Early Warning System with Real Time Tilt Monitoring

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***Abstract*—Remote sensing is becoming popular for real time monitoring of a wide variety of objects and phenomena like assets, structural health, ambient air quality. This paper reports the real-world implementation of a remote sensor system that was employed to monitor the stability of a seawall during repair work using cost effective tilt sensors. The system consisted of custom made remote sensing nodes, providing measurements in real time to a robust backend server that presented the data in the form of an interactive web application. An accelerometer paired with a Wi-Fi chip was sealed in a weatherproof casing to construct the tilt sensors and the data was transmitted back to the server over 4G cellular network for processing. To ensure a quick response should sudden movement be detected, SMS text messages could be dispatched to all parties involved. Four pairs of remote sensors were deployed, each capable of real time monitoring of the wall's angle of inclination to an accuracy of ±0.05°.**

Keywords— Wireless Sensor Networks, Remote Sensing, Monitoring Systems, Early Warning System

I. Introduction

Recent developments in low cost sensor technology, wireless communication, data science and computing technology provide an opportunity to observe and measure multiple features of interest remotely, in real time, at a large number of locations. Remote sensing is finding applications in infrastructure monitoring [1], precision agriculture [2], air pollution monitoring [3], horticulture [4], or in early warning systems [5, 6]. This project required an early warning system to be developed that would measure the tilt of a structurally vulnerable wall and send real-time alerts to repair personnel if the tilt exceeded predefined limits.

II. Design Overview

Survey of the seawall under the historic Ferry Building on Auckland's Waitematā Harbour had revealed damage that needed urgent attention. While repairs were carried out, it was crucial to continuously monitor the wall for potential movement that could signal a risk to divers undertaking the work. A 25 m long section of the seawall needed to be monitored in real time. The developed remote sensing solution involved 4 clusters of accelerometer based sensors. Each cluster contained a pair of identical co-located sensing nodes for fault tolerance and redundancy. The deployed sensors were capable of real time monitoring of the tilt to an accuracy of ±0.05°. Each cluster was fastened to the wall approximately 2 m above the high-tide line with horizontal spacing of approximately 5 m. The locations of the sensor nodes can be seen in Fig. 1. The sensors were mains powered and transmitted their readings for storage on a remote server in real time, using a 4G enabled gateway. The details of this architecture can be seen in Fig. 2. The server allowed the data to be accessed anywhere from a browser, using a secure login. The server also checked the data for consistency and constantly calculated ongoing trends in real time. If any ongoing trend exceeded an allowable threshold, a text alert was to be sent out to advise which node cluster has detected abnormalities. The backend infrastructure is shown in Fig. 3.

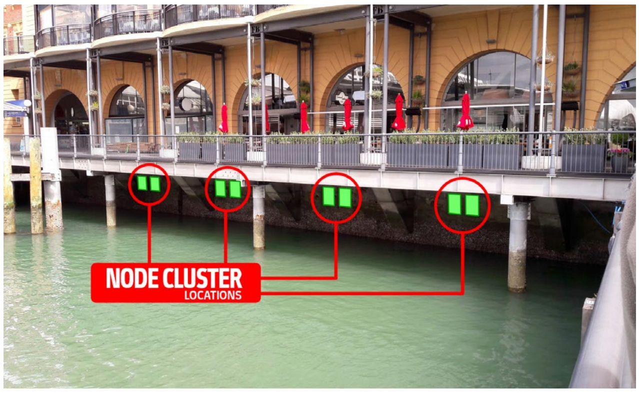

Fig. 1. Deployment of sensors on the seawall under the Ferry Building

A. Tilt Sensors

A number of approaches were considered to measure the angle of inclination of the seawall. Accelerometer based tilt sensors [7] were deemed to be feasible given the cost and time constraints of the project. Accelerometers are sensors that measure the magnitude and direction of acceleration forces acting on them. With the absence of external forces, they are especially adept at measuring acceleration due to gravity. Accelerometers presented a low cost method of measuring the angle of the seawall relative to earth's gravity. The tilt angle was measured as

$$\theta_z = \tan^{-1}\left[\frac{A_z}{\sqrt{A_x^2 + A_y^2}}\right] \quad (1),$$

where θ_z is the angle of inclination and A_x, A_y and A_z are the accelerometer readings for x, y and z axes respectively. The sensors needed a minimum resolution equivalent to a 0.07° angular tilt which was on the boundary of the reliable performance limits of the accelerometers used (Invensense MPU9250) and there was uncertainty regarding the reliability of the measurements. There was also insufficient time to perform temperature calibration of the accelerometers given a very tight timeline for deployment. Consequently, significant signal processing techniques were developed to increase the nodes' accuracy and ensure the reliability of the measurements. The nodes were also calibrated in software for both gravity and temperature along with averaging and sanity

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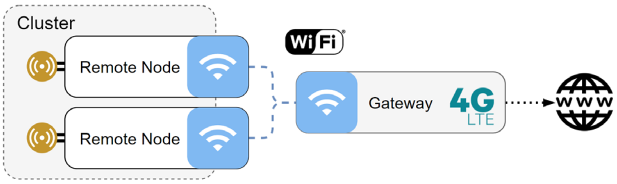

Fig. 2. Diagram showing the communication architecture

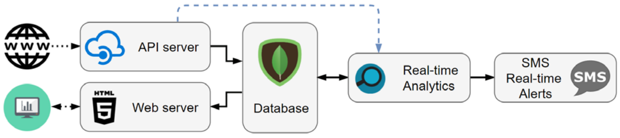

Fig. 3. Diagram showing the backend infrastructure

checking across each node cluster pair. This was followed by modeling, in real-time, both data trends, and ongoing deviations. This resulted in a measurement accuracy of less than 0.05°.

The measured data needed to be transmitted wirelessly from the nodes and accessible through standard internet browsers in real time. There are a number of solutions available for this including ZigBee [3], LoRaWAN [8], Sigfox [8]. However, due to time constraints these options could not be fully explored at the time of the development. A combination of Wi-Fi and cellular technology was chosen as an easy to implement alternative. Each remote node is equipped with an ESP 8266 Wi-Fi module [9] which communicates with MikroTik RBwAPR-2nD-LTE, a 4G Cellular enabled Wi-Fi Router. Unlike the aforementioned alternatives, this approach has the benefit of supporting high frequency sampling rates, with each node transmitting a packet of data every ten seconds. The higher sampling rate enables the system to provide a faster response (e.g. real-time text alert) if any movement in the wall is detected. Sampling at a high rate also provides the opportunity for noise reduction by averaging of the readings.

To provide power to each node, they were wired into a mains connection local to the installation site. This approach was chosen for two reasons. Firstly, time restrictions meant an accurate power budget could not be established so alternatives such as battery power came with higher failure risks. Secondly, there was uncertainty in the required sampling rate. A higher sampling rate meant more prompt response if the wall were to move. However, it also requires

(a) (b)

Fig. 4. Photo (a) shows the tilt sensor before being encased in waterproof resin. Photo (b) shows sensor "cluster 4" on the seawall.

considerably more power to sustain. Using mains power removed this uncertainty and ensured that a reliable solution was ready for installation before work on the wall began.

III. Data Processing

The sensors were designed so that after installation they could be remotely updated allowing for software upgrades without requiring physical access to the seawall. This was achieved using Wi-Fi and a custom file server from which the nodes could fetch new firmware binaries by way of HTTP GET request. This is beneficial due to restrictions on physical access to the site. The nodes were designed and deployed in pairs, allowing for continued calibration among each node pair. This increases the accuracy of the solution provided, and also ensures redundancy in each monitoring point if any node fails. The internal components were encased in a waterproof polyurethane resin (Electrolube - UR5597RP500G). This ensures that the sensors are protected from any splashes that may occur, while also being resistant to corrosion due to salt spray and salty air. Figure 4 shows the tilt sensors.

The raw data comes in the form of accelerometer readings from 3 axes, along with temperature readings and a timestamp. The corresponding angle is calculated using (1) and then adjusted to remove temperature correlation by using Iterative Principle Component Analysis (IPCA) [10] and long-term sensor drift using incremental linear regression [11]. Fig. 5 shows the raw angles computed using (1) and the final tilt angle estimation after temperature and sensor drift correction. The calibrated data for the four pair of sensors could be accessed by the end user through a web portal. Figure 6 shows the wall's angle of inclination from "cluster 1" for a duration of 34 days.

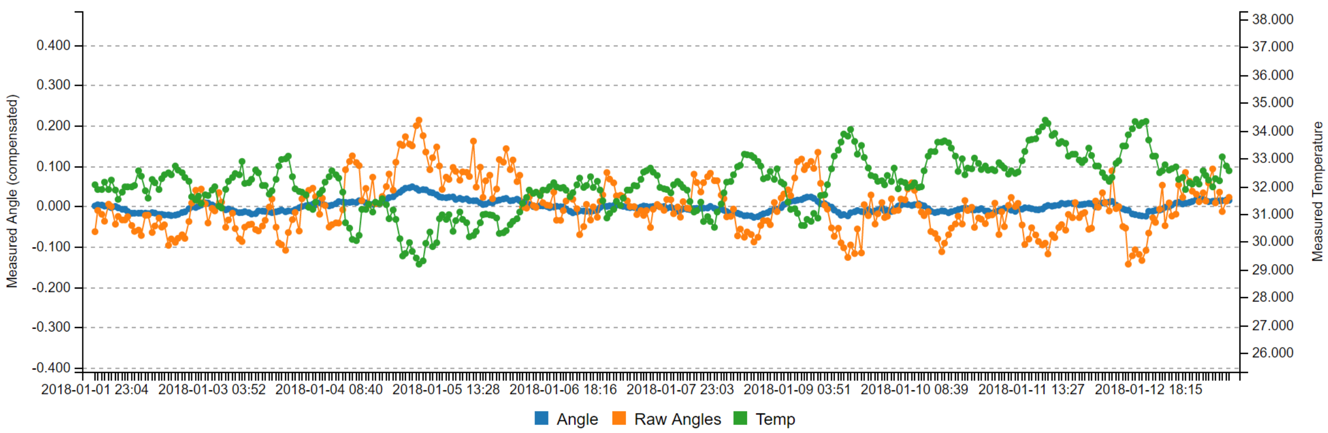

Fig. 5. Illustration of calibrated tilt angle measurement

Fig. 6. Web portal showing a real-time plot from a seawall node cluster

IV. Conclusion and Future Work

The remote sensing system was designed to provide early warning if the seawall began to move; offering safety and peace of mind to all stakeholders. The total cost of the system was less than 1000 NZ dollar. It was operational for more than four months providing vital real-time information and alerts about the state of the wall. This information was crucial to the safety of those working on wall and those occupying the terminal above. There are several improvements we wish to implement in the future. Firstly, we want to power the sensors from batteries rather than mains. The next iteration of these nodes should also include more accurate, factory calibrated accelerometers. These would provide more accurate measurement. The current remote nodes establish links to an internet connected Wi-Fi gateway for communication. This approach is not ideal if we want to accommodate a large number of sensor nodes that require long-range communication and long battery life. An IoT communication technology, e.g. LoRaWAN, will make the system more suitable for large scale infrastructure monitoring across a range of sensor requirements.

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