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Vehicle Health Monitoring System In A Developing Nation.

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ABSTRACT

Vehicle health monitoring in a Developing Nation (VHMDN) is a collection of data relevant to the present and future performance of a vehicle system and its transformation into information to be used to support operational decisions. The ideal was conceived due to the fact that Standard Organization of Nigeria (SON) a body design to regulate the strength of material has not work to expectation in the Country. This paper is design to embraces an integration of sensors, communication technologies, and Artificial intelligence to provide vehicle wide abilities to diagnose problems and recommend solutions as well as to estimate the total remaining life spam of the material. In Africa, the major concentration of Vehicle parts are mainly on fairly used components or parts, which is popularly called "TOKUBO" and these parts life time cannot be quantifier, the idea was based on the fact that new parts are very expensive and can be of lower standard or may be imported from undeveloped Nation. The introduction begins with a brief history of VHM technology development. Recent research has begun to recognize that the VHM problem is fundamentally one of the statistical pattern recognition (SPR) and a paradigm to address such a problem is described in detail herein as it forms the basis for organization of this theme issue.

KEYWORDS: sensors, communication Technology, Artificial Intelligence.

INTRODUCTION

The concept of integrated vehicle health management in developing Nation (VHMDN) is the failure inherent by the Standard Organization of Nigeria (SON) whose responsibility is the implementation of standardization and quality assurance for products. Essentially, standardization is regarded as the "catalyst' which stimulates industrialization and the confidence to effectively participate in the export trade where competitiveness (function of quality, price and delivery time) is the determinant of acceptability. The outcome of any particular standardization activity leads to documented criteria which help among other things in: Inspiring confidence in suppliers and customers locally and internationally, establishing safety criteria, providing good after-sales services and customer support, product certification, and assisting communication and trade. The concept of VHMDN is an evolution of diagnostic and prognostic systems. Which involved the implementation of a sensor that will enables continuous monitoring and real- time assessment of vehicle functional health, predicts remaining useful life of fault or near failure components, and uses this information to improve operational decisions. Here, maintenance operations benefits from reduced occurrences of unexpected faults as the health management system will provide early identification of failure precursors while, simultaneously, condition-based maintenance (CBM) is enabled, which can enhance availability, mission reliability, system life and affordability. Here the vehicle is being designed with a fully functional sensor system that performs fault detection, isolation, and reconfiguration across numerous components and subsystems (e.g airframe structure, engine, electronics, hydraulics, fuel, and electric power system. In the most general terms, it is necessary for us to differentiate between damage and undamaged part. Then damage can be defined as changes introduced into a system that adversely affect its current or future performance. It means that damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial and often undamaged state. This theme issue is focused on the study of damage identification in structural and mechanical systems. Therefore, the definition of damage will be limited to changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affects the current or future performance of these systems In terms of length-scales, all damage begins at them a material level. The term damage does not necessarily imply a total loss of system functionality, but rather that the system is no longer operating in its optimal manner. As the damage grows, it will reach a point where it affects the system operation to a point that is no longer acceptable to the user. This point is referred to as failure. The process of implementing a damage identification strategy for vehicle, or Cars as well as any mobility engineering infrastructure is referred to as Vehicle health monitoring (VHM). Damage identification is carried out in conjunction with five closely related disciplines that include SHM, condition monitoring, non-destructive evaluation (NDE), statistical process control(SPC) and damage prognosis (DP). Typically, SHM is associated with on line global damage identification in structural systems such as vehicle, aircraft and buildings etc. CM is analogous to SHM, but addresses damage identification in rotating and reciprocating machinery, such as those used in manufacturing and power generation. NDE is usually carried out off-line in a local manner after the damage has been located. There are exceptions to this rule, as NDE is also used as a monitoring tool for structures such as pressure vessels and rails. NDE is therefore primarily used for Damage characterization and as a severity check when there is an actual knowledge of the damage location. SPC is process-based rather than structure-based and uses a variety of sensors to monitor changes in a process, one cause of which can result from structural damage. Once damage has been detected, DP is used to predict the remaining useful life of a system. This theme issue will primarily address SPC and CM, and will conclude with an article that introduces the damage prognosis problem.

MOTIVATION FOR VHMDN TECHNOLOGY DEVELOPMENT

Many portions of our technical infrastructure are approaching or exceeding their initial design life. As a result of economic issues, Vehicle (car) structures are being used in spite of aging and the associated damage accumulation. Therefore, the ability to monitor the health of this structure is becoming increasingly important. Most often, the replacement is done by used part(s) which life spam is not ascertain but because of the cost of new parts, there are needs for management of the Vehicle by the uses which will constituted a big risk to the owner or passage and generally a danger to the nation at large. Most of the accidents course in Nigeria today is mainly the replacement of substandard of used parts. VHM is the technology that will allow the current time-based maintenance philosophies to evolve into potentially more cost effective condition-based maintenance philosophies. The concept of condition-based maintenance is that a sensing system on the structure will monitor the system response and notify the operator that damage has been detected. Life-safety and economic benefits associated with such a philosophy will only be realized if the monitoring system provides sufficient warning such that corrective action can be taken before the damage evolves to a failure level. The trade-off associated with implementing such a philosophy is that it requires a more sophisticated monitoring hardware to be deployed on the system and it requires a sophisticated data analysis procedure that can be used to interrogate theme assured data. SHM has the potential to extend the maintenance cycles and, hence, keep the equipment out in the field where it can continue to generate revenues for the owner. Also, the vehicle owners would like to base their lease fees on the amount of system life used up during the lease time rather than on the current simple time-based lease fee arrangements. Such a business model will not be realized without the ability to monitor the damage initiation and evolution in the rental hardware.

BRIEF HISTORICAL OVERVIEW

It is the authors speculation that damage identification, as determined by changes in the dynamic response of systems, has been practiced in a qualitative manner, using acoustic techniques (e.g. tap tests on train wheels), since modern man has used tools. More recently, the development of quantifiable VHM approaches has been closely coupled with the evolution, miniaturization and cost reductions of digital computing hardware. To date, the most successful application of VHM technology has been for CM of rotating machinery. The rotating machinery application has taken an almost exclusive non-model based approach to damage identification. The identification process is based on pattern recognition applied to displacement, velocity or acceleration time histories, generally measure data single point on the housing or shafts of the machinery during normal operating conditions and start up or shut down transients. Often this pattern recognition is performed only in a qualitative manner based on a visual comparison of the spectra obtained from the system at different times .Databases have been developed that allow specific types of damage to be identified from particular features of the vibration signature . For rotating machinery systems, the approximate damage location is generally known making a single-channel fast Fourier transform analyser sufficient for most periodic monitoring activities. Typical damage that can be identified includes loose or damaged bearings, misaligned shafts and chipped gear teeth. Today, commercial software integrated with measurement hardware is marketed to help the user systematically apply this technology to the operating equipment.

This research has focused on such cross-sector interpretation, although there is also a broader view in the literature that is to see potential applications of VHMDN to non-vehicle systems, like production machines, industrial process plants, or power generation plants. VHMDN was first conceptualized by NASA. The first publication found was a report written in 1992, entitled 'Research and Technology Goals and Objectives for VHM. This report stated VHM as the highest priority technology for present and future NASA space transportation systems. The concept of VHM is said to date back to the early 1970s, although there is no evidence of this in the literature of those years. The literature on VHM has been mainly published after 2000, with earliest articles appearing at the end of the 1990s. Afterwards between 2006 and 2008, Conferences have been the most popular dissemination route for research on VHM, with the 'IEEE Aerospace Conference' being the leading one. This conference, along with similar technical conferences (e.g. the 'Digital Avionic Systems Conference' or the 'AIAA Space Exploration Conference') has been the forum for discussion about the principles, applications, and developments of VHM. Almost no articles have appeared as special reports, typically from government agencies and military organizations. Collectively, these articles have covered a range of aspects of VHM, with approximately 35 per cent describing the potential impacts or cost-benefit analyses, 15 percent discussing design approaches , and 25 per cent focusing on examples of either fielded or under development VHM systems (e.g. references . Other topics are related to technology evolution and integration, logistic support, and development planning. In terms of affiliation, the authors tend to be associated with manufacturing organizations of VHM equipped vehicles, components, or prime contractors responsible for integrating the systems. The largest contributions come from NASA, The US DoD, the Boeing Company, and Honeywell Corporation. There have been relatively few contributions from academic institutions, and those that exist have originated in the research centre of US universities, such as the 'Applied Research Laboratory" at Pennsylvania State University or the 'Intelligent Control

Systems Laboratory' at Georgia Institute of Technology.

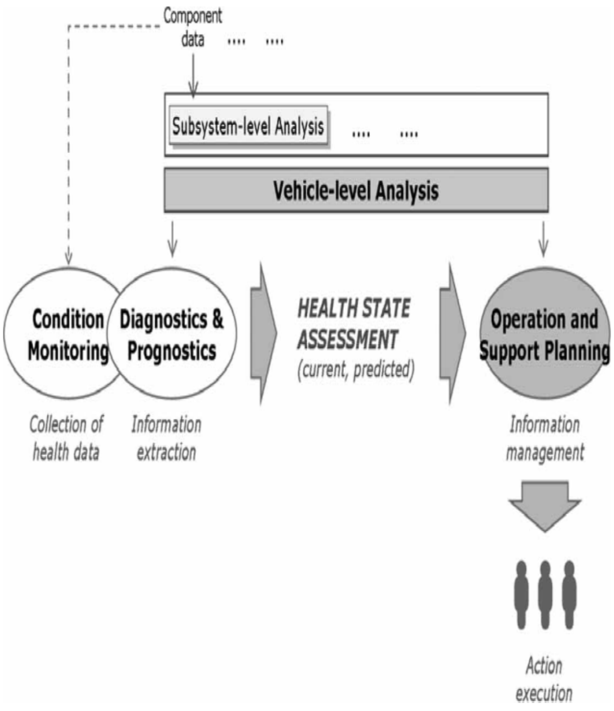
The success of CM is due to Minimal operational and environmental variability associated with this type of monitoring, well-defined damage types that occur at known locations, large data bases that included data from damaged systems, well-established correlation between damage and features extracted from the measured data, and clear and quantifiable economic benefits that this technology can provide. These factors have allowed this application of SHM to have made the transition from a research topic to industry practice several decades ago resulting in comprehensive condition management systems such as the US Navy's Integrated Condition Assessment System.

Definition of VHMDN

There is no unanimously or even generally accepted definition of VHMDN yet various authors have proposed their own illustration of the concept. By comparing the various interpretations, the concept of VHM can be generalized as 'the capture of vehicle condition, both current and predicted, and the use of this information to enhance operational decisions, support actions, and subsequent business performance'. Figure 1 shows how a VHM system that is intended to operate. Health data are collected from vehicle components, structures, and elements and used to make diagnoses and prognoses of the present and future health of the vehicle. This information is further processed to formulate appropriate operation and support actions and presented to the people who should decide and execute the actions. Here, the first critical issue is that information regarding vehicle condition must be acted upon to generate reactive plans rather than merely processing health data and presenting them for later manipulation and use. This differentiates the idea of health management from health monitoring, in which there is no requirement to specify the use of the data that is collected. The second critical issue is in the notion of integration. The health management system will consider the vehicle as a whole; it will merge all vehicle functions rather than be implemented separately on individual subsystems, components, and elements. In comparison to the classical approach of using loosely coupled federated systems, the single VHM system will help streamline isolation of root cause of failures as well as facilitating improved decision-making in fault conditions. On these bases, an IVHM system can be considered as an advanced vehicle instrumentation system that enables cost-effective ultra-high system availability, thereby ensuring operation safety. In a wider sense, the VHM proposition can be seen as the capability to efficiently perform checkout, testing, and monitoring of subsystems, and components before, during, and after operation and must support fault-tolerant response including system/subsystem reconfiguration to prevent catastrophic failure; and the planning and scheduling of post operational maintenance and all these activities are performed to understand the state of the vehicle and its components, in other to restore the vehicle to nominal system status when malfunctions occur, and to minimize safety risks and mission impacts that result from system failures. It also involved an effort to coordinate, integrate, and apply advanced software, sensors, and design technologies to increase the level of intelligence, autonomy, and health state determination and response of future vehicle.

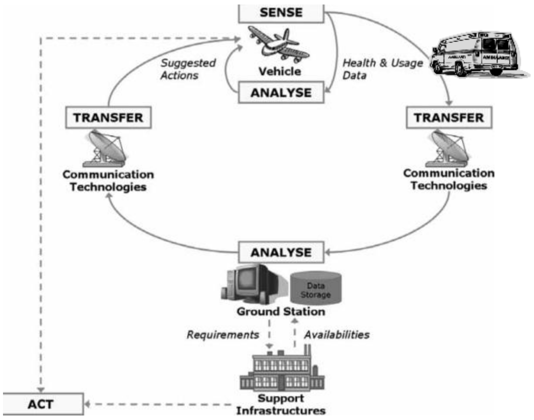
Roemer *et al.* 'Integrates component, subsystem, and system level health monitoring strategies, consisting of anomaly/diagnostic/prognostic technologies, with an integrated modeling architecture that addresses failure mode mitigation and lifecycle costs

Price *et al.* 'An example of an intelligence sensing system. The purpose of such system is to detect and measure certain quantities, and to use the information and knowledge obtained from the measured data, and any prior knowledge, to make intelligent, forward-looking decisions, and initiate actions' Wilmering 'The unified capability of an arbitrarily complex system of systems to accurately assess the current state of member system health, predict some future state of the health of member systems, and assess that state of health within the appropriate framework of available resources and operational demand' Paris *et al.* 'The process of assessing, preserving, and restoring system functionality across flight and ground systems' Jakovljevic and Artner 'Ensures the reliable capture of the "health status" of the overall aerospace system and helps to prevent its degradation or failure by providing reliable information about problems and faults' Karsai *et al.* 'Its goal is to provide better ways for operating and maintaining aerospace vehicles using techniques, such as condition monitoring, anomaly detection, fault isolation, and managing the vehicle operations



Configurations of VHM systems

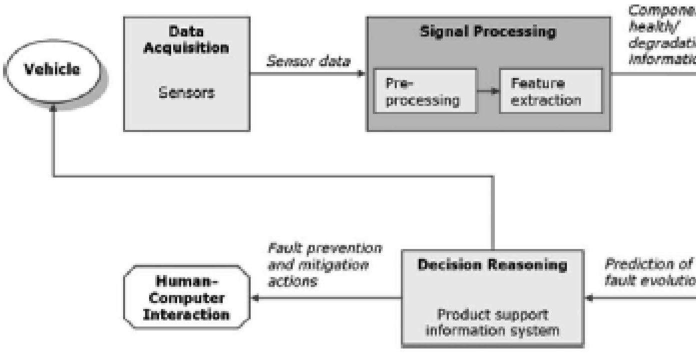
A VHM system comprises a set of sensors and associated data processing hardware and software distributed between the vehicle and its support system. Here, for example, consider an bus. As illustrated in Fig. 2, the IVHM system requires appropriate sensors to be positioned on critical components of the aircraft, monitoring the relevant subsystems (e.g. engine, propulsion, avionics, and structures) and state variables (e.g. temperature, pressure, speed, flow rate, and vibrations). The data collected by sensing devices are analysed onboard the vehicle. At the same time, health and usage data are also transmitted to a ground support centre where additional data analysis capabilities are deployed. In this case, wireless networks or more simple communication technologies are used to send the data from the aircraft to the remote support centre so that analysis can still be performed in-flight. to cover an automobile and implement remote diagnosis and maintenance systems . A VHM system will integrate onboard and remote hardware and software resources to collect, monitor, and analyse vehicle health data. The system can be seen in a range of configurations, depending on the amount of analysis that is performed onboard the vehicle or alternatively diverted to the remote support.



Technology principles for VHM systems

The basic functional architecture of a VHM system. Here, the first step is the use of sensors to measure state awareness variables that are indicative of potential failure modes and also to identifies components of low standard that do not march with the system . In addition to conventional sensors used for monitoring and control (e.g. temperature, speed, and flow rate sensors), sensor devices that are specifically tailored to health management applications (e.g. strain gauges, ultrasonic sensors, acoustic emission sensors, and proximity devices) are available. Although sensor suites tend to be specific to the application domain, a few developmental sensor technologies are taking central stage in the VHM domain. These include micro and fibre optic technologies that reduce sensor size, weight, and support requirements together with increasingly advanced smart sensors that have opened up the possibility for widespread introduction of embedded sensor systems. Similarly, the availability of a specific protocol

(IEEE 802.11) is fostering an intensive use of wireless sensor networks, which ensure quick and accurate information transfer with significant space savings. Sensor data are preliminarily processed to remove noises and then manipulated to extract fault features. The techniques commonly used to 'clean' the types of data derived from VHM sensors include, e.g. low-pass filtering and time synchronous averaging. Fast Fourier transform and short time Fourier transform-based methods are very popular approaches in the extraction of condition indicators, while wavelet theory finds extensive application as both denoising method and feature extractor. The diagnostic module analyses fault features to detect, identify, and isolate impending and incipient failure conditions. Diagnostic information is combined with historical data in the prognostic module and is used to generate an estimation of the time to failure of components and subsystems. Concerning the enabling techniques, both model-based and data driven reasoning have been used in VHM applications. Being based on the construction of a mathematical model of the physical system, model-based reasoning can be performed according to a variety of approaches, ranging from Lagrangian dynamics, Hamilton dynamic, and approximation methods as some of the most common model-based diagnostics techniques, to physics-based, autoregressive moving average and particle filtering methods as examples of typical prognostics schemes. Conversely, database reasoning relies on training construct models of the system (e.g. artificial neural network and expert systems) with known fault patterns. Popular methods for pattern recognition in VHM systems include statistical correlation/regression methods, fuzzy-logic classification, and neural network clustering techniques. Nevertheless, prognoses of failure conditions are often executed by just analyzing the statistical form of historical data according to experience-based techniques, typically the Bayesian probability theory or Weibull modeling. Finally, the diagnostics and prognostic information is turned into product support actions through an information system that transmits selected information to the automatic recovery systems onboard the vehicle and to technology enabled support managers. At the current state of practice, there is no well-established set of candidate methods for VHM support planning, thus meaning that any modeling strategy or optimization routine can be applied.



Configurations of VHM systems

The statistical pattern recognition paradigm

There are many ways by which one can organize a discussion of VHMDN. The authors have chosen to follow the one described in a previous Phil.Trans.R.Soc.A Article (Farraretal.2001) that defines the VHMDN process in terms of a four-step statistical pattern recognition paradigm. This following four-step process includes

(i) operational evaluation,

(ii) data acquisition, normalization and cleansing,

(iii) feature selection and information condensation, and

(iv) statistical model development for feature discrimination.

(a) Operational evaluation

Operational evaluation attempts to answer four (4) questions regarding the implementation of a damage identification capability.

(i) What are the life-safety and/or economic justification for performing VHMDN?

(ii) How is damage denied for the system being investigated and, for multiple damage possibilities, which cases are of the most concern? What are the conditions, both operational and environmental, under which the system to be monitored functions?

(iv) What are the limitations on acquiring data in the operational environment?

Operational evaluation begins to set the limitations on what will be monitored and how the monitoring will be accomplished. This evaluation starts to tailor the damage identification process to features that are unique to the system being monitored and tries to take advantage of unique features of the damage that is to be detected.

(b) **Data acquisition, normalization and cleansing**

The data acquisition portion of the VHMDN process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/ storage/transmittal hardware. Again, this process will be application specific. Economic considerations will play a major role in making these decisions. The interval at which the data should be collected is another consideration that must be addressed.

As data can be measured under varying conditions, the ability to normalize the databecomesveryimportanttothedamageidentificationprocess.Asitappliesto SHM, data normalization is the process of separating changes in sensor reading caused by damage from those caused by varying operational and environmental conditions. One of the most common procedures is to normalize the measured responses by the measured inputs. When environmental or operational variability is an issue, the need can arise to normalize the data in some temporal fashion to facilitate the comparison of data measured at similar time so fan environmental or operational cycle. Sources of variability in the data acquisition process and with the system being monitored need to be identified and minimized to the extent possible. In general, not all sources of variability can be eliminated. Therefore, it is necessary to make the appropriate measurements such that these sources can be statistically quantified. Variability can arise from changing environmental and test conditions, changes in the data reduction process and unit-to-unit inconsistence ie Data cleansing is the process of selectively choosing data to pass on to or reject from the feature selection process. The data cleansing process is usually based on the knowledge gained by individuals directly involved with the data acquisition. As an example, an inspection of the test set-up may reveal that a sensor was loosely mounted and, hence, based on the judgment of the individuals performing the measurement, this set of data or the data from that particular sensor may be selectively deleted from the feature selection process. Signal processing techniques such as altering and resampling can also be thought of as data cleansing procedures. Finally, it should be noted that the data acquisition, normalization and cleansing portion of the SHM process should not be static. Insight gained from the feature selection process and the statistical model development process will provide information regarding changes that can improve the data acquisition process. A number of articles contained in this theme issue specifically address various aspects of the data acquisition and data normalization issues as they apply to SHM

(c) **Feature extraction and information condensation**

The area of the VHM process that receives the most attention in the technical literature is the identification of data features that allows one to distinguish between the undamaged and damaged structure. As such, numerous articles in this theme issue are devoted to the feature extraction portion of VHM Inherent in this feature selection process is the condensation of the data. The best features for damage identification are, again, application specific. One of the most common feature extraction methods is based on correlating measured system response quantities, such as vibration amplitude or frequency, with the rsthand observations of the degrading system. Another method of developing features for damage identification is to apply engineered flaws, similar to ones expected in actual operating conditions, to systems and develop an initial understanding of the parameters that are sensitive to the expected damage. The flawed system can also be used to validate that the diagnostic measurements are sensitive enough to distinguish between features identified from the undamaged and damaged system. The use of analytical tools such as experimentally validated finite element models can be a great asset in this process. In many cases, the analytical tools are used to perform numerical experiments where the laws are introduced through computer simulation. Damage accumulation testing, during which significant structural components of the system under study are degraded by subjecting them to realistic loading conditions, can also be used to identify appropriate features. This process may involve induced-damage testing, fatigue testing, corrosion growth or temperature cycling to accumulate certain types of damage in an accelerated fashion. Insight into the appropriate features can be gained from several types of analytical and experimental studies as described above and is usually the result of information obtained from some combination of these studies. The operational implementation and diagnostic measurement technologies needed to perform SHM produce more data than traditional uses of structural dynamics information. A condensation of the data is advantageous and necessary when comparisons of many feature sets obtained over the lifetime of the structure are envisioned. Also, because data will be acquired from a structure over an extended period of time and in an operational environment, robust data reduction techniques must be developed to retain features sensitivity to the structural changes of interest in the presence of environmental and operational variability. To further aid in the extraction and recording of quality data needed to perform VHM, the statistical significance of the features should be characterized and used in the condensation process.

(d) Statistical model development

The portion of the VHM process that has received the least attention in the technical literature is the development of statistical models for discrimination between features from the undamaged and damaged structures. Statistical model development is concerned with the implementation of the algorithms that operate on the extracted features to quantify the damage state of the structure. The algorithms used in statistical model development usually fall into three categories. When data are available from both the undamaged and damaged structure, the statistical pattern recognition algorithms fall into the general classification referred to as supervised learning. Group classification and regression analysis are categories of the supervised learning algorithms. Unsupervised learning refers to algorithms that are applied to data not containing examples from the damaged structure. Out lier or novelty detection is the primary class of algorithms applied in unsupervised learning applications. All of the algorithms analyse statistical distributions of the measured or derived features to enhance the damage identification process.

The damage state of a system can be described to answer the following questions.

(i) Existence: Is there damage in the system?

(ii) Location: Where is the damage in the system?

(iii) Type: What kind of damage is present?

(iv) Extent: How severe is the damage?

(v) Prognosis: How much useful life remains?

Answers to these questions in the order presented represent increasing knowledge of the damage state. When applied in an unsupervised learning mode, statistical models are typically used to answer questions regarding the existence and location of damage. When applied in a supervised learning mode and coupled with analytical models, the statistical procedures can be used to better determine the type of damage, the extent of damage and remaining useful life of the structure. The statistical models are also used to minimize false indications of damage. False indications of damage fall into two categories: (i) false-positive damage indication (indication of damage when none is present) and (ii) false-negative damage indication (no indication of damage when damage is present). Errors of the rest type are undesirable, as they will cause unnecessary downtime and consequent loss of revenue as well as loss of condenses in the monitoring system. More importantly, there are clear safety issues if misclassications of the second type occur. Many pattern recognition algorithms allow one to weigh one type of error above the other; this weighting may be one of the factors decided at the operational evaluation stage. Articles appearing within this theme issue that focus on the statistical modelling portion of the SHM process include

Challenges for VHM

The basic premise of VHM feature selection is that damage will significantly alter the stiffness, mass or energy dissipation properties of a system, which, in turn, alter the measured dynamic response of that system. Although the basis for feature selection appears intuitive, its actual application poses many significant technical challenges. The most fundamental challenge is the fact that damage is typically a local phenomenon and may not significantly intense the lower-frequency global response of structures that is normally measured during system operation. Stated another way, this fundamental challenge is similar to that in many engineering fields where the ability to capture the system response on widely varying length- and time-scales, as is needed to model turbulence or to develop phenomenological models of energy dissipation, has proven difficult. Another fundamental challenge is that in many situations feature selection and damage identification must be performed in an unsupervised learning mode. That is, data from damaged systems are not available. Damage can accumulate over widely varying time-scales, which poses significant challenges for the SHM sensing system. This challenge is supplemented by many practical issues associated with making accurate and repeatable measurements over long periods of time at a limited number of locations on complex structures often operating in adverse environments.

Finally, a significant challenge for VHM is to develop the capability to dene the required sensing system properties before field deployment and, if possible, to demonstratethatthesensorsystemitselfwillnotbedamagedwhendeployedinthe field. If the possibility of sensor damage exists, it will be necessary to monitor the sensors themselves. This monitoring can be accomplished either by developing appropriate self-validating sensors or by using the sensors to report on each other’s condition. Sensor networks should also be fail-safe. If a sensor fails, the damage identification algorithms must be able to adapt to the new network. This adaptive capability implies that a certain amount of redundancy must be built into the sensor network.

In addition to the challenges described above, there are other non-technical issues that must be addressed before SHM technology can make the transition from a research topic to actual practice. These issues include convincing structural system owners that the SHM technology provides an economic benefit over their current maintenance approaches and convincing regulatory agencies that this technology provides a significant life-safety benefit. All these challenges lead to the current state of SHM technology, where outside of condition monitoring for rotating machinery applications SHM remains a research topic that is still making the transition to field demonstrations and subsequent field deployment. There are lots of on-going and new structural monitoring activities, but these systems have been put in place without a pre- denied damage to be detected and without the corresponding data interrogation procedure. As such, these monitoring activities do not represent a fully integrated hardware/software VHM system with pre-denied damage identification goals.

Tools for designing IVHM systems

The tools proposed in the literature for the design of VHM systems can be generalized as system-level methodologies that look at either optimizing use of the different technology resources or assisting in their allocation across the extended system. Within the first category, a failure modes, effects, and criticality analysis (FMECA) study is strongly recommended during the early stages of the design process to link the candidate failure modes to their severity, frequency of occurrence, and testability. Advanced FMECA approaches are available, which analyse failure symptoms and may also suggest the sensor suites and diagnostics and prognostics technologies that are most appropriate for the VHM system. At the same time, a strong generic favour is shown in the literature towards the use of trade studies as a methodology to identify the most balanced technical solution among a set of viable options. Specific trade-studies approaches are available to assist designers of VHM systems. For example, Vachtsevanos *et al.* propose a formal framework that applies the integrated product and process design methodology for the selection of the best alternative technologies for PHM components, sensors, and algorithms. Similarly, Banks and Merenich propose a software application to support the exploration of the technical and economic performances associated to different designs solutions, and Keller *et al.* present a design platform where a simulation model is combined with several cost/benefit models to support cost/benefit trades. Use of simulation for technology related trade-offs is also proposed by Kacprzynski *et al.* and Ge *et al.* while analytical cost-benefit models are proposed by Byer *et al.* , Banks *et al.*Wilmering and Ramesh , and Banks *et al*. Tools for resource allocations have instead typically the appearance of system architectures which suggest the distribution of IVHM functions across technological components of the system, such as the software framework described by Swearingen and Keller for developing modular IVHM architectures based on the OSA/CBM standard. Other examples include the framework described by Paris *et al.* which modularizes VHM functions and integrates them into avionics, health management, and control components, or the architecture given by Aaseng for distributing the typical IVHM functions of an aircraft plat form between the vehicle, the operations support, and the logistics infrastructure.

CONCLUDING REMARKS

The development of robust VHM technology has many elements that make it a potential grand challenge for the engineering community. First, almost every industry wants to detect damage in its structural and mechanical infrastructure at the earliest possible time. Industries desire to perform such monitoring is based on the tremendous economic and life-safety benefits that this technology has the potential to offer. And also to identify, interpret, and summarize the literature currently available on VHM. The investigation has focused on the literature explicitly related to the context of vehicle systems. A more informed prospect could therefore be achieved in the future by also considering research dealing with other types of engineering systems. It is through system-level integration and transition from health monitoring to management that VHM realizes new ways to provide value to an extended set of end customers. Similarly, what creates the business case for VHM is not technical innovation; rather it is a novel financial approach to asset lifecycle. On the other hand, the article has taken a very wide view of IVHM in that it has carried out a cross-sector investigation as so contributed to a general understanding of the concept which can overarch all potential application domains. On this basis, 11 findings have been established.

In summary, VHM is a capability to capture vehicle condition, both current and predicted, and use of this information enhance operational decisions, support actions, and subsequent business performance. The concept was originated in the aerospace sector in the 1970s, and to date most contributors have been from industrial, military, and governmental organizations involved with developing VHM systems. Although substantially driven by end-user pressures to improve cost-effectiveness of maintenance and support activities, VHM is being increasingly developed as a competitive proposition for aftercare service providers. An VHM system will involve synergistic deployment of sensor technologies and reasoning techniques, tackled to the provision of a proactive decision support capability. It will consist of onboard and remote instrumentation systems, and can be implemented in a diverse range of configurations. To be effective, an VHM system needs to be designed according to an open system standard and to be constructed into the host vehicle. Several tools are available to support VHM design, which assist in the solution of technology-related trade-offs and in the definition of the most appropriate architecture of the system. There are a few examples of successful VHM applications in the literature. These demonstrate that the technology is mature, but also tend to emphasize expectations from future developments. Despite many potential benefits related to VHM, a serious barrier to adoption results from the problem of accurately assessing the trade-offs between the associated costs, risks, and rewords. These findings support the view that VHM has the potential for improving safety and cost-effectiveness of new and legacy vehicles by linking maintenance, operations, and logistics to the present and future health of the vehicle but that the cost and complexity of the technology are perceived as potential inhibitors to widespread adoption. The principal issues concern the lack of consolidated tools and methodologies that can guide an early assessment of the most appropriate level of VHM implementation. An in-depth evaluation of the use of VHM within emerging forms of service contracting and a better understanding of the existing applications would also facilitate a wider adoption of VHM. The conclusions of this review provide a platform on which to base future work. A true paradigm shift is taking place in the way complex assets are designed, operated, and maintained. Stringent enhanced diagnostics, prognostics, and health management requirements have begun to be placed on the development of new applications. VHM follows and interprets this trend by specifically integrating component, subsystem, and system level strategies to deliver the richest possible information and decision support during vehicle field performance. This is enabled by the recent advances in sensor, communication, and software technologies and seems to be a significant opportunity to improve the management of the product through its lifecycle and also the identification of standard components for replacement in case of damaged, which extends well beyond the field of vehicle systems and potentially includes any complex technical asset.

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