STRUCTURAL HEALTH MONITORING 2003

From Diagnostics & Prognostics To Structural Health Management

Edited by

Fu-Kuo Chang

Department of Aeronautics and Astronautics
Stanford University, Stanford, CA 94305

Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford University, Stanford, CA
September 15–17, 2003

Sponsors:
Air Force Office of Scientific Research
Army Research Office
National Science Foundation

DES*tech* Publications, Inc.

Remote Readiness Asset Prognostic and Diagnostic System (RRAPDS) Near-Term Applications

S. A. MAROTTA, T. K. OOI, J. A. GILBERT and M. V. BOWER

ABSTRACT

The Remote Readiness Asset Prognostic and Diagnostic System (RRAPDS) is a joint U.S. Army Aviation and Missile Command Research, Development and Engineering Center (AMRDEC)/U.S. Army Tank Automotive and Armaments Command, Armaments Research, Development and Engineering Center (TARDEC) Science and Technology Objective (STO) program. After several years of development, the RRAPDS program is sufficiently mature at this time to incorporate into an Army system. Several missile systems supported by the AMRDEC are in the planning stages of incorporating a modified RRAPDS system into their systems. The RRAPDS applications will ultimately provide an integrated system transparent to the war fighter that monitors health/condition and delivers advanced diagnostics/prognostics while an asset is tactically deployed, in storage, and/or being transported. The near-term RRAPDS devices will monitor environmental conditions and collect temperature, humidity, and vibration/shock data to improve the reliability of the missile. All data will be time stamped to enhance the diagnostic and prognostic capability. Significant variables and trends can be identified using data mining techniques. Data collected can be analyzed to update missile design parameters such as failure rate of components, test costs, environmental thresholds, etc., and to predict spare parts requirements. On-line health monitoring and smart diagnostics/ prognostics strategies will lead to significant savings in the total life cycle costs by improving systems' reliability, maintainability, and availability. RRAPDS will allow for real-time access of source data and provide critical information needed for reduced sustainment costs and enhanced force readiness. Sensor data analyzed by data mining algorithms and predictive trending has the potential to extend life and save millions in maintenance costs. Over time, data collected can be used to refine missile designs and improve reliability, resulting in improved overall life cycle.

Stephen A. Marotta and Teng K. Ooi, US Army, Aviation and Missile Research Development and Engineering Center (AMRDEC)
John A. Gilbert and Mark V. Bower, University of Alabama, Huntsville

INTRODUCTION

This paper introduces RRAPDS, an integrated system whose technological advances will allow for real time access of source data, enable remote prognostics/diagnostics, and create higher efficiency mission planning/performance. The assurance of reliable weapons systems will greatly enhance confidence in their safety, reduce probability of mission failures, and diminish the cost of operation and maintenance. By applying RRAPDS across Army systems, significantly lower acquisition, operation, and support costs, and therefore total LCC, will result and once fielded, will positively impact Army logistics.

BACKGROUND AND CONTEXT

Driven by the need for dramatically more affordable defense technologies, Department of Defense (DoD) leaders have been challenging the defense research community to adapt a total systems approach to optimize total system performance and minimize the cost of ownership in new acquisition programs as well as deployed systems. As more and more DoD decisions are based on total ownership cost drives it has become crucial to manage the LCC of DoD programs.

Life Cycle Management (LCM) has come to fruition as an integrated approach to minimizing the environmental burdens associated with a system over its total life cycle. Use of LCM increases the effectiveness while decreasing cost over the life of a system. This is accomplished by taking into account the system's performance, effectiveness, reliability, maintainability and supportability. LCM attempts to use available information to improve systems' reliability, maintainability and availability.

The fundamental problem facing defense researchers involved in designing and building missile systems is how to collect the information necessary to effectively implement a LCM plan. In essence, how do you monitor health/condition and deliver advanced diagnostics/prognostics while an asset is tactically deployed, in storage, and/or being transported?

The DoD currently does not have the capability to monitor critical environmental data for individual missiles/munitions. In the past, missiles/munitions were most likely stored for long periods of time within the various military depot environments. In the present however, missiles/munitions can expect deployment into a theater of operations and then be returned to stocks for a potential future deployment. This is expected to occur several times in an asset's life cycle with extremes being experienced during each deployment as a result of handling and transportation as well as theater storage. Due to this situation, the potential detrimental effects a missile/munition has encountered must be recorded to assess its current health and assure its readiness. Without a means to record an asset's history, assess its condition, and assure its war fighting capability, significant costs must be incurred to test hardware upon its return.

DoD leadership has recognized the importance of health monitoring and failure prediction in weapon systems as a goal towards successfully sustaining a combat effective fighting force. Therefore, guidance has been established to include the tools for logistics situational awareness and embedded diagnostics and prognostics in all new weapon systems.

PROBLEM STATEMENT

A request was made to investigate advances in design to improve LCM and tools to improve logistics situational awareness and embedded diagnostics and prognostics in all new weapon systems.

RESPONSE

In response to the identified problem, it was determined that a sound system engineering approach be used in the development of a low-cost, autonomous missile and munitions "health" monitoring system called RRAPDS. RRAPDS will monitor environmental conditions such as temperature humidity, shock, vibration, chemical, etc., inside the missile/munition or at the pallet level. Sensor data will be stored in on-board memory and be accessible via fixed or mobile radio frequency interrogators. The environmental data will be analyzed using advanced failure prognostics algorithms, which can be done in the monitoring device itself or by remote users. The data will be stored in databases and used to effectively manage the LCC of the system, increase reliability, reduce operations and support and ultimately increase the user's confidence.

RRAPDS CONCEPT

The RRAPDS concept consists of an assembly of low-power sensors located on the weapon system to collect environmental data, a processor termed the Asset Electronics Package to autonomously control RRAPDS operation, a power source capable of 10 or more years of continuous system life, a capability to transmit real-time data, and the necessary tools to provide seamless user's interface (see Figure 1). RRAPDS will utilize existing, emerging and future technologies to achieve reliable parametric condition monitoring from much smaller packaging, for longer periods of operation and at more extreme operating conditions than currently feasible. RRAPDS will apply and integrate current and future advances in Micro-Electromechanical Systems (MEMS), micro-communications, micro-data processing, and intelligent power management. These technology advancements will allow for real-time access of source data, enable remote prognostics/diagnostics and create higher efficiency mission planning/performance.

Additionally, RRAPDS will leverage on-going work to characterize Plastics Encapsulated Microcircuits, solder joints, propellants and adhesives to accurately detect phenomena linked to weapon component failures. Models based on constitutive material properties in critical missile applications will enable the advanced determination and prediction of component and system remaining useful life.

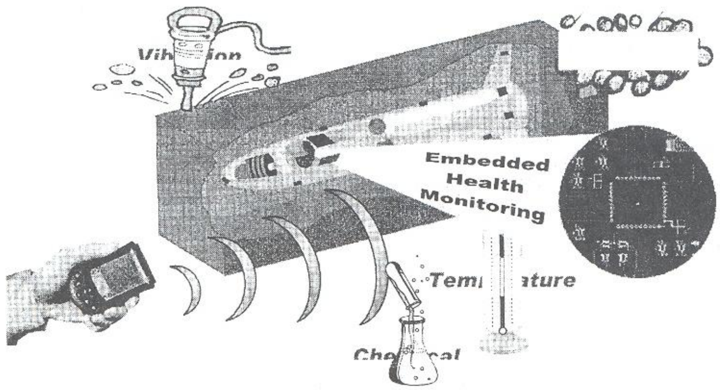

Figure 1. Conceptual diagram of U.S. Army missile health monitoring.

BENEFITS

DoD leadership has recognized the importance of health monitoring and failure prediction in weapon systems as a goal towards successfully sustaining a combat effective fighting force. Lack of data has already proven to be very costly. The collection of real time, accurate data can ensure readiness. Guidance has therefore been established to include the tools for logistics situational awareness and embedded diagnostics and prognostics in all new weapon systems.

During the mid-1980s, the Army experienced very alarming premature degradation of the ammunition stockpile. The stockpiles rapid deterioration was a result of problems related to design deficiencies, process vulnerabilities and the inability of commodities to withstand the storage and operational environments to which they were subjected. Further investigation into the root cause found that the armaments research and development communities did not have adequate life cycle tools, necessary to assure and assess material robustness against premature failure/deterioration.

RRAPDS offers the capability to detect the elements that cause degradation and facilitates true predictive deterioration analysis. RRAPDS would significantly improve the stockpile management process and improved efficiencies will reduce operation and support costs. Current inspection procedures are largely visually based. Although all stocks may not be exposed to the same environmental extremes, without accurate data, a worst-case scenario must be applied across the board. High maintenance costs are therefore incurred when stocks must be labeled as returns. Through implementation of RRAPDS, history can be obtained for the entire stockpile.

An important element of RRAPDS is its tie in to predictive engineering accelerated aging studies and models with the objective of providing early prediction of whether an item will survive the unique 20+ year life cycle environment of Army material. Predictive engineering provides tools and methods aimed at reducing premature degradation and/or failure of weapon systems in storage or operational use. The key is to provide products that are optimized (i.e. safety, performance and longevity) for an entire life cycle thereby reducing the total ownership cost. This is accomplished by (1) ensuring that the product design and production processes will yield robust products insensitive to both storage and use environments, and (2) extending shelf/service life, improving stockpile management through applications of proactive models, and providing more efficient product evaluation after products are fielded.

Through the use of predictive technologies, data collected from RRAPDS will provide designers with a better understanding of an asset's environment when tactically deployed, in storage or in transit. Predictive engineering will reduce the total cost of ownership by helping to identify, eliminate, or mitigate critical design weak links, sensitive processes and operational and storage sensitivities/incompatibilities that precipitate the degradation of systems in storage or operational use. Accelerated conditioning can be used to simulate the aging phenomenon. Feedback from the field will enable continuous munition reliability and design improvements by assisting in identifying failure mechanisms. Models can be developed that predict shelf/service life impacting future safety, reliability, and performance of weapon systems.

The predictive engineering process augments and compliments the traditional suite of life cycle, Reliability, Availability, and Maintainability (RAM) requirements. Cycle time can be reduced by early elimination of problematic components or processes while avoiding the negative cost implications that occur when these problems are carried forward and are discovered late in development, production, fielding or deployment. Additionally, these abilities to predict readiness characteristics lead to decision models that enable LCM and the ability to develop and implement strategies for procurement surveillance frequencies, maintenance decisions, demil needs, recycle, recover, reuse processes, etc.

RRAPDS, once fielded, will positively impact Army logistics, contribute to the "Revolution in Military Logistics," and result in significantly lower operating and support costs. By achieving a high level of logistics situational awareness, RRAPDS will prevent the unnecessary loss of deployed missile assets within degraded environments and allow for condition-based maintenance. RRAPDS will enable source data automation to optimize supply and allow for anticipatory maintenance to accurately plan requirements and prevent cascading equipment degradation.

In Army's planned Future Combat Systems (FCS), RRAPDS will re-engineer Army logistics from its current "wholesale or retail" definition to a single logistics system able to exploit distribution-based velocity and transportation rather than supply-based logistics mass. FCS on-the-weapon diagnostics/prognostics will trigger supply and maintenance actions, resulting in greater efficiency and lower logistics costs. In the FCS, where highly mobile, lightweight, lethal and sustainable war fighting is the goal; RRAPDS gives the user assured precision kills over the battlefield with the weapons at his disposal. The awareness of a weapon's capability through prognostics allows the minimum of assets to be carried on the vehicle, giving greater firepower in a lighter, more mobile package. The AMRDEC and ARDEC in conjunction the Army Research Laboratory will perform the necessary research and development in the next few years to embed sensors in propellants and composites, and detect levels of critical chemicals. These sensors located at high stress locations internal to the weapon; in addition to highly integrated core RRAPDS functionality (temperature sensing, humidity sensing, vibration sensing, data processing and RF communications) will enhance RRAPDS prognostics capabilities on-board FCS weapons.

SYSTEM ENGINEERING PROCESS

A detailed systems engineering process has been tailored to design the RRAPDS system. The developed systems engineering process is an iterative, logical sequence of analysis, design, test and decision activities to assure delivery of an optimized RRAPDS system that addresses all the end user's needs and mission requirements, with the greatest probability of success and at the lowest possible cost.

Every engineering effort begins with a statement of a perceived need and in the case of the RRAPDS system that need is to provide the means of remotely identifying an asset's current and historical condition, determining/predicting its readiness for combat or performing condition-based maintenance. Once this perceived need is known the critical first step of the system engineering design process can start. The critical first step is the functional analysis.

Functional Analysis

The functional analysis activity identifies the essential functions the RRAPDS system must perform, and addresses the "what" and "why" questions relative to the design of the RRAPDS system. In this activity the RRAPDS performance requirements will be analyzed and dividing into discrete tasks or activities. The primary system functions will be identified and decomposed into sub-functions at ever-increasing levels of detail. Functional analysis will support the RRAPDS mission analysis in defining functional areas, sequences, and interfaces. Functional analysis is composed of two primary process segments: functional identification; and requirements allocation.

Functional Identification

A function is a characteristic action to be accomplished by one of the system elements of hardware, software, facilities, personnel, procedural data, and any combination thereof. Functional identification and decomposition can be performed with respect to logical groupings, time ordering, data flow, control flow, or some other criterion. The stepwise decomposition of a system can be viewed as top-down approach to problem solving.

Functional identification for RRAPDS will be accomplished through the use of Functional Flow Block Diagrams (FFBD's) depicting task sequences and relationships, and timeline analyses depicting the time dependence of tasks. The purpose of the FFBD's is to indicate the sequential relationship of all RRPADS functions that must be accomplished by the system in the performance of a segment of the program. FFBD's depict the time sequence of functional events. Some functions may be performed in parallel, or alternate paths may be taken. The duration of the function and the time between functions is not shown but may vary from a fraction of a second to many weeks. The FFBD's are function-oriented, not equipment-oriented. In other words, they identify "what" must happen and do not assume a particular answer as to "how" a function will be performed.

Requirements Allocation

Requirements allocation is a process that will be used to decompose the RRAPDS system-level requirements until a level is reached at which a specific hardware item or software routine can fulfill the needed functional/performance requirements. It is the logical extension of the initial functional identification and an integral part of any functional analysis effort. Some straightforward allocation of functional requirements can be made, but the procedure may involve the use of supporting analyses and simulations to allocate system-level requirements.

The RRAPDS functional analysis and requirements allocation is designed to permit the capability of tracking the system requirements from a system function to elements of the system, which, collectively and individually, perform the function. RRAPDS requirement traceability will include the tracking of the allocated design requirements through the work breakdown structure between the system level and the lowest level of assembly. Traceability of systems engineering documentation will ensure the impact of changes to requirements at any level of the RRAPDS systems engineering documentation or program specifications can be reviewed for impact on the total system, and that the rationale can be reviewed without the need to reconstruct analyses. This will significantly decrease development time and design cost of the RRAPDS system ultimately cutting down on the total cost of the system through its life cycle.

Trade Studies

Trade studies are used as a formal decision-making preparatory step providing a structured, analytical framework for evaluating a set of alternative concepts or designs where the rationale for selection is unclear, complex, or difficult to understand, and the final decision carries a lot of leverage for future action and cost. Trade studies performed in the development of RRAPDS will be performed up-front as an essential part of the systems engineering process. The trade studies will be controlled to integrate and balance all design-for and engineering requirements as well as provide a documented decision rationale. This analysis will aid in follow on RRAPDS redesign effort.

Specification Development

The preparation of the various requirement specifications is the culmination of the requirements analysis and allocation efforts and the principal output of the systems engineering process. The objective of these requirement specifications is to provide, through this top-down process, a set of formal requirement documents identifying functional and performance requirements at various levels of detail. These documents are prepared to support further development, evaluations and acquisitions. They establish requirements in terms of both complete design details and performance and identify "what" is required, not "how" it is accomplished.

Life Cycle Cost Analysis

In parallel to the RRAPDS system engineering process activities a LCC analysis will be performed to identify LCC drivers, total cost to the government, cost-risk items, and cost-effective changes. Computer modeling will be utilized to identify and analyze LCC drivers. Cost drivers are the parameters that control operation and support costs such as reliability, maintainability, and support equipment. Cost drivers are areas where resources can best be applied to achieve the greatest benefit in reduced costs. Modeling for LCC is also useful in cost-benefit and cost-effectiveness studies.

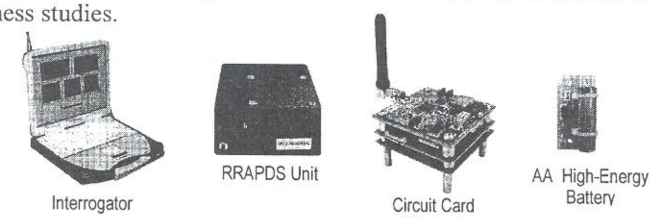

Figure 2. Current prototype technology for missile health monitoring.

CONCLUSIONS

As the total systems approach to optimize total system performance and minimize the cost of ownership increases, so will the importance of health monitoring and failure prediction in weapon systems. This paper has described one way the defense researchers have proposed to answer DoD challenges to adapt a total systems approach. Prototype RRAPDS technology is illustrated in Figure 2.

RRAPDS will accurately detect phenomena linked to weapon component failures and enable the advanced determination and prediction of critical failures. This prognostic information can initiate supply and maintenance actions resulting in greatly streamlined logistics operations and assist in determining missile/munitions shelf life. Additionally, RRAPDS will allow for real-time access of source data and provide critical information needed for reduced sustainment costs and enhanced force readiness. Sensor data analyzed by data mining algorithms and predictive trending has the potential to extend life and save millions in maintenance costs. Over time, the data collected can be used to refine missile designs and improve reliability, resulting in improved overall life cycle.

REFERENCES

1. R. Little. 2003 AMRDEC Information Briefing, "Propellant Bondline Sensor for Missile Health Monitoring"
2. M. Triplett. 2003 AMRDEC Information Briefing, "Health Monitoring of Graphite Reinforced Composites in Missile Applications"
3. J. Holt and S. Burgett 2003 AMRDEC Information Briefing, "Low Power Chemical Sensor for Missile Health Monitoring"
4. J. Fedewitz and M. Hillard. 2001 TARDEC Information Briefing, "Conventional Munitions Remote Readiness Asset Prognostic/Diagnostic System "