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Structural Cyber-Physical Systems: A Confluence of Structural Health Monitoring and Control Technologies

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Structural Cyber-Physical Systems: A Confluence of Structural Health Monitoring and Control Technologies[1]

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HIGHLIGHTS

- Presentation of a new paradigm for structural cyber-physical systems (SCPS).
- Review of attempted cyber-physical systems for civil engineering applications.
- Methods in structural health monitoring relevant to cyber-physical systems.
- Structural control devices and algorithms that complement cyber-physical systems.
- Benefits of wireless smart sensors and their potential to overcome SCPS challenges.

ABSTRACT

Many bridges in the nation's transportation infrastructure network have been found to be structurally deficient. In face of a natural or man-made disaster, this poses a serious threat to the execution of emergency respondent logistics, as the failure of such structures could disconnect communities from the necessary provisions and services that must remain accessible after a disaster. To predict such an eventuality, dependable information on structural status for decision-making can be obtained from structural health monitoring (SHM) systems. However, the avoidance of such a situation is preferred. Structural control systems offer an option to improve structural response during extreme loading events. To this date, some bridges have been instrumented with SHM and control systems that operate simultaneously, but independently without using the information that each provides to enhance operational efficiency in the other. If the information on structural status provided by an SHM system could be used to inform a control system, the likelihood of structural failure during a disaster could be significantly reduced. This paper reviews the necessary state-of-the-art technologies in SHM and control for the initial development of a structural cyber-physical system (SCPS). The limitations of these technologies and methods are also presented. This paper also introduces the concept of an SCPS, where monitoring data can be used as additional evaluation criteria for control strategies. Cyber-physical systems are highly complex systems with multiple sensing networks and

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[1] SHM – structural health monitoring
SCPS – structural cyber-physical system
CPS – cyber-physical system
WSN – wireless sensor network
TMD – tuned mass damper
TLCD – tuned liquid column damper
AMD – active mass damper
ER – electrorheological
MR – magnetorheological
RMS – root-mean-square
EDM – evaluation and decision-making
FE – finite element
WASHMS – Wind and Structural Health Monitoring System
WSSN – wireless smart sensor network
ISHMP – Illinois Structural Health Monitoring Project
SOA – service-oriented architecture
SDDLV – stochastic dynamic damage locating vector
MSI – maximum stress index
WSS – wireless smart sensor
WSC – wireless structural control
WCPS – wireless cyber-physical simulator
GNTVT – Guangzhou New TV Tower

computing systems that intercommunicate for intelligent controlling actions. Future research scopes and foreseeable challenges for the implementation of an SCPS are discussed.

KEY WORDS: structural control, structural health monitoring, cyber-physical systems, wireless smart sensors, adaptive control, statistical pattern recognition

1. INTRODUCTION

The improved performance and safety of civil structures is the primary goal of civil engineers. Transportation infrastructure is one of the most critical engineered products that serve our society and allow it to operate and grow. Yet, every day in the United States 260 million trips are made over structurally deficient bridges and one out of nine bridges is classified as structurally deficient [1]. A structurally deficient bridge has a deck, superstructure or substructure in poor condition or its load-carrying capacity is significantly below minimum standards [2]. Greater concern arises when it is considered that the cyclic nature of bridge loading accelerates the damage of said structures dramatically. Damage begins at the material level, grows and later spreads to the component level [3]. The state of these structurally deficient bridges already concerns the component level, only a step away from generalized system damage.

The state of the current transportation infrastructure has called for the development of several monitoring and mitigating strategies. The most recent report on bridge inspection practices by the Transportation Research Board states that the most common method of non-destructive testing is still visual inspection [4]. The objective of inspections is to identify the onset of damage in a timely manner to avoid structural failure. Failure is reached when damage grows, since damage itself does not imply a total loss of system functionality, but rather that the system is not operating in its optimal condition. However, visual inspections have several drawbacks. The costs and traffic interruptions incurred during visual inspection, such as the usage of platform units to identify corrosion progression in bridge girders, restrict the frequency with which these inspections can be carried out. Usually, only well-experienced trained professionals are capable of identifying damage effectively. Moreover, damage is oftentimes hidden from view so that vulnerabilities could potentially not be detected on time. Non-destructive testing and structural health monitoring (SHM) methods have been developed for objective and automated detection of damage and structural assessment.

In response to needs of performance enhancement, structural control systems have also been introduced in several types of civil structures subjected to seismic, wind and cyclic loads. High-rise buildings are particularly susceptible to wind loading and their displacement and acceleration can pose a problem to human habitation. Accelerations in medium-rise buildings and bridges due to seismic loading can cause even greater problems in terms of structural component failure. Many different structural control systems have been developed to mitigate these problems with outstanding results. Control systems can also be used to adjust loading on structural components if the required values are not met during the construction phase or after an extreme loading event.

The objective of this paper is to highlight key contributions in the fields of SHM and structural control that form the major building blocks of structural cyber-physical systems (SCPSs), and to conceptually introduce the SCPS as a logical solution to further improve structural control in civil structures. A cyber-physical system (CPS) is a highly complex network of embedded systems, sensor networks and actuation systems that are controlled by a computing and communication core [5]. CPSs have been introduced in many fields including medical devices, aerospace systems, transportation vehicles and factory automation. Several technological advances have contributed to the development of CPSs, including low-cost small smart sensors, computing capacity of low-cost microcontrollers, wireless communication, abundant Internet bandwidth, and improvements in energy harvesting methods.

Research in wireless sensor networks (WSNs) is the main contributor to CPS development [6]. WSNs are mainly centered on issues concerning sensing, retrieval, communication, and coverage, while CPSs focus on the development of cross-domain intelligence for decision and actuation from multiple sensor networks. Some of the principal challenges in WSNs are also present in CPSs, including data mining, database management, and communication among multi-domain data sources. Two major features exclusively present in CPSs include the interconnection among multiple networks and management of cross-network communication flows. Since different types of sensors are oftentimes used in CPS, data exchanges need to occur over these heterogeneous networks, posing a new challenge. The amount of collected data can also be very large, relying on data mining technologies to retrieve useful knowledge using spatial and temporal correlations.

A CPS must also have the ability of overcoming uncertainties inherently introduced by the physical system and its environment. System robustness and tolerance to component failure, both in physical and virtual domains, must be present. Synchronization across time and space between the collection, computation, communication and actuation components must be accomplished. Finally, the merging of time-based systems with event-based systems for feedback control is essential. This allows the system to become automatic so that real-time control and long-term monitoring can enhance event-based damage identification systems by triggering actuation using threshold exceedance criteria.

This paper is structured in a way to present the current state-of-the-art research in sensor and structural control technologies and how it makes way to the development of an SCPS. First, contributions offered by structural control research are presented. Second, developments in smart sensor technology and health monitoring methods are examined. Third, current developments in CPSs for civil structures applications are reviewed. Finally, the concept of SCPS is introduced along with the research areas that must be expanded in order to attain practicability, followed by conclusions on the research review and the newly introduced concept.

2. CONTRIBUTIONS OFFERED BY STRUCTURAL CONTROL RESEARCH

The principal objective of structural control is to reduce structural response by determining and applying the required modifications in the structure's dissipative capacity or by sending the appropriate signal to actuators that modify said response [7,8]. It can also be used to adjust loading on structural components if these surpass the allowed values during the construction phase. Similarly, since component capacity is typically reduced after an extreme event, structural control systems can reroute a loading pattern to reduce loading in compromised components. In order to attain these response modifications, several control systems have been engineered: passive, active, and semi-active control systems.

Passive systems are materials or devices that increase structural damping, stiffness or strength. Passive control systems are energy dissipating systems that are typically designed for a specific structure to respond to a specific type of loading. Some examples of passive control devices include tuned mass dampers (TMDs) [9–11], tuned liquid column dampers (TLCDs) [12,13], tuned inerter dampers [14–16], and tuned viscous mass dampers [17,18]. Tuned dampers consisting of a single damping unit can only be tuned to a single frequency, so that, while a single modal response may be reduced, response due to other modes may be increased. Compared to TMDs, the frequency tuning and installation of a TLCD is much easier, fabrication is much cheaper and almost no maintenance is required [7]. A TLCD contains a body of liquid as a secondary mass that is tuned as a dynamic vibration absorber. The TLCD is highly nonlinear because of the liquid sloshing or the presence of orifices. Base isolation systems have also been developed to span passive, active and semi-active device usage [19]. One principal advantage of passive systems is that bounded-input, bounded-output structural stability is maintained, so that their inclusion in a structure does not result in an increased detrimental response regardless of the input. Passive control systems also do not require external power in order to operate, so they continue to provide damping capabilities during power outages.

Active control systems reduce response by means of controllable forcing devices that act on the structure based on data collected by sensors and calculations executed based on control laws and real-time information processing. Some active control systems include active TMDs, distributed actuators, active tendon and cable systems, active coupled building systems, and active strut control [20–22]. An active device commonly used is the active mass damper (AMD). The AMD provides a damping control force to add mechanical energy into a structure, as well as a restoring force while not occupying as much space as mechanical springs [7]. Active control devices have the great of advantage of providing a broader range of response modifications than passive devices and are also adaptable to varying loading conditions in real-time due to the sensor networks they depend on. They also tend to be smaller in size than passive devices [23]. However, their dependability on external power has made researchers turn their attention to the development of an alternate structural control system.

Semi-active damper and hybrid control systems combine the most advantageous properties of active and passive control systems. They do not require a lot of power to operate and many can do so using battery power [7,21,24,25]. Since semi-active damper systems are energy dissipating systems, they cannot destabilize the structural system in the bounded-input, bounded-output sense as an active control system can. Hybrid mass dampers, the most common control devices in full-scale civil structures, work as TMDs with the ability to actively change their tuned frequency using much less energy than an AMD [26]. Passive components in hybrid mass dampers can also attenuate a phenomenon known as interstory response amplification, which results from active control forces that are too large for the structure to carry [27]. Semi-active TLCDs have been found to provide an additional 15-25% response reduction over a passive system [28,29]. Smart semi-active TMDs provide similar optimized results for changing dynamic characteristics using minimal energy [30–32].

Semi-active controllable fluid dampers have been developed using electrorheological (ER) or magnetorheological (MR) fluids. ER and MR fluids can change from a Newtonian fluid to a linear viscous fluid and to a semi-solid with controllable yield strength in milliseconds when exposed to an electrical or magnetic field, respectively. MR fluid dampers present several significant advantages over ER fluid dampers. ER fluid dampers have available yield stress values ranging only from 3.0 to 3.5 kPa, while MR fluid dampers attain yield stresses an order of magnitude larger [7,33–35]. ER fluids cannot tolerate common impurities, such as water, while MR fluids exhibit no change in yield stress when exposed to the same impurities as well as impurities commonly encountered during fabrication. ER fluid dampers require high voltage and power supplies to operate, while MR fluid dampers require much less power. MR fluid dampers can generate controlling forces comparable to active control systems. When a power supply is not available, an MR fluid damper can provide damping as a passive viscous fluid device. Moreover, MR fluid dampers have been shown to be scalable for civil engineering applications [36,37].

In a collaborative research project between the Hong Kong Polytechnic University, the Central South University of China, and the University of Illinois at Urbana-Champaign, 312 MR fluid dampers have been installed for rain and wind vibration control in the cable-stayed bridge at Dongting Lake. This is the world's first installation of MR fluid damping technology on a bridge structure

[38]. The choice of using MR fluid dampers instead of passive viscous dampers for rain and wind vibration mitigation of the cable stays is founded on two principal reasons. First, due to the varying lengths of cables, passive dampers of the same size can only achieve optimal damping of a limited number of cables while not providing sufficient damping to others. MR dampers can offer a wide range of damping capabilities independently of size since their damping capacities rely on the input voltage. Second, passive viscous dampers can only optimally damp a single mode of vibration. Although rain and wind induced vibrations are mostly dominated by lower frequencies, it is unclear how to predict the mode at which a certain cable will vibrate in order to determine a priori which mode must be controlled. Because of the adaptability MR dampers offer, these devices can optimally control whichever mode of vibration results as dominant after installation by changing the input voltage.

The development of versatile and powerful controlling devices such as the AMD and the MR fluid damper would not represent such a significant contribution were it not for the establishment of effective control laws. Control design evaluation test beds have been established to validate control algorithms under development. As a result, these benchmark problems also bring further information regarding the advantages and limitations of these control devices. A study presented by Jung *et al.* [39] evaluates a clipped-optimal control algorithm for MR fluid dampers using numerically simulated responses from seismic excitation on the ASCE first generation benchmark problem for a cable-stayed bridge in Cape Girardeau, Missouri. Three dynamic models are used and compared in the simulation: the Bingham model, the Bouc-Wen model and the modified Bouc-Wen model. The parameters needed for these models are optimized using data from experiments performed on a full-scale MR fluid damper. It is found that the control strategy applied to these MR fluid dampers reduces peak and normed responses significantly and similarly to the active control system that was evaluated for comparison. Moreover, it is found that an MR fluid damper can be dependably and manageably modeled using the more computationally tractable Bouc-Wen and modified Bouc-Wen models. In another study, the effectiveness of an MR damper to reduce peak and root-mean-square (RMS) responses on a series of experiments performed on a three-story test structure subjected to a one-dimensional ground excitation using a clipped-optimal control strategy was also evaluated [40]. In this case, the semi-active system was also found to be efficient in reducing peak and RMS responses while generating smaller control forces than the passive-on system used for comparison. A review of models of vibration control systems with hysteresis focused on the Bouc-Wen model can be found in Chang *et al.* [41]. The incorporation of non-symmetrical hysteresis into the Bouc-Wen model using a genetic algorithm can be found in Kwok *et al.* [42]. Bahar *et al.* [43] presents a new inverse model of MR dampers using a normalized Bouc-Wen model. Additional information on parametric modeling of the non-linear behavior of MR dampers can be found in Wang and Liao [44].

In order to standardize performance evaluation procedures for structural control algorithms, two other benchmark problems for two different control systems at the National Center for Earthquake Engineering Research have been established. These benchmark problems can be used to evaluate the effectiveness and applicability of other structural control algorithms and to assess control design issues, such as model order reduction, control-structure interaction, sensor noise, and computational delays. The first established evaluation model is based on an experimental structure of a three-story, single-bay steel building with an active mass damper [45]. This AMD consists of a single hydraulic actuator with steel masses attached to the end of the piston rod. Natural frequencies, damping ratios, dimensions and masses per floor of the model are known and the ratios of model quantities (force, mass, time, displacement, and acceleration) to those corresponding to the prototype structure are also known. The second benchmark problem consists of a model of a three-story, tendon-controlled laboratory model [46]. The structure has a hydraulic control actuator connected by a stiff steel frame to four diagonal pre-tensioned tendons at the first story. Since hydraulic actuators are open-loop unstable, a feedback control system is used to improve performance. The control system uses displacement measurements as the primary feedback signal.

The controller to be assessed for each of these benchmark problems is evaluated based on 10 criteria given in terms of RMS and peak response quantities. The RMS evaluation criteria include the controller's ability to minimize the maximum RMS interstory drift and absolute acceleration, the required physical size of the controlling device (based on the RMS actuator displacement), the power required to operate it (based on the RMS actuator velocity), and the required magnitude of the forces to be generated (based on the RMS absolute acceleration). For the AMD benchmark problem, the peak response criteria additionally include the controller's ability to minimize peak interstory drift, peak accelerations, displacement and velocity of the AMD relative to the third floor, and absolute acceleration of the AMD [45]. For the active tendon system problem, the peak response criteria additionally include the controller's ability to minimize the nondimensionalized peak interstory drifts due to the earthquake records of El Centro 1940 and Hachinohe 1968, and the ability to minimize the required control resources such that they do not exceed the control constraints of voltage, stroke, and maximum control force [46]. Benchmark problems can be further expanded to incorporate additional evaluation criteria that include efficiency of structural monitoring parameter extraction and the parameter's contribution to improve performance of the control algorithm.

A benchmark problem for seismically excited base-isolated buildings has been used extensively to evaluate the performance of different control algorithms [47–50]. A decentralized hierarchical strategy for hybrid (MR damper and passive non-linear) base isolation was evaluated using this benchmark problem [43]. Decentralization of control systems has shown to be very promising and convenient for large-scale civil structures, as they reduce feedback latency and lower demand on communication range [51,52]. Subasri *et al.* [53] combined active control with base isolation using a discrete direct adaptive extreme learning machine controller evaluated on this same benchmark problem. Shook *et al.* [54] uses the same benchmark problem to evaluate the performance of an isolation system composed of elastomeric bearings, friction-pendulum bearings, shape memory alloy wires, and MR dampers using neuro-fuzzy logic control algorithms to model the shape memory alloy and MR components. Pozo *et al.* [55] evaluate a static velocity-based feedback controller and a dynamic acceleration feedback controller design for robust active control of base-isolated structures. Taflanidis *et al.* [56] use the base-isolation benchmark problem to validate a control method whose objective is to maximize structural reliability with a stochastic simulation-based nonlinear controller design. Another evaluation of a hybrid isolation system using clipped-optimal strategy based on fuzzy control was performed [57]. Yang *et al.* [58] use a 5-story model with an AMD on the roof to evaluate an algorithm of modified predictive control with direct output feedback using an offline method to find feedback gain. Johnson *et al.* [59] evaluated reduced-order, multiobjective optimal controllers using l_1 and H_∞ constraints on a structural control building model benchmark developed at the University of Notre Dame. Control of response to wind excitation of a tall, slender building is also presented in a benchmark problem with an AMD system using Lyapunov functions [60].

The efficiency of a controller oftentimes depends on the available information on varying parameters. A control problem can be classified as closed-loop (feedback control) or open-loop (feedforward control). Feedback control uses the continually monitored response of the structure as input to determine the control signal to be sent back. On the other hand, the output control signal in feedforward control depends on the measured excitation. When both the system response and excitation are used to determine the control signal, the problem becomes a feedback-feedforward control system. Adaptive controllers are feedback or feedback-feedforward control mechanisms that include additional layers of information to improve performance, including a reference model and an adjustment mechanism. Figure 1 diagrammatically illustrates a feedback-feedforward adaptive control strategy. The reference model is developed based on previous knowledge of the structure and represents the targeted state of the structure. The adjustment mechanism receives information from the reference model, the structure's current state and unknown parameters, and the control signal sent to the structure. The controller calculates the control force based on the current system state and the adjustable parameters estimated by the adaptive mechanism. Many adaptive control strategies have been examined and developed for civil structures subjected to large loading.

The key aspect of the adaptive control system is the adjustment mechanism. An evaluation on the performance of an adaptive control strategy using an adaptive mechanism based on the quadratic Lyapunov function error-estimating matrix has been performed [61]. The study proposes a systematic procedure to accelerate the convergence rate of the adjustable parameters by simultaneously magnifying the adaptation weighing coefficients in the error-estimating matrix. The performance is verified on a single-degree-of-freedom active tendon structure subjected to earthquake excitation. In another study, a time delay control algorithm for structural response control is investigated for the first time [62]. The time delay control algorithm is a simple algorithm that exhibits particular tolerance to unknown system dynamics and disturbance. Numerical and experimental validations of the algorithm for an active mass damper (AMD) system for vibration suppression of a building structure under wind loading are performed. It is found that the strategy is effective to reduce acceleration response comparably to the LQG control algorithm for an AMD system [63]. The researchers responsible for this study successfully address potential practical issues such as determining the allowable control gain range and reducing time delay. Adaptive control algorithms have also been developed for nonlinear response models. In Ikhouane *et al.* [64], an adaptive controller is designed to obtain performance bounds and corroborate the closed-loop stability of a Bouc-Wen model. The nonlinear response is found to be uniformly bounded and the efficiency of the controller to reduce response to external excitation is verified via numerical simulations. These studies represent significant contributions in adaptive control algorithms applicable to active and semi-active control devices that overcome challenges presented by unknown system parameters.

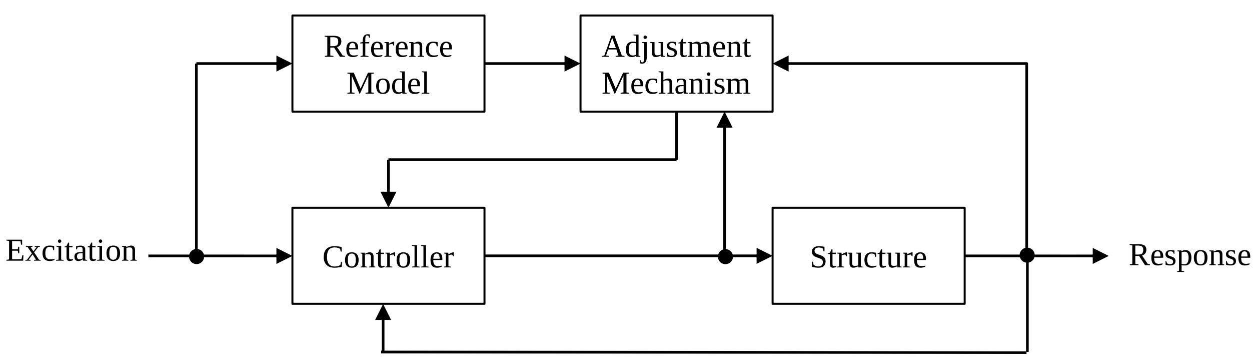

Figure 1. Feedback-feedforward adaptive control strategy.

The deployment of control systems in civil structures can quickly escalate in complexity and cost if tethered sensor networks are used. The development of wireless sensors to command actuators represents a significant contribution to address this issue. Yet, bandwidth and range limitations in wireless communication channels can only be overcome by using decentralized networks. Partially decentralized linear quadratic regulation control schemes using redundant state estimation to minimize data communication among sensors have been developed [65,66]. The strategy is validated using numerical simulations and laboratory experiments of a seismically excited six-story building with semi-active control devices. By embedding steady-state Kalman estimators, the wireless sensors are shown to be capable of collecting output and supplying actuator commands. The resulting state estimates are compared to local measured data. Feedback control forces are computed using these local estimates when the error between measured and estimated state data is small. When the error is larger than a specified threshold value, the measured values are wirelessly transmitted to the network so that the other sensors can update their own estimates. This minimizes wireless communication, consequently saving power and reducing data loss.

The recent advances in structural control presented in this article represent crucial steps towards the intelligent integration of control and health monitoring. Adaptive algorithms overcome the drawbacks imposed by the lack of structural parameter information, which is ideal in instances of partially downed networks. However, if a network is complete or partially present, improved parameter estimations can be obtained through an evaluation and decision-making (EDM) system. Depending on the promptness required for response, either rapid on-line or off-line evaluation could be performed to increase robustness in the control strategy. Decentralized wireless networks used in structural control can also incorporate SHM capabilities to enhance robustness in control algorithms. In addition, with the development of semi-active damping devices, control forces comparable to those provided by active devices can be attained while preserving power. In case of a power outage, a semi-active device becomes a passive device, which, in spite of not necessarily being optimally tuned, still improves response while guaranteeing bound-input, bound-output structural stability.

3. CONTRIBUTIONS OFFERED BY SHM AND SMART SENSING TECHNOLOGY

SHM can be carried out as a long-term strategy where information on the structure's ability to continue operating is evaluated in light of inevitable aging and damage accumulation. The process involves the observation of the structure over time using periodically spaced measurements, extraction of damage sensitive features from these measurements and a statistical analysis of these features to determine the current state of the system [67]. Rapid condition screening is oftentimes used to provide real-time and reliable information about system performance during and after an extreme event [3].

The statistical analysis of extracted damage sensitive features helps discriminate between features from the damaged and undamaged states of the structure in question [68]. Statistical models help answer questions regarding the existence, location, type, and extent of damage. They can also offer information on the structure's prognosis [69–74]. When data are available from both the undamaged and damaged states, the statistical pattern recognition algorithm falls into a general classification known as supervised learning. Unsupervised learning occurs when the algorithms are applied to data that does not contain damaged samples [75]. Unsupervised learning environments can only provide information on existence and location of damage. The main advantage of supervised learning is that damage type and extent and prognosis can be determined due the availability of correlated measured features [76–78].

Vibration-based monitoring methods allow a versatility that other NDE methods may not. The basic premise of most vibration-based damage detection methods is that damage will alter the stiffness, mass, or energy dissipation properties of a system, which in turn alter the measured dynamic response of the system. Plenty of information such as damage location, type and extent as well as local strain and cable tension force can be determined using ambient vibration [79–84]. The usage of ambient vibration as the main excitation source for vibration measurement is highly convenient since service of the civil structure needs not to be stopped. However, these methods are not very dependable in small sensor networks due their insensitivity to global damage detection. The majority of SHM research conducted over the last 30 years has attempted to identify damage in structures on a more global basis [3]. A fundamental challenge of global-based damage identification is that damage is typically a local phenomenon and may not significantly influence the lower-frequency global response of a structure that is normally measured during vibration tests. When a small number of sensors is used, global-based damage detection becomes very difficult to implement since the damage inflicted at a component level does not have enough influence in a small sensor network [85]. Moreover, when a system is then exposed to variable environmental and operational conditions such as temperature, moisture and loading that affect global vibration characteristics, the changes in dynamic response associated to these varying conditions can often mask subtler structural changes caused by damage [75,86–91].

Vibration-based damage detection methods are also affected by uncertainties in key input parameters, such as measured frequencies and mode shape data. However, when these methods are incorporated with statistical pattern recognition techniques, accuracy in structural health assessment is improved [92]. A study of the effectiveness of statistical pattern comparison and statistical model development in an unsupervised learning environment to represent the level of damage on Portage Creek Bridge in British Columbia, Canada has been performed [93]. The statistical model development approach uses an unsupervised learning technique to develop a reference model of strain variability to which subsequent data patterns are compared by means of computed residuals (R-values), while the statistical pattern comparison approach uses a data block as a reference block to which pattern from other blocks are compared.

Another example of combining vibration-based damage detection methods with unsupervised statistical pattern recognition approaches is the usage of parent and offspring finite element (FE) models calibrated with artificial neural networks to incorporate uncertainties into component and system reliability assessments. The limitations of models arise from the non-stationary nature of structural behavior induced by environmental factors. Modeling uncertainties such as boundary conditions, material properties, loads, deterioration, and damage can be included in calibrated parent and offspring models to reduce epistemic uncertainty in measurement and data post-processing [94]. A one-time initially calibrated FE model can be used to predict system reliability, but SHM data can be used to continuously calibrate a family of FE models. Artificial neural networks are used to calibrate the FE models and uncertainties in modeling, in measurement (e.g. data acquisition accuracy and sensor resolution), and in data post-processing (e.g. failure modes and assumed distributions). It has been found that by calibrating a parent model and determining offspring models that incorporate uncertainties, estimates of structural response and probability of failure become more realistic as opposed to the estimates determined using the one-time calibrated FE model [95]. This calibration method has been used to determine a distribution of load rating for a bascule bridge [94].

Time series or autoregressive models [96] have been combined with Mahalanobis distance-based outlier detection algorithms to identify changes [97,98]. Gul and Catbas [99] present a methodology where this combination is implemented and modified using random decrement functions to eliminate the stochastic effects of the input and increase separation between the reference data and the investigated data. Although statistical methods are typically useful in reducing false indications of damage [75], false negative and false positive indications in these combined methods must be reduced. In order to enhance statistical pattern recognition methods, statistical control charts and hypothesis testing modified using model spectra and residual autocorrelation together with resampling-based threshold construction methods has been proposed [100]. Ljung-Box statistic and Cosh spectral distance are the algorithms used in a study that include simulated and laboratory testing. These algorithms are found to be very conservative and more sensitive and stable than residual variance and Mahalanobis distance of coefficients.

Probabilistic or adaptive methods, such as Bayesian neural networks or extended Kalman filtering, are robust and fault tolerant and can operate with uncertain and incomplete information [101–105]. These are very attractive qualities in methods to detect damage in large civil structures, since these are often affected by loads that are not easily controlled or measured (such as traffic and wind excitation) and have small amplitude responses corrupted by noise [106,107]. Recursive Bayesian filtering is also used to identify damage and to assess structural condition and prognosis [108]. These methods, however, depend on comparing current data to previously collected data by means of adaptive parameters. More complex nodes will always offer a better data fit on the data used for learning, but over-parameterization makes poor predictions for new cases, so excessive layers must be penalized. These characteristics make these models highly complex and probabilistically dependent. Adaptive recursive least squares filtering using measured or estimated structural responses and a reasonable estimate of the input force, such as an earthquake, is used to directly identify changes in structural stiffness for the ASCE benchmark SHM problem [109]. Least mean squares algorithms are a class of adaptive filter used to mimic a desired filter by finding the filter coefficients that relate to producing the least mean squares of the error signal (difference between the desired and the actual signal) [110]. A wavelet-neural network module with a Bayesian updating scheme can be used to determine differences between measured and predicted signals [111]. The wavelet-neural network module can determine behavioral patterns of a structure [112]. This information is fed to a Bayesian updating scheme that describes the error signal between the measured signal and the signal predicted by the neural network. Ko and Ni [38] pose three reasons to prefer a neural network-based multi-stage diagnosis strategy. Neural networks can be employed for different identification purposes, so that they can fulfill monitoring objectives at different stages. They can also yield satisfactory results (identification and regional location of damage, for instance) when only modal data from a few measurement points are available. Lastly, neural network-based methods use information from forward problems at the training stage and avoid direct solution to inverse problems. The complexity of a CPS using monitoring information for actuation can be significantly reduced if such methods are used, since they are applicable to different monitoring states, provide forward problem solutions, and can effectively operate using smaller sensor networks.

As supervised learning environments collect more data to determine damage type, extent and prognosis, sensor networks must have a greater number of nodes. Several large-scale structures have been used as test beds to evaluate new sensing technologies and determine new areas for improvement. The Wind and Structural Health Monitoring System (WASHMS) was the largest monitoring system in the world at its time, with 800 sensors permanently installed on three cable-supported bridges [38]. Neural networks were chosen as the most favorable monitoring methodology after an exhaustive feasibility study of vibration-based damage detection methods. The study determines that, due to the low modal sensitivity of bridges to structural damage, methods that are highly tolerant to missing data, measurement noise, and structural modeling uncertainty can be applied to large bridges for vibration-based damage identification.

A very comprehensive monitoring system with several sensor networks integrated for evaluation and decision-making has been deployed at the Zhijiang Bridge [113]. This system includes an information acquisition system, a data management system, an EDM system, and an application service system. The information acquisition system consists of several sensor networks connected to data acquisition and transmission modules by means of an anti-interference shielding line, in turn connected to a remote industrial computer via Ethernet and LAN. This data acquisition and transmission module serves as a data preprocessing and temporary storage facility. The networks used are purposed for monitoring the bridge's working environment, including: acceleration sensors for vibration monitoring, impact force in bridge pier, earthquake response, cable tension estimation, section stress, and fatigue and crack formation monitoring; fiber grating strain sensors for anchor force monitoring at steel-concrete joint segments; optical fiber grating temperature sensors; a bridge weigh-in-motion system for vehicle load monitoring; and GPS receivers for spatial deformation monitoring. The GPS clock is used to synchronize the two acquisition stations for stress, temperature, and vibration sensors. The data management system collects, files, inquires, stores, and manages data from the health monitoring subsystem. A data processing module in the EDM system performs statistical analyses, forecasts trends based on the collected monitoring data, and fetches key indices to report on the status of the bridge. The status evaluation module performs real-time analysis, evaluates structural status, and performs damage identification.

A wireless smart sensor network (WSSN) can be capable of operating with distributed data processing and triggering capabilities for power and computational efficiency for large-scale modal analysis and damage detection. The most renowned test bed to this date for its extensive and successful deployment of a WSSN is the second Jindo Bridge in Korea. The deployment consists of Imote2 smart sensor platforms, custom-designed multi-metric sensor boards (SHM-A and SHM-W), base stations, and software provided by the Illinois Structural Health Monitoring Project (ISHMP) Services Toolsuite [84,114,115]. The WSSN on the Jindo Bridge is powered by solar panels and remains on sleep mode to extend its lifetime initiating monitoring upon excessive wind and vibration detected by SHM-W and SHM-A sensor boards, respectively. These functions are made possible by the service-oriented architecture (SOA) used in the software system, which allows the usage of the same services to build different applications so that each service needs not to be adjusted for each new desired application [114]. This feature makes way to the development of different health assessment features of a structure while not expanding on complexity. Some application services in the ISHMP Toolsuite include synchronized sensing (*SyncSensing*), correlation function estimation, the Eigensystem Realization Algorithm, Stochastic Subspace Identification, Frequency Domain Decomposition, and the Stochastic Damage Locating Vector method. *SnoozeAlarm* controls the sleep-wake cycle service that allows the gateway node to gain access to leaf nodes while remaining in deep sleep mode. *ThresholdSentry* allows the usage of triggering values to awaken the necessary sensors for collection and data processing.

Some other relevant applications that have been developed based on the SOA are *SHMSAutoBalance* for the SHM-S wireless strain sensor board [116], *DecentralizedDamageIdentification* [117], and *CableTensionEstimation* [118]. The SHM-S sensor combines a typical foil-type strain gauge with the friction-type magnet strain sensor, FGMH-1. The sensor is easily and rapidly deployed, performs well in variable temperature, and is capable of overcoming the drawbacks that other strain sensors have. It records low-level ambient strain by amplifying the strain signal up to 2507 times, has better analog-to-digital converter resolution, overcomes inherent circuit noise, and it operates automatically. *DecentralizedDamageIdentification* performs output-only modal analysis using the natural excitation technique in conjunction with the Eigensystem Realization Algorithm. This is followed by computations for damage detection using the stochastic dynamic damage locating vector method with the maximum stress index and the average stress index. These operations are performed using a decentralized network of Imote2 nodes for better power and time efficiency. *CableTensionEstimation* uses applications provided by the ISHMP Services Toolsuite that ensure autonomous operation, sustainable energy harvesting and power consumption, and Internet remote access. Using acceleration signals, the program estimates the power spectrum to determine the natural frequencies of the cables with an automated peak-picking method, and calculates tension forces by performing linear least square fitting with the natural frequencies. This information determined within the network is then transmitted to the base station, reducing power consumption and wireless data transmission. Vibration-based cable tension force estimation sensors can also be developed from off-the-shelf commercial components. Such is the case of a cable tension force estimation system that determines tension force considering cable sag and bending stiffness [84]. Welch's method is used to average Fourier spectra from segments of a one-time history record to remove the non-stationary qualities that short-duration signals impose.

Wireless smart sensors (WSSs) present many advances that propel CPS development. On-board computation capabilities of WSSs for autonomous monitoring allow preprocessed data communication for multi-functionality in CPSs. Moreover, their low cost make the deployment of a dense array of sensors on large civil structures both economical and feasible [117]. Actuation interfaces provide a way to have on-board decision-making components in order to more effectively and quickly command actuation for controlling purposes [119]. All information collected in an SHM system can be used to enhance adaptive control and for additional controller evaluation criteria.

The usage of low-cost equipment with on-board computing capabilities such as WSSs has allowed the deployment of highly dense sensor networks. It is desirable to have a dense array of nodes to reveal the status of a civil structure with greater resolution. However, when the network is partially destroyed due to a natural or man-made disaster, adaptive methods should then be used due to their robustness and fault tolerance. Networks such as those deployed at the Jindo and Zhijiang bridges ought to be evaluated to adapt to such a situation. The SOA provided at the WSSN of the Jindo Bridge along with the triggering capability allow a great potential robustness in face of emergency situations. Software that incorporates adaptive methods can be developed and executed in such instances when network density has been diminished due to an emergency situation. A decision support environment is necessary in order to communicate alerts providing information of any anomalies detected. Alerts can be given when part of the network is found unresponsive and response network subnets can be awakened to provide further damage information. These alerts should also include recommendations, such as immediate inspection, repair or activation of emergency response actions [120]. These response actions can include the engagement of structural control systems.

4. CURRENT RESEARCH IN STRUCTURAL CYBER-PHYSICAL SYSTEMS

A CPS is a confluence of embedded systems, real-time systems, distributed sensor systems and controls whose operations are monitored, coordinated, controlled and integrated by a computing and communication core [5]. A CPS bridges the virtual world of computing and communications with the continuous physical world using interconnected processing elements in wired or wireless networks connecting smart sensors to actuators. Some developments that have contributed to the implementation of CPSs are the availability of low-cost, small smart sensors; the computing capacity of low-cost, reduced-size microcontrollers; wireless communication; abundant internet bandwidth; and improvements in energy harvesting methods. Challenges that have been identified in any general CPS application include: the ability of computing components to overcome uncertainties inherently introduced by the physical system and its environment; synchronization across time and space between collection, computation, communication, and actuation components; robustness and tolerance of the system to component failure, either in the physical or virtual domain; development of smaller and more powerful actuators; and merging of time-based systems with event-based systems for feedback control. CPSs have been applied in medical devices, aerospace systems, transportation vehicles, defense systems, robotic systems, process control, factory automation, emergency management, and environmental control [5,121–134].

Several studies present CPS design approaches to civil engineering applications in SHM, structural control, and combined situations. Real-time hybrid testing presents a challenging CPS where physical and computational components must be perfectly synchronized at run-time in order to achieve reliable results. Huang *et al.* [135] evaluate the efficiency of a middleware architecture to maintain predictable timing between all physical and virtual components. Another study presents the use of CPSs to monitoring temporary structures for the improvement of safety in the construction industry [136]. One CPS design approach has been developed to satisfy the health monitoring (i.e. physical) requirements and the constraints imposed by a WSN (i.e. virtual component) [137]. The limitations to a centralized network architecture are apparent: data can only be collected from a reduced number of nodes in a reasonable time frame, which results in the detection of only the most severe damage. This means that a timely detection of structural failure resulting from extreme events, such as an earthquake or an explosion, is not possible [138]. Since WSNs incur in high-energy consumption and long delays when sensors are used as simple data collection devices, a multi-level computing architecture is proposed to selectively activate additional sensors only in the damaged regions, allowing much of the network to remain asleep. This is accomplished by using a hierarchical decentralized system consisting of grouping nodes into clusters. Cluster members collect raw data from their accelerometers and transform their data into the frequency domain through Fast Fourier Transforms and power spectrum analysis. This information is communicated to the cluster head motes, where cross-spectral density and singular value decomposition is carried out to extract the structure's mode shape vector and communicate it to the base station. The current flexibility matrix is calculated at this level and used to determine the existence and location of damage. The approach is tested using the Intel Imote2 platform with TinyOS software on a cantilever beam with single damage and a simulated truss with multiple damage locations and intensities. Although this study addresses the issues presented by the limitations of WSSs as physical constraints, it does not include any command computed in a virtual space to affect a physical component.

A type of CPS of great interest is the wireless structural control (WSC) system. This type of CPS uses a feedback control loop to influence the dynamic response of structures using sensor data collected through WSNs. As such, WSC systems play a crucial role in protecting civil infrastructure in the event of earthquakes and other disasters. Unfortunately, since WSC systems are so expensive and time-consuming to deploy, most research performed on them has been on laboratory-scale structures. Such is the case of the WSC system tested by Swartz and Lynch [65], where embedded steady-state Kalman estimators are used to minimize wireless communication in a seismically excited laboratory-scale six-story building. Because of this testing limitation, the delays and data losses that would be expected to occur in wireless networks deployed on large civil structures is not captured and so has not been exhaustively addressed. This problem has been partially resolved by developing a Wireless Cyber-Physical Simulator (WCPS) that combines realistic simulations of WSNs and structures [139]. WCPS integrates Simulink to represent structural system dynamics and the controller with TOSSIM to simulate the WSN based on realistic wireless link models. The interfaces between the Simulink model and TOSSIM are the Interfacing Block and the Data Block, two MATLAB embedded functions in Simulink. The WCPS has been used to develop a WSC benchmark problem for an active mass driver [140]. This benchmark problem provides a method to evaluate wireless control design issues such as network-induced delay, data loss, available sensor measurements, and measurement noise.

In a strict sense, structural control strategies are CPSs since physical information is collected and used to determine physical actions in a cyber realm. However, the complexity and cross-domain communication between several networks for intelligent decisions that characterizes a CPS is not present in these systems. The delays incorporated into a more complex wireless, networked control systems are being studied and tended to with improvements to communication protocols [141]. In order to improve stability and performance (i.e. minimize packet loss and time-varying delays), a passivity-based architecture for a robotic system has been designed and tested [142]. The use of wireless networks for control represents a significant step towards the incorporation of global and component status into the controlling algorithm.

Some studies have commenced integration between SHM and controlling systems in civil structures. The Guangzhou New TV Tower (GNTVT), also known as the Canton Tower, is the most heavily instrumented super tall structure in the world. Its complicated SHM system was designed and implemented by the Hong Kong Polytechnic University for in-construction and in-service monitoring. The integration of in-construction and in-service monitoring strategies allows the establishment of a dynamically calibrated baseline model, a model that updates modal information at various stages of construction until completion [143]. This type of baseline model eases computational effort when substructure techniques are used. The GNTVT has inspired several investigations and developments that include new monitoring frameworks to improve wireless communication distance [144], improvements on sensor placement [145], evaluation of vibration-based SHM and damage detection methods [146,147], methods to eliminate noise from vibration responses [148], deformation monitoring [149], and modal parameter identification and updating for high-rise structures [150].

The SHM system consists of six modules: a sensory system, a data acquisition and transmission system, a data processing and control system, a data management system, a structural health evaluation system, and an inspection and maintenance system. Sensors collect data on loading sources, structural response and environmental conditions. The on-line condition evaluation system compares measurement data with design values, FEM analysis results, and predetermined patterns and thresholds for quick assessment. The off-line condition evaluation system consists of damage diagnostic and prognostic algorithms for a more detailed health and safety assessment.

Information from the SHM system is used to verify the effectiveness of a wind vibration control system. The hybrid control system consists of two tuned mass dampers coupled with two active mass dampers and two tuned mass dampers suspended at different heights. The control system is activated by signals from anemometers and a seismograph. Ad hoc transducers provide feedback to the vibration control algorithm. These ad hoc signals are also transmitted to the monitoring center for comparison with structural response signals to detect possible faults in the ad hoc transducers. This technique of redundancy and cross-domain networking is a step closer to the integration of monitoring and actuation networks, which characterizes a CPS.

Another study that integrates SHM and structural control systems proposes an energy harvesting, cable tension-estimating and vibration-controlling strategy [83]. In order to supply energy to wireless sensors and an MR damper, an electromagnetic induction device is used. It is found that the electromagnetic induction device generates sufficient energy to operate an Imote2 wireless sensor node twice per day for a month. This translates into enough power to operate 45 Imote2 sensors for a one-time sensing. Free vibration tests were also performed to evaluate cable tension estimation and vibration controlling capabilities. It is found that electromagnetic field signals provide similar power spectral information as acceleration signals to estimate cable tension with 2.5% error. The MR damper also provides damping 20% larger than a passive optimally tuned device.

Although this multi-functional system and the GNTVT systems are irrefutably combining SHM and structural control functionalities on the same structures, they do not address several issues related to the development of an SCPS. The interconnectivity required between SHM and structural control sensing networks and virtual components that define an SCPS has not been addressed in any study to this date. Information sharing between monitoring and control systems is necessary to continually validate effectiveness of both systems and to provide additional health assessment and control criteria for smarter decisions. Full-scale implementations of WSC systems still need to be performed. Benchmark problems that incorporate SHM evaluation criteria into controlling algorithms need to be developed. The following section will define what an SCPS should consist of, what aspects have already been addressed and which problems still need to be researched.

5. PROPOSED STRUCTURAL CYBER-PHYSICAL SYSTEM PARADIGM

An SCPS is an autonomous, comprehensive system targeted to improve structural performance and maintenance integrated with an alert system for public safety. An SCPS consists of two main overlapping systems: a control system and a monitoring system. Figure 2 shows the communication sequences to be expected in an SHM system, a structural control system, and in an SCPS. All three systems consist of virtual (circular) and physical (rectangular) components that depend on complete and stable communication to operate efficiently.

Communication in an SCPS begins when a structure encounters an excitation. This excitation may be seismic, wind or impact in case of immediate structural response control, or it may be ambient vibration for purposes of maintenance or a post-event assessment and mitigation strategy. The excitation may or may not be recorded by a sensing network, represented by the dashed communication arrow between the excitation and the sensing network in Figure 2c, depending on the nature of the monitoring and control algorithms employed in the specific SCPS. Control algorithms that necessitate to record excitation make part of feedforward control strategies. Feedback control and output-only SHM strategies can be performed without excitation information. However, structural response must always be measured by sensing networks. This is so because the SCPS contains integrated SHM and alert systems, which fully rely on structural response for their operations.

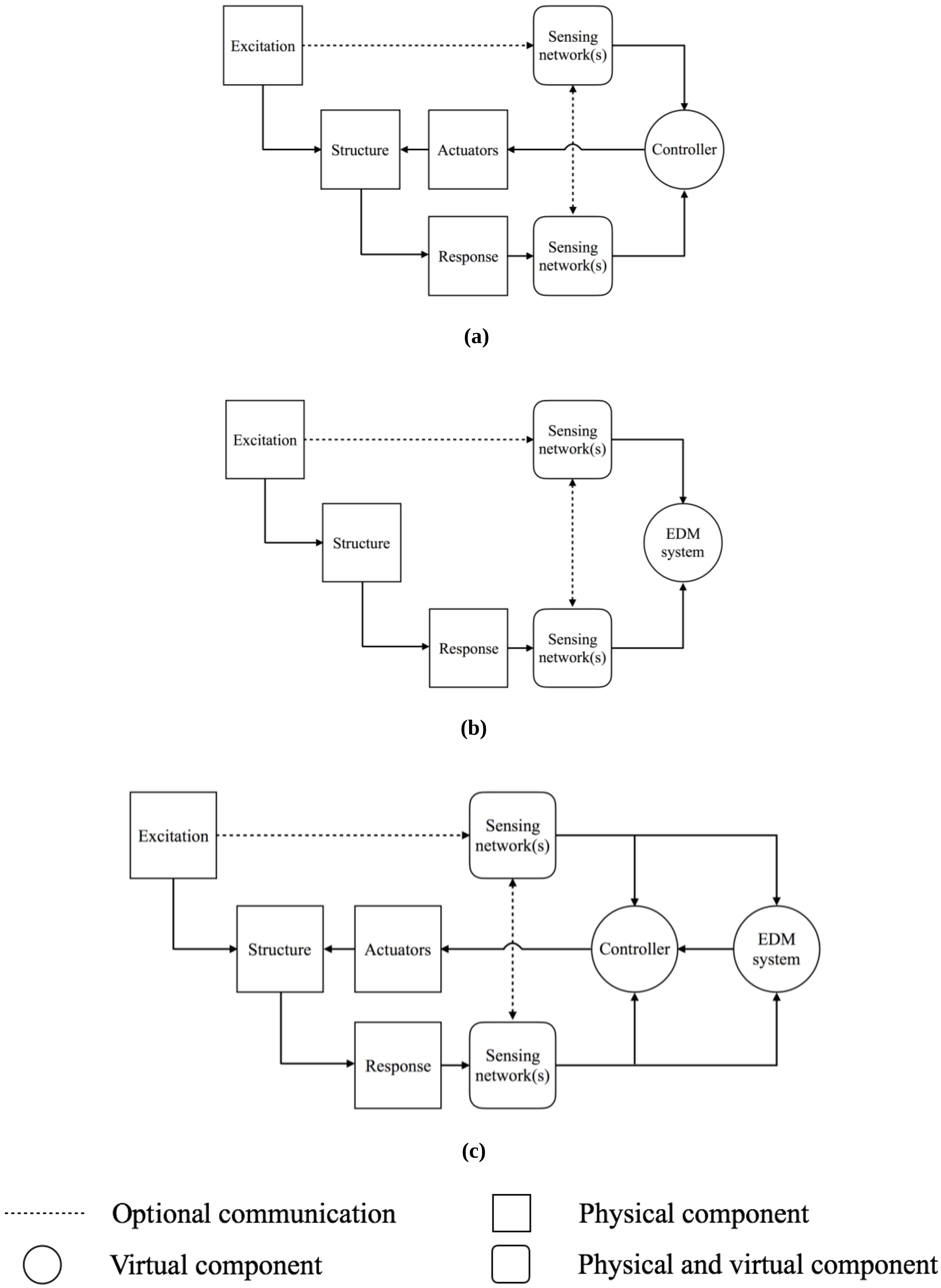

Figure 2. Communication of components in a: (a) structural control system, (b) structural health monitoring system, (c) structural cyber-physical system.

Sensing networks are both physical and virtual components as long as they consist of the physical sensing element interfaced to at least one digitizing feature, such as an integrated analog-digital converter, memory, or on-board computational ability. Since sensing devices are the last physical components in the SCPS workflow before virtual components begin to take part, networks that combine physical and virtual components are preferred in an SCPS because they can facilitate the subsequent communication flows without requiring human intervention to proceed. WSNs are an example of sensing networks that interface physical and virtual features. In SCPSs, the selection of a sensing network must also be carefully made based on the hazards the structure is anticipated to face. For instance, networks in areas of high seismic risk must be capable of triggering upon reaching a threshold in acceleration and have a large measurement range and sampling frequency to capture significant time-domain and frequency-domain information about the excitation and structural response without saturation or aliasing.

If WSSNs are used, data can be pre-processed to filter out unnecessary noise and find abnormal structural behavior. Useful data can be extracted on-board and then sent to an EDM system and to a controller. Nodes in WSSNs can share information with each other to increase network reliability and operability. This data can be sent to an EDM system for damage identification, general structural condition assessment, and prognosis. Alerts can be transmitted to stakeholders or the public via Internet, radio or cellular towers so that timely safety actions can take place.

The data sent to the EDM system can be statistically analyzed to enhance the controlling algorithm with additional performance criteria. In order to allow autonomy in an SCPS, the controller and the EDM system must be able to operate independently, but allowing data flows from the EDM system to the controller to serve as enhancements to performance criteria. A reference model in both systems allows redundancy by comparing and adjusting decision-critical information using probabilistic and adaptive methods, resulting in smarter decisions. The usage of active or semi-active control devices is necessary in an SCPS in order to implement adaptive control strategies. The adjustment mechanism in a feedback-feedforward adaptive control system allows the inclusion of updated information on the structure resulting from the condition assessment performed at the EDM system level. Information such as current loading condition and capacity is critical to improve resiliency and safety of structural control systems, and it can only be provided by SHM assessments. For example, tension estimation and damage identification are fundamental monitoring information in bridge cable structures. In order to implement an automatic tension control strategy, the output control tension force will depend on loading changes and damage information to update the reference model (refer to Figure 1). The controller can then operate physical actuators for structural response control more safely and accurately.

An SCPS such as the one described above has many requirements at each step of operation. The technologies needed to commence SCPS development can be found in much of the SHM and structural control research presented thus far. Due to the large number of sensors that are required for a dependable health monitoring scheme on a large civil structure, control and monitoring systems that require no excitation recording will likely be favored to reduce complexity and power consumption. Output-only damage detecting and probabilistic monitoring methods are very useful in these situations, as well as robust and fault-tolerant adaptive control systems. As adaptive control systems have been tested for both linear and nonlinear response models, these systems have been shown to be useful to control structures that have reached local plasticity, as is common during seismic events.

The applicability of adaptive control algorithms to semi-active control devices presents a great opportunity to combine the robustness and fault tolerance of an algorithm to the versatility and economical advantages that semi-active control devices have. MR fluid dampers, for instance, have been shown to be scalable for civil engineering applications and provide damping forces comparable to those offered by active control devices. These control forces can be attained in milliseconds by changing input voltage. MR fluid dampers do not require a lot of power to operate and behave as a passive viscous fluid damper during power outs, which can often be encountered in an emergency situation. MR fluid dampers can also be operated on battery power. Since these devices are energy dissipating mechanisms, structural stability is ensured if a command malfunction was to occur. Moreover, MR fluids can achieve great yield stresses in spite of temperature variation and impurities. Research involving MR fluid dampers has been greatly facilitated by the development of computationally tractable models for simulation, such as the Bouc-Wen and modified Bouc-Wen models.

Low-cost WSSs for on-board processing can be used to deploy large networks and avoid data losses while saving power and time during communication. Decentralization strategies can be used to overcome bandwidth and range limitations. The Imote2 platform has been extensively used in these research topics and their SOA has made way for further programming possibilities of new algorithms for monitoring strategies. This feature can be used for the development of algorithms that allow cross-communication between control and monitoring systems. The research performed in WSC systems provides the first step toward this cross-communication requirement. Research in time delay control algorithms can enhance WSC systems to expand their networks for larger structures.

Additional cross-domain interactions between the monitoring and control systems still need to be addressed. Queuing and scheduling of networks to prevent interference issues need to be investigated. Efficient filtering and feature extraction methods for the controller and evaluation and decision-making levels need to be defined and improved. Communication between the EDM system and the controller needs to be addressed for compatibility issues and possible time delays. Merging of time-based systems with event-based systems is necessary to simultaneously perform efficient real-time control and long-term monitoring, as well as to perform event-based damage identification and make way for threshold triggering systems. Control criteria need to be developed to include monitoring results such as damage state, deformation, stresses, strains and internal forces at the component and global level. Time delays in control algorithms need to be further investigated within expanded benchmark problems that simultaneously evaluate monitoring and control systems. Some adaptive control algorithms such as the clipped-optimal control strategy and the time delay control algorithm have been tested on competent control devices. Incorporation of monitoring data into the ASCE first generation benchmark problem for the cable-stayed bridge in Cape Girardeau is recommendable. Finally, as greater power demands are expected due to the increased complexity that an SCPS entails, new power harvesting methods will consequently need to be developed as critical system components.

6. CONCLUSIONS

An SCPS offers a viable and convenient option for increased safety in buildings and transportation infrastructure. An SCPS incorporates the benefits of an SHM system with structural control systems by including monitoring data to enhance controlling actions. During and after disastrous events, sensing networks may result affected, partially loosing response or excitation measurements. Adaptive methods offer a solution to this lack of information due to the partially downed sensing networks. Probabilistic and statistical pattern recognition methods are also pertinent for increased robustness due to their fault tolerance.

Semi-active control devices are the most appropriate type of actuator for an SCPS. Several devices have been successfully scaled and used in civil engineering applications. MR fluid dampers, for instance, have been found to be insensitive to variations in environmental conditions. They also possess other advantages that qualify them for emergency situations, such as low power consumption and battery operability, continued passive damping capabilities in the event of a power outage, and manageable numerical modeling for realistic simulations. The use of WSSs in WSC systems is desirable for large systems that need to reduce cost and complexity. WSSs allow autonomous monitoring with actuation possibilities. Triggering options and network decentralization strategies are available for power and computational efficiencies. The SOA in the Imote2 platform allows programming expansion for multi-functionality. These multiple functions can include filtering, cleansing, scheduling, triggering and partial processing. This monitoring data can be further processed at an EDM system to then be used for the enhancement of adaptive control strategies.

Cross-domain interactions and communication protocols between control and monitoring systems need to be addressed. Relevant control criteria originated from monitoring data needs to be determined. Benchmark control problems must be expanded to include structural status as evaluation criteria. Monitoring and control test beds with deployed sensing networks such as the second Jindo Bridge, the Zhijiang Bridge, the GNTVT and the WASHMS exist and may need relatively minor modifications to test the SCPSs. Further power harvesting methods must be investigated to supply the increased demand directly proportional to the complexity of an SCPS.

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