Coupling Wireless Sensor Networks and Unmanned Aerial Vehicles in Bridge Health Monitoring Systems

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Abstract

Bridges are exposed to different types of damages within their lifetime. Bridge maintenance is an essential procedure that can significantly affect lifetime and serviceability of bridges. First step in bridge maintenance is inspection. Visual inspection has been traditionally the dominant method of bridge inspection. Although visual inspection is still used by several authorities to inspect bridges, it is prone to errors, due to human biased judgment. Using wireless sensor networks is a non-destructive method that can help bridge maintenance teams to monitor bridge health. Although there are many advantages associated with using wireless sensor networks in bridges, there are some downsides such as battery failure and large volume of collected and transmitted data. Unmanned aerial vehicle is a mobile robotic agent that can help wireless sensor networks to overcome some of its shortcomings. This paper initially explores the advantages and disadvantages of using wireless sensor networks in bridge health monitoring systems. Then, the advantages of using unmanned aerial vehicles in bridge health monitoring systems are discussed. And finally, this paper investigates possible synergies of coupling unmanned aerial vehicles and wireless sensor networks in bridge health monitoring systems that might help bridge health monitoring systems to overcome some of its traditional limitations. The contribution of this paper is to identify and discuss the possible synergies between unmanned aerial vehicles and wireless sensor networks in bridge health monitoring systems.

Keywords

Bridge Health Monitoring Systems; Unmanned Aerial Vehicles; UAV; Wireless Sensor Networks

1 Introduction

Human-made structures are exposed to different kinds of damages. Damages may happen due to the severe structure ambient factors, e.g. weather condition, which may frequently happen to the structure or due to the less frequent factors, e.g. natural disasters, which may or may not happen to the structure during its lifetime. In order to maintain an acceptable level of service for a structure, it is necessary to monitor the health condition of the structure and take the necessary actions to maintain its health – e.g. repairing damaged parts or redesigning. Ponte Fabricio Bridge, which was made in 62 BC in Rome, and still in service, is a good illustration of the importance of the structural maintenance. It shows that a good design accompanied with good maintenance service can expand the lifetime of a structure to more than two thousand years [1].

First step in maintenance is inspection. Amongst the numerous ways to inspect structure health, visual inspection, traditionally, has been the common method. However, by having massive structures – in terms of dimensions – in the twentieth century, mostly after the Second World War, visual inspection was not able to satisfy the requirements for structure health inspection. Cabled (wired) sensors replaced the visual inspection method gradually. Nevertheless, the visual inspection is remained as a common and, most importantly, low-priced method for structure health monitoring usually in small and medium scale structures [2].

Bridges, as highly loaded structures, also need proper inspection. Researchers have investigated the use of new technologies in bridge health monitoring systems (BHMS) for more than a decade. Pines and Aktan [3] highlighted the lack of accuracy in visual inspection. A study by Federal Highway Administration revealed that around 56% of the average condition ratings by visual inspection were incorrect [3]. Oh et al. [4] noted that the majority of systems that have been used for bridge health monitoring rely on manual processes of counting the cracks, measuring cracks' lengths and widths and using static images that have been taken from bridges. The reliability of these methods depends on inspectors experience in bridge inspection. Consequently, sensors have been used in bridge health monitoring to overcome drawbacks of visual inspections.

Using sensors in structural health monitoring instead of visual inspection has brought many advantages to structural maintenance. Although sensors are more accurate than visual inspections there are a few disadvantages associated with them. Sensor networks in structural health monitoring were cabled sensor networks and there was traditionally an important downside to the cabled sensors: the cost of the system. Since cabling and instrumentation in cabled sensors are expensive, gradually there was a trend to find a more economically reasonable method for structural health monitoring. In last decade, the wireless sensor technology became available and was used in structural health monitoring but the price was still high at that moment. Having lower-priced sensors with more powerful wireless technologies increased the interest in using wireless sensors. Not only lower prices make wireless sensors attractive in structural health monitoring, but also having less cabling and instrumentation makes them more favorable to construction industry. These factors combined with faster communication technology, fast and low-price computation technology, and a government regulated playground play a vital role in making wireless sensor technology promising to construction and facility managers [5-6].

Safety concerns, inaccessibility to some of bridge sections and the hardness of bridge inspection on heavy traffic situations arise the question of the possibility of bridge inspection without use of workforce. Metni and Hamel [7] discussed the use of unmanned aerial vehicles (UAVs) in bridge inspection. Metni and Hamel [7] mentioned that aging infrastructure is a constant concern to the societies in western European countries as it is estimated that half of the bridge life cost is due to its long lifetime maintenance cost. As Metni and Hamel [7] argued, use of drone in bridge inspection would have advantages over traditional inspection methods like visual inspection. UAVs bring many advantages in to bridge inspection process including reducing work accidents, budget reduction, less bridge lane closure and possibility of using other non-destructive crack detection techniques [7].

Although it has been more than a decade since Lynch et al. [8] introduced the concept of using wireless sensor systems in infrastructures, the construction industry still struggles to have a widely acceptable and implementable smart wireless sensor networks (WSN) for BHMS. This study presents a study of critical elements and downsides of WSN in BHMS. The use of UAVs in BHMS is also explored. A summary of previous applications and potential areas that UAVs can be coupled with WSN to provide a faster, safer, and more efficient BHMS is presented [Figure 1].

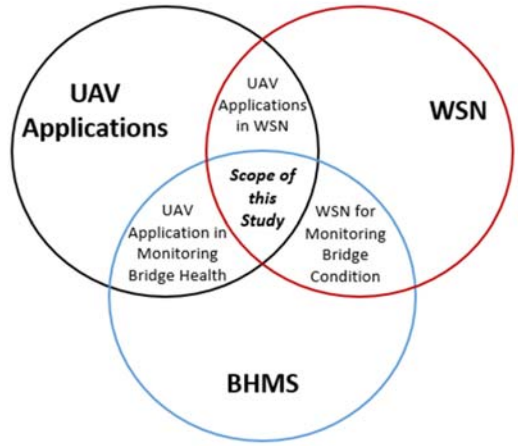

Figure 1. Scope of this study.

2 Wireless Sensor Networks in Bridge Health Monitoring Systems

There are three important elements in designing any BHMS: (1) identifying the inspection elements in bridge, (2) choosing a suitable sensor (hardware) and sensor networks platform, and (3) planning to overcome the common, and known, challenges that may be associated with selected sensor network platforms. This section focuses on these three aforementioned factors and discusses challenges associated with them. Moreover, a brief overview of general challenges associated with any WSN is also presented.

2.1 Identifying the Right Inspection Elements in Bridge Health Monitoring Systems

Finding the elements that need to be inspected is the first step in designing an inspection system for any kinds of infrastructure. In bridge health monitoring, recognizing the must-investigable elements plays a crucial role in designing a proper BHMS. In order to recognize bridge must-investigable elements, it is important to have a thorough look to the bridge inspection manuals. It is worth noting that although recognizing the must-investigable bridge elements is a crucial step in designing a BHMS, the ability of wireless sensor in monitoring any bridge element is still debatable.

NYDOT [9] breaks down bridges to different bridge components and discusses the process of inspection regarding specifications of each component. NYDOT [9] considers stream channel, scour and erosion, abutments and wing-walls, piers, deck and superstructure as the elements that need to be inspected. NYDPT [9] is not only consider bridge elements to be inspected but also focus on some features like stream channel, scour and erosion as the features which need to be inspected. The reason that there is a focus by NYDOT [9] on these environmental features is that environmental factors can seriously affect bridge health conditions. Environmental factors are explicitly highlighted in bridge inspection manuals. For instance, NYDOT [9] mentioned the importance of stream channel as *"the most dynamic system affecting the condition of bridges."*

Bridge inspection manuals help bridge inspectors to design the most appropriate BHMS for any bridge regarding its specifications, though it is not the only tool that guides to design a useful BHMS. Having a methodical view to the failure causes in failed bridges, assist construction managers to design effective BHMS [10].

Wardhana and Hadipriono [10] studied bridge failures in the United States from 1989 to 2000. Their study revealed that there were more than 500 reports of bridge failures in the United States from 1989 to 2000 [10]. The average age of failed bridges was 52.5 years with bridges that were in the construction phase to a 157 year-old one. Another finding by Wardhana and Hadipriono [10] study points out that steel beam/girder bridges are the dominant type of failed bridges with 29% of total failed bridges. The other common types of failures happens in steel truss, concrete beam/girder, and concrete slab bridges with 21%, 6%, and 5% of total failed bridges, respectively [10].

Most of failed bridges have steel or concrete structures. It is important to focus on structural materials of bridges in order to see what the critical factors are in inspection phase. It is believed that accelerations, temperature, wind, inclination and cable tension are among the most important structural-related factors in BHMS [11].

2.2 Sensor Platforms and Sensor Networks in BHMS

After identifying the inspection elements in BHMS, the appropriate sensor platform should be chosen. Numerous motes have been used in structural and bridge health monitoring. Lynch et al. [8] used WiMMS to prove the wireless system proof of concept in in structural health monitoring. MicaZ, Imote2 and some high sensitivity accelerometer board, such as SHM-DAQ board, have been also used in the area of structural and bridge health monitoring systems. Choosing the most suitable sensor network architecture is an important aspect of designing a BHMS, however discussing sensor platform and network architecture are out of the scope of this paper.

2.3 Challenges Associated with Using Wireless Sensor Networks in Bridge Health Monitoring Systems

Apart from the fact that choosing the appropriate sensor platform is important for BHMS, sensors energy dependency should also be appropriated chosen in any WSN [12]. Yoo et al. [12] argued that one of the most important issues in deploying wireless sensors in structures is energy limitation due to the high-energy consumption nature of the wireless sensors. Mainly because of huge portion of energy needed to transmit the data to the base station - hub. In order to overcome high-energy consumption nature of wireless sensors, Yoo et al. [12] proposed that wireless sensors should be more energy dependable. In other words, wireless sensors should be able to work with their energy supplies – batteries – for a reasonable period of time or they should use undependable, and potentially more sustainable, rechargeable batteries.

Not only high energy consumption nature of wireless sensors may act as an obstacle in the process of sending and receiving the data between base station and sensors, Yoo et al [12] indicated that traffic overload caused by huge volume of transferred data between base station and sensors can also lead to a problem in wireless sensor networks of structural health monitoring systems. Power management and data transfer problems in WSN are not the only downsides of implementing WSN in BHMS. Hoult et al. [13] identifies other major downsides of WSN such as data transmission bandwidth, reliability, and time synchronization. Another challenge indicated in the literature was wireless networks' incapability to achieve real time transmission of data; however, this can be achieved by lowering sample rates [13-14].

3 Unmanned Aerial Vehicles and Wireless Sensor Networks

Investigating the possibility of using UAVs in sensor networks appeared for the first time, in 2001, in a white paper by United States Department of Energy (USDOE). In 2001, USDOE investigated the feasibility of using cooperative UAV-based communication as a backbone for sensor networks. The feasibility of using UAVs to provide communication connectivity to the sensors that cannot communicate with each other due to distance and geographical constraints was the objective of this white paper. Since the focus was on the cooperative UAV-base communication, authors of USDOE [15] tried to explore whether or not a group of UAVs can possibly divide a ground-based sensor network into a few sub-networks (subnets) and help the sensor networks by uplinking sensors-collected data and transmit to the base ground station.

But the application of UAVs in WSN is not limited to relaying features. UAVs can act as mobile base station, which can improve the WSN status in terms of data traffic load balancing and energy consumptions. Also UAVs can act as mobile sensing nodes, which can potentially act as extra mobile nodes augmenting the network by bringing additional information [16]. Teh et al., [16] argues that a combination of UAVs and WSN may result in unique applications such as:

1. Remote data mulling: UAVs act as data agents, which can upload data to the network and/or send the data back to base stations.
2. 3D sampling of sensor data for urban pollution monitoring: Consider having ground-deployed WSN in an area, UAVs can potentially provide three-dimensional sampling, which can be used for further analysis.
3. Traffic monitoring

The applications of UAVs in WSN are not limited to the above-mentioned applications. Corke et al. [17] used UAVs to deploy sensors on specified ground locations. This application improves the robustness in designing any WSNs. It brings the flexibility of flying UAVs to any location to design more flexible and location-independent WSNs. However, this application is only a concept and fully autonomous use of UAVs for sensor deployment has not been fully applicable due to the current UAVs limitation on carrying loads to far distances.

4 Unmanned Aerial Vehicles Applications in Bridge Health Monitoring Systems

UAVs have been conventionally used for enhancing visual inspection of bridges by providing detailed images of hard-to-reach areas of bridges. Although taking photos and recording videos for post-inspection uses are some of the traditional uses of UAVs in BHMS, other visual uses of UAVs in BHMS like developing 3D models of existent bridges has also been investigated [18].

It is argued that using UAVs has some advantages compare to the traditional bridge inspection methods; including reducing work accident risk, and ultimately increasing safety, budget reduction, robustness and possibility of using other non-destructive methods [7]. UAVs have also been used for transmitting wireless power to wireless sensor nodes, installed in a bridge [19].

Although numerous advantages of using UAVs for bridge inspection purposes have been counted, there are some disadvantages associated with using UAVs in bridge inspection systems. Wind gusts and turbulences, no-fly zones, hazardous zones and difficulty in path planning are some of the issues that need to be considered in using UAVs for bridge inspection purposes [20].

5 Discussion and Conclusion

Traditionally, infrastructures health conditions have been monitored with visual inspection and also other forms of non-destructive inspection method including cabled (wired) sensors. Due to many disadvantages of wired sensors, most importantly high cost, using wireless sensors in structural health monitoring is becoming a trend nowadays. Numerous elements have been measured regarding the infrastructure health monitoring; including accelerations, and temperature as the most common sensed elements. Choosing the right elements to measure in a structure depends on the necessity of measuring these elements in terms of their effects on structural lifetime health. Despite the effort that have been placed in implementing vibration-based WSN in bridge health monitoring, some important elements, which are already highly emphasized in bridge inspection manuals, have been forgotten to take into account in the process of implementing WSN in bridge health monitoring. Wardhana and Hadipriono [10] study of failed bridges in the United States revealed that 53% of total causes of bridge failures are associated with flood/scour. It raises the importance of bridges environmental condition monitoring. Deploying WSN in order to measure some of these ambient factors, such as level of water, which might contribute to predicting flood and scour, could be a novel approach in measuring bridges ambient factors. UAVs can be used in order to deploy sensors in bridge surrounding environment to measure bridge ambient factors. UAVs might be good agents for deploying wireless sensors in bridge surrounding environment due to flexibility that they provide for deployments.

Although WSN have been implemented and used for BHMS purposes, there have been some technical issues concerning widespread use of them including: time synchronization and sensors energy dependency. Energy dependency and sensors' battery lifetime is one of the most critical issues in WSN. It is been concluded that UAVs can help to solve sensor battery problems. Lifetime of wireless sensors are dependent on sensors' battery lifetime. Wireless sensors batteries need to be charged after a while if network administrator wants to keep sensors working. Charging wireless nodes may not be a problem in simple scenario but recharging sensors batteries that are deployed in hard-to-reach environment, such as some parts of bridges that are hardly accessible by maintenance team, makes it hard and expensive for network administrator to recharge wireless sensors. UAVs can act as power transfer agents to (re) charge the wireless sensors. The concept of using wireless power to supply energy to another agent goes back to 1964, when it has been tried to supply a flying helicopter with wireless power. Griffin and Detweiler [21] and Johnson et al. [19] proved the concept of wireless magnetic resonant power transfer to wireless nodes in a WSN. BHMS can use the mobility of UAVs and use UAVs as mobile battery chargers in order to charge sensor batteries in WSN in bridges.

Wireless sensor failure is another common phenomena that might happen in any WSN. Sensors (nodes) can fail due to any reason including battery or transmitter failure. Wireless network planners usually deploy more number of sensors than the estimated number of needed sensors in order to avoid the effects of any future sensor failure. Node failure could potentially slow down the data transfer in the network [6]. UAVs can be used to deploy wireless sensors in any area in bridges that are hardly accessible by humans.

Data transfer is another critical issue in WSN. Volume of data might be large, which makes receiving live data hard. UAVs can be potentially used as temporary hubs to ease the data transfer in WSN.

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