

Conditioned-Based Maintenance at USC - Part II: Implementation of CBM through the Application of Data Source Integration

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Abstract

The University of South Carolina is currently implementing the procedure presented in the publication "Integration of Maintenance Management Systems and Health Monitoring Systems through Historical Data Investigation." This particular application is attempting to merge TAMMS-A records with data collected from Intelligent Automation Corporation's Vibration Management Unit (VMU), both in use by the South Carolina Army National Guard. To date, the University has been successful in the development of a single relational database from which further analysis can be done. Primary linguistic characteristics of TAMMS-A faults were determined and show a high possibility for successful implementation of natural language processing. Descriptions of the relational schema used for generic HUMS importation is also discussed. Future work will focus on the development of the natural language processor and HUMS metadata tagging. This study concludes possible improvements in CBM implementation include language standardization by maintenance crews and open-format data storage for HUMS data.

Background

History

Since 1998 the University of South Carolina (USC) and the South Carolina Army National Guard (SCARNG) have participated in a number of important projects that were directed at reducing the Army aviation costs through improved logistics technology, better data management, and prompt decision making. This modern aviation maintenance transformation produces higher operational readiness using fewer, more capable resources, provides commanders with relevant maintenance-based readiness information at every level, and shifts the paradigm from preventative and reactive practices to proactive analytical maintenance processes, now commonly referred to as Condition-Based Maintenance (CBM). Per the Office of the Secretary of Defense (OSD), CBM is defined as “set of maintenance processes and capabilities derived, in large part, from the real-time assessment of weapon system condition obtained from embedded sensors and/or external tests and measures using portable equipment.”

The Commander of AMCOM supports the unprecedented transformation from the Industrial Age to the Information Age using existing and emerging technologies that analyze near real-time aviation systems data to provide prediction and response maintenance capability. Several technological advances and initiatives by Army leaders at various levels have made a move toward CBM a reality for Army Aviation. The benefits of these technologies have already been proven for helicopter on combat missions, training, and maintenance flight conditions. Considering the long history of participation with health monitoring systems and data collection, the University of South Carolina is in a position to provide leadership, vision, and a path forward to maximize the effectiveness of these benefits across the broad spectrum of Army Aviation.

The transition to CBM requires a collaborative effort on a massive scale and is contingent on identifying and incorporating enhanced and emerging technologies into existing and future aviation systems. This will require new tools, test equipment, and embedded on-board diagnosis systems. Even more critical, the transition to CBM involves the construction of data-centric, platform-operating capabilities built around carefully developed robust algorithms. This will allow soldiers in the field, support analysts, and engineers the ability to simultaneously, and in real-time, translate aircraft conditional data and proactively respond to maintenance needs based on the actual aircraft condition.

The University of South Carolina has supported the U.S. Army by conducting research to support timely and

cost-effective aircraft maintenance program enhancements. Research emphasis has been to collect and analyze data and to formulate requirements for and assist in the transition toward Condition-Based Maintenance for the Armed Forces.

Program Objectives

The research program at USC seeks to deliver results which directly contribute to CBM efforts and objectives as follows:

- Link and integrate maintenance management data with onboard sensor data with test metrics and to quantify the importance of each data field relative to CBM
- Understand the physics and the root causes of faults of components or systems
- Explore the development of models for early detection of faults
- Develop models to predict remaining life of components and systems.

Program Processes

These program goals will be accomplished through the following processes:

- Qualitatively operationalize the CBM objectives through ongoing activities of surveying engineers, pilots, maintainers and crew chiefs on the non-tangible and mission benefits of the VMEP system such as safety, morale, mission capabilities, confidence on the system, and system liability.
- Quantitatively operationalize the CBM objectives through our ongoing quantitative management and vibrations data that are being collected, analyzed and processed. The most obvious outcome of these activities is the cost benefits and mission benefits models.
- Combine the qualitative and quantitative measures from the processes listed above to determine if the current implementation is meeting the planned CBM objectives. The combined measures will also be presented and evaluated mathematically, parametrically, and mechanistically as a diagnosis model or physical model of subsystems or components.
- Create preliminary, predictive mathematical models of component, subsystem, and aircraft performance that serve to guide future CBM activities on individual aircraft. Based on available literatures on prognosis studies, this will be the first scientific step in developing accurate prognosis models of components, subsystems, and entire systems.
- Interrogate and validate the historical field data through the use of component test stands. These test stands will be used to refine and improve our prognosis models by examining the process of component failures in order to correlate their observed conditions with the determined parameters.

USC CBM ROADMAP

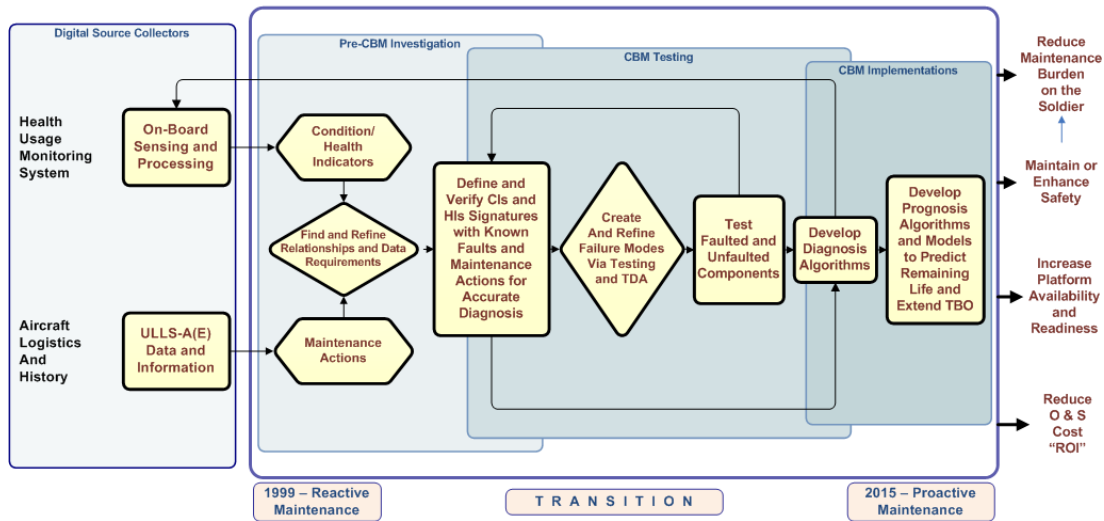


Figure 1--The procedural roadmap currently being implemented by the USC CBM research program

CBM Roadmap

As the growth and awareness of CBM develop, many ideas and technologies have arisen in efforts to improve CBM. Unfortunately without a plan or path, many of these ideas will never fully mature. There is need for a standardized methodology and roadmap for CBM to reach its full potential. In conjunction with the South Carolina Army National Guard, the University of South Carolina has the resources and channels to develop a roadmap to investigate the transformation of CBM. This can be done in a way that will address a broad array of strategic and tactical issues so as to accomplish the CBM specific objectives. The activities of USC are being performed as a joint industry, academic, and government team.

The roadmap consists of three phases: initial investigation, component and system testing, and the implementation of a fully-capable CBM system. This roadmap is driven by the currently available digital source collectors, which through integration and linking will direct the needs of laboratory testing. The results of this self-refining process will ultimately lead to the development of diagnosis and prognosis algorithms which will facilitate proactive CBM practices.

Introduction

Overview of CBM data collection

The University of South Carolina (USC) is currently developing a procedure for integrating the disparate data types generated by Maintenance Management Systems and Health and Usage Monitoring Systems. This process merges the two datasets through a complex

process of information extraction and event matching. Presently, the core of this investigation focuses upon the various rotorcraft models available through the University's partnership with the South Carolina Army National Guard (SCARNG). Over the past eight years, USC has acquired from SCARNG selected fields from The Army Maintenance Management System for Aviation (TAMMS-A) as well as archive files from HUMS equipment.

Implementation requirements

Extracting useful information from the TAMMS-A records requires the development of a Natural Language Processor (NLP) capable of reading the textual descriptions of individual faults and actions. A software interpreter implements a dictionary of terms and a set of grammar rules, which can be determined through the characterization of a sufficiently large historical record base. Having a thorough understanding of various lingual characteristics such as word frequency distribution and lexicon size can be used to optimize the creation of a dictionary for the NLP.

For HUMS records, the only prerequisites for beginning the integration process are knowledge of the sensor locations, indicator calculation algorithms, and the proprietary file formats which store the data. Furthermore, the dataset needs to be sufficiently continuous to reach a meaningful understanding of the values and trends present.

Use of historical and current data

Presently, USC has achieved the first stages of the integration process, namely preliminary lingual analysis of MMS data and relational database importation of

HUMS files. The results these early integration attempts will give a preliminary indication of the strengths and weaknesses of the current implementation of TAMMS-A and HUMS by SCARNG and allow for suggested refinements to be given. Also, the utility value of various data exploration applications will offer insight into the future development of real-time maintenance and diagnostics software. Based upon the usefulness of the integrated dataset, it is possible to make a feasible prediction of features and tools that will be available for the next generation of maintenance programs.

Current Implementation

TAMMS-A

The current sample of TAMMS-A records that have been collected by the University of South Carolina were obtained from a Unit Level Logistics System for Aviation (ULLS-A) through direct interaction with SCARNG personnel. Previously, one or two designated persons at the base would download the data in the form of reports from the local server which would then be later filtered for sensitive information and imported into USC's CBM data server. As of the fall of 2007, SCARNG had migrated its maintenance management system to the new ULLS-A(E) system, which boasts an increasingly higher capacity for data storage and data portability. The future method of TAMMS-A data collection is still under discussion, but will likely incorporate an automated system of extraction from SCARNG or another location with an increased efficiency.

IAC Technologies

The particular aircraft at SCARNG from which the TAMMS-A data has been collected are equipped with Intelligent Automation Corporation (IAC) Vibration Management Units (VMU). The AH-64 installment of this HUMS device implements 18 accelerometers and 3 tachometers for vibration and usage sensing. The accelerometers are located throughout the aircraft, particularly where vibration is a known problem for the AH-64, such as tail rotor drive train (TRDT) components. Most of the data generated by the VMU are condition indicators which are designed to identify a specific fault for a given component. After each flight, the data is downloaded to a portable ground-based station (GBS) from which it can be examined, allowing for problems to be identified. The IAC software then automatically uploads the data to a facility data server from which unit-level health and usage can be assessed, and then each facility server uploads the data to a central IAC server, where it is stored for later research. All data collected by USC has been through this central server with the cooperation of IAC.

Achievements

ULLS-A Processing

To date, the main focus of management data analysis by USC has been a sample of approximately 210,000 records from TAMMS-A forms 2408-13-1 and 2408-13-2. Selected fields from these forms describe all inspections, faults, and corrective actions performed on the fleet from 1998 to 2006. Various lingual parameters have been determined for the fault description such as the theoretical lexicon limit, record size distribution, and term frequency distribution.

The number of words per record follows a Poisson distribution with a mean value of 7.95 words per record. This would predict that 93.9 percent of all fault descriptions are 12 words or less, indicating a relatively simple grammar structure. Manual inspection of the records agrees with this, since a large number of the sentences consist of a single noun-phrase and verb-phrase.

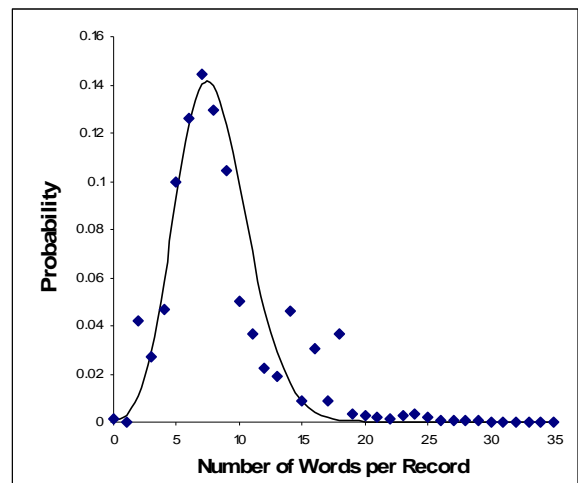


Figure 2—The probability distribution of individual record word counts

Plotting the number of unique terms versus the record count shows a possible horizontal asymptotic behavior for large record counts. Regression analysis of this curve predicts that the theoretical lexicon size limit for fault descriptions is less than 24,000 terms, which includes a large number of synonyms and abbreviations. This is roughly 5 percent of the number of headwords found in a comprehensive English dictionary, and so represents only a small subset of the English language.

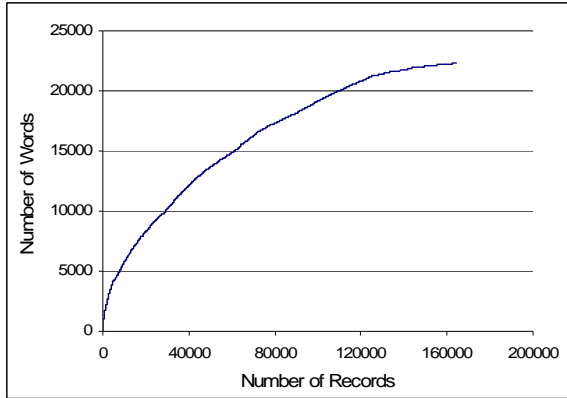


Figure 3—The number of unique terms used to describe maintenance faults compared to the record set size

The total number of non-distinct words in the record sample is approximately 1.4 million, with a heavy distribution towards a small set of frequently used terms. Of the 24,000 unique terms, less than 8,300 occur more than two times in the entire record set, and more than 95 percent of all words belong to the top 10 percent of the most frequently used terms.

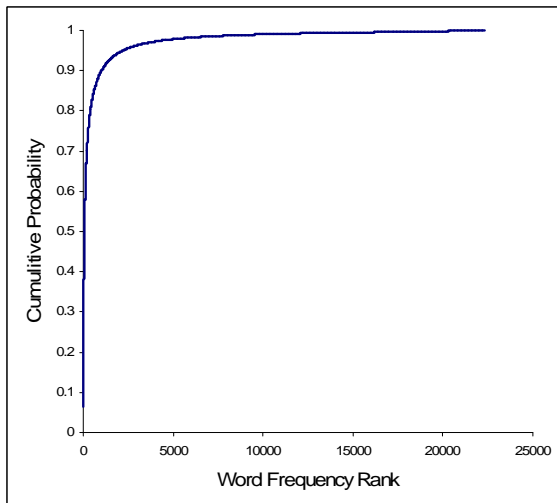


Figure 4—The cumulative probability distribution of word usage frequency sorted by term usage rank

Combining this word frequency distribution with word count per record distribution allows the determination of a required dictionary size for a sufficient word retention rate. A dictionary consisting of only the top 20 percent of used terms in the fault descriptions allows for nearly 80 percent of those records to be conveyed. The final determination of dictionary size requires the defining of the point of diminishing returns: where the work required to define additional terms is greater than the benefit of increased retention capacity.

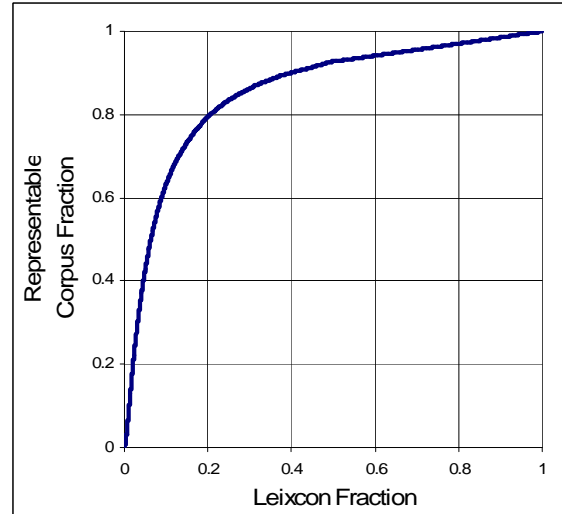


Figure 5—The fraction of records that can be represented as a function of defined lexicon fraction

Historical VMU Data

On the HUMS side of the integration process, the University of South Carolina has made a prototype relational data importation application which is capable of converting the proprietary VMU data files into a generic database for further analysis. The IAC GBS software retrieves data through a Microsoft Access database which contains references to external data files. The GBS frontend loads the relevant files and produces graphs and indicators for the user. Each data file stores one data type for a given flight or portion of a flight, and files are stored in a directory structure defined by the aircraft model, tail number, and flight time.

Since each data type is stored in a particular format possibly with multiple versions, it is inefficient to develop an importation application which directly converts the files into a relational table. This would require heavy monitoring during the data collection process and logging of files that failed to import. Therefore, the importation occurs in two steps: direct file copying and processing. Files are first directly inserted into a table row, and, as file format specifications become available, are then processed into generic data tables. This allows for any file types from any system to be collected and stored without regard to file names or directory structure, with the end result of a simple to query multi-platform data set.

The generic database schema is designed with a high degree of abstraction in order to accommodate a diversity of data sources. Data is broken into two main categories: sensor data and indicator data. Sensor data is defined as all data directly measured or deduced from sensors installed on the aircraft. It is further subdivided into its domain characteristics: time domain or frequency domain. Time domain data comprises the

bulk of sensors and includes raw accelerometer readings and temperature values. Frequency domain data is commonly used to characterize vibration signals in terms of frequency components and their respective amplitudes, usually by the application of a Fourier transform. The other main category of data, indicator data, is defined as parameters derived from sensor data through the application of a specific algorithm. This comprehensive data class is equivalent to the VMU condition indicators, but also includes parameters which are designated as health indicators by other manufacturers.

A third sensor domain, namely order-domain data, has not yet been accommodated, and is presently being developed. Due to the two stage importation, order-domain data from the years of collection has not been lost, but rather has been waiting in the files table for processing. Following its implementation, data collected from the SCARNG VMUs will begin its metadata tagging stage.

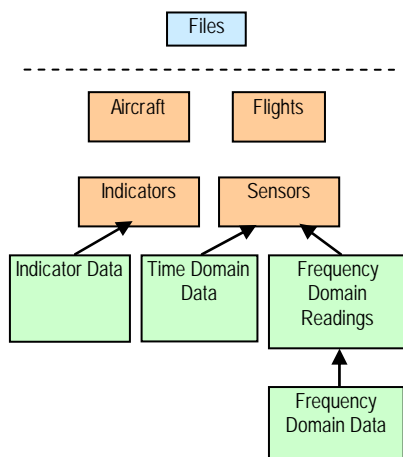


Figure 6—Simplified database relational diagram for HUMS data

Conclusions and Future Work

The preliminary analysis results of the TAMMS-A records offer a promising insight into the capability of developing a functioning natural language processor for interpreting fault descriptions. Using a dictionary of only 5,000 terms should allow for comprehensive term recognition of 4 out of every 5 records. In terms of long-term implementation of a CBM system, however, there remains a large room for improvement in TAMMS-A writing practices. Adoption of a constructed English language such as Simplified Technical English (STE) would allow for maintenance actions to be described in a much-reduced lexicon of about 2,000 words while still being readable to any natural English speaker. This could be implemented

using a software input method editor (IME) which would restrict any writing to the approved list of words thus pushing NLP retention rates to nearly 100 percent.

In terms of HUMS capability, IAC's VMU currently used by SCARNG is sufficient for the integration process in its current form. As CBM advances, the need for a more comprehensive onboard system with a larger number of sensors will continue to grow, and IAC along with other manufacturers are already in the process of developing the next generation of increasingly capable HUMS kits. In terms of data processing, VMU data reasonably structured for relational data importation, and the generic database schema was heavily influenced by its structure. The University of South Carolina recognizes the future of CBM will no doubt involve several different manufacturers of HUMS systems, and encourages an open-specification approach to data formatting to promote interoperability of data types and third-party analysis.

The next phase in development for the USC research team will focus on developing a prototype language processor as well as characterization of the VMU data set as a whole. Following this the implementation, the metadata tagging phase will begin. From the experience gained through this process, a more definitive algorithm for event matching can be derived, and through the preliminary final results it will be possible to evaluate the overall effectiveness of the integration process. When complete, the path to a front-end fully-integrated CBM system will become increasingly apparent, allowing for the next generation of maintenance systems to unparalleled in their capabilities and performance.

Appendix A—Common Terms

Condition Based Maintenance:

Condition-Based Maintenance (CBM) is the nomenclature assigned to a maintenance process that is based upon the electronically determined condition of a component, sub-system or system.

Condition:

Condition is based upon electronic measurements that can be related to condition without the need to disassembly and inspect through conventional means.

General CBM Objectives:

- Reduce unscheduled maintenance and maintenance workload.
- Decrease maintenance and logistics footprints.
- Perform and integrate advanced engineering, maintenance, and information technologies.
- Maintenance only upon evidence of need.
- Improve diagnosis and prognosis capabilities.
- Use real-time assessments of material condition obtained from embedded sensors and/or external tests and measurements using portable equipment.

- Increase operational availability.

Condition Indicators (CI):

Condition indicator algorithms come in many varieties and capabilities. These condition indicators are in turn used to develop Health Indicators (HI).

Health Indicator (HI):

The Health Indicator (HI) is a non-dimensional metric that is constructed (calculated) by the manipulation of related condition indicators (the output of condition algorithms). The time history of a perfect HI would identically track (match) the time history of the CI.

Diagnosis:

Faults in bearings, gears and shafts can be detected. These detections are reported as magnitudes. Faulted shafts are the easiest to detect, and bearing faults are the most difficult.

Prognosis:

When it is possible to detect an increase in the magnitude of a detection algorithm output as a function of a tangible usage metric, it is possible to predict the useful service life remaining. This prediction is known as prognosis. A tangible usage metric is that usage metric that relates most directly to the loads and cycles causing the fault (or incipient fault) to propagate. In the case of a helicopter power train, there are many potential metrics:

- Flight time
- Operating time (running time)
- Power spectrum
- Time integral of applied power (throughput power)
- Time integral of applied power normalized for the system S-N Characteristic (Normalized Throughput Power.)

Usage of Mechanical Systems:

Usage is defined as time integral of the power applied to the mechanical system. This usage is also known as generic system usage.

Flight Profile:

A flight profile is a series of ground and flight phases (or events). The simulation program is limited to the simulation of mechanical power train health during flight operations and ground operations when the rotor is turning. The analyst (user) will be able to create flight profiles or use an existing flight profiles. For the purposes of this simulation, the program needs to know the sequence of the various phases and the time spent in each phase.

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Appendix B—Biographies



Abdel-Moez E. Bayoumi, Ph.D., has over 25 years teaching and research experience. Dr. Bayoumi is Director of the Condition-Based Maintenance Center, Director of the Biomedical Engineering and Professor of Mechanical Engineering at the University of South Carolina College of Engineering and Computing. Before joining USC, he was a Professor of Mechanical and Aerospace Engineering at North Carolina State University, a project manager at Hewlett-Packard Company, and Professor of Mechanical and Materials Engineering at Washington State University. He has been actively involved in developing strong programs in mechanical systems. His research activities have been focused in mechanical behavior of materials and design, diagnosis and prognosis of mechanical systems, and design for manufacturability. He has published over 100 papers and supervised fourteen doctoral and thirty-five masters' students.



General Lester D. Eisner is currently serving as the Deputy Adjutant General, South Carolina Army National Guard. He was commissioned into the U.S. Army in 1976. BG Eisner has held key various staff and command positions including battalion and brigade command. He has logged over 5000 hours in various U.S. Army fixed and rotary winged aircraft, including the UH-60 and AH-64. He is a graduate of the U.S. Army War College. BG Eisner has provided key leadership for many years in the development of embedded diagnostics technology for the U.S. Army helicopter fleet. He served as the Director of the Vibration Management Enhancement Program.



Chief Warrant Officer Five Lemuell Grant graduated from Georgia State University with a BS in Criminal Justice. He served over 40 years as an Army Aviator, Instructor Pilot and Maintenance Test Flight Examiner. During his career, he was twice awarded The Distinguished Flying Cross, fifty-six Air Medals and the Broken Wing Award. He was instrumental in the development of the Army Vibration Analyzer (AVA) and the Vibration Management Enhancement Program (VMEP). He continues to work in the field of Conditioned Based Maintenance.



Ronak Shah received his B.S. degree in Economics from the Moore School of Business at USC in May 2007 specializing in Applied Microeconomics with a minor in Computer Science with a focus on Database design and development. Throughout his college career, he has been involved in a number of open source projects through the Open Source Developers Network, and has developed a programming background and skills in web applications development and content management. Ronak is currently working on a M.A. in Economics at USC while working with the Condition-Based Maintenance center in conjunction with the US Army on Cost-Benefit Analysis modeling for CBM objectives.



Nicholas Goodman received his B.S. degree in Mechanical Engineering in May 2006 with a minor in Mathematics and Computer Science, specializing in Artificial Intelligence. Following a six month language study trip to East Asia, he began working towards a M.S. in Mechanical Engineering, with a specialization in Mathematics. Nicholas is also a seasoned programmer who has significant experience in working with control systems and software development. He is currently investigating the development of neural network algorithms for the analysis of rotorcraft vibrations and maintenance data in support of CBM objectives for the U.S. Army.



Dr. John Keller received his B.S. (1995) in Aerospace Engineering from Penn State University. He went on to receive his M.S. (1997) and Ph.D. (2001) in Aerospace Engineering from Penn State University, with a Fellowship from the Rotorcraft Center of Excellence. Dr. Keller has been an Aerospace Engineer with the Aeromechanics Division of the Aviation Engineering Directorate since 2001.