Towards Cyber-Physical Systems Design for Structural Health Monitoring: Hurdles and Opportunities

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Large civil structures such as bridges, buildings, and aerospace vehicles from the backbone of our society are critical to public safety. Wired sensor networks are usually adopted for structural health monitoring (SHM) applications. This is also an important Smart City application. Recent wireless sensor networks (WSNs) technology promises the eventual ability to cover such a structure and continuously monitor its health. However, researchers from both engineering and computer science domains face numerous hurdles such as application-specific requirements in reaching this goal. These hurdles have a cumulative effect on severely resource-constrained WSNs. This paper provides a comprehensive investigation of WSN-based SHM applications with an emphasis on networking perspectives in order to get insights into a cyber-physical system (CPS) design. *First*, we provide the SHM philosophy and conduct extensive comparative studies regarding various aspects of benefits and hurdles of going wireless for SHM. *Second*, we propose a taxonomy of SHM techniques and their applicability to WSNs. *Third*, we show a transition from the WSN-based SHM towards the CPS design, expecting that such a design will mitigate WSN resource constraints and satisfy SHM application-specific requirements to a great extent. For each of these, we discuss a surge of existing schemes with an emphasis on limitations of the state-of-the-art, and we point out open issues. *Finally*, we propose a series of design guidelines for a potential CPS. This paper will help both engineering and computer science domain researchers/engineers and respective communities in designing future CPS to ensure the economic benefit and public safety in functioning civil structures.

Categories and Subject Descriptors: C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.2.4 [**Computer-Communication Networks**]: Distributed Systems; C.4 [**Computer-Communication Networks**]: Performance of Systems

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1. INTRODUCTION

Our daily lives are becoming more and more reliant on civil and mechanical structural systems, including high-rise buildings, long suspension bridges, large aerospace

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vehicles, long-distance subway tunnels, and pipelines, among others. These are our economic and industrial prosperity [Bhuiyan et al. 2016; Liu et al. 2015b; Zimmerman et al. 2013; Farrar and Worden 2012; Wang et al. 2012a], which are usually remotely programmed by our civil, structural, mechanical, electrical, or aerospace (CSMEA) engineering communities. The safety of these structures is a major issue and is one of the critical issues in Smart City applications. Indeed, none of us would stay at our homes/offices in high-rise buildings or move around on bridges or aerospace vehicles comfortably if we were not guaranteed safety in these environments. These structures start deteriorating once they are built and used. Such deterioration significantly affects the performance and safety of structures, and therefore, the safety of mankind.

In today's society, we often hear about structural failure events around the world. A subset of such event lists that occur in the years between 2002 and 2016 can be found on Wikipedia[1,2]. In the US, it has been reported that more than 123 bridges are found to have been partially or fully collapsed in the years between 1989 and 2001. These are mainly due to (i) triggering events such as earthquakes, vehicle collisions, or overloads, (ii) design and construction errors, and (iii) structural deterioration such as cracks, scours, or fatigues [Spencer and Cho 2011; Wardhana and Hadipriono 2003]. Upon further investigation, we find structural failures that happened between 2012 and 2015 have increased by more than 40% around the world, compared to failure events in the years between 2002 and 2011.

Fig. 1 depicts a few snapshots of structural failure events that have occurred in different countries, revealing civil structures vulnerability to damage and failure during natural catastrophes. The failure events of the I-35W Bridge (see Fig. 1(a)) in Minnesota in 2007 and a garment industry building in Bangladesh in 2013 have provided a reminder for the governments and the CSMEA engineering communities of the importance of structural health diagnostics. The Australian transportation authorities (ATA) estimate that bridges would need more than 92 billion AUD in order to fix the existing deficiencies or replace them. From the developing world, considering India, China, Bangladesh, the facts are more scary if one calculates how many people are being killed by structural failures. For example, the building collapsed in 2013 in Bangladesh is the deadliest structural failure in modern human history, and killed over 1,000 people (see Fig. 1(3)).

The process of determining and tracking structural integrity or characterizing the nature of health status in terms of its level of safety to withstand infrequent but remarkable structural response or forcing events such as damage, cracks, corrosion, yielding, overload) in structures are often referred to as structural health monitoring (SHM), which is usually carried out by CSMEA engineering communities [Farrar and Worden 2012; Farrar and Lieven 2007; Lynch and Loh 2006].

Currently, wired network systems developed by CSMEA engineering dominate SHM applications where sensors are permanently wired up to report back to a central/global system [Rice and Spencer 2009; Musiani et al. 2007b]. However, maintaining such a wired network based SHM system is cumbersome with large-scale structures. Furthermore, it is inherently associated with the hassles and the costs of kilometers of cabling (wire breaks may happen), installation, and maintenance.

Instead, it is commonly believed that wireless sensor network (WSN) systems will play a significant role for SHM in the near future, due to their intrinsic advantages. On the one hand, researchers in engineering domains are discovering that WSN technologies should not only be viewed as simply a substitute for traditional wired SHM systems, but should also be seen as playing a better role in structural response data

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[1] http://en.wikipedia.org/wiki/List_of_structural_failures_and_collapses

[2] https://en.wikipedia.org/wiki/List_of_bridge_failures

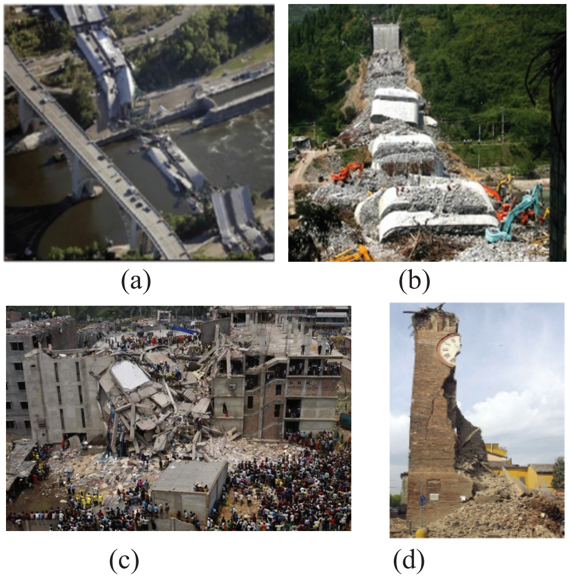

Fig. 1. Recent structural events: (a) I-35 Bridge in Minneapolis, USA; (b) a highway bridge in Zhuzhou, China; (c) an industrial building in Bangladesh; (d) a heritage tower crumbles down in earthquake Italy.

processing and real-time monitoring operations. On the other hand, WSN systems can be easily, flexibly, and reliably deployed and maintained [Alam et al. 2015]. Moreover, it is cost-effective in terms of time, economic benefit, and real-time operation compared to wired systems. Thus, it is assumed that the structural safety and integrity will be better assured by WSNs in the near future, which is the goal of researchers/engineers in these multi-disciplinary fields.

However, we find that researchers/engineers face a number of hurdles in reaching the goal above. A WSN itself has severe resource or performance limitations, e.g., energy, communication, and reliability. In addition, this severity is enhanced by some SHM-specific requirements, including high-resolution data acquisition, a large volume of data transmission, application-specific deployment, and long-term monitoring requirements. Based on our experience gained from collaboration with civil engineers in various SHM projects, on the one hand, we find that the monitoring performed by SHM systems themselves is not enough to capture an unusual event such as damage occurring in the structure. This makes the operations meaningless in many cases. If the decision by a WSN is not sufficiently accurate to determine the extent of an event, the event cannot be detected. The situation becomes more serious when a large structure is given for monitoring. Broadly speaking, SHM research attempts to use wireless sensors to localize damage and detect its extent through a structural response (via Hurdles in reliable data collection, online signal processing, in-network decision making, and application-specific fault-tolerance should still be evolved and improved [Zimmerman et al. 2013; Lo et al. 2013; Smarsly and Law 2014; Liu et al. 2015b; Bhuiyan et al. 2015a; Alam et al. pear]. The goal of assuring the safety and reliability using WSN-based SHM will be achieved once the resource limitations of WSNs and the hurdles in SHM applications can be overcome.

Bearing the same goal in mind, in this paper we conduct a comprehensive investigation of WSN-based SHM applications, with an emphasis on networking perspectives and insights into a cyber-physical system (CPS). The main objective of this investigation is to explore potential design challenges and guidelines towards CPS designs. The limitation of this investigation is that we mainly attempt to cover networking perspectives for SHM and we will not cover structural systems, sensor technologies, signal processing, and event detection perspectives. The major contributions are as follows.

First, we start with a brief discussion on the state-of-the-art reviews and our motivation. We then provide the SHM philosophy and conduct extensive comparative studies regarding various aspects of benefits and hurdles of going wireless for SHM. We compare the WSN-based SHM with the wired sensor network-based SHM and then with other WSN-based applications. These will provide a realization of practical hurdles in wired sensor networks and in designing future WSN systems.

Second, we provide a taxonomy of WSN-based SHM solutions covering some seminal solutions found in both CSMEA engineering and computer science and engineering (CSE) literature, and we place an emphasis on networking perspectives. We organize the taxonomy in a hierarchical manner and describe each of level of it, while we also offer some potential open issues (OIy, $y = 1, 2 \ldots n$) during the description.

Third, we envisage to show a transition from WSN-based SHM systems towards a cyber-physical system (CPS) design, which is expected to be an emerging multidisciplinary frontier, enabling revolutionary changes in this research. This is due to (i) the increasing demand to provide low-cost and timely monitoring of the deteriorating infrastructures, and (ii) advances in integrated wireless sensing technologies. Based on our experiences, we bring up an important concern: the isolation of the cyber system issues (such as wireless communication, computation, control) and physical system issues (such as dynamics in physical process, SHM techniques) may result in suboptimal WSN-based SHM solutions, since the dynamics in the physical systems may affect the performance in the WSN system. Taking this concern into account, we attempt to analyze hurdles related to the CPS design.

Fourth, we discuss important design requirements of the CPS refocusing on the SHM application demands that we found to be useful for the CPS design. Most of these requirements are relevant to network perspectives.

Finally, we propose a series of design guidelines for the potential CPS design, including a CPS model. In the model, we address the concern about structural dynamics (the evolution of a system state in time) and include a computation model. Each sensor is given the model to compute the dynamics.

2. GOING WIRELESS FOR SHM: SHM PHILOSOPHY AND COMPARATIVE STUDIES

In this section, we begin with a background, including an SHM philosophy and domain-specific terms definition, which will help non-specialist to comprehend domain-specific matters (*a summary of related reviews can be found in Appendix A of the supplemental file*). Next, we present extensive comparative studies between WSN-based SHM applications, wired-based SHM, and other applications. Finally, we list recent state-of-the-art WSN-based SHM schemes with their key ideas.

2.1. SHM Philosophy

Structural health monitoring (SHM) refers to the process of characterizing and implementing an event (e.g., damage) of interest for engineering structures [Farrar and Lieven 2007]. The monitoring process engages the observation of a structural system over long periods, using samples of data acquired periodically with adequate sensors. It also involves sensitivity feature extraction and statistical correlations to determine the actual "health" status of the system [Farrar and Worden 2012; Lynch and Loh 2006; Rice and Spencer 2009].

Generally, the objective of SHM is to handle a four-level classification system:

- Level 1: Identification of the presence of an event (such as damage) and the type of events (such as cracks, corrosion).

Table I. Comparative studies of structural health monitoring (SHM) system aspects along with SHM requirements.

SHM requirements		**Wired-based SHM System**	**WSN-based SHM System**
Cost/effort	**Equipment**	Cost-inefficient, enormous	Cost-efficient, miniature or compact
	Cabling	Long (miles of) cables	No cables
	Deployment time	Months ~ years	Hours ~ days
	Deployment cost	High, labor-intensive	Low, relatively effortless
High spatial density		X0~X00 (X=1.2.,..,) sensing points (Many cases, requiring more sensing points to obtain more detailed information of structures)	X00~X000 sensing points (having available sensing points to obtain more detailed information of structures)
Sampling	**Fast/delay on command or event triggered**	Delay <µs	Delay: Seconds ~ minutes (due to the wireless link)
	Data acquisition system	Expensive	Low-cost
	High frequency	Frequency >10KHz	Frequency < 10KHz
	Synchronized errors	Sync error <1µs	Large sync error
Fast and reliable data delivery		• 100% reliable data delivery • Instant delivery • Often multi-hop bandwidth	• Unreliable data delivery • Data can get lost • Single hop bandwidth < 100kbps
Reliable and accurate event (damage) detection		Benefit from centralized or global algorithms, but constrained by low density & flexibility	Constrained by limited computation power, but benefits from high density and flexibility (due to decision making ability)
SHM-specific deployment methods		Possible to adopt easily	Difficult-to-adopt (WSNs are often unattended and communication-constrained)
Other features		• Most cases have centralized, complete but reliable monitoring	• Able to provide quick, ad-hoc, and reliable/unreliable monitoring (due to the wireless communication)

— Level 2: Identification of the geometric location of the event.
— Level 3: Quantification of the severity of the event.
— Level 4: Prediction of the remaining service life of the structure.

To date, damage event detection methods based on vibration do not use any structural models, but primarily provide Level 1 and Level 2 event identification. When vibration-based methods are coupled with a structural model, Level 3 event identification can be obtained. Level 4 is the prediction associated with the fields of fracture mechanics, fatigue-life analysis, or structural modeling evaluation. This level is also used for structural model updating [Zimmerman and Lynch 2009]. To date, the scope of SHM research in WSNs is to provide Level 1 and Level 3 identification [Lynch and Loh 2006], due to cost inefficiency (see Table 1 for cost differences between wired-based and WSN-based SHM).

2.1.1. Domain-Specific Term Definitions. There are several terms usually used by researchers/engineers from multiple domains in analyzing SHM. We think that these terms can be uncommon to non-specialists from other WSN applications.

Definition 3.1 [Finite Element Model (FEM)]. *A computer-based numerical model for calculating the behavior and strength of structural mechanics, such as vibration and displacement. Via FEM, a complex structural model is simplified by breaking it down into small elements. These elements are blocks that contain the information of the entire property of the structure, where* physical *aspects correspond to such elements / components.*

Definition 3.3 [Modal Frequency or Natural Frequency] *When such an element in Definition 3.2 is hit and the external influence (force) is removed, it will vibrate at its natural frequency. The natural frequency is defined as the number of times a system will oscillate between its original position and its displaced position.*

Definition 3.4 [Mode Shape]. *Each type of mechanical structure has a specific pattern of vibration at a specific frequency, called mode shape. More specifically, it basically shows how a structure will vibrate, and in what pattern. For example, a mode looks like* $\{2.56, 7.45, 10.56, 6.34\}Hz$ [Bhuiyan et al. 2014].

Definition 3.5 [Substructure and Subnetwork]. *A part of a structure can be regarded as substructure that can be monitored independently without caring about the whole structure, e.g., a number of floors or a section of a building, a superstructure or long-span of a bridge, a part or a section of an aircraft, a specific plant of nuclear power plants [Xing and Mita 2012]. The group of sensors deployed around the substructure can form a subnetwork [Bhuiyan et al. 2014] and can carry out monitoring operations.*

Definition 3.2 [Structural Events]. *As a general term in SHM, events can be defined as changes introduced into a structural system that negatively affect its performance. As far as engineering structures are taken into account, changes in structural elements, connections, or boundary conditions, which cause a deteriorated performance of the structure, can be defined as an event of damage. Normal activities can introduce damage to the structure. Damage itself is called an event and also it is caused by other associated reasons. For example, buildings can be damaged due to corrosion, cracks, concrete spalling or scour aging, and daily activities. Traffic and wind loads cause damage to bridges. On the other hand, excessive loads produced by cyclones, hurricanes, earthquakes can cause the event of damage to structures.*

Definition 3.6 [Cyber-Physical System: CPS]. CPS has emerged as a unifying name for systems where the cyber system aspects (the computing and communication) and the physical system aspects are tightly integrated, both at the design time and during operation. Such systems use computations and communication deeply embedded in and interacting with physical processes to add new capabilities to physical systems. Buildings, bridges, aircraft, cars, factories, and similar physical structures with their functions are just a few examples of CPSs. The characterizing feature of these systems is the interaction between physical processes governed by the laws of physics and an execution platform (i.e., cyber system) which comprises embedded software and hardware devices such as sensors, actuators, processors, and communication networks to interconnect them. The physical process involves the elements and the physical connectivity between the elements of a structure (as in Definition 3.2). Any changes in the elements, even micro-elements and their connectivity can be closely monitored by the cyber system, which is still a challenging task. In an intended CPS, physical system aspects and cyber system aspects should be tightly combined. That is to say, SHM applications are characteristic examples of a complex CPS where neither the "cyber" aspects nor the "physical" aspects can adequately be considered in isolation.

2.2. Moving from Wired Network towards WSN-based SHM

Before 1980, in response to critical situations on structural vulnerability to the event of damage and failure during natural catastrophes, early detection of such deterioration is achieved by visual inspection. During either routine maintenance visits or occasional visits, a maintenance team is used to be sent to the site to investigate a known or a suspected problem. Such inspections are time-consuming, costly, risky, and therefore infrequent and unsafe. Additionally, human errors are involved in such inspections [Farrar and Worden 2012; Farrar and Lieven 2007; Rice and Spencer 2009], although visual inspections are still used. To make functions of structures safe, reliable, and durable, the CSMEA engineering communities seek novel sensing technolo-

Table II. A list of prominent WSN schemes with their key ideas for SHM applications.

Acronym/ Label	**Key Idea**	**Proposed Year**	**Reference**
MODEM	Model-based in-network decision making in the CPS for SHM applcaitions	2016	[Bhuiyan et al. 2016]
SenStore	A cyberinfrastructure platform implementation based on data-to-decision for SHM	2016	[Zhang et al. 2016]
MSHM	SHM systems based on wireless, mobility, and smartphone	2016, 2015	[Oraczewski et al. 2016; Ekin et al. 2015]
DependSHM	Dependable SHM using WSNs	2015	[Bhuiyan et al. 2015b]
SCoverage	Generalized coverage-preserving scheduling in WSN-based SHM	2014	[Liu et al. 2014]
FTSHM	Fault-tolerant WSN deployment	2014	[Bhuiyan et al. 2015a]
WCPS	Wireless cyber-physical system simulator	2013	[Li et al. 2013]
DisERA	Distributed version of Eigen-system realization algorithm (ERA)	2013	[Liu et al. 2015a]
ADIMS	Online all-digital impact monitoring system	2013	[Qiu et al. 2013]
d-SVD	Distributed version of singular value decomposition for SHM	2012	[Jindal and Liu 2012]
WiSeMote	A design of a new wireless sensor mote and a base station for SHM	2012	[Hoover 2012]
ClusterSHM	Cluster-based modal analysis in WSNs	2011	[Liu et al. 2011b]
GoertzelSHM	Data acquisition via the Goertzel algorithm	2011	[Bocca et al. 2011]
RTSHM	Real-time wireless data acquisition for SHM	2011	[Linderman et al. 2011]
GENESI	Green sensor networks for SHM	2011	[Brendan et al. 2011]
SPEM	Wireless sensor placement using the effective independence method	2010	[Li et al. 2010]
TorreAquila	A WSN system deployed in Torre Aquila	2009	[Ceriotti et al. 2009]
FScale	Full-scale structural health monitoring system using WSNs	2009	[Rice and Spencer 2009]
BriMon	A WSN-based SHM for Bridge monitoring	2008	[Bocca et al. 2011]
DLAC	Damage localization assurance criterion algorithm for SHM	2008, 2012	[Hackmann et al. 2012]
GGB	A WSN-based SHM deployment on the Golden Gate Bridge	2007	[Kim et al. 2007]
SHiMer	A wireless platform for sensing and actuation	2007	[Musiani et al. 2007a]
netSHM	Networking software system for SHM	2006	[Chintalapudi et al. 2006]
SyncSHM	Synchronized WSNs for modal analysis in SHM	2009, 2012	[Sazonov et al. 2012; Araujo et al. 2012]
Wisden	A WSN-based data acquisition system	2004	[Xu et al. 2004]
ModularWSN	A modular wireless sensor system for SHM	2002, 2003	[Tanner et al. 2003]

gies and systematical techniques/tools that can be used to promptly identify the onset of structural damage in an instrumented structural system. Eventually, structural health monitoring (SHM) emerged.

The research on SHM system using wired sensor networks has been an active research topic since the 1980s in the CSMEA engineering domains. Over the past decades, CSMEA engineering communities utilize advanced wired sensor platforms (typically via optical fibers, coaxial cables, pneumatic tubes, piezoelectric sensors, among others) to gather information about structures for SHM. Sensors are wired up to report to a global system [Farrar and Worden 2012; Lynch and Loh 2006; Linderman et al. 2011; Xing and Mita 2012; Pentaris et al. 2013; Yi and H.N.Li 2012; Whelan et al. 2013]. However, manipulating wired networks is cumbersome with aged structures. It can be better realized from Table I, where we carry out a comparative study of wired sensor networks and WSN-based SHM solutions. Different values of this comparative study in Table I are gathered from existing literature [Rice and Spencer 2009; Li et al. 2013; Jindal and Liu 2012; Musiani et al. 2007a; Liu et al. 2011b; Pentaris et al. 2013; Kimura and Latifi 2005; Lynch and Loh 2006]. Particularly, as highlighted, the cost of running data and power cables is high to each individual sensor deployed in challenging environments, such as a subway tunnel or a long suspension bridge. The deployment of kilometers of cables is labor-intensive and time-consuming. Furthermorer, once wire connections break caused by hazardous events like earthquakes [Lei et al. 2012; Bhuiyan et al. 2013], detection of a broken wire or a fault may take a long period, during which all the measurements could lose their importance. In addition, a long wire replacement operation on a high-speed railway bridge, on a high-rise building, or on hundred kilometers long pipelines require stopping their functions. All these instances cause the investment of the SHM system to be prohibitively high.

In contrast, there are significant benefits in deploying wireless systems, i.e., WSN-based SHM. A comprehensive comparative study between wired sensor network based SHM and WSN-based SHM is conducted in Table I. In general, the drawbacks with the wired network-based SHM system (as highlighted in Table I) enable CSMEA engineering domains to pursue shifting from wired sensor network based SHM to WSN-based SHM [Farrar and Worden 2012].

2.3. The Benefits of Going Wireless: A Comparative Study

The research on SHM systems using wireless sensor networks (WSNs) has been a research topic since the last decade. Example state-of-the-art schemes include Wisden [Xu et al. 2004], GGB [Kim et al. 2007], netSHM [Chintalapudi et al. 2006], Modular-WSN [Oraczewski et al. 2016] (for acronym descriptions, refer to Table II). Over the past several years, the CSMEA engineering domains have gradually targeted the implementation of analytical methods to detect and quantify structural damage by using wireless sensing technologies [Rice and Spencer 2009; Farrar and Worden 2012; Hackmann et al. 2012; Araujo et al. 2012; Linderman et al. 2010; Nagayama et al. 2006; Smarsly and Law 2014], due to intrinsic benefits of using WSNs as shown in Table I. A few of the benefits among many offered by envisioned WSN-based SHM systems are early detection of events, avoidance of catastrophic collapses, improved public safety, and reduced maintenance disruptions and operation time/costs [Farrar and Worden 2012; Bhuiyan et al. 2014; Wang et al. 2012a; Rice and Spencer 2009; Linderman et al. 2011; Li et al. 2013; Liu et al. 2015a; Bhuiyan et al. 2013; Hsu et al. 2011].

While WSNs are gradually receiving attention from the CSMEA as an attractive tool, engineering SHM applications are receiving attention from the computer science domain. According to the computer science and engineering domains, wireless sensors of WSNs are not only sensors defined by the conventional perception, but rather are autonomous data acquisition nodes in which structural sensing elements such as strain gauges, accelerometers, linear voltage displacement transducers, inclinometers, the onboard microprocessor, and wireless communication elements are integrated [Liu et al. 2015a; Jindal and Liu 2012]. Numerous research efforts, designs, prototypes, and experiments of WSN-based SHM have been suggested, implemented, and validated both in academic and commercial domains. Example prominent schemes are described with their key ideas in TABLE II.

Among them, a state-of-the-art scheme verified on the Golden Gate Bridge (GGB) can be seen, which is regarded as the first systematic WSN-based SHM deployment [Kim et al. 2007]. Another technique, called Wisden, devises a prototype software system and conducts experiments with it on both a test structure and realistic structure. Wisden is a design for a WSN for structural data acquisition, and it delivers time-synchronized structural-response data reliably from several locations over multiple hops to a central server or base station (BS). Another scheme, netSHM, provides a WSN design software for SHM [Chintalapudi et al. 2006]. It offers a programmable sensor actuator-network that allows CSMEA engineers to implement and test algorithms in a higher-level language such as C or Matlab without having to understand

Table III. Comparative studies of health monitoring aspects of WSN-based SHM application and WSN-based other applications.

	WSN-based generic applications	**WSN-based SHM applications**
Sensor types	Light, temperature, humidity, etc.	Acceleration, corrosion, strain-gauge, strain gages, accelerometers, linear voltage displacement transducers, inclinometers, piezoelectric pads, among others etc.
Deployment	Often random, uniform, grid, etc.	Often Application-specific
Sampling	Low frequency (X times per second, minute or day)	High frequency (X00 times per second)
	Not necessarily synchronized in many cases	Synchronized sensing • All the sensors work simultaneously • Synchronization error <1ms
Data types	Light, temperature, etc.	Vibration, strain, displacement (also acoustic emission), etc.
Detection model	Sensors collect the energy emitted by the targets/objects/environmental phenomena and make corresponding conclusions	1) The raw data from multiple sensor nodes are collected 2) Some vibration characteristics are identified 3) The changes of characteristics → event
Sampling	X times per second, minute or day	X00 times per second
Data volume	Received energy level: X bytes	Raw measured at each sensor node: X000~X0000 bytes
Data delivery	Possible to have 100% data delivery	Not possible to have necessary 100% many times
Processing/ Detection Algorithms	Light-weight • Relatively simple: 0/1 decision; average/max/min; comparison; sometimes, majority voting • Many cases, the algorithms involves simple processing and are computationally not intensive	Heavy-weight • Relatively complicated: SHM algorithms are based on a bunch of data (>X000 level) • SHM algorithms involves complex signal-processing (e.g., SVD, Eigen-system realization, and are computationally intensive

the intricacies of wireless networking. It offers a generic API in the higher-level language that allows users specifically task wireless sensor nodes. An inclusive design for SHM application called BriMon is a design of a WSN system for long term railway bridge monitoring. It aims to predict if there is any damage event in a bridge before a train goes along the bridge.

The schemes above are the representative examples of the state-of-the-art technologies and applications of WSNs for SHM. Although these schemes come with innovative ideas, their validation is still under investigation and experimentation. In the SHM system implemented on the Guangzhou New TV Tower (GNTVT), the wireless sensor system is partially adopted [Ni et al. 2009], due to the limitations on the WSNs. SPEM [Li et al. 2010] details the WSN deployment method on the GNTVT.

2.4. WSN-based SHM vs. WSN-based other Applications

In this subsection, we offer a comparative study between WSN-based SHM applications and WSN-based other applications in terms of health monitoring aspects. This will provide a perception of differences between these two types of applications to respective non-specialist and expert researchers/engineers.

Generally, if we look at different types of generic applications of WSNs, such as event or target detection and environment monitoring [Gungor and Hancke 2009; Alam et al.

2015], a sensor detects an event after receiving data acoustically, or in the form of light, or temperature emitted by the event/target, as shown Table III. This usually requires the collection and processing of several data points. Moreover, many assumptions are used to model the network model-associated problems, such as unit disk or convex sensing regions, or data aggregation by average (which is unfortunately not realistic in SHM). It is often seen that the event/target detection decision can simply be made at sensors in a local manner (such as 0/1 local decision without much computation), and/or detection can also be made in a distributed manner without much computation and communication. Even if the detection is made in a BS (in a centralized manner), the amount of raw data transmitted is very small.

As shown in Table III, we may claim the following in cases of some other WSN applications: (i) they generally have simple type of sensors, low frequency sampling, low volume data ($X\sim X0, X=1\ldots n$), 100% data delivery; (ii) they need light-weight processing, detection, and monitoring algorithms. However, one may argue that such a claim is not right, as there are still huge complexities and hurdles (such as communication, computation, detection) in achieving those algorithms successfully in WSNs in practice. As a result, everyday there are plenty of research works and new ideas published in the communities that focus on numerous issues, including the issues in Table III.

In contrast, WSNs usually face more challenges for SHM than for the traditional target/object detection, as SHM requires more complex event detection by monitoring the integrity of structures. A comprehensive study of WSN-based other applications and WSN-based SHM applications is provided in Table III. Based on the issues, as shown in Table III (right column) and based on the classification system, as described in Section IIA, WSN-based SHM attempts to answer questions shortly like:

- Q1: is there any event in the structure? [complex structural event detection that should be captured from structural physical elements]
- Q2: what type of event has occurred in the structure? [different events show different signal strengths]
- Q3: where is the area of the event? [event localization: difficult to find appropriate coordinates of the complex event]
- Q4: how severe is the strength of the event? [difficult to estimate the quantity or strength of the complex event]

Particularly, based on our experiences with civil collaborators, they generally implement centralized SHM algorithms to obtain the structural raw response data (i.e., vibration, strain), where signals are collected at high sampling frequency (such as 560 Hz or more) for a long enough period of time. Some data analysis algorithms in SHM such as ARX, ERA, FDD, NExT, FFT, SVD (for abbreviation description, refer to Table IV) are made distributed through the idea of 'divide and conquer' and multi-level damage localization. These algorithms or methods are found to be used in many prominent works, such as DLAC, DisERA, Fscale, ClusterSHM, WCPS, RDSHM, d-SVD, WiSe-Mote, as shown in Table II.

The algorithms normally work in a round-by-round manner. The key ideas of some prominent schemes cover different research issues, as shown in Table II and Table III. Each sensor shares the response data with multiple sensors, and then transmits it to the BS. The data from each sensor involved is no longer a single value, but a sequence of data generally having over thousands of data points at each of the rounds, such as 2048 samples (see TABLE B in Appendix D). Due to the severe resource constraints, it is hard to get such a huge amount of raw data received at the BS and get a decision in time. Such algorithms also require significant engineering domain knowledge in order to address those questions (i.e., Q1-Q4). However, applying them directly within a WSN is much more difficult than that of algorithms used in other WSN applications

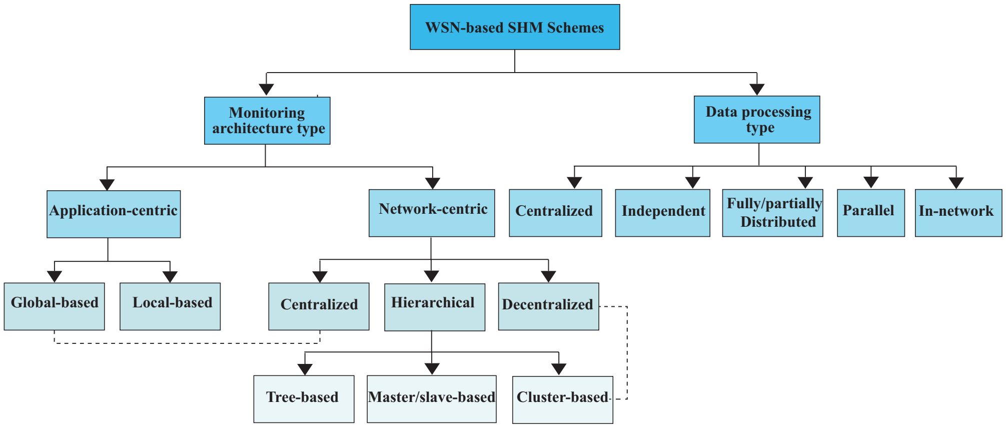

Fig. 2. A taxonomy of WSN-based SHM schemes.

(such as target/object detection, environment monitoring). Thus, WSN-based systems need improvement. In a later section, we will show to shift from a WSN-based SHM to a CPS design.

3. TAXONOMY OF WSN-BASED SHM SOLUTIONS

There are a various existing WSN-based solutions suggested by CSMEA engineering and CSE communities. We put an emphasis on those solutions that are related to network perspectives, covering most types of solutions found in both CSMEA engineering and CSE literature. Therefore, in this section we provide a taxonomy of WSN-based SHM solutions. We organize the taxonomy in a hierarchical manner, as depicted in Fig. 2. Basically, WSN-based solutions can be divided into two types: monitoring architecture and data processing styles. We describe each of them in detail with their hierarchy. During the discussion, we offer some potential open issues (OI) during the description. We organize the taxonomy in a hierarchical manner, which can be found in the Appendix C. Basically, WSN-based solutions can be divided into two types: monitoring architecture and data processing styles, as shown in Fig. 2.

We classify the monitoring architecture into two types based on their functions: application-centric and network-centric. Application performance issues (such as event occurrence, detection, monitoring algorithms, and facts about the event found in the practical field), which are relevant to *physical* aspects and depends on some SHM-specific requirements. Here, facts include structural events such as rare events, the type of events, the type of structures, and interference situation. In addition to the requirements described in TABLES I and III, there are other requirements such as high-quality sensor deployment, full-scale data collection, non-faulty data collection, and real-time event detection [Lo et al. 2013; Liu et al. 2013; Linderman et al. 2011; Smarsly and Law 2014; Liu et al. 2015b; Bhuiyan et al. 2015a; Liu et al. 2011a; Bhuiyan et al. 2014]. The reason is that there are occurrences of false-negative and false-positive structural event detections [Bhuiyan et al. 2015b; Flynn 2010]. In addition, we have discovered that WSN deployment for SHM should satisfy applications-specific requirements to avoid meaningless monitoring operations. Wired-network based SHM is normally assumed as to be effective for fully satisfying the SHM-specific requirements. There are currently a few WSN-based solutions available that attempt to satisfy the application-specific requirements to a great extent. Such requirements are like ensuring a high percentage of damage detection quality and accuracy [Santos et al. 2016], a low percentage of false positive rates. However, to achieve a fully-applicable WSN solution for SHM applications, there are certain application-specific challenges that need to be faced. We highlight some of such solutions in the following.

There are mainly two kinds of application-centric monitoring schemes: global-based and local-based. *Global-based SHM is defined by the numerical methods that consider the global signal (such as vibration and strain) characteristics of a structure in order to identify an event of interest via mode shapes and natural frequencies* In contrast to the above, *local-based SHM schemes* are those that can identify health status, say damage, cracks, and defects in structures at their elements/components or sub-components length-scales. Sophisticated ultrasound, thermal, X-ray, magnetic, or optical imaging techniques are used in those schemes. In fact, an event of damage in a structure is an intrinsically *local phenomenon*. We describe each of them in detail with their hierarchy in Appendix B, while we also offer some potential open issues during the description.

4. MOVING FROM WSN-BASED SHM TOWARDS A CPS DESIGN

We envisage a transition from a WSN-based SHM system towards a CPS design. We analyze related hurdles to the CPS design. For each of the hurdles, a set of existing schemes are discussed with an emphasis on the limitations of the state-of-the-arts and future research directions in the new open areas.

4.1. Insights into the CPS

Current implementation costs and time for a wired sensor network are high, making the realization of a large-scale network prohibitively expensive. Compared to the wired network-based systems, WSN-based SHM systems with optimized control techniques are believed to have the potential to offer not only a healthy and comfortable environment, but also lower maintenance costs and time. Such a system is a typical example of a complex cyber-physical system (CPS) [Bhuiyan et al. 2016; Hackmann et al. 2014; Wu et al. 2011; Zhang et al. 2016; Li et al. 2013; Bocca et al. 2011]. We need to be able to make real-time decisions using all available CPS inputs.

On the one hand, designing a CPS of WSN-based structural event monitoring system with respect to applications-specific requirements, we consider shifting from separately analyzing the WSN performance (computation, communication, control–cyber aspects) and the application performance (event occurrences, detection algorithms, and facts about events in the practical field–physical aspects). More particularly, research on WSN-based SHM as a CPS, cyber aspects involve data acquisition/sensing, signal processing, communication, data management, information technology, and control, essentially requiring expert knowledge from computer science and engineering. As previously described, a structure consists of *physical* elements/components. Thus, physical aspects involve physical elements of structures, system modeling, information processing, damage/crack event detection. These aspects mainly involve expert knowledge from CSMEA engineering communities.

On the other hand, designing a WSN-based SHM system is an interesting multidisciplinary topic. There is still a lack of integration and collaboration by (i) CSE communities and (ii) CSMEA engineering domains, ClusterSHM [Liu et al. 2011b], SPEM [Li et al. 2010], and [Hackmann et al. 2014; Bhuiyan et al. 2013]. Over the years, while CSMEA engineering communities have developed powerful SHM techniques for analyzing, modeling, and controlling physical processes, CSE communities have achieved similar developments in cyber systems [Wu et al. 2011; Tan et al. 2013; Matteo et al. 2011; Bhuiyan et al. 2016; Hackmann et al. 2014; Wu et al. 2011; Zhang et al. 2016]

However, there is still a big gap between the cyber aspects, where information is exchanged and transformed, and the physical aspects, in which the dynamics and physics of physical structural systems are captured and tracked. As discussed before, vibration-based SHM requires sensed data that well represents the physical response of the structure both in amplitude and phase. An analysis of the extensive dynamicity in them later refers to a change in the physical system. We think that the isolation of the cyber aspects and the physical aspects in a CPS solution may result in suboptimal WSN-based SHM solutions, since the dynamics in the structural systems may affect the performance in the WSN. To support this, we make the following observations.

- **Observation 1.** It is commonly observed that, “no structural event/change (such as damage)” occurs in a structure. Regarding this in a resource-constrained WSN, the large volume of data really does not always need to be transmitted to the BS. Instead, a simplified decision transmission may be interesting in the case of a “no change” detection. However, if a change has occurred in the structure, in addition to transmitting a decision on the possible change, a node may need to transmit all of its collected data towards an upstream node or the BS upon request. The nodes may have additional interactions between them. For example, they need to communicate to the neighboring nodes in the region of the change, and to further analyze the data for ensuing the state of the change. This implies that a change in the physical structural system results in an extensive communication and computation in the WSN system, especially between the nodes in the region around the change.

  Therefore, the integration between both systems is a CPS. In CPS, finding a distributed decision maker for event detection and the region of interest is essential to reduce the volume of data in the case of “no event” in the region. The region can be assumed as a substructure, part, section, or span of the physical structure. If there is an event such as damage at a region, say in a substructure of a structure, a group of sensors say, a subnetwork of the network, around the damage should operate for a prolonged time. Sensors in the other subnetworks (or in the other regions) can sleep to reduce the energy consumption.
- **Observation 2.** Under any fault occurrence in a practical WSN-based SHM system, we discovered an interesting and unknown fact, both faulty and non-faulty wireless sensors can generate abnormal signals or decisions. This indicates that there is a possibility of both a structural damage event and a sensor fault occurring at the same time. Faulty sensors may cause an “undamaged location to be identified as damaged (false positive)” or a “damaged location as undamaged (false negative)” diagnosis. As a result, removing faulty signals from the measured signals and identifying what happens exactly in a physical structural system is a challenging task. We have to enable the WSN system to make a deep analysis on such facts so that the situation (either sensor fault or damage) can be discovered. This can only be achieved by fully integrating WSN system with the structural system (i.e., CPS). Without having a design of such CPS, it would be difficult to make a decision on such a situation.

There are some insights of such a CPS design in MODEM [Bhuiyan et al. 2016], SenStore[Zhang et al. 2016], DLAC [Hackmann et al. 2012], WCPS [Li et al. 2013], GoertzelSHM [Bocca et al. 2011], d-SVD [Jindal and Liu 2012] and [Hackmann et al. 2014]. Particularly, WCPS represents an exemplary class of cyber-physical systems that perform close-loop control using a WSN. It develops a wireless CPS, an integrated environment that combines realistic simulations of both WSNs and structures, targeting control delays and data loss in WSNs deployed on large civil structures. However, many of other schemes do not provide requirements and guidance on how to design such a CPS for SHM applications and discuss the underlying WSN issues and the SHM requirements when designing a CPS. In our recent work, TPSP [Bhuiyan et al. 2014], we try to come up with some performance analyses in a CPS in terms of both cyber WSN and physical structural system aspects. However, we think it is still a very preliminary step. Therefore, we plan to work on the CPS design further. Working on comprehensive CPS design can certainly be an interesting open issue (OI1).

4.2. Hurdles and Issues towards the CPS Design

To achieve a sustainable and scalable CPS for SHM applications, a number of design hurdles and issues should be considered comprehensively. Table I shows a comparative study of them. Among all of them, the most important design hurdles and key design issues are described in the following.

4.2.1. Sensor Node Constraints and Energy Conservation. WSNs are discerned with numerous benefits, including having a low cost and being easily deployed for SHM, as highlighted in Table I. From Table I, it can be observed when compared to wired networks and other high-end technologies, such as personal computers and personal digital assistants. However, these appealing benefits hint that resources available to each individual sensor node are extremely constrained. Batteries are the main source of energy supplied in sensor nodes. Although constraints on sensor hardware may disappear as fabrication techniques advance, the *energy constraint* remains to be the victim of Moore's Law, since more transistors require more power. On the other hand, the battery capacity has just doubled within 35 years according to [Kiehne 2003]. Though recent advances in energy harvesting technologies for SHM applications have increased in recent years [Le et al. 2015], there are still limitations in deploying such technologies with small scale sensors, including extracting energy from the local environments to power WSNs as stand-alone systems and reliability of such SHM systems.

Advanced sensor platforms such as MICA2 are supplied power by two AA batteries that last several weeks. The most widely-used sensor platform for SHM applications is Intel Imote2, which is supplied power by only two AAA batteries that last from several weeks to a few months, only when energy conserving methodologies (low duty cycle, MAC protocols) and efficient processing and transmission algorithms can be utilized. In WSNs, communication/transmission cost is believed to dominate the energy consumption. The energy cost of transmitting 1 Kb on a distance of 100m is almost the same as that for the execution of 3 million instructions by using a general-purpose processor. Since these constraints exist (that cannot be removed in the near future) in designing of WSNs, optimizing the design of WSNs (such as finding methods for minimum energy consumption) has become important.

The sensor nodes also have *memory* constraints. MICA2 has a 128KB program memory and 4KB RAM. The total code space of TinyOS (the most commonly used operating system for sensor platforms) is approximately 4KB [Levis 2006]. The computation capability is constrained by limited energy and complexity. The MICA2 has an 8-bit ATmega128L CPU. Thus, sophisticated monitoring algorithms, such as SHM algorithms, which require various complex parameters through SVD, FDD, RD, NExt, ERA (see Table III), to make a decision on an event, may not be feasible for such nodes. To close the gap between the limited energy supply and the increasing demand of the sustainable CPS of WSN-based SHM deployment, energy conservation needs to be considered carefully in the CPS design.

4.2.2. Low-quality Communications. As a whole, with the requirements of low cost and low energy, the design of WSNs has mainly been for low-communication cost in many other applications, as shown in Table III. For applications such as SHM, the demands are more diversified sensing technologies and various type data acquisition methods. Specially, for the application of acquisition of large amounts of data such as the vibration and image data in SHM, the communication requirements for WSNs have enlarged. We highlight some important issues in the following.

- **Long Distance Communication with Heavy Load.** For high quality SHM, sensors have to be placed at critical locations that are of the CSMEA engineering's importance so that the event detection can be achieved accurately, according to the literature from CSMEA engineering [Li et al. 2010; Bhuiyan et al. 2013; Beygzadeh et al. 2013; Zhang et al. 2012]. However, such placement leaves challenge in data transmission over long communication distances. This is because modern civil structures like long-span bridges, and subway tunnels, have lengths ranging from one hundred meters to over several kilometers. The communication distance from sensors to sensors and sensors to the BS in WSNs would still be too long, leaving challenges in wireless connectivity and data transmission over the long distance.

— **Bandwidth Limitations.** One of the major constraints is on wireless communication capabilities, where wireless bandwidth is very limited [Srinivasan et al. 2008]. This constraint makes the transmission of large blocks of data over a wireless channel impossible. Theoretical bandwidths in industrial standards, like IEEE 802.11 and Zigbee, can be up to 54 Mb/s and 250 kb/s, respectively; nonetheless the achievable performance is much worse in practical situations, mainly due to the radio interference caused by simultaneous communications. Additionally, as requirements described in TABLES I and III, sensors deployed for SHM applications produce so much data and can push their radios to transmit the huge amount of data. The sensors using their constrained radios cannot even send their data in a hop in real-time. Thus, a potential research open issue (OI2) is to develop an SHM application-specific real-time data transmission scheme considering bandwidth limitations. In fact, a major task in the CPS design is to keep the network traffic carrying capacity at a reasonable level, even in the presence of dense sensor deployments on the structure.

— **Unreliable Channels.** Sensor nodes in WSNs communicate over wireless channels, which can be accessed by anyone within the cover range. Communications over wireless channels are, in general, not reliable compared with those over wired channels. They are vulnerable to numerous abnormalities, such as channel error and congestion, which can cause the packets to be interfered with or lost. Moreover, the quality of communications is strongly impacted by factors in the structural environments that can be time-varying.

— **Latency.** Latency is a result of the nature of WSN communication, such as multi-hop routing, network congestion, and node processing capability. This latency makes it difficult to achieve synchronization among sensor nodes, and further impacts timely structural event detection and monitoring.

4.2.3. Fault Tolerance. Traditional wired-network-based SHM systems in the CSMEA engineering communities do not usually focus on these requirements. They still prefer the use of wired networks for SHM that are not usually prone to fault/failure, even though in many cases, there is no need to tackle a fault. However, there are also hurdles on the fault tolerance capability of wireless sensor nodes. In addition to the wireless communication vulnerability to faults (as described earlier), various faults or failures in WSNs may occur for numerous reasons such as software/hardware faults, node fault removal, or energy depletion. Under any of the fault occurrences in a practical SHM, we found an undiscovered yet interesting fact: both faulty and non-faulty sensors can generate abnormal signals or decisions, as described in our previous work [Bhuiyan et al. 2014; Liu et al. 2011a; Liu et al. 2015b]. This identifies that, besides other fault tolerance supports, the application-specific fault tolerance in an envisioned CPS should be taken into account (see Observation 2 earlier of this section).

5. DESIGN REQUIREMENTS OF THE CPS: REFOCUSING ON APPLICATION-SPECIFIC DEMANDS

In this section, we discuss important design requirements of the CPS refocusing on the SHM application demands that we found to be useful for a CPS. Most of these require-

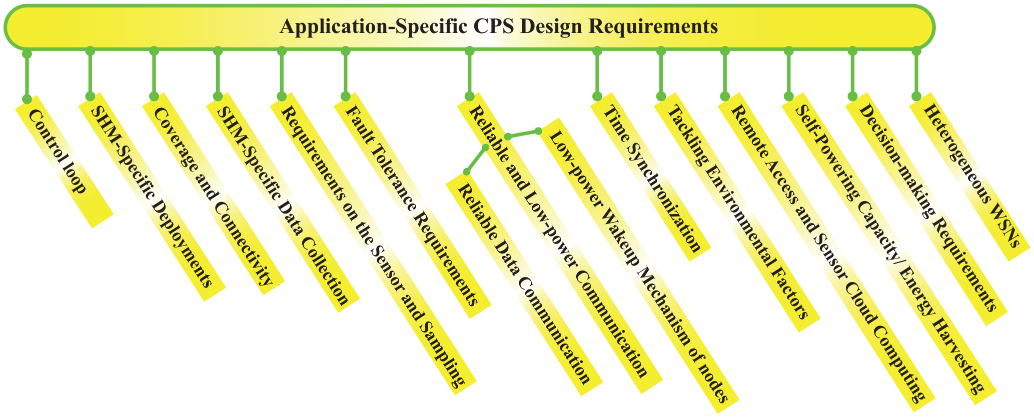

Fig. 3. SHM Application-Specific CPS Design Requirements.

ments are relevant to networking perspectives. We provide Fig. 3, which illustrates the list of networking issues.

Control in the CPS. The last two decades have been featured by a revolution in SHM applications with wired sensors, wireless sensors, and actuators technologies both reducing in size, power demands, and unit costs. However, the structural dynamic response collection or sensing and data transmissions over the network need to face many challenges, including high data loss or low communication reliability, high energy cost, and low real-time performance. The term “control” can be used to mitigate these challenges to a great extent. A physical system related control, called structural control, can be used to limit the response of structures, for example during external disturbances such as strong winds or large seismic events. There can be another control, called wireless control, in terms of cyber aspects in the CPS for high level communication performance in the networks. As a result, there is a great demand for wireless structural control (WSC) in the CPS, realistic control loop, and simulation tools that realistically model wireless characteristics and the structural dynamics of the WSC (more details can be found in Appendix E).

SHM-Specific Deployments. The major objectives of WSN deployment for SHM are to ensure that the monitoring quality of locations, coverage for these locations, the quality of links, and the network connectivity. CSMEA engineering communities often use specific deployment methods for SHM applications, for example, effective independence method (EFI), kinetic energy method (KEM), and genetic algorithm [Li et al. 2010; Yi and H.N.Li 2012]. These methods are centered around the questions of how to place sensor nodes over the given monitoring structure in an efficient way, while sensor localization and communication efficiency are not very strict in SHM systems. When applying these deployments for CPS, communication reliability should be addressed.

Coverage and Connectivity Requirements. There are challenges in maintaining both coverage and connectivity in a CPS. To prolong the WSN lifetime, a commonly used method is “energy-efficient coverage-preserving scheduling (EECPS)”, in which at any time, only a fraction of sensor nodes are activated to fulfill the function. To find out which nodes should be activated at a certain time is the key for the EECPS, and such problems have been studied extensively. Existing solutions are based on the assumption that each node has a fixed coverage area, and once the event/target occurs in this area, it can be detected by this sensor. However, this coverage model should be justified for SHM applications.

Requirements on the Sensor and Sampling. Selecting sampling frequency for data collection is another important issue of the CPS. Different kinds of sensors are employed in wired network-based SHM, including, but not limited to, acceleration, resistance strain, piezoelectric vibration, optical fiber strain, dip angle, acoustic emission, and stress measurement sensors [Liu et al. 2015b; Wang et al. 2012b]. Every sensor has various physical mechanisms and operates in different ways. As the mission of SHM systems is a complicated one, an envisioned CPS may be able to monitor many physical and electrical failures in different components of structure; it may need to various sensors working together. The choices of the sensor network sampling frequency, from X0Hz to X000Hz, working mode, and compatibility should be considered when using each of the sensors. Potential research work on these issues to integrate various sensors to state-of-art sensor platforms can be an interesting topic (OI9).

SHM Application-specific Fault Tolerance Requirements. To mitigate the constraint on fault tolerance capability, some important concerns that will be seen in a CPS must be addressed. Due to the communication faults, packets may be lost easily in structural environments. On one hand, we have found that, the loss of such a packet may make the total structural monitoring operation by a WSN meaningless, resulting in resource wasting. On the other hand, there are some sensor faults, which are common but difficult to detect:

- Sensor debonding faults in SHM.
- Faulty signals caused by precision degradation and breakage, especially in vibration capturing in SHM
- Faults in offset, bias, or gain factors
- Noise faults

Most of the data faults fall in these fault models. Since these types of faults cannot be easily identified, they directly interrupt the SHM system from detecting damage.

Reliable and Low-power Communication Requirements It is well-known that a deployed WSN performs well in a controlled situation but poorly in practice, even at low data rates. In different structural environments, links can be highly dynamic and can be bursty [Wang et al. 2012a; Matteo et al. 2011]. Thus, during the data routing, the reliability requirement should be guaranteed. On the other hand, in the case of SHM application, if a data packet transmitted by a node placed at an optimal location drops on the way, important data (containing aggregated mode shape or a simplified decision on an extremity of an event status) may be lost. In the situation of sending an "alert," an SHM system poses additional reliability requirements. Such problems exist in generic WSN applications, which often consider a flat sensing field with moderate dimensions [Zhang et al. 2012]. However, the deployments reach an extreme via the pathological extension along the horizontal or vertical dimension in a large structure monitoring. Thus, WSN placement methodology should be performed with the intention that a subset of possible poor/vulnerable location points can be found and the methodology can place sensors near to those locations. Here, the location points are the locations at which the network may be poorly connected, or not connected at all.

Time Synchronization. Each wireless sensor in WSNs has its own clock. Initially, it is not synchronized with other sensor nodes. Time synchronization (TS) is a vital aspect for SHM systems, as it is accountable for the communication of the sensors to the global BS's database. In other words, there are various requirements on synchronous and real-time data collection of the vibration data, which are distributed over different parts of a deployment. Because of the delay of radio transmission or inherent internal sensor clock errors, the collected data from different wireless sensors in WSNs may initially be unsynchronized. The TS error in a WSN can cause inaccuracy in SHM. According to existing wired network deployment from CSMEA engineering communities, it is particularly essential for the vibration mode analysis, or mode shape of a structure, structural stability analysis, and structural lifetime measurements, which contain a large number of sensors and are distributed over different locations of structures. The signals must be sampled synchronously by the nodes; otherwise, there will be incorrect information due to samples grouped together coming at different times of the vibration phase, resulting in an incorrect mode shape.

Remote Access and Sensor Cloud Computing. Internet and cellular networks do help to connect WSNs in distant regions and utilize their sensing data. Sensor nodes might require sending their readings to the decision making system via the Internet. Internet access availability may be an issue. The reason is that the WSN has thus far only been considered as a standalone system. Therefore, sensors do not require access to the Internet. Moreover, the traditional Internet uses the IPv4 technique, which is unsuitable for WSNs due to the limited address space of IPv4. Currently, there are a few research efforts [Hui and Culler 2010], which have been using IPv6 technology on WSNs to address the limited address problem. As a CPS spans from WSNs to the Internet, there are many inter-networking issues that have to be solved.

Along with other requirements, further discussion of the requirements in an application-specific manner can be found in Appendix D that can greatly help potential researchers/engineers on the improvement on the existing systems.

6. CPS DESIGN GUIDELINES

Everyday, plenty of research efforts are published handling various computation and communication research challenges. We have indicate a series of open issues (OI for short) during the discussion and more open issues can be found in Appendix F. After reviewing a surge of schemes and discussing the open issues, we propose four design guidelines for the future CPS.

6.1. Design Guideline 1: Equation-based CPS Architecture

Modeling a CPS poses some challenges to the perspective on the requirements of both CSMEA engineering communities and CSE communities; this is a perspective that is sensitive to the interplay between the cyber and physical aspects of the systems. We consider shifting from separately analyzing the network performance of WSNs such as information, communication, and intelligence, and the structural event monitoring application performance such as the situation about the event appeared in the practical field, event occurrence, application-specific event monitoring algorithms. A CPS might be partly similar to the traditional embedded system that integrates the physical processes with abstract computations. However, dissimilar to the traditional embedded systems, the CPS is a network of sensors with physical inputs and outputs.

Bearing the requirements in mind, we present a CPS model, which efficiently maps the structural event identification and the region (or substructure) of the event occurrence onto a distributed WSN. Fig. 4 shows the CPS model, which mainly consists of four parts. A major feature of the CPS design is the tight combination and coordination of the computational resources and the physical elements.

- The underlying physical structural system consists of the physical elements (see Definition 3.2), which are governed by laws in physics as specified by nature, forced excitation, and the event occurrence.
- There are many computing platforms (wireless sensors), which are capable of sensing, computing, transmitting, as well as controlling the structural system. The sensors are connected by a network (via wireless links). The sensors and the communication network form the "cyber" part of the CPS, which has to be designed carefully, such that the integrated SHM achieves certain specified functionalities.
- There are equations used in capturing structural dynamics, which is given to the sensors which use the equation to collect structural element-state information.

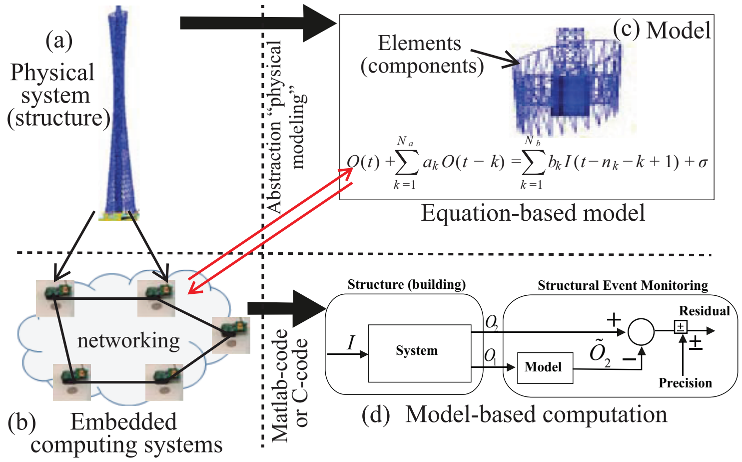

Fig. 4. Modeling a CPS for SHM.

— The sensors are given a computation model to make decisions regarding an event on the structure.

An individual sensor can be given this equation-based model. Using the equation, the sensor can get the status information of all physical elements within its vicinity. Using the computation model, the sensor can decide whether there is any structural event. This information can be shared within a group of sensors, in a distributed manner. Thus, a large amount of data does not need to be shared and transmitted to the BS. If a change appears in the elements, these sensors are able to detect it when compared with a threshold, a reference dataset, or its neighboring sensors. This implies that, if there is a change, the WSN needs extra communication and computation. Otherwise, the communication, computation, and data collection can be controlled.

In another example, the CPS model depicted in Fig. 4 is comprised of a physical layer and a cyber layer. The physical layer is comprised of sensors and actuators that are responsible for data collection and for monitoring the physical elements of structures, respectively. Various types of signals collected from the structures by sensors using their attached sensing units are also processed in this layer, and are sent to the cyber layer as the CPS inputs of the real-time decision making system. In the cyber layer, upon receipt of the inputs, the decision making system performs the abstract computations to examine the collected signals, and then relays its decision to the actuators in the physical layer by a sequence of control processes.

6.2. Design Guideline 2: Proper Networking Model for the CPS

The second design guideline is to verify an appropriate networking model before the CPS design and analysis. Networking models include the sensing model, the interference model, the node distribution model, and the topology model. In the previous WSN-based schemes, many simple networking models are assumed, such as the unit-disc model, the exclusive interference model, and the uniform or random node distribution model. These are widely used to simplify the system design and the theoretical analysis. There are plenty of deployment schemes proposed by computer science researchers using these models [Bhuiyan et al. 2015a; Li et al. 2010; Yi and H.N.Li 2012]. However, the achieved monitoring performances from real systems are usually complicated and are far beyond what those simple networking models describe. Simple models fail to accurately capture the essence of real behaviors of the network.

It has previously been discussed that WSN deployment for monitoring structural events (e.g., damage, cracks) is not as straightforward as in other applications. Detection of structural damage in SHM is performed through vibration and strain characteristics. With the generic WSN deployment methods, effective SHM may not be possible. This is because the spatial information to describe the dynamic behavior of a structure or sensitivity of an event (damage) is not sufficient at many locations, where monitoring damage is due largely to structural location sensitivity. For example, existing sensor placement methods that use grids or intersection points may not be suitable for SHM. The intersection points of cells in a grid cannot be considered as the candidate sensor locations regarding structural properties. As a consequence, conclusions made from those models may provide inaccurate or even misleading results in practice.

On the one hand, it is well-known that a deployed network performs well in a controlled situation but poorly in practice, even at low data rates [Bhuiyan et al. 2014]. In many monitoring environments, especially in different structural environments, links can be highly dynamic and can be bursty. Taking these facts into account, we discussed that the sensor placement in our scheme is subject to structural constraints. This constraint includes the physical structural model (such as bearing load zone, wall obstacles, pillars, and piers). Wireless communication is not suitable at some locations (such as there is a wall or pillar between two sensor nodes, or high interference). The communication link reliability may also vary from one location to another, one substructure to another, or one structural environment to another. Thus, during the data routing, the reliability requirement should be guaranteed. On the other hand, in the case of SHM application, if a data packet transmitted by a node placed at an optimal location drops on the way, an important data (containing aggregated mode shape or a simplified decision on an extremity of a damage state) may be lost. Since the sensor placement for an SHM scheme is characterized by the high location quality indicator, so as to fulfill the CSMEA domain requirements, the placement affects not only the routing protocols employed for data collection, but also the reliable collection of the transmitted data at the BS. The situation becomes more serious if an SHM user expects to collect all the recorded vibration signals, e.g., such a volume of data generated may require compression to reduce the amount of data transmitted [Ceriotti et al. 2009].

As mentioned in Section III, there has been some research works following the guideline, such as [Srinivasan et al. 2008], where a more realistic sensing model and communication model are used, and significant system performance improvement has been achieved. In line with OI2 and OI7, a proper networking model considering the above concerns can be developed, as to have better SHM system performance. We think that presenting a realistic and proper networking model brings additional challenges for the theoretical analysis and protocol design; however, it will be able to ensure the research results are more applicable to real situations. The second design guideline can directly benefit SHM application. Due to the sophisticated physical features, aforementioned simple networking models fail to obtain the desired performance in those applications.

In order to meet SHM-specific deployment requirements and computer science communication requirements, a subset of redundant sensor nodes may be given with an intention to find a subset of possible poor/vulnerable points (the locations at which the network may be poorly connected, or not connected at all) and place sensors near those locations. Then, the network performance can be further improved.

6.3. Design Guideline 3: Technical Sensor Data Cloud

As described earlier, structural data is considered big data when collected at a high rate, where the data is generated with high volume and resolution. A sensor can nei-

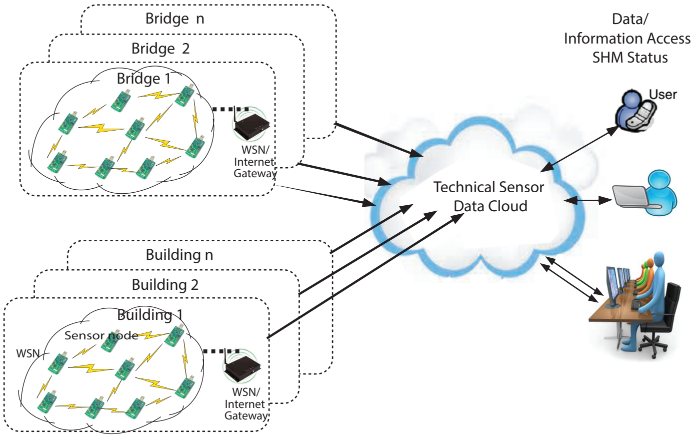

Fig. 5. Integration of sensor data sensed from multiple structral systems using technical Data Cloud.

ther store/process all raw data locally, nor transfer the raw data to the BS in real-time. This is because it is difficult to process using tiny on-hand database management tools or traditional data processing applications, due to energy and communication constraints. Also, monitoring various events such as structural event (or health) monitoring from a remote center based on the big data is difficult. Technology for cloud data storage services has evolved rapidly in the last several years, providing inexpensive, robust, and secure data storage and processing. It can be interesting if an error-less and secure monitoring of big data can be uploaded from the sensor to the cloud and can be accessed from a remote center.

Fig. 5 shows the basic concept of technical data cloud (TDC) as a cloud-based service with an aim to provide an off-the shelf, secure, and dependable solution for aggregating and storing error-less big data and to provide event monitoring from a remote center. It is normal that a restricted region or a modern city has a set of high-rise buildings $(1, 2 \ldots n)$ and a set of long-span bridges $(1, 2 \ldots n)$ among other large-scale structures. Every building or bridge can be covered and monitored by a WSN. The WSN should be connected to the cloud and should upload all data to the cloud. Similarly, all of the buildings and bridges of the region/city can be monitored from a remote center using the sensor big data on the cloud. In this way, some of the WSN constraints, such as communication, can be greatly improved and the SHM can be carried out in real-time.

6.4. Design Guideline 4: Event-Sensitive Data Transmission

As described previously, many existing solutions are a kind of suboptimal solutions that primarily target either computing system aspects or physical structural system aspects. However, the "network performance" of these solutions can be improved by considering the real situation in the physical process of the structural event. Before arguing to support this concern, we need to know the *substructure*, which is a part/section/span/unit of a large structure. A WSN can be deployed and then organized in groups in such a way that each group of sensors (which can be called a subnetwork) should cover a substructure.

In order to get an optimal solution, we first can think of two points:

- The situation of the event occurrence.
- The specific substructure (if there is an event).

Then, we enable the network to reduce its total energy cost by minimizing the amount of communication and computation tasks in the network, based on the event occurrence in the substructure. Typically, the common situation in SHM is that a structural “event” (say damage) is a relatively rare event in the structure. For example, it can be argued that, in common occasions, there is “no event” that occurs in a structure.

It can also be argued that, in an unusual situation, if there is an “event” of damage in the structure, the event may first occur in a substructure of the structure rather than occurring over the whole structure at a time. In such a situation, only the subnetwork covering the substructure will have more interactions (communication, computation.) than other subnetworks of the WSN. Moreover, data loss often occurs during the data transmission between the wireless nodes and the BS. In WSN applications for SHM, the errors caused by data loss inevitably affects the data analysis of the structure and subsequent decision-making at the BS. However, there are various schemes suggested using methods like reliable data transmission, compressive sampling, and transmission round by round, to recover the lost data. Unfortunately, they still require high energy consumption and latency in data transmission, and timely (online) monitoring is not possible.

Regarding this concern in a resource-constrained WSN, there is no further use for frequent data collection and data transmission, i.e., the large volume of collected data from the nodes located in all of the substructures of the structure really does not need to be transmitted to all neighbors or upstream sensors over WSNs. This can be achieved by the substructure and subnetwork-oriented event monitoring and by making a localized decision in such complex event. A precise decision, “0” for “no damage event” situation is necessary. This is similar to the traditional target/event detection of the sensors in the WSN (like “0/1” decision for a target’s absence/presence). This may only need to transmit local decisions to their neighbors or the upstream sensors in the subnetwork, considering only the presence of the event.

In SHM applications, the events occur rarely, but once they occur the information should be sent to the BS quickly for necessary actions. It is important that a scheme be required to promptly wake up a deployed WSN. Setting one sensor node to monitor the possible event continuously and to broadcast wake-up alerts to all other nodes can be a technique. Capturing the rare events in a fast and energy-efficient manner is another key issue in WSNs.

7. CONCLUSION

In this paper, we have conducted a comprehensive investigation on WSN-based SHM applications with an emphasis on networking perspectives and provide insights into a cyber-physical system (CPS). We have provided the SHM philosophy, comparative studies, and a taxonomy of SHM techniques in order to investigate the benefits and hurdles in WSN-based SHM over wired network-based SHM and in designing the CPS. This has been a hugely important topic, as we observe recent attention, improvements, and protocols being made by the researchers/engineers across the multiple engineering disciplines, as well as the computer science and engineering discipline. We have also discussed the possible design hurdles and requirements for an envisioned CPS. In the end, we have pointed out plenty of future research directions and useful design guidelines for the CPS design. We believe that this paper will help CSMEA researchers, non-experts/experts, and respective research communities to conduct further research and to ensure economic benefits and public safety in functioning civil structures.

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