LoRa Structural Monitoring Wireless Sensor Networks

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Abstract: The demand for sensor-based information has seen a rapidly increasing demand due to the massive deployment of Structural Health Monitoring (SHM) systems. SHM allows for the analysis aimed to the prediction of forthcoming incidents and enables the evaluation of a structure's status. The advances in the Internet of Things (IoT) structures to retrieve data anytime, everywhere through the internet represents a promising paradigm for SHM. Among the various technologies and topologies that are now evolving, Wireless Sensor Networks (WSNs) have become well suited for the implementation of monitoring systems, especially in low power wide area network (LPWAN) structures. LoRa modulation technology is a suitable technical solution for sensor node communication. In this study, two LoRa-based systems for Structural Health Monitoring (SHM) are presented, located in Sicily and Calabria, Italy. Accelerometric sensors are encapsulated into solar harvesting powered sensor nodes and are used to monitor the variation of inclinations of the mounting location. LoRaWAN gateways interface the nodes towards the internet, enabling the Internet of Things (IoT) paradigm for the monitoring solution. In this article, an overview of the system structure is given, with nodes and gateways' hardware features provided. Inclination monitoring using accelerometric data is explained, and real scenario recorded data are given. Brief power analysis for the sensor nodes is also reported.

1 INTRODUCTION

Structural health monitoring (SHM) is the process of integrity estimation of structures at every stage of their life based on suitable analysis of measured data. Using this technique it is possible to increase safety and decrease costs of maintenance, performing detection, localization and assessment of the damage at earlier stages. This allows an anticipated knowledge of the damage for maintenance planning and future organization. By applying the aforementioned strategies, an economic benefit can be achieved (Martinez-Luengo et al., 2019; Orcesi et al., 2011). In general, an SHM system contains three main elements: a sensor system, a data processing structure, and a health evaluation system. The sensor elements monitor the physical phenomenon, producing a signal which is acquired by the processing sub-system. Different kinds of sensors can be integrated into one SHM block, allowing data to be merged. The processing block allows the raw data to be presented to the health evaluation system in order to allow the analysis of the current state. SHM can be applied to a wide variety of elements and structures, from small-scale installations to big civil constructions (Amafabia et al., n.d.; Catbas, 2009; Ni et al., 2009; Ragnoli et al., 2022; Sohn et al., 2003). In the past, engineers have collected usable data for structural monitoring using wired and single-hop wireless data-collecting devices (Ishikawa et al., 2008; Paolucci et al., 2020). The location and quantity

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of sensor nodes may be constrained by power limitations and wiring restrictions, possibly increasing the cost and overall complexity of the system. Employing WSNs, these problems are frequently assisted, especially by adopting Internet of Things (IoT) principles and using interconnected nodes to develop flexible infrastructures for data collection and analysis. In IoT applications, the physical elements which contain sensing equipment are connected to the internet, thus allowing data to be exchanged universally between various kinds of platforms. This separates the physical system implementation technology for the acquisition process from the sequent sub-systems, allowing system modularity. New wireless communication technologies are demonstrating effectiveness in WSN implementations through the development of innovative ad-hoc hardware; thus, significant academic and corporate research efforts are being reported in this area. WSNs have seen a rapid expansion in recent years (Mainetti et al., 2011), which report those approaches being used for a variety of unique applications (Jino Ramson et al., 2017), among those monitoring the environment (Oliveira et al., 2011), industrial systems (Gungor et al., 2009), health-related and wearable applications (Awotunde et al., 2022), early warning system (Ragnoli et al., 2020). The implementation of optimal SHM solutions is a difficult task for the large number of variables involved; thus, finding the best one from the current options or creating a new system is not trivial. The implementation technology, network topology, and costs of the structures are various, and finding a method that fits all parameters is difficult.

In this work, the application of a LoRa-based monitoring system for structural health monitoring in two real scenarios is presented. The system is installed in two different locations: the first is in a construction site in Calabria, Italy, while the second is located in a rockfall protection barrier in Sicily, Italy. Monitoring the movements of housings caused by soil drift due to landslides is the interest in the first case. In the second case, rockfall barriers are being monitored. The sensor nodes are standalone elements in a LoRaWAN (Haxhibeqiri et al., 2018), (LoRa and LoRaWAN: A Technical Overview, 2020) star network where the centre is the gateway. Access to the internet layer is provided using a portable solar-powered gateway implementation. A user interface is provided by a remote dashboard panel for data analysis and warning implementation. This paper is structured as follows. In section two, different solutions for SHM based on wireless networks will be briefly reviewed to give an overview of state of the art. In section three a high-level system overview is given, with a description of functionality. A hardware description of the nodes and gateway assembly is given in section four, with electrical measurements of power performances, and considerations on the long-term reliability. In section five real scenario data are shown.

2 RELATED WORK

In (Zhiguo et al., 2022), the authors review the current process and future trends of SHM applied to bridge monitoring, focusing on transmission and analytics methods of the sensing data, prediction, and early-warning models. Some extensively applied sensing technologies are reviewed and compared. Some wireless data transmission technologies are discussed (i.e., ZigBee, Bluetooth, NB-IoT, Wi-Fi, LoRa) along with artificial intelligence (AI) data processing methods. Composite structures are widely employed in building scenarios; however, those are prone to impact damage. In (Amafabia et al., 2017), the authors review SHM monitoring techniques applied to the aforementioned structures. In (Mascarenas et al., 2007), the authors present a wireless impedance sensor node equipped with an integrated circuit chip for measuring and recording the electrical impedance of a piezoelectric transducer. A microcontroller performs local computing, and a wireless Xbee module (Vaibhav et al., 2016) transmits the structural information to a base station.

A network of sensor nodes for structural monitoring is implemented by (Pakzad et al., 2008). The Golden Gate Bridge's linear mounting of the devices makes the multi-hop transmission topology particularly appropriate for the investigation. In order to prevent data loss, significant effort is made to investigate the data transmission reliability in pipeline mode. Remote Structural Health Monitoring (RSHM) is a perfect solution for tracking critical damage to urban structures. In (Sidorov et al., 2019), the authors propose a LoRa-based IoT sensor for monitoring the health of bolted joints (Vangelista, 2017). The management of risk associated with landslides has gained significant attention in SHM as a result of growing awareness of the economic and social effects of these catastrophes (Rossi et al., 2019). Movements on slopes can be detected using wireless sensor nodes equipped with microelectromechanical system (MEMS) inertial measurement unit (IMU) sensors. In (Fekih Romdhane et al., 2017), in order to test the viability of a LoRa-based network in hostile conditions, the authors deploy a WSN on an uninhabited hillside landslide, concentrating on the communication zone coverage. The authors (Ramesh, 2009) present the design and deployment of a landslide detection system at Anthoniar Colony, India. There have been a lot of studies done to explain and separate various types of structural movement. Different patterns of accelerometer data in the behaviour of physical structures have been shown in the literature (Sabato et al., 2017). The experiments conducted by the authors, which used information from the accelerometer to categorize movements, made use of the idea of pattern recognition. In addition to assisting in the analysis of the structural stability and the deployment of safety and mitigation devices, this information serves as fundamental knowledge in civil engineering.

3 SYSTEM DESCRIPTION AND FUNCTIONALITY

WSNs benefit from the employment of Low Power Wide Area Network (LPWAN) technologies as the state of the art that reports, allowing to development of IoT systems. LPWANs (Bernardo et al., 2020) can be oriented to obtain sensor nodes with particularly good energetic performances, which makes a perfect fit for energy-harvesting powered devices (Ruan et al., 2017). These technologies are employed in applications where a small amount of data is transferred with intermittent behaviour (B. S. Chaudhari et al., 2020), resulting in less complicated transceiver circuits. The Media Access Control (MAC) layer deployment often occupies the highest portion of the costs of the whole system (B. S. and Z. M. Chaudhari, 2020). The LoRaWAN MAC layer is regulated by the LoRa Alliance (LoRa Alliance, 2022) and provides a solution for MAC access by providing free interfacing of the network by only deploying dedicated LoRaWAN gateways. Interfacing LoRaWAN gateways with web services allows the establishment of a reliable and low-cost network, as will be shown following. In Figure 1, we find the general architecture of a LoRaWAN-based WSN network. The sensor nodes use LoRa modulation by Semtech, which is a Chirp Spreading Spectrum (CSS)-based method. This physical layer is employed to communicate with the gateway over a single hop link.

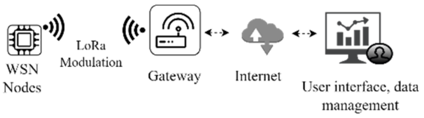

Figure 1: LoRaWAN IoT network general architecture.

A comparison of the energetic efficiency of LPWAN IoT devices based on different technologies is presented in (Finnegan et al., 2018). LoRa modulation stacks up against other IoT technologies (Lauridsen et al., 2017), reporting good coverage even when operating in poor link conditions.

According to the system proposed in this work, sensor nodes are equipped with MEMS accelerometers. Other elements, such as GPS tracking devices and environmental sensors for relative humidity, barometric pressure, and ambient temperature, are fitted onboard. The nodes send packets every 60 minutes to the gateway using LoRa transmissions. This component is battery-powered, charged by solar energy harvesting using a solar panel. It is connected to the internet using Long Term Evolution (LTE) and a Subscriber Identity Module (SIM), which enables cellular network communication. The Things Network (The Things Network, 2022) exchange service manages the packets received at the gateway and employs a JavaScript payload decoding function to encapsulate the incoming bytes into a JavaScript Object Notation (JSON) element: the measured quantities are represented by a numerical value and a key-value field in the object. The packets are sent via MQ Telemetry Transport (MQTT) integration to a Node-RED (OpenJS Fundation, 2022) server instance, which enables a workflow for data analysis and user interface, moreover, as an alarm triggering service. The collected data is also stored in a database. The application-specific block scheme is displayed in Figure 2, where the first block represents the mounting scenario in the two respective cases, respectively.

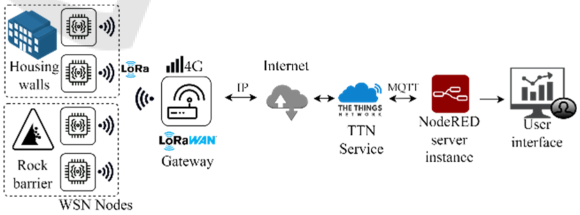

Figure 2: System architecture scheme.

In Calabria location, the WSN's nodes are mounted on the housing walls in specific positions where it is necessary to monitor the variation of inclination in the structure (Figure. 3). In Sicily location, the nodes are positioned on the rockfall barrier's steel cables and nets, in positions particularly prone to movement in case of an event. The LoRa gateways are placed at locations to allow all sensing devices to have radio communication despite the nodes being located at different heights and positions and facing sunlight to ensure optimal battery charge accumulation.

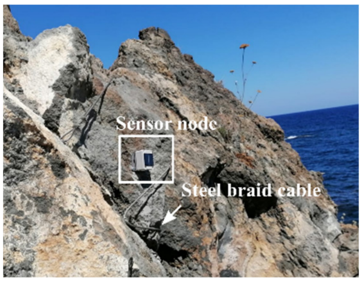

Figure 3: Sensor node on a steel braid cable-protected rock formation.

4 HARDWARE DESCRIPTION

The nodes are electronic systems that include a microcontroller, motion, and environmental sensors, a GPS modem, and a battery management unit working with a compact 5 V solar panel. Programming and debugging are available using a USB connection available as a port of Silicon Labs CP2102 (SiliconLabs, 2017) UART to USB circuit. The microcontroller is an STM32L (STMicroelectronics, 2016b) from STMicroelectronics, 32-bit ARM Cortex M3-based, designed for low-power systems. The low-power operating mode with current absorption down to a few microamperes makes this MicroController Unit well suited to battery-powered applications, especially if harvesting-based. A 3700 mAh lithium polymer (LiPo) battery powers the device, and its charge state is readable by the MCU analog-to-digital converter (ADC). Texas Instruments BQ21040 (Texas Instruments, 2019) single cell charging integrated circuit charges it via sun harvesting or from the USB connection. Supply voltage at 3.3 V is available thanks to a Nisshinbo RP104N331 (Nisshinbo, 2018) Low Drop-out (LDO) regulator. Ublox MAX-7Q (u-blox, 2021) is the GPS modem installed on the device. The movement sensor is an STMicroelectronics MEMS-based digital output 3-axis accelerometer mode LIS3DH (STMicroelectronics, 2016). The chip is powered at 3.3 V, connected to the microcontroller via I^{2}C, and reports a 2 µA sleep current. The Semtech SX1276 (Semtech, 2020) LoRa unit is a transceiver based on the spread spectrum communication technique, connected using SPI to the microcontroller. SX1276 can attain a sensitivity of over -148dBm. Moreover, this integrated circuit is also reasonably priced. The transmission (TX) power of the transceiver is 13 dBm. An 868 MHz ISM band planar dipole antenna model connects the wireless module to enable radio communication. The node operating temperature range is from -40 to +85 °C, and a valve ensures the correct barometric pressure distribution inside the enclosure. In Figure 4 a block scheme of the node is reported.

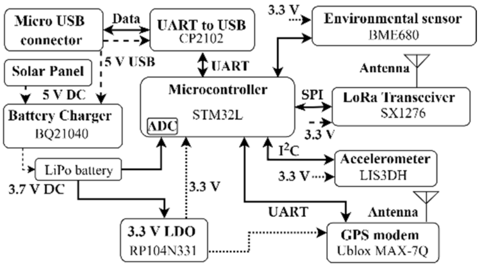

Figure 4: Hardware block scheme of the sensor node.

The node operates sequentially as follows: it first operates in low power mode, which means the circuitry is in a standby state to achieve lower current absorption. Standby is deactivated at user-chosen intervals. The data collecting process starts with GPS position retrieving. If a GPS response signal cannot be received until a timeout of 30 seconds during satellite connection attempts, the node continues with sensor reading. If the link is successful, latitude and longitude are obtained. The LoRa transmission starts after ending the retrieval of data from the environmental unit and accelerometer.

If the node cannot access LoRaWAN, successive retries until a total of 8 attempts will be performed. If the connection is not successful after those attempts, the node will enter standby mode until next transmission interval.

At complete data transferring the node switches back to low power mode until the next send interval. The nodes employ the Adaptive Data Rate (ADR) (Li et al., 2018) feature of LoRaWAN. In Figure 5 a flow diagram of the node operating procedure is reported.

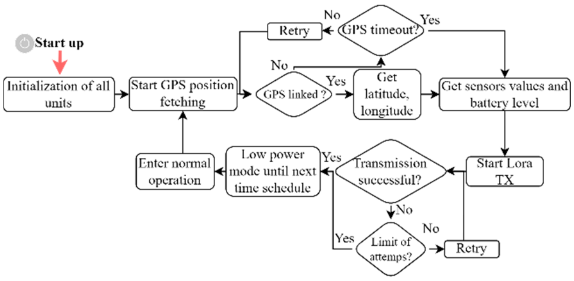

Figure 5: Sensor node's operating diagram.

The Milesight UG65 (Xiamen Milesight IoT Co., 2022) LoRaWAN gateways allow data transfer towards the internet layer through the Things Network service. These LTE-enabled devices are by a lead-acid battery, recharged through solar harvesting by a polycrystalline panel. The rated typical total power dissipation of the unit is 2.9 W. A waterproof IP65 enclosure is used to encapsulate the gateways and battery system, which includes the battery charge regulator circuit.

5 RESULTS

Achieving low power requirements for nodes in a WSN is fundamental. In the presented SHM system, this has been addressed by employing standby phases between each data-sending interval. The nodes report a current absorption of an average of 16 µA in sleep mode and 36 mA average in active mode. Once the initial start-up is done, where there is the first GPS satellite connection, therefore a longer activity time span is necessary. The next active period lasts an average of 5 seconds. Estimating the battery duration with a sending interval of 1 hour with the aforementioned active mode duration gives a battery life of more than five years in case of total darkness. This is estimated without taking into consideration the degradation of the LiPo cell. Solar harvesting gives a sufficient level of energy to keep the battery charged at full state, as will be shown from the sample data following in this paper. Figure 6 shows a current absorption measurement of a node in the initial start-up phase, where it is possible to see current peaks due to GPS and LoRa communications.

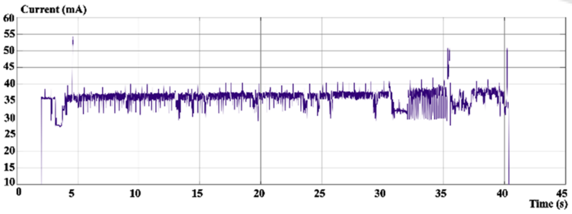

Figure 6: Sensor nodes measured current absorption during an initial start-up and data transmission cycle.

A remote monitoring web platform has been implemented using the NodeRED web service to allow the management personnel to observe the status of the structural elements. The dashboard instance holds a monitoring panel for each sensor node. To access data, the user must have an enabled email address and password. The structural nodes report location as GPS position, inclination data along three axes as tilt in degrees, battery voltage, temperature in Celsius degrees, relative humidity, and barometric pressure in Hectopascal. The inclination in degrees is calculated from accelerometric data along the three frame body axis, with respect to a reference system (x,y,z), where the z direction is opposite to the direction of the gravitational acceleration vector g, see Figure 7.

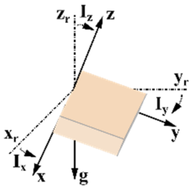

Figure 7: Axis reference for inclination measurement.

Using the following formula is possible to calculate the inclinations, where I_x represents the inclination angle with respect to reference x axis in this case. Applying different acceleration values at the numerator is possible to obtain the inclination of the other frame axis.

$$I_x = \frac{(cos^{-1}(\frac{a_x}{\sqrt{{a_x}^2 + {a_y}^2 + {a_z}^2}}) \cdot 180}{\pi} \tag{1}$$

During a normal state of a sensor node, the reported inclinations are stable, this mean that no structural variation has been reported, as the example reported in the following Figure 8, relative to the three nodes in the Calabria location.

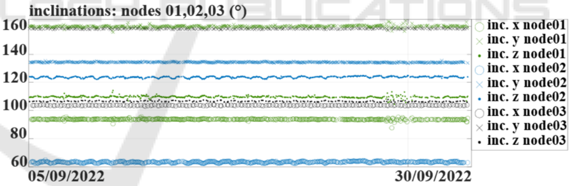

Figure 8: measured inclination sampled data from three sensor nodes in Calabria during the period 05 – 30 September 2022.

When a structural movement happens, the system senses and quantifies a variation in the inclination of a sensor node, allowing a warning to be triggered. In the following Figure 9, a displacement relative to an axial rotation has been recorded.

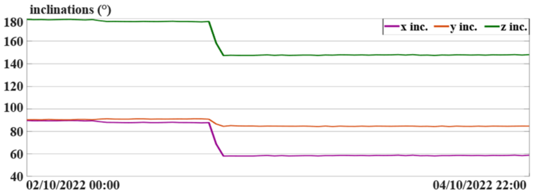

Figure 9: Sensor nodes operating diagram.

The system is continuously operating, and using the GPS unit is possible to track the nodes and execute checks in case of warnings. This is useful for maintenance and enables the fastest risk-reduction technique and hazard plan in case of events, also in case of vandalism. In the following Figures 10 – 13, some reported data collected in the period of 05 – 30 September 2022 are reported. The reported temperature and humidity are considered inside the waterproof enclosure of each sensor node.

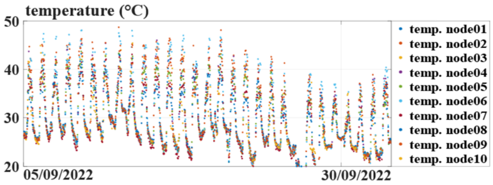

Figure 10: Recorded temperature in the period 05-30 September 2022.

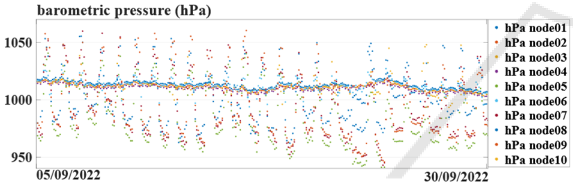

Figure 11: Recorded barometric pressure in the period 05-30 September 2022.

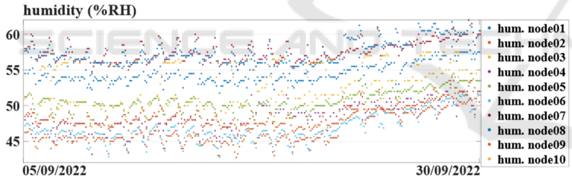

Figure 12: Recorded humidity in the period 05-30 September 2022.

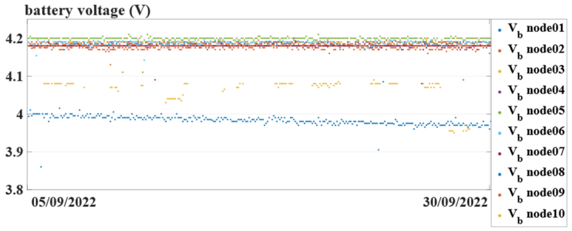

Figure 13: Recorded nodes battery voltage in the period 05-30 September 2022.

Data exchange and post-processing can be implemented with various solutions, but in a low-cost WSN, this should be addressed in an economical manner: the LoRaWAN implementation, with TTN structure employment, allows obtaining a good performance in terms of deployment cost and complexity. The system presented in this study allows for flexibility thanks to its fully portable characteristic, which allows quicker installation with respect to other mentioned solutions.

The modularity of the system is another key factor; it can be equipped with different sensing hardware despite the LoRa blocks remaining the same. The system can be employed in many applications of SHM: safety-enhancing mechanisms, industrial production, and Building Information Modelling (Tang et al., 2019) are some examples.

6 CONCLUSIONS

In this paper, a LoRa-based structural health monitoring system was presented. The paper reports the description of functionality, hardware, and real scenario results. The electronic system was developed on low-cost elements, allowing the deployment of a modular WSN. The nodes are accelerometer-based but also report values of temperature, barometric pressure, and relative humidity, which is also useful for environmental monitoring. The nodes communicate with portable LoRaWAN gateways using LoRa technology, allowing an IoT structure thanks to the integration of web services enabled by interfacing the gateways with the internet using LTE. The WSN was installed in real scenarios, in Sicily, Italy, on rockfall barriers and in Calabria, Italy, on housings subjected to landslide. Measurement of current absorption of the nodes is reported along with a consideration of battery life in the worst-case scenario. Real scenario data is reported, showing how the inclinations along three special axes can vary in case of structural movement events. The integration of the presented system with other IoT-enabled structures and services is used by the local authorities to ensure inhabitants' safety, viability management and optimize the on-field operations. Future developments of this work will be in the optimization of packet transmission to reduce the packet loss and a possible implementation of better resource allocation algorithms. The integration of AI frameworks for preventive maintenance will also be evaluated for integration.

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REFERENCES

Amafabia, D. M., Montalvão, D., David-West, O., & Haritos, G. (n.d.). A Review of Structural Health Monitoring Techniques as Applied to Composite Structures. Structural Durability & Health Monitoring 2017, 11(2), 91-147. https://doi.org/10.3970/sdhm.2017.011.091.

Amafabia, D. M., Montalvão, D., David-West, O., & Haritos, G. (2017). A Review of Structural Health Monitoring Techniques as Applied to Composite Structures. Structural Durability & Health Monitoring, 11.

Amphenol. (n.d.). 868MHz ISM Band PCB Antenna PIOV008NRA.

Awotunde, J. B., Jimoh, R. G., AbdulRaheem, M., Oladipo, I. D., Folorunso, S. O., & Ajamu, G. J. (2022). IoT-Based Wearable Body Sensor Network for COVID-19 Pandemic (pp. 253–275). doi: 10.1007/978-3-030-77302-1_14

Bernardo, G. di, Narayana, A., & Hazarika, R. (2020). Choice of effective LPWAN protocol for IoT System: Sigfox and LoRa. International Journal of Engineering Research and Applications Www.Ijera.Com, 10(11), 53–57. doi: 10.9790/9622-1011015357

Catbas, F. N. (2009). Structural health monitoring: applications and data analysis. In Structural Health Monitoring of Civil Infrastructure Systems (pp. 1–39). Elsevier. doi: 10.1533/9781845696825.1

Chaudhari, B. S. and Z. M. (2020). LPWAN Technologies for IoT and M2M Applications. Academic Press.

Chaudhari, B. S., Zennaro, M., & Borkar, S. (2020). LPWAN Technologies: Emerging Application Characteristics, Requirements, and Design Considerations. Future Internet, 12(3), 46. doi: 10.3390/fi12030046

Fekih Romdhane, R., Lami, Y., Genon-Catalot, D., Fourty, N., Lagreze, A., Jongmans, D., & Baillet, L. (2017). Wireless sensors network for landslides prevention. 2017 IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications (CIVEMSA), 222–227. doi: 10.1109/CIVEMSA.2017.7995330

Finnegan, J., & Brown, S. (2018). An Analysis of the Energy Consumption of LPWA-based IoT Devices. 2018 International Symposium on Networks, Computers and Communications (ISNCC), 1–6. doi: 10.1109/ISNCC.2018.8531068

Gungor, V. C., & Hancke, G. P. (2009). Industrial Wireless Sensor Networks: Challenges, Design Principles, and Technical Approaches. IEEE Transactions on Industrial Electronics, 56(10), 4258–4265. doi: 10.1109/TIE.2009.2015754

Haxhibeqiri, J., de Poorter, E., Moerman, I., & Hoebeke, J. (2018). A Survey of LoRaWAN for IoT: From Technology to Application. Sensors, 18(11), 3995. doi: 10.3390/s18113995

Ishikawa, K. I., & Mita, A. (2008). Time synchronization of a wired sensor network for structural health monitoring. Smart Materials and Structures, 17(1). doi: 10.1088/0964-1726/17/01/015016

Jino Ramson, S. R., & Moni, D. J. (2017). Applications of wireless sensor networks — A survey. 2017 International Conference on Innovations in Electrical, Electronics, Instrumentation and Media Technology (ICEEIMT), 325–329. doi: 10.1109/ICIEEIMT.2017.8116858

Lauridsen, M., Nguyen, H., Vejlgaard, B., Kovacs, I. Z., Mogensen, P., & Sorensen, M. (2017). Coverage Comparison of GPRS, NB-IoT, LoRa, and SigFox in a 7800 km2 Area. 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), 1–5. doi: 10.1109/VTCSpring.2017.8108182

Li, S., Raza, U., & Khan, A. (2018). How Agile is the Adaptive Data Rate Mechanism of LoRaWAN? 2018 IEEE Global Communications Conference (GLOBECOM), 206–212. doi: 10.1109/GLOCOM.2018.8647469

LoRa Alliance. (2022). LoRa Alliance Website. https://lora-alliance.org/.

LoRa and LoRaWAN: A Technical Overview LoRa® and LoRaWAN®: A Technical Overview. (2020).

Mainetti, L., Patrono, L., & Vilei, A. (2011). Evolution of Wireless Sensor Networks towards the Internet of Things: a Survey. In SoftCOM 2011, 19th International Conference on Software, Telecommunications and Computer Networks.

Martinez-Luengo, M., & Shafiee, M. (2019). Guidelines and Cost-Benefit Analysis of the Structural Health Monitoring Implementation in Offshore Wind Turbine Support Structures. Energies, 12(6), 1176. doi: 10.3390/en12061176

Mascarenas, D. L., D Todd, M., Park, G., & Farrar, C. R. (2007). Development of an impedance-based wireless sensor node for structural health monitoring. Smart Materials and Structures, 16(6).

Ni, Y. Q., Xia, Y., Liao, W. Y., & Ko, J. M. (2009). Technology innovation in developing the structural health monitoring system for Guangzhou New TV Tower. Structural Control and Health Monitoring, 16(1), 73–98. doi: 10.1002/stc.303

Nisshinbo. (2018). Datasheet RP104x series 150mA ultra low supply current ldo regulator.

Oliveira, L. M. L., & Rodrigues, J. J. P. C. (2011). Wireless sensor networks: A survey on environmental monitoring. In Journal of Communications (Vol. 6, Issue 2, pp. 143–151). doi: 10.4304/jcm.6.2.143-151

OpenJS Fundation. (2022). Node-RED website, https://nodered.org/.

Orcesi, A. D., & Frangopol, D. M. (2011). Optimization of bridge maintenance strategies based on structural health monitoring information. Structural Safety, 33(1), 26–41. doi: 10.1016/j.strusafe.2010.05.002

Pakzad, S. N., Fenves, G. L., Sukun, K., & Culler, D. E. (2008). Design and Implementation of Scalable Wireless Sensor Network for Structural Monitoring. JOURNAL OF INFRASTRUCTURE SYSTEMS. doi: 10.1061/ASCE1076-0342200814:189

Paolucci, R., Muttillo, M., di Luzio, M., Alaggio, R., & Ferri, G. (2020, September 23). Electronic Sensory System for Structural Health Monitoring Applications. 2020 5th International Conference on Smart and Sustainable Technologies, SpliTech 2020. doi: 10.23919/SpliTech49282.2020.9243798

Ragnoli, M., Barile, G., Leoni, A., Ferri, G., & Stornelli, V. (2020). An autonomous low-power lora-based flood-monitoring system. Journal of Low Power Electronics and Applications, 10(2). doi: 10.3390/jlpea10020015

Ragnoli, M., Leoni, A., Barile, G., Ferri, G., & Stornelli, V. (2022). LoRa-Based Wireless Sensors Network for Rockfall and Landslide Monitoring: A Case Study in Pantelleria Island with Portable LoRaWAN Access. Journal of Low Power Electronics and Applications, 12(3), 47. doi: 10.3390/jlpea12030047

Ramesh, M. v. (2009). Real-time wireless sensor network for landslide detection. Proceedings - 2009 3rd International Conference on Sensor Technologies and Applications, SENSORCOMM 2009, 405–409. doi: 10.1109/SENSORCOMM.2009.67

Rossi, M., Guzzetti, F., Salvati, P., Donnini, M., Napolitano, E., & Bianchi, C. (2019). A predictive model of societal landslide risk in Italy. In Earth-Science Reviews (Vol. 196). Elsevier B.V. doi: 10.1016/j.earscirev.2019.04.021

Ruan, T., Chew, Z. J., & Zhu, M. (2017). Energy-Aware Approaches for Energy Harvesting Powered Wireless Sensor Nodes. IEEE Sensors Journal, 17(7), 2165–2173. doi: 10.1109/JSEN.2017.2665680

Sabato, A., Niezrecki, C., & Fortino, G. (2017). Wireless MEMS-Based Accelerometer Sensor Boards for Structural Vibration Monitoring: A Review. IEEE Sensors Journal, 17(2).

Semtech. (2020). Datasheet SX1276/77/78/79 - 137 MHz to 1020 MHz Low Power Long Range transceiver.

Sidorov, M., Nhut, P. V., Matsumoto, Y., & Ohmura, R. (2019). LoRa-Based Precision Wireless Structural Health Monitoring System for Bolted Joints in a Smart City Environment. IEEE Access, 7, 179235–179251. doi: 10.1109/ACCESS.2019.2958835

SiliconLabs. (2017). Datasheet CP2102/9 single-chip USB-TO-UART bridge.

Sohn, H., Charles R. Farrar, Francois M. Hemez, Devin D. Shunk, Daniel W. Stinemates, Brett R. Nadler, & Jerry J. Czarnecki. (2003). A review of structural health monitoring literature: 1996–2001. Los Alamos National Laboratory.

STMicroelectronics. (2016a). LIS3DH MEMS digital output motion sensor: ultra-low-power high-performance 3-axis “nano” accelerometer. Retrieved from www.st.com

STMicroelectronics. (2016b). STM32L151x6/8/B STM32L152x6/8/B Ultra-low-power 32-bit MCU ARM®-based Cortex®-M3, 128KB Flash, 16KB SRAM, 4KB EEPROM, LCD, USB, ADC, AC. Retrieved from www.st.com

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., & Gao, X. (2019). A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. Automation in Construction, 101, 127–139. doi: 10.1016/j.autcon.2019.01.020

Texas Instruments. (2019). Datasheet bq21040 0.8-A, Single-Input, Single Cell Li-Ion and Li-Pol Battery Charger.

The Things Network. TTN Website (2022). https://www.thethingsnetwork.org/ .

u-blox. (2021). MAX-7 u-blox 7 GNSS modules Datasheet.

Vaibhav, K., Sonal, M., & Ankush, K. (2016). A Review on XBEE Technology. International Journal of Emerging Technologies in Engineering Research (IJETER), 4(4).

Vangelista, L. (2017). Frequency Shift Chirp Modulation: The LoRa Modulation. IEEE Signal Processing Letters, 24(12), 1818–1821. doi: 10.1109/LSP.2017.2762960

Xiamen Milesight IoT Co., Ltd. (2022). UG65 Gateway Datasheet.

Zhiguo, H., Wentao, L., Hadi, S., Hao, Z., Haiyi, Z., & Pengcheng, J. (2022). Integrated structural health monitoring in bridge engineering. Automation in Construction, 136.