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(article starts on next page)

THE ROAD TO SENSOR-DRIVEN CLOUD-BASED INFRASTRUCTURE MANAGEMENT

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Abstract

Today, the accelerated degradation of many concrete structures poses a major challenge for the proper maintenance of the transport infrastructure. Therefore, inspection and maintenance operations constitute an important part of the recurrent costs of infrastructure. Furthermore, the increasing migration of population to urban areas has made sustainable development an imperative need. This need has become a driving force for innovation and new challenges such as the concept of smart cities and infrastructure. The successful utilization of newly available technologies will enable a whole new range of possibilities such as sensor driven cloud-based strategies for infrastructure management, which will promote an upgrade of the current infrastructure network to a new generation of safer, more efficient and more sustainable smart infrastructure: the infrastructure 2.0. The aim of this paper is to review the state-of-the-art of the different key technologies comprising a smart monitoring system, focusing on the aspects that are required to ensure a successful implementation of such system. The main result of the study is a scientific roadmap that can serve as a guide for traffic administrations and academic institutions in their task to develop and create a new infrastructure management strategy based on emerging technologies and innovative processes.

1. Introduction

Infrastructures are the fundamental facilities and systems required to support societal activity within a certain region. In particular, the transport infrastructure consisting of mainly roads, bridges and tunnels, is one of the oldest and most crucial elements for society as it embodies the physical platform for the transportation of passengers and goods [1]. Since deterioration of the transport infrastructure poses a serious public safety issue and has a negative impact on the nation’s economy, to effectively maintain the performance of the transport infrastructure is of utmost importance. Nevertheless, the accelerated degradation of structures caused by prolonged exposure to harsh environments added to the advanced age of many structures and the ever-increasing level of demands in terms of traffic loads, volume and vehicle speeds [2], represents an enormous challenge for the effective management of the transport infrastructure, which is often translated into an increased frequency of inspections and maintenance operations. Due to the conservative nature of the construction industry relying on traditional methods and lagging behind in innovation compared to other sectors, these inspections are today very inefficient and, together with maintenance operations, constitute a major part of the recurrent costs of infrastructure, which represent a significant share of the annual budget in developed countries [3].

New management methodologies must, therefore, be developed based on newly available technologies and new ways of thinking, to deliver smart systems that could minimize the number of interventions in the transport infrastructure as well as their extent and duration. Along these lines, current technological development is taking society to a new era where an unprecedented type of knowledge will be accessible through the combination of: (i) extensive wireless sensor networks; (ii) ubiquitous and remote access to cloud-stored data and services; (iii) constantly increasing computational power and more efficient calculation algorithms; and (iv) novel tools to visualize digital information. The successful utilization of the aforementioned technologies will enable a whole new range of possibilities such as a sensor-driven cloud-based strategy for infrastructure management. The main aim of this paper is to investigate the feasibility of combining emerging technologies to create an integrated system that enables an upgrade of the current infrastructure network through a new generation of smart structures. The study focuses on the aspects that are required to ensure that such a system could be successfully implemented in practice.

2. Review of emerging technologies

In order to create a system that minimizes the need for structural inspections, some sort of Structural Health Monitoring (SHM) system must be implemented. A SHM system is a technology based on the continuous condition assessment of a structure through the analysis of data acquired on-site by a distributed network of sensors [4]. If properly implemented, SHM systems could extend the service life of structures by ensuring the early identification of deterioration and/or damage, thereby allowing relatively minor corrective actions to be taken before the damage grows to a state where major actions are required [5]. For a SHM to be effective a streamline of data must undergo four different steps: acquisition; management; analysis; and visualization. In the following section, a review of the different existing technologies enabling these four steps is presented.

2.1 Data acquisition – Sensor networks

Sensors are critical elements in SHM systems, which must be chosen adequately to serve the intended purpose under the expected conditions and for a certain time span. Sensors can be subdivided according to various features, e.g. wired/wireless, embedded/external or active/passive. Each type of sensor possesses its own advantages and drawbacks, which must be considered with care. Regarding the measured properties, the most commonly used sensors in SHM applications include sensors measuring kinematic parameters, such as displacements, strains and accelerations, dynamic quantities, such as vibrations and forces and environmental factors, such as temperature or relative humidity (RH), some of which are commercially available for concrete applications, see e.g. [6]–[8]. Conventional sensors often present difficulties to perform stable and reliable readings in the long term. Many sensors can be easily affected by changes in temperature, humidity, cable length, magnetic or electric fields, etc, whereas other sensors need to be powered, which requires the use of batteries, thus limiting the service life of the sensors [9]. Nevertheless, the common problems that are often encountered with conventional sensors today will most likely be overcome in the future as new sensing technologies are developed for bridge monitoring and other large structure applications. Two examples of novel sensor applications, currently under development, which possess great potential for the long-term monitoring of reinforced concrete structures are smart cement-based sensor [10] and polymeric optic fibre [11].

2.2 Data management – Cloud services

In large infrastructures with distributed sensor networks containing tens or hundreds of sensors measuring continuously, the amount of generated data can easily surpass the storage capacity of any modern computer. To manage such data volumes and enhance accessibility to the content, a series of cloud-based platforms exists, which provide a wide range of services for users with the only requirement of an internet connection. These platforms are referred to as PaaS (Platform as a Service) and can be defined as a cloud computing model in which a third-party provider delivers hardware and software tools (usually those needed for application development) which can be accessed anywhere via a web browser. One of the main advantages of a PaaS providers is that they host the hardware and software on its own infrastructure, thereby freeing users from having to install in-house hardware and software to develop or run new applications. Some of the best-known PaaS include Microsoft Azure, Google App Engine or Amazon Web Services.

2.3 Data analysis – Machine learning

Another of the key steps towards the implementation of an effective SHM system is the analysis of the measured data. Individual data values by themselves are meaningless. They need to be situated in a context, relativized to other parameters and combined with a certain set of assumptions to extract relevant information. This information must be placed within a theoretical background and used in conjunction with a model to obtain knowledge. Lastly, this knowledge can eventually be turned into expertise, i.e. the required parameters for decision making, through experience and training. The first two steps are relatively easy to automate but for the last one, an experienced and trained operator is still required. This could change in the near future through the implementation of artificial intelligence, i.e. machine learning algorithms, which could not just become a decision support tool for engineers but also unlock the path towards predictive structural assessment.

Machine Learning is currently being used in many existing fields of research to develop countless applications, some of which are fully operational in everyday situations such as spam filters or face recognition systems. For structural health monitoring applications, two main anomaly detection approaches, which may classify as precursors of today's machine learning, have been previously used for damage identification: model-driven methods and data-driven methods. The former rely on high-fidelity physical models to detect deviations of the measured data whereas the latter usually adopt a statistical representation of the system where data appearing in regions of very low density may indicate deviation from normality [12]. In civil engineering, the application of machine learning has been also attempted, particularly for vibration-based damage assessment of steel bridges, see e.g. [13]–[16]. However, owing to the large size and one-of-a-kind nature of the transport infrastructure elements, the development of effective and generic machine learning algorithms for structural health monitoring have not yet been developed.

2.4 Data visualization – BIM

Effective data visualization is another crucial aspect for the successful implementation of an integrated SHM system. The information, whether it is raw measured data or a sophisticated damage index, needs to be conveyed in a clear, efficient and intuitive way to the operator. Building Information Modelling (BIM), combining 3D computer-aided design visualization with integrated data, is a process originally intended to improve the performance of building projects during their construction phase and service life. Due to the high complexity of the transport infrastructure elements, BIM stands out as a very promising alternative for its integration within a SHM system. Today, a variety of BIM software is available, including both more user-friendly and intuitive commercial packages and more flexible, free open-source programmes. Perhaps, one of the major technical challenges is to find a suitable interface that enables the effective integration of real-time measured data with a 3D design model. A very promising solution to this technical challenge is provided by Autodesk FORGE [17], a connected cloud platform comprised of web services, and technical resources that allows for the development of customized and scalable solutions.

Augmented Reality (AR) also possesses a great potential for the visualization of data on-site, which could represent a giant leap in the efficiency of structural inspections. By visualizing information regarding the real condition of the structure as an overlay displayed on the actual structure, inspection operators could easily spot the location of deficient elements and focus on critical elements, notably reducing the time and extent of the inspection and subsequently minimizing the cost and disruption to the infrastructure users.

3. A scientific roadmap to sensor-driven cloud-based infrastructure management

Based on the four steps constituting a SHM system and the different reviewed technologies, a roadmap towards sensor-driven cloud-based infrastructure management has been drafted. This roadmap, referred to as SensIT and presented in Fig. 1 as an infographic, identifies the critical areas where further research is required and how these areas are interrelated.

- Sensor technology: the first obstacle to overcome in the creation of an integrated SHM system is the deployment of a sensor network that measures different kinematic and physicochemical parameters to form the basis for remaining steps. Ideally, robust and stable sensors which are not affected by external stimuli and can surpass the service life of the parent structure should be developed. This data should be then combined with environmental information as well as previous damage report in the case of existing structures to offer a holistic view of the structural condition.

- Cloud-based services: the integration of existing cloud platforms is a key aspect to ensure the efficiency, flexibility and scalability of the system. Cloud platforms play multiple roles as: a means to obtain the necessary storage; a platform to carry out remote calculations; and a tool to manage, share and access data from virtually any place in the world.
- Machine Learning: with the steady gain in computational power, these types of algorithms have shown their immense potential for pattern recognition and anomaly detection in multiple areas. Novel algorithms need to be developed focused specifically in the needs of the construction industry and particularly for structural health monitoring of concrete structures. Moreover, these algorithms might benefit from reciprocal data retrofitting with detailed finite element analyses.
- Real-time BIM: a digital twin of the physical structure created through BIM can become a very suitable channel to convey the information related to the structure condition of the transport infrastructure. Interactive BIM applications with an intuitive, user-friendly and cross-platform interface should be developed to offer an effective and versatile decision support tool for the owner/manager/operator of the structure.

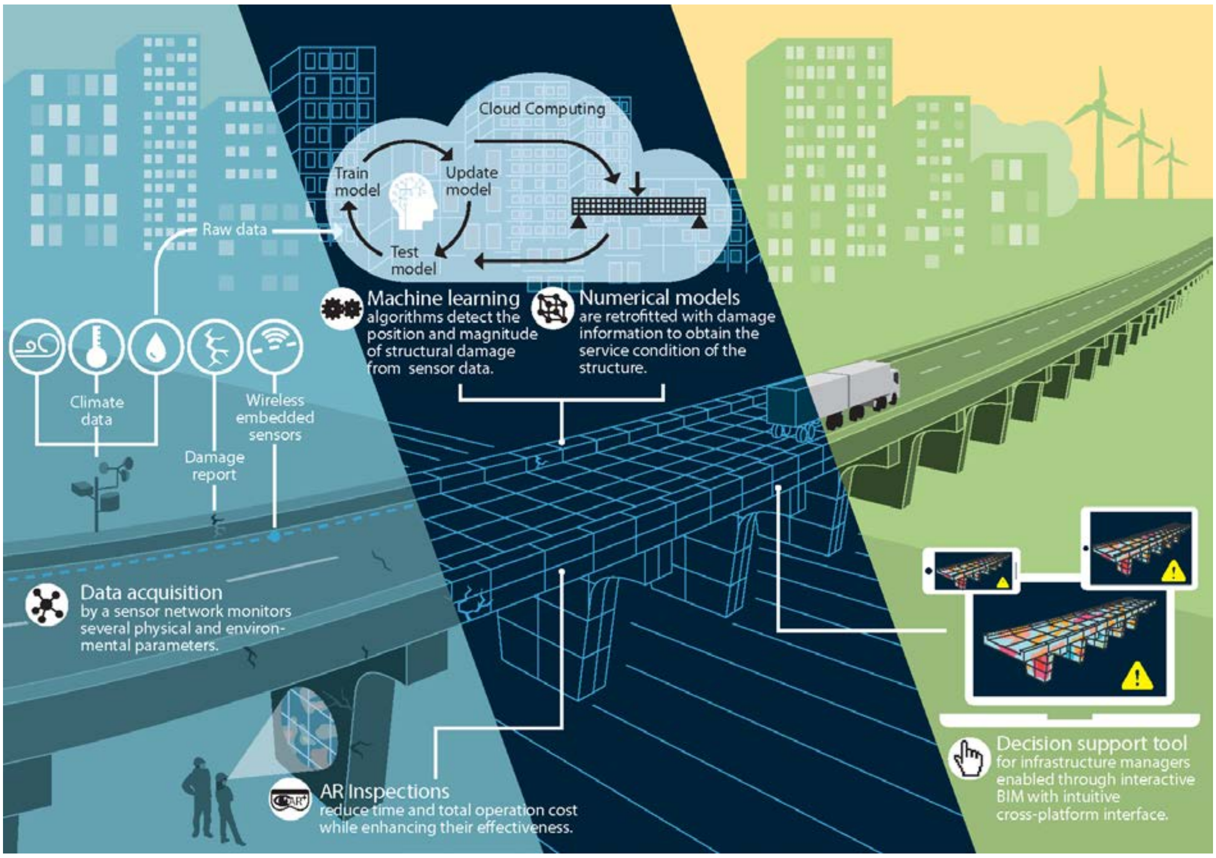

Figure 1: Schematic representation of the SensIT monitoring system.

It is worthwhile mentioning that the approach discussed in this paper presents two main limitations that hinder its full applicability as of today. The first limitation is the absence of sensors specifically developed for concrete applications, which can provide accurate, stable and reliable measurements during the entire service life of the infrastructure. The second is the lack of advanced numerical models that can describe the various multi-physics phenomena involved in the deterioration mechanisms of concrete, including corrosion of reinforcement, alkali-silica reaction, etc. to support the development of machine learning algorithms.

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