COVER SHEET

Title: **Design Framework for Vibration Monitoring Systems for Helicopter Rotor Blade Monitoring using Wireless Sensor Networks**

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ABSTRACT

The pursue of methods for supporting Structural Health Monitoring (SHM) has been an important driver for the technological innovation in several engineering fields such as wireless communication, sensing and power harvesting. However, despite of the innovative and scientific value of these advances, the adoption of SHM and associated technologies by industry has not occurred at the expected pace. One of the possible reasons for this is the lack of a systematic design process for condition monitoring systems tailored to actual mechanical systems. This paper proposes a design framework for a vibration monitoring system that integrates the predictive maintenance needs with the technological developments on SHM methods and related technologies.

The framework involves three stages. The first stage corresponds to the identification of the characterization of the system function and its failure and the expected function of the monitoring system. The next stage aims at decomposing the vibration signal according to the dynamic behavior of the system and associated failure. The last stage corresponds to the technological implementation of the vibration monitoring system. To illustrate the applicability of this framework a case study on the development of a vibration monitoring system for helicopter rotor blades by using an autonomous sensor network is presented.

INTRODUCTION

Vibrations constitute an indispensable parameter of modern condition monitoring systems for mechanical machinery and structures. Several motivations justify the spread use of vibration monitoring; the most important are for safety, maintenance optimization and operations. Vibration sensors are included in almost all the protection systems that aim to stopping the machines when dangerous vibration levels are reached by preventing catastrophic failures.

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Vibration analysis is also considered as a pillar of predictive maintenance for diagnostic of rotating and reciprocating machinery within Condition Monitoring Systems (CMS) and for engineering structures within Structural Health Monitoring (SHM) systems. For highly specialized applications as in the case of helicopters, vibration profiles are consulted not only as descriptors of developing failures, but also as indicators of the loading condition of the rotorcraft, as considered by Health and Usage Monitoring Systems (HUMS). Although there are several differences, as seen in Table I, all these approaches strive for more efficient monitoring while increasing the safety and reliability of the monitored systems.

In later years there has been a growing interest in the use of Wireless Sensor Networks (WSN) for expanding the traditional limits of vibration monitoring. Autonomous WSN can be employed at complex environments that were traditionally prohibited for wired sensing. This is the case for helicopter rotor blades, which despite of being the main source of vibration for the rotorcraft have remained unmonitored due to the difficulties of communication with rotating frames [1].

However the implementation of WSN for complex applications, as in the rotor case, faces important limitations, in particular in relation with power consumption and integration with the hosting structure [2]. Yet advancing in the WSN implementation is possible when carefully deciding upon the goals, the methods and the components of the monitoring system. Although there is a vast expertise on use of vibration within CMS, SHM and HUMS, there is little consensus among these with regard to designing vibration monitoring systems. This paper discusses a framework for supporting the decision making process for the design of vibration monitoring systems. The framework is applied in a case of monitoring helicopter main rotor blades using wireless sensor networks.

DESIGN SUPPORT FRAMEWORK

The design of a vibration monitoring system that employs wireless sensor networks is by essence a complex and multidisciplinary problem, therefore the use of systems engineering is called upon. Design oriented systems engineering embraces several methods that support the creation of new *artifacts* while understanding the rationales of their design processes. By doing so, improved design processes have emerged that are capable of more efficient creation of better artifacts. Those methods include the creation of conceptual structures or frameworks intended to serve as a guideline for the design process.

TABLE I: COMPARISON OF CMS, HUMS, SHM

|	Condition Monitoring Systems (CMS)	Health and Usage Monitoring Systems (HUMS)	Structural Health Monitoring (SHM)
Origins	Industry Rotating Machinery	Aviation, Helicopters	Civil Structures, Engineering Structure
Diagnostic Techniques	Vibration analysis Thermography Oil Analysis	Vibration Analysis Doppler based blade tracking.	Vibration-based techniques Electro-Mechanical Acoustic, Guided Waves
Data analysis	Profile Analysis Trend monitoring.	Profile Analysis Operation- based diagnostics.	Statistical approach. Supervised and unsupervised learning.
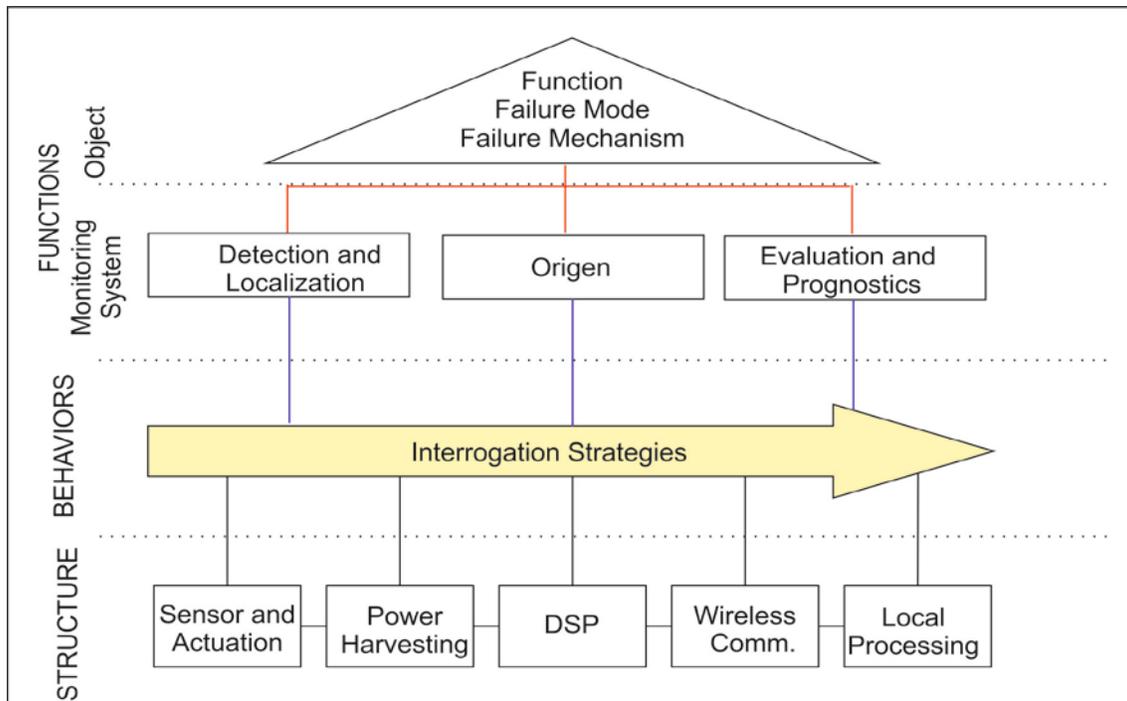
Figure 1. Decision Framework for Vibration Monitoring Systems using WSN.

For the selected case, a design framework is required not only to select upon the actual components of the monitoring system, but also to support the decision making *process* of interrogation of a system based on the rationale of the object functionalities and its failures. *FBS* models [3] are chosen here as a suitable design method by their ability to distinguish the following levels of object representation: Function, Behavior and Structure. The basis of the FBS modeling is that the transition from the function to the structure is performed via the *synthesis* of the physical behaviors. [4].

Based on the FBS approach, a design framework for vibration monitoring systems using WSN is proposed, as shown in Figure 1. The definition of the *function* or goals of the monitoring system is performed in two substeps: (1a) the relation between the loss of function of the components of the monitored system and the failure mechanisms and, (1b) the expectations of the monitoring system regarding the damage evaluation. The *behavior* (2) deals with the interrogation strategies to use the vibration signal to disclose the participating loads and failures mechanisms acting on the components. Finally, the *structure* (3) corresponds to the actual technological implementation of WSN, namely the communication protocol, signal processing techniques and networks.

Step 1 Functions of the Monitored and the Monitoring System

The main function of a vibration monitoring system can be stated in an over-simplistic way as *monitoring the failure of a mechanical system*. This primitive statement triggers some relevant questions, such as (i) *what is meant by failure*?, (ii) *how does failure relate to the mechanical system?* and (iii) *what is expected from the monitoring process?* In Figure 1 the function category in the FBS approach is split into the object

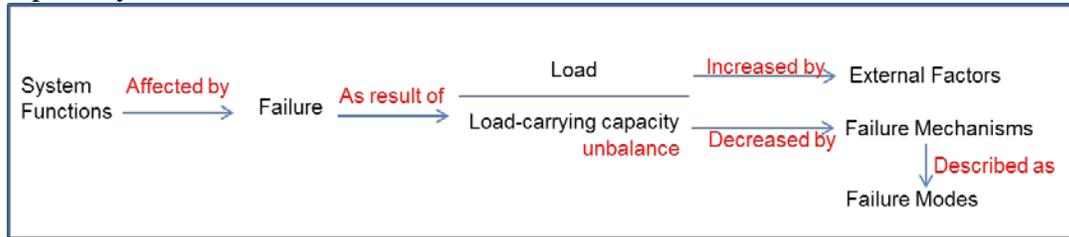to be monitored and the function of the monitoring system. Each of them is discussed separately below.

Figure 2. Relation between system function and failure

SUBSTEP 1a: FUNCTIONALITY AND FAILURE

According to Tinga [5], failure encompasses not only the actual physical damage of a part, but may also merely represent an impaired functioning of a system. Therefore the concept of failure has to be closely linked to the functions of the system. The occurrence of a failure process is always a result of an imbalance between the load on a system and the load-carrying capacity of that system. In this context, load refers to the extent to which a part is exposed to external influences, while the load-carrying capacity refers to whether it can withstand the external influences without failing. The *failure mechanisms* taking place at the material level are the main reasons behind the reduction of the load-carrying capacity. Moreover, the different ways in which the failure mechanisms develop and lead to the functionality loss are known as *failure modes*. Hence there can be a spectrum of failure modes or descriptors between the failure mechanism and the effect on the system function. This is schematically shown in Figure 2.

Vibration monitoring can contribute with the evaluation of the failure process by supporting the following aspects: *a)* the quantification of external loads, *b)* the interrogation for failure mechanisms at the local level and, *c)* characterization of failure modes.

SUBSTEP 1b. MONITORING SYSTEM FUNCTIONS

The designer of a monitoring systems has to define the scope of the interrogation system. This requires to focus on the detection of the failure, its origins and an estimation about the damage evolution. These functions are described in a generic way as follows.

1. Detection and Localization (Existence): Since all the materials have inherent flaws or imperfections [6], damage detection seeks for identifying failure mechanisms that become active and lead to potential functionality loss. Furthermore, depending on whether the failure mechanism is displayed on discrete locations or over the component, the localization strategy can focus at the failure mechanisms or failure modes. For example, the detection of corrosion is closely linked with finding the corroded zone, while for fatigue – a more distributed failure mechanism- the monitoring localization must focus on the failure modes such as cracks.

2. Classification (Origins): Given the fact that simultaneous failure mechanisms and failure modes can be displayed on the component, the use of classifiers for identifying the failure mechanism and failure modes becomes necessary.

3. Severity Evaluation and Prognostics (Evolution): Damage severity can relate to the quantification of the size of the failure parameter, such as the crack size and overall vibration level, and the relation with the functionality loss. However, for a complete evaluation of the failure, not only the failure mechanism and failure mode have to be estimated, but also the internal loads. For instance, micro cracks can be present throughout the complete rotor blade, however on high stress intensity zones of the blade the micro cracks are more likely to grow and merge with others to form larger cracks. Furthermore the question of remaining life depends heavily on the current damage severity, but also on the rate at which the damage evolves.

Step 2 Behaviors: Interrogation Strategies

After defining the requirements of the monitoring system, the FBS model asks for the behaviors that link the selected functions with the actual components of the monitoring system. The word behavior refers to the interrogation strategy for the system using vibration signals.

The need for a strategy when performing vibration monitoring becomes significant when considering the several possible levels of hierarchy that failure modes can display. For example, consider the case of vibration monitoring for a car. One of the failure modes of a car is a non-working engine. The engine also has several failure modes, like a lack of fuel or a broken crankshaft. The effect on the perceived vibration due to any of these failures may differ considerably and therefore a complete interrogation of each failure mode may become very complex. Therefore the monitoring system has to deal with the complexity by defining levels in the depth of analysis for the different system components. The choice of interrogation strategy depends on the dynamic behavior displayed by the system during failure. Several interrogation strategies can be applied, as be discussed next.

Event detection is a continuous surveillance mode that usually focuses on identifying the existence of a damage due to transient loads, such as impacts. This type of interrogation aims at providing warning about major changes in the system, rather than the event itself. Alternatively, the focus can be on monitoring the response of the system under operational loads. Furthermore, by complementing the vibration response with information on the operational loads of the system, a quicker estimation of the functionality loss, and therefore *performance monitoring*, is possible.

More elaborated interrogation strategies look at the load-carrying capacity of a system. The overall load-carrying capacity of a component depends on its inertial, stiffness and damping distribution. Failure mechanisms may also affect the *overall dynamic behavior* of the system, and therefore reduce its load-carrying capacity. This enables vibration based methods to be used to evaluate the overall dynamic response of the systems and, therefore their *integrity*.

For *localized failure* mechanisms (wear, corrosion) and failure modes (cracks, delamination), it can be possible that the overall dynamic characterization may not be sensitive enough. Thus local techniques are employed to interrogate the condition of the material. In general, acoustic and guided waves based techniques are preferred for

interrogation of local defects over vibration based techniques, since the latter concern mainly to low frequencies which display little sensitivity for small defects.

Step 3 : States : Technological Implementation for WSN

A Wireless Sensor Network (WSN) consists of a large number of sensors and actuators, which are typically tiny, low-cost, low-powered radio devices dedicated to performing certain functions such as collecting various environmental data and transmitting them to central processing units [7]. There are several major aspects for the design and implementation of a WSN, which are closely related to the interrogation strategy defined in the previous step. The following paragraphs discuss the dilemmas regarding communication protocol, local processing and power supply.

The coordination of the different aspects of the WSN communication is done by the *communication protocol* that refers to the common *code of conduct* of the nodes or communication rules of the nodes. One of the most critical aspects for simultaneous vibration measurements is synchronization. The synchronization requirements are linked to the measurement sampling frequency defined by the local processing needs, and the size of the network. For synchronized measurements, time division multiple access (TDMA) makes the communication highly deterministic and power efficient. However this strategy may not be very appropriate for event detection, then low power listening capabilities of carrier sense multiple access (CMSA) based protocols are more suitable [8].

The data collected by the sensors can be processed on the node locally or transmitted directly to the central processing unit. However the line between *processing and communicating* is difficult to set off. Although communication is traditionally more power demanding compared to sensing and processing, increasing complexity on the local processing also involves more demanding electronics and higher power supply requirements [9].

Power restrictions are the main critical factor for implementation of autonomous WSN, however surrounding vibrations can be used to power up piezoelectric based power harvesting schemes. There are two main possibilities for power harvesting. One refers to the employing direct forces from high load intensity locations such as dampers or actuators. Another option is by harvesting from strains, and although the power extraction is lower than in the first option, strain based harvesting is easier to deploy throughout structures [10]. The choice of harvesting strategy has direct relevance on the network size and topology.

CASE STUDY: HELICOPTER ROTOR BLADE

As mentioned in the introduction, the main rotor is the principal source for the vibrations for helicopters, therefore the rotor performance and blade condition are closely related to the blades' vibration profile. The use of WSN sets important possibilities for the expansion of HUMS to rotor health monitoring, however the implementation is heavily limited by the energy and other mechanical constraints. The proposed framework has been used to develop several scenarios regarding WSN deployment.

TABLE II. TWO POSSIBLE CONFIGURATIONS OF WSN FOR THE CASE STUDY

Configuration 1. Macro Layer: Performance Monitoring

Function	System: Main Rotor. System Function: Lift Failure Mode: Unbalance, Vibrations Failure Mechanism: Not determined: Monitoring Function: Detection of unbalance. Localization of suspicious blade.
Behavior	Interrogation Strategy: Response to Operational Loads Evaluating the general aspects of rotor vibration during flight. Several flight conditions present. Selective sensors on the blades perform simultaneous vibration monitoring.
Structure	Communication Protocol: Scheduled Measurements. TDMA. Signal Processing: Time Analysis, Spectral analysis. Cross correlations. Network Size: Small < 5 sensors per blade.

Configuration 2. Meso Layer: Integrity Analysis

Function	System: Individual Blade. System Function: Lift Failure Mode: Mass Unbalance, Vibrations Failure Mechanism: 1- (Uneven) Erosion of the coating layer. 2- Moisture absorption Monitoring Function: Detection of mass unbalance. Classification of failure mechanisms
Behavior	Interrogation Strategy: Overall Dynamic Behavior Characterization of significant changes of mass distribution that affect the entire blade response. Distinguishing between two possible failure mechanisms. One increases the total mass while the other reduces the total mass.
Structure	Communication Protocol: On request. Synchronized measurements. TDMA. Signal Processing: Modal based. Operational Modal Analysis Network Size: Medium 10< 50 sensors per blade.

Table II provides an overview of two configurations. The first configuration is denoted as *macro* layer since it aims at assisting in the overall performance evaluation of the rotor. The second configuration is referred to as *meso* layer, which focuses on the dynamic behavior of each individual blade.

Abnormal vibration due to unbalance is chosen as the displayed failure mode for both configurations. However for the macro layer, the failure mechanism behind the perceived vibrations is unknown. This means that the objective of the configuration is to quantify the external loads and to evaluate the failure mode. On the contrary, the meso layer aims to discern the failure mechanism that causes the mass redistribution on the blades, whether it is due to an increment on the static loading because of moisture absorption or due to loss of mass because of erosion.

The interrogation strategies differ for each configuration. For the macro layer it is based on measurements of the response of the blades to multiple flight conditions by comparing *simultaneous* measurements within and between the blades. The dynamic behavior characterization at the meso configuration is performed by Operational Modal Analysis (OMA). The choice of interrogation method influences the decisions regarding the technological implementation, for instance about the network size, local processing, synchronization and power requirements. Further details of the configurations are found in Sanchez et al [2].

CONCLUSIONS AND FUTURE WORK

The paper addresses the problem of design methods for vibration monitoring systems employing wireless sensor networks. Although several engineering fields make use of vibration monitoring, there is little consensus among these in relation with designing vibration monitoring systems. System engineering methodologies are used to address this complex and multidisciplinary design problem. The proposed framework uses the FBS model to define the different levels in the decision making process and the order in which those decisions have to be addressed when designing a wireless sensor network for vibration monitoring. The rationale behind the framework is of a physical nature, by looking at the monitored system main functions, the failure process and its relation with dynamic behaviour of the components. The applicability of the framework is demonstrated with the case study of a helicopter main rotor blades, for which two monitoring configurations are proposed for performance monitoring and blade integrity assessment.

Future developments in relation with the design of vibration monitoring systems include developing a quantitative method for assisting the decision making at the different levels of the framework, but in particular the technological implementation at the structure level.

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