Design and Development of Low-Cost Federated Learning-Empowered Digital Twin Framework for Structural Health Monitoring (SHM) of Civil Structures built under PMGSY

Summary: The Pradhan Mantri Gram Sadak Yojna (PMGSY) facilitates all-weather road and bridge connectivity in the related parts of rural regions of our country. However, a recent study has shown that civil infrastructures (such as roads and bridges) built under PMGSY are frequently vulnerable to several environmental changes, vehicle loads, chemical reactions, and human-generated factors that can cause considerably negative affects on their condition. The traditional non-harmful assessment techniques such as visual inspection, thermography, X-ray, etc. often need skilled labor and convenience that can be usually achieved at an expense of disruption to the ongoing operating services of such infrastructures. Hence, the necessity of utilizing enhanced Structural Health Monitoring (SHM) techniques for predicting the aging, identification of damages, and preventing the serious failures that can threaten several lives is turning out to be gradually more crucial related to the requirement of structural protection. Usually, wireless sensor networks are frequently considered for evaluating the overall health state for SHM. However, it is extremely impractical to detect all sensors in all locations for sampling the required information due to various Degrees of Freedom (DOFs) in complex civil structures with low monitoring cost.

Usually, Optimal Sensor Placement (OSP) techniques are frequently considered for evaluating the overall health state for SHM since, it can precisely find out the accuracy of the sampling and measurement in such dynamic civil structures. On the other hand, with the recent developments in disruptive technologies such as AI, ML, IoT, etc. and as per the diversified needs of OSP in such complex civil structures, Multi-Objective OSP (MOOSP) techniques are also getting increasing attention. However, MOOSP optimization problems are certainly linked with higher computational cost. In addition, it is almost infeasible to choose one or a rare optimal fitness function from the available optimum solution sets closest to the Pareto front, specifically for real civil structures. Though, converting multi-objective optimization into single-objective optimization by specifying certain weight factors is useful, however, this synthetic change disrupts the intrinsic features of several techniques in collective optimization. On the other hand, existing techniques utilizing only physics-driven frameworks usually works with pre-processed information rather than straightly with huge volume of raw data. However, disregarding the physics completely may lead to a low-performance model, that cannot be further compensated by increasing the data size.

In this proposal, we propose a federated learning-empowered digital twin SHM framework with a novel sensor placement algorithm that utilizes fog computing platform for handling continuous data and also facilitates the 2-way response for continuously improving the digital as well as the physical civil structures built under PMGSY. The framework will include a low-cost wireless SHM sensor unit, which will utilize cost-effective MEMS sensors and facilitate data communication via the NB-IoT protocol. The framework will also include an enhanced sensor placement algorithm for SHM based on multi-objective iterative optimization using iterative weight-factor updating process in order to resolve the issues related to multi-objective problem for different sensor spots. Hence, the impact of disturbance deriving via estimation of the weight factor will likely gets reduced to a greater extent and which is the novelty of this framework.

In addition, the novelty of this framework lies in the fact that the framework will be developed for supporting modal assessment over longer period of time period with cost-effective MEMS sensors that will further simplify large-scale structural deployments. In addition, the SHM sensor unit will assure exceptionally less power consumption as well as facilitating global connectivity via NB-IoT network infrastructure. The outcome of the final product will be available in the form of a digital twin-driven SHM based on fog computing and federated learning for real-time supervision and preemptive maintenance of civil infrastructures constructed under PMGSY.

Objectives

- To develop a fog-driven digital twin framework that will facilitate 2-way mapping between physical structure and its digital replica including communication among physical structure, machine and the human for real-time intelligent monitoring system.
- To develop an SHM sensor board that will utilize MEMS sensors and Narrowband IoT protocol (NB-IoT) to establish long term bridge modal analysis over extended periods of time with long-range connectivity in 4G network infrastructure at low power consumption.
- To develop an enhanced sensor placement technique for SHM based on iterative weight-factor update process that will resolve the issues related to multi-objective problem for sensor placements.
- To develop an algorithm for constructing a combined fitness function via normalization and weight factors that will be solved by an iterative approach as well as a genetic algorithm for the estimation of the adaptive weight factors.
- To develop an efficient and fast digital twin that will be connected to the physical counterpart in supporting real time engineering decisions by combining physics-based model with a federated learning classifier.

Prior Art: SHM usually focuses on the analysis of modal vibration of civil structures since it possibly detects structural damage as a priori. With the recent advancements in computational performance of microcontrollers along with novel features of federated learning models and MEMS sensors, it is now feasible to execute SHM in embedded systems. SHM research typically focuses on the development of physics-based or mathematical models that leave little scope for iterative updates or real-time monitoring. On the other hand, w.r.t. several degrees of freedom in huge structures and high inspection costs, numerous efforts have also been made for the designing and development of the Optimal Sensor Placement (OSP) strategy since a single technique has been usually found to be unsatisfactory for determining the OSP technique. OSP algorithms employed either focus on optimizing a single fitness function or engage in complex and expensive computations. In addition, with the recent advancements in IoT, fog computing, federated and deep learning models, HPC devices, etc, Digital Twin (DT) has facilitated the construction process more digitalized, and it is now feasible to generate digital information corresponding to the civil infrastructures.

The SHM-based CPS developed till now in the industrial exercise is not found to be appropriate for vibration-driven, dynamic, and battery-empowered SHM systems with longer life expectancy. Recently, a general tendency found in industrial SHM systems is that they are replacing costly piezoelectric sensors with additional reasonably priced MEMS sensors since the latter one has been found to be sustainable technology for SHM systems with a significant cost saving prospective. Existing SHM systems generally claim that dynamic analysis was generally carried out in an uninterrupted way in their systems and in conjunction with static investigation, however it is usually not because of the issues related to the power as well as cost concerns.

Recent studies on narrowband protocols have established cost-efficient applications and longer sensor lifetime with reduced power consumption [1]. Additionally, recent advancements in sensor design technology have facilitated the use of more affordable MEMS sensors as a replacement for the more expensive piezo-electric sensors [2]. Brunelli et al. [3] performed a comparative study of piezoelectric sensors with MEMS to demonstrate the latter's cost reduction advantages. However, the practical usage of MEMS sensors remains limited due to their reliance on either short-range and power-inefficient WiFi communication systems or wired power cabling with no battery backup, leading to poor performance. There is a lack of a unified framework that combines the MEMS sensors with the NB-IoT protocol for long-range and power-efficient wireless LTE-based applications. H. Wang et al. [5] performed static analysis using low-bandwidth with less-power-consuming sensors. However, parallel static and dynamic analysis require a greater bandwidth range that also has a long lifetime. Polonelli et al. [6] developed a sensor board that utilizes the LoRaWAN protocol for communicating the data and assessing the cracks in structures by assuring a prolonged battery lifetime. But, the bandwidth requirement, as well as the sampling rate of crack meters, is an order of magnitude lesser than what is usually expected for a vibration-based SHM.

In addition, the field of Optimal Sensor Placement (OSP) has historically attracted significant research attention in the recent studies focussing on developing more orthogonal sensor placement criteria that yield comparably efficient modal identification results for different SHM architectures. Wang et al. [7] presented a 2-way sensor placement technique for response recreation generated via the ill-posedness of the response recreation mathematical simulation. Manohar et al. [8] proposed optimal sensor positions for signal recreation in a system via machine learning as well as sparse sampling. Zhao et al. [10] has presented the correct assessment of deformation recreation, that was validated by the efficacy of optimal sensor placement using wing frames corresponding to several loads. Lin et al. [11] proposed a multi-type response wear detection method but it was associated with high computation costs. Due to the numerous degrees of freedoms involved within a bridge structure, different fitness objectives play a unique role of importance in the determination of a sensor distribution strategy. Thus, careful mapping of these singular objectives under a multi-objective algorithm is the need of the hour.

On the other hand, recent developments in IoT and Wireless Sensor Networks have led to the emergence of Digital Twin (DT)-based techniques for SHM owing to their extremely high diagnostic accuracy and scalability [12]. The DT technology provides significant advancements over traditional manual monitoring strategies in terms of monetary, labor-work, and computation requirements. Additionally, advancements in fog Computing provide higher-performance parallel computation and massive storage advantages. Shim et al. [13] proposed a DT technique for bridge infrastructures that have the capability to monitor the structural behavior constantly, as well as a timely assessment of several other aspects of infrastructure such as cracks, material properties, etc. Revetria et al. [15] designed a DT-driven passive monitoring technique for mechanical infrastructures in order to enhance the protection of the working environment by utilizing key components like strain gauges, FEA toolbox of Matlab and Arduino card [16]. This highlights the tremendous scope for the unification of these two strategies to develop remote, iteratively updating bridge monitoring with enormous data handling capabilities. Current research outcomes have verified and assessed that the DT–driven techniques have attained an acceptable rate of accuracy as well as proficiency in estimating the pattern of production of performance w.r.t. the alterations in working conditions and data efficiencies [18].

Therefore, to the best of our knowledge, there has not been any effective development of such CPS-based SHM systems specifically in an industrial or start-up practice that utilizes the capabilities of NB-IoT protocol and optimal placement of MEMS sensors for enabling digital twin-empowered and vibration-driven SHM for roads and bridges. Motivated by the aforementioned concerns, we propose a unique combination of the NB-IoT and MEMS-based optimal sensor placement algorithm with the fog computing-based DT technology to construct a cost-efficient high-computation remotely-hosted SHM service. The service will enable end-to-end structure-human interaction through a mobile-hosted web-based dashboard for real-time monitoring and future predictive analysis for structural health monitoring of roads and bridges. In addition, this technology has considerable advantages over the popularly employed LoRaWan protocol in terms of limitless band occupation and gateway-free direct mobile operator connection, making it adept for practical CPS industry applications at a much-reduced cost.

Stochastic methods employed for weight updating often suffer premature convergence as they get stuck in the local fitness function values. Random application of weight factors, applied to counter the above problem, leads to the stacking up of order differences and computation errors. Castro-Triguero et al. [19] illustrated the disadvantages of parametric uncertainty on application to a multi-objective problem for modal analysis due to propagation of errors.

This work uniquely combines a novel Multi-objective Sensor Placement Algorithm (SPA) with narrowband-IoT (NB-IoT) technology powered Micro-Electro-Mechanical Systems for cost-effective 4G-LTE connections for battery-powered, far-reaching coverage that establishes a dynamic vibration-based communication link with a longer lifetime. This technology has considerable advantages over the popularly employed LoRaWan protocol in terms of limitless band occupation and gateway-free direct mobile operator connection, making it adept for practical industry applications at a much-reduced cost.

To provide a cot-effective handling of the multiple singular fitness functions, we propose an adaptive weight factor update technique to convert a multi-objective optimization into a lower calculation algorithm by employing a single objective function that uses a Genetic Algorithm (GA) based approach for faster convergence and greater accuracy.

This work proposes the unification of the DT strategy with a cloud-computation model for increased cost-efficiency, parallel-processing power, and massive storage capabilities. This work answers the increasing demand for a remotely accessible BSHM model service that is capable of handling huge amounts of data with high-performing computational requirements to establish two-way feedback and perform real-time analysis for future planning and crisis-avoidance.

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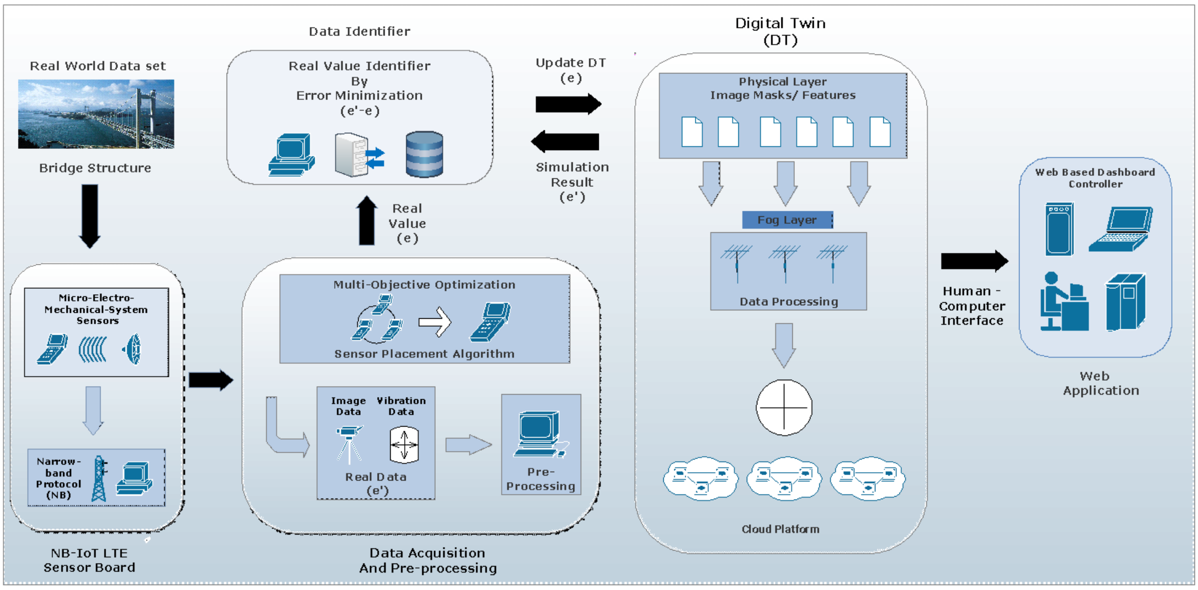
Proposed Methodology

In this proposal, we propose a federated learning-empowered digital twin framework with a novel sensor placement algorithm that utilizes fog computing platform for handling continuous data and also facilitates the 2-way response for continuously improving the digital as well as the physical civil structures. The framework will include an enhanced sensor placement algorithm for SHM based on multi-objective iterative optimization using iterative weight-factor updating process in order to resolve the issues related to multi-objective problem for different sensor spots. Hence, the impact of disturbance deriving via estimation of the weight factor will likely gets reduced to a greater extent and which is the novelty of this framework.

The framework will also include a low-cost wireless SHM sensor unit, which will utilize cost-effective MEMS sensors and facilitate data communication via the NB-IoT protocol. The novelty of this framework lies in the fact that the framework will be developed for supporting modal assessment over longer period of time period with cost-effective MEMS sensors that will further simplify large-scale structural deployments. In addition, the SHM sensor unit will assure exceptionally less power consumption as well as facilitating global connectivity via NB-IoT network infrastructure. The outcome of the final product will be available in the form of a digital twin technology based on fog computing and federated learning for real-time supervision and preemptive maintenance of civil infrastructures.

Detailed Methodology

The model framework facilitates human-structure interaction through low-cost NB-IoT protocol-based MEM sensors empowered by a unique Sensor Placement Algorithm (SPA) that further utilizes an iteratively updating cloud-based Digital Twin platform to establish a web-based dashboard as the final deliverable. The real-world image and vibration dataset is acquired through wireless MEMS accelerometers powered by a Narrowband IoT protocol that achieves a cost and power-efficient modal analysis technique with long-range connectivity over extended periods of time. The Optimal Sensor Placement (OSP) strategy for the NB-MEMS sensors is implemented through a multi-objective optimization that tackles six unique objectives of mode testing altogether through an adaptive weight factor training Genetic Algorithm (GA). The real-world data is stored in the form of an iteratively updating digital replica that consists of several deep learning submodels, including ResNets and U-Nets as well as mathematical and numerical models to store the vibrational data accumulated. This Digital twin structure is hosted on a cloud-based platform that establishes continuous two-way feedback between the physical and digital structures to perform real-time structural heath analysis and predict the behavior of the bridge in hypothetical or future possibilities. The DT simulation result is fed into the data identifier to perform error minimization against the processed real value data, to perform a persistent real-time update of the digital model. The final human-computer interface for data analysis is enabled by a web-based dashboard that stimulates real-time monitoring and assessment of the bridges' structural health.



Phase-Wise Methodology

- **Phase I: Development of low-cost wireless SHM monitoring sensor board:** This phase involves the development of untethered sensor node by utilizing low-cost MEMS sensors and utilizes the NB-IoT protocol for facilitating long-standing modal investigation with long-range connectivity at low power consumption. Initially, the investigation of most relevant module of NB-IoT and its related configuration will be done followed by the design of entire SHM board.

- **Phase II: Development of Enhanced Sensor Placement Technique:** This phase involves the development of enhanced sensor placement technique by continuously updating the adaptive weight factors and by utilizing a multi-objective function in amalgation with an enhanced iterative optimization approach. In addition, we will utilize the existing optimal sensor placement techniques that will further get converted into the related equivalent structures for achieving the mathematical-driven optimizations.

- **Phase III: IN-Field Validation**: This phase focuses in verifying the precision of acquisitions as well as in validating and verifying the measurement correctness of our system in contrast to certain off-the-shelf piezoelectric transducers. In addition, this phase also involves assessment of the system in our disruptive technologies lab. In addition, the bridge test structure will be mounted on an oscillating plate, which can impose customized vibrations for simulating the usual building behaviors.

- **Phase IV: Construction of Digital Twin Model:** This phase involves the construction of a digital twin for a damaged structure in which a physics-driven computational framework will be employed for the overall monitoring of various damage patterns. In addition, a federated learning classifier will be trained with the data retrieved from a stochastic computational framework to create the digital twin framework for SHM. This novel technique permits the utilization of a physics-based model for the development of an enhanced digital twin, which will be further linked to the physical twin for facilitating real time engineering assessments.

- **Phase V System Testing**: Finally, this phase involves testing of SHM monitoring sensor board on numerous operational conditions and assessment of their impact on the accuracy of digital twin. This phase also involves the development of a web-based dashboard that contains a real-time tally of the parameters useful for Bridge Structural Health Monitoring (BSHM). It facilitates end-to-end communication between the human and the physical structure without the need for direct interaction or study, in a power-efficient manner. This human-computer interface provides a web-based application for real-time monitoring and timely analysis and calamity prediction of the bridge infrastructure.

Novelty Aspects

The novelty of our proposal lies in the fact that the proposed digital twin-empowered SHM system will utilize the NB-IoT protocol that is a licensed band and will utilize its improvements over LoRaWAN [22], which is generally not found to be appropriate enough for extreme data rate SHM applications. The overall goal is to design and develop a framework that combines Narrowband-IoT technology in Micro-Electro-Mechanical System (MEMS) sensors to a novel Sensor Placement Algorithm (SPA) for a fog-hosted Digital Twin (DT) platform to provide a cost-efficient, durable, remote monitoring for real-time analysis. Following are some of the novel points in comparison to the designs of SHM proposed till now in the recent state-of-the-art or in industrial applications:

- **Cost-efficient SHM with Long-Range Connectivity**: Current techniques for SHM involving piezo-electric sensors, multiple fitness functions, and LoRaWAN protocol are too expensive and take huge power consumption, leading to several hindrances in its technology development. The NB-IoT technology provides a cable-free installation that establishes long-range connectivity and partial coverage reduces the required number of nodes that leading to severe cost reduction.

- **Durable Network with a Longer Lifetime:** SHM involves long, sustained monitoring of the structure, thus requiring sensors that are durable and do not need to be replaced often. The lower computation costs associated with the optimal placement of MEMS sensors lead to limited usage and inherently stronger battery life due to a significant reduction in the frequency of renewal of these sensor models.

- **Remote Human-Structure Interface for SHM using a Fog-Driven Digital Twin model**: To the best of our knowledge, there is scarcity of one combined digital twin-driven and vibration-based and battery-powered SHM with prolonged life expectancy that will utilize fog computing platform for handling constant data with high-performing computational requirements for increased cost-efficiency, parallel processing, and massive storage capabilities. This also aids in future predictions as federated learning models can learn trends in real-time and predict future failures, leading to the avoidance of catastrophes.

- **Multi-objective Optimization through a Single Objective**: The SHM designs proposed till now in the industry practice or in the state-of-the-art has utilized a single technique that generally overlook all performances of mode testing and is generally considered to be insufficient for finding out the optimal sensor placement. Even in such designs, the multi-objective optimization problem incurs extra computational effort if different sensor placement techniques are applied together. This model achieves the various objectives needed for optimization through a weighted problem without adding up the order differences or associated costs. It solves all the fitness functions at the same time, improving upon traditional methods that have not been able to solve all the unique orthogonal objectives of the OSP problem altogether.