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Full-scale bridge expansion joint monitoring using a real-time wireless network

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Abstract. Bridges are critical to the civil engineering infrastructure network as they facilitate movement of people, the transportation of goods and services. Given the aging of bridge infrastructure, federal officials mandate visual inspections biennially to identify necessary repair actions which are time, cost, and labor-intensive. Additionally, the expansion joints of bridges are rarely monitored due to cost. However, expansion joints are critical as they absorb movement from thermal effects, loadings strains, impact, abutment settlement, and vehicle motion movement. Thus, the need to monitor bridge expansion joints efficiently, at a low cost, and wirelessly is desired. This paper addresses bridge joint monitoring needs to develop a cost-effective, real-time wireless system that can be validated in a full-scale bridge structure. To this end, a wireless expansion joint monitoring was developed using commercial-off-the-shelf (COTS) sensors. An in-service bridge was selected as a testbed to validate the performance of the developed system compared with traditional displacement sensor, LVDT, temperature and humidity sensors. The short-term monitoring campaign with the wireless sensor system with the internet protocol version 6 over the time slotted channel hopping mode of IEEE 802.15.4e (6TiSCH) network showed reliable results, providing high potential of the developed system for effective joint monitoring at a low cost.

Keywords: bridge monitoring; expansion joints; wireless sensor networks

1. Introduction

Maintaining the safety, stability, and longevity of a bridge is of utmost importance. Bridges are subjected to constant movement from numerous sources, including environmental temperature swings leading to expansion and shrinkage, dead and live loads including moving vehicle loading,

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impact, and abutment settlement (Phares 2005, Malla *et al.* 2006). A bridge must be capable of withstanding the stresses caused by such external loadings and disturbances to function properly. Several bridge monitoring systems have been in place throughout the nation; however, current methods of bridge monitoring fall short of their intended purposes. The present methods of bridge monitoring are overwhelmingly based on manual visual inspection.

The deck expansion joint systems integral to bridge construction, and are designed to accommodate the movements of bridge components due to thermal expansion and other factors, studies have shown that these of multiple varieties have not performed satisfactorily (Benson 1986, Chang and Lee 2002, Dahir and Mellott 1985, Frederick 1984, Hamilton 1985, Voigt and Yrjanson 1992). As a result, there has been accelerated decks and bearings degradation, leading to structural failure; It is natural to expect that such an event to be more pronounced and frequent in older bridges. For example, many bridges built in the 1960s and '70s do not meet today's design and safety standards, and these old bridge failures are becoming more common (Casas *et al.* 2003). The poor performance of bridge joints and their important role in the stability and performance of a bridge necessitate the development of a continuous monitoring system. A continuous monitoring system can help detect problems sooner so steps can be taken to prevent further deterioration and possible bridge failure. In addition, the data collected can be analyzed to assess the health and performance of the bridge.

To date, several researchers monitored bridge expansion joints using traditional sensors around the world. In Hong Kong, China, the Ting Kau Bridge expansion joint displacement was measured from a structural health monitoring (SHM) system where the displacement and temperature were correlated. (Ni *et al.* 2007). In this study, the established baseline correlation pattern was used to detect anomalies in the bridge and was beneficial in providing a process for design verification and bridge condition assessment. The I-35W St. Anthony Falls Bridge in Minneapolis, Minnesota also adopted anomaly detection methods (Hedegaard *et al.* 2017). A finite element (FE) model has been used to detect changes in the response of the bridge over the Yangtze River in Jiangsu, China (Xia *et al.* 2017). For these bridges, the expansion joints were monitored with traditional wired sensors, which are costly and need extensive maintenance due to the degradation of miles of wires.

Based on the previous bridge studies, joint monitoring systems vary greatly depending on the needs and demands of the structure. These bridges were equipped with various sensors to accurately collect the required information for data verification and provide real-time information on the conditions of the bridge. However, most bridges worldwide are not equipped with the technology to monitor the expansion joint because current systems are labor-intensive, time-consuming, and costly. A study shows that the estimated cost for maintaining expansion joints is between 7% to 8% of the total maintenance cost of the bridge (Marques Lima and Brito 2009). As a critical component of the transportation network, it is crucial to assess defects in, or damages to, the bridges using methods that continuously monitor the bridge expansion joints. Thus, developing a process that can alert engineers of potential damage in a time-efficient and cost-effective manner is vital.

In the last several decades, wireless sensor technologies have drawn significant attention in hardware, software, communication, and power supply. Many researchers working on civil infrastructure have also attempted to deploy wireless sensors on the bridge in the early millennium to achieve continuous monitoring at a lower cost (Jang *et al.* 2010, Rice *et al.* 2010, Cho *et al.* 2010). For example, a hybrid sensor to measure the expansion joint using a traditional LVDT and a wireless platform was developed and implemented on the Founders Bridge in Connecticut (Jang *et al.* 2013). However, limitations arose due to the poor accuracy of digital sensors and clocks, short communication range, and high-power consumption with low-efficiency renewable energy.

Typically, industrial sensing and control systems have stringent timing and reliability requirements on communication, i.e., all packets must be delivered before the application-specific deadlines with ultra-high reliability. However, commercial wireless technologies like Wi-Fi or Bluetooth cannot provide such guarantees since they are designed to maximize the overall throughput. Thus, dynamic network traffic and unexpected interferences can cause unbounded packet loss. In recent years, 6TiSCH has received increasing attention from both industry and academia based on its wide deployment in many industrial domains, including advanced manufacturing, industrial process control, smart grids, and healthcare (Wang *et al.* 2021, Sisinni *et al.* 2018, Da Xu *et al.* 2014, Breivold and Sandstrom 2015). 6TiSCH is a representative real-time wireless networking technology that offers industrial performance in terms of timing, reliability, and power consumption. Recently, Wang *et al.* (2021) developed the 6TiSCH communication platform. This platform has higher computational power with integrated sensors, and a real-time wireless communication protocol has been developed for a dense array of sensors. Furthermore, the gathered data were routed through an autonomous dynamic network scheme and processed in a cloud-based analytics platform. In addition, the power consumption is minimal, so small solar panels can supply continuous power to the sensing system without interruption.

Other emerging Internet of Things (IoT) technologies that could be used for bridge monitoring are LoRa (Wixted *et al.* 2016) and NB-IoT (Ratasuk *et al.* 2016). LoRa is a physical proprietary radio communication technique operating in a non-licensed band below 1 GHz. Although the sub-GHz band enables long-range communication (3-10 miles), it leads to an extremely low data rate (0.3-50 kbps), which cannot support a large amount of sensor data to be transported. Meanwhile, LoRa's upper layers lack real-time communication support - its MAC layer uses an ALOHA-like simple mechanism without collision avoidance, thus introducing significant packet losses and increasing power consumption.

Narrowband (NB)-IoT is another low-power and wide-range communication technology. Developed by 3GPP, NB-IoT is integrated into the LTE standard and can work seamlessly with existing LTE infrastructure. The cellular support for NB-IoT improves its performance and security. However, it must operate on the licensed spectrum and is only available to established mobile network operators. Thus, 6TiSCH is the selected technology as the network infrastructure of this paper since it supports reliable real-time communication and operates on non-licensed bands.

This paper presents the development of a wireless low-cost bridge expansion joint monitoring system, the deployment of the system on an in-service bridge, and the performance discussion. The components of the developed expansion joint monitoring systems including the hardware, software, communication, and power supply will be provided in detail. The developed system was deployed on an in-service bridge representing a typical bridge in Connecticut so that the findings can be used for other bridges as well.

2. Wireless sensor network components

2.1 Communication architecture: 6TiSCH network

The critical technology for the wireless sensor network utilized in this paper is the 6TiSCH network. 6TiSCH is based on the Time-Slotted Channel Hopping (TSCH) technology, a MAC layer specified in IEEE 802.15.4e, with a design inherited from WirelessHART and ISA100.11a (Breivold and Sandstrom 2015, Dujovne *et al.* 2014). In TSCH, total time is divided into time slots, each using

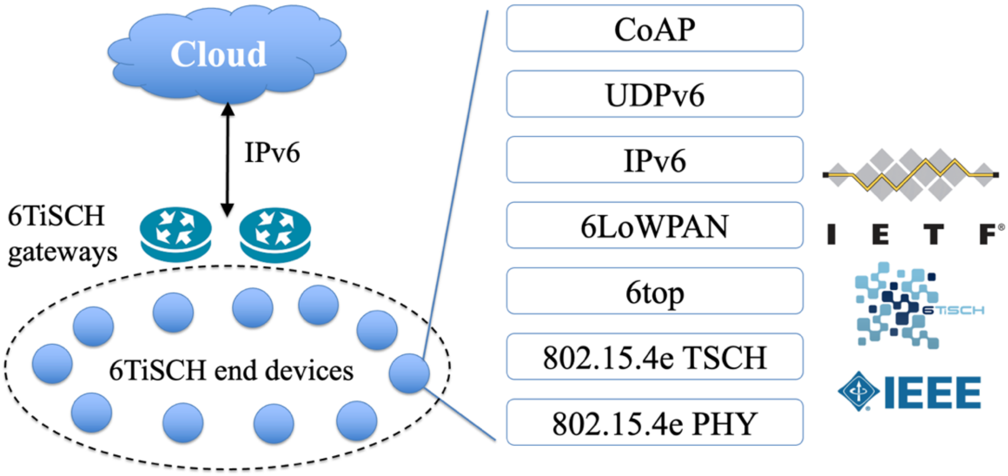


Fig. 1 Overview of the 6TiSCH network architecture (Wang *et al*. 2021)

a different channel assigned by the channel hopping function. This channel hopping feature reduces the impact of multipath fading and yields 99.99% end-to-end reliability (Watteyne *et al*. 2009). Additionally, within TSCH, end devices only turn on their communication module in the active time slots and enter the sleep mode in other slots to save power. The 6TiSCH network combines the 802.15.4e data link layer and an IP-enabled upper layer stack to achieve deterministic network performance and seamless integration with Internet services (Wang *et al*. 2021). In the network layer, 6TiSCH employs the Routing Protocol for Low-Power and Lossy Networks (RPL) to form a tree-based multi-hop network that can cover a large-scale area.

The overall network architecture of the full-blown 6TiSCH testbed and its protocol stack is shown in Fig. 1. It consists of end devices, one or multiple gateways, and a network management and visualization system, typically deployed in the cloud. A 6TiSCH end device is an embedded device equipped with sensors and/or actuators running a 6TiSCH stack to collect physical data from a testbed. The layered structure of the 6TiSCH stack is shown on the right side of Fig. 1. The 6TiSCH is based on the IEEE 802.15.4e PHY radio, and the stack runs on the TSCH mode of IEEE 802.15.4e to provide deterministic channel access with low latency and reliable packet delivery. On top of the TSCH layer, the 6TiSCH Operation (6top) Sublayer manages the time and channel resources in a 6TiSCH network by adding, deleting, and relocating cells to support the traffic from individual end devices. The primary function of the 6LoWPAN layer is protocol adaptation between standard IPv6 *datagrams* and 802.15.4e *frames*, which are incompatible for communication. The datagrams are then transported to the UDPv6 layer. In the top application layer, the Constrained Application Protocol (CoAP) enables constrained devices called nodes or end devices to communicate with internet services. Thus, the CoAP layer provides access to individual end devices from the internet. These seven layers enable efficient data communication between the gateways and the end devices.

2.2 Hardware architecture

The 6TiSCH gateway is an embedded Linux OS with a 6TiSCH Access Point that serves as the coordinator and the border router of a 6TiSCH network. To maintain a large-scale 6TiSCH network,

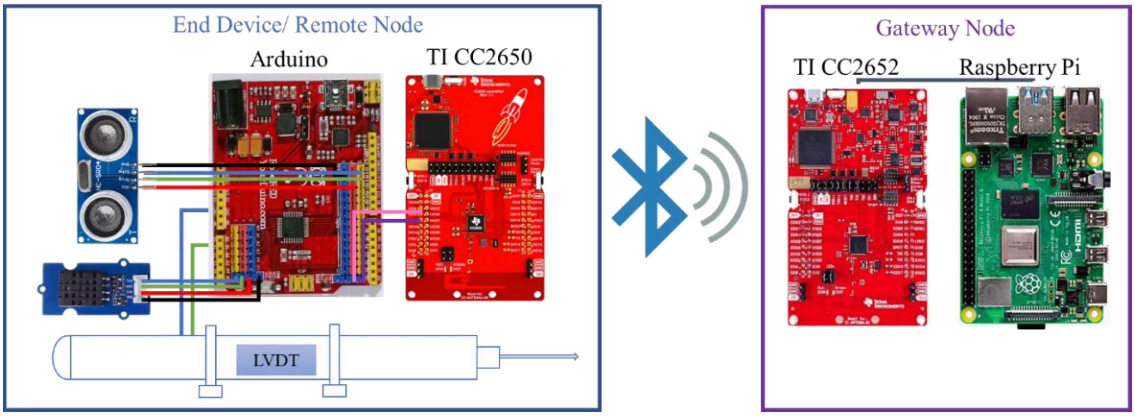


Fig. 2 Connection schematics of an end device (left) and the gateway (right)

a rich set of topology and schedule management functions is developed on the gateway to achieving real-time, robust, and self-adaptive network resource management.

The end device is composed of a network card and the sensors controller. As shown in Fig. 2, a TI CC2650 Launchpad is used as the IEEE 802.15.4e-enabled network card that can transmit sensor data packets to the TI CC2652 gateway. Once the gateway has received the packets, the data is forwarded to the data center, which can be a local server or a cloud server. An Arduino UNO derivative, YourDuino RoboRED, connected with wired serial communication has been adopted as the sensor controller since the implementation of the 6TiSCH stack consumes most of the memory and computational resource of TI CC2650. The adaptation of Arduino as the controller simplifies the function and development of each end device due to the developer community having large libraries of sensor-controlling functions. Therefore, with serial communication, CC2650 can easily read sensor data from the Arduino-based sensor controller with low overhead and thus increases the stability and development efficiency.

Data collection consists of a controller, transmitter, receiver, and processor. As the controller, Arduino samples data from its attached sensors and transmits it to TI CC2650 via wired serial communication. As the transmitter, TI CC2650 reads sensor data from serial communication and transmits it to the 6TiSCH gateway through wireless IEEE 802.15.4e radio. The 6TiSCH gateway is the receiver and processor to convert the radio signal to an IP. The IP structured data can be stored in a local server or uploaded to a cloud server through the internet. Once the gateway receives and processes the data, users can access and export said data via a local or cloud server.

2.3 RESTful web service

A comprehensive RESTful web service is deployed to provide real-time monitoring, analysis, and visualization of 6TiSCH networks (see Fig. 3). A RESTful web service uses a Representational State Transfer (REST) architecture to provide a simple and comprehensible application programming interface (API) (Deljouyi and Ramsin 2022). Benefiting from this web service, end users can monitor the sensor readings, network performance, and the current communication schedules in real time. It also allows network engineers and researchersto export sensor readings and network statistic data and perform various network analysis tasks. Therefore, the 6TiSCH-enabled wireless monitoring testbed was successfully developed for field testing.

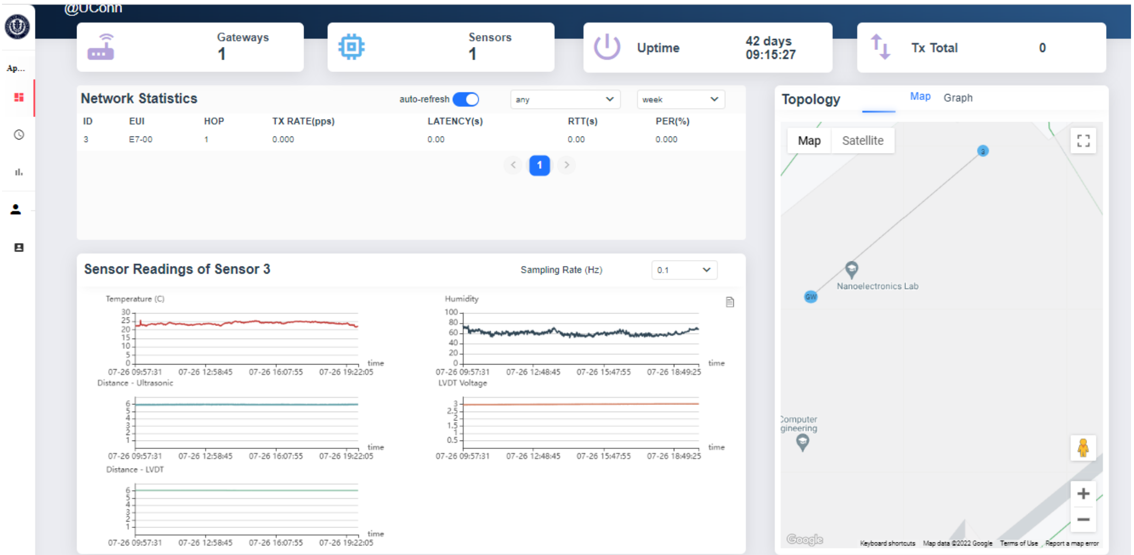


Fig. 3 Screenshot of the network management and visualization system

Fig. 4 Candidate Bridge in Coventry, CT

3. Full-scale field experiments

3.1 Bridge description

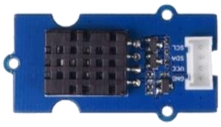
The testbed bridge used in this study and results presented in this paper is a steel girder bridge (Bridge 01531) in Coventry, CT, as shown in Fig. 4. The bridge was built in 1959 and spans 151.9 ft across the Willimantic River. This bridge was selected based on the maximum span length, percentage of trucks, a zero-skew angle for simple joint monitoring, availability for testing generously provided by the Connecticut Department of Transportation, and proximity from the campus of the University of Connecticut. These factors were examined from the 2021 National Bridge Inventory (NBI) database for 5,625 state-owned bridges in Connecticut.

The expansion joint of the testbed bridge is identified as an asphaltic plug joint shown in Fig. 5(a). The asphaltic joint falls under the small movement joint category and based on normal design

(a) Street view of the joint (b) Beam end and the abutment

Fig. 5 Expansion joint information on the testbed bridge shown in Fig. 4

Table 1 Sensor specifications

Sensor Model	Accuracy	Operating Voltage	Measurement Range	Photo
Ultrasonic Distance Sensor HC-SR04	2 mm	3.2-5.2V DC	3-350 cm (1-137in)	
Grove - Temperature & Humidity Sensor V2.0	Temperature: ± 0.5℃ Humidity: ± 3% RH	2.5-5.5V DC	Temperature: -40 ~ + 80℃ Humidity: 0 ~ 100% RH	
Govee Bluetooth Digital Hygrometer H5075001	Temperature: ± 0.32℃ Humidity: ± 3% RH	2 AAA Batteries	Temperature: -20 ~ + 60 ℃ Humidity: 0 ~ 99% RH	
Transtek Series 350 DC Gaging Transducer Model 0356	Infinite (Analog)	6-28V DC	± 3 in (76.2 mm)	

specifications, the maximum movement of such joint should be up to 2 inches (Price 1984, AASHTO, 1998, Malla *et al.* 2006). As shown in Fig. 5(b), the gap between the beam end and the abutment is targeted for the sensor location because it is the only exposed location that allows bridge expansion.

3.2 Sensor setup

A wireless sensor system was developed to collect the temperature, humidity, and displacement from the testbed bridge. COTS wireless sensors were carefully examined for the joint monitoring application considering accuracy, operating voltage, and measurement range. An ultrasonic distance sensor, HC-SR04, and Grove temperature and humidity sensor v. 2.0 were chosen for the deployment. Reference sensors were employed to examine the accuracy of the digital sensors. A TransTek Series 350 DC Gaging Transducer with infinite resolution (an LVDT sensor) and a Govee Bluetooth Digital Hygrometer were used. The specifications of all four sensors are presented in Table 1.

With all components, a comprehensive wireless sensor system schematic was developed (Fig. 6). The reference sensors included the LVDT transducer, the data acquisition block, and a Govee

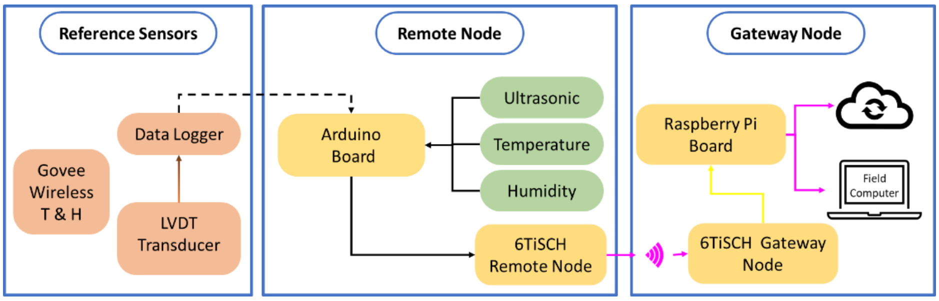


Fig. 6 Sensor schematic containing reference sensor, remote node, and gateway node

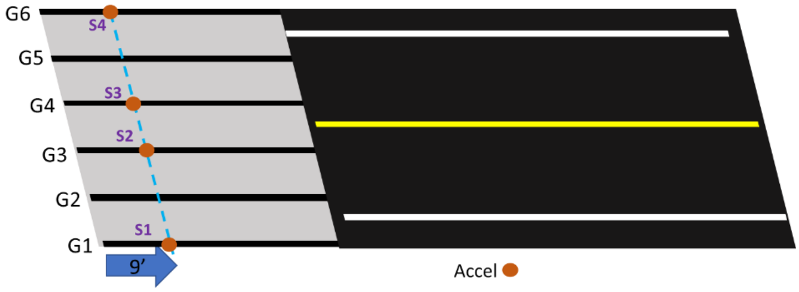


Fig. 7 Vibration testing sensor layout on the bridge

wireless temperature and humidity sensor to validate the performance of the wireless sensors. The remote node is the end device to collect data from the ultrasonic sensor and the temperature and humidity sensor connected to an Arduino board. Among the reference sensors, the LVDT was also connected to the Arduino board to achieve synchronous data collection with the ultrasonic sensor. The collected data were treated by the 6TiSCH layer and transferred to the gateway node. The gateway node consisted of a Raspberry Pi board connected with a 6TiSCH gateway node for communication. The transferred data from the remote node to the gateway node was stored in a flash (volatile memory) and then uploaded to the cloud using Wi-Fi. For Wi-Fi communication, a Wi-Fi hotspot was connected to the Raspberry Pi board. Finally, the data can be viewed on a cloud-based server.

3.3 Deployment

Before deploying the wireless displacement sensor system, a vibration monitoring campaign was conducted. As shown in Fig. 7, PCB 353B33 wired accelerometers were placed at the underside of selected girders were equipped with a PCB power supply, a PCB signal conditioner, and a VibPilot system was used for data acquisition (Piezotronics 2023, VibPilot 2010). The vibration data was acquired at 256 Hz for 600 seconds.

The acceleration data collected at the locations (S1, S2, S3, and S4) specified in Fig. 7 are presented as a time history shown in Fig. 8. G1 – G6 indicate the number of the girders of the bridge. The maximum vertical acceleration recorded was 0.0026 g at girder 3. The peaks are most likely caused by passing vehicles on the road. Thus, to reduce the effects of passing vehicles, girder 6 was selected to deploy the wireless sensor system.

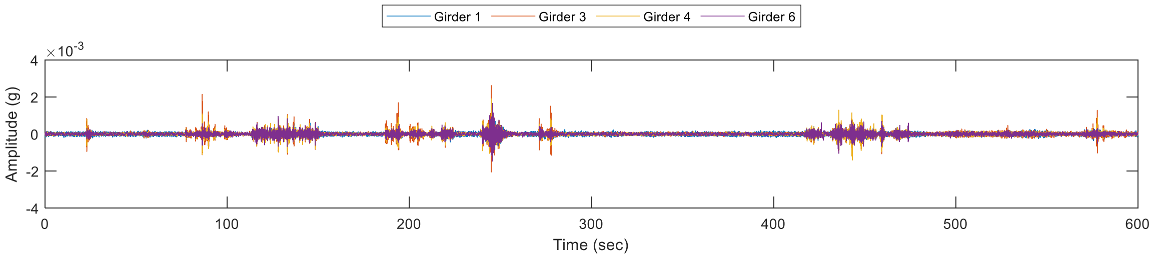


Fig. 8 Time history of vertical acceleration at S1 to S4

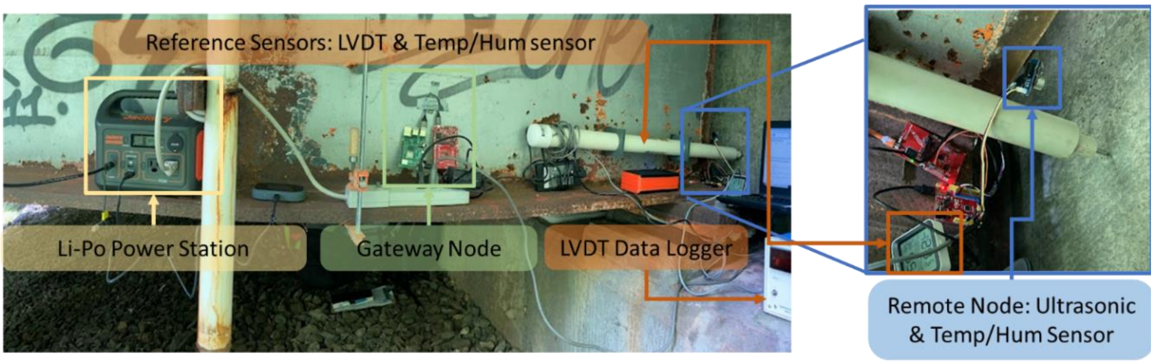


Fig. 9 Test setup of displacement monitoring campaign

The wireless sensor system developed herein was deployed on the selected bridge (Fig. 4) for a short-term monitoring of joint movement in July 2022 as shown in Fig. 9.The reference sensors, including the LVDT, temperature and humidity sensors, were deployed with the wireless displacement and temperature & humidity sensors to measure the gap between the beam end and the abutment of girder 6, as mentioned. Because both gateway and remote nodes were located nearby, in this case near the abutment. All components were powered by a Lithium-Polymer (Li-Po) power bank battery and a high-capacity power station supplied by solar panels. During a 10-hour monitoring period, the system was fully functional and continuously collected all three data without any loss of power. Therefore, the field monitoring experiment successfully validated the stability of the developed wireless sensor system.

4. Results and discussions

4.1 Results

The data collected from the wireless sensors from the remote node were compared to the reference sensors as shown in Fig. 10. The temperature, humidity, and displacement measured by wireless and reference sensors match reasonably well. The temperature experienced throughout this test showed ranges of 22°C to 25°C, and the humidity was between 55% RH to 70% RH. Because of the relatively narrow temperature range, the displacement did not show significant change. Therefore, the short-term test campaign was successful.

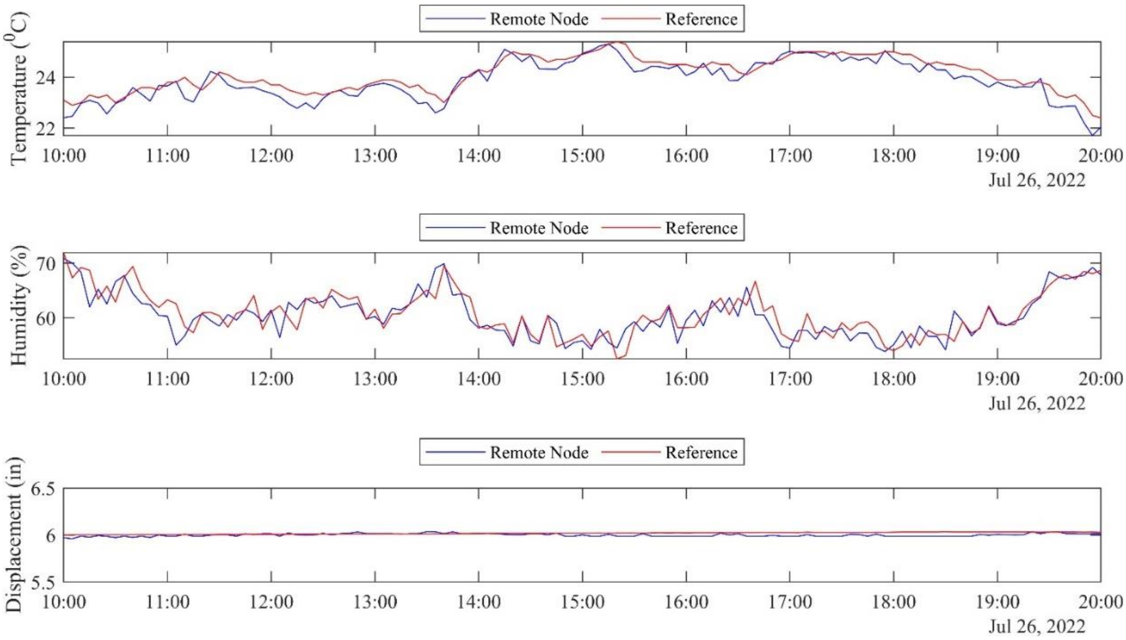


Fig. 10 Collected Data from Wireless Sensors (Remote Node) and the Reference Sensors, top: Temperature, middle: humidity, bottom: displacement

4.2 Discussions and recommendations for future work

There were a few limitations of the 6TiSCH network in its original form before it was adopted for infrastructure monitoring. First, because the 6TiSCH network is designed for low-power and lossy networks, additional design considerations have been taken to ensure timing, reliability, and power consumption for long-term deployment. To reduce power consumption and achieve extended battery life, 6TiSCH devices only wake up when they turn on the radio module and transmit packets. Each transmission takes 1-time slot, which is usually 10 milliseconds.

Because the maximum payload size per packet is around 100 bytes to minimize the power consumption, ideally, each device's maximum bandwidth is 10 kilobytes per second (kBPS). The 6TiSCH chooses to optimize power consumption and accepts the tradeoff of lower bandwidth. Therefore, using the 6TiSCH network for continuous monitoring of raw acceleration with high sampling frequency is not suitable. To use the 6TiSCH network to monitor acceleration, an onboard computation protocol should be developed where only the monitoring results, not raw time histories, should be transferred.

For reliability, it is noted that the byte operations of Arduino's serial library are limited and, thus, prevent the design of a complete protocol with integrity check and recovery for sensor data exchange over serial. However, it is possible to transmit Arduino's default string format. For example, this procedure would transmit a string "16" of length two instead of the integer 16. Therefore, to improve the serial communication reliability, a fixed length of transmitted strings from Arduino by dynamic zero-padding is employed to avoid data inconsistencies. The format of the strings should be revisited and programmed as needed to re-configure the number and type of sensors. Further research to design and deploy a long-term monitoring system on the testbed is still underway.

5. Conclusions

A new wireless sensor system using the 6TiSCH network for bridge expansion joints was developed and its performance was validated by implementing it on an in-service bridge in the field. The 6TiSCH network, hardware, and software components of the wireless sensing system were carefully selected and fine-tuned for bridge joint monitoring. The system was deployed in a bridge in Coventry, CT to monitor the beam end displacement along with the temperature and humidity using a set of wireless sensor system developed in this study and reference sensors. From the short-term monitoring field experiment done, the collected data showed reasonable match between the wireless sensor system and the reference sensors, showing that the wireless bridge joint sensing system developed worked satisfactorily in the field. All systems were powered by renewable energy source, providing long-term deployment potential of the wireless bridge joint sensor system. The limitations of the 6TiSCH network and Arduino for the system were considered and successfully addressed for the data collection. The developed wireless bridge joint monitoring system, thus, has shown significant potential for monitoring bridge joints with reasonable performance, ease of usage, and low cost. Further development and implementation of the system for long-term bridge joint monitoring in the field are underway. The developed sensor system can enhance the transportation infrastructure's durability by timely detection of special damaging events to prevent further deterioration and possible bridge failure. The collected long-term displacement data can be employed to develop a baseline correlation curve to serve as a performance rubric for the expansion joints and improve bridge design for the New England region. In addition, continuous monitoring of expansion joints of aging bridges can assist the development of new expansion joints under climate change, ever-increasing temperature fluctuation, and heavy winter storms or hurricane events.

Acknowledgments

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