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Lessons from Bridge Structural Health Monitoring (SHM) and Their Implications for the Development of Cyber-Physical Systems

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Abstract: This paper summarizes the lessons learned after several decades of exploring and applying Structural Health Monitoring (SHM) in operating bridge structures. The challenges in real-time imaging and processing of large amounts of sensor data at various bandwidths, synchronization, quality check and archival, and most importantly, the interpretation of the structural condition, performance, and health are necessary for effective applications of SHM to major bridges and other infrastructures. Writers note that such SHM applications have served as the forerunners of cyber infrastructures, which are now recognized as the key to smart infrastructures and smart cities. Continued explorations of SHM in conjunction with control, therefore, remain vital for assuring satisfactory infrastructure system performance at the operational, damageability, and safety limit-states in the future. Researchers in the SHM of actually constructed systems, given their experience in monitoring major structures in the field, are well positioned to contribute to these vital needs. Especially, SHM researchers who have learned how to integrate the contributions from various disciplines such as civil, electrical, mechanical, and materials engineering; computer and social sciences; and architecture and urban planning would appear to be well equipped and could become instrumental in assessing the health and performance of urban regions, which today must function by optimizing and balancing the needs of Livability, Sustainability, and Resilience (LSR).

Keywords: structural health monitoring; sensing; imaging; intelligent infrastructures; cyber-physical systems

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1. Introduction

Constructed structures have been inspected and maintained since ancient times to ensure their functionality and safety. The means used in inspections and maintenance evolved over time, following experience as well as scientific and technological developments. For example, bridge testing was introduced in the 19th century, along with sensors for measuring deflections and displacements [1,2]. Remote monitoring was introduced in the 1920s, along with the development of the first embeddable strain sensors [3]. However, remote monitoring was very scarcely used due to many challenges related to the deployment of sensors, remote data collection, and large data analysis. The last quarter of the 20th century witnessed rapid development of various technologies and dialogue as well as collaborations between aerospace, space, electrical, naval, and civil engineers, enabling feasible remote monitoring of infrastructures. As a result, modern Structural Health Monitoring (SHM) was born and is rapidly developing, evolving, and expanding, promising full commercial maturity in the first quarter of the 21st century.

This paper focuses on the development of SHM, which spans approximately 40 years. The ambition of this paper, however, is not to perform a comprehensive and detailed literature review of SHM development over the last 40 years but rather to emphasize the lessons learned regarding the challenges for its effective and widespread implementation as well as increasing the potential for associated technology, experience, and knowledge promising to impact all infrastructures and systems in an intelligent city.

We may trace the origins of research interest in existing infrastructure to the U.S.–Japan Cooperative Earthquake Research Program on testing large-scale building models, which began in 1979, with its reinforced concrete building phase completed in 1984 [4]. Based on its findings and implications, the leading earthquake structural engineering experts in the U.S., as well as the Program Managers at the U.S. National Science Foundation (NSF), recognized the significance of structural engineering research on the problems of existing structures as opposed to just the design of new structures, and the concept of vulnerability evaluation was born. Subsequently, the U.S. NSF identified Civil Infrastructure Systems (CIS) as a critical strategic research area in the late 1980s and later identified and structured the fundamental research needs into the categories of "deterioration science", "assessment technologies", and "renewal engineering" [5].

The U.S. Federal Highway Administration (FHWA) has also promoted and sponsored research on structural control and smart structures since the 1990s. Following the 1993 plunge of Amtrak's cross-country Sunset Limited passenger train off a bridge into Big Bayou Canot near Mobile, AL (U.S.), resulting in 47 deaths [6], FHWA Advanced Research Office advocated an exploration into the feasibility of bridge monitoring as a means of mitigating the risk of similar events.

Early research in SHM was presented in a variety of venues, the most comprehensive being the SPIE Symposia on Smart Structures and Materials (renamed SPIE Smart Structures and Non-destructive Evaluation, where SPIE stands for the International Society for Optics and Photonics). Following early research in aerospace, space, automotive, defense, and civil infrastructures, the first International Workshop on Structural Health Monitoring (IWSHM) took place at Stanford University in 1997 with the support of NSF, various defense research agencies, and the aerospace industry. Since 1997, this biannual event has been bringing together leading researchers and industry stakeholders from all disciplines interested in health monitoring, and starting in 2000 and 2002, respectively, the biannual European Workshop on SHM (EWSHM) and the Asia-Pacific Workshop on SHM (APWSHM) are alternating with IWSHM. The International Society for Structural Health Monitoring of Intelligent Infrastructure (ISHMII) was established in 2002 with a focus on civil structures and infrastructure and organized biannual workshops and conferences. At present, besides the abovementioned specialized venues, many other professional venues include sessions or mini symposia on SHM.

The Seongsu Bridge disaster on 21 October 1994, when a section of the Seongsu Bridge collapsed onto the Han River in Seoul, South Korea, resulting in 32 deaths and injuring 17 other people [7], heightened international interest in bridge safety and health monitoring. Following a notable example that was the Wind and Structural Health Monitoring System installed on the Tsing Ma Bridge in Hong Kong, commissioned in 1997 [8], Structural Health Monitoring, Smart Bridges, and/or Intelligent Bridges became the subject of much research and application projects in the world. In the U.S., following extensive testing on a decommissioned I-40 bridge over Rio-Grande at Albuquerque [9], Los Alamos National Laboratories provided an overview of the status and needs for Structural Health Monitoring and damage prognosis [10].

Despite the increasing interest in Structural Health Monitoring in the late 1990s and early 2000s, the technology was not deemed mature enough for extensive applications. However, over the last few decades, structural collapses have continued to occur worldwide, including in several European Countries. As an example, in Italy, there were four cases of bridge failure (the Petrulla viaduct in 2014 [11], the Annone overpass in 2016 [12], and the Fossano bridge in 2017 [13]) in five years, including the collapse in 2018 of the iconic Morandi's Bridge over the Polcevera river in Genoa [14], which could be generally attributed to structural degradation phenomena and other durability-related issues, insufficient maintenance, excessive loads, or limited robustness. As a result of those events and the increasing awareness of the potential benefits of Structural Health Monitoring, a number of guidelines for bridge monitoring started being issued throughout the world, such as the Italian standard UNI/TR 11634 [15], the Chinese standard GB 50982-2014 [16], the Austrian standard RVS 13.03.01 [17], the British guidelines CS470 [18], and the SAMCO Guidelines for Structural Health Monitoring [19]. Among them, the Italian standard is noteworthy because it is the only document reporting the principles for the design of Structural Health Monitoring systems.

The regulatory activity exploited the significant research efforts in the field carried out between the end of the past century and the beginning of the current one. Since the 2000s, many Journals related to SHM emerged in North America and overseas, and international societies such as ISHMII, the International Association for Bridge Management and Safety (IABMAS), the Experimental Vibration Analysis for Civil Engineering Structures (EVACES), and the International Association for Structural Control and Monitoring (IASCM) were established. However, despite such intense international interest, there have not been many applications to actual bridges or other structures, i.e., SHM did not become mainstream in ensuring the safety and optimization of the management of structures. We do see, however, widespread applications limited to operational safety and automated tolling of long-span bridges.

One of the first large-scale applications of SHM was the monitoring of the Versoix Bridge in Switzerland with more than 100 fiber optic sensors in 1996 [20]. Among the few examples, we note that a Structural Health Monitoring (SHM) system with approximately 500 sensors was installed on the I35 Saint Anthony Falls Bridge, which replaced the one that collapsed in Minneapolis in 2007. The data from this system are archived by the University of Minnesota, whose researchers recently reported on the lessons learned from this large-scale SHM application [21].

A research program that started in 1997 at Drexel University with the support of FHWA demonstrated an SHM application on a long-span bridge crossing the Delaware River [22]. This application showed the feasibility of constructing a field-calibrated FE model and developing a real-time, multiscale monitoring system integrating real-time imaging, sensing, communication, and computing systems to support the operational and structural safety and security of major long-span bridges. An FHWA Report on these experiences [23] has been cited by many. The Drexel application also revealed the challenges in convincing bridge owners to support and embrace such a leap to leveraging advanced technology for managing bridges in the USA. The terrorist attacks that led to the collapse of the World Trade Towers in New York City in 2001 inadvertently negatively affected collaborations between university researchers, infrastructure owners, and managers. Many owners opted to classify information on structural systems to avoid providing any data or metadata that might reveal weaknesses of monitored structures, which in turn could be targeted by terrorists. In part because of this, even though interest in this field of research has persisted since 2001, there has been a noticeable decline in publications on substantial SHM applications to actual bridges or buildings in the USA.

However, similar research projects undertaken in Europe and the Far East helped to elevate the profile of SHM research on bridges and other critical structural systems in the world. In recent years, several large research projects have been initiated in Europe and Italy, focusing on Structural Health Monitoring of bridges. Among them, it is worth mentioning the activities of the National Center for Sustainable Mobility [24], which focuses, among other things, on Structural Health Monitoring of bridges and other road infrastructures; the ReLUIS–CSLLPP Project, focused on the application of the "Guidelines for risk classification and management, safety assessment, and monitoring of existing bridges" (D.M. 204/2022) [25]; and the EU-funded IM-SAFE Project, aimed at paving the way to a new Structural Health Monitoring European standard [26].

Overall, there has been continuous interest in smart infrastructures and, more recently, smart cities, all of which require a generalization of SHM approaches. SHM researchers offer great potential to contribute, given their experience in monitoring major structures and infrastructure. The main objective of this paper is to take advantage of the experiences of the last several decades in SHM research and applications to bridges and summarize the challenges to meaningful applications of SHM, especially the challenges of leveraging multimodal real-time monitoring for managing the operations and safety of infrastructures.

2. Challenges in SHM Applications to Infrastructures

The last decades have shown us that research and applications in SHM of infrastructures were performed in a narrow technology-push approach as opposed to a market-pull manner. Currently, there is a significant market pull developing for SHM, given the public frustration with a lack of infrastructure performance—especially under high-stress conditions such as peak demands and natural hazards, coupled with the cost of maintaining, repairing, and improving the transportation, water, and energy infrastructures, as well as the building stock in cities. We must first acknowledge that in the 21st Century, we still do not understand how most complex civil engineered systems behave and the actual safety we may expect after these systems are constructed, aged, deteriorated, or damaged.

For example, the American Road and Transportation Builders Association [27] reports that 222,000 U.S. bridges (36% of all bridges) need major repairs or should be replaced at a cost of $319 Billion. Currently, federal and state budgets for bridge repair and replacement are under $30 Billion. Similar considerations apply to European Countries where most bridges were built after World War II according to outdated codes and standards, and they are now approaching the end of their lifecycle, requiring significant budgets for their repair, renovation, or replacement. Obviously, any technology that may reliably identify bridges amongst those that are assumed to be unsafe due to their "poor" conditions based on visual inspection, pinpointing precise mechanisms that require upgrading so that available funds may be used effectively by focusing on these and not every "poor" bridge, would be needed and should be most welcome.

Meanwhile, a recent article in the Wall Street Journal [28] discusses how "*Robots fly, walk, swim and crawl with new sensors and artificial intelligence to spot—and sometimes fix—problems. The problem, however, is that companies, governments, and militaries with vast infrastructures already have systems for maintaining them. And those systems are dependent on people who are used to doing things a certain way. . .the biggest barrier to adoption of this kind of technology is probably human–says Adam Middleton, a managing director at Siemens Energy- If people feel for example that this is impinging on their expertise, it's going to be potentially difficult to get them to understand and appreciate*".

The writers agree that one of the remaining barriers to market pull for technology is the skepticism of the current stakeholders. This includes both implementation (engineering level) and decision-making (managerial level). Despite the research and technology development for SHM and smart systems since the 1990s, there are very few researchers, engineers, and managers, who truly appreciate the challenges in transforming the current state of practice for infrastructure management.

Perhaps the most significant challenge for SHM in operating infrastructures is the limited understanding of the necessary expertise and knowledge required by a multidisciplinary team to ensure a successful application. We need to comprehend the minimum qualifications and experiences of the stakeholders and experts that should come together for any meaningful application. Especially, a lack of integrated multidisciplinary teams that work effectively for SHM technology applications is perhaps an even more critical barrier than the resistance by current stakeholders that manage infrastructures and their inspections, maintenance, and repairs.

Another important challenge is the lack of methodologies for performing a long-term cost-benefit analysis of an SHM implementation. The latter has a cost, which financially involved parties (e.g., owners or managers of the structures) perceive as an investment from which they expect long-term payoff (e.g., reduced maintenance, retrofit, or replacement costs). In other words, before investing in an SHM system, an owner or manager of a structure would like to estimate the expected long-term cost savings that will be enabled by that SHM system. Evaluation of these monetary benefits in the long term requires the development of methodologies that enable evaluation of the value of information provided by the SHM, which is not a trivial task and is still under development (e.g., see [29,30]).

3. Expertise Needed for SHM and Associated Infrastructure Technology

The main task of an integrated team is to identify and implement the most suitable SHM strategy that will result in a technically meaningful application. To better understand this task, it is necessary to understand the complexity of SHM activities and the principal roles of the stakeholders. Figure 1 schematically shows principal SHM activities and sub-activities.

Monitoring strategy	Installation of SHM system	Oper. & Maint. of SHM system	Data analysis & management	Closing activities
Establishing aims of SHM	Installation of sensors	Collecting data (reading of sensors)	Data processing (cleansing, etc.)	Interruption of monitoring
Selection of monitored parameters	Installation of accessories (boxes, cables…)	Providing for electrical supply	Data interpretation	Dismantling of monitoring system
			Data analysis	
Selection of monitoring systems	Installation of reading units and firmware	Providing for communication lines (wired or wireless)	Storage of all SHM data and metadata	Storage of monitoring components
Design of sensor network	Installation of data analysis software	Implementation of maintenance plans for hardware	Integration of data and metadata	
Schedule of monitoring	Interface with users (software)	Firmware and software upgrades	Visualization of data and metadata	
Data exploitation plan		Repairs and replacements	Accessibility to data and metadata	
Costs			Export of data and metadata	
			The use of data	

Figure 1. Principal SHM activities [31].

More detail, including the principal roles of the stakeholders and their involvement in the SHM process, can be found in [32]. A successful application first needs buy-in and support from every one of these stakeholders, and different entities may have one or more of the roles listed below:

- Infrastructure owners and managers (monitoring authority);
- Practicing consulting engineers currently engaged in inspections, maintenance, repair, and replacements (engineering consultants);
- Local, state, and national political leaders—those especially in charge of financing the operations, inspections, and maintenance (political and financial authority);
- Construction engineers and managers who are engaged in repair, maintenance, and renewal contracts (contractors);
- Public users and political influencers. Especially the legal experts who are enablers defining the constraints that govern contracts between infrastructure owners and technology service providers need to be crystal clear and supportive to permit innovation (legal authority);
- Manufacturer of the SHM hardware and software who can understand the needs and provide products and services for the specific project (sensors, imaging, and associated communication and computing equipment manufacturers);

- Contractor who can install the hardware and software components of the SHM system safely and reliably (monitoring contractor);
- Finally, the SHM integrated team with the right backgrounds and expertise, with access to state-of-the-art sensing, data acquisition, communication, and archival technology and the capability of reliable interpretation of data (monitoring consultant).

Note that one entity can have multiple roles, depending on the specifics of the project (e.g., a monitoring company may often play the role of contractor as well, while a department of transportation may often play the role of monitoring authority and consultant). A successful SHM team for a bridge or a broader infrastructure system should be led by an engineer with deep domain knowledge regarding the structure of the infrastructure system that is to be monitored. The lead engineer needs a well-rounded background and the necessary qualifications for leading a large multidisciplinary team while securing the support of all the parties listed above. For example, if the infrastructure is a long-span bridge, the lead engineer needs to be a bridge-structural engineer with a deep knowledge of how the integrated bridge structure–substructure–foundation, and soil/water system would behave over its lifecycle under normal operations as well as during extreme operational demand scenarios and probable hazards, in addition to the associated social, political, financial, and organizational systems.

The engineer should especially have an appreciation of the level of risk associated with each hazard and how the structural system may behave under such hazards, e.g., accidents, overloads, dynamic amplification and resonance, fatigue, extreme temperature changes, earthquake, wind, flood, and soil-foundation failures. The critical regions and elements of the structure, critical force levels at these elements, potential force redistributions, and the anticipated failure modes should be conceptually understood. The desired performance of the infrastructure system during serviceability, durability, safety, and resilience limit-states should be clearly established, and the risks associated with failure at any one limit-state should be estimated.

Finally, whether the current organization in charge of the infrastructure is properly supported with funds and institutional knowledge commensurate with the risks of nonutility and nonperformance at each critical limit-state should be evaluated, and any limitations should be clearly established. Upon the lead engineer's evaluation of the infrastructure systems' functions, organization, and physical and material characteristics, as well as the performance requirements, operating environment, and multi-hazard risks, it would be possible to design an SHM system. The tentative Design Steps are listed in Table 1, which reveals the significant breadth and depth of multidisciplinary knowledge and experience that needs to be integrated for successful SHM.

Table 1. SHM DESIGN CONSIDERATIONS.

1. STRUCTURAL SYSTEM RELATED
(i) HISTORY OF PAST PERFORMANCE
(ii) VULNERABILITIES
(iii) FAILURE MODE(S)
(iv) CRITICAL REGIONS & ELEMENTS
(v) SITE, SOIL, FOUNDATIONS
(vi) LIVE LOADING & HAZARD ENVIRONMENT
(vii) PERFORMANCE CRITERIA
2. SHM OPPORTUNITIES/PURPOSE:
(i) CONSTRUCTION SAFETY, INTRINSIC STRESSES
(ii) CONFIRMING DESIGN ASSUMPTIONS
(iii) CONDITION ASSESSMENT AFTER OVERLOADS
(iv) LIFECYCLE ASSET MANAGEMENT:
(a) OPERATIONAL PERFORMANCE
(b) STRUCTURAL SAFETY
(c) POST-EVENT PERFORMANCE

Table 1. *Cont.*

3. SENSING, IMAGING & DATA SYSTEM
(i) CONTACT-WISE: contact, contactless, remote (satellite)
(ii) TECHNOLOGY-WISE: optic sensing, electrical sensing, Electro-magnetic sensing
(iii) COMMUNICATION-WISE: wired, wireless.
(iv) PARAMETER-WISE: strain, acceleration, wave-propagation, temperature, humidity, environmental, etc.
(v) CONTROLLED TESTING FOR DIGITAL TWIN
(a) Test method; Wired vs. wireless SENSING
(vi) LIFECYCLE MONITORING
(a) Fiber optic vs. discrete vs both
(b) Accelerations + dislacements + strains + HUMIDITY + SNIFFING
(c) REAL TIME MULTI-MODAL IMAGING & DATA
(vii) SENSOR & CAMERA DENSITY, INSTALLATION & PROTECTION
(viii) CALIBRATION BEFORE INSTALLATION
(ix) PERIODIC IN-SITU CALIBRATION
(x) ON-SITE COMMUNICATION AND CLOUD STORAGE
(xi) DATA ACQUISITION AND ARCHIVAL REGIMES
(xii) REAL TIME ON-SITE DATA QUALITY CHECK
(xiii) REAL-TIME ON-SITE INTERPRETATION/ACTION
(xiv) LONG-TERM INTERPRETATION, DECISION, ARCHIVAL
4. SHM SYSTEM OPTIMIZATION
5. SHM SYSTEM MAINTENANCE & UPGRADE
6. LEVERAGING SHM AS A BASIS FOR VISUAL INSPECTIONS & OPERATIONAL OPTIMIZATION
7. DECISION FOR SYSTEM SAFETY & LOAD LIMITS DURING OPERATION & FOLLOWING EVENTS

4. Digital Twin Requirements

A critical prerequisite for designing SHM is the construction of a digital twin. The term digital twin is being increasingly used often without any specifications. To construct a digital twin for infrastructure, one should start with a 3D CAD model of the complete system, including the foundations and soil, and transform this into a finite element model with sufficient detail to include all critical elements, connections, supports, and boundaries. Actual in situ material properties need to be established through sampling and laboratory testing. Then, a series of loading and vibration tests need to be performed to measure the dynamic characteristics as well as displacements and strains under known loads and at different bandwidths. The digital twin should be calibrated to exhibit the global and local behaviors that are measured during these tests. The twin may then be subjected to sensitivity studies under various load and hazard scenarios to decide on the spatial density and modalities of sensing and imaging for lifecycle SHM [33].

Given the recent availability of wireless sensors (accelerometers, tiltmeters, displacement and deformation sensors, and strain gages, in addition to wind and weather stations and weigh-in-motion scales), radio/internet communications, cloud computation, and data archival (requiring IT and data analytics specialists with advanced math, statistics, physics, computer science, and electrical engineering backgrounds), currently available sensing, imaging, communication, and computing capabilities have greatly advanced. Remote sensing and imaging using lasers and Lidar, unmanned aerial vehicles (UAVs—in air and water), and robots on the structure, including in water, have become available for difficult and dangerous access conditions. It follows that the tools for sensing and imaging, as well as data communication, archival, and analytics for interpretation, may have come of age.

The remaining challenge is to leverage the digital twin and heuristic knowledge for interpreting the weather and external load conditions, accelerations, deformations, and strain-and-stress histories at the critical regions for assessing conditions, deterioration, and damage. The impacts of weather, especially temperature variations and differential temperatures, in addition to intrinsic self-equilibrating stresses and their flow within the structure over time due to weather and climate, must be included in evaluating the structural conditions based on measurements. An increasing number of studies are focused on those aspects (see, for instance, [34–36] and the references therein). However, the limited quantity of comparative studies, considering the heterogeneity of available methods and monitored structures, is still preventing us from reaching a broad consensus on the selection of the most effective approaches. Thus, a pressing requirement is currently to educate the infrastructure system engineers and administrators, imparting to them the insights gleaned from the data to gain their long-term support for SHM. In this perspective, collecting and organizing the large number of experiences disseminated in the literature (see, for instance, [37–39]) might help to increase awareness about the potentialities and limitations of the available technologies. The domain knowledge required for interpretation is a barrier, and machine learning techniques, such as neural networks, deep learning, and artificial intelligence in general, remain exploratory and cannot be relied on until sufficient data and knowledge are acquired.

5. Ontology for Technology Integration Requirements

Despite the pressing need to correctly establish the performance and safety of an existing structural system such as a bridge or a fleet of bridges, which may or may not be subjected to known overloads and/or events such as an earthquake or typhoon, there needs sufficient awareness of the scope of technology leveraging and integration needs in terms of breadth and depth. Writers constructed Table 2 to illustrate how a spectrum of analytical and experimental technology tools need to be mobilized in an integrated fashion to estimate the current conditions and safety of a major bridge or an existing population of bridges and how to monitor their performance, safety, and health. The experience, knowledge, wisdom, technology, and skills that are required for the implementation of each of the Steps in the Ontology are not easy to bring together, especially without the necessary values, policy, and investment needed for such an in-depth evaluation of infrastructures. Yet, smart, sustainable, and resilient cities of the future do require such investments in motivation and resources.

Table 2. Ontology of Technology Tools/Applications for SHM of Bridges.

(1) Prioritizing bridges of a bridge population or members of a large bridge for SHM	**Construct a Database** of design, construction, inspections, repairs, and heuristics	**Automated FE construction** using database & wide-area imaging, LIDAR + GPS for actual as-built dimensions & details	**Structure/Rank the Population of bridges and members for performance risk** by leveraging heuristics & FE analyses	**Identify bridge test specimens for physical on-site testing** for evaluation of bridge, site, foundations, and soil
(2) Bridge, foundation, and site Inspection by experts for Condition & Performance Evaluation	**In-depth close range visual inspection of critical members, close range, and UAV photos to document &** incorporate in the database	**NDE & vibration monitoring with FE analyses to determine critical members & BCs for decisions** for site soil and fnd testing needs	**Leverage knowledge engineering & expert opinions** for integrating & evaluating results from field and analyses	**Expand Database to an information warehouse** for the archival of all historic and current data/info for future use
(3) Capture & Document 3D Geometry, Materials, and in-situ stresses with advanced tech quantitatively	**Surveying using new generation laser and photogrammetry and GPS to check displacements and local NDT**	**Controlled load tests; Monitoring weather, live loads, and temps over seasons to characterize loading environment**	**Ambient + Forced excitation testing for operating and intrinsic modal properties at different seasons**	**Develop Digital Twin and 3D CAD** with flythrough for simulations for risk analyses

Table 2. *Cont.*

(4) Establish critical demand envelopes and capacity	**Identify critical operational conditions, hazards & vulnerabilities**	**Scenario & cost of failure analyses for risk assessment to identify/rank critical risks**	**Risk mitigation actions: Hazard avoidance, Retrofit, Control, remove from use, etc.**	**Implementation of acceptable corrective actions for risk mitigation and resiliency**
(5) Real-Time Operational, Security and Structural Health Monitoring	Control operational and safety enhancements such as variable lanes and speed limits and weather-related warnings	Automated weigh-in-motion+ law enforcement for speed and forbidden lane change; license plate recognition	Security monitoring by video analytics for suspect vehicles, sniffing sensors	SHM by tracking critical responses in real-time for on-line rating & compare with simulation for asset management

6. SHM System Performance Requirements

A properly designed and installed SHM system, including the data and image acquisition regimes, would be expected to provide major input into asset management. The system should provide support for operational efficiency and safety in addition to structural condition assessment along the lifecycle, especially informing needed maintenance, repair, and safety following hazards. To this aim, automation of data processing procedures plays a primary role in the implementation of effective SHM strategies (see, for instance, [40,41] and the references therein). Data and images of interest need to be archived and reviewed via replay, especially after high-demand operations and suspected condition changes [42]. Naturally, the SHM system would require its own occasional calibration and maintenance and possibly revisions as needed. Therefore, it is not meaningful to envision that an SHM system would be installed and then left to the organization for its lifecycle use. The SHM team should remain on a long-term (multi-year or even lifecycle) maintenance contract while the organization's engineers may be trained to leverage the system output for asset management. If the financial conditions of the infrastructure organization permit, it would be desirable to form a unit within the organization with the knowledge capable of fully leveraging and maintaining the SHM system [43]. Such arrangements may require legal and organizational changes.

7. Monitoring the Performance and Health of Urban Infrastructure Systems

While the research and application needed for advancing the SHM of individual infrastructure elements such as bridges and tunnels are significant, the challenges of integrated performance and health monitoring of entire infrastructure systems such as an urban transportation system, a water delivery or sewer system, an electrical grid, energy utilization in a tract of buildings, and a wind farm, or even an entire community along with all its human, natural, and engineered elements as well as infrastructures may appear daunting. The path towards such systems with greatly increasing scope and complexity requires transforming SHM into intelligent systems that are governed by a multitude of agents. Only after collecting data to understand the behavior of each of these agents and their interactions can we proceed to manage multiple integrated complex systems. In this context, increasing attention has been recently paid to remote sensing technologies, which have been proven to be effective in large-scale monitoring as well as in monitoring the displacements induced by various hazard sources, such as landslides, subsidence, or scouring (see, for instance, [44–46]), and to identify the causes of structural collapses occurred in recent years and affecting nonmonitored structures [47].

In addition to expanding technology and data interpretation challenges of infrastructure health and performance monitoring, we need to better define the expected performance of urban infrastructures. Livability (including inclusivity), sustainability, and resilience (LSR) are now widely recognized as the three guiding principles of modern urban design [48–51]. Advancing and integrating these principles to serve as the objectives of innovative urban planning and the execution of urban designs is discussed by Alberti [52].

The gaps in urban designers' approach to the concepts of livability, sustainability, and resilience, and civil engineers' approach to sustainability and resilience while often ignoring livability are due to the significant gaps that remain between various civil engineering domains and between civil engineers, architects, urban planners as well as social and information scientists. Today, in North America, urban livability, sustainability, and resilience remain in the custody of somewhat separated communities. Livability is a beacon for planners, architects, public health officials, and social sciences [53,54]; Sustainability is a beacon for environmentalists [55]; and the contemporary environmentalism following [56] based on balancing the social, environmental, and economic (triple) bottom lines.

After Hurricane Sandy [57], Resilience emerged as a beacon for environmentalists (ecological resilience), urban planners and social scientists (community resilience), economists and insurers (economic resilience), and elected officials, public security officials, emergency managers, first responders, and civil engineers specializing in multi-hazard risk mitigation (disaster resilience). Unfortunately, various communities researching and practicing Livability, Sustainability, and Resilience (LSR) in the US have not yet come together to develop a common language and explore the integration of LSR as the performance goal of the overarching complex system of systems within which each discipline functions [58]. The U.S. NSF indicates that "any successful strategy seeking to mitigate the anthropogenic contributions to climate change and to implement adaptation solutions that increase the resilience of communities must include civil infrastructure innovation. Balancing civil infrastructure needs with the associated social and environmental effects is increasingly more challenging due to the increase of natural hazard risks exacerbated by climate change and by progressive infrastructure aging and deterioration. Furthermore, infrastructure aging and deterioration disproportionately affect marginalized, low-income communities that are not considered priorities in typical civil infrastructure investments [59]". NSF 23-079 indicates topics of interest for civil engineering research on urban infrastructures: (1) Green construction, operation, and maintenance of civil infrastructure; (2) Smart, civil infrastructure for health, security, and economic growth; (3) Sustainable and integrated civil infrastructure systems; (4) Climate change-informed design and system science methods. Each of these areas would greatly benefit from health and performance monitoring by expanding SHM, as discussed further below.

8. Advanced Cyber-Physical Systems of the Future

NSF's Cyber-Physical System (CPS) Program (NSF 21-551) may bring us closer to achieving monitoring of the health and performance of urban regions for LSR, as discussed above. CPS is envisioned to leverage all the elements of SHM and build on these to transform current infrastructures and cities into intelligent systems (see Figure 2). Artificial intelligence is expected to be a critical element in cyber-physical systems, such as self-driving cars, optimal power grids, energy-efficient self-regulating buildings, and effective firefighting.

Some of these applications, such as self-driving cars and building energy control, have already been initiated. Opportunities in the medical field are especially attractive. It is important to fully understand and leverage the lessons learned for reliable and effective SHM of infrastructures to accomplish successful CPS applications. Perhaps the most significant challenge, however, remains data interpretation, especially when images and data from many scales, altitudes, locations, frequency bands, and durations obtained by a multitude of sensors and sources (such as cellphone location data) must be organized, integrated, and analyzed for decision-making.

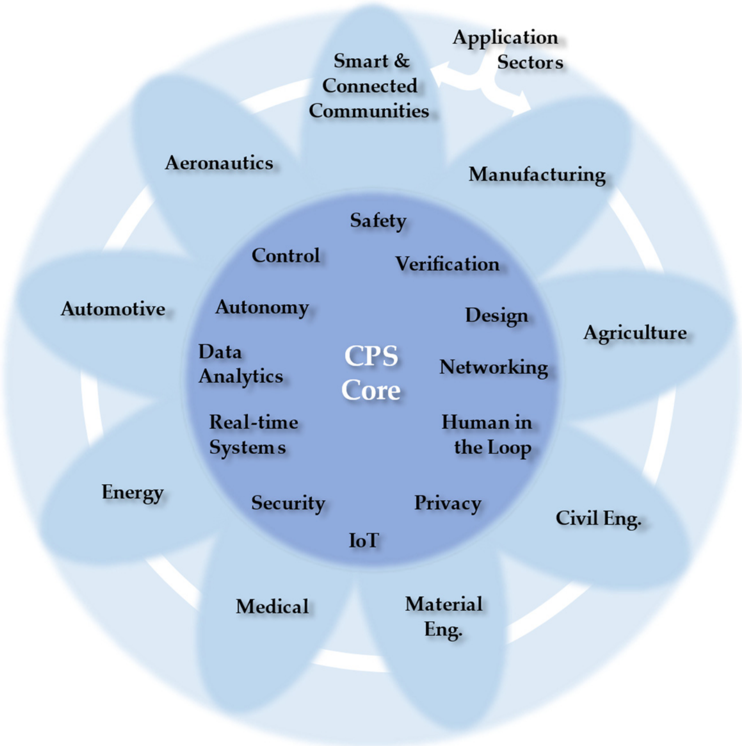

Figure 2. Cyber-Physical Systems [60].

9. The Role of Artificial Intelligence in SHM

Several SHM researchers have advocated that SHM is fundamentally a damage prognosis problem based on anomaly detection in data. This may be the case for some basic mechanical and aerospace systems, but it falls short of the societal expectations from SHM of infrastructures. Infrastructures are complex systems with adaptive characteristics, given the social and natural elements and phenomena that interact with the engineered. The operational, serviceability, damageability, failure, and resilience limit states of infrastructures correspond to distinct changes and adaptations to the system characteristics and require extensive heuristic knowledge that cannot be expected to be taught to an AI system, even with deep learning.

Until we may collect sufficient controlled data from human, natural, and engineered subsystems and elements of infrastructures that would correspond to the entire spectrum of operational conditions, external loads, the flow of internal self-equilibrating forces arising from fabrication and construction, and perturbations due to all probable hazards, it is not realistic to expect purely AI-based interpretation, even if encouraging applicative perspectives can be foreseen in the application of physics-informed machine learning [61]. It would be prudent to focus on manners of controlled data collection for calibration and training, as well as data collection under natural conditions, so that we may advance data analytics for interpretation and decision. Naturally, further advances in sensing, imaging, robotics, etc., would be valuable for advancing the performance and health monitoring of urban infrastructures for LSR.

10. Monetary Benefits and Policy Considerations

Two intercorrelated barriers to the widespread implementation of SHM are the lack of methods to evaluate the long-term monetary benefits of SHM and the lack of policy for its implementation. First, the civil engineering community must acknowledge our current lack of knowledge on how civil engineered systems, designed and constructed by a variety of codes, specifications, and construction materials and methods, behave and perform under the spectrum of loads and actions they would be subjected to, as well as their actual level of safety, expected lifecycle, and the recommended minimum required inspection and maintenance regimes. SHM data offers the potential to enhance our current civil-engineered system knowledge, which is critical for public well-being, and this is a major driver for SHM policy.

Current research on the evaluation of measurable monetary benefits of SHM is based on estimating the Value of Information provided by SHM (e.g., see [29,62]). The idea is to study the reduction in infrastructural maintenance, repair, and replacement costs resulting from optimization enabled by information provided by SHM. However, while this idea might seem simple, it is actually very complex due to the range of uncertainties involved in the process and the time scale of SHM implementation. A typical yet noncomprehensive list of sources of uncertainty is given below:

- Uncertainty in the actual safety and the prediction of the evolution of the loss of performance structures (how fast would structures degrade over time).
- Uncertainty in the prediction of the evolution of costs of interventions (maintenance, repair, or replacement) in relation to the state of the structure at the time of intervention.
- Uncertainty in the evaluation of savings provided by SHM information over time.
- Uncertainty in the prediction of long-term SHM costs over time (including data management and analysis, maintenance, repairs, and upgrades).
- Uncertainty in the reliability of SHM information (i.e., reliability of SHM).
- Uncertainty in the evolution of the economy in general (e.g., change in interest rates over time).
- Uncertainty in the prediction of the level of improvement of the structural performance after the intervention, as well as the prediction of the evolution of the subsequent loss of performance.

Considering these uncertainties and current policies, infrastructure managers are reluctant to invest in SHM in the long term as they cannot quantify its monetary benefits. That is one of the reasons why, at present, SHM is mostly applied in the relatively short term to structures with recognized deficiencies to assess their current condition and plan interventions.

We note that to make rational use of SHM, the Italian code D.M. 204/2022 defines a procedure to rank bridges according to their importance and a multi-risk assessment procedure, and it prescribes the priority application of SHM to those bridges classified under the highest classes of attention. In addition, the ReLUIS Consortium recently published guidelines for the use of InSAR satellite data for civil SHM applications [63], remarking on the potential of this remote sensing technology for monitoring the behavior of civil structures at a large scale and aiming to identify those structures in each area that exhibit anomalous response. However, we must refer to the Ontology in Table 2 and recognize the challenges associated with ranking and qualifying bridges for asset management.

Furthermore, applying SHM to structures with recognized deficiencies means that the loss is already incurred—the structure is used with restrictions, and the cost of the intervention will most likely be high. Implementing SHM at an earlier stage has the potential to greatly reduce these losses, but comprehensive studies that could demonstrate this are still in the research phase and suffer from a lack of available data.

Evaluation of monetary benefits based on the Value of Information, however, does not consider the safety aspects of SHM, as there is no monetary value that can be assigned to the loss of human lives. In addition, there are other benefits of SHM, such as enhancement of livability, sustainability, and resilience, including post-event evaluations of structures and preservation of societal well-being, which are not considered. To ensure these benefits, the new policy on the implementation of SHM in the case of critical structures that have high impacts on public well-being is strongly recommended. Examples of similar policies include mandatory bi-annual visual inspection of bridges in the U.S., mandatory monitoring of dams in Switzerland, and mandatory monitoring of high-rise buildings in Singapore. Based on these experiences, the policy for implementation of SHM may identify what types of structures should be equipped with SHM (i.e., setting criteria for the identification of these structures), what are the minimum requirements for SHM (including the reliability of SHM system and data analysis algorithms), and what are the workflows (guidelines) on the actions to be performed in the case SHM identifies changes in structural performance or condition. Codes for the implementation of SHM, which have already been developed in some countries (see Section 1), are good first steps towards the creation of such policies. Meanwhile, the current AASHTO Guidelines for Bridge Management Systems [64] in the U.S.A. may be greatly enhanced by the inclusion of SHM policy and how effective SHM may justify extending the interval between current biannual inspections.

11. Conclusions

SHM has been a valuable tool for a better understanding of the reality of the built and natural environments. While we admire the still-standing Roman bridges, Aqueducts, and Domes, our current codes and construction methods have not eliminated the lack of performance and, especially, the safety of many of our current constructed systems under a variety of design shortcomings, material and construction deficiencies, aging, lack of maintenance, accidents, and natural hazards. Further, many civil engineers have little understanding of the actual construction and operational behaviors of contemporary constructed systems due to a lack of laboratory studies or measurements in the field. Many civil engineers graduate without experiencing or observing any destructive testing of simple structural systems and even members in a laboratory.

The writers hope that the lessons learned from 40+ years of research and applications in SHM will be beneficial in transforming civil engineering from a code-based to a performance-based profession, in addition to enhancing the performance of infrastructures as well as enabling a broader range of cyber-physical systems. We cannot accept a complete lack of structural monitoring during the construction and operation of systems that cost many Tens of Millions of dollars or Euros and more at the present day. Field measurements and monitoring have to become an internal part of civil engineering education.

It is expected that future research will also help to integrate the human and social environment into the natural and engineered systems so that we may truly advance and come closer to intelligent urban regions that are more livable, sustainable, and resilient. Civil engineers and their collaborators have a major role to play in reaching such a goal if common civil engineering education and practice are properly integrated with all the critical science and engineering fields discussed above. It is obvious that we will continue to need some civil engineers as technicians; however, we will need a different breed of multidisciplinary engineers, architects, and planners who would be capable of designing, constructing, and managing infrastructures and urban regions and helping develop the policy changes discussed above. Educating such individuals would not require the hundreds of civil engineering programs we have in some countries such as the U.S.A.

The above efforts must be supported by suitable policies that favor planned long-term societal benefits over ad-hoc short-term solutions. An important potential of SHM is in educating civil engineers regarding the actual—as opposed to assumed - responses and behavior of constructed systems by providing portals from actual SHM systems to classrooms. In this perspective, the present paper focused on about 40 years of development of SHM, emphasizing the lessons learned regarding the challenges for its effective and widespread implementation as well as increasing the potential for associated technology, experience, and knowledge promising to impact all infrastructures and systems in an intelligent city. In particular, the challenges to SHM applications to infrastructures, the required expertise and infrastructure technology, and the opportunities for advancing the cyber-physical systems of the future to enhance livability, sustainability, and resilience of urban infrastructure systems are identified and discussed, thus outlining the expected trajectory of development of SHM in the future.

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