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A Literature Review on the Development of Remote Sensing in Damage Detection of Civil Structures

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Remote sensing technologies have a direct impact on gaining structural damage information due to their powerful flexibilities, such as wide field of view, non-contact, low cost, and fast response capacities. It is because remote sensing is often applied to monitor near-real-time damage for large-scale events. Therefore, diverse types of remote sensing data became available and various methods have been designed and reported for structural damage assessment. In this line, a number of remote sensing procedures have been proposed to develop an extensive range of temporal, spectral, and spatial parameters. In this study, a comparative review is conducted in order to present the applied remote sensing-based damage detection approaches in buildings and bridges. It should be noted that the survey is supported by an extensive list for up-to-date references. Based on this review, it can be concluded that remote sensing has widely attracted attentions in different structural engineering fields due to its ability in providing fast response in terms of continuous monitoring for large areas after a natural hazard.

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1. INTRODUCTION

In recent years, there has been a vast theoretical and experimental investigations in various problems encountered in different structures, from basic structural components to complex structural systems (e.g., bridges and buildings). This is due to the fact that structures are built to support a load, namely static or dynamic loads. In this direction, many structures need to be designed to withstand dynamic loads even though they spend most of the time supporting static loads. Static loads are those that are gradually applied and remain in place for longer duration of time. These loads are not time dependent. As an illustration, a live load on a structure is considered as a static load. Besides, most of the loadings applied to civil engineering structures, include seismic loadings are usually considered as equivalent static loads [1,2]. On the other hand, time dependent dynamic loads such as machinery vibrations, earthquakes, wind storms, sea waves, and traffic can cause intensive and continuous vibrational motions which can cause changing of the structural properties (i.e. mass, stiffness or damping) and lading to change in the dynamic responses, such as natural frequencies, mode shapes and damping ratios [3,4]. Therefore, in-service structural systems in civil engineering such as tall buildings, long hydraulic structures, and long span bridges are damage-prone under these loads during their service life [5–10]. Moreover, these loads can cause intensive and stable vibrational motions, which can be damaging to human inhabitants. Based on these explanations, vibration is a serious concern in civil structures. It is due to the fact that existence of damage can disturb functionality and safety of the structure [11].

Our planet is constantly affected by natural events, i.e. earthquakes, wind excitations, floods, tsunamis, thunder, and drought which can cause severe damage [12–15]. Therefore, rapid, reliable and operative structural health monitoring (SHM) and damage detection systems are crucial to decrease casualties and loss after mentioned disasters [16]. In this regard, remote sensing is a powerful tool to identify damage. This is due to the fact that remote sensing is able to arrange a fast response. It can also provide monitoring of large areas after the disaster [17].

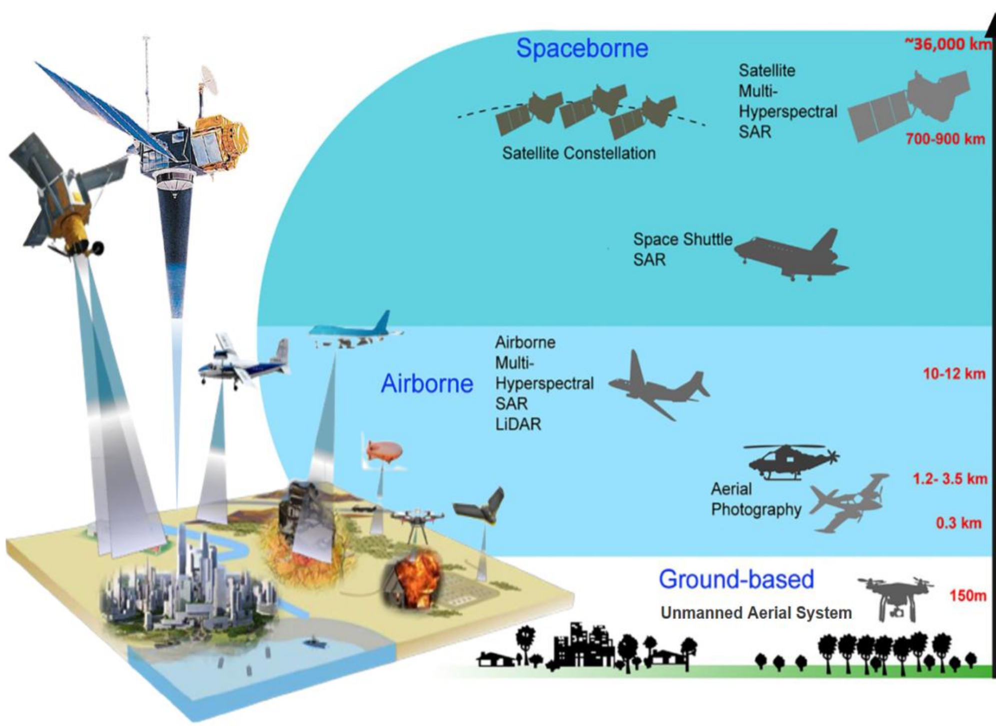


Fig. 1. Remote sensing platforms [23]

Remote sensing using spaceborne or airborne sensors has been frequently operated for real-time monitoring of civil structures [18]. A number of remote sensing procedures have been proposed to develop an extensive range of temporal, spectral, and spatial parameters. For the past fifty years, several Commercial Remote Sensing (CRS) and Spatial Information (SI) technologies for wide-bandwidth spectral information sensing and imaging have been developed integrally with satellite/airborne/ground-based surveillance platforms such as IKONOS, Quickbird, OrbView-3, SPOT, orthotropic and small-format aerial photography, Synthetic Aperture Radar (SAR), Light Detection And Ranging (LiDAR) scans and optical image technologies [19]. Fig. 1 demonstrates the remote sensing platforms along with their distance from the ground. In recent years, a high demand from academic and industrial fields has requested to apply remote sensing-based damage detection. In this regard, a number of strategies and schemes have been developed for structural damage assessment [20–22].

A number of researchers have reported the applicability of remote sensing techniques and technologies to benefit structural health monitoring methods. Based on the above explanation, the state-of-the-art advances of remote sensing in damage detection of civil structures are reviewed in this paper. The followings are covered in the subsequent sections: a brief background of remote sensing is presented in Section 2, while its damage detection-based applications are detailed in Section 3. Section 4 is addressed the limitations and future challenges of remote sensing. Finally, the conclusion is drawn in Section 5.

2. BACKGROUND

Remote sensing is defined as the analysis of object properties, area or phenomenon on the earth's surface through data acquired from a device that is not in contact with the object, area, or phenomenon under investigation, i.e. terrestrial aircraft and satellites in order to obtain information about the asset [24]. With the advancement of modern wireless communication technologies, Internet of Things (IoT) has also become a widely used technology in the field of various intelligent services and applications [25]. For example, Wireless Sensor Networks (WSNs), as the basic layer of IoT, can support real-time and continuous remote sensing data transmission which is based on frequency division multiplexing technology [24]. Therefore, they have recently been employed for SHM systems. Figs. 2, 3 and 4 present the components of a remote sensing system, the concept of IoT, and overview of WSNs, respectively. As can be seen from Fig. 4, in the monitoring process, the network of accelerometers is utilized to create a database using response data collection in buildings, bridges, and roads [26].

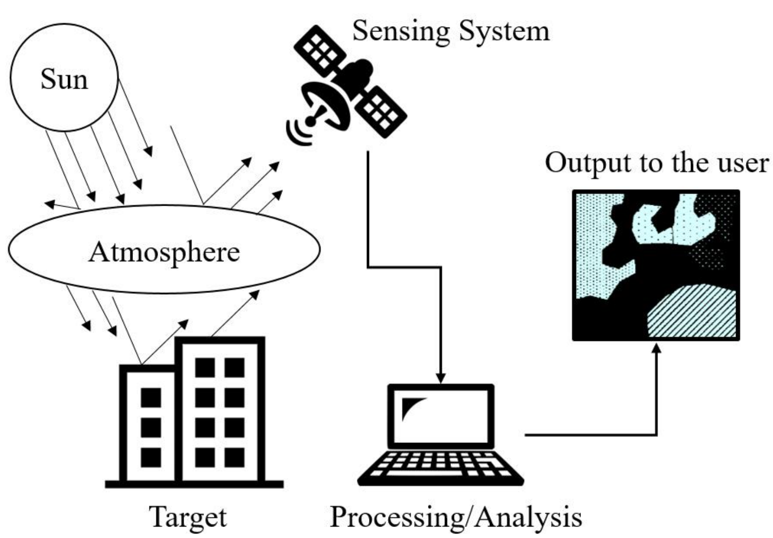


Fig. 2. Components of a remote sensing system

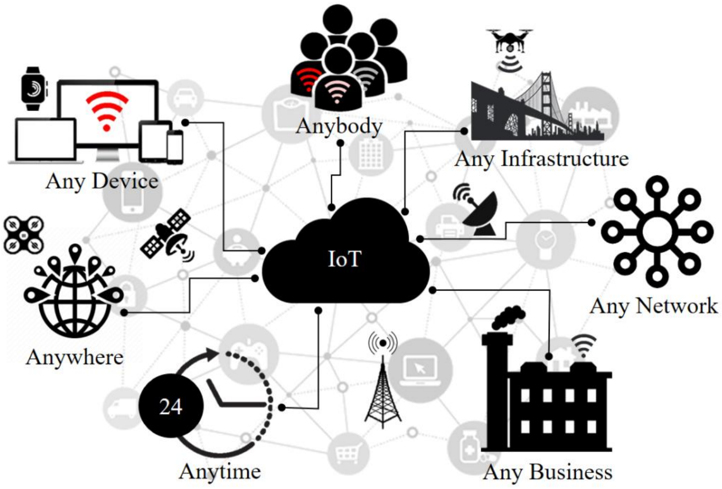


Fig. 3. The concept of IoT [27]

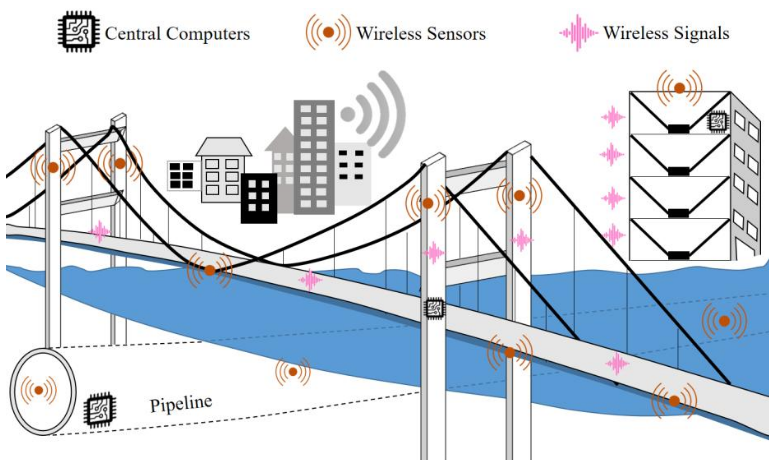


Fig. 4. Wireless sensor networks [26]

Sensors	Type	Examples
Sensors	Active	Synthetic Aperture Radar (SAR), Laser Meter, Photo Conductive Cell, etc.
	Passive	Optical Mechanical Sensor, Radiometer, Photography, Camera, Infrared, etc.
	Temperature	Thermocouple, Thermistor, Resistance Temperature Detector (RTD), etc.
	Pressure	Vacuum, Fiber Optic Pressure, Electronic, etc.
	Image	Complementary Metal Oxide Semiconductor (CMOS), etc.
	Acceleration	Accelerometers, Gyroscope
	Flow	Differential Pressure, Position Displacement, etc.
	Level	Differential Pressure, Ultrasonic Radio Frequency, etc.
	Displacement	Linear Variable Differential Transformer (LVDT), Capacitive, etc.
	Location	Linear Variable Differential Transformer (LVDT), Capacitive, etc.
	Position	Linear Variable Differential Transformer (LVDT), Capacitive, etc.
	Biosensor	Electrochemical, Resonant Mirror, etc.

Fig. 5. Classification of sensors

One of the approaches for structural health monitoring consists of two parts, comprising a sensor network for data collection and data mining for knowledge extraction [3,28,29]. According to [30], "A sensor is a transducer that receives an input signal or stimulus and responds with an electrical signal bearing a known relationship to the input" which can be active, passive, or other types, as shown in Fig. 5 [30,31]. The correlation of data can be obtained by generating patterns in data mining [32,33]. Big data analytics is also able to acquire useful knowledge from massive databases which were recorded by different sensors [27].

Remote sensing contains a wide range of applications. For example, a large-scale dataset, termed "NWPU-RESISC45" was proposed by [34] which comprised 31500 images from 100 countries, covering 45 scene classes with 700 images in each class. Fig. 6 shows two samples of each class from this dataset.

3. REMOTE SENSING APPLICATIONS IN DAMAGE DETECTION

Remote sensing systems have various platforms (i.e. spaceborne, airborne and ground-based) using SAR, LiDAR and optical image technologies. The followings intend to review their recent applications in damage detection of civil structures, i.e. buildings and bridges which carried out by several investigators.

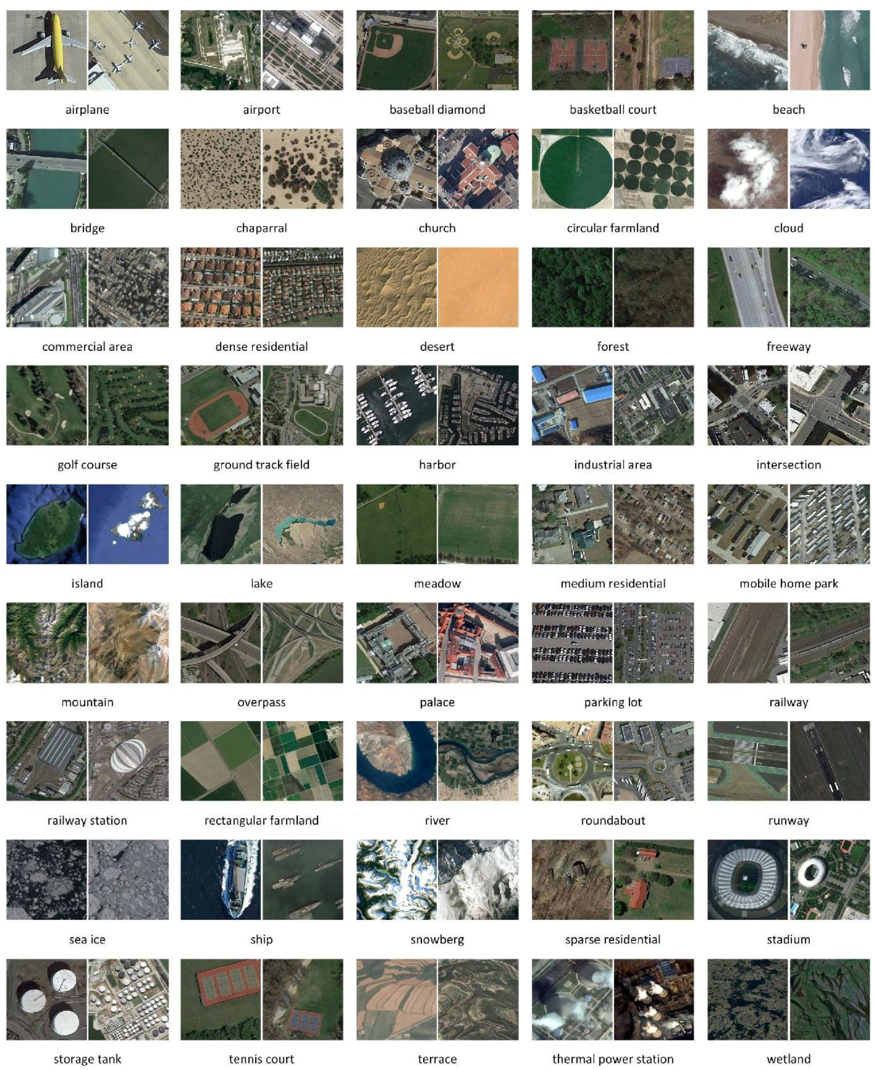


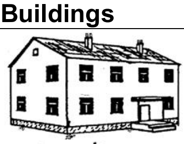
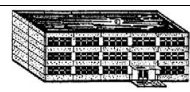
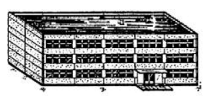
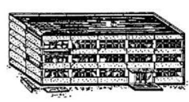
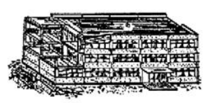
Fig. 6. Example images from the proposed NWPU-RESISC45 dataset [34]

3.1 Building Damage Detection-Based on Remote Sensing

Earthquakes are one of the extremely catastrophic natural disasters to affect mankind [35–38]. Building damage identification is the most serious engineering concern after each earthquake event. This is because it is significant to know the location, severity and depth of damages for rescue, humanitarian and reconstruction operations in disaster areas. Due to this concern, classification of damage levels in masonry and reinforced buildings has been investigated as reported by [39] (see Table 1). This research also summarized the applicable remote sensing data for building damage assessment. According to their report, data types could be classified in three types, i.e. optical, SAR and LiDAR. The acquisition platform was divided in two parts, i.e. air borne (e.g. unmanned aerial vehicle, airplane, or balloon) and space borne (e.g. QuickBird, Advanced Land Observing Satellite (ALOS), and Satellites for Observation and Communications (SAOCOM)).

A comprehensive review on remote sensing based proxies for urban disaster risk management was carried out by [40]. In this research, a number of examples related to remote sensing-based built-up proxies were presented, as shown in Fig. 7.

Table 1. Damage classification in buildings [39]

Masonry Buildings	Reinforced Buildings	Damage Classification	
		1st level: No structural damage, slight non-structural damage	Negligible to slight damage
		2nd level: Slight structural damage, moderate non-structural damage	Moderate damage
		3rd level: Moderate structural damage, heavy non-structural damage	Substantial to heavy damage
		4th level: Heavy structural damage, very heavy non-structural damage	Very heavy damage
		5th level: Very heavy structural damage	Destruction

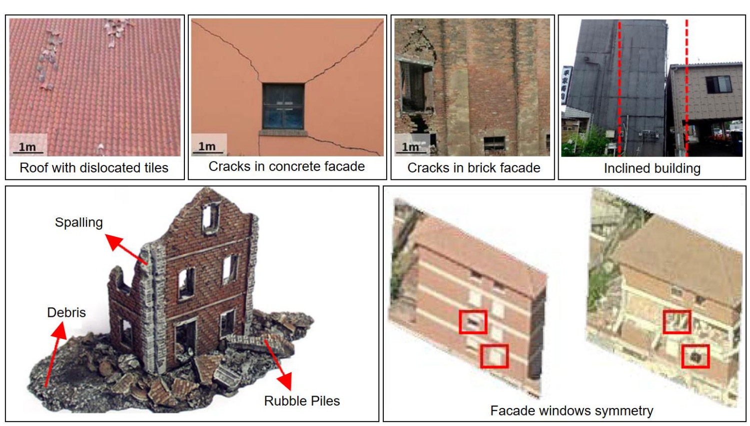


Fig. 7. Examples of remote sensing [40]

Geographic Information Technologies (GIS) is another remote sensing system which can be used for structural damage identification of buildings, right after natural events. Accordingly, a remote sensing system using pre and post event was established by [41] to define automatic detection of damaged buildings in Van Ercis earthquake, which occurred in Turkey on October 2011. In this work, Normalized Digital Surface Models (nDSM) were created using subtracting the Digital Elevation Model (DEM) and Digital Surface Model (DSM) (see Fig. 8). The authors claimed that their method is fast and accurate enough to identify the damaged structures. In Fig. 8, the intact and collapsed buildings after earthquake are shown in green and red colors, respectively. The yellow color polygons represent the buildings that did not exist in the pre-earthquake model.

Another pre- and post-disaster remote sensing building damage detection scheme using a siamese neural network were developed by [42] (see Fig. 9). xBD which is a large-scale dataset of building damage assessment including 850,736 building annotations and covers 45,362 km^2 of images, was employed in this study. The proposed framework is shown in Fig. 9 which divided in two parts, i.e. the pre-disaster images for buildings localization and the damage level classification. It was concluded that their developed strategy was helpful for detection of damaged buildings. Table 2 shows the damage levels and their descriptions which can be detected by provided method. The authors combined different models in order to improve the accuracy on the fusion model and the findings proved that the attention mechanism was effective for the detection of damaged buildings.

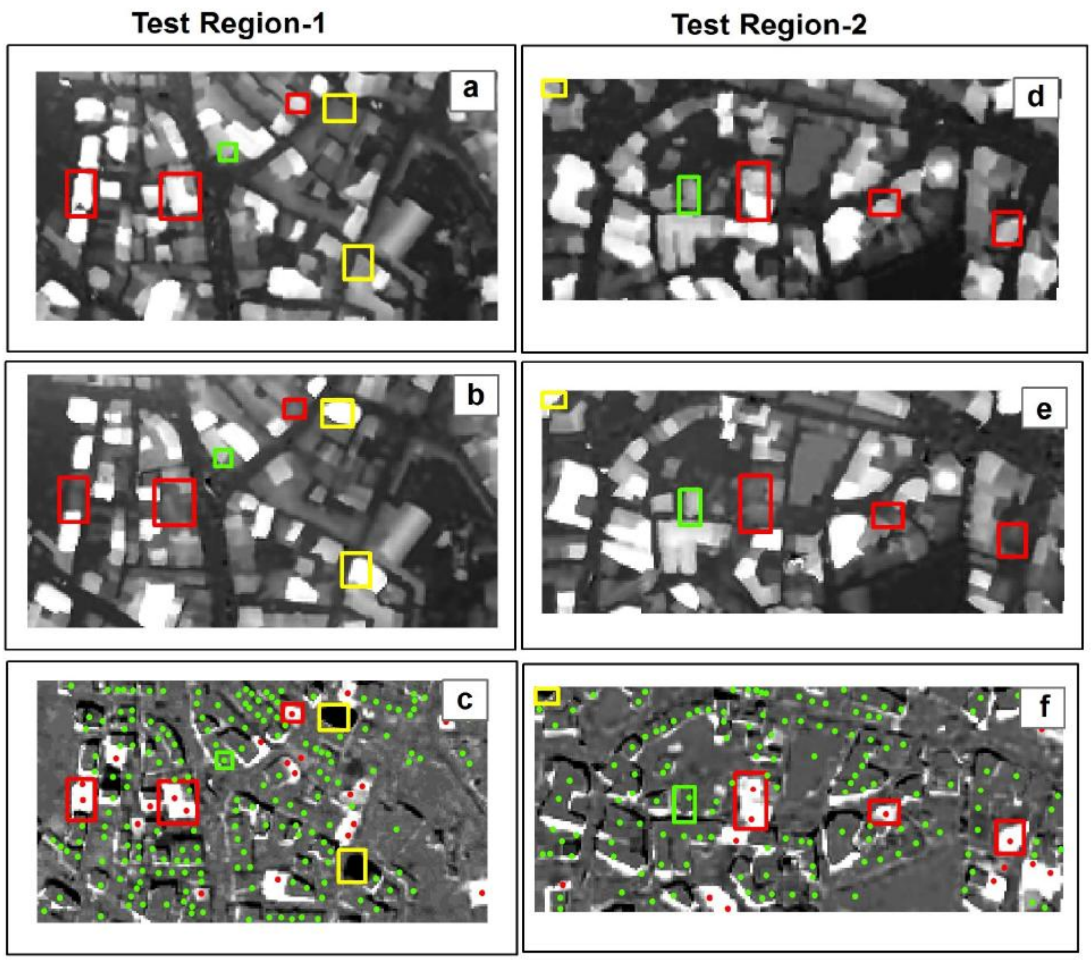


Fig. 8. Test Region-1: (a) 2010 Ndsm, (b) 2011Ndsm, (c) 2010 nDSM -2011 Ndsm, and Test Region-2: (d) 2010 Ndsm, (e) 2011Ndsm, and (f) 2010 nDSM - 2011 nDSM [41]

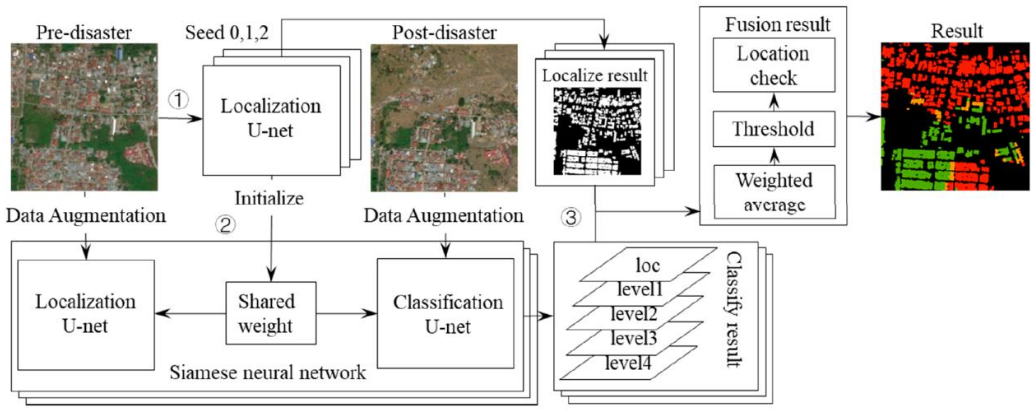


Fig. 9. The proposed building damage detection methodology integrated with remote sensing [42]

Table 2. Detectable components of damaged buildings [42]

Level of Damage		Condition of structural members
0	Undamaged	Intact building without structural damage • No sign of water, fire and crack
1	Slight damage	Missing components in roof, limited visible damage • Burn mark, water surrounding building
2	Major damage	Partial failure in walls and roof, • Building burnt or surrounded by flow / mud
3	Collapsed	Building entirely destroyed • No sign of building existence

3.2 Bridge Damage Detection-Based on Remote Sensing

Satellite Persistent Scatterer Interferometry (PSI) data was employed to develop a novel bridge health monitoring methodology by [43]. In this research, the displacements of bridge structures were assessed for damage detection. The workflow of the proposed strategy is shown in Fig. 10. To demonstrate the performance of the method, the displacement characteristics of two bridges were studied, i.e. the Nanjing-Dashengguan High-speed Railway Bridge (NDHRB) and the Nanjing-Yangtze River Bridge (NYRB) with 1272m and 1576m lengths, respectively. Fig. 11(a) is presenting the location of these bridges, the blue rectangle is NDHRB in China and the yellow rectangle represents NYRB. This Figure also demonstrates the applied burst coverage of SAR data which is showed by red and white rectangles. More details of the aforesaid bridges including their structures, tracks and layouts illustrate in Fig. 11(b-f). For implementation of the proposed method, two separate SAR datasets in were employed in this research. The first and second datasets contain 75 images and 66 images, respectively which were recorded in two years. It should be noted that their outcomes were very much alike (see Fig. 12). As it can be seen from this figure, the topographic error and its statistics using the two tracks were clearly identified. The distribution of the topographic error was also similar in both cases with uniform distribution.

Using Global Positioning System (GPS) is one of the popular technologies to monitor the real-time health condition and structural behavior of bridges. In addition, Galileo Satellite Navigation System (Galileo) with a number of satellites is able to assist GPS technology in order to achieve more accurate results. In this direction, Galileo augmenting GPS was used by [44] to increase the reliability of GPS data. Global Navigation Satellite System (GNSS) datasets obtained from the Forth Road Bridge (FRB) were used in this research. FRB with 2500m length is located in Scotland. The result of this study were employed to detect the local dominant frequencies in (X,Y,Z) directions and (E, N, U) baseline components for four stations (i.e. SHM1, SHM2, SHM3, and SHM4) (see Fig. 13). This Figure also shows the bridge panorama, position deviations, and the distribution of the GNSS sensors.

In recent years, wind engineers have realized the impact of non-synoptic wind events, which have not been appropriately presented in wind loading codes [45]. In this direction, Meng et al. [46] described the background of GeoSHM whish is referring to 'Global Navigation Satellite System and Earth Observation for Structural Health Monitoring of Long-span Bridges' using selected wind and bridge performance data. The authors also performed the GeoSHM sensor system on FRB in Scotland. Fig. 14 illustrates the status of the GeoSHM sensor system installed on the FRB. Using the bridge response and wind speed data collected from the GeoSHM sensor system over a two-year period, this research has demonstrated the susceptibility of the FRB to wind loads. The overview of the GeoSHM system is also summarized in Fig. 15. The GeoSHM dataset was extracted from the predefined GeoSHM data containing sampling frequencies by the University of Nottingham. Then it was utilized for combining with other sub-systems, e.g. wireless sensor networks and optical fibres.

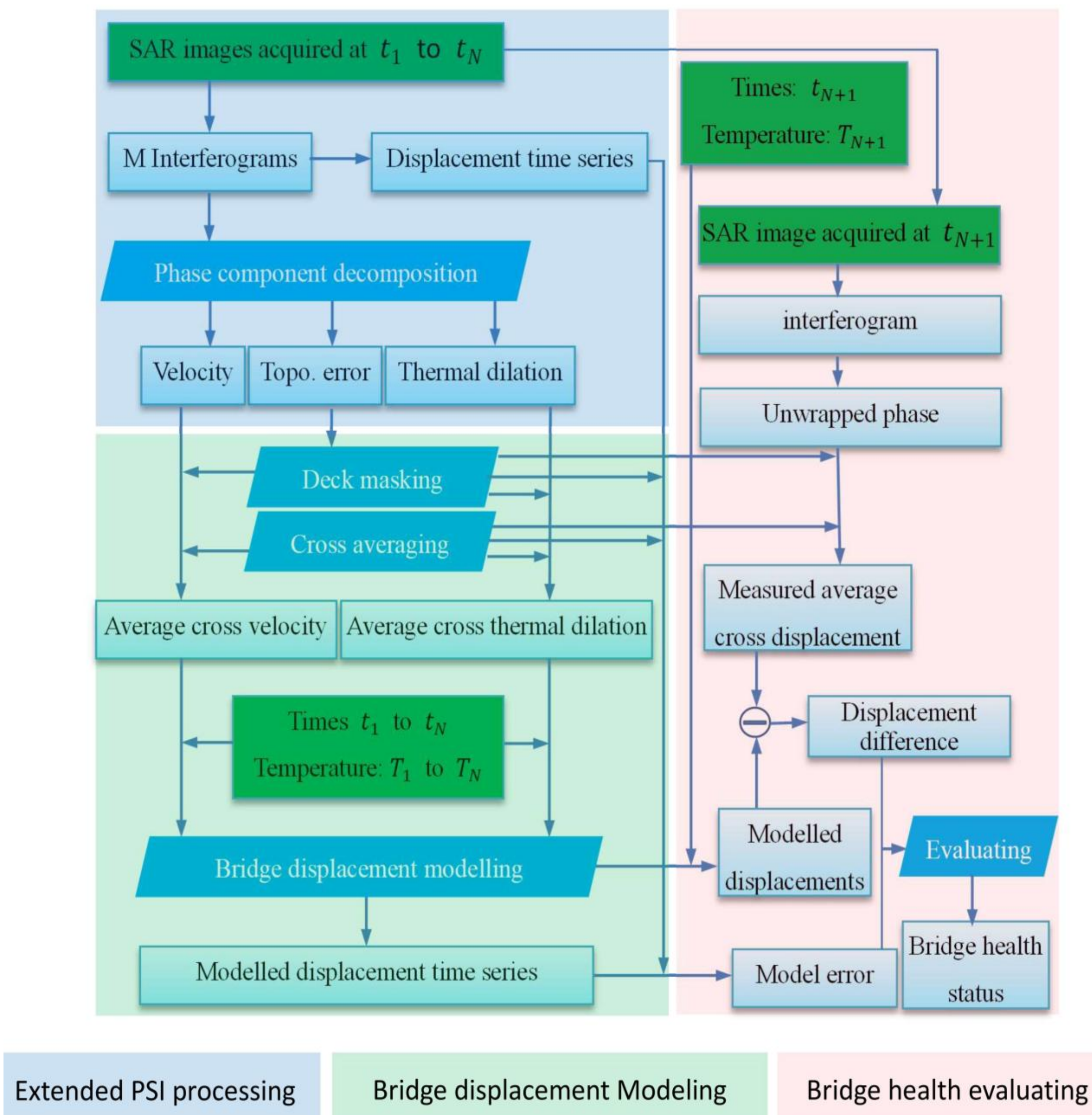


Fig. 10. Flow chart of the proposed methodology by [43]

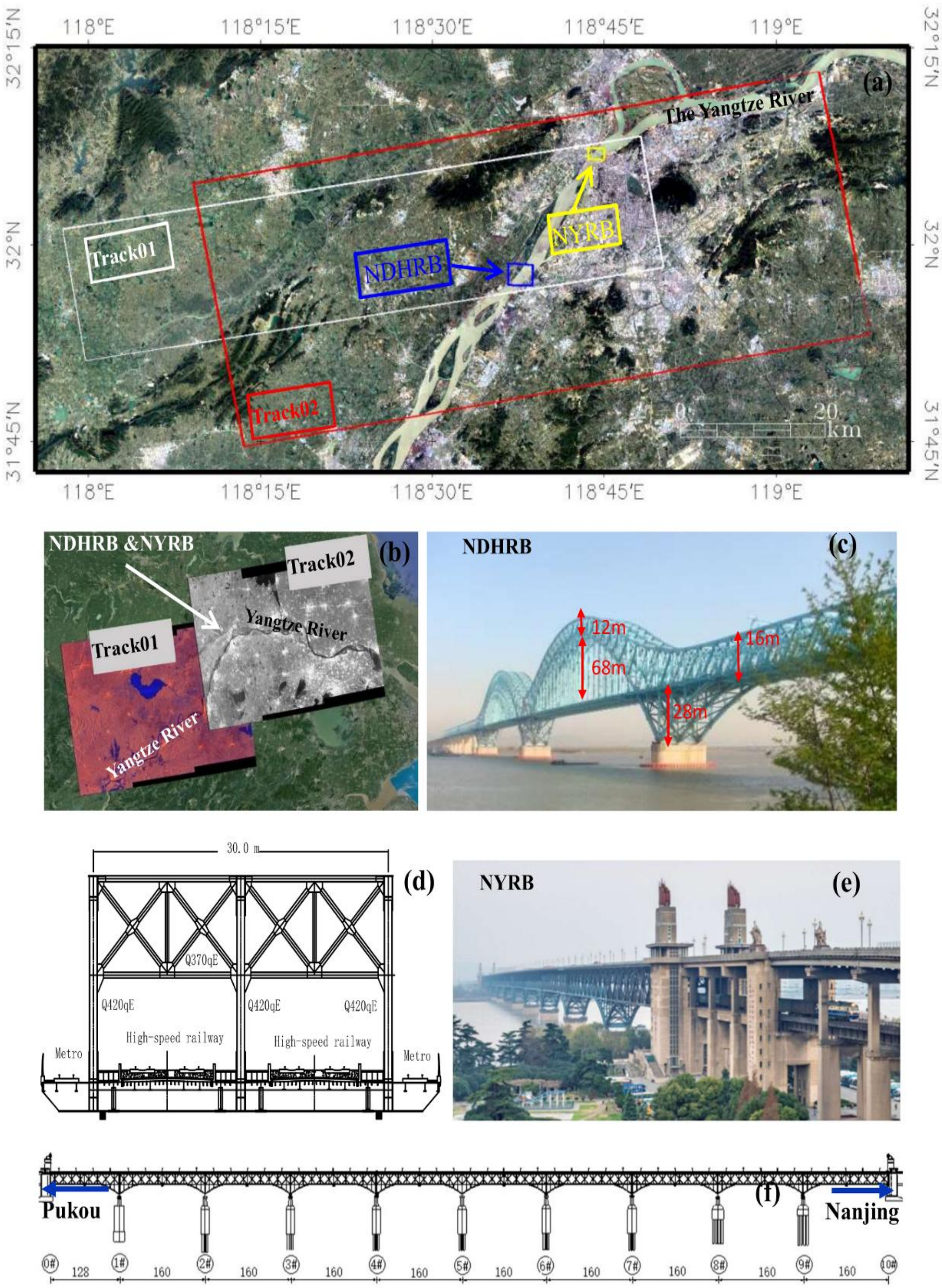


Fig. 11. (a) SAR image presenting the location of bridges and burst coverage, (b) Tracks footprint, (c) NDHRB, (d) NDHRB cross-section, (e) NYRB, and (f) NYRB layout [43]

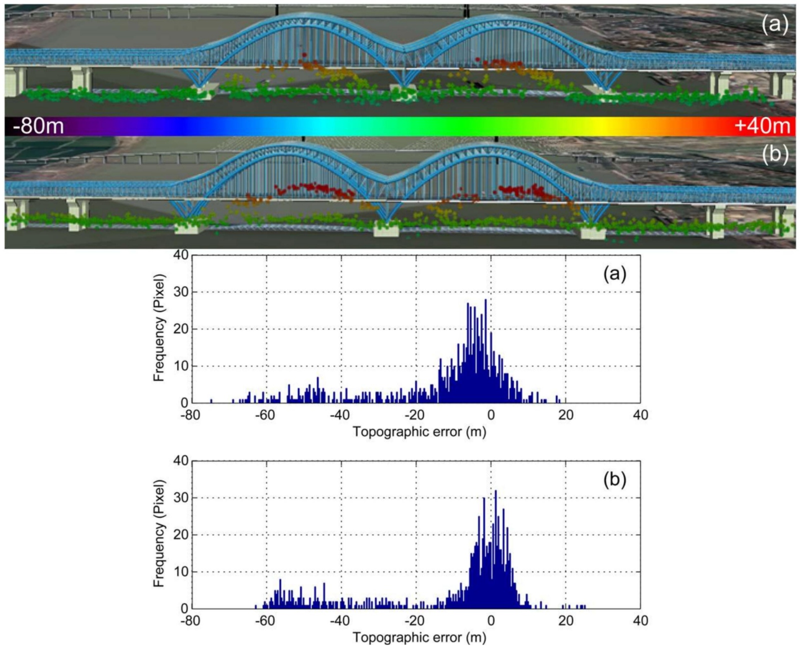
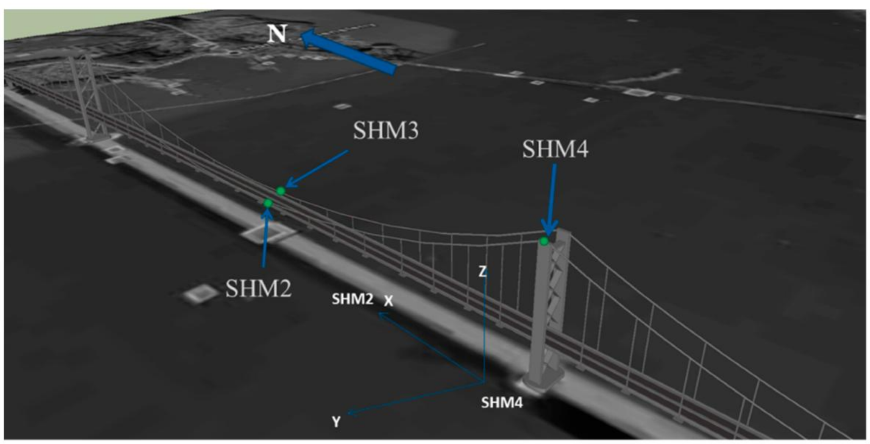
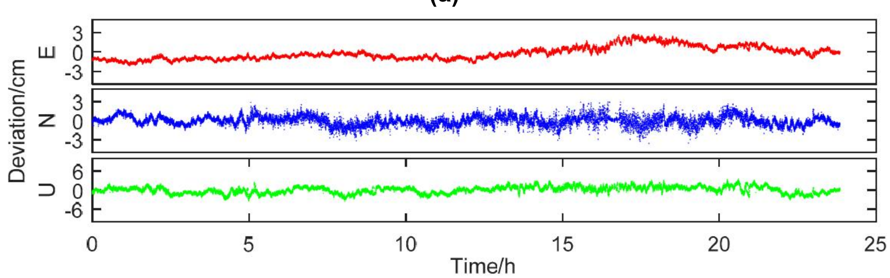


Fig. 12. Estimated topographic errors and their statistics at (a) Track 01, and (b) Track 02. [43]



(a)



(b)

Fig. 13. (a) GNSS sensors and coordinate system definition, and (b) Galileo augmenting GPS position deviations [44]

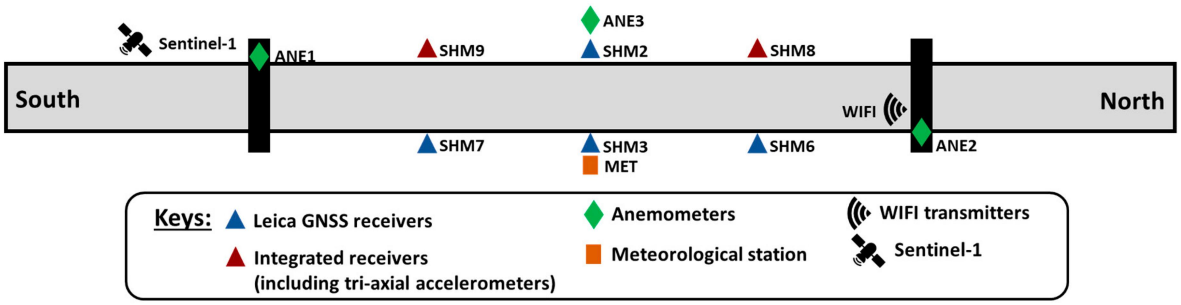


Fig. 14. GeoSHM sensor system of the FRB [46]

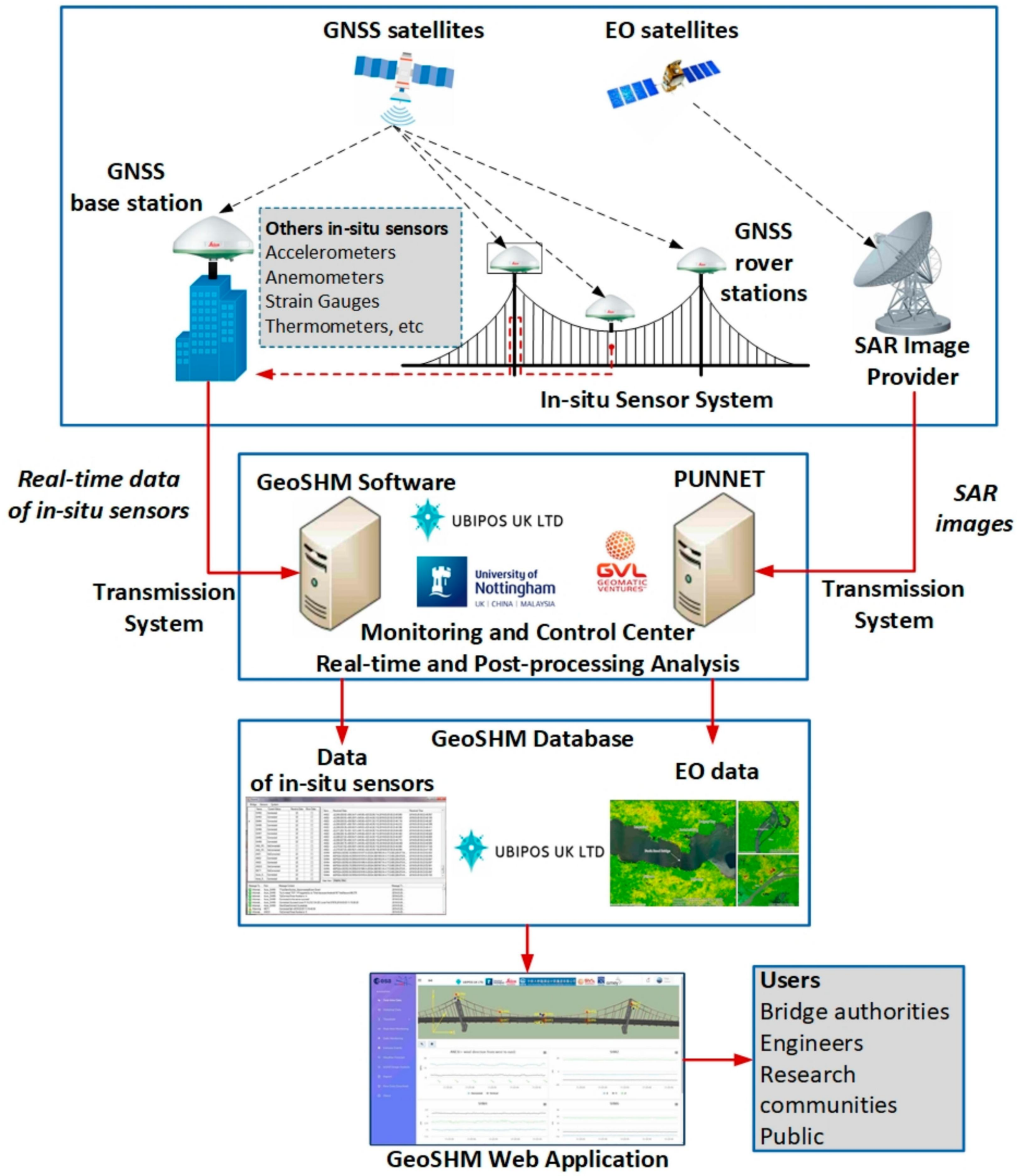


Fig. 15. General structure of the GeoSHM system [46]

The National Building Information Model Standard (NBIMS) described Building Information Modelling (BIM) as ‘‘a digital representation of physical and functional characteristics of a facility and it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward”. Therefore, BIM denotes actual objects. In the same line, Fig. 16 displays the distribution of introduced technologies for data acquisition from real-life processes and integration between virtual models and physical building. As it can be observed from this figure, amongst eight types of technologies, laser scanning was the most used technology for Bridging BIM and Building (BBB) reported by [47]. The research also developed a programmed laser scanning remote sensing approach for BrIM (Bridge Information Model) data using the Jacques Cartier Bridge in Canada (see Fig. 17(a-b)). It was concluded that the developed system was able to identify the damaged structural elements fast and accurately due to the object geometry recovery of the laser scanning technique (see Fig. 17(c)). Multiple features such as user specified scan area and density, data filtering, scan scripting, automatic target recognition, automatic extraction, and other tools were provided to ensure the accuracy and reliability of the collected data. A comparison between the as-built and the developed object stage using an Iterative Closest Points (ICP)-based approach was also conducted in this study in order to assure the correctness of the structure.

Inefficient and unreliable damage assessment is a typical drawback of conventional non-destructive testing (NDT) techniques. As a result, it is required to improve the performance of NDT approaches by using non-contact remote sensing technology in order to have a more accurate damage detection results. Therefore, a laser speckle imaging system (LSIS) has been developed by [48] to achieve remote strain sensing (see Fig. 18(a)). The proposed LSIS was used to investigate the anisotropic properties of un-notched and circular notched specimens in cold-rolled aluminium sheet. An extensometer was used to validate the LSIS results (see Fig 18(b)). It was concluded that the developed remote sensing-based NDT scheme was capable of providing consistent results.

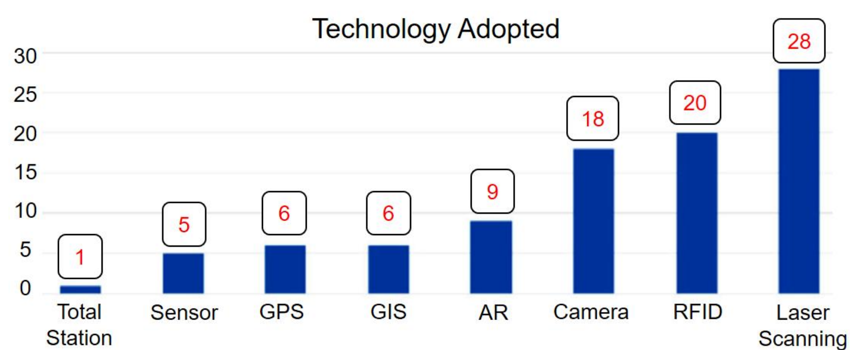


Fig. 16. Technologies for BIM [47]

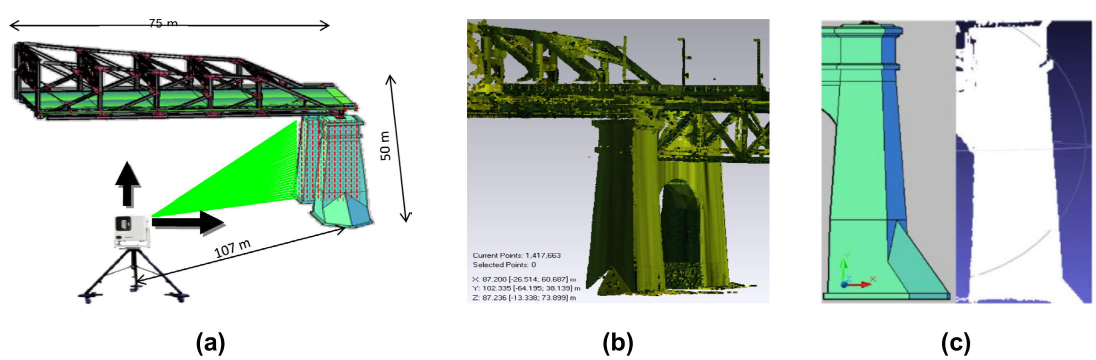
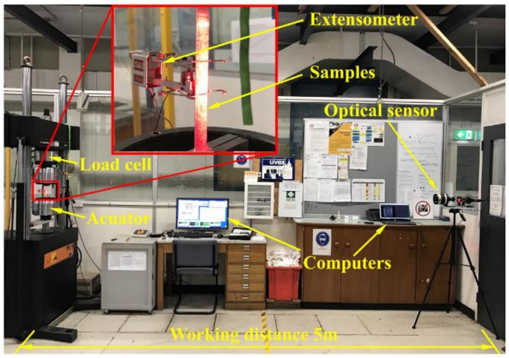
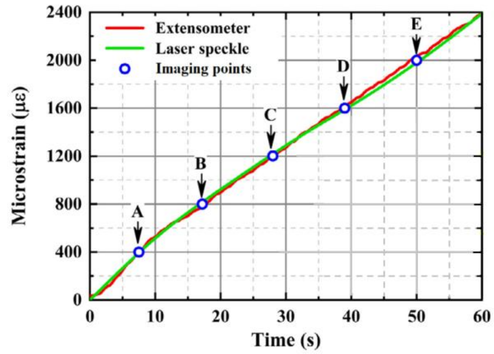


Fig. 17. (a) Layout of the scanning problem, (b) Data acquisition, and (c) BrIM results vs. scanned results [47]



(a)



(b)

Fig. 18. (a) Laboratory test of the laser speckle imaging sensor, and (b) Validation of LSIS results [48]

4. MAJOR PROBLEMS AND FUTURE CHALLENGES

A number of remote sensing strategies have been employed in structural health monitoring, i.e. SAR, LiDAR and optical image technologies. According to [42], the most used remote sensing images belonged to SAR and optical data. It is known that the SAR data is less affected by atmospheric conditions. It has been employed for disaster management and emergency purposes. Therefore, SAR (e.g. backscatter products or phase data of SAR) is one of the most efficient tools in structural damage detection. However, it should be noted that its data processing step is complicated. The processing of optical data is easier than SAR data. Optical images can also deliver an acceptable perspective of target. In addition, it is not difficult to interpret their data. Therefore, different optical-based damage detection methodologies have been developed widely, such as methods based on pixels, objects, machine learning, deep learning, single-temporal and multi-temporal optical images. In spite of this, optical-based remote sensing technology is significantly depending on sun illumination. It means that the optical images can be simply affected by weather conditions (i.e. cloud coverage and shadow effect) which can reduce the applicability of this technology. LiDAR is another remote sensing technology which is able to achieve 3D data from natural events and it can be used in damage detection of civil structures. However, this type of data is not always accessible. A report by [49] demonstrates the ability of radar data for detecting damaged areas under cloud and shadow conditions, as shown in Fig. 19. Table 3 also summarizes the major potentials and challenges of remote sensing technologies.

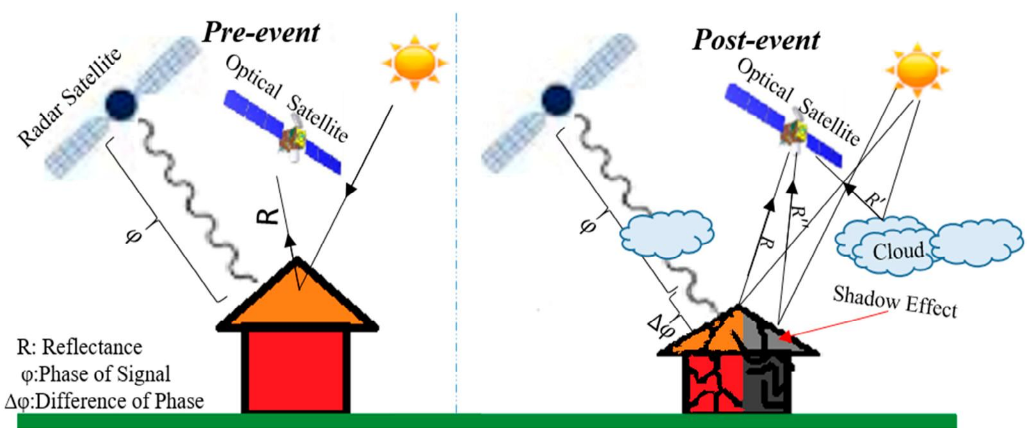


Fig. 19. The ability of radar data for detecting damaged areas under cloud and shadow conditions [49]

Table 3. Summary to the advantages and drawbacks of common remote sensing technologies

Methods	Advantage(s)	Disadvantage(s)
Optical image	• Acceptable perspective of target • Simple data processing • Easy to interpret data • Efficient tool in damage detection	• Depending on sun illumination • Affected by weather conditions • Functional in daytime
SAR	• Minimal atmospheric effects • Effective for disaster management • Operational for emergency purposes • Efficient tool in damage detection • Day or night capability	• Complicated data processing • Large datasets • Difficult to interpret data
LiDAR	• Safe data collection method • Suitable for difficult-to-access areas • Effective for natural events • Efficient tool in damage detection • Automated functionality • Fast and accurate • Day or night capability	• Requires experience to operate • Expensive sensors • Very large datasets • Difficult to interpret data

Remote sensing with Unmanned Aerial Systems (UASs) is also a game-changer in various fields such as environmental monitoring, surveillance, aerial photography, digital communications, search and rescue operations and military [50]. Fig. 20 presents several models of UASs for remote sensing. The potential for UAS-based generation of high-quality images of structural details to detect structural damage and support condition assessment of civil structures is very high, particularly in difficult-to-access areas. On the other hand, IoT, Mobile Edge Computing (MEC), and fog computing are changing the physical world with traditional societies and industries to one huge database system which can support real-time applications [25]. In the same line, most applications in the Internet of Drone (IoD) environment assume drones to be flying camera surveillance [52]. Therefore, the potential application of non-contact measurement devices, i.e., UASs, along with IoT technology attracts industrial and academic interest to allow smart damage detection of civil structures. Hence, the traditional SHM needs to upgrade to IoT-based SHM using IoD-based monitor systems, comprising UASs and remote sensing. It is because traditional approaches are challenged by real-time, low-cost and quality-guaranteed SHM.

Fig. 20. A number of UASs for remote sensing: (a) Fixed-wing UAS, (b) Rotary-wing UASs and unmanned helicopters, and (c) Hybrid UAVs, umbrella-UASs, and bionic-UASs [51]

5. CONCLUSION

Remote sensing has been utilized widely for disaster assessment and the detection of damaged civil structures due to its non-contact, low cost, wide field of view, and fast response capacities. Therefore, it can monitor near-real-time damage for large-scale events. In this study, an attempt was made to show the efficiency and applicability of remote sensing in structural health monitoring. Based on the presented literature, a number of researches have focused on applying remote sensing systems to improve SHM techniques for damage assessment of civil engineering structures. The reason for this comes from the fact that the earth is continuously affected by natural disasters with no predictable failure of civil structures, leading to serious concerns, i.e., catastrophic collapse, economic costs, human injuries and death. Hence, remote sensing can provide fast response in terms of continuous monitoring for large areas after the disaster.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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