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Review Article

Application of MEMS-based accelerometer wireless sensor systems for monitoring of blast-induced ground vibration and structural health: a review

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Abstract: Ubiquitous wireless sensor network (WSN) enables low-cost monitoring applications such as blast-induced ground vibration (BIGV) and structural health monitoring (SHM). In particular, monitoring and analysing the ambiguous BIGV waves are essential requisite to control and protect surrounding grievous damage structures. Similarly, improving health and longevity of structures using WSN is a new facet that owes to diminish the low-cost installation. Recent advances in WSNs are forging new prospects for sensors. A variety of intelligent sensors are integrated into the wireless system to monitor environmental, and health of civil infrastructures. Considering the current trends in the area of development of wireless monitoring prototypes, Micro-Electro-Mechanical-Systems (MEMS) accelerometer sensors are widely prevalent owing to the small size and inexpensive. In general, BIGV waves are less intensity and low-frequency signals. Hence, it is essential to select an appropriate accelerometer to detect micro-vibration waves. The study exemplifies a summarised review of recently made MEMS-based accelerometer wireless systems for intelligent and reliable monitoring of BIGV and SHM since the last decade. This research effort focuses on the numerous adopted accelerometers and their characteristics such as sensitivity, noise density, measurement range, bandwidth, resolution, network topologies, and performance of designed systems to analyse the micro-vibration levels comprehensively.

1 Introduction

Vibration and air noise are common environmental issues often faced and described in mining; civil construction; pipeline; shaft; tunnel; quarrying and dam operation where blasting operation is inevitable. The blast-induced ground vibrations may create problems for surrounding residents, dwellings that adversely affect the nearby structures in and around mine area are considered as a severe issue. Thus, it is essential to monitor the effects of ground vibration using high explosives in the blasting process to measure and evaluate for prediction of possible effects. For instance, Singh and Singh [1] pointed out that only small portion of total explosive energy (20–30%) used to fragment and break the rock mass and remaining energy was dissipated in the form of ground vibration, air noise, and back breaks. Currently, various researchers have used conventional monitoring systems (seismographs) such as Minimate Plus, UVS 1500, and MR 202-CE to measure ground vibrations and structural vibration purposes (Fig. 1). These instruments have one or more triaxial geophone sensors to measure the vibration in terms of the peak vector sum. The maximum range of the geophone sensor is up to 254 $\mathrm{mm\,s^{-1}}$. The various seismographs with features applied by researchers to measure the blast-induced ground vibration (BIGV) along with vibration of structures are described in Table 1. Presently, the available monitoring devices are cable-based communication system type and have limitation such as:

- susceptible to failure due to breakage in the wire;
- wire impedance owing to the length of wire not possible to extend;
- cannot transfer the measured data in real-time;
- expensive systems;
- limited storage memory;
- need an expert to operate;
- tedious and time-consuming process.

Thus, development of a real-time, economical, reliable, continuous monitoring and maintenance-free ameliorative solution for BIGV monitoring and structural health monitoring (SHM) is the essential pre-requisite. In recent years, information and communication technologies have been a growing interest and inexpensive micro-electro-mechanical-systems (MEMS) technology that has been enabled in the applications of environmental and industrial monitoring. In addition, these sensors are embedded within the wireless sensor network (WSN). As a result, both MEMS sensors and radio frequency (RF) modules were enhanced thereby transmission abilities have opened the door for the application of vibration measurement with novel methods such as the utilisation of WSNs for the realisation of low-cost monitoring systems. The main objective of integrating various

Fig. 1 *Different seismographs used to measure ground vibration in mines*
(a) Yan *et al.* [2], ***(b)*** Monjezi *et al.* [3], ***(c)*** Shi *et al.* [4], ***(d)*** Ataei *et al.* [5]

Table 1 Types of different seismographs with specifications

Source	Type of seismograph	Recording format, mm s^{-1}	Frequency range, Hz	Sample rate, samples/s	Trigger levels, mm/s	Trigger noise, dB	Memory (no. of events)
Ghasemi [6]	PDAS-100 (portable data acquisition system)	peak vector sum	2–250	300	0.1–250	96	NA
Yan [2]	Instantel – Minimate Pro4	peak vector sum	2–250	1024	0.13–254	88–148	8000
Ghoraba [7]	Instantel-Blast mate III	peak vector sum	2–300	1024	0.1–254	100–148	300
Faradonbeh [8]	Vibra ZEB VM	peak vector sum	2–250	2048	0.01–250	100–148	6000
Monjezi [3]	MR 2002-CE	peak vector sum	1–315	500	0.00007–115	96–130	NA
Kostic [4]	Vibralok type mobile type	peak vector sum	2–250	1000	0.1–200	96–148	NA
Shi [9]	Seismic YBJ-1	peak vector sum	2–250	1024	0.1–250	96–130	NA
Khandelwal [10]	SINCO-6	peak vector sum	6–150	2048	0–500	88–130	NA
Ataei [5]	Instantel-Minimate Plus	peak vector sum	2–300	1024	0.1–254	88–148	300
Afeni [11]	UVS 1500 vibrometer	peak vector sum	0–250	1024	0.05–250	158	NA
Ragam [12]	Instantel-Minimate Plus	peak vector sum	2–300	1024	0.1–254	100-148	300

MEMS sensors within the WSN has been initiated by researchers at the turn of the new millennium.

Few researchers have already remarked the advantages of MEMS technology over conventional monitoring systems [13]. The catastrophic incidents such as flooding, blasting, and earthquake are unenviable and grievously damage to the health of structures. Hence, it is essential to measure the vibration of structure health with a low-cost and reliable monitoring system to know the real-time condition. The aim of an inexpensive SHM system includes enhancement of safety, hazard mitigation, and increment of structure's lifespan. The main contribution of this study compared to current development efforts can be described in many ways:

- Existing conventional instruments along with their specifications and limitations typically discussed based on the previous research literature and survey.
- The survey focuses on a variety of MEMS-based accelerometer systems, platforms, RF modules, and types of network protocols, which are being used practically in vibration measurements as in both the cases blasting in mines and structural health.
- The study mainly focuses on MEMS technology accelerometer sensor characteristics such as the types of involving sensors, noise density, sensitivity, bandwidth (BW), measurement range, and resolution which are more helpful to select an appropriate sensor for specific vibration monitoring applications.

2 Characteristics of a wireless sensor system

Typically, WSN consists of two sections depicted in Fig. 2. They are battery operated transmitter section as well as receiver section associated with PC and/or server. Usually, the transmitter section has been made by four major sub-units: sensing unit, signal condition unit, computational core unit, and radio transceiver to establish wireless communication [15]. The functionality of the receiver section is similar to the transmitter section, however with a reverse functionality. It receives the signal from the transmitter section and the original information is reconstructed by the down-convert procedure before transferring it to a central unit for further processing. The sensing device is the heart of the wireless prototype. It can measure and transform the dynamic acceleration of physical parameters into proportional electrical (voltages) signal. Various sensors are widely used to monitor structures; earthquake; landslide; traffic-induced ground vibration; vibrations caused by pile driving and BIGV includes geophones; accelerometers; velocity sensors; optical; resonance and strain gauges. Sensing devices are embedded in a single board [16]. However, most of the authors deployed only a single sensor to concentrate on the sense of a single physical quantity to increase efficiency and reduce the power consumption [17].

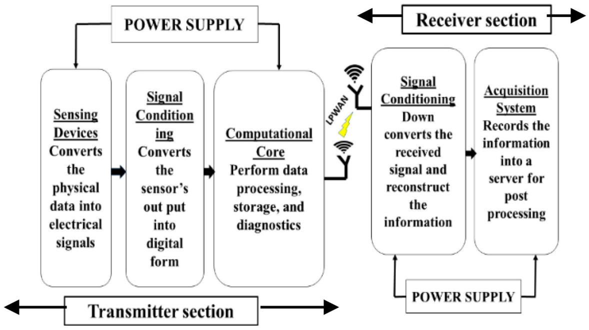

Fig. 2 *Functional architecture of sensing node's transmitter and receiver in a wireless system [14]*

Generally, BIGV signals are dominant at a lower frequency (i.e. <100 Hz). As a result, the measurement and signal processing of low frequency and micro vibration signal needs more challenging than in measuring a high-frequency vibration signal. In particular, to measure low-amplitude and low-frequency vibration signal, high sensitivity, high resolution, and a low noise accelerometer is required. The MEMS-based accelerometer sensors are versatile and available in a variety of sizes, designs, and ranges. In this study, a wide emphasis is given to the important specification of accelerometer sensors such as noise density of sensor (ND), measurement range, sensitivity, and frequency response or BW. The ND is defined as the square root of the power spectral density of the noise output, while sensitivity is the rate of the amount of change in the output signal to change in input acceleration. Table 2 represents the specifications and optimal values of the accelerometer sensor to detect low-amplitude and low-frequency signal [14].

Measurement range describes the amplitude that can be detected and BW represents the range of frequencies operated by the accelerometer sensor. Consequently, the MEMS accelerometer sensor nominal resolution (i.e. smallest detectable amplitude increment in dynamic acceleration) must connect the BW as well as ND in a non-linear manner. Based on the type of application, the MEMS-accelerometers are used for distinct resolutions. For instance, ambient vibration monitoring resolution of $<0.98\ \mathrm{m\,s^{-2}}$ (i.e. for the action of mg) is needed, whereas a resolution on the order of $9.86 \times 10^{-3}\ \mathrm{m\,s^{-2}}$ (i.e. mg) is enough for normal-purpose vibration detection and modal parameter extraction [14].

The signal condition unit is used for converting the analogue output of the sensor to a digital domain, which is processed by a digital electronics technique. Generally, the analogue-to-digital converter (ADC) is responsible to perform this operation. In this unit, amplification, signal filtering, linearisation, and compensation may be performed. Accordingly, the designed sensor board (node) resolution mainly depends on the effective number of ADC, full-

Table 2 Accelerometer sensor specifications and optimal value ranges [14]

Specification	Definition	Optimum value
noise-density, $m\,s^{-2}\,Hz^{-0.5}$	output power spectral density of noise	$<0.49 \times 10^{-3}$
sensitivity, $mV\,m^{-1}\,s^{-2}$	the rate of change output to the acceleration input	>100
measured range, $m\,s^{-2}$	detectable acceleration amplitude range	±14.71
BW, Hz	detectable frequency	0.10–50
resolution, $m\,s^{-2}$	smallest detectable acceleration	0.98×10^{-3}

Table 3 Comparison of existed wireless protocols

Feature	WiMAX	ZigBee	Bluetooth	Wi-Fi	Mobile communication	LoRa
IEEE standard	802.16	802.15.4	802.15.1	802.11 a/c/b/d/g/n	2G-GSM, CDMA,-3G-UMTS, CDMA 2000, 4G-LTE	802.15.4g
operating frequency band	2–66 GHz	868/915 MHz, 2.4 GHz	2.4 GHz	5–60 GHz	865 MHz, 2.4 GHz	915 MHz in the US, 868 MHz in Europe, 433 MHz in Asia
data rate	1 Mb/s–1 Gb/s	40–250 kb/s	1–24 Mb/s	11 and 54 Mb/s	2G: 50–100 kb/s;3G: 200 kb/s;4G: 0.1–1 Gb/s	290 bps–50 kbps
transmission range	<50 km	10–100 m	<10 m	25 m	entire cellular area	2–5 km urban, 15 km suburban, 45 km rural
power consumption	medium	very low	medium	high	medium	very low
cost	high	low	low	high	medium	high
complexity	high	low	high	high	high	low

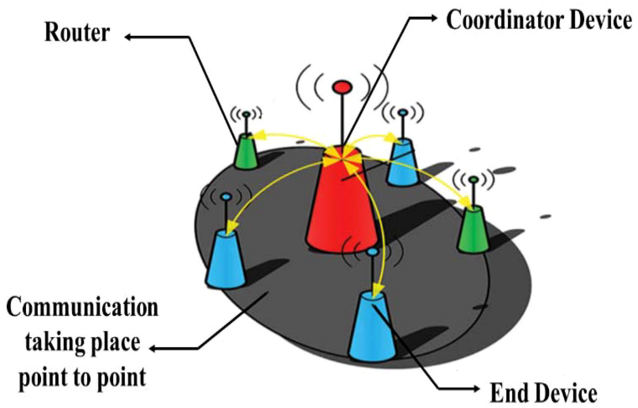

Fig. 3 *Typical single-hop network topology [22]*

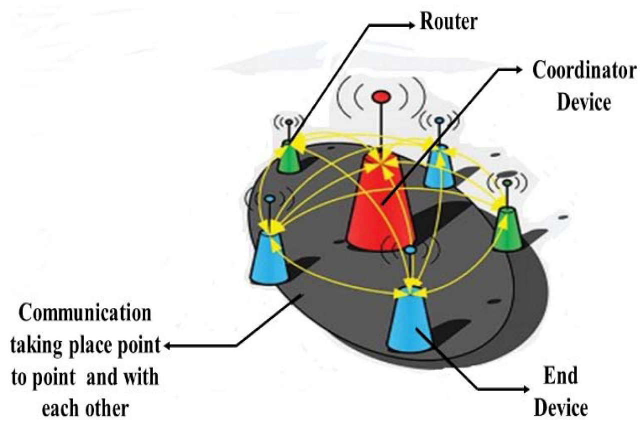

Fig. 4 *Typical multi-hop (tree) network topology [22]*

scale measurement range (volts), and sensitivity of the accelerometer. For BIGV monitoring and SHM applications, an ADC with 16-bit is sufficient to detect micro vibrations. However, some particular applications with higher range values of ADCs are preferable [18]. The computational core is the only major difference between the wire-based system and a wireless system. It consists of a micro-control-unit (MCU) that permits data processing in and on a sensor board as well as checking and measuring on-board cycles. In particular, the size of the MCU decides its performance speed and consumption of power. Hence, high-resolution MCUs are suitable for measuring micro vibration and it may consume 25% of the total board's power [19]. To store measured data, memory is also integrated into computation core to load diagnostic algorithms. Various distinct memory sizes along with algorithms are available to the vibration monitoring.

Finally, a RF is a module used to send and/or receive data. It permits each designed node to communicate with remaining nodes to transfer the measured data. One of the major challenges in mines is that the distance from the blast source point to mine office too long (i.e. around 1 km). Hence, to transmit recorded data need a long-range RF module with high-speed data sampling, high-fidelity sensing, and high-transmission rate is required. Table 3 summarises the different wireless protocols with features [20, 21].

Most of the researchers use single-hop (also named as star topology) and multi-hop (also called *ad hoc*) network topologies for communication. In star topology (Fig. 3), it requires a central top-level node (i.e. gateway) to which all other designed boards are connected and send data solely. This is simple and most commonly adopted method and supports high sampling rate, large data size, precise node-to-node synchronisation. It provides limited data loss as routing the packets only need a queue for all of the nodes to transmit directly to the base station [23].

The main limitations of this topology cannot cover long ranges and spatially limited by the radio range. On the other side, the multi-hop topology (Fig. 4) uses two or more nodes to transmit the data from a sensor board node to the destination. Thus, this method is very complex and versatile connecting intermediary used nodes that convey data and instructions (commands) between two intermediate nodes that are not in the direct radio range. Every intermediate node acts as a transmitter as well as a receiver to retrieve the signal to the gateway. The major advantage of multi-hop is to solve the glitches associated with large-scale sensor deployment. This communication involves not only the ineffective shortest routing path but also the nodes necessary to deliver the correct data. In this regard, the design of the multi-hop network is a non-trivial task [24]. Data loss along with time synchronisation issues (e.g. Jitter, delay, and throughput) may happen if the communicated data among intermediately nodes increases in a multi-hop network. Thus, to enhance sensing accuracy and power consumption, an effective cluster-head type protocol must be considered.

Table 4 Comparison of the developed MEMS-based accelerometer wireless sensor systems [14]

Author	Accelerometer Type	Noise-density, 10^{-3} m s^{-2} $Hz^{-0.5}$	Sensitivity, mV m^{-1} s^{-2}	Measurement range, m s^{-2}	BW, Hz	Resolution, 10^{-3} m s^{-2}	ADC, bit	Type of transmission
Ooi [25]	ADXL-203	0.011	1000	±1.666	0.5–2500	0.005	16	—
Lai [26]	TT-3	—	—	—	—	—	—	single-hop
Ragam [27]	ADXL 345	0.0415	—	±19.61	0.5–1600	—	16	single hop
Pakzad [24]	SD1221	0.05	203.96	±0.98	0.1–25	0.31	16	mutli-hop
Park [28]	SD1221L	0.05	203.96	±19.61	0.1–300	0.62	16	single-hop
Whelan [29]	LISL02AL	0.29	67.30	±19.61	0–50	2.63	12	single-hop
Meyer [30]	LIS2L06AL	0.88	22.43	±58.84	0–100	11.16	12	multi-hop
Chae [31]	AC310-002	0.13	203.96	±19.61	0–300	2.79	16	single-hop
Hu [32]	SD-1221	0.05	203.96	±0.98	0–50	0.44	12	multi-hop
Sabato [33]	SF1600	0.003	122.37	±29.42	0–1500	0.14	—	single-hop
Koler [34]	SF1500	0.003	122.37	±29.42	0.1–1500	0.14	24	multi-hop

3 Related works

In this section, the proposed wireless MEMS-type accelerometer sensor systems along with their specifications are chronologically listed. Few researchers are involved in designing and developing MEMS accelerometer sensor boards to measure the ground vibration (i.e. micro vibration) by performing the blast in mines. Thus, this section not only discusses the monitoring of the BIGV but also other monitoring applications such as structural health using the MEMS accelerometer sensor boards. Table 4 presents their main specifications and comparison among them. The design and developed MEMS-based sensor wireless prototypes for BIGV monitoring application are depicted in Fig. 5.

3.1 MEMS-based accelerometer wireless sensor systems for BIGV monitoring

In 2006, Kwon *et al.* developed a MEMS-based wireless blasting vibration sensor using RF transmission to measure the ground displacement due to tunnel blasting. The designed sensor board is equipped with an accelerometer sensor, which is designed by using MEMS fabrication technology within a range of ±50 m s^{-2}, a data logger, an amplifier circuit, and a ZigBee chip. The designed prototype can sense and measure in two-axis and three-axis and provide a resolution at 10×10^{-3} m s^{-2} for 1000 Hz BW. To evaluate the sensor board performance, conducted a precision test at Korea Testing Laboratory. The main motto of this test was to precisely analyse the capacity of measurement vibration of the designed MEMS-based accelerometer sensor along with a reference accelerometer. The results of the test show a 3% error rate between the designed and reference accelerometer sensor [37]. In 2008, Kim *et al.* proposed an inexpensive wireless and automated data collection (WADC) system including a MEMS-based accelerometer sensor, ADC, and ZigBee module. The developed WADC sensor board especially measure blast-induced ground vibrations for tunnel construction. The WADC was tested by installing 15 nodes over a 20-m long around the tunnel. The PC (i.e. receiver) along with a ZigBee coordinator placed at the pit-mouth of the tunnel receives information in 10-s intervals [36]. In continuation to the previous results, Jung Yeol *et al.* in 2010 developed a tiny, low- cost, accurate sensor board based on TinyOS 2.0 platform embedding MCU, on a 16-bit ADC, a low pass filter and a ChipCon 2420 chip for a RF communication module to monitor the ground vibration due to blasting for tunnel construction. In this, every transmitter node was set up to send the data in a 200 ms interval at a 300 Hz sampling rate [35].

In 2014, Ooi *et al.* used an ADXL 203CE accelerometer manufactured by Analog Devices [38] having a resolution of 0.005×10^{-3} m s^{-2} to measure ground surface vibration during underground blasting. The MEMS accelerometer sensor was used due to low ND (110 m s^{-2} $Hz^{-0.5}$) with a full BW of 2500 Hz. The sensor analogue output signal was processed by a 16-bit ADC with 5 V operating voltage. Due to the above said features, it is adopted

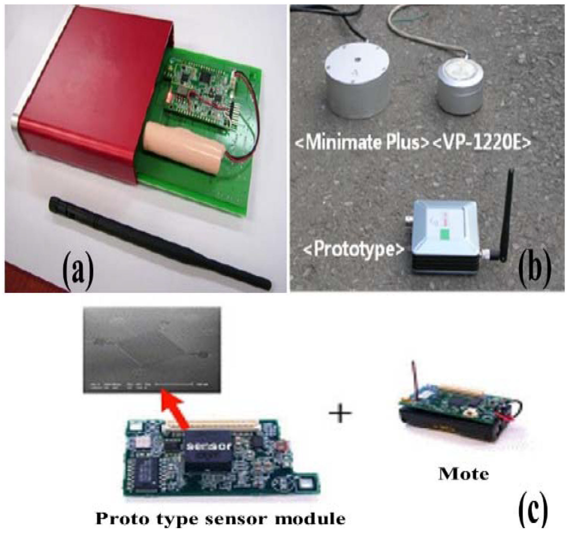

Fig. 5 *Proposed MEMS-based accelerometer wireless sensor prototypes for BIGV monitoring*
(a) Jung Yeol *et al.* [35], ***(b)*** Jung Yeol *et al.* [36], ***(c)*** Kwon *et al.* [37]

for resolving micro vibrations. In their investigation, the two ADXL203 CE were validated and measured at one second interval performed near the blast-radius of the underground blast area at the Anderson Road Development Zone, Hong Kong and recorded the peak acceleration as 4.3 m s^{-1} [25]. In 2014, Lai *et al.* proposed a WSN system to monitor the blast-induced vibration for the tunnel structure. This system is equipped with a UBOX-5016 vibration monitor, a WLS9600 telemetry module and a three-axis velocity sensor. The response of the event was analysed by BM View software. The prototype was tested over one month at a new tunnel, which is located in the existing line K64 + 300–K67 + 700, Xi'an, Shaanxi Province and measuring ground vibration in terms of peak particle velocity (PPV) varying from 2.74 to 11.84 cm s^{-1} at various points [26]. Ragam *et al.* designed and developed a WSN blast-induced vibration-monitoring system, which includes an ADXL 345 accelerometer and ZigBee as an RF module. The prototype was installed along with a minimate plus seismograph at the ACC Dungri lime stone mine, India. The authors monitored the ground vibration in terms of PPV. The recorded PPV varies from 0.191 to 8.60 mm s^{-1} [27].

3.2 MEMS-based accelerometer wireless sensor systems for SHM

A novel wireless sensor solution (WSS) system developed by Whelan *et al.* in 2008 incorporates the Tmote Sky platform. The WSS system was embedded with an ultra-low-power microcontroller unit (16-bit MSP430F16111) by Texas instrument

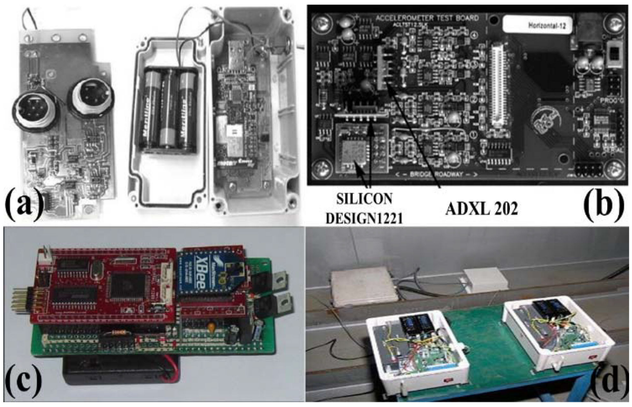

Fig. 6 *Proposed MEMS-based accelerometer wireless sensor prototypes for SHM*
(a) Whelan *et al.* [29], ***(b)*** Pakzad *et al.* [45], ***(c)*** Park *et al.* [28], ***(d)*** Chae *et al.* [49]

and ChipCon CC2420 2.4 GHz transceiver with a data rate of 250 kbps for the establishment of RF transmission to monitor the static and dynamic vibrations of structures [29].

In this WSS, a wireless node consists of a dual-axis LIS2L02AL MEMS accelerometer sensor manufactured by ST Microelectronics [39] along with a strain transducer and powered by three rechargeable battery sets. The system has a signal condition unit including a power gain amplifier to enhance the features of a 12-bit ADC. The power consumption in active mode for the total acceleration-monitoring section was 79.4 mW, whereas for the total strain monitoring section was 106.3 mW. Thus, in active mode, the sensor board's total power consumption was almost equivalent to 185.7 mW. The developed WSS was deployed in the field and tested in the laboratory [40, 41]. In 2008, Pakzad *et al.* proposed a sensor board based on the MicaZ sensor platform. The sensor board was equipped with a dual axis ADXL 202 accelerometer manufactured by Analog Devices [42] and a single-axis low noise SD-1221 MEMS accelerometer by Silicon Design [43]. Later, the sensor board modified by the addition of two low noise single axis SD-1221 sensors along with an ADXL 202 MEMS accelerometer sensor [44].

The SD-1221 accelerometer sensors used to have low ND $\left(0.05\times\ 10^{-3}\mathrm{m\,s^{-2}\ Hz^{-0.5}}\right)$ and high sensitivity $\left(\ 203.96\,\mathrm{mV\,m^{-1}\,s^{-2}}\right)$ to resolve the measurement of micro vibration. The modified sensor board integrated an ATmega 128 MCU, a 16-bit ADC along with a 2.4 GHz XBee module for RF communication. The total power consumed by updating the sensor board was equal to 240 mW. The designed sensor board prototype was validated by installing a 64- node WSN at the Golden Gate Bridge. The results show that it is able to detect the vibrations around an average of about 49.03×10^{-3} m s^{-2} and natural frequencies are starting at 0.11 Hz [45]. Later, the system was installed around four months for monitoring the bridge. Depending on the obtained results and properties of the bridge's modal, the statistical vibration analysis was done [46]. Meyer *et al.* in 2009 developed a prototype depending upon the Tmote Sky platform by integrating the sensor board with a temperature sensor, a humidity sensor and a dual-axis LIS2L06AL MEMS accelerometer by ST microelectronics [47]. Due to the sensor low ND $\left(0.88\times\ 10^{-3}\mathrm{m\,s^{-2}\ Hz^{-0.5}}\right)$ and BW (100 Hz), the achievable resolution was $11.16\times\ 10^{-3}\mathrm{m\,s^{-2}}$. A 12-bit ADC $\left(32.65\times\ 10^{-3}\mathrm{m\,s^{-2}}\right)$ was used to process the output of the accelerometer analogue signal to lower the resolution. The designed prototype was installed with a seven-node WSN using a multi-hop network topology [30] for monitoring the bridge deck vibrations around a period of one year and a half. The obtained results proved the accuracy of estimated values within 5–10% of the evaluated from the data recorded using a wire-based system [48].

Park *et al.* in 2010 proposed a novel acceleration-based smart sensor node (Acc-SSN). The sensor board's computational core having ATmega128 MCU and 16-bit ADC was used along with a 2.4 GHz ZigBee RF module for communication. The sensor board deployed with an SD-1221L single-axis accelerometer [43] with a resolution of $0.62\times\ 10^{-3}\mathrm{m\,s^{-2}}$. The signal condition unit consisted of an amplifier, a high pass filter with a 0.1 Hz cut-off frequency, and an anti-aliasing filter with a 100 Hz cut-off frequency. The developed system was validated by installing a seven-node WSN using a single hop network topology with a distance of a 6-m long on a concrete slab which was excited by an electromagnetic shaker. The results of the Acc-SSN can measure vibrations having an average amplitude of about $196.12\times10^{-3}\mathrm{m\,s^{-2}}$ at 25 Hz first mode frequency [28]. In 2012, Chae *et al.* proposed the u-node, a WSN system embedding multiple sensors including accelerometers, a thermometer, a strain gauge, and a wind gauge. The system was equipped with ES-U2 accelerometers manufactured by Kinematics Inc., an AC310-002 MEMS-based accelerometer manufactured by New Cons Tech Inc. [49], Atmel 128L MCU, 16-bit AD788 ADC (resolution $0.37\times\ 10^{-3}\mathrm{m\,s^{-2}}$), and a ZigBee wireless radio for RF communication. The sensor board was tested on the Yongjong grand Bridge, Korea over a period of 3 months. The final results of the u-node showed that the vibration was recorded with an average amplitude of $196.12\times\ 10^{-3}\mathrm{m\,s^{-2}}$ and evaluated the frequency using the fast Fourier transform (FFT) board as low as 3 Hz [31]. In 2013, Hu *et al.* developed an S-Mote WSN sensor board to measure acceleration and strain of the structure. The prototype consists of an MSP430F1611 MCU, a 12-bit ADC, and a ChipCon CC2420 for RF communication purpose. The sensor board deployed an SD-1221L single-axis accelerometer sensor [43] having low ND and BW subsequently. The system was validated with 250 s measurement performed on the Zhendian Highway Bridge, China. The results showed that the measured vibration has an average amplitude of $19.61\times\ 10^{-3}\mathrm{m\,s^{-2}}$ and observed natural frequencies are below 20 Hz determined by an off-board FFT [32].

Sabato *et al.* in 2014 developed the acceleration evaluator (ALE) sensor board by integrating a single axis SiFlex 1600SN manufactured by Colibrays Inc. [50], a 24-bit ADC as sensing element, a 2.4 GHz RF module for the establishment of a single-hop communication and operated by ±12 V battery. The system was tested in the laboratory to measure vibrations having an average amplitude of 9.81×10^{-3} M s^{-2} and a frequency of 0.2 Hz [33]. The sensor board was used for measuring the behaviour of a stone pinnacle during an earthquake with a peak ground acceleration of 1.56.m . s^{-2} and a natural frequency of 0.77 Hz [51]. Furthermore, ALE performance for SHM purposes is validated by carrying out shaking table tests on the real-size model of a stone pinnacle of the Washington D.C. National Cathedral [52]. In 2015, Hohler *et al.* developed a tea n-nodes wireless system to measure the structural vibration. The system was equipped by a 24-ADC, a digital filter, three SiFlex 1500 [53] manufactured by Colibrays Inc., an analogue modulator. The sensor board consumed 750 mW of the total power. The system is tested with a shaker-table by giving sinusoidal excitation ranging from 0.1 to 90 Hz over a period of 10 s to 2 min [34, 54]. Table 4 shows a summary of developed wireless systems with a MEMS accelerometer by different researchers and a few examples of the proposed MEMS-based accelerometer prototypes are depicted in Fig. 6.

4 Research challenges and future trends

Over the past few decades, conventional monitoring systems have been widely used to measure the ground vibration due to blasting by installing in different open cast mines. The recorded vibration data were used for evaluating PPV, dominant frequency, and natural frequency. Nevertheless, the conventional systems suffer from several drawbacks such as expensive, limited memory, and cannot measure real-time data processing. For such reasons, researchers have come up with a novel technology called WSN based on a MEMS accelerometer sensor for BIGV monitoring and SHM. Selection of an appropriate accelerometer sensor is one of the difficult tasks while designing a system depending on the application. BIGV (i.e. micro vibration) application needs high resolution, high sensitivity, and a low ND MEMS-based accelerometer for accurate monitoring. A WSN made up of one more node and many efforts are made to develop accurate and less energy consumption algorithm for individual processing node task. However, the authors are facing some challenges such as converting the designed sensor boards into pure data acquiring intelligent systems which make the WSN most powerful and efficient [55, 56]. It means the power consumption, reliability of data transmission, BW (i.e. frequency response), and long-range communication are still a big task, which is essential to be addressed to improve the efficiency of the network. Battery life is one of the major challenges because it gives a finite source of energy, which is not sufficient to perform long-time monitoring.

To overcome, use solar batteries, putting sensors in sleep mode and implement energy harvesting algorithms are considered. Similarly, the long-range data transmission reliability is also the problem of the WSN. Usually, the distance between the blast site and the monitoring station is too long (>1 km) and requires one more router (repeaters) to transmit the data to the destination accurately. While in this process, there may be chances of failures such as limited packets are retrieved (i.e. a number of repeaters), failure of a node due to time synchronisation [57]. The WSN was congested and consumed more power when it was measuring a large amount of recorded data. To facilitate, researchers are more concentrated on the design of scalable networks and control algorithms to improve the performance of the network [58] and used long-range RF modules (i.e. LoRa) to establish communication (i.e. up to 45 km for rural areas) [21].

5 Conclusion

The survey elucidates the existing conventional vibration measurement instruments on regular basis in the mining and civil industry. The existing devices have numerous flaws such as relatively expensive, low memory, and do not communicate the vibration information in real time. Hence, there is a requirement for intelligent systems, which can measure the vibration in terms of PPV; in particular, it should be cost-effective, robust, and have the ability of reliable wireless data collection. The major issues in real-time BIGV monitoring and SHM applications are the selection of measuring parameters, efficient sensors, and installation of designed sensor prototypes within mines and buildings.

In this context, a rich collection of MEMS-based accelerometer wireless sensor systems for monitoring of BIGV along with structural health are analysed in a comprehensive manner. Furthermore, discussed several important issues such as types of sensors and their specifications, signal condition, network type, and available wide-range RF protocols, and other devices. This wireless technology has been brought up in the late 2000s and modifications in the technology are going on concurrently. The essential attributes of developed ideal sensor prototypes should be safe, an establishment of reliable communication, accurate measurement and must be robust.

In initial days, the deployed wireless systems are equipped with two-axis, high-noise density, low-sensitivity, and low-resolution ADC MEMS type accelerometer sensor equipped with a ZigBee RF chip for measuring blast-induced ground vibrations. Later, a lot of development has been made to improve the efficiency of sensing and condition unit. Few researchers have made wireless sensor systems by designing high-measurement range, high sensitivity and low noise density MEMS fabricated technology accelerometer sensor coupled with ADC and long-range RF module for monitoring of tunnel induced ground vibrations due to blasting (i.e. WADC). On the contrary, high-resolution and very low-noise single axis MEMS accelerometer sensor integrating with very-high-resolution ADC based sensor prototypes are developed (i.e. Acc-SSN and ALE) for SHM applications. A developed wireless system for BIGV and SHM using either single-hop or multi-hop network topology would be established for a reliable communication (Table 4). Therefore, the implementation of MEMS-based accelerometer wireless sensor systems for both applications such as BIGV monitoring and SHM was considered as an alternative method to replace the conventional systems to measure the micro-vibrations and also enhances the performance, robustness, and provides efficiency. Additionally, reaming research challenges includes increased battery life, proper functioning of deployed systems in harsh environments and future trends are summarised in Section 4.

6 References

[1] Singh, T.N., Singh, V.: 'An intelligent approach to prediction and control ground vibration in mines', *Geotech. Geol. Eng.*, 2005, **23**, (2), pp. 249–262

[2] Yan, P., Lu, W., Zhang, J., *et al.*: 'Evaluation of human response to blasting vibration from excavation of a large scale rock slope: a case study', *Earthq. Eng. Eng. Vib.*, 2017, **16**, (2), pp. 435–446

[3] Monjezi, M., Hasanipanah, M., Khandelwal, M.: 'Evaluation and prediction of blast-induced ground vibration at shur river Dam, Iran, by artificial neural network', *Neural. Comput. Appl.*, 2013, **22**, (7), pp. 1637–1643

[4] Kostić, S., Perc, M., Vasović, N., *et al.*: 'Predictions of experimentally observed stochastic ground vibrations induced by blasting', *PLOS One*, 2013, **8**, (2), p. e82056

[5] Ataei, M., Sereshki, F.: 'Improved prediction of blast-induced vibrations in limestone mines using genetic algorithm', *J. Min. Environ.*, 2017, **8**, (2), pp. 291–304

[6] Ghasemi, E., Kalhori, H., Bagherpour, R.: 'A new hybrid ANFIS–PSO model for prediction of peak particle velocity due to bench blasting', *Eng. Comput.*, 2016, **32**, (4), pp. 607–614

[7] Ghoraba, S., Monjezi, M., Talebi, N., *et al.*: 'Estimation of ground vibration produced by blasting operations through intelligent and empirical models', *Environ. Earth Sci.*, 2016, **75**, (15), pp. 1137–1146

[8] Faradonbeh, R.S., Armaghani, D.J., Majid, M.A., *et al.*: 'Prediction of ground vibration due to quarry blasting based on gene expression programming: a new model for peak particle velocity prediction', *Int. J. Environ. Sci. Technol.*, 2016, **13**, (6), pp. 1453–1464

[9] Shi, X., Qiu, X., Zhou, J., *et al.*: 'A comparative study of ground and underground vibrations induced by bench blasting', *Shock Vib.*, 2016, **2016**, pp. 1–9

[10] Khandelwal, M., Singh, T.N.: 'Evaluation of blast-induced ground vibration predictors', *Soil Dyn. Earthq. Eng.*, 2007, **27**, (2), pp. 116–125

[11] Afeni, T.B., Osasan, S.K.: 'Assessment of noise and ground vibration induced during blasting operations in an open pit mine—a case study on Ewekoro limestone quarry, Nigeria', *Min. Sci. Techol.*, 2009, **19**, (4), pp. 420–424

[12] Ragam, P., Nimaje, D.S.: 'Evaluation and prediction of blast-induced peak particle velocity using artificial neural network: a case study', *Noise Vib. Worldwide*, 2018, **49**, (3), pp. 111–119

[13] Hsu, V., Kahn, J.M., Pister, K.S.: 'Wireless communications for smart dust', Electronics Research Laboratory, College of Engineering, University of California, M98/2, 1998

[14] Sabato, A., Niezrecki, C., Fortino, G.: 'Wireless MEMS-based accelerometer sensor boards for structural vibration monitoring: a review', *IEEE Sens. J.*, 2017, **17**, (2), pp. 226–235

[15] Lynch, J.P., Loh, K. J.: 'A summary review of wireless sensors and sensor networks for structural health monitoring', *Shock Vib. Digest.*, 2006, **38**, (2), pp. 91–130

[16] Jo, H., Sim, S.H., Mechitov, K.A., *et al.*: 'Hybrid wireless smart sensor network for full-scale structural healthmonitoring of a cable-stayed bridge'. Proc. SPIE 7981, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, California, USA, April 2011, **vol. 7981**, pp. 798105–798120

[17] Pakzad, S.N., Kim, S., Fenves, G.L., *et al.*: 'Multi-purpose wireless accelerometers for civil infrastructure monitoring'. Proc. 5th Int. Workshop on Structural Health, Stanford, California, USA, September 2005, pp. 1–8

[18] Wang, D.H., Liao, W.H.: 'Wireless transmission for health monitoring of large structures', *IEEE Trans. Instrum. Meas.*, 2006, **55**, (3), pp. 972–981

[19] Sinha, A., Chandrakasan, A.: 'Dynamic power management in wireless sensor networks', *IEEE Des. Test. Comput.*, 2001, **18**, (2), pp. 62–74

[20] Peng, C., Huang, J.: 'A home energy monitoring and control system based on ZigBee technology', *Int. J. Green Energy*, 2016, **13**, (15), pp. 1615–1623

[21] de Carvalho Silva, J., Rodrigues, J.J., Alberti, A.M., *et al.*: 'LoRaWAN—a low power WAN protocol for internet of things: a review and opportunities'. 2nd Int. Multidisciplinary Conf. on Comput. and Energy Sci., Split, Croatia, July 2017, pp. 1–6

[22] Waseem, M.H., Alamzeb, M., Mustafa, B., *et al.*: 'Design of a low-cost underwater wireless sensor network for water quality monitoring', *IETE J. Res.*, 2013, **59**, (5), pp. 523–534

[23] Mukherjee, B.: 'WDM-based local lightwave networks. I. Single-hop systems', *IEEE Netw.*, 1992, **6**, (3), pp. 12–27

[24] Pakzad, S.N., Fenves, G.L., Kim, S., *et al.*: 'Design and implementation of scalable wireless sensor network for structural monitoring', *J. infrastruct. syst.*, 2008, **14**, (1), pp. 89–101

[25] Ooi, G.L., Wang, Y.H.: 'Applying MEMS accelerometers to measure ground vibration and characterize landslide initiation features in laboratory flume test'. Proc. Geo-Congress 2014 Geo-characterization and Modelling for Sustainability, Atlanta, Georgia, February 2014, pp. 2019–2028

[26] Lai, J., Fan, H., Chen, J., *et al.*: 'Blasting vibration monitoring of undercrossing railway tunnel using wireless sensor network', *Int. J. Distrib. Sens. Netw.*, 2015, **11**, (6), p. 703980

[27] Ragam, P., Nimaje, D.S.: 'Monitoring of blast-induced ground vibration using WSN and prediction with an ANN approach of ACC Dungri limestone mine, India', *J. Vibroeng.*, 2018, **20**, (2), pp. 1051–1062

[28] Park, J.H., Kim, J.T., Hong, D.S., *et al.*: 'Autonomous smart sensor nodes for global and local damage detection of prestressed concrete bridges based on accelerations and impedance measurements', *Smart Struct. Syst*, 2010, **6**, (5–6), pp. 711–730

[29] Whelan, M.J., Janoyan, K.D.: 'Design of a robust, high-rate wireless sensor network for static and dynamic structural monitoring', *J. Intell. Mater. Syst. Struct.*, 2009, **20**, (7), pp. 849–863

[30] Meyer, J., Bischoff, R., Feltrin, G.: 'Microelectromechanical systems (MEMS)', in Boller, C., Chang, F.K., Fujino, Y. (Eds): '*Encyclopaedia of structural health monitoring*' (Wiley, New York, 2009, 1st edn.), pp. 1–10

[31] Chae, M.J., Yoo, H.S., Kim, J.Y.*, et al.*: 'Development of a wireless sensor network system for suspension bridge health monitoring', *Autom. Constr.*, 2012, **21**, pp. 237–252

[32] Hu, X., Wang, B., Ji, H.: 'A wireless sensor network-based structural health monitoring system for highway bridges', *Comput.-Aided Civil Infrastruct. Eng.*, 2013, **28**, (3), pp. 193–209

[33] Sabato, A., Feng, M.Q.: 'Feasibility of frequency-modulated wireless transmission for a multi-purpose MEMS-based accelerometer', *Sensors*, 2014, **14**, (9), pp. 16563–16585

[34] Kohler, M.D., Hao, S., Mishra, N.*, et al.*: 'ShakeNet: a portable wireless sensor network for instrumenting large civil structures', U.S. Geological Survey Open-File Report 2015–1134, 2015

[35] Kim, J., Kwon, S., Park, S.*, et al.*: 'A MEMS-based commutation module with vibration sensor for wireless sensor network-based tunnel-blasting monitoring', *KSCE J. Civil Eng.*, 2013, **17**, (7), pp. 1644–1653

[36] Kim, J.R., Yoo, H.S., Kwon, S.W.*, et al.*: 'Integrated tunnel monitoring system using wireless automated data collection technology'. Proc. 25th Int. Symp. on Automation and Robotics in Construction, Vilnius, Lithuania, June 2008, pp. 337–342

[37] Kwon, S.W., Kwan, S.K., Kim, J.Y.*, et al.*: 'Wireless vibration sensor for tunnel construction'. Proc. 23rd Int. Symp. on Automation and Robotics in Construction (ISARC 2006), Tokyo, Japan, October 2006, pp. 614–620

[38] 'ADXL 203CE-MEMS Accelerometer'. Available at www.analog.com/en/products/sensors-mems/accelerometers/adxl203.html, 10 accessed January 2018

[39] 'LIS2L02AL—MEMS Inertial Sensor'. Available at http://pdf.datasheetcatalog.com/datasheets2/18/185417_1.pdf, accessed 10 January 2018

[40] Whelan, M.J., Janoyan, K.D.: 'In-service diagnostics of a highway bridge from a progressive damage case study', *J. Bridge Eng.*, 2009, **15**, (5), pp. 597–607

[41] Whelan, M.J., Gangone, M.V., Janoyan, K.D.: 'Operational modal analysis of a multi-span skew bridge using real-time wireless sensor networks. *J. Vib. Control*, 2011, **17**, (13), pp. 1952–1963

[42] 'ADXL202: Low-Cost ± 2 g/ ± 10 g Dual Axis Accelerometers'. Available at http://www.analog.com, accessed 10 January 2018

[43] 'SD-1221: Low-Noise Analog Accelerometer'. Available at http://www.silicondesigns.com/pdfs/1221.pdf, accessed 10 January 2018

[44] 'ADXL210: Low-Cost ± 2 g/ ± 10 g Dual Axis Accelerometers'. Available at http://www.analog.com, accessed 10 January 2018

[45] Pakzad, S.N.: 'Development and deployment of large scale wireless sensor network on a long-span bridge', *Smart Struct. Syst.*, 2010, **6**, (5), pp. 525–543

[46] Pakzad, S.N., Fenves, G.L.: 'Statistical analysis of vibration modes of a suspension bridge using spatially dense wireless sensor network', *J. Struct. Eng.*, 2009, **135**, (7), pp. 863–872

[47] 'LIS2L06AL—MEMS INERTIAL SENSOR: 2-axis— ± 6 g UltracompactLinear Accelerometer'. Available at http://www.st.com/web/en/resource/technical/document/datasheet/CD00068417.pdf, accessed 10 January 2018

[48] Meyer, J., Bischoff, R., Feltrin, G.*, et al.*: 'Wireless sensor networks for long-term structural health monitoring', *Smart Struct. Syst.*, 2010, **6**, (3), pp. 263–275

[49] 'AC310-002: ± 2 g Capacitive Micro machined Accelerometer'. Available at http://www.joosh.co.kr/bbs/board.php?bo_table=product04&wr_id=41&page=5, accessed 20 January 2018

[50] 'SF1600SN.A: Single Axis Best in Class Seismic Accelerometer', http://www.colibrys.com, accessed 20 January 2018

[51] Sabato, A.: 'A novel, wireless acceleration evaluator used for health monitoring of aging structures and bridges'. Proc. 10th Int. Workshop on Structural Health Monitoring (IWSHM 2015), Stanford, CA, USA, September 2015, pp. 1–3

[52] Sabato, A., Feng, M.Q., Fukuda, Y.*, et al.*: 'A novel wireless accelerometer board for measuring low-frequency and low-amplitude structural vibration', *IEEE Sens. J.*, 2016, **16**, (9), pp. 2942–2949

[53] 'SF1600SN.A: Single Axis Best in Class Seismic Accelerometer'. Available at http://www.colibrys.com, accessed 4 February 2018

[54] Kohler, M.D., Heaton, T.H., Cheng, M.H.: 'The community seismic network and quake-catcher network: enabling structural health monitoring through instrumentation by community participants'. Proc. SPIE 8692, Sens. and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, April 2013, p. 86923X

[55] Dargie, W.: 'Dynamic power management in wireless sensor networks: state-of-the-art', *IEEE Sens. J.*, 2012, **12**, (5), pp. 1518–1528

[56] Torfs, T., Sterken, T., Brebels, S.*, et al.*: 'Low power wireless sensor network for building monitoring', *IEEE Sens. J.*, 2013, **13**, (3), pp. 909–915

[57] Kim, S.: 'Wireless sensor networks for structural health monitoring', M.S. thesis, Dept. Elect. Eng. Comput. Sci., Univ. California, Berkeley, Berkeley, CA, USA, 2005

[58] Mukhopadhyay, S.C., Ihara, I.: 'Sensors and technologies for structural health monitoring: a review', in Mukhopadhyay, S.C. (Ed): '*New developments in sensing technology for structural health monitoring*', **vol. 96** (Springer Nature, Berlin, 2011), pp. 1–14