for a radiating aperture on a vehicle or fixed ground site.

Comparisons between alternatives employing the same technology expose the impacts of inter- and intra-system interactions as a result of differing configurations. Because the same canonical structure is used in both settings, the predicted system performance is normalized to the performance of the canonical primitive. The comparison or trend that emerges remains valid regardless of the actual response magnitude in the modeled primitive. When employed in this way, the canonical design primitive becomes a probe structure allowing for the creation of integration sensitivity functions and n-dimensional response surfaces [7-8]. Using one configuration as a baseline, the performance data from each of the others can be normalized to it. Presenting this comparison in the form of a contour plot allows for a visualization of a response surface such as the one shown in Figure 4. The response surface approach allows large quantities of data to be viewed, and compared, simultaneously.

Comparisons between architecture candidates using different technologies require additional consideration. The effective probe structure changes between models when the canonical design primitive changes as a result of a different technology. In these situations, the models under comparison are not normalized by the same canonical probe performance levels. A nominal performance indicator can usually be produced based on other system constraints. Computational fluid dynamic models may estimate that the RAT in Figure 3d produces \( x \) volt-amps of prime power. This is not to say that ram air technology will not produce more, only that given the constraints on average airspeed and allowable blade diameter, \( x \) volt-amps is the estimated nominal output. Comparative analysis between architectures employing different technologies involves multivariate changes in the system model, but the performance assessment is more rigorous, repeatable, and objective than heuristic methods.

VI. FUZZY INFERENCE

It has been shown that canonical decomposition allows for detailed analysis of system coupling and architectural sensitivity while remaining tolerant of ambiguity in the final form of the subsystem components. The accommodation of ambiguity is continued in the comparative analysis methods described in the previous section. What remains is an ambiguity tolerant mechanism to provide overall assessment feedback to the architecture search process.

Fuzzy logic is an extension of classical logic that enables computation on imprecise relationships using linguistic variables. Most importantly, whereas classical set membership is all-or-nothing, fuzzy set theory supports partial membership in a set. In this way, a quantity can have degrees of membership in one or more sets. These attributes make fuzzy logic an attractive means of applying mathematical rigor, objectivity, and repeatability to the artificially crisp data sets produced from comparative analysis of inherently ambiguous architecture definitions. More information on fuzzy logic and fuzzy set theory can be found in [9].

A Fuzzy Inference System (FIS) establishes a mapping between input and output variables using fuzzy logic. A FIS is composed of a set of membership functions to fuzzify the input quantities, a number of rules in the form of IF-THEN statements, fuzzy operators, an implication method on fuzzy membership functions for output variables, and an aggregation method to defuzzify the result [10]. Figure 5 illustrates the composition of a Mamdani type FIS. The FIS represents the means by which comparative data sets can be assessed and feedback is provided to the architecture search process.
The number and type of input variables for the architecture assessment FIS is customizable and highly dependent upon the nature of the comparison. Comparative data sets may undergo preconditioning to highlight global or local features including: deviation magnitude and direction, average response levels, surface gradients, or broken thresholds. For each input variable, fuzzy response levels must be specified and encoded via the fuzzy membership functions. A suitable rule set can be the most challenging aspect of FIS design. The membership function shapes and rule set form the basis for the output value representing the assessment of the architecture. As a result, much care must be taken in the design and validation of the FIS rule set.

The output of the FIS is a single crisp data point representing the overall architecture assessment, and thus the output of the CDFC method. Of special interest is the use of this output as a fitness value for Smart Architecting methods described in [1]. In addition to a composite assessor, fuzzy assessment results can be generated to provide the architecting team with indicators of constituent performance measures. These can be useful for traditional search methods that work to manually adjust the architecture under development. In either scenario, the feedback mechanism can be facilitated via one or more fuzzy assessors.

VII. CONCLUSION

Assessment is a critical step in the architecture search process. Heuristic and subject matter expert based approaches handle the ambiguity of system architecting quite well, but can suffer from lack of objectivity and repeatability. Traditional macro-level analytical assessments improve upon this shortcoming, but their computational simplicity prevents analysts from identifying important underlying characteristics of an architecture [4].

This paper summarized recent research addressing the need for an objective, repeatable and defensible assessment approach that can tolerate the ambiguous nature of system architecting. The theory and underlying principles of the Canonical Decomposition Fuzzy Comparative method were introduced herein. This method provides the systems architecting community with access to tools traditionally reserved for the detailed design community. The analytical rigor of these computational techniques and the calculus of fuzzy logic make the CDFC approach objective, repeatable, and defensible. The use of canonical design primitives, comparative analysis, and fuzzy inference make the CDFC approach tolerant of ambiguity.

As with any other systems architecting method, process, or tool, the CDFC approach is customizable. The degree to which each element is used is at the discretion of the architect. Each of the elements described herein have been prototyped and used individually in either current research or in practical application. Current and future research is focused on refining the interaction between the elements so as to create a cohesive and customizable assessment methodology.

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