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Systems Engineering the Lifecycle – An Approach for Developing Complex Systems Using Control Theory

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ABSTRACT

Systems Engineering is an interdisciplinary approach that concentrates on the design and application of the whole as distinct from the parts. For complex systems, this includes the challenge that the behavior of the system as a whole is not intuitively understood by understanding the components. Classic System Engineering models establish a perception of a beginning and an end of the systems engineering process. Unfortunately, a long period between product launch and discovery of unexpected behavior for systems may occur with a protracted lifecycle.

A Systems Engineering approach based upon the "control theory" model establishes a high correlation between interdisciplinary models to facilitate feedback throughout the system lifecycle to tune capabilities to user satisfaction. This close coupling extends well beyond tracing of requirements to qualification testing fulfillment as practiced in the traditional "V" model. The system itself is a traceability link providing lifecycle feedback control on the current fulfillment of requirements versus expected fulfillment. The institution of this approach will establish a Systems Engineering feedback measure of user satisfaction from system inception to retirement, rather than merely a front-end design activity.

INTRODUCTION

The classic Systems Engineering "V" model is used to ensure that requirements are expanded and fulfilled. However, this model carries the perception of a beginning and an end of the Systems Engineering process that limits its scope, and ultimately its effectiveness. Current research shows that "lean" principles espoused within the Department of Defense (DoD) offer the continuous improvement essential for complex systems [1]. In today's complex systems there will be discovery of unanticipated behavior over the product lifecycle that requires monitoring, analysis, action and evaluation as part of the Plan/Do/Check/Act (PDCA) process. This is especially true in complex systems, because by their very nature they typically involve many stakeholders and long lifecycles. In practice, even with the best application of System Engineering, the stakeholder representatives involved in the early stages are statistically insignificant given the total population of end users. The needs of the entire customer community are not fully understood as the users are part of the dynamics of a complex system. This often means the Systems Engineering artifacts – especially those related to behavior, use of new capabilities, and performance assumptions – are nearly impossible to fully comprehend in a single, front end analysis phase of a traditional Systems Engineering process. Applying an engineering process that couples lean principles with a multi-disciplined model-based approach ensures a high level of collaboration between the domains represented by functional architecture, logical architecture, and human factors to minimize the initial error in desired system behavior. The purpose of modeling is to achieve insight, or develop an intuitive feeling for the behavior of a system[2]. In a model-based approach, the architecture models are inputs into a standard feedback control system (see Figure 1) that establish the controlling factors of the system, the necessary monitored attributes to measure customer (e.g. warfighter) satisfaction, and the criteria used to evaluate and adjust the capability models accordingly. This process is continued throughout the system lifecycle in order to focus on improvements driven by customer expectation which often changes as exposure to new capabilities drives user innovation of additional useful applications.

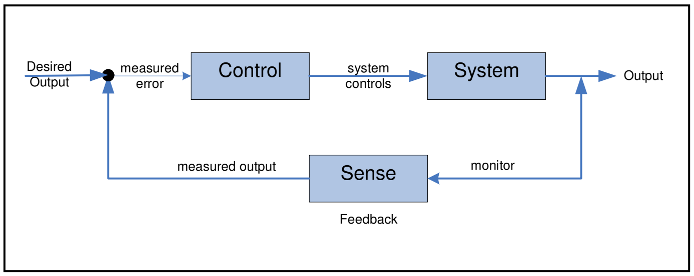

Figure 1: Simple Control Model.

BACKGROUND

In 2006, there were several key reports that explored more effective methods of integrating software engineering, systems engineering, human factors, and the acquisition process. The Deputy Under Secretary of Defense (DUSD) Acquisition, Technology, and Logistics (AT&L) Defense Software Strategy Summit [3] identified the following issues:

1. The impact of system requirements upon software is not consistently quantified and managed.
2. Fundamental systems engineering decisions are made without full participation of software engineers.
3. The quantity and quality of software engineering expertise are insufficient for dealing with complex modern systems.

Additionally, in 2007 the National Research Council produced a report on Human-System integration in the process of developing systems [4], identifying five principles critical to the success of human-intensive system evolution:

1. Satisficing[1] the requirements of the system stakeholders
2. Incremental growth of system definition and stakeholder commitment
3. Iterative system definition and development
4. Concurrent system definition and development
5. Management of project risk

The application of control theory to the process is synergistic with the Incremental Commitment Model (ICM) introduced through research conducted at the University of Southern California [5], and is complementary to in-process changes identified in the Joint Capabilities Integration and Development Systems (JCIDS) and Defense Acquisition Systems documents. Although these concepts are discussed separately in the following paragraphs, they provide the opportunity to transform product performance when applied properly together.

INCREMENTAL COMMITMENT MODEL

The Incremental Commitment Model (ICM) by Boehm and Lane in its simplest form looks to identify and define commitment points along the overall lifecycle. They state that "Requirements and commitment cannot be monolithic or fully pre-specifiable for complex, human-intensive systems; increasingly detailed understanding, trust, definition and commitment is achieved through an evolutionary process."[5] Specifically, trying to force this understanding prematurely and precisely generally leads to poor business or mission performance. A key aspect of the ICM is that there is not a large single commitment to the capabilities initially envisioned, but there are smaller commitments to see whether the prospects of success are favorable. In addition, there is a decision to increase the commitment based on better information on the prospects of success that emerge from each incremental gamble.

The ICM advocates several tenets that align well with a controls model where the system is executing and at the same time adjustments to the system are being fed into another iteration. ICM supports concurrent engineering of requirements and solutions. Additionally, ICM promotes a stabilized incremental development concurrent with a separate change processing and rebaselining activity preparatory for a subsequent increment. This is to incorporate a streamlined process that avoids unnecessary documents, phases, and reviews based on a clear risk assessment.

CONTROL THEORY AS A FRAMEWORK

A simple feedback control framework contains a Control, a System, and a Sensing block as shown in Figure 2. The Control block takes inputs that provide the initiating reference on the controlling factors of the System. The System response is monitored with the Sense feedback providing a measured output. This feedback is referenced to the Inputs to provide a measured error that is then corrected by the Control. This loop continues to adjust to differences between the expectation provided by the input and the actual response.

This feedback control model provides an excellent approach to managing high quality development of complex systems. The initial input is the models that define the capabilities of the system. The most balanced method for

[1] A decision-making strategy where consensus is reached on adequacy for the whole population of stakeholders, but may not be the best or optimal solution for any individual stakeholder. The combination of satisfy and suffice.

doing so includes four models: a functional model validated through a behavioral model that exposes the tasks elaborated in a human factors model - all solidified in a reliability performance model.

The control measures derived from these models include the requirements, design, processes, personnel/training, and physical material solution artifacts of the system. The system response to these controlling factors will provide an output of system use that indicates the user satisfaction with the supplied capabilities. Because the system is complex, error from expectation may be detected as unplanned behavior, incorrect execution, refined capability definition, and/or additional capability desires. The larger stakeholder population utilizing the system in deployed operation provides a greater statistical representation of the intended capability usage, thereby establishing an essential feedback of user satisfaction with the deployed implementation. Correcting the models from the known response brings the system closer to the true desired behavior as the process repeats. The originally unknown behavioral complexity of both material solution and human interaction as one system becomes exposed and refined.

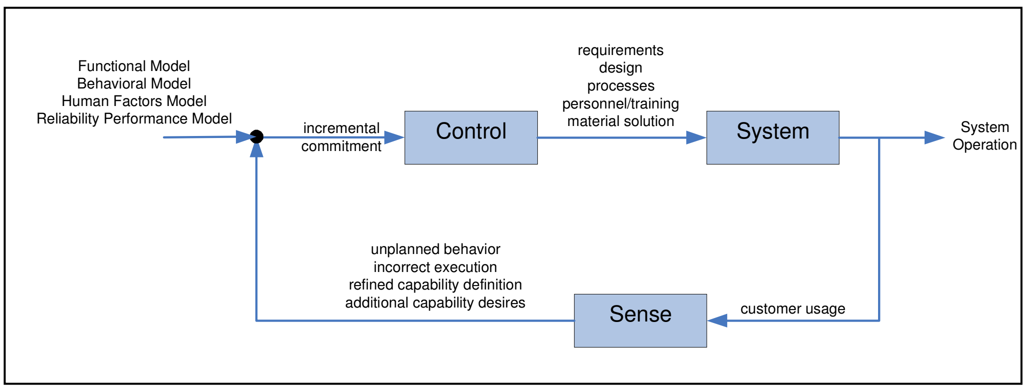

Figure 2: User Satisfaction Control Model.

The control model is most useful as automation is enabled in the Control block to transform the model error correction into the controlling factors (e.g. requirements, design). This is possible through a myriad of integrated engineering tools, but must utilize an integrated analysis methodology that directly translates the model into controls that Program Managers can impose upon their suppliers. Otherwise, the valuable field information may be mis-communicated to the material suppliers, which will result in an excessively long settling time to "satisficing" the end user expectations. Additionally, automation is important in gathering, measuring, analyzing, and correcting undesired system response. The challenge remains on how to measure the response, translate that into a metric on user satisfaction, and adjust the capability models in a disciplined manner.

WEB ANALYTICS PATTERN

Web analytics, such as those provided by Google Analytics, provide a framework for evaluating customer satisfaction. Web Analytics evaluate how a user gets to a company's site, how they navigate through the site, where they spend their time, and how they become customers. The purpose is to use the analytics to improve the desired end results. Visualization mechanisms are provided to organize the data in various manners, such as identifying trends based on geographical or demographical criteria (e.g., are most of those visiting the website from a region where media advertising is being used).

Much can be gained from a similar approach to understanding user satisfaction with capabilities in a complex system. Collecting data on how a user accesses a capability, amount of time dwelling on a specific aspect of the capability, and navigation of what capability is used prior to and subsequent to each capability. Analyzing this data can be indicative of what the user finds most useful, least useful, and what they utilize in a way previously not envisioned. Geographical and demographical analysis can provide insight into capability use related to the mission profile, training, maturity, or role of the user.

When following a Systems Engineering approach with the lifecycle in mind, the collection of the stakeholder usage data does not need to be intrusive. Many of the parameters can be inferred from data that is available and useful for other purposes, such as usage data for Condition-Based Maintenance (CBM). The application of usage data for multiple purposes that benefit the stakeholders provides a higher level of return on investment (ROI) for a set of collected information.

JOINING CONTROL THEORY AND ICM TOGETHER

It has been established that vehicle programs are complex systems that have extended lifecycles. Furthermore, we have established that complex human-intensive systems cannot be fully understood with one pass through the analysis phase, and that full commitment is usually not achieved if left to the end. We have also shown that a control model can provide a simple framework for the iterative nature of developing complex systems. Additional success comes from joining the two together.

Therefore, as one develops complex systems using an iterative control theory framework, it is desirable to gain customer commitment each time through the feedback loop, which can be gained in many ways. It could be as simple as demonstrating that the requirements included in the prototype system trace to their initial higher level requirements. It may be that data can be collected from the system to perform Reliability Centered Maintenance (RCM) analysis and/or CBM analysis to see if the as-built system meets reliability or operational availability metrics and predictions. Securing incremental customer commitment on the operational flow and/or user interface is another way to avoid costly changes later in the product's lifecycle. Finally, on each iteration through the feedback loop the customer remains highly engaged in the development and validation process. Perhaps the most important benefit of the process is that it gives the acquisition authority the ability to abort or reset the development process at any point if expectations are not being met, or following the "satisficing" principle that the capabilities are sufficiently complete. This reduces the possibility of these large or complex projects being delivered only to miss the mark by a wide margin or to require a long funding cycle to meet pre-established performance goals that are beyond that which is necessary to meet the stakeholder expectations.

CONCLUSION

The classic Systems Engineering "V" model is effective in assuring that discipline is used in the conversion of capability desires into an implementation that is validated to fulfill those desires. However, this model carries a perception of a beginning and an end of the systems and does not easily accommodate ambiguities and/or the ability to abort continuation without total loss. The combination of an incremental commitment approach coupled with a customer satisfaction feedback control mechanism combined within a total lifecycle Systems Engineering plan overcomes these limitations. A higher level of interaction on a more frequent basis occurs between systems engineering, software engineering, human factors, and a statistically significant stakeholder population. Capabilities are translated into acceptable solutions in a shorter period of time. Costs are contained by greater understanding across all stakeholders and by terminating commitment to additional capabilities when the user contentment has reached a level at which all stakeholders can be satisfied, even if not optimal.

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