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Development of IoT based bridge health monitoring system: A work in progress

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1. Introduction

Bridges are critical infrastructure, connecting people and places across the world and facilitating the transfer of goods and resources. Bridge failure can lead to large economic and political ramifications, which highlights the importance of Structural Health Monitoring (SHM) and maintenance particularly under varying environmental effects and variable loads (Sharaf, 2013). Reliable bridge health monitoring is essential for the timely maintenance response. Traditional wire-based technologies for structural health monitoring can be costly, time consuming and sometimes unsafe to install due to the complex structures of the bridges, and the size and weight of this equipment and heavy load of traffic.

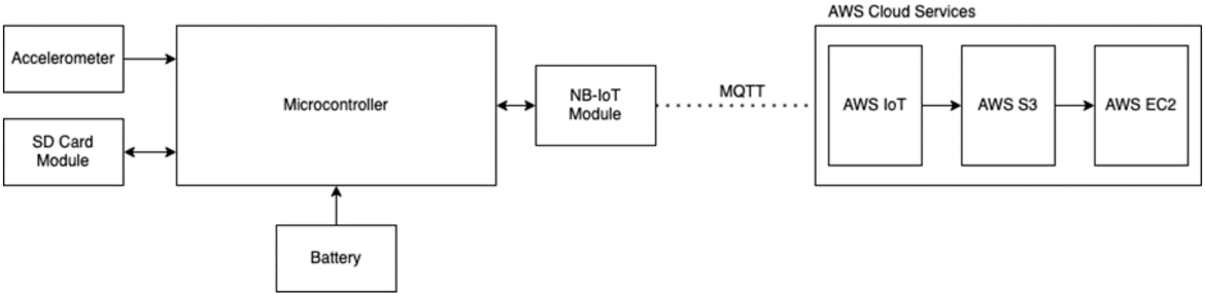
New advancements in technologies like miniaturized sensors, low power wide area network communication, cloud data storage and computing can bring new approaches to SHM (Kamal and Mansoor, 2022). In particular, accelerometers have been utilised in SHM to measure vibrations, bridge displacement, and identify fundamental frequencies, which are useful indicators for identifying structural health. Affordable sensors such as Micro-Electro-Mechanical Systems (MEMS) based accelerometer sensors have demonstrated comparable performance to piezoelectric accelerometers typically used in wired SHM applications (Sabato et al., 2016).

This paper presents the ongoing work developing an Internet of Things (IoT)-based vibration SHM system, which can capture the bridge accelerations and upload data directly to cloud-based services for processing and analysis. Using miniaturised accelerometers, IoT capable microcontrollers, narrow band IoT communication and Amazon Web Services, the prototype acts as a bridge health screening and early warning system, aimed at reducing the cost and time required for traditional wired sensing equipment. The paper presents the suitability of a cost effective IoT based system for data gathering, traffic inference and analysis leading to bridge health monitoring.

2. System prototype

The proposed system schematic is shown in Figure 1. The functionality of the system is described by a number of layers. The hardware includes the accelerometer sensor, microcontroller entity with local storage and Real Time Clock (RTC), power supply, and NB-IoT communication module. The sensing layer describes the sampling of the accelerometer at a given output data rate and saving to local storage in a SD card. The transmission layer encompasses the transmission of stored data to S3 storage via AWS IoT Core over NB-IoT using MQTT protocol. Finally, the access layer describes interaction with the collected data including data processing and dashboard display.

Figure 1: The proposed system



In the project, three different hardware platforms were investigated for acceleration data collection. The commercial Libelium Waspmote (Libelium, 2023) was discarded due to minimal support for the Waspmote software libraries and limited SRAM on the microcontroller. The RAK wireless WisTrio RAK5010 (RAKwireless, 2023) was also tested, but had connectivity issues over NB-IoT, and was replaced with an Arduino based MKR NB1500 (Arduino, 2023). Arduino MKR NB1500 platform has inbuilt IoT and RTC modules, external SD card shield and the ADXL345 accelerometer. The hardware was housed in purpose-built enclosures, shown in Figure 2.

Figure 2: From left to right, Libelium Waspmote, RAKwireless WisTrio RAK5010 and Arduino MKR NB 1500

3. Methods

3.1 Data collection

An experiment was conducted in September 2022 on the Stirling Bridge in Fremantle, Perth to compare data from three modalities, visual (video) data, wired vibration data and data from the IoT prototype. Stirling Bridge is a 415 metre, seven span twin post-tensioned segmental spine concrete bridge (Institute of Transport, 1963). Due to Stirling Bridge’s proximity to the Fremantle dockyard and as a major arterial road, it experiences a mix of traffic loads, from Class 1 vehicles (passenger cars) to larger trucks (Class 7+), as per the vehicle classes described in (Patrick, 2018).

The IoT sensor, as well as a number of industrial accelerometers were placed inside the girder box in the centre of a span to maximise the bridge vibrations. Cameras were placed roadside at the beginning and end of the selected span to visually capture the traffic conditions. The IoT prototype utilised an ADXL345 accelerometer (Analog Devices, 2022), which collects data at 100 Hz, with a resolution of 3.9mg/LSB (10-bit ADC). Data is flushed to the external SD card storage every 10 seconds, resulting in an overall data rate slightly less than 100 Hz due to some opportunity loss during the saving process.

The industrial wired accelerometer used for this comparison is the analog Kistler 8330A3 ServoK-Beam Accelerometer (Kistler Instruments, 2006). This sensor has a reported sensitivity of 1200mV/g, and recorded acceleration in the vertical (z) direction at 100Hz throughout the experiment. The Kistler accelerometer needs the additional equipment that is contained in several large, heavy metal containers and required experienced operators to setup and use the

equipment. Additionally, equipment of this size and cost requires considerable resources to operate and secure for longer testing periods. Figure 3 clearly demonstrates the benefits of a smaller, microcontroller based IoT sensing device.
The experimental data was collected in three parts. The first part, about 7.5-8 hours, was collected inside one of the girder boxes. The sensors were then moved to the girder on the opposite side where they collected data for approximately 42 hours. Finally, as there were difficulties with installing the necessary equipment in close proximity to the industrial sensors, and the degradation of the signal strength over the bridge span, 30-40 minutes of data was also collected along the roadside.

Figure 3: The IoT prototype sensor (circled in red) and the wired accelerometers set up for roadside testing at Stirling Bridge, WA

The data collected by the IoT system can be sent using a MQTT broker over the Telstra network and received by AWS IoT core. Messages are then published to a topic and stored in a Simple Storage Service (S3) bucket. A dashboard was developed to display the incoming data using the Dash/Plotly python library with options of time sliding, zoom in and out, individual axis and multiple axes selection.
With the current SRAM in the Arduino board, 2kB messages can be sent reliably in approximately 1.5 second intervals. Experiments have shown that one minute of 3 axis (x, y, z acceleration) data requires 80 seconds to send to AWS, while recording and transmitting only Z-axis data of one minute duration takes 40 seconds to upload to AWS. It is imperative to increase the message size (or reduce data size) and the upload time, due to opportunity loss (time not spent recording data) and because AWS charges per message. In future, the research will focus on improving these aspects.

3.2 Data analysis

An analysis was conducted in both the time and frequency domains to compare the data collected by wired sensor and IoT sensor. The IoT prototype timestamps each sample using an internal timer, generated by an internal RTC module. The RTC module datetime is set during the code upload via serial connection from laptop, and it was observed that uploading results in a 5-10 second compilation time delay which propagates to the RTC module. The Kistler 8330A3 has no timestamping mechanism for individual samples and is assumed operating at 100 Hz throughout recording.
The synchronisation of the acceleration profiles from both of the sensors proved difficult as there was 5 to 30 second random difference between both profiles. We intend to incorporate an externally generated synchronization event in future data collection.

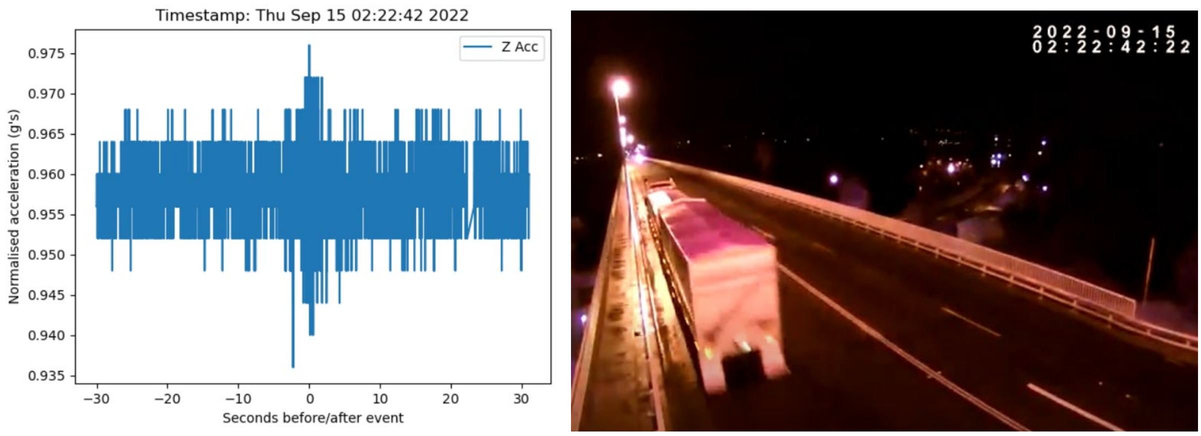
4. Results & discussion

4.1. Comparing IoT and video modalities – inferences on traffic conditions

The traffic density varied during the roadside testing period, and the synchronisation issue made the comparison of all three modalities difficult. However, a qualitative comparison of the captured acceleration data from the IoT sensor and the video data was carried out. Observations, such as speed and vehicle class, are based on visual analysis of the video data.

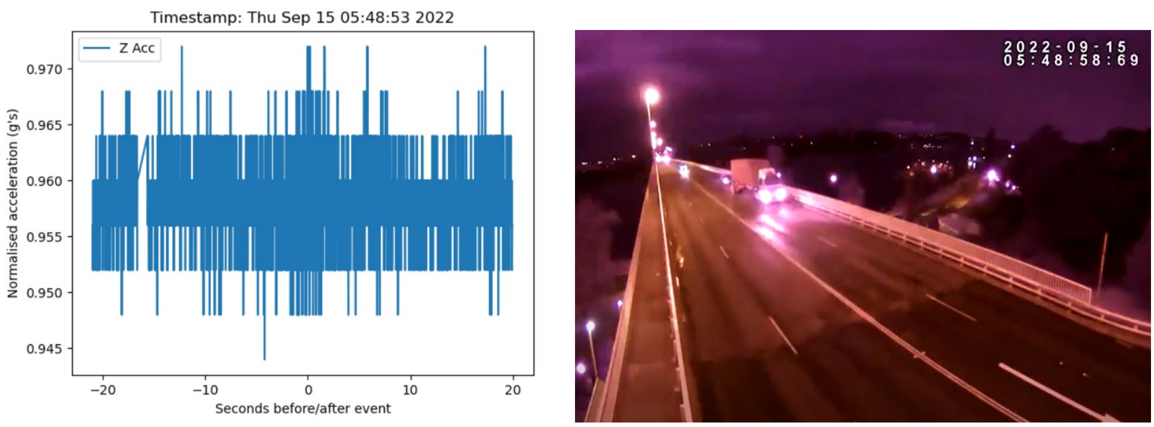
An example of the correlation between a significant IoT response and the passing of traffic is shown in Figure 4. A single truck is passing overhead (only traffic for 30 seconds either side of the event) and a corresponding impulse is observed in the recorded accelerometer data. As the IoT sensor is a digital one, the accelerometer data is depicted in steps (4mg) according to the digital resolution.

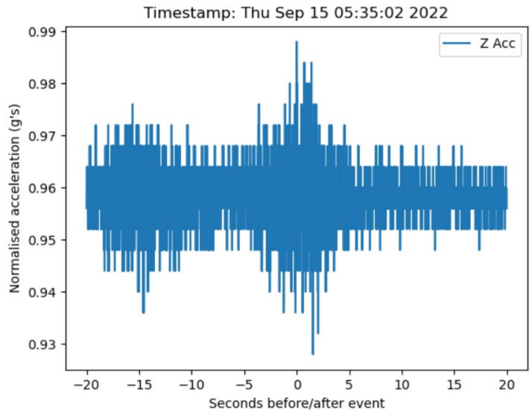
Figure 4: The response of the IoT accelerometer sensor (left) to a truck passing overhead (right)



The magnitude of the IoT response is variable from case-to-case and is difficult to apply a magnitude threshold as the bridge vibrations vary with the number of vehicles, their load and speed. For the events that have been checked by the authors, all cases of heavy vehicles (large trucks etc) do correspond to a recorded acceleration event with an impulse between 0.972 and 0.948 (approx. 4 standard deviations from the mean). Two different traffic patterns are shown in Figure 5. In Figure 5 (top), a single truck alongside two cars is moving slowly, resulting in a minimal response from the IoT sensor. Conversely, in Figure 5 (bottom), one truck is moving quickly on the sensor side of the road, while two cars pass by on the opposite side. There are drastic differences in the magnitudes of the observed responses for events with similar loads/vehicles and distances from the sensor.

Figure 5: Demonstrating the variability in the IoT response for two different traffic patterns.



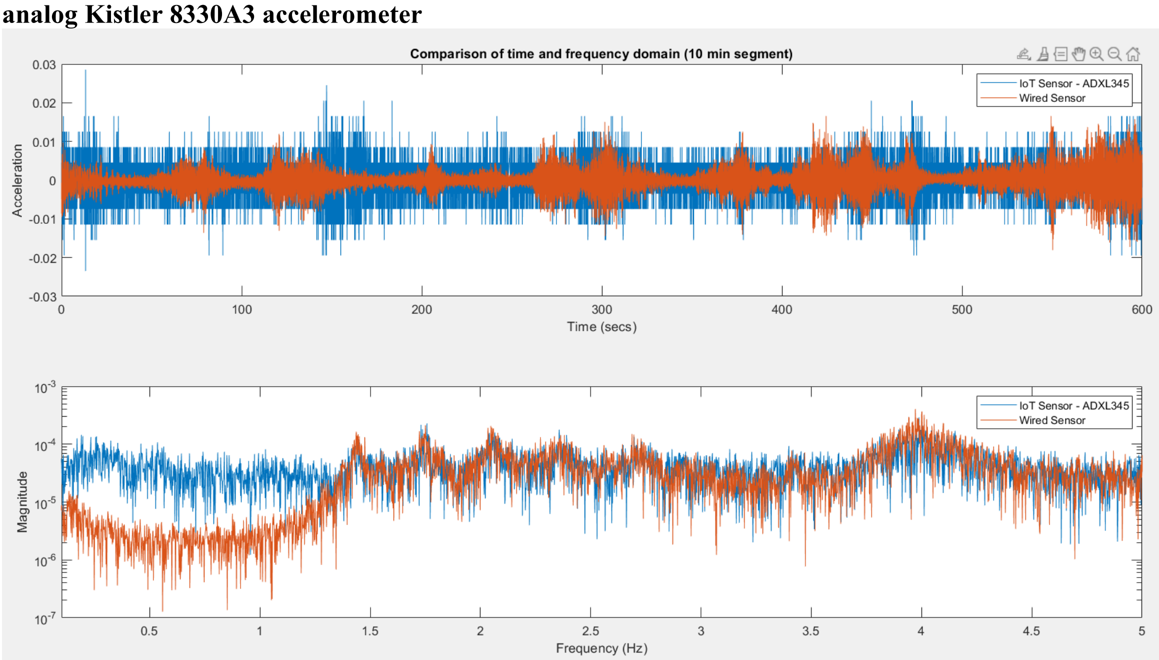


The qualitative analysis of these results demonstrates that further experiments and in-depth statistical analysis could lead to better correlation between traffic load and class against accelerometer data. A video analytics software to extract the vehicle speeds and classes would further assist the analysis of the data.

4.2. Comparison of IoT sensor and wired sensor

The responses of the digital IoT sensor (ADXL345) and the analog industrial wired sensor (Kistler 8330A3) were compared using the data collected from the Stirling bridge. A precise time domain comparison proved difficult due to synchronization issues in the two data sets as the sensors were utilizing different clocks, though it is obvious from Figure 6 (top) that both sensors had a similar time domain response. A frequency domain analysis was performed on 10-minute portions of the wired acceleration data, and the corresponding part of the IoT sensor data, Figure 6 (bottom).

Figure 6: The time and frequency domain (limited to 5Hz) comparison of the digital ADXL345, and the analog Kistler 8330A3 accelerometer



The comparison of time domain results shows similarities in the structure of accelerometer profiles of the analog wired sensor and digital accelerometers, though time synchronization is needed. The ADXL345 suffered from much greater deviations from the mean, even during 'quiet' periods. This can obscure vibrations due to smaller or slower vehicles, which the Kistler accelerometer can discern more clearly. The frequency domain results do show similarities in the frequency and magnitude to the Kistler spectrum at low frequencies, particularly from 1.5 Hz to 5 Hz range, though there is magnitude difference in lower frequency range. Identification of the fundamental modes of vibration of the bridges is relevant for structural health monitoring as these modes have been observed to shift as a result of any damage to the structure. Therefore, it was concluded that there is need for a higher sensitivity accelerometer. The 10-bit ADC of the ADXL345 has an equivalent analog sensitivity of approximately 450mV/g, while the Kistler8330A3 has a greater sensitivity of 1200mV/g. Consequently, after exploring a number of options for replacement accelerometers, authors selected MMA8451 (NXP Semiconductors, 2017), which has an improved sensitivity of 0.25mg/LSB (14-bit ADC), and a lower theoretical RMS noise. Further research will be undertaken with a more sensitive accelerometer.

6. Conclusion

The research work successfully developed a pipeline, hardware, and software, for Structure Health Monitoring of the bridge structure. Traditional bridge health monitoring systems require regular bridge inspections, while the proposed system needs one time installation and later can generate timely alerts. The proposed system is cost effective, easy to install and has an additional communication component that can quickly transfer the data to the cloud for further analysis. Along with the bridge health information, the system can give valuable information related to traffic class and frequency after further research work. The future research work encompasses further comparison of analog wired accelerometer against digital accelerometers with enhanced resolution, noise removal and filtering, improving the data transfer rate over IoT communication link and data processing at the cloud leading to alert generation. The research team will further investigate the application of machine learning models on the collected data to gain valuable insights, which was not possible earlier.

Acknowledgements

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