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RESEARCH ARTICLE

Implementation of a Secure Storage Using Blockchain for PCA-FRF Sensor Data of Plate-Like Structures

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ABSTRACT Structural Health Monitoring (SHM) systems have widely been used to guarantee the safe functioning of electrical, mechanical, civil, and aerospace engineering assets. It is required to improve the SHM systems from different aspects in terms of smartification, performance, beneficiation, sustainment, automation, cost-effectivity, and safety using cutting-edge technologies. Blockchain is currently the most revolutionary technology in computer science. Implementation of Blockchain in different fields of academia and industry has recently given very good results. However, application of Blockchain in SHM is still in the infancy stage. Therefore, many challenges are still ahead. One of the main potential applications of Blockchain is to secure the sensor data. In this study, a local Blockchain approach is developed as a secure storage using the extracted Principal Components (PCs) of Frequency Response Function (FRF) data obtained from modal analysis of a plate-like structure. In general, Secure Hash Algorithm (SHA) is one of the most practical hash functions with efficient performance which has been employed in Bitcoin. Therefore, in this research, SHA-256 is considered to generate the hash for each block. To the best of our knowledge, this is the first attempt to develop a secure storage for SHM data using Blockchain.

INDEX TERMS Blockchain, data security, frequency response function, industry 4.0, modal analysis, principal component analysis, structural health monitoring, big data.

I. INTRODUCTION

The focus on damage detection systems have been on the rise for engineering applications in order to evaluate the structural integrity using SHM methods [1]. Therefore, effective and reliable damage detection approaches are very significant to monitor engineering assets for the occurrence, location and severity of any damage [2]. To this end, there has recently been a vast motivation on theoretical and experimental condition assessment systems from small scale components, (e.g. couplers [3], beam-like [4] and plate-like structures [5]) to large scale structures, (e.g. buildings [6], bridges [7], pipelines [8], oil and gas platforms [9], railways [10], tunnels [11], dams [12], transmission towers [13], wind turbine structures [14], and offshore structures [15]) in order to make satisfactory decisions on structural maintenance, repair, and rehabilitation. SHM is the process of applying a damage detection approach to evaluate the health condition of civil, mechanical, and aerospace in-service structures. In general, damage detection techniques can be considered in two categories due to their detection abilities which include local-based and global-based techniques [16]. Non-destructive test approaches, e.g. visual inspections, ultrasonic, acoustic emissions, radiography, etc. are local-based damage detection methods with various drawbacks [17]. For instance, the aforesaid costly techniques

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normally necessitate prior knowledge of the damage location which makes them inefficient, especially in big and complicated structures. On the other hand, global-based methods, e.g. vibration-based techniques are based on global structural response and they have been developed to overcome the aforementioned drawbacks [18], [19]. The basic concept behind vibration-based approaches is that the damage-induced changes in the physical properties such as stiffness, mass, and damping will trigger measurable changes in modal properties (mode shapes, modal damping, and natural frequencies) [20], [21], [22]. Hence, it is intuitive that damage can be detected through the investigation of the changes in structural vibration characteristics [23].

Besides, different methods and models such as the application of modal reduction and mode superposition technique for efficient estimation of critical (highly stressed) areas in civil structures [24], spatial incompatibility filters [25], data mining [26], [27], artificial neural network [28], clustering analysis [8], genetic algorithm [29], deep learning [30], fuzzy logic [31], principal component analysis [32], Bayesian [33], support vector machine [34], particle swarm optimization [35], decision tree [36], regression analysis [37], remote sensing [38], unmanned aerial systems [39], [40], and anomaly detection [41] have been also applied in SHM.

The traditional SHM is mainly based on visual inspections which is laborious, difficult to inspect the load-carrying structural members, time-consuming, and requires human judgment [42], [43]. Therefore, as mentioned before, vibration-based methods have been developed to overcome the above limitations [44]. Most of the vibration-based SHM methods can be considered as some kind of pattern recognition due to their capability to discover the changes among two data, (e.g. before and after damage) [45], [46]. For example, modal analysis is a common vibration-based approach which has been utilized to detect damage from any changes in structural vibration characteristics with prior knowledge of the undamaged state [47].

The term ‘‘industry’’ refers to the creation of products, services, and facilities within an economy. Our world has experienced four steps of industrialization (see Table 1). The fourth industrial revolution (i.e. Industry 4.0) is a smart technological platform along with digital innovations using various contributions [48], [49], [50], [51], [52]. For example, Big Data is one of the key contributions of Industry 4.0 that refers to large databases [53]. With the development in the application scope of computing tools, it is required to apply more precise systematic solutions for Big Data problems [54]. To this end, data-driven strategies based on data mining have been employed to obtain useful patterns from recorded sensor data [55]. Data mining is defined as ‘‘the process of exploring massive amounts of data (Big Data) to discover patterns such as the rules of association or temporal sequences’’ [56]. Despite the above trends, in the 2020s, the world is changing at an ever faster rate as the internet and digital revolutions become the drivers of commerce today. This is due to the fact that emerging Industry 4.0 technologies such as Blockchain [57] are reaching human-like precision and reliability on high complexity tasks with the most significant global impact across sectors [58]. It is because these technologies are felt throughout our daily lives. For example, Blockchain technology has recently attracted huge attention from practitioners and academics in various fields such as business [59], energy [60], manufacturing [61], smart cities [62], smart grids [63], finance [64], healthcare [65], and transportation [66]. In the same line, computer-based technologies and their applications pervade everywhere in real life, especially in different fields of engineering. For instance, the traditional SHM should be upgraded to Blockchain-based and Internet of Things (IoT)-based SHM. As mentioned earlier, it is because traditional approaches are challenged by real-time, low-cost, and quality-guaranteed SHM. Besides, the advantage of using new technologies is their automation, intelligence, and specialization. Therefore, it is required to integrate the application of emerging technologies and structural damage detection approaches to guarantee more reliable SHM systems. It is worth noting that IoT is an emerging evolutionary technology comprising billions of physical devices around the world containing embedded sophisticated chips, sensors and actuators which able to connect, collect, share, interact, and exchange any type of data [67], [68], [69].

Blockchain technology is a growing reality of our modern society [70]. Moreover, Big Data analytics can also extract meaningful information from the oceans of data produced by sensor devices [71]. The implementation of Blockchain-based solutions could solve several issues, i.e. the high maintenance cost of centralized approaches [72]. In the era of information technology (IT), every transaction made on a Blockchain network has to be verified consensually by the thousands of linked computers. Verified transactions are then added as a block in the chain. A unique hash is assigned to each block which cannot be edited or changed, making the entire chain secure and impenetrable.

Based on the literature review, it is felt to improve the smartification and security of SHM systems using the fourth industrial revolution technologies due to the demanding computational processes of physical signals. Therefore, by taking advantage of the recent advances in the IT field, the current research offers a new way to compute recorded sensor data for condition monitoring of structures which is needed to address the limitations of SHM. Hence, in the present study, an attempt is made to investigate the applicability of Blockchain technology for improvement of SHM systems. The rest of this paper comprises the following sections. A brief background of vibration-based SHM, FRF, PCA, and Blockchain are described in Section 2. The construction of PCA-FRF is performed in Section 3. The details of experimental work are presented in Section 4. Then, Section 5 introduces the developed Blockchain algorithm. The implementation of the Blockchain is also discussed in Section 5. Future work direction is addressed in Section 6. Last but not least, Section 7 highlights the conclusion.

TABLE 1. Global industrial revolution and their contribution

Industrialization Steps	Key Contributions
Fourth Industrial Revolution (IR 4.0)	• Internet of Things (IoT) • Smart factories / Smart Manufacturing / Robotics • Circular economy / Product – Lifecycle – Management (PLM) • Data mining / Big data analytics / Deep Learning • AI / Machine learning • Smart sensors / Remote sensing / Wireless sensor network / Online monitoring • Cloud computing / Cognitive computing / Mobile computing • Cybersecurity / Blockchain • Digital twin / Smart tasks and diagnostics / Smartification • Virtual reality / Augmented reality / Building Information Modelling (BIM) • Unmanned Aerial Vehicles (UAVs) / Internet of Drone / Smart cities • Smart environment / Sustainable development / Renewable energy
Third Industrial Revolution (IR 3.0)	• Production Automation / Computer and Automation • Information and Technology / Telecommunication • Linear economy • Leveraging Electrical Mechanization • First programmable logic controller (PLC) • Industrial Robotics / Electronic and nuclear industries • Business Computers / Supercomputers / Business software • Internet / World Wide Web
Second Industrial Revolution (IR 2.0)	• Electrical Energy / Steam power and petroleum • Skyscrapers • Large scale iron and steel production • Telephones and telegraphs, typewriter, phonograph, motion pictures • Widespread use of machinery in manufacturing • Automobile, airplanes, diesel engines, bicycles, railroads • Chemical, Rubber, paper mills, fertilizers • Applied Science • New forms of business organizations
First Industrial Revolution (IR 1.0)	• Mechanical Production • New Energy Resources / Water and Steam Power • New raw materials / Iron, coal, textile, steam industries • New machines / Spinning Jenny and the Power loom • Factory system, division of labor, specialization • The locomotive • Expansion of world trade

TABLE 2. Summary of possible factors for vibration-based parameter identification.

Factors	Opportunities
Linearity	Linear versus nonlinear
Modelling range	Local versus global
Mass distribution	Discrete, continuous lumped-mass, etc.
Modelling domain	Physical versus modal space, time- versus frequency-domain
Inputs and outputs	Single-input, single-output versus multi-inputs, multi-outputs
Input availability	Input-output systems, output-only forced vibration, ambient

II. BACKGROUND AND OVERVIEW OF PRINCIPLES

A. VIBRATION-BASED DAMAGE DETECTION

Vibration-based damage detection comprises two significant parts, i.e. modal parameter estimation methods such as Experimental Modal Analysis (EMA), Operational Modal Analysis (OMA) and Impact- Synchronous Modal Analysis (ISMA) and detection / identification systems such as FRF change, natural frequency change, mode shape change, modal flexibility change, strain mode shape / mode shape curvature, modal strain energy change, and matrix methods. The second part uses the first component to quantify and detect damage. Hence, they are highly influenced by each other [37]. It is worth noting that the selection of a suitable identification / detection strategy relies on several aspects, summarized in Table 2 [73].

OMA frequently employs the output-only measurements while EMA operates with input and output measurements to identify the modal parameters [74], [75]. OMA is generally applied in practical engineering. This is due to the facts that (1) it is difficult to shut down the system while the structure is in-service, or (2) the artificial excitation source (i.e. impact hammer or shaker) is not able to excite the structure. Consequently, real operating vibration environment can be considered to implement the OMA method [76]. However, the extraction of damping properties is not an easy task using OMA [77]. On the other hand, EMA is regularly conducted by means of artificial excitation [78]. ISMA is another modal analysis technique with de-noising properties. This input–output model identification approach can be described as applying EMA developments through Impact-Synchronous Time Averaging strategy. For that reason, ISMA is able to measure the FRF data of in-service structures because of de-noising properties. Several developments and improvements on the ISMA technique have been made over the decade [79], [80], [81], [82], with the recent development method includes the scope of inertial sensor based human behavior recognition using machine learning approach, which enable semi-automated features for ISMA modal testing [83]. Generally, the phase difference information between acceleration response and cyclic load component suppresses the non-synchronous components, enabling

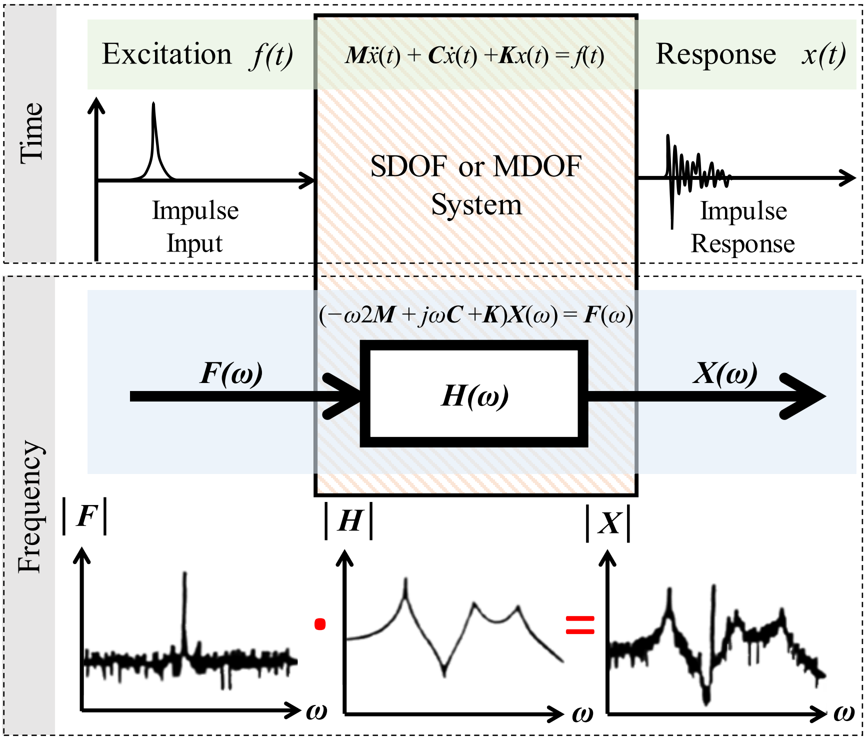


FIGURE 1. Concept of frequency response function.

ISMA to be conducted on a structure that is exposed to noise or is in-operation without compromising the quality of the modal parameters extracted [84], [85]. A comparison between ISMA and OMA techniques was also conducted by the authors of [86]. According to their research, the OMA could generally provide a better performance for complex and large structures, while the outputs of ISMA was superior to OMA results for in-service structures. This is due to the fact that an artificial excitation is required to implement for the ISMA procedure, which is not applicable for large structures. Hence, OMA and ISMA are suitable tools for large static structures and in-operating structures, respectively.

B. FREQUENCY RESPONSE FUNCTION (FRF)

Figure 1 shows the concept of FRF which is at the foundation of modern system analysis. To explain this, when a linear system, i.e. a Single Degree-of-Freedom (SDOF) or a Multi-degree-of-freedom (MDOF) is excited by a dynamic force, it will respond at the identical frequency along with its corresponding amplitude which is representing the frequency of excitation. In general, the phase of the dynamic response is not the same as the external force, i.e. excitation. Thus, this phase difference can change the frequency. Hence, it is not required to excite the system using a specific frequency at the time. Therefore, the response signals and the excitation must be subjected to the Fourier transform with the aim to achieve how the system responds at different frequencies [87]. For this reason, FRF can be considered as one of the most significant measurements of modal analysis acquired from a data analyzer. Fast Fourier Transform (FFT) is used to transform the time-domain responses into the frequency domain. As it can be seen from Figure 1, FRF ($H(\omega)$) is the ratio of the Fourier transform of output responses ($X(\omega)$) to the Fourier transform of input excitation ($F(\omega)$) [88].

C. PRINCIPAL COMPONENT ANALYSIS (PCA)

PCA is a commonly applied multivariate numerical method to decrease the dimensionality of datasets [89]. This approach is also known as Karhunen-Loeve Technique (KLT) which is used to maximize the scatter of all projected samples by selecting a dimensionality decreasing linear projection [90]. In addition, it is also applied to data exploration, prediction assessment modeling, and online fault diagnosis [91], [92]. In other words, PCA can be used in a linearity form for representing high-dimensional data into low-dimensional data with minimum decrease of data [93], [94]. Accordingly, the solution of an eigenvalue problem is produced from the PCA method by using covariance matrix determination, eigenvector evaluation, and orthogonal projection. An orthogonal projection converts multidimensional data into lower dimensions of independent data which is called "principal components". Figure 2 illustrates the architecture of PCA showing the first principal components with maximum variance in several dimensions. This figure also presents the definition as well as the applications of PCA.

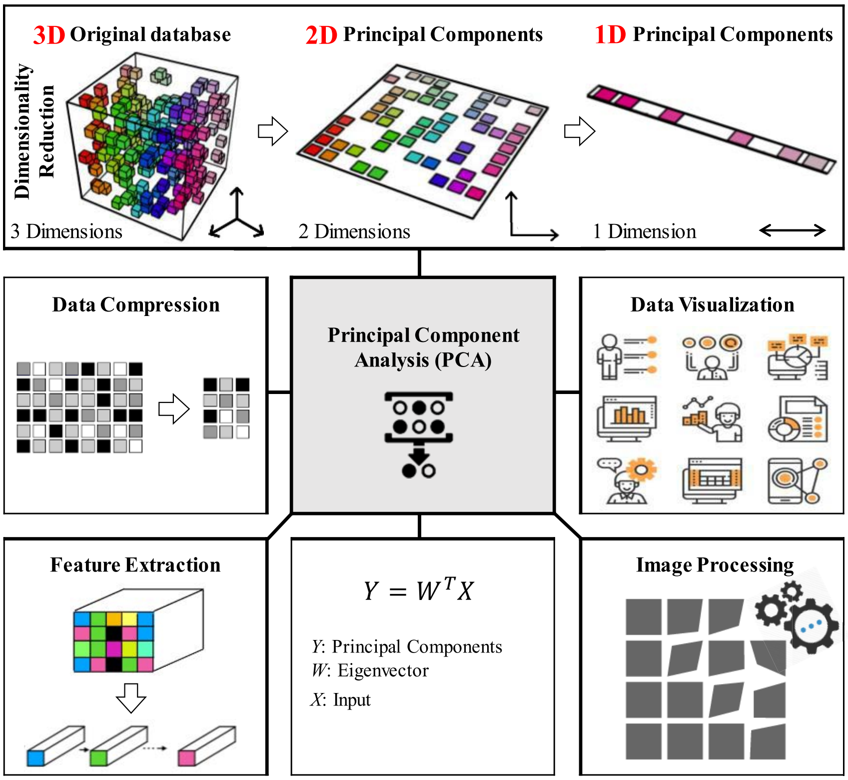


FIGURE 2. Overview of principal component analysis.

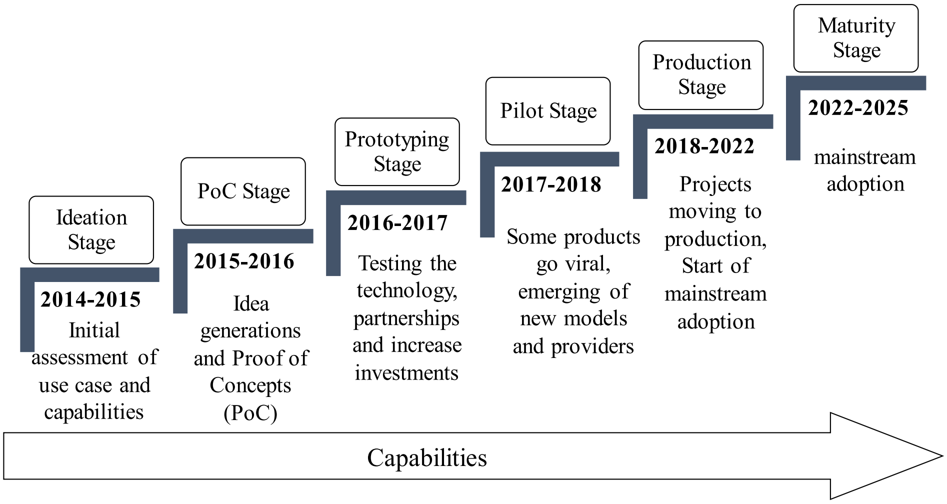
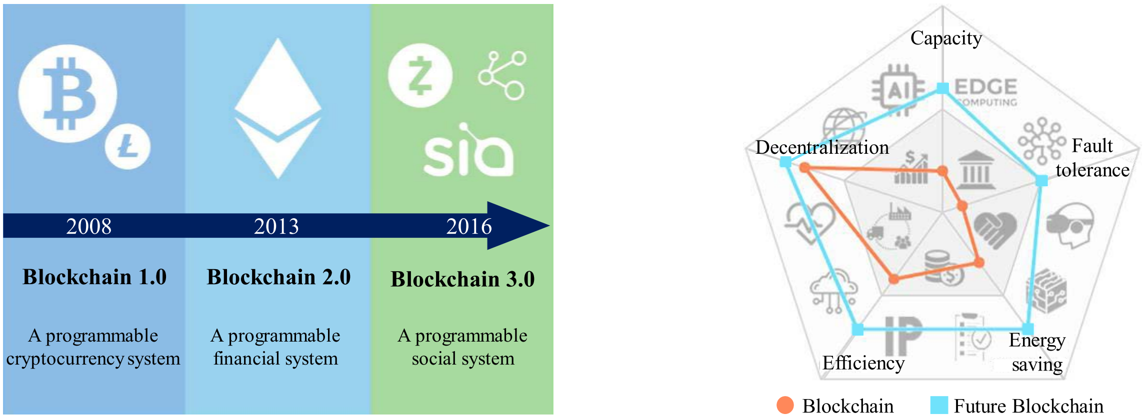


FIGURE 3. Timeline for blockchain adoption in industries adapted from [97].

D. BLOCKCHAIN TECHNOLOGY

In the past few years, Blockchain has been the most important development in IT field [95] and right now the most revolutionary technology in computer science. "It is only a matter of time until Blockchain becomes just another normal part of everyday life, like smartphones and the World Wide Web". In the IT world, 'Blockchain' is a self-explanatory term which is able to store a database using blocks. A 'block' is referring to a storage unit or space for digital information, and a 'chain' is representing the locations of stored databases. The very first block in a chain is known as the 'genesis' block. Blockchain as a decentralized ledger increases accuracy in transactions along with several benefits, i.e. economic efficiency, data security, and time efficiency [96]. Data security is the main focus of current study. According to a report by [97], Blockchain has achieved major breakthrough and adoptions



(a)

(b)

FIGURE 4. (a) Evolution of blockchain, and (b) Potential applications of blockchain and future blockchain [100].

in industries. In this regard, Figure 3 shows a timeline for Blockchain adoption.

With using Blockchain, reliable and secure information can be transferred across private and public sectors automatically. Therefore, it is possible to securely store, control and verify the databases using Blockchain. With better data comes better decision-making [98]. Don Tapscott, Executive Chairperson, Blockchain Research Institute and Co-author of Blockchain Revolution: How the Technology Behind Bitcoin is Changing Money, Business, and the World [99] said: "The digital revolution's first era failed to solve pressing social, economic and environmental challenges. Blockchain offers a once-in-a-generation opportunity to get it right. Blockchain skillfully champions the opportunities offered by a new internet of value." Figure 4(a) illustrates the evolution of Blockchain from 2008 until now. Likewise, Figure 4(b) presents the potential applications of future Blockchain.

In Blockchain, a "Block" holds a number of elements, i.e. index, data, hash, previous hash and timestamp. Figure 5 presents the typical structure of a Blockchain. To know Blockchain, it is important to understand what a "hash" is. A "hash" is a sequence of random characters in the "block" which representing a digital fingerprint of digital data. Each hash value is connected to its particular input. Therefore, it is not possible to generate a unique hash value by adding dissimilar data [101]. In the same way, the Blockchain will constantly expand as blocks (including files along with data) as more data are linked to the previous block using a hash. This hash can be created by proceeding subjects of the block using a hash function.

A Blockchain-based conceptual framework was proposed by the authors of [102] to improve the efficiency of SHM-related technologies for civil structures through making connection between hardware and software components (see Figure 6). In this regard, the authors of this study aimed to develop the reliability of current damage detection platforms through the integration of vibration-based methods and Blockchain. As it can be observed from Figure 6, SHM process of the in-service structure starts with data measurement. In most cases, the input excitation and output response are measured in time domain. However, it is difficult to study damage identification in such manner. Hereupon, time domain data can be transformed to frequency domain using modal analysis and modal domain data can be extracted from frequency domain. Consequently, the modal domain methods play a significant role in structural damage identification and their popularity is much more than time domain or frequency domain approach. This is due to the fact that, the modal properties such as natural frequencies, modal damping and mode shapes have their physical meaning and they are easier to interpret in compare to mathematical features obtained from time or frequency domain. Then, Blockchain technology is utilized to increase the reliability of the recorded database. The Blockchain algorithm will validate all sensor data base on these blocks to determine that the sensor is giving genuine signals for further processing. In the next step, applicable vibration-based damage detection algorithm using artificial intelligence and machine learning is suggested to be applied for training the database in order to generate the test design, and patterns creation. Last but not least, pattern validation is also detailed to determine the severity and location of damage.

III. CONSTRUCTION OF THE PCA-FRF

In this study, the correlated variables of FRF sensor data are extracted using PCA to construct the uncorrelated variables, i.e. PCs. To aid the aim, the original sensor data in an N-dimensional space can be transformed by an orthogonal projection to a lower space, i.e. P-dimensional space ($P < N$). A Matrix with M spectral lines and N measurement points represents the raw FRFs, as follows [103]:

$$H = [h_{ij}(\omega)]_{M\times N} \tag{1}$$

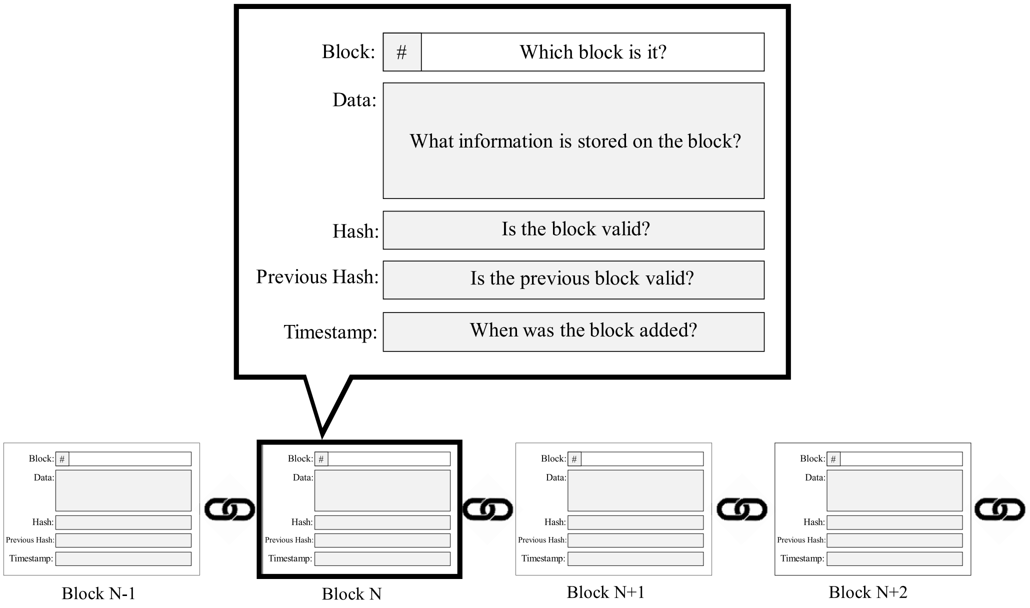


FIGURE 5. Structure of a blockchain.

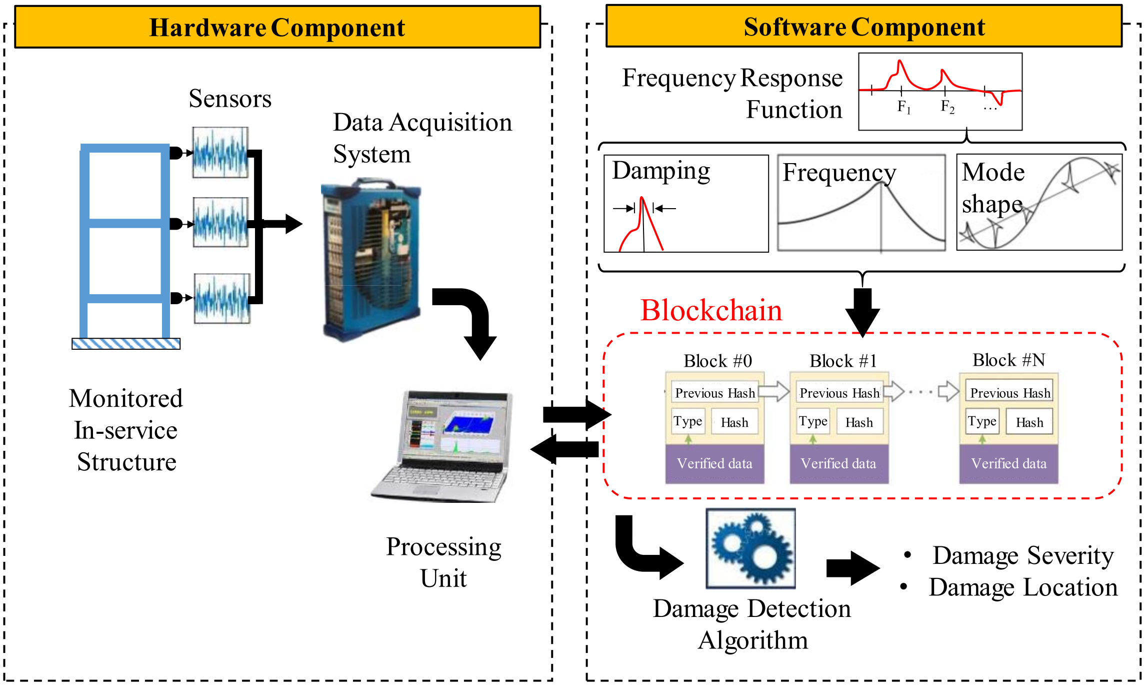


FIGURE 6. Schematic illustration of the proposed conceptual framework by [102].

The "auto-scaling" of FRF matrix (H) is conducted to create zero mean variables. It also helps to generate a unit variance by standard deviation. The following equations present the theoretical formulation of PCA-FRF construction through the corresponding references [104], [105], [106].

The mean response of the *j-th* column is stated as:

$$\bar{H}_j = \frac{1}{M}\sum_{i=1}^{M} h_{ij} \tag{2}$$

The corresponding standard deviation S_j is:

$$S_j = \sqrt{\frac{\sum_{i=1}^{M}\left(h_{ij}(\omega) - \bar{H}_j\right)^2}{M}} \tag{3}$$

An element $h_{ij}(\omega)$ of the FRF matrix can be substituted by the following Equation in order to achieve a response variation matrix $\tilde{H}$.

$$\tilde{h}_{ij}(\omega) = \frac{h_{ij} - \bar{H}_j}{S_j} \tag{4}$$

The covariance matrix $[C]_{M\times N}$ can be defined by the response variation matrix, as follows:

$$[C]_{M\times N} = [\tilde{H}]^T_{N\times M}[\widetilde{H}]_{M\times N} \tag{5}$$

The PCs comprise the eigenvalues and correlated eigenvectors (λ_i, Ψ_i) of the covariance matrix:

$$[C]\{\Psi_i\} = \lambda_i\{\Psi_i\} \tag{6}$$

The projection matrix $[A]_{M\times N}$ of the response variation matrix $\tilde{H}$ on the N PCs is also defined as:

$$[A]_{M\times N} = [\tilde{H}(\omega)]_{M\times N}[\Psi]_{N\times N} \tag{7}$$

The projection and eigenvector matrices, i.e. *[A]*, [Ψ], are divided into two sub-matrices with K and (N-K) principal components. K and (N-K) are related to the important features and uncertainties, respectively.

$$\begin{aligned} \lceil\tilde{H}_R\rceil &= [A]\,[\Psi]^T \\ &= \lceil[A_1]_{M\times N} \vdots [A_2]_{M\times(N-K)}\rceil \\ &\quad \times [[\Psi_1]_{M\times K} \vdots [\Psi_2]_{M\times(N-K)}]^T \\ &\cong [A_1]_{M\times K}\,[\Psi_1]^T_{K\times N} \end{aligned} \tag{8}$$

The first PC (i.e. maximum eigenvalue along with its corresponding eigenvector) indicates the direction and amount of highest variability in the original raw FRF data. The second PC shows the second most significant contribution from the original raw FRF data. It is worth nothing that PC1 is orthogonal to PC2. According to [107], it is proven that the first two PCs are sufficient to represent the multiple FRFs. Therefore, PC1 and PC2 are considered in this study to plot the PCA-FRF sensor data.

IV. EXPERIMENTAL WORK

Figure 7 shows the experimental setup for this study which was conducted by the Advanced Shock and Vibration Research (ASVR) Group of University of Malaya. A Perspex plate with the dimensions of 48 cm × 20 cm × 0.9 cm and mass of 1.1 kg was used as the test structure. Table 2 briefly explains the representation of the components for this study. Each of the four corners of the plate was ground-supported using screws to simulate an automobile chassis with wheel suspensions, where the supports represent the suspension components. The vibration modes of the test rig were heaving, rolling, pitching and bending, which were similar to the modes of a vehicle chassis.

Figure 8 shows a schematic view of the test setup. EMA using the roving accelerometer technique was conducted to acquire the FRFs of the five measurement points. Five Wilcoxon Research model S100C accelerometers with built-in charge amplifiers were mounted below the plate by cyanoacrylate adhesive. The impact location was fixed at a point near Edge 4 of the plate to simulate actual impact on the wheel when the vehicle passes a road bump or pothole. PCB model 086C03 impact hammer was used. For data acquisition, the National Instrument-Universal Serial Bus (NI-USB 9234) signal acquisition module was used to acquire the dynamic signals from the five accelerometers and the impact hammer before post-processing the FRFs in LabVIEW software. The frequency range for this study was 0Hz to 120Hz with 241 frequency points. PCA algorithm was then applied on the FRFs to build the PCA-FRF for damage assessment.

TABLE 3. Representation of components.

Component of actual automobile	Component of experimental test rig
Chassis	Perspex plate
Wheel	Aluminum support
Suspension/spring components of wheel	Steel plates

Stiffness reduction at the suspension/spring is a common automobile fault. To simulate the fault, the tightness of the screws that connect the steel plates with the plate were adjusted according to the desired damage severity. The accelerometers were also mounted at the plate instead of mounting them directly at the supports to simulate the actual conditions, where it is difficult to mount sensors at the wheel/suspensions area. Therefore, the measurement points were located away from the four edges and were labeled as Point 1, 2, 3, 4 and 5 to reflect the real-life condition.

Table 4 indicates the detailed description of damage cases simulated on the plate-like structure. Overall, twenty-four damage conditions were simulated. At each of the four edges, single damage with six damage levels were simulated, where DL1 indicates the lowest damage severity and DL6 indicates the highest damage severity. Stiffness reduction was simulated by adjusting the tightness of the screw. The tightening force of the screws was measured by FlexiForce A201 force sensors, which were placed between the two thin steel plates of the supports. Table 3 also lists the tightening force of the screws at each of the edges for all simulated conditions. For healthy state or undamaged condition, all screws were tightened to 150N. The screws at the damage location were then loosened to 113N, 75N, 38N and 0N for damage levels of DL1, DL2, DL3, and DL4, respectively. For DL5 damage cases, one screw was removed and the other screw was loosened to 0N at the damage location. Both screws at the damage location were removed for DL6 damage cases.

V. RESULTS AND DISCUSSIONS

FRF measurements of the intact and damaged cases of the test specimen were collected from EMA. Curve fitting was carried out on each set of FRFs to construct the data structures. The curve fitting tool used in this study was the LabVIEW FDPI fit algorithm. It was a frequency domain multiple degrees of freedom modal analysis method to estimate modes in a narrow frequency band. Then, PCA was applied to

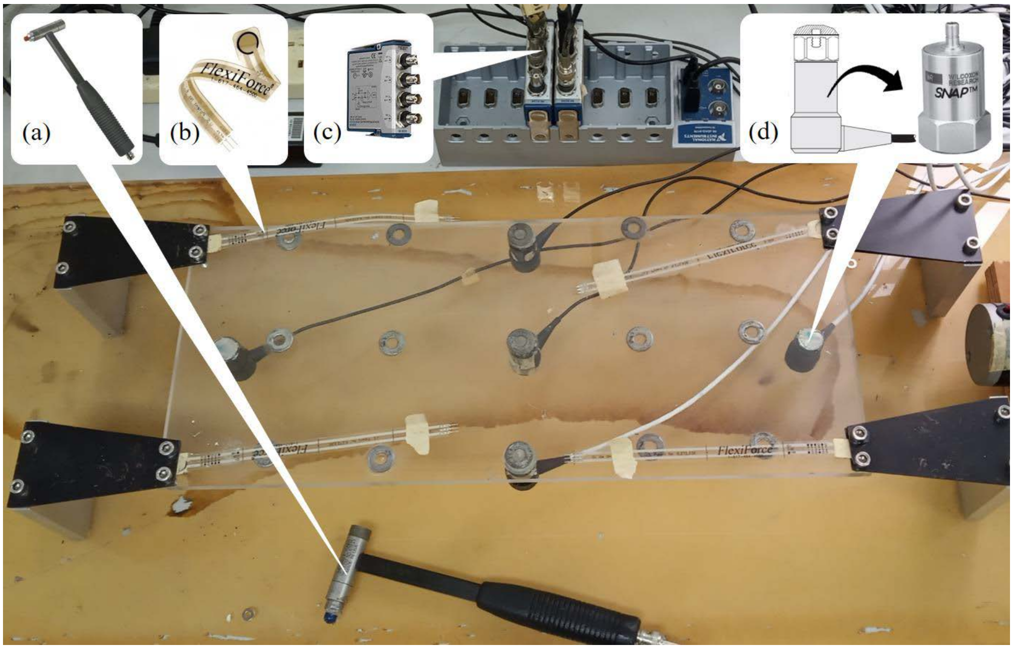


FIGURE 7. Laboratory test setup: (a) Impact hammer PCB 086C03, (b) FlexiForce sensor A201, (c) Signal acquisition module NI-USB9234, and (d) Accelerometer Wilcoxon Snap model S100CS.

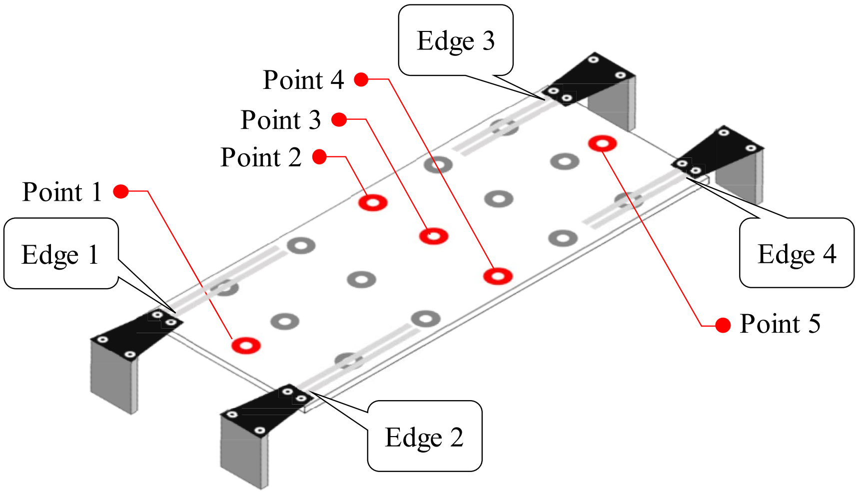


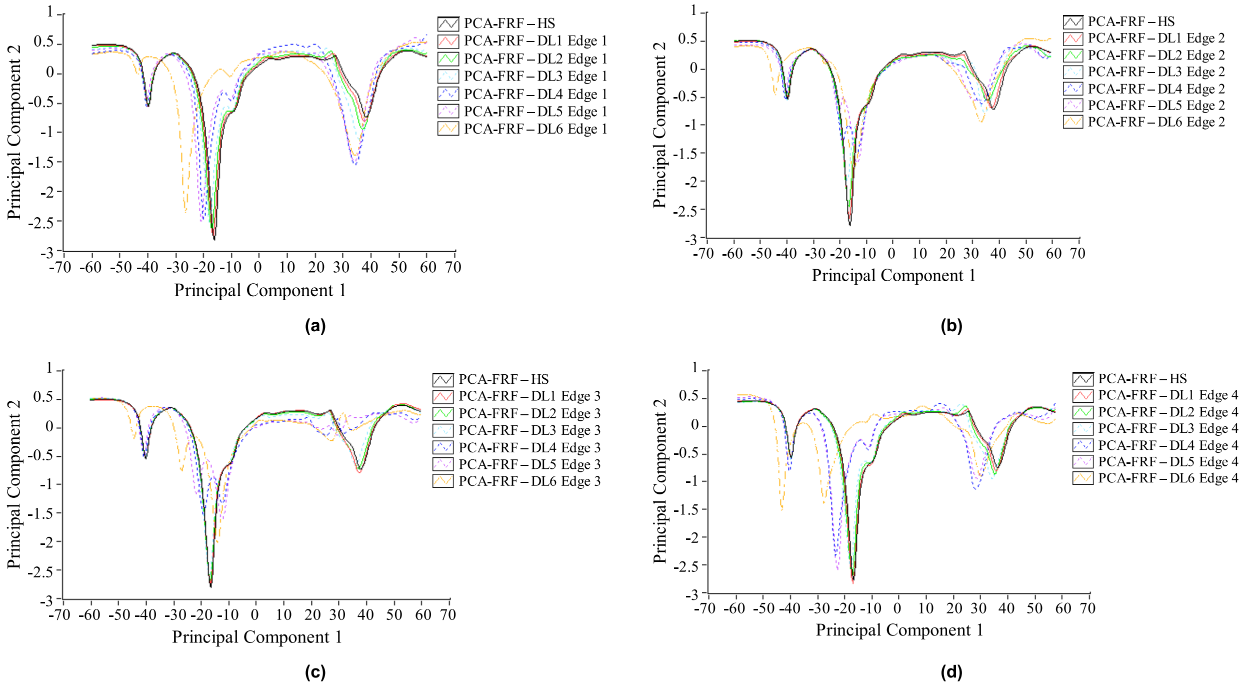
FIGURE 8. Schematic view of the test setup.

build the PCA-FRF for damage assessment. Figure 9 shows the constructed PCA-FRF data for undamaged and damaged states. More information about the conducted feature extraction process can be found in [107] which has been carried out by the co-authors of current study. In this work, the PCA-FRF has been used as the input to develop a secure storage scheme using Blockchain technology.

In this paper a SHM-based approach is presented, utilizing the technical principles of private Blockchains. Blockchain works on a network by many different participants (or nodes) based on transparency. To this end, in Blockchain, a predeveloped interaction is generated by a transaction which is called a block. Information can be exchanged between nodes using this interaction. Then, all nodes are continually synchronized using transactions to grow as blocks. Besides, each block is chained to another using a hash. It should be noted that a cryptographic hash function can produce the hash through running contents of the block [108]. Consequently, the hash of the previous block can be maintained in each block. As a result, any unmatched data or any modification is obviously detectable in the following block. Eventually, a secure network is created using valid data amongst all participants including trusted and untrusted nodes. The only data, which acknowledged by the majority, can consider

TABLE 4. The detailed description of damage cases in the plate-like structure.

Damage Case	Specification					
	Damage Scenario	Damage Location	Tightening Force (N)			
			Edge 1	Edge 2	Edge 3	Edge 4
Healthy State (HS)	All screws tightened	No damage	150	150	150	150
Damage Level 1 (DL1)	Both screws at its respective damage Location loosened	Edge 1	113	150	150	150
		Edge 2	150	113	150	150
		Edge 3	150	150	113	150
		Edge 4	150	150	150	113
Damage Level 2 (DL2)	Both screws at its respective damage location loosened	Edge 1	75	150	150	150
		Edge 2	150	75	150	150
		Edge 3	150	150	75	150
		Edge 4	150	150	150	75
Damage Level 3 (DL3)	Both screws at its respective damage location loosened	Edge 1	38	150	150	150
		Edge 2	150	38	150	150
		Edge 3	150	150	38	150
		Edge 4	150	150	150	38
Damage Level 4 (DL4)	Both screws at its respective damage location loosened	Edge 1	0	150	150	150
		Edge 2	150	0	150	150
		Edge 3	150	150	0	150
		Edge 4	150	150	150	0
Damage Level 5 (DL5)	One screw removed, the other screw loosened at its respective damage location	Edge 1	0	150	150	150
		Edge 2	150	0	150	150
		Edge 3	150	150	0	150
		Edge 4	150	150	150	0
Damage Level 6 (DL6)	Both screws removed at their respective damage location	Edge 1	0	150	150	150
		Edge 2	150	0	150	150
		Edge 3	150	150	0	150
		Edge 4	150	150	150	0



(a) (b) (c) (d)

FIGURE 9. PCA-FRF of healthy case and all damage cases in (a) Edge 1, (b) Edge 2, (c) Edge 3, and (d) Edge 4.

valid. Hence, according to the Blockchain strategy, any entrance of data to the Blockchain cannot be done due to accessibility of all nodes. Therefore, the agreement from the majority is required for any entry in the Blockchain.

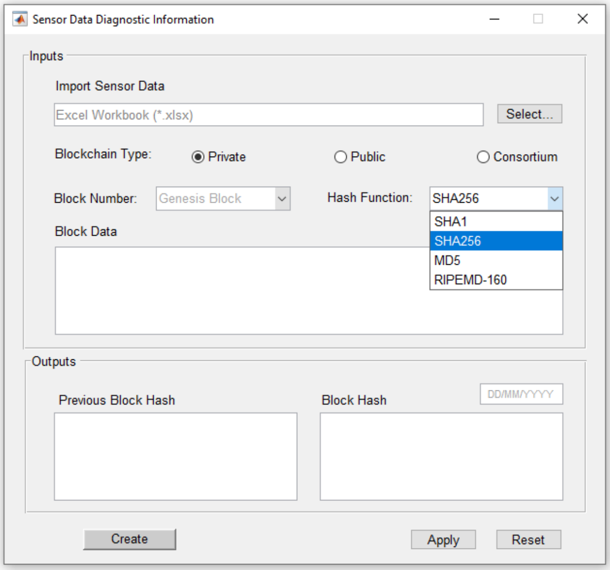
TABLE 5. Block hash results of Blockchain implementation.

Block No.	Block Data	Block Hash	Previous Block Hash
Genesis Block	Undamaged	5dba0392669e39f30245034f870726ac51057116d4a2277dcce7c1baf2568802	_
Block #1	DL1 Edge 1	65835187c58885d379a9759ca9274e223d3f9b3f6c02650f28a590096243a4ed	5dba0392669e39f30245034f870726ac51057116d4a2277dcce7c1baf2568802
Block #2	DL1 Edge 2	36e84e9ba51beca843199a6a21a058760833b57dc699ff00b5a9d64b265b5364	65835187c58885d379a9759ca9274e223d3f9b3f6c02650f28a590096243a4ed
Block #3	DL1 Edge 3	86cdf721c940f1757b5e74fccff0da535b64973dd64098f089d774c3950cce56	36e84e9ba51beca843199a6a21a058760833b57dc699ff00b5a9d64b265b5364
Block #4	DL1 Edge 4	c37e8aea182bb1199e7626cff6abeb64ea4426fd42f64ceba522601ad21e723e	86cdf721c940f1757b5e74fccff0da535b64973dd64098f089d774c3950cce56
Block #5	DL2 Edge 1	5838e8718832eac1253e5c84004ba2a0754d4404d3bd10b316f1cce9cda09a6a	c37e8aea182bb1199e7626cff6abeb64ea4426fd42f64ceba522601ad21e723e
Block #6	DL2 Edge 2	ae5a85f5bf584556415e3a1b91c3a27b7f0e8263ef8081eb0e9deb11188c7114	5838e8718832eac1253e5c84004ba2a0754d4404d3bd10b316f1cce9cda09a6a
Block #7	DL2 Edge 3	0c8ea9ef609c3ed211686561a139fe379bf454b947603ee03bb130c546932483	ae5a85f5bf584556415e3a1b91c3a27b7f0e8263ef8081eb0e9deb11188c7114
Block #8	DL2 Edge 4	db0891038a7c970bd4b3761471339f9086f4ae5d404b2bf72d7c373abf89e2c3	0c8ea9ef609c3ed211686561a139fe379bf454b947603ee03bb130c546932483
Block #9	DL3 Edge 1	64010597f13d51cebe2a3139cd93495babc5bef91720ee04c0b571041291bc0e	db0891038a7c970bd4b3761471339f9086f4ae5d404b2bf72d7c373abf89e2c3
Block #10	DL3 Edge 2	02aa8ecdb5b6b41efdb29a33435e41d21876f5665f992ba484e780fc193cb89c	64010597f13d51cebe2a3139cd93495babc5bef91720ee04c0b571041291bc0e
Block #11	DL3 Edge 3	29d5b6b04185876a8f7772fa98aec15204d5bdf31deec351f780b712f6e6fe20	02aa8ecdb5b6b41efdb29a33435e41d21876f5665f992ba484e780fc193cb89c
Block #12	DL3 Edge 4	710ca949851d164e1283273ddd41fd79275d0c745236bb772d3f480ea5309c17	29d5b6b04185876a8f7772fa98aec15204d5bdf31deec351f780b712f6e6fe20
Block #13	DL4 Edge 1	cfd7b7767e1241c8ac1e6606592fc4c39e84b5a193a6ee1fea45505c1ea3bd35	710ca949851d164e1283273ddd41fd79275d0c745236bb772d3f480ea5309c17
Block #14	DL4 Edge 2	6c36dff31a4135e5bea3fe6b07e06d9bf364306c4db49662257c215ba4881a31	cfd7b7767e1241c8ac1e6606592fc4c39e84b5a193a6ee1fea45505c1ea3bd35
Block #15	DL4 Edge 3	81706b341f03df0146878e43bef96de0a4d192911671a014a55e94a7cb7c05ed	6c36dff31a4135e5bea3fe6b07e06d9bf364306c4db49662257c215ba4881a31
Block #16	DL4 Edge 4	593e8c552cdbab712a434cab4090cd3d5c221d4bdbafc787f44b7902417572b2	81706b341f03df0146878e43bef96de0a4d192911671a014a55e94a7cb7c05ed
Block #17	DL5 Edge 1	d12e45b2a395eb53582af6876825553cfbb8279a663de8c154a91043f8187840	593e8c552cdbab712a434cab4090cd3d5c221d4bdbafc787f44b7902417572b2
Block #18	DL5 Edge 2	04651e4da49ea056caba8f6095ffb8a6e59b74e1dca94112aa085ed2fb3dd338	d12e45b2a395eb53582af6876825553cfbb8279a663de8c154a91043f8187840
Block #19	DL5 Edge 3	92389f155c57c80362027ca76522cd58664670770f3556f9fd6396cc864f2cad	04651e4da49ea056caba8f6095ffb8a6e59b74e1dca94112aa085ed2fb3dd338
Block #20	DL5 Edge 4	0714ff1dc0175f8e6e88df0b28de70e4b5be01220aa75197cc29d628a3cd1da0	92389f155c57c80362027ca76522cd58664670770f3556f9fd6396cc864f2cad
Block #21	DL6 Edge 1	18419ec5d3e88c61e22f617207a5e5a30c6d4a456dd0dca6e39bed7c54351e9c	0714ff1dc0175f8e6e88df0b28de70e4b5be01220aa75197cc29d628a3cd1da0
Block #22	DL6 Edge 2	c5d09c553c5c2501d14723970b8bf058ffc36b07ca2ee73d78998c2351029339	18419ec5d3e88c61e22f617207a5e5a30c6d4a456dd0dca6e39bed7c54351e9c
Block #23	DL6 Edge 3	148e31f8beaf1439dd2535128c43600b20f5b2f6ef7105fb969a0e10a567b2f2	c5d09c553c5c2501d14723970b8bf058ffc36b07ca2ee73d78998c2351029339
Block #24	DL6 Edge 4	bb631ead3761f8ba2870b576ebf1660a18bad4d65c81217cef27732b0241efbd	148e31f8beaf1439dd2535128c43600b20f5b2f6ef7105fb969a0e10a567b2f2

```
1. Import a module to work with dates as well as times.
Begin Definition
    2. Define a Block by making an object class.
    # Block is initialized the attributes of the class using its instance by providing several variables, i.e. an index, a timestamp, some transactions (data), the self-hash (key), and the hash of the previous block.
    3. Import a module to implement common interface to different message digests.
    # Blocks are connected through hashing;
    # Unique digital fingerprint: transaction + previous blocks fingerprint;
    #Hashing method: 'SHA-256'
End Definition
    4. Create Genesis Block
    # Return Block (Previous Block Hash = None)
Repeat
    5. Add a new Block to the chain
    # Create a hash value for an input of any type;
    # Next Index = Length of Blockchain + 1;
    # Add inner and outer hash.
    6. Validate the chain
    # If is Valid Chain (new block), received Blockchain is valid. Replacing current Blockchain with received Blockchain.
    # Else received Blockchain invalid.
Return
    End
```

FIGURE 10. Framework of the developed blockchain algorithm.

For implementation of the Blockchain, a local algorithm was developed to secure the recorded database. The simulation was implemented in Python (Version 3.8.3) using Visual Studio Code (Version 1.47.1) 2020 in 64-bit. Hash functions are key components of Blockchain [109]. The hash value was generated by executing the cryptographic hash function [110]. Nowadays, various hash functions exist, such as Message Digest (MD) family (e.g. MD2, MD4, MD5) designed and developed by Ronald Rivest [111] at Massachusetts Institute of Technology from



Blockchain Type: ● Private ○ Public ○ Consortium

Block Number: Genesis Block

Hash Function: SHA256

FIGURE 11. Proposed visual interface.

1989 until 1991, Race Integrity Primitive Evaluation Message Digest (RIPEMD) family, (e.g. RIPEMD-128, RIPEMD-160, RIPEMD-320) introduced in 1992 and developed in 1996 [112], [113], Whirlpool stemmed from the revised edition of Advanced Encryption Standard (AES) developed by Vincent Rijmen and Paulo Barreto in 2000 [114], and Secure hash algorithm (SHA) family (e.g. SHA-0, SHA-1, SHA-256, SHA-384, SHA-512) developed by the National Institute of Standards and Technology (NIST) and National Security Agency (NSA) in the USA from 1993 until 2014 [115], [116], [117], [118]. In SHA, the performance of hash operations depends on the length of the hashed message. SHA-2 is one of the most powerful, practical, and secure standards in the hash functions families with efficient performance and good resistance for attacks [117], [119]. For example, SHA-256 as an ideal cryptographic hash function has been employed in Bitcoin. SHA-256 is a kind of SHA that generates a 256 bits output from any input [108], [120]. Based on the above descriptions, SHA-256 was considered in this research to generate the hash for each new block. Figure 10 and Table 5 present the framework of the developed Blockchain algorithm and the simulation results, respectively.

VI. FUTURE WORK DIRECTION

In the past few years, close to 90% of real-world data has been generated because of IoT technology [67], [69]. As a matter of fact, this new generation of digital networks has made lots of contributions to our daily life. Other computer-based knowledge discovery technologies such as Blockchain and data mining have also recently gained growing attention in SHM because of their potential ability to be combined with diagnostic systems. However, at the beginning of the new decade, it is time for industrial and academic structural assessment markets to take the next step using the aforesaid emerging technologies. Besides, what all of these technologies have in common is their connection with wireless sensors network (WSN), which eventually could be considered as a practical tool in SHM. Therefore, WSN data can be diagnosed by the emergence of new technologies which has inspired a paradigm shift for the fourth industrial revolution. In this regard, a software interface is proposed to use for future research work, as indicated in Figure 11. The main idea behind the proposed Blockchain-based WSN data diagnostic concept comes from the fact that the emerging technologies are changing the physical world with traditional societies and industries to a huge database system that can support real-time applications.

VII. CONCLUSION

Damage detection using FRF data is one to most significant SHM techniques which has been widely performed in the last decades. The PCA has been also employed by many researchers to improve the practicability of FRFs in damage detection. Therefore, the co-authors of this work have recently developed a novel PCA-reduction method on raw FRFs to build the PCA-FRF. In addition, advanced computational techniques such as Blockchain and data mining have also recently gained growing attention in SHM due to their potential capacity to be integrated with diagnostic systems. To this end, in this research, the constructed PCA-FRF data has been used to develop a Blockchain algorithm. As a result, data security which is one of the main factors in Blockchain technology has been addressed as the main focus of current study. To the best of our knowledge, this is the first attempt to implement a secure storage for SHM data using Blockchain.

REFERENCES

[1] M. Gordan, H. A. Razak, Z. Ismail, and K. Ghaedi, "Recent developments in damage identification of structures using data mining," *Latin Amer. J. Solids Struct.*, vol. 14, no. 13, pp. 2373–2401, 2017.
[2] M. A. Saleh, R. Kempers, and G. W. Melenka, "A comparative study on the electromechanical properties of 3D-printed rigid and flexible continuous wire polymer composites for structural health monitoring," *Sens. Actuators A, Phys.*, vol. 328, Sep. 2021, Art. no. 112764.
[3] H. H. Ghayeb, H. A. Razak, N. H. R. Sulong, K. H. Mo, F. Abutaha, and M. Gordan, "Performance of mechanical steel bar splices using grouted couplers under uniaxial tension," *J. Building Eng.*, vol. 34, Feb. 2021, Art. no. 101892.
[4] A. Majumdar and B. Nanda, "A comparative study on inverse vibration based damage assessment techniques in beam structure using ant colony optimization and particle swarm optimization," *Adv. Sci., Eng. Med.*, vol. 12, no. 7, pp. 918–923, Jul. 2020.
[5] H. P. Wang, H. Chen, C. Chen, H.-Y. Zhang, H. Jiang, T. Song, and S.-Y. Feng, "The structural performance of CFRP composite plates assembled with fiber Bragg grating sensors," *Symmetry*, vol. 13, no. 9, pp. 1–21, 2021.
[6] S. S. Eshkevari, L. Cronin, S. S. Eshkevari, and S. N. Pakzad, "Input estimation of nonlinear systems using probabilistic neural network," *Mech. Syst. Signal Process.*, vol. 166, Mar. 2022, Art. no. 108368.
[7] I. Ahmad and F. U. Khan, "Multi-mode vibration based electromagnetic type micro power generator for structural health monitoring of bridges," *Sens. Actuators A, Phys.*, vol. 275, pp. 154–161, Jun. 2018.
[8] A. E. Bouzenad, M. El Mountassir, S. Yaacoubi, F. Dahmene, M. Koabaz, L. Buchheit, and W. Ke, "A semi-supervised based K-means algorithm for optimal guided waves structural health monitoring: A case study," *Inventions*, vol. 4, no. 1, p. 17, Mar. 2019.

[9] S. M. Berneti and M. Shahbazian, ‘‘An imperialist competitive algorithm artificial neural network method to predict oil flow rate of the wells,’’ *Int. J. Comput. Appl.*, vol. 26, no. 10, pp. 47–50, Jul. 2011.

[10] Y. W. Sasy Chan, H. P. Wang, and P. Xiang, ‘‘Optical fiber sensors for monitoring railway infrastructures: A review towards smart concept,’’ *Symmetry*, vol. 13, no. 12, pp. 1–18, 2021.

[11] T. Wang, B. Shi, and Y. Zhu, ‘‘Structural monitoring and performance assessment of shield tunnels during the operation period, based on distributed optical-fiber sensors,’’ *Symmetry*, vol. 11, no. 7, p. 940, Jul. 2019.

[12] B. Chen, Z. Wu, J. Liang, and Y. Dou, ‘‘Time-varying identification model for crack monitoring data from concrete dams based on support vector regression and the Bayesian framework,’’ *Math. Problems Eng.*, vol. 2017, pp. 1–11, Feb. 2017.

[13] H.-L. Minh, S. Khatir, M. A. Wahab, and T. Cuong-Le, ‘‘An enhancing particle swarm optimization algorithm (EHVPSO) for damage identification in 3D transmission tower,’’ *Eng. Struct.*, vol. 242, Sep. 2021, Art. no. 112412.

[14] C.-U. Nguyen, T.-C. Huynh, and J.-T. Kim, ‘‘Vibration-based damage detection in wind turbine towers using artificial neural networks,’’ *Struct. Monit. Maintenance*, vol. 5, pp. 507–519, Dec. 2018.

[15] A. Mojtahedi, H. Hokmabady, S. S. Z. Abyaneh, and H. Nassiraei, ‘‘Establishment of a hybrid fuzzy–krill herd approach for novelty detection applied to damage classification of offshore jacket-type structures,’’ *J. Mar. Sci. Technol.*, vol. 24, no. 3, pp. 812–829, Sep. 2019.

[16] W. Fan and P. Qiao, ‘‘Vibration-based damage identification methods: A review and comparative study,’’ *Struct. Health Monitor.*, vol. 10, no. 1, pp. 83–111, 2011.

[17] M. Gordan, O. Z. Chao, S.-R. Sabbagh-Yazdi, L. K. Wee, K. Ghaedi, and Z. Ismail, ‘‘From cognitive bias toward advanced computational intelligence for smart infrastructure monitoring,’’ *Frontiers Psychol.*, vol. 13, Mar. 2022, Art. no. 846610.

[18] M. M. Alamdari, J. Li, and B. Samali, ‘‘Damage identification using 2-D discrete wavelet transform on extended operational mode shapes,’’ *Arch. Civil Mech. Eng.*, vol. 15, no. 3, pp. 698–710, May 2015.

[19] Y. Diao, D. Jia, G. Liu, Z. Sun, and J. Xu, ‘‘Structural damage identification using modified Hilbert–Huang transform and support vector machine,’’ *J. Civil Struct. Health Monitor.*, vol. 11, no. 4, pp. 1155–1174, Sep. 2021.

[20] M. Gordan, A. Haddadiasl, A. K. Marsono, and M. M. Tap, ‘‘Investigation the behavior of a four-storey steel frame using viscous damper,’’ *Appl. Mech. Mater.*, vol. 735, pp. 149–153, Feb. 2015.

[21] M. Gordan, ‘‘Experimental investigation of passive tuned mass damper and fluid viscous damper on a slender two dimension steel frame,’’ M.S. thesis, Dept. Struct. Mater., Univ. Technol. Malaysia (UTM), Johor Bahru, Malaysia, 2014.

[22] M. Gordan, M. Izadifar, A. Haddadiasl, J. Ahad, R. Abadi, and H. Mohammadhosseini, ‘‘Interaction of across-wind and along-wind with tall buildings,’’ *Aust. J. Basic Appl. Sci.*, vol. 8, no. 19, pp. 96–101, 2014.

[23] S. K. U. Rehman, Z. Ibrahim, S. A. Memon, and M. Jameel, ‘‘Nondestructive test methods for concrete bridges: A review,’’ *Constructions Buildings Mater.*, vol. 107, pp. 58–86, Mar. 2016.

[24] C. Strzalka and M. Zehn, ‘‘The influence of loading position in a priori high stress detection using mode superposition,’’ *Rep. Mech. Eng.*, vol. 1, no. 1, pp. 93–102, Oct. 2020.

[25] M. Krommer, M. Zellhofer, and H. Irschik, ‘‘Structural health monitoring of multi-storey frame structures using piezoelectric incompatibility filters: Theory and numerical verification,’’ *J. Appl. Comput. Mech.*, vol. 7, pp. 1138–1157, Jun. 2021.

[26] M. Gordan, S.-R. Sabbagh-Yazdi, Z. Ismail, K. Ghaedi, P. Carroll, D. McCrum, and B. Samali, ‘‘State-of-the-art review on advancements of data mining in structural health monitoring,’’ *Measurement*, vol. 193, Apr. 2022, Art. no. 110939.

[27] M. Gordan, Z. B. Ismail, H. A. Razak, K. Ghaedi, and H. H. Ghayeb, ‘‘Optimization-based evolutionary data mining techniques for structural health monitoring,’’ *J. Civil Eng. Construct.*, vol. 9, no. 1, pp. 14–23, Feb. 2020.

[28] M. Gordan, H. A. Razak, Z. Ismail, and K. Ghaedi, ‘‘Data mining based damage identification using imperialist competitive algorithm and artificial neural network,’’ *Latin Amer. J. Solids Struct.*, vol. 15, no. 8, pp. 1–14, Aug. 2018.

[29] T.-C. Le and D.-D. Ho, ‘‘Structural damage identification of plates using two-stage approach combining modal strain energy method and genetic algorithm,’’ in *Modern Mechanics and Applications*. Singapore: Springer, 2022, pp. 1004–1017.

[30] M. Li, D. Jia, Z. Wu, S. Qiu, and W. He, ‘‘Structural damage identification using strain mode differences by the iFEM based on the convolutional neural network (CNN),’’ *Mech. Syst. Signal Process.*, vol. 165, Feb. 2022, Art. no. 108289.

[31] B.-D. Nguyen and H.-A. Pham, ‘‘Fuzzy structural identification of bar-type structures using differential evolution,’’ in *Modern Mechanics and Applications*. Singapore: Springer, 2022, pp. 1033–1051.

[32] A. Meixedo, J. Santos, D. Ribeiro, R. Calçada, and M. D. Todd, ‘‘Online unsupervised detection of structural changes using train–induced dynamic responses,’’ *Mech. Syst. Signal Process.*, vol. 165, Feb. 2022, Art. no. 108268.

[33] Y. C. Zhu, W. Xiong, and X. D. Song, ‘‘Structural performance assessment considering both observed and latent environmental and operational conditions: A Gaussian process and probability principal component analysis method,’’ *Struct. Heal. Monit.*, vol. 2022, pp. 1–16, Jun. 2022.

[34] W. Liu, X. Wu, L. Zhang, Y. Wang, and J. Teng, ‘‘Structural health-monitoring and assessment in tunnels: Hybrid simulation approach,’’ *J. Perform. Constructed Facilities*, vol. 34, no. 4, pp. 1–13, Aug. 2020.

[35] H. H. Ghayeb, H. A. Razak, N. H. R. Sulong, A. N. Hanoon, F. Abutaha, H. A. Ibrahim, M. Gordan, and M. F. Alnahhal, ‘‘Predicting the mechanical properties of concrete using intelligent techniques to reduce CO_2 emissions,’’ *Mater. Construct.*, vol. 69, no. 334, pp. 1–20, 2019.

[36] S. Kim, D. M. Frangopol, and B. Zhu, ‘‘Probabilistic optimum inspection/repair planning to extend lifetime of deteriorating structures,’’ *J. Perform. Constructed Facilities*, vol. 25, no. 6, pp. 534–545, 2011.

[37] H. Monajemi, ‘‘Model updating and damage detection of frame structures using output-only measurements,’’ Ph.D. thesis, Dept. Civil Eng., Univ. Malaya, Kuala Lumpur, Malaysia, 2018.

[38] K. Ghaedi, M. Gordan, Z. Ismail, H. Hashim, and M. Talebkhah, ‘‘A literature review on the development of remote sensing in damage detection of civil structures,’’ *J. Eng. Res. Rep.*, vol. 20, pp. 39–56, Jul. 2021.

[39] C. Luo, L. Yu, J. Yan, Z. Li, P. Ren, X. Bai, E. Yang, and Y. Liu, ‘‘Autonomous detection of damage to multiple steel surfaces from 360° panoramas using deep neural networks,’’ *Comput.-Aided Civil Infrastruct. Eng.*, vol. 36, no. 12, pp. 1585–1599, Dec. 2021.

[40] M. Gordan, Z. Ismail, K. Ghaedi, Z. Ibrahim, H. Hashim, H. H. Ghayeb, and M. Talebkhah, ‘‘A brief overview and future perspective of unmanned aerial systems for in-service structural health monitoring,’’ *Eng. Adv.*, vol. 1, no. 1, pp. 9–15, Feb. 2021.

[41] H. Salehi, S. Das, S. Biswas, and R. Burgueño, ‘‘Data mining methodology employing artificial intelligence and a probabilistic approach for energy-efficient structural health monitoring with noisy and delayed signals,’’ *Expert Syst. Appl.*, vol. 135, pp. 259–272, Nov. 2019.

[42] M. Gordan, ‘‘Data mining for structural damage identification using hybrid artificial neural network based algorithm for beam and slab girder,’’ Ph.D. thesis, Dept. Civil Eng., Univ. Malaya, Kuala Lumpur, Malaysia, 2020.

[43] M. Gordan, S.-R. Sabbagh-Yazdi, Z. Ismail, K. Ghaedi, and H. H. Ghayeb, ‘‘Data mining-based structural damage identification of composite bridge using support vector machine,’’ *J. Artif. Intell. Data Min.*, vol. 9, no. 4, pp. 415–423, 2021.

[44] M. Gordan, K. Ghaedi, Z. Ismail, H. Benisi, H. Hashim, and H. H. Ghayeb, ‘‘From conventional to sustainable SHM: Implementation of artificial intelligence in the department of civil engineering, university of malaya,’’ in *Proc. IEEE Int. Conf. Artif. Intell. Eng. Technol. (IICAIET)*, Sep. 2021, pp. 1–6.

[45] M. Gordan, Z. Ismail, H. A. Razak, K. Ghaedi, Z. Ibrahim, Z. X. Tan, and H. H. Ghayeb, ‘‘Data mining-based damage identification of a slab-on-girder bridge using inverse analysis,’’ *Measurement*, vol. 151, Feb. 2020, Art. no. 107175.

[46] M. Gordan, H. A. Razak, Z. Ismail, K. Ghaedi, Z. X. Tan, and H. H. Ghayeb, ‘‘A hybrid ANN-based imperial competitive algorithm methodology for structural damage identification of slab-on-girder bridge using data mining,’’ *Appl. Soft Comput.*, vol. 88, Mar. 2020, Art. no. 106013.

[47] Z. X. Tan, D. P. Thambiratnam, T. H. T. Chan, M. Gordan, and H. A. Razak, ‘‘Damage detection in steel-concrete composite bridge using vibration characteristics and artificial neural network,’’ *Struct. Infrastruct. Eng.*, vol. 16, no. 9, pp. 1247–1261, Sep. 2020.

[48] A. Nayyar and A. Kumar, *A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development*. Cham, Switzerland: Springer, 2020.

[49] A. Chauhan, S. K. Jakhar, and C. Chauhan, "The interplay of circular economy with industry 4.0 enabled smart city drivers of healthcare waste disposal," *J. Cleaner Prod.*, vol. 279, Jan. 2021, Art. no. 123854.

[50] C.-C. Kuo, J. Z. Shyu, and K. Ding, "Industrial revitalization via industry 4.0—A comparative policy analysis among China, Germany and the USA," *Global Transitions*, vol. 1, pp. 3–14, Jan. 2019.

[51] H. Oliff and Y. Liu, "Towards industry 4.0 utilizing data-mining techniques: A case study on quality improvement," *Proc. CIRP*, vol. 63, pp. 167–172, Jan. 2017.

[52] K. Douaioui, M. Fri, C. Mabroukki, and E. L. A. Semma, "The interaction between industry 4.0 and smart logistics: Concepts and perspectives," in *Proc. Int. Colloq. Logistics Supply Chain Manage. (LOGISTIQUA)*, 2018, pp. 128–132.

[53] M. A. Lazar, Z. Pan, R.-M. Ragguett, Y. Lee, M. Subramaniapillai, R. B. Mansur, N. Rodrigues, and R. S. McIntyre, "Digital revolution in depression: A technologies update for clinicians," *Personalized Med. Psychiatry*, vols. 4–6, pp. 1–6, Dec. 2017.

[54] M. Talebkhah, A. Sali, M. Marjani, M. Gordan, S. J. Hashim, and F. Z. Rokhani, "IoT and big data applications in smart cities: Recent advances, challenges, and critical issues," *IEEE Access*, vol. 9, pp. 55465–55484, 2021.

[55] M. Gordan, Z. Ismail, Z. Ibrahim, and H. Hashim, "Data mining technology for structural control systems: Concept, development, and comparison," in *Recent Trends in Artificial Neural Networks*. London, U.K.: IntechOpen, 2019.

[56] L. L. Benites-Lazaro, L. Giatti, and A. Giarolla, "Topic modeling method for analyzing social actor discourses on climate change, energy and food security," *Energy Res. Social Sci.*, vol. 45, pp. 318–330, Nov. 2018.

[57] S. Nakamoto. (2008). *Bitcoin: A Peer-to-Peer Electronic Cash System*. [Online]. Available: https://Www.Bitcoin.Org

[58] V. S. Kumar and C. Krishnamoorthi, "Development of electrical transduction based wearable tactile sensors for human vital signs monitor: Fundamentals, methodologies and applications," *Sens. Actuators, A Phys.*, vol. 321, Apr. 2021, Art. no. 112582.

[59] S. Gomathi, M. Soni, G. Dhiman, R. Govindaraj, and P. Kumar, "A survey on applications and security issues of blockchain technology in business sectors," *Mater. Today Proc.*, pp. 1–11, Mar. 2021.

[60] Q. Wang and M. Su, "Integrating blockchain technology into the energy sector—From theory of blockchain to research and application of energy blockchain," *Comput. Sci. Rev.*, vol. 37, Aug. 2020, Art. no. 100275.

[61] J. Leng, G. Ruan, P. Jiang, K. Xu, Q. Liu, X. Zhou, and C. Liu, "Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey," *Renew. Sustain. Energy Rev.*, vol. 132, Oct. 2020, Art. no. 110112.

[62] U. Majeed, L. U. Khan, I. Yaqoob, S. M. A. Kazmi, K. Salah, and C. S. Hong, "Blockchain for IoT-based smart cities: Recent advances, requirements, and future challenges," *J. Netw. Comput. Appl.*, vol. 181, May 2021, Art. no. 103007.

[63] A. Hasankhani, S. M. Hakimi, M. Bisheh-Niasar, M. Shafie-khah, and H. Asadolahi, "Blockchain technology in the future smart grids: A comprehensive review and frameworks," *Int. J. Electr. Power Energy Syst.*, vol. 129, Jul. 2021, Art. no. 106811.

[64] M. Kowalski, Z. W. Y. Lee, and T. K. H. Chan, "Blockchain technology and trust relationships in trade finance," *Technol. Forecast. Soc. Chang.*, vol. 166, May 2021, Art. no. 120641.

[65] R. Saranya and A. Murugan, "A systematic review of enabling blockchain in healthcare system: Analysis, current status, challenges and future direction," *Mater. Today, Proc.*, pp. 1–6, Jul. 2021.

[66] R. Chaudhary, A. Jindal, G. S. Aujla, S. Aggarwal, N. Kumar, and K.-K.-R. Choo, "BEST: Blockchain-based secure energy trading in SDN-enabled intelligent transportation system," *Comput. Secur.*, vol. 85, pp. 288–299, Aug. 2019.

[67] H. Zhang, J. Guo, X. Xie, R. Bie, and Y. Sun, "Environmental effect removal based structural health monitoring in the Internet of Things," in *Proc. 7th Int. Conf. Innov. Mobile Internet Services Ubiquitous Comput.*, Jul. 2013, pp. 512–517.

[68] N. M. Kumar and P. K. Mallick, "Blockchain technology for security issues and challenges in IoT," *Proc. Comput. Sci.*, vol. 132, pp. 1815–1823, Jan. 2018.

[69] D. E. Kouicem, A. Bouabdallah, and H. Lakhlef, "Internet of Things security: A top-down survey," *Comput. Netw.*, vol. 141, pp. 199–221, Aug. 2018.

[70] B. Jo, R. Khan, and Y.-S. Lee, "Hybrid blockchain and Internet-of-Things network for underground structure health monitoring," *Sensors*, vol. 18, no. 12, p. 4268, Dec. 2018.

[71] M. Talebkhah, A. Sali, M. Marjani, M. Gordan, S. J. Hashim, and F. Z. Rokhani, "Edge computing: Architecture, applications and future perspectives," in *Proc. IEEE 2nd Int. Conf. Artif. Intell. Eng. Technol. (IICAIET)*, Sep. 2020, pp. 1–6.

[72] F. Casino, T. Dasaklis, and C. Patsakis, "A systematic literature review of blockchain-based applications: Current status, classification and open issues," *Telematics Inform.*, vol. 36, pp. 55–81, Mar. 2019.

[73] F. N. Çatbaş, T. Kijewski-Correa, and A. E. Aktan, *Structural Identification of Constructed Systems: Approaches, Methods, and Technologies for Effective Practice of St-Id*. Richmond, VA, USA: American Society of Civil Engineers (ASCE), 2013.

[74] C. Qu, T. Yi, and H. Li, "Mode identification by eigensystem realization algorithm through virtual frequency response function," *Struct. Control Health Monitor.*, vol. 26, no. 10, pp. 1–19, Oct. 2019.

[75] C.-X. Qu, T.-H. Yi, and H.-N. Li, "Modal identification for superstructure using virtual impulse response," *Adv. Struct. Eng.*, vol. 22, no. 16, pp. 1–9, 2019.

[76] A. G. A. Rahman, Z. C. Ong, and Z. Ismail, "Enhancement of coherence functions using time signals in modal analysis," *Measurement*, vol. 44, no. 10, pp. 2112–2123, Dec. 2011.

[77] L. S. V. K. M. Lee and S. Charles, "Investigation of integrity and effectiveness of RC bridge deck rehabilitation with CFRP composites," Struct. Syst. Res. Project, Univ. California, San Diego, CA, USA, Tech. Rep. SSRP-2004/08, 2004.

[78] J. Hou, L. Jankowski, and J. Ou, "Frequency-domain substructure isolation for local damage identification," *Adv. Struct. Eng.*, vol. 18, no. 1, pp. 137–154, 2015.

[79] H. C. Lim, Z. C. Ong, and A. Brandt, "Implementation of phase controlled impact device for enhancement of frequency response function in operational modal testing," *J. Franklin Inst.*, vol. 355, no. 1, pp. 291–313, Jan. 2018.

[80] H. C. Lim, Z. C. Ong, Z. Ismail, and S. Y. Khoo, "A performance study of controlled impact timing on harmonics reduction in operational modal testing," *J. Dyn. Syst., Meas., Control*, vol. 141, no. 3, Mar. 2019.

[81] Z. C. Ong, H. C. Lim, and A. Brandt, "Automated impact device with non-synchronous impacts: A practical solution for modal testing during operation," *J. Zhejiang Univ. Sci. A*, vol. 19, no. 6, pp. 452–460, Jun. 2018.

[82] A. Rahman, Z. Ismail, S. Noroozi, and Z. Ong, "Enhancement of impact-synchronous modal analysis with number of averages," *J. Vibrat. Control*, vol. 20, no. 11, pp. 1645–1655, Aug. 2014.

[83] F. B. Zahid, Z. C. Ong, S. Y. Khoo, and M. F. M. Salleh, "Inertial sensor based human behavior recognition in modal testing using machine learning approach," *Meas. Sci. Technol.*, vol. 32, no. 11, Nov. 2021, Art. no. 115905.

[84] Z. C. Ong, H. C. Lim, A. Brandt, Z. Ismail, and S. Y. Khoo, "An inconsistent phase selection assessment for harmonic peaks elimination in operational modal testing," *Arch. Appl. Mech.*, vol. 89, no. 12, pp. 2415–2430, Dec. 2019.

[85] S. Chen, Z. C. Ong, W. H. Lam, K.-S. Lim, and K. W. Lai, "Operational damage identification scheme utilizing de-noised frequency response functions and artificial neural network," *J. Nondestruct. Eval.*, vol. 39, no. 3, pp. 1–9, Sep. 2020.

[86] F. B. Zahid, Z. C. Ong, and S. Y. Khoo, "A review of operational modal analysis techniques for in-service modal identification," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 42, no. 8, Aug. 2020.

[87] S. Chilakapati and S. L. J. Mamidala, "Study of vibration transmissibility of operational industrial machines," M.S. thesis Elect. Eng., Dept. Appl. Signal Process., Blekinge Inst. Technol., Karlskrona, Sweden, 2016.

[88] M. Gordan, Z. Ismail, H. A. Razak, and Z. Ibrahim, "Vibration-based structural damage identification using data mining," in *Proc. 24th Int. Congr. Sound Vib. (ICSV)*, London, U.K., 2017, pp. 1–8.

[89] O. R. de Lautour and P. Omenzetter, "Nearest neighbor and learning vector quantization classification for damage detection using time series analysis," *Struct. Control Heal. Monit.*, vol. 17, no. 6, pp. 614–631, 2010.

[90] P. N. Belhumeur, J. P. Hespanha, and D. Kriegman, "Eigenfaces vs. fisherfaces: Recognition using class specific linear projection," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 19, no. 7, pp. 711–720, Jul. 1997.

[91] T. Yiqiu, Z. Lei, and J. Lun, "Analysis of the evaluation indices from TSRST," *J. Mater. Civil Eng.*, vol. 24, no. 10, pp. 1310–1316, Oct. 2012.

[92] H. Lin, H. Li, G. Shao, Y. Ye, and Y. Yang, "Zero-point fault detection of load cells in truck scale based on recursive principal component analysis and comprehensive evaluation method," *Measurement*, vol. 159, Jul. 2020, Art. no. 107706.

[93] C.-Y. Kao and C.-H. Loh, "Monitoring of long-term static deformation data of fei-tsui arch dam using artificial neural network-based approaches," *Struct. Control Health Monitor.*, vol. 20, no. 3, pp. 282–303, Mar. 2013.

[94] G. P. Zhang, "Neural networks for classification: A survey," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.*, vol. 30, no. 4, pp. 451–462, Nov. 2000.

[95] S. Peng, *Blockchain for Big Data: AI, IoT and Cloud Perspectives*. Boca Raton, FL, USA: Taylor & Francis, 2021.

[96] S. Ashurst, S. Tempesta, and S. Kampakis, *Blockchain Applied: Practical Technology and Use Cases of Enterprise Blockchain for the Real World*. New York, NY, USA: Taylor & Francis, 2021.

[97] A. Ibrahim, M. Irfan, I. Huang, and R. C. C. Cheung, "A survey of breakthrough in blockchain technology: Adoptions, applications, challenges and future research," *Comput. Commun.*, vol. 169, pp. 179–201, Mar. 2021.

[98] M. Van Rijmenam and P. Ryan, *Blockchain Transforming Your Business and Our World*. London, U.K.: Taylor & Francis, 2019.

[99] D. Tapscott and A. Tapscott, *Blockchain Revolution: How the Technology Behind Bitcoin is Changing Money, Business, and the World*. New York, NY, USA: Penguin Random House, 2018.

[100] L. Qiao, S. Dang, B. Shihada, M.-S. Alouini, R. Nowak, and Z. Lv, "Can blockchain link the future?" *Digit. Commun. Netw.*, pp. 1–8, Jul. 2021.

[101] L. Severeijns, "What is blockchain? How is it going to affect business?" Vrije Univ., Amsterdam, The Netherlands, Tech. Rep., 2017.

[102] M. Gordan, Z. Ismail, F. A. M. Rahim, O. Z. Chao, Z. Ibrahim, H. Hashim, and L. C. Kiong, "Defining a conceptual framework for vibration-based damage detection platforms using blockchain," *J. Civ. Eng. Mater. Appl.*, vol. 5, no. 1, pp. 25–33, 2021.

[103] A. Esfandiari, M. Nabiyan, and F. R. Rofooei, "Structural damage detection using principal component analysis of frequency response function data," *Struct. Control Health Monitor.*, vol. 27, no. 7, pp. 1–21, Jul. 2020.

[104] L. Hao, P. L. Lewin, J. A. Hunter, D. J. Swaffield, A. Contin, C. Walton, and M. Michel, "Discrimination of multiple PD sources using wavelet decomposition and principal component analysis," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 5, pp. 1702–1711, Oct. 2011.

[105] X. G. Hua, Y. Q. Ni, J. M. Ko, and K. Y. Wong, "Modeling of Temperature–Frequency correlation using combined principal component analysis and support vector regression technique," *J. Comput. Civil Eng.*, vol. 21, no. 2, pp. 122–135, Mar. 2007.

[106] K. Kuźniar and Z. Waszczyszyn, "Neural networks and principal component analysis for identification of building natural periods," *J. Comput. Civil Eng.*, vol. 20, no. 6, pp. 431–436, Nov. 2006.

[107] P. Y. Siow, Z. C. Ong, S. Y. Khoo, and K. S. Lim, "Damage sensitive PCA-FRF feature in unsupervised machine learning for damage detection of plate-like structures," *Int. J. Struct. Stability Dyn.*, vol. 21, no. 2, pp. 1–29, 2021.

[108] J. J. Sikorski, J. Haughton, and M. Kraft, "Blockchain technology in the chemical industry: Machine-to-machine electricity market," *Appl. Energy*, vol. 195, pp. 234–246, Jun. 2017.

[109] T. M. Fernandez-Carames and P. Fraga-Lamas, "Towards post-quantum blockchain: A review on blockchain cryptography resistant to quantum computing attacks," *IEEE Access*, vol. 8, pp. 21091–21116, 2020.

[110] S. Rahmadika and K. H. Rhee, "Blockchain technology for providing an architecture model of decentralized personal health information," *Int. J. Eng. Bus. Manag.*, vol. 10, Jul. 2018, Art. no. 1847979018790589.

[111] R. L. Rivest, "The MD4 message digest algorithm," in *Proc. Crypto*, 1991, pp. 303–311.

[112] A. Bosselaers and B. Preneel, *Integrity Primitives for Secure Information Systems: Final Ripe Report of Race Integrity Primitives Evaluation*. Berlin, Germany: Springer, 1995.

[113] H. Dobbertin, A. Bosselaers, and B. Preneel, "RIPEMD-160: A strengthened version of RIPEMD," in *Proc. Int. Workshop Fast Softw. Encryption*, 1996, pp. 71–82.

[114] P. S. L. M. Barreto and V. Rijmen, "The Whirlpool hashing function," in *Proc. 1st Open NESSIE Workshop*, 2000, pp. 1–20.

[115] A. J. Menezes, *Topics in Cryptology*. San Francisco, CA, USA: Springer, 2005.

[116] E. Andreeva, B. Mennink, B. Preneel, and M. Skrobot, "Security analysis and comparison of the SHA-3 finalists BLAKE, Grøstl, JH, Keccak, and Skein," in *Proc. Int. Conf. Cryptol. Afr.*, 2012, pp. 287–305.

[117] A. A. Alkandari, I. F. Al-Shaikhli, and M. A. Alahmad, "Cryptographic hash function: A high level view," in *Proc. Int. Conf. Informat. Creative Multimedia*, Sep. 2013, pp. 128–134.

[118] P. Pritzker, *SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions*. Gaithersburg, MD, USA: National Institute of Standards and Technology, 2014.

[119] M. Narayan, *Unit-2 Cryptography Mechanisms*. New Delhi, India: The People's Univ.-IGNOU, 2021.

[120] J. Li, J. Wu, and L. Chen, "Block-secure: Blockchain based scheme for secure P2P cloud storage," *Inf. Sci.*, vol. 465, pp. 219–231, Oct. 2018.

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