Design and deployment of a LoRa-based wireless sensor network for structural health monitoring system

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Abstract

Structural health monitoring applications aiming at the early warning to reduce the damage due to sudden collapsing are ledged thanks to the rapid development of circuitry and sensing devices. Recently, Semtech long-range (LoRa) wireless communication technology allows to facilitate the development of data communication network over a large-area, improving sensing reliability, extending battery life as well as reducing total system costs. This work presents the design and deployment of a LoRa-based structural health monitoring system. The vibration and displacement parameters being read from innovative MEMS sensors were uploaded to a real-time database server for analysis and evaluation. In addition, for the sake of providing information to the public, a web page is also developed to provide an interactive map composing obtained sensing values and corresponding charts. A case study on an actual health monitoring system for two major bridges in Can Tho City, Vietnam was conducted for validating the feasibility of the system.

Keywords: LoRa technology, MSP432, structural health monitoring, wireless sensor networks

1. Introduction

Structures are frequently exposed to harsh loading scenarios and extreme, unanticipated environmental conditions, resulting in structural degradation over a long period. Structural health monitoring (SHM) offers an automatic mated method for tracking structural health by combining damage detection algorithms with structural monitoring systems. Structural monitoring systems are commonly used for tracking structural behavior during induced vibration or natural excitation tests (e.g. earthquakes, tsunami, and so on). The monitoring system is primarily responsible for collecting the measurement information from the sensors installed in the structure and for storing the measurement data in the central repository. Damage detection methods may generally be defined as one of two types: Methods to locally or globally detect damage. Local damage detection methods are intended to identify damage based on screening structures at their component or sub- length scales. A lot of non-destructive assessment (NDE) technologies, like ultrasonic inspection, can be categorized as support for the detection of local damage. Although local NDEs are prone to structural damage phenomena (e.g. cracks, yields), local inspection technologies typically allow skilled technicians to work in the field and thus increase their costs [1-6]. Its low-cost attributes initially aroused interest in wireless sensors. Wireless sensors can be identified as autonomous nodes for data acquisition that can be linked to traditional structural sensors (e.g. accelerometer, linear voltage displacement transducer, inclinometer, and so forth). Wireless sensors are also regarded as a network where elements of mobile computing and wireless communication combine with sensing transducer. The rapid development of the integrated circuits manufacturing industry and modern sensor technology, wireless sensor networks (WSNs) have been widely used in SHM to assess

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the status of major structures. In the SHM system, different types of sensors collect data and monitor infrastructure in real-time [7-12].

Mekong Delta is a wet and unstable land so that many structures are often sloping, collapsing, and damaged. It is necessary to develop a Structural Health Monitoring (SHM) system to surveillance structures such as bridges, buildings, etc. as well as to establish early warning systems to minimize the damage and maintenance costs [13-15]. The aim of this work is to develop and implement the SHM by integrating the recent advantages of electronics and telecommunications, e.g. MEMS sensors and Semtech long- communication technology, to provide rapid and effective data collection and analysis for the SHM system, taking into account system cost.

The rest of this paper is organized as follows: After stating various causes, effects, and solutions to structural health and summarizing the related works in Section 1, Section 2 provides an overview of Semtech LoRa technology with many benefits for long-term monitoring performance of physical sensing systems. The design and deployment of a LoRa-based wireless sensor network for a structural health monitoring system are described in Section 3. The system was built up based on innovative integrated-circuit and sensor technologies and LoRa to deploy a low-power consumption and wide-area monitoring system. In Sections 4, experimental results are discussed and evaluated for the measurements of a real system being deployed for health monitoring of two major bridges in Can Tho City, Vietnam. Finally, Section 5 concludes this paper before discussing future works.

2. Overview of LoRa Physical Layer

Modulation of the Chirp Spread Spectrum (CSS) is a primary technique used in Semtech LoRa technology. These describe LoRa transmissions as a trade-off between low data rate for long-range communications (up to several kilometers) and low power consumption since CSS offers ultra-long-range spread spectrum communication with high immunity interference consuming low energy.

LoRa technology suits remote sensing system requirements in which a small chunk of data produced by sensing devices is collected, then sent to the base station to feed decision systems. This collection is periodically conducted with the aim of preserving the lifetime of the battery power supply in sensor nod es. LoRa transceivers work with center frequency (CF) in the range of 137 MHz to 1020 MHz, programmable in steps of 61 Hz. Other main parameters of LoRa physical layer as follows:

- Bandwidth (Bw): The ability to choose the bandwidth (from 7.8 kHz to 500 kHz) makes it possible to trade between air time and communication range.
- Coding rate (CR): LoRa uses Forward Error Correction (FEC) to improve interference robustness. For each radio link, four options for the coding rate can be selected.
- Spreading factor (SF): The spread factor (SF) is another key parameter for LoRa performance tuning. SF can be defined as a function of the received signal-to-noise ratio (SNR). Spreading factors can be selected from 6 to 12 [16, 17].

3. System design and implementation



Fig. 1. Block diagram of the system.

3.1. Sensor node architecture

The diagram of the design block and the supervisor principle is shown in Fig. 2. In the diagram above, the central block is the MSP432P401R microcontroller that performs the tasks: reading data from the sensor block, including ADXL345, ADXL355, and D7S seismic sensors, take coordinate and time data from the GPS module at the experimental location (see Table 1 for further details). The analog-digital conversion (ADC) capability allows data digitization at a maximum conversion rate of 1 Mps with a configurable resolution of 8 to 14-bit The data is then aggregated and sent by the LoRa signal to the receiver and switched to standby mode to receive information about the packet from the receiver. In standby mode, if the monitor receives the packet from the receiver, the microcontroller will read the packet through the data receiving buffer of the LoRa Module. The power block is responsible for powering the whole circuit, but the LoRa Module only uses 3.3V and to provide the necessary current, it needs its own 3.3V regulator circuit [16, 18-22].



Fig. 2. Block diagram of the sensor node.

Table 1. Specifications of sensors used in the system [19-23].

Parameter	ADXL345	ADXL355	D7S	Unit
Supply voltage	2-3.6	2-3.6	2.1-5.5	V
Measurement range	±2, ±4, ±8, ±16	±2, ±4,±8		g
Output resolution	10,13	20		bits
Bandwidth	3200	1000		Hz
Sensibility at ±2g	256	256000		LSB/g
Current demanded	140	200	300	μΑ

In this system, we use ADXL345 and ADXL355 with corresponding to the resolution 10-13 bits and 20 bits respectively. The sensitivity of the ADXL355 sensor for each axis at $\pm 2g$ about 256000 LSB/g is much higher than that of the ADXL345 sensor about 256 LSB/g. The ADXL355 sensor is, therefore, more appropriate for capturing the accelerated values with smaller shifts. System requirement is the accuracy of less than 1° with the inclination depending on application conditions such as large temperature fluctuations, vibration. In this case, the ADXL345 has an initial offset of about 1.3°, so it is necessary to make several corrections with the appropriate compensation to achieve the accuracy of inclination, thereby meeting the accuracy requirement. For ADXL355, the maximum offset deviation is 0.5°, so it complies with the requirements.

For low-cost accelerometers such as the ADXL345 but with high noise, the high sensibility and allows for measurement of tilt changes of less than 1.0° in applications of the static accelerometer of the tilt sensor, as well as dynamic acceleration due to motion or shock. In contrast, for high-cost accelerometer sensors such as ADXL355 for low noise, the small scale is suitable for applications in which we need to measure larger vibrations such as sudden movement or displacement. If the movement is large, we can choose some types of accelerometer with high sensitivity range such as a seismic sensor [19, 20].

D7S is a compact, ultra-low consumption, and high-precision seismic sensor. If an earthquake occurs with a seismic intensity equal to or greater than level 5 at the Japan Meteorological Agency (JMA) seismic intensity (SI) scale, the D7S will trigger an alarm signal to notify [21-23]. In addition, D7S is equipped with I2C communications to allow the user to acquire SI values as well as the peak acceleration of the past 05 earthquakes that have occurred [21, 22].



Fig. 3. A photograph of sensor node: The electronic parts placed in an IP65 waterproof plastic box to shield them from external effects.



Fig. 4. Flow chart of the sensor node process.

The MSP432P401R is a new generation of MCUs with advanced mixed-signal features targeting lowpower consumption systems while providing significant performance processing thanks to 32-bit ARM Cortex-M4 MCU and a built-in Floating-Point Unit FPU). Its operating time base can be configured enabling a system clock rate up to 48 MHz. It is analog-digital conversion (ADC) capabilities that allow data digitization at a maximum conversion rate of 1 Msps with a configurable resolution from 8 to 14-bit. The system's power supply is from the battery, so the energy-saving problem is extremely significant. Choosing to use the MSP432P401R processor and LoRa wireless communication technology help ed solve the energy problem [18]. Fig. 3 shows the electric circuit board of sensors which was mounted inside an IP65 waterproof plastic box. The LoRa module antenna is located outside the box to ensure good radio signal connections. The flowchart algorith m for the MSP432P401R processor is described in Fig. 4. In this program, switching LoRa to sleep helps the system reduce power consumption to extend battery life.

3.2. Sink node architecture

The sink node of the WSN consists of an MSP432P401R microcontroller unit, an ESP8266 wireless communication module, and a LoRa transceiver module. The transceiver modules LoRa 433 MHz serves for the transmission of data between the sink node and sensor node (see Fig. 5 and Fig. 6). The GPS Neo-6M module was used to obtain the geo-location of the node from the satellite (see Table 2).



Fig. 5. Block diagram of the sink node.

Device	LoRa Ra-02	GPS Neo-6M	NodeMCU ESP 8266	Unit
Power supply	2-3.6	3.3-5.5	5-9	V
Coverage	1-15			km
Interface	SPI	UART	SPI, I €, UART,	
Power consumption	28	50	15	mA

Table 2. Technical specifications of major electronic devices used in the sink node [24-26].





Fig. 6. The electronic circuit board of the sink node.

3.3. Firebase real-time database

Firebase Real-time Database is a NoSQL data form stored in the cloud server that allows you to store and synchronize user data in real-time. The data is stored as JSON objects and can be handled easily by developers. Firebase provides us with a set of SDKs so that we can easily build mobile and web applications, while real-synchronization helps users access their data on any computer or smartphone [27]. The ESP8266 module is employed in this system to set up an internet connection to upload collected data from sensor nodes to the Firebase which is the backend of a system to store collected data [26]. Such data can be accessed offline and viewed online via a web browser running on PCs or smartphones.

4. Experimental Measurements

4.1. System deployment

Despite low data rate 27 kbps, LoRa technology features low power operation, long communication range (2-5 km in urban areas), it is suitable for long time structural health monitoring systems. We chose the two bridges Quang Trung and Hung Loi with 610 m and 630 m respectively for experimental places. The sink node locates in the middle to facilitate data collection from both sensor nodes and then upload to the Firebase server via an internet connection.



Fig. 7. System deployment at node A-Hung Loi Bridge and node B-Quang Trung Bridge, Can Tho city, Vietnam.



4.2. Data collection and analysis

0.4

0.2

0

Fig. 8. Comparison collected (Roll, Pitch, and Yaw) values between ADXL345 and ADXL355.

Measurement range, frequency range (bandwidth) and resolution are three common attributes that often quantify the performance of a vibration sensing node. The ADXL345 accelerometer has a higher measurement range ($\pm 16g$) than the ADXL355 values ($\pm 8g$) in this study (see Table 1). An accelerator's measurement range reflects the maximum linear acceleration the sensor is able to detect. The output signal of the accelerator would saturate beyond the measurement range causing significant distortion and making it very difficult to extract useful information from the measurements. It is therefore important to ensure that the MEMS accelerometer supports peak acceleration levels. Otherwise, in a vibration sensing node, the noise in acceleration measurements will have a strong impact on its ability to detect changes in vibration. Even though, technical specifications and our initial experimental results (as can be seen in Fig. 8) show that with a noise density 16 times lower than that of the ADXL345, the ADXL355 is ideal for the detection of low-level vibrations [19, 20].



(c) On the evening from 5:30 PM to 6:30 PM. (d) At night from 9:00 PM to 10:00 PM.

Fig. 9. Snapshot of collected data from the D7S seismic sensor at the Hung Loi Bridge in an experimental measurement.

0.4

0.2

0



Fig. 10. Snapshot of Firebase database.

In Fig. 9, The experimental results were sampled for 1 hour at 4 sessions of the day. The sensor values are recorded periodically for 1 second if the seismic is detected by the sensor. If no seismic value is detected, the read time will last 2 seconds. The mean values of each sensor will be sent to the sink node in about 10 seconds. Although the highest vibration value at each session of the JMA seismic intensity scale is at level 5, except for the values collected at lunch (at level 4), the frequency at level 5 in the evening is less frequent than in the morning and afternoon [23]. In addition, the vibration values in the evening are much lower than those measured in the morning and afternoon. These differences also show the speed of the vehicles as well as the traffic that has had an impact on the Hung Loi Bridge.

The results of the vibration comparison (as can be seen in Fig. 9) show that the vibration of the Hung Loi Bridge in the morning and afternoon due to the density of crowded traffic during the rush hour is more serious than that at midday. Even though the data in the evening is not as high as in the morning and afternoon, there is still a large amount of vibration due to high-speed transportation. The seismic impact of a high-speed truck on the bridge span is much greater than that of a low-speed truck during rush hours.

The Firebase web console is shown in Fig. 10, displaying data from two sensor nodes on experimental bridges in this work, the sensor values are read and stored in the Firebase cloud to allow real-time synchronization of cross-platforms. Data can be retrieved from the database and then processed to display current data on the web page or to export it as formatted files, for example, a sheet file.

5. Conclusion and Future Work

In this paper, we presented the design and implementation of a LoRa-based structural health monitoring system. The system allows monitoring of seismic intensity and vibration of several constructions in real-time with a visual web map application in light of long-distance wireless technology and cloud database service. We deployed a LoRa star network consisting of sensor nodes and a gateway for data gathering, then uploading to the cloud server via an internet connection. Each sensor node equips innovative sensors for measuring structural health parameters such as vibration due to the dynamic load of vehicle and pedestrian, temperature, as well as displacement parameter. To validate the feasibility of the proposed system, experimental measurements were conducted for Quang Trung and Hung Loi Bridge in Can Tho City, Vietnam. They are two main bridges of the city with the distance between them around

2 kilometers. Experimental results show that sensor quality and deployment strategies cause a significant impact on the accuracy of obtained parameters and efficiency of the system. For future work, we plan to enhance both the quality and quantity of sensors used aiming at developing automatic diagnostic and early warning systems.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Tuyen Phong Truong, Dung Anh Duong, and Tai Hong Duc Nguyen conducted the system design and testing phases. All the authors discussed the results, wrote the paper and contributed to the revision of the paper. All the authors had approved the final version.

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