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A FRAMEWORK FOR AUTOMATED DATA ACQUISITION FOR SAFETY-ORIENTED MAINTENANCE OF BUILDINGS

Shabtai Isaac[1]
[1]Ben-Gurion University of the Negev, Beer-Sheva, Israel

Abstract

Existing maintenance methods in the building industry are insufficient. A major factor contributing to this situation is the lack of in-service system data, which characterizes the building industry. A framework for automated data acquisition to support optimal safety-oriented maintenance of complex building systems is presented in this paper. It is inspired by methods used in the aviation industry but is tailored to the requirements of the building industry. The method is verified through an application in a real-life case study of an automated parking garage.

Introduction

The construction industry in general displays a poor performance in terms of safety, compared with other industries. This is true for construction processes (Edrei and Isaac 2017), but often also for building and infrastructure maintenance (e.g., Biondini and Frangopol 2015, Lee et al. 2017, Nawi et al. 2017, Zanini et al. 2016). Yet, buildings are also becoming more and more complex, and this could potentially exacerbate existing maintenance-related safety problems. Deringer et al. (2012) note several trends which are increasing the complexity and difficulty of properly maintaining buildings, including advanced digital control technologies and more ambitious performance goals, which increase the risk of failures. Cowlard et al. (2013) and Hopkin et al. (2016) mention the need for new approaches to fire safety as buildings become increasingly complex. Magruk (2015) discusses the increased vulnerability of "smart buildings" whose systems contain intelligent network devices.

Several safety-oriented maintenance methods have been previously proposed for the building industry (Pukite and Geipele 2017). However, the research on property maintenance is in general still underdeveloped (Wu et al .2010; Lind and Muyingo 2012). Specifically, maintenance methods that have been previously proposed invariably require the analysis of in-service data (e.g. Morgado et al. 2017). Yet due to the uniqueness of buildings and the fragmentation of the industry, there is in practice often very little historical failure and maintenance data on which to rely, to improve safety management by implementing methods that are based on rigorous data analysis (Wu et al. 2010).

The acquisition of building in-service data for safety-oriented maintenance is currently a challenge when carried out manually. In their absence, maintenance is often based on (possibly erroneous) rules-of-thumb, which is likely to result in inefficient and/or possibly unsafe maintenance practices. Automation presents a possible solution to this problem, by enabling real-time data collection and monitoring. Several studies have consequently focused on the application of novel technologies, such as sensor and actuator networks and camera-equipped UAVs to enable real-time automated monitoring of building systems (e.g., Guerrieri et al. 2013, Ham et al. 2016).

Experience from other domains in which automation has been introduced, such as flight deck systems and operating rooms, indicates that the integration of automated components in a management system is not trivial. Several challenges can be expected in the actual application of automated systems:

- A challenge of incorporating frequent changes and novel, unexpected circumstances, within the automated system (Dekker et al. 2002).
- A lack of clarity as to when automated systems should initiate communication with human operators and require their intervention (Sarter et al. 1997).
- Problems of data overload, especially on those occasions when something has gone wrong, which requires human operators to quickly digest and interpret large amounts of relevant data as the events unfold (Woods 1996).

The problem of data overload can be particularly vexing. Automated systems have shown a tendency to increase in scope over time, especially in complex environments, and to become more and more demanding in terms of administrative burdens. There is always a danger of crossing a line, whereupon the system turns from an aid into a hindrance, which users will try to avoid since it takes up too much of their time. With an automated "real-time" system that is based on large amounts of monitoring data, and may contain practically limitless inputs, this danger becomes particularly relevant. This paper consequently seeks to provide a formal framework for automated data acquisition that will support an optimal safety-oriented maintenance of complex building systems.

Safety-Oriented Building Maintenance

Safety-oriented building maintenance involves planning the maintenance of safety-relevant building systems, to reduce safety risks to an acceptable level. The output of this planning process consists of building maintenance programs, which aim to ensure that buildings are in a safe condition and fit for use, and that their condition meets all statutory requirements (Alner and Fellows, 1990). Such maintenance programs should also refer to the work necessary to maintain the value of the physical assets of the building stock, and the quality of the building (Horner et al. 1997).

Prevailing approaches to building maintenance can be divided into three basic strategies, which are standardized in the industry, e.g., under European EN 13306 (Lind and Muyingo 2012):

- *Corrective*: ad-hoc activities are undertaken when an element in a building breaks down.
- *Condition-based*: the optimal time to perform maintenance is determined according to the actual state of each building element, through a condition survey.
- *Preventive*: time-based planned activities that aim to reduce the probability of occurrence of failure and avoiding sudden failure.

While preventive maintenance can improve health and safety, it tends to involve many unnecessary tasks on elements that could have remained in a safe and acceptable operating condition for a much longer time, and which are usually very demanding in terms of spare parts and labor (Horner et al 1997). According to Wu et al. (2010), the lack of failure data and maintenance data is the main challenge for building maintenance from both the academic researchers' and industrial practitioners' points of view. *Reliability* defines the ability of an item to perform its required functions under stated conditions for a specific period and is an essential factor in assessing the performance of building services systems. However, from the practitioners' viewpoint, reliability validation is a time-consuming and an administrative burden. Furthermore, it proves very hard to optimize preventive maintenance policies for practitioners due to a lack of sufficient failure data, which are used to fit lifetime distributions. Remarkably, industrial practitioners face the same problem as academic researchers who complain about not having sufficient data for their research. How to collect and log various reliability and maintainability related data is thus a challenge for both academia and industrial practitioners (Wu et al. 2010). Any application of technologies for automated data acquisition needs to meet this challenge.

Learning from other Industries

Buildings, and the processes of designing and constructing them, are widely seen as being unique when compared with other industries. Evidence of this viewpoint, and comments on it, abound. Rossi et al. (2012), for example. comment that each building is a unique product, which evolves differently during its lifetime, and this has implications for conducting life-cycle assessments of buildings. De Ridder (2011) states that the uniqueness of each building prevents the learning of lessons, and results in suboptimal performance. A potential result of this viewpoint could be that it disconnects construction from other fields of research and practice in engineering, leaving it to be developed in relative isolation. A more nuanced approach, while still acknowledging the unique nature of construction and buildings, may uncover beneficial similarities with other domains in engineering, enriching both research and practice with new models and methods. This might be especially useful in the case of automated data collection for safety-oriented maintenance since the use of sensor and actuator networks for this purpose is quite common in other industries. Such an approach has not been sufficiently explored, even though many other industries also involve complex multidisciplinary systems. In fact, there are claims that this approach is precluded because of the variable, decentralized, project-based characteristics of the building industry. For example, Lind and Muyingo (2012) state that the idea that building maintenance can benefit from the experience in other industrial sectors, such as the airline industry, is mistaken.

The aviation industry is closely associated with safety culture, because of comparatively high levels of risk awareness and preventive measures, and airlines can be regarded as "high-reliability organizations" (Atak and Kingma 2011). This paper is based on a study of methods used in the aviation industry, in particular MSG-3 'Operator/Manufacturer Scheduled Maintenance Development'. MSG-3 is a document that was developed by the Airlines for America (Airlines for America 2015), and which is currently the leading and mandatory maintenance technique in aviation.

Proposed Approach

The objective of this this paper is to propose formal framework for planning the automated data acquisition that will support an optimal safety-oriented maintenance of complex building systems. The framework supports the definition of efficient scheduled monitoring tasks and intervals, to avoid information overload. These tasks and intervals become the basis for the building's maintenance processes. The framework should consequently be easy to implement by facility maintenance personnel.

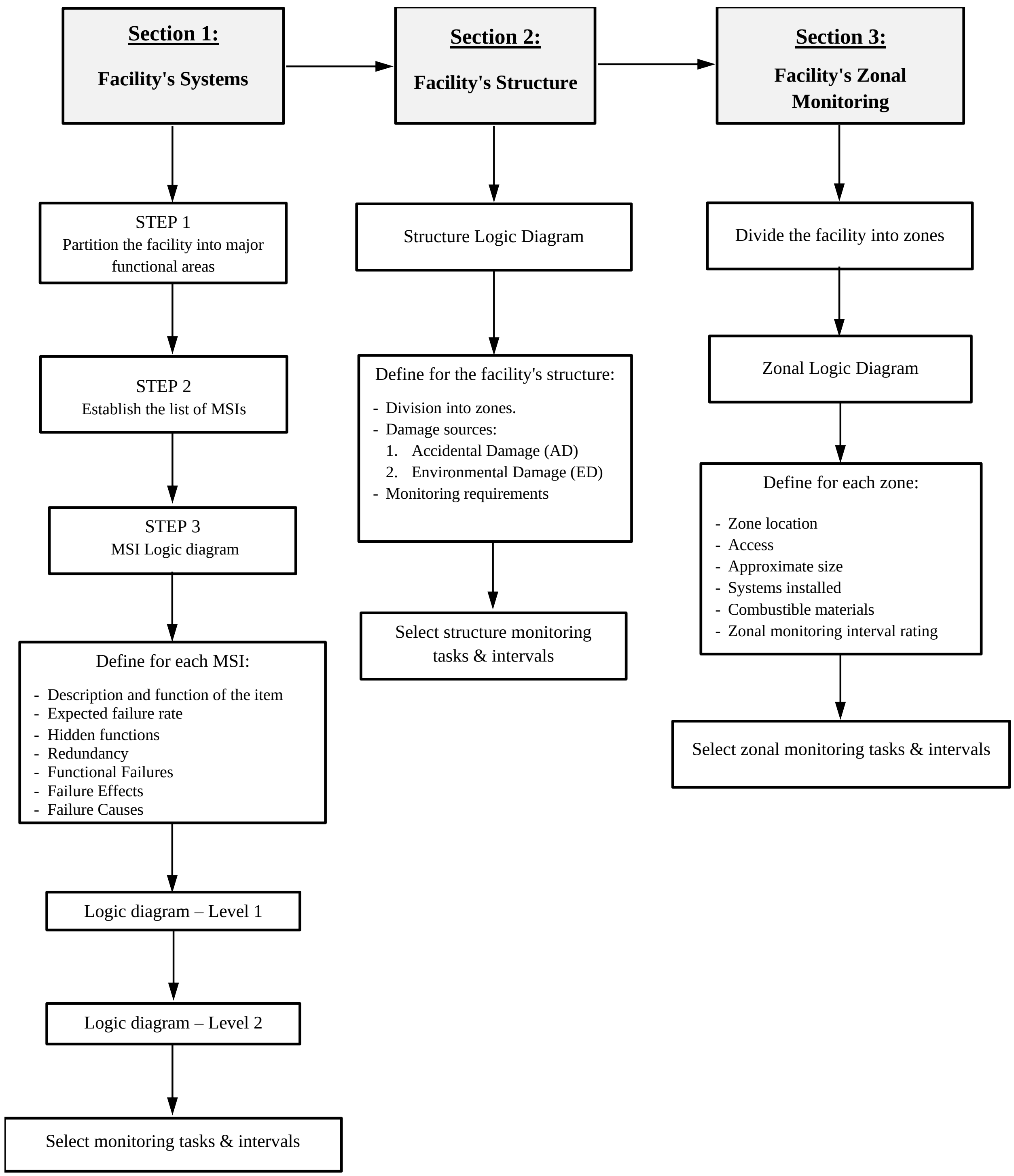

Figure 1: Proposed Framework

To enable the systematic collection of the necessary data, the framework is organized in three sections, where each section addresses a different division of the building into systems and subsystems, as will be further explained (Figure 1):

- Section 1: *Building systems* and components.
- Section 2: *Structural analysis* of the building.
- Section 3: *Zonal inspections*.

A building is thus addressed as an ensemble of complex systems, each of which needs to be analyzed in detail.

This approach is based on the assumption that a single straight-forward hierarchical division into systems and components is unlikely to be sufficient, given the interdependencies of the different systems in a building.

For each division a systematic process is employed to identify the system's significance or nature; and based on an analytical and integrated review of the maintenance concerns, a logic diagram is used to determine the monitoring tasks and intervals. The objective of these monitoring tasks is to prevent deterioration of the inherent safety and reliability levels of the building, by readily identifying any malfunctions.

Section 1: Building Systems

The main purpose of the first division of the framework is to identify the *Maintenance Significant Items* (MSI) of each system, and to define the monitoring tasks for each of these items. Planned automated monitoring is based on the function of the item, its main parts, the expected failure rate (based on life expectancy), the functional failures, the failure effects (safety or operational) and causes. Next, monitoring tasks are selected using a decision logic diagram (not included in the paper for reasons of brevity) and the technical data available. This is carried out through an evaluation of failure consequences, and a determination of the specific type of tasks according to the failure consequences. It may be reviewed overtime based on implementation and in-service information.

This process of identifying MSIs is a conservative process using engineering judgment based on the anticipated consequences of failure. First, the building is divided into major systems and subsystems, up to the level at which all replaceable components have been identified. The level above the lowest level of replaceable components is considered the Highest Manageable Level; i.e., one which is high enough to avoid unnecessary analysis, but low enough to be properly analyzed and ensure that all functions, functional failures and failure causes are covered. Then, a series of questions is applied to the list of items that have been identified:

- Could a failure be undetectable or not likely to be detected during normal duties?
- Could a failure affect safety, including safety/emergency systems or equipment?
- Could a failure have a significant operational impact?
- Could a failure have a significant economic impact?

For those items for which at least one of the four questions is answered with a "YES," further analysis is required. The decision logic has two levels of analysis:

Level 1 Analysis requires the evaluation of each functional failure to determine the failure effect category, i.e., safety, operational, economic, hidden safety or hidden non-safety

Level 2 Analysis takes the failure causes for each functional failure into account to select the specific type of tasks required.

In the next stage, the most appropriate monitoring task and interval is selected, based on available data and good engineering judgment.

Section 2: Structural Monitoring

Some, or all, of the building systems may be affected by the consequences of structural damage that remains undetected. To prevent this from occurring, each structural item is assessed in terms of susceptibility to any form of damage, and the degree of difficulty involved in detecting such damage. Once this is established, an automated structural monitoring process can be developed which is effective in detecting and preventing structural degradation due to *Fatigue Damage*, *Environmental Deterioration*, or *Accidental Damage* throughout the operational life of the building:

Accidental Damage (AD) is characterized by the occurrence of a random discrete event which may reduce the inherent level of residual strength. Sources of such damage include erosion from rain, hail, lightning, spillage, freezing, thawing, etc., and those resulting from human error during the structure's construction, operation or maintenance that are not included in other damage sources. The consequence of damage may not be readily apparent and may include internal damage.

Environmental Deterioration (ED) is characterized by structural deterioration because of a chemical interaction with its climate or environment. Assessments are required to cover corrosion, including stress corrosion, and deterioration of non-metallic materials. Corrosion may or may not be time/usage dependent.

Fatigue Damage (FD) is characterized by the initiation of a crack or cracks due to cyclic loading and subsequent propagation. It is a cumulative process with respect to high cyclic loading of the structure.

The building's structure consists of all loads carrying structural members. A *Structural Significant Item* (SSI) is any detail, element, or assembly, which contributes significantly to carrying loads, and whose failure could affect the structural integrity necessary for the safety of the building. An SSI may or may not contain a Principal Structural Element. A Principal Structural Element is any element which contributes significantly to carrying loads, and whose consequence of failure is catastrophic. All Principal Structural Elements are considered as structurally significant.

The most applicable and effective structural monitoring tasks are selected for each deterioration process of the SSI. To assure a direct correlation between the structural damage tolerance evaluations and the structural monitoring, it is necessary to define *monitoring thresholds* and intervals for each task. The monitoring threshold for each SSI monitoring task is a function of the source of damage and can be based on the monitoring interval (for Accidental Damage), on relevant service experience and contractors' recommendations (for Environmental Deterioration), and on a threshold to be established by the contractor and approved by the appropriate regulatory authority (for Fatigue Damage).

The scheduled structural monitoring tasks and intervals are based on an assessment of structural design information, fatigue and damage tolerance evaluations, service experience with similar structure and pertinent test results. The selection of structural monitoring tasks should include the following considerations:

- The sources of structural deterioration: Accidental Damage, Environmental Deterioration, and Fatigue Damage.
- The susceptibility of the structure to each source of deterioration with regards to the operating environment.
- The applicability and effectiveness of various methods of preventing, controlling, or detecting structural deterioration, considering monitoring thresholds and intervals.

Section 3: Zonal Monitoring

The third section of the framework, following the analysis of the building's systems and structure, concerns Zonal Monitoring. This type of monitoring allows an evaluation of the possible contribution to degradation and functional failure of many adjacent supporting components such as plumbing, ducting, electrical wiring installations, etc. For this type of analysis, the building is divided externally and internally into work zones, and a monitoring plan is developed for each zone. The plan presents information about the zone, such as its location, access, approximate size, systems installed, and combustible materials in the zone. It also contains a developed zonal monitoring interval rating table, based on identification of the zones' density of components, likelihood of accidental damage and environmental deterioration. Finally, a monitoring schedule is defined to address these damages.

Application of the Proposed Approach

To assess the applicability and comprehensiveness of the proposed approach, it was tested in a case study of an automated parking garage. Local regulations and standards either did not apply to automated garage systems or did not include specific norms or methods for their monitoring and analysis for safety-oriented maintenance purposes. The case-study used to verify the proposed framework was based on a typical kind of automated parking system, installed in a residential building with capacity of 10 cars. Using the previously defined framework, an analysis was carried out in 3 sections:

1. Garage Systems
2. Garage Structure.
3. Zonal Monitoring.

Garage Systems Analysis

The procedure for identifying the Maintenance Significant Items (MSIs) of each system, and for defining the monitoring tasks of these items, was implemented for the automated parking garage. To select the MSIs, the garage was divided into major and subsidiary functional areas in a top-down approach. For example, the "Garage Entrance" was identified as a major functional system, with 3 sub-systems:

1. Entrance Gate
2. Fencing
3. Control Stand

For each sub-functional system, monitoring tasks were developed and intervals were determined, using an Integrated Logic diagram (which is not described in detail here for reasons of brevity.

Garage Structural Analysis

The procedure for defining the structural monitoring tasks was applied to the complete undivided garage structure, which is a concrete structure reinforced with steel. Causes for both Accidental Damage (AD) and Environmental Deterioration (ED) were identified. Regarding Fatigue Damage (FD), which can be characterized by the initiation of cracks in the structure due to cyclic loading of vehicles, and their subsequent propagation, these were assessed as having a negligible effect on the concrete structure.

Zonal Inspections Analysis

After the division of the garage into zones, a monitoring plan was defined for each zone with aid of the previously described approach. The garage is divided into three zones:

1. Street level
2. Transitional level.
3. Underground level

A monitoring schedule was defined for each zone that would address potential damages.

Conclusions

The acquisition of building in-service data for safety-oriented maintenance is currently a challenge when carried out manually. Automation presents a possible solution to this problem, by enabling real-time data collection and monitoring. However, the actual application of automated monitoring systems is known to create new challenges, including problems of data overload. Consequently, a formal framework is presented for planning the automated data acquisition that will support an optimal safety-oriented maintenance of building systems. Whereas previous publications argued that methods from other domains, such as those common in the aircraft industry, are not well-suited for the building industry, this paper shows that while acknowledging the unique characteristics of the building industry, such methods can provide a source of inspiration.

The proposed framework supports the definition of efficient automated monitoring tasks and intervals, to avoid information overload. These tasks and intervals become the basis for the building's maintenance processes. To enable the systematic collection of the necessary data, the framework addresses buildings as an ensemble of complex systems, each of which needs to be analyzed in detail. Given the interdependencies of the different systems in a building, a single straight-forward hierarchical division into systems and components is unlikely to be sufficient. Consequently, the framework is organized in three sections, where each section addresses a different division of the building.

The proposed framework enables the identification of the most significant building systems for maintenance and the consequences of their failures, determining monitoring tasks and intervals, and selecting the most effective automated monitoring strategy among those applicable. The framework relies on resources that can be applied within reasonable scope, and its outputs include practical instructions for the maintenance personnel. The framework was comprehensively applied to an automated parking garage example to verify its feasibility.

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