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UTILIZATION OF MODEL-BASED APPROACHES IN CONDITION BASED MAINTENANCE PROGRAMS

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ABSTRACT

All CBM+ solutions must establish a business case considering cost of implementation and sustainment of value with a quantifiable return on investment. The business case must be traceable to specific failure modes, associated failure effects, criticality, and risk. Risk is not limited to safety and operational risks. Predictive systems by definition return both true and false predictions representing operational and financial risk from high false positive rates. There is also risk of losing operator confidence in predictive systems when there is a high false positive rate. All of these risks must be quantified and considered in the design and development of CBM+ systems. Model based approaches are effective in accelerating development, defining advanced functional characteristics, and efficiently testing dynamic effects of complex systems. CBM+ maintenance strategies rely on performance of complex systems.

INTRODUCTION

Development of a Condition Based Maintenance Plus (CBM+) program both in new acquisition and legacy systems is a complex endeavor. According to the Department of Defense CBM+ guidebook, "CBM+ is the application and integration of appropriate processes, technologies, and knowledge-based capabilities to improve the reliability and maintenance effectiveness of DoD systems and components [1]." The U.S. Army has embraced CBM+ with a strong emphasis on advancing from post failure diagnostics (i.e. fault isolation) to predictive maintenance, and ultimately to prognostic capabilities. The fundamental obstacle facing all programs is how to craft an effective CBM+ program as part of a cohesive maintenance program and asset management strategy. Central to the application of CBM+ is a clear understanding of why to pursue CBM+ in the first place. The "why" of CBM+ resides in the key phrase "to improve the reliability and maintenance effectiveness of DoD systems and components [1]." Development and implementation of CBM+ programs does not mean that all current maintenance actions following the traditional "PM" interval-based model will be eliminated. It does mean that where technologies can be leveraged to provide factual data for more informed decisions and a clear business case to invest in the architecture to collect, process, store, and analyze specific data can be made, there is value in developing a CBM+ strategy for specific systems, subsystems, or components. The identification of where appropriate sensors or measurement devices can and should be incorporated into the design in order to support identification of impending failure and degradation of system health is critical and must be part of the CBM+ business case.

CONDITION BASED MAINTENANCE PLUS (CBM+)

There are numerous opinions on what constitutes a CBM+ program. CBM+ is a maintenance approach leveraging technology and information to monitor health. "The goal of all maintenance approaches (health monitoring included) is to either: 1) Wait as long as possible to perform maintenance so that the amount of life in parts or subsystems that is thrown away is minimized, while avoiding failure; or 2) Find the optimum maintenance policy consisting of scheduled and unscheduled maintenance so that life-cycle cost is minimized while satisfying system availability and safety requirements.[2]" For the purpose of this paper, the concept of CBM+ is defined broadly as an outgrowth of a shift in managing equipment reliability towards system health assessment, diagnostics, and prognostics. The system health assessment is inherently based on degradation, not pass/fail states rooted in probability mathematics typically applied to measuring equipment reliability. Health assessment is about detecting and forecasting degradation (time-based or initiated from other operational influences) from a higher "healthy" state toward a lower "unhealthy" state where the risk of the equipment providing the desired capability is unacceptable. This concept is the central tenet to developing CBM+ systems.

There is a distinction that must be made in CBM+ for diagnostics. Diagnostics are used in fault isolation, the troubleshooting aspect of diagnostics where the objective is to restore operation post failure. Systems that provide fault isolation are designed to discover a condition that has already resulted in loss of function and isolate the cause to a specific fault or Line Replaceable Unit (LRU) for rapid restoration to a functioning state. The basis for many fault isolation diagnostics is detecting simple pass/fail conditions and in some cases counting events where a parameter is exceeding "tripping" a threshold reported as a fault code. Fault isolation systems are therefore typically not providing time based degradation information for prediction. Fault isolation is providing information for rapid restoration of function once a failure occurs. Diagnostics that provide prediction typically measure parameters directly that indicate degradation of a functioning system in a time-space related to equipment usage. The measurements of these parameters feed into degradation models used in prognostics. Prognostic models support a near real-time prediction of reliability degradation and remaining useful life.

An effective CBM+ maintenance strategy is the path to the ability to make operational decisions, plan materiel logistics, pre-position spares, and schedule maintenance all based on system health. There are distinct diagnostic and prognostic functional layers essential to realizing a capability to make such decisions from the context of system health. Specifically: "A core component of this strategy is based on the ability to (1) accurately predict the onset of impending faults/failures or remaining useful life of critical components and (2) quickly and efficiently isolate the root cause of failures once failure effects have been observed."[3]

Design and implementation requires integrating a complex combination of technology including: highly reliable and accurate diagnostic hardware (embedded sensors, portable and laboratory monitoring technologies), algorithms and software designed for diagnostics, network architecture for collecting and storing data, software design and computer systems for prognostic modeling, and network systems for management of equipment health information at the enterprise level. The foundation of a CBM+ strategy is a diagnostic system design integrating sensors at the lowest level of mechanical, electrical, and electronics systems. The design is complex and the investment required for implementation significant. In addition, the continuous improvement engineering effort to achieve an accurate assessment of the current state of the systems in near-real time must be sustainable and traceable through the life cycle to specific failure modes, causes, mechanisms, and symptoms. There is also a need to address conditions present above the component level. A much too common degrader of system reliability are the soft faults and intermittent failures which are typically resident in connecting hardware or software and not the LRU itself. There is considerable risk in the design process requiring methods to qualitatively and quantitatively validate assumptions, analyze alternatives, develop corrective solutions, and assess the impact solutions will have on performance. This requires an approach that allows experimentation and evaluation of design decisions without the expense and risk of prototyping and testing.

WHY A MODEL BASED APPROACH?

The application of CBM+ in military systems has very high expectations. The objectives are substantial, including achieving desired availability at lower cost, more efficient repair through high accuracy fault isolation, accurate prediction of impending failure and accurate assessment of remaining useful life. The level of integration and complexity of the systems architecture is higher than most, if not all, industrial applications of condition based maintenance. The desired impact is to provide near real-time trends to operational unit decision makers, pre-planning inputs to maintenance, individual asset management decisions at enterprise levels, and provide better granularity for understanding and controlling life cycle costs. The expectations and objectives require incorporating rigorous methods to manage risk for decisions in the development process. Decision quality must be high, the approach to producing quality decisions must be capable of incorporating multiple types of information into a structure that enables confirmation or disproof of assumptions with qualitative and quantitative evaluation of performance at every stage of development. In that regard, there is significant risk in addressing CBM system design as a traditional design activity where subsystems are separately developed and integrated in the later stages of development. Because the interfaces and interactions are complex and critical to achieving the accuracy needed to realize the benefit, a more complete understanding of system behavior is required in early development. As the system design matures, a model provides traceability and configuration control throughout the design process including sustaining engineering activities during redesign or modification efforts during operation and support of the fielded system. For legacy systems, existing systems engineering models can be leveraged as a starting point for applying CBM+ strategies. Modeling is an approach that facilitates effective CBM+ design and development.

Ultimately, a CBM+ strategy is about quantification. DOD policy states “CBM+ has to buy its way into a program” with the only interpretation of knowing when that is achieved requiring a measure of performance [1]. It does not make sense to rely solely on test performance data to mature a design necessitating costly expenditures on hardware and software development for design decisions. Design decisions based on model based approaches have lower cost and better management of risk earlier in development. Updating the model throughout the systems engineering process, validating it as representative of actual outcomes with a prescribed confidence level, will increase efficiency in improving the design and reduce risk in satisfying expectations and achieving desired objectives.

WHAT TYPE OF MODEL APPLIES?

The term modeling in engineering has multiple meanings depending on context. All are typically multivariate and hierarchical. System engineering models can be physical representations of system design modeling functionality, space claim, weight and other system characteristics. Physics based engineering models describe physical interactions during service such as operational stresses, environmental, and other factors. Reliability models represent probability relationships for system failure, rolling up the probability of failure events at lower levels to characterize the impact at upper levels. The mathematical calculations for each type of model and the architectural relationships are specific to the context. A model based approach to incorporating effective CBM+ systems as part of a cohesive maintenance plan requires architectural relationships and mathematical calculations that are not typically resident in the most common engineering models.

Modeling CBM+ systems is fundamentally a systems engineering task. However, the systems engineering task not only models characteristics of system function (i.e. the behavior domain) but also the interactions of Prognostic Health Monitoring (PHM) functions with Reliability, Availability, and Maintainability (RAM) of the system. The model must support representation of functional, qualitative, and quantitative relationships of system operation and support. Functional design interactions at system, subsystem, assembly, and component level must be represented for RAM, mission profile and cost. Evaluation of a CBM+ strategy requires representation of system design to include sensor type, location, and coverage of the functional design of the PHM system. The model must support PHM design assessment with respect to fault detection, fault isolation, and the maintenance actions in response to detection.

What Are the Basic Model Requirements?

As previously stated, the model should follow a systems engineering approach requiring the ability to model the system with regard to:

- Boundaries, properties, and functions
- Hierarchical functional relationships down to the point where individual failure component failure characteristics can be portrayed
- System operations flow properties that receive an input in the hierarchy then supply, process, control, or transmit an output in the hierarchy that produces functions
- Portrayal and identification of functional dependencies and effects at multiple levels in the system
- Defining and capturing causal relationships, failure mechanisms, failure symptoms, and fault conditions
- PHM system sensor location and type to include the ability to quantify performance and reliability of PHM systems
- Identification and assessment of failure modes detectable by the PHM system design (i.e. what is covered) preferably tied to Failure Mode, Effects, and Criticality Analysis (FMECA) for the system
- Quantification of cost avoidance as a demonstration of the value of CBM+ strategy in sustaining the system.

The last requirement is what is supported by the information modeled in all the other requirements. The analytical requirement of the model to use metrics describing system RAM and cost to quantify PHM system performance is central to the models value in analyzing alternatives and making decisions in the trade space. The capability to perform trade space analysis and calculation of failure mode level cost estimates critical to sustainment cost avoidance and cost optimized strategies is a primary output of the model.

What Result Must the Model Produce?

In short, a basic description of the what the model must produce is a complex joining of attributes that qualitatively and quantitatively describe system operation in a functional design context, system failure in a causal and symptom context, system performance in a RAM context, and PHM design, coverage, and diagnostic performance impact on RAM and cost. This short description states a basic level of sophistication needed to support model based decisions for a CBM+ strategy. The design, development, and improvement of a CBM+ strategy as a path to making operational, field level maintenance, and enterprise level asset management decisions is a challenge necessitating a method that is well documented, traceable, configurable, integrated, and capable of being continuously improved within the DoD Systems Engineering process. A system engineering based model, tailored to the requirements of design and implementation of CBM+ strategy, is a logical solution.

CASE STUDY

PHM ~~Technologies~~ Technology (PHMT) has developed a commercial-off-the-shelf (COTS) model based engineering tool for the "design, safety, reliability and health management of complex systems [4]." One feature of the software is the capability to model CBM strategies to include the coverage and performance provided by application of health monitoring methods and technologies. The U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) acquired a license for the Maintenance Aware Design environment (MADe) software to evaluate applying it as a model based solution in support of TARDEC's 30-Year Strategic Vision and the Army Materiel Command's (AMC) CBM+ Five-Year Plan. The AMC Five-Year Plan highlights the five pillars of CBM+ as: data collection; data distribution and transmission; data storage/warehousing; data analysis; and data-driven actions/decisions. A model based solution, supported by a suitable software tool, relates to several Supporting Objectives (SO) within the Five-Year Plan to include:

- SO 1: Develop and Implement Sensor Strategy, Policy, and Procedures
- SO 6: Integrate Reliability Centered Maintenance (RCM) and CBM+
- SO 25: Cost-Effectiveness Analysis (CEA) and Cost Benefit Analysis (CBA)
- SO 27: Metrics
- SO 26: Realize Value from CBM+ Investments [5]

A model based approach, using software capabilities like those found in MADe, brings together the complex attributes essential to navigating the decisions in a CBM+ design process and improving performance of the design throughout the life cycle. The model forms the basis for evaluating the tradeoffs in terms of cost between the occurrence of specific failure modes and the technology investment required to acquire and manage collected data to detect the presence of those failure modes and their associated impact on system availability. Figure 1 depicts a basic model as a basis for decisions in the CBM+ design process.

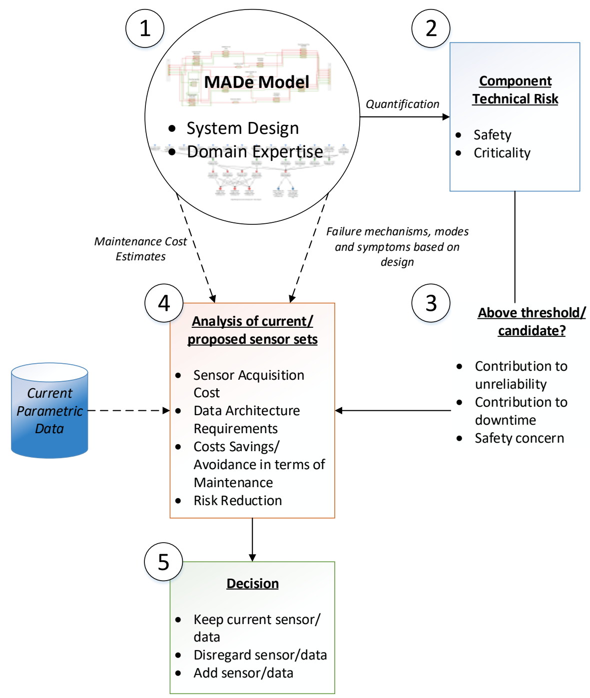

Figure 1: Application of MADe within the CBM+ Decision Process

Quantification of a system level business case for CBM+ involves modeling the system in a manner that captures the complex relationships. This requires a modeling approach that describes interrelationships among entities that comprise the system. Interrelationships that impact reliability of the system, "need to be captured in the "white-box" or bottom up approaches to system reliability analysis [6].” White box models are in contrast to black box models when it comes to describing relationships in a system. Without getting to far into the theory and mathematics, black box models define relationships only as inputs and outputs from the entities (i.e. system, subsystem, component, etc) in the model. A Reliability Block Diagram (RBD) is an example of a black box model. White box models define relationships that are not strictly input/output, but also relationships that are bi-directional flowing between entities (e.g. built-in test), some measurement functions (e.g. exceeding parameters), or system interactions that alter system mode of operation (e.g. degraded mode or back up mode). One approach to white box modeling is the application of Fuzzy Cognitive Logic in defining system interaction. The word “fuzzy” may put off people who perceive it to coincide with the common definition of “unclear” when in fact the mathematical power of fuzzy logic compared to Boolean logic enables much better representation of relationships in applications like CBM+ where the interactions are complex and the objective is defining and detecting the transition from a state of heath to a state of un-health. A simplified description, Boolean logic is an instantaneous state transition (true/false or pass/fail) while fuzzy logic is continuum for a “degrading” state transition. The MADe software tool uses fuzzy logic. Fuzzy Cognitive Mapping (FCM) applies fuzzy logic to map relationships between entities such as subsystems, assemblies, components and parts.

The functional approach within MADe utilizes FCM in order to understand the effect of failures on functions at all hardware levels (subsystem, component, part, etc.) in complex systems. This approach allows clear mapping of failure causes, mechanisms, faults and symptoms to loss of function and incorporates engineering domain expertise (electric, mechanical, hydraulic, chemical, and thermal). FCM methodology provides a logical reasoning for mapping system relationships, including interrelationships in a “white box” approach to system reliability analysis. The FCM methodology is based on the interactions required for system function resulting in a model reduced to factual knowledge that can be verified or disproved by observation or experimentation. The fundamental advantage of the logical reasoning behind FCM is that it recognizes that the transition from the functioning to the failed state is typically not instantaneous, but instead the consequence of degradation that is measureable in terms of the interactions required for system function. Thus, this approach, when combined with collected sensor data, can be effectively utilized to develop the business case for an optimized sensor solution.

CONCLUSION

A model-based analysis approach, as illustrated with MADe, provides a consistent systems engineering approach to overcoming the challenges in designing, implementing, and optimizing diagnostic and prognostic architecture that enables a realized value from CBM+ investments. Initial evaluation for applying modeling demonstrated how effective a model with certain capabilities is in providing a detailed understanding of the complex underlying relationships between Physics of Failure (failure mechanisms and symptoms), risk, and costs necessary to realize the value and benefit of CBM+ implementation.

Preliminary efforts with a model based approach, using the capabilities of MADe, focused on illustrating the process as well as providing a foundation for supporting a business case for applying sensors and/or other CBM+ strategies in order to reduce cost, improve readiness, and/or reduce technical risk. Figure 2 illustrates the process and the utilization of MADe capabilities in developing a CBM+ strategy.

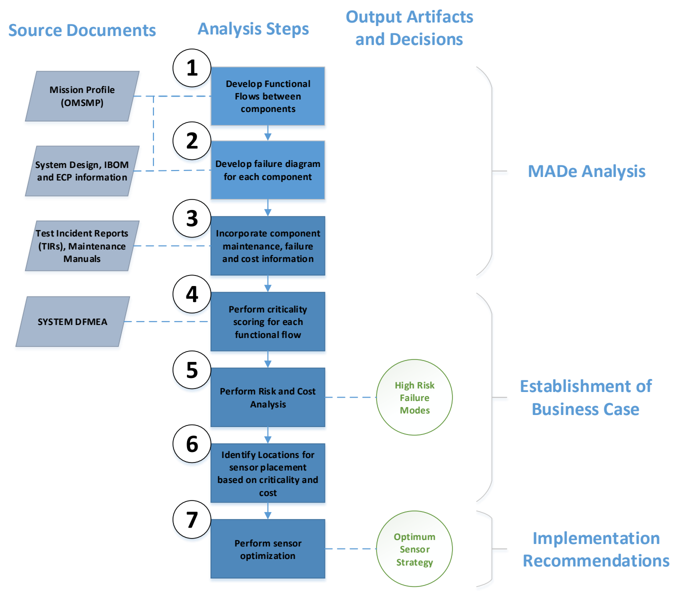

Figure 2: Analysis Inputs, Process, and Outputs for a Model Based Approach (MADe shown as the Modeling Software Tool)

Applying a model based approach with more detailed maintenance cost estimates and broader field data sources related to these components, including details of maintenance actions and sensor data related to those maintenance actions, will aid in refining additional aspects of the model approach using MADe. Input to the model, such as failure mechanism initiating probabilities, failure symptoms from an operator viewpoint, and refinement of maintenance costs, will provide better fidelity for demonstrating realized value of a CBM+ strategy. The most valuable output of the model is a finalized and verifiable business case.

The application of a model based approach and the process illustrated in Figure 2 is appropriate for new acquisition and legacy systems. With new acquisition, an obvious advantage is including the hardware and software for the health monitoring technologies in early development. For legacy systems, the challenges will include limitations of existing space, weight, and access. However, all of these attributes can be accurately modelled enabling greater understanding of system interactions and better fidelity to the business case as the foundation for decisions.

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