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STRUCTURAL HEALTH MONITORING

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40.1 INTRODUCTION

Structures are all around us. Structures are ubiquitous in the physical world we live in. The structures we live or work in need to shield us from the weather elements, withstand some degree of degradation over time, and stay strong over a time scale that is comparatively longer than one's lifetime. The vehicles we travel in need to offer comfort and safety through the modes of transportation and be able to protect us through collisions. We expect likewise of the transportation infrastructure we travel on: the railroads, bridges, ramps, etc.

Structures don't last forever; to build and operate structures within a reasonable budget, they are designed to support a specific load over a limited lifetime and withstand environmental changes to a limited degree. Structural health degrades over time as intended. It is important to make sure that a structure continues to offer the required level of service as it ages. Structural failures are very expensive and often cost lives. Structural health monitoring (SHM) is essential to inspect a structure's health over time to ensure it continues to meet operational requirement. SHM is essential to ensure public safety and efficiency.

SHM has been done mostly manually and periodically. The interval between inspections varies, depending on the operating organizations' practice. It is not rare to hear of annual or even biannual inspections. Modern SHM systems take advantage of the rapid advance in low-power processors, sensors, wireless communication, and data storage to automate the inspection process. Such SHM systems started to deploy

Internet of Things and Data Analytics Handbook, First Edition. Edited by Hwaiyu Geng.

Companion website: www.wiley.com/go/Geng/iot_data_analytics_handbook/

within the past decade [1]. With the rapid decline in the cost of enabling technologies, it is becoming practical to consider real-time continuous monitoring broadly.

This chapter presents the authors' firsthand experience at designing and implementing a SHM solution for bridges. It is intended as a case of practicing the engineering approach described in the earlier chapter on IoT and smart infrastructure.

40.2 REQUIREMENT

The SHM system was designed based on requirement from a team at National Taiwan University of Science and Technology, led by Prof. Chung-I Yen and Prof. Wei F. Lee, that has expertise in applying modern SHM for bridge monitoring [2, 3]. From here onward we will refer to each edge sensor device as a Bridge Monitoring Unit (BMU).

40.2.1 Operating Environment

The BMU will be deployed directly on bridges. The system needs to be able to withstand direct exposure to all sorts of weather conditions.

40.2.2 Power Supply

At some target sites there could already be grid power available from prior installation of environmental monitoring equipment. In most cases there is not prior power supply installation. It is strongly preferred if the BMU could operate without the expensive installation of grid power. Whether solar or grid power is used, it is required to have backup battery that could keep the system operating for 5 days after losing primary power source.

40.2.3 Monitoring Only

The BMU is only required to perform passive monitoring. No supervisory control is required.

40.2.4 Connectivity

The BMU is required to support both wired and wireless connectivity. Occasionally, some sites already have wired connectivity from prior monitoring equipment installation. Nevertheless, wireless connectivity should be the norm in most cases.

The BMU is expected to utilize local wireless service provider's 3G service for uplink to server. On structures where multiple monitoring units are deployed, it would be cost efficient to share uplink.

Connectivity, wired or wireless, could be unreliable. Connectivity could be lost during critical event when the data is most important. This would be the case during an intense typhoon or earthquake that damages a local cell tower. It is therefore required for the BMU to retain up to 20 days of data. When data could not reach the server, it could be retrieved from the BMU eventually. In the event of major structural failure, such data could be extremely valuable for forensic analysis.

40.2.5 Data Acquisition

The BMU is required to monitor both dynamic and static parameters. Dynamic parameters include acceleration in three axes and inclination in two axes. Static parameters include water level, water velocity, and structure temperature. Sampling rate of dynamic parameters should be configurable, from 50 to 200 Hz.

As specific choice of sensors may change over time, it would be ideal if the BMU could accommodate different sensor interfaces.

The data samples should be grouped into a file every 30 seconds and timestamped.

Notably, all sampled data needs to be transmitted to server for analysis and long-term archive.

40.2.6 Robustness

The BMU should be able to tolerate intermittent wireless connectivity to server, as 3G connections are known to drop often. In the case of unreliable connectivity, data transmission to server should resume when connectivity is restored.

The BMU should be able to operate in the absence of GPS reception and still meet all previous requirements over short duration.

40.3 ENGINEERING DECISIONS

40.3.1 Power Supply

We understand that grid power may not be available in most sites. Even when grid power is available, its constant availability could not be counted on. We decided to utilize a rechargeable battery as the primary power source, which is recharged by grid power or solar panels as applicable.

We chose lithium iron phosphate ($LiFePO_4$) chemistry over the more common lithium ion or lithium polymer because it better retains capacity over longer cycles, ensuring adequate capacity over years of deployment. Lithium iron phosphate has lower energy density, resulting in larger and heavier battery. This is less of a concern for SHM application since it would be static once deployed at a site. Capacity retention over large number of cycles is more important.

Due to obstruction by the structure and foliage, it is possible that the site could afford direct sunlight on the solar panel only during certain time each day. For such sites one should choose solar panel of higher power rating so that it could adequately recharge the battery in the limited hours of direct sunlight.

40.3.2 Connectivity

The requirement that all sampled data needs to be transmitted to server for analysis and long-term archive is a tall one. It rules out low-power mesh networking options like 802.15.4 which could not support the needed bandwidth.

Wi-Fi could provide the needed bandwidth. Wi-Fi is common enough that we could easily get parts that support the long-distance transmission. Typical bridges span hundreds of meters. Some bridges could span kilometers. This one-dimensional topology is not a good fit for the typical Wi-Fi installation where one Access Point serves edge devices over a circular area. We decided that Wi-Fi mesh would be a practical way to link multiple systems deployed on one bridge to an edge router, using intermediate BMUs to relay the traffic from BMUs further away. An edge router would act as the gateway to remote server. For sites with only a single system, it could be simpler to support 3G uplink directly in a BMU.

With either 3G or Wi-Fi, to reduce bandwidth and power consumption, we would compress data before transmission. Each 30 seconds window of data is saved into a file, whose name includes the current date–time and unique ID of the BMU. The file is then compressed and saved to flash storage before queueing it for transmission. The compression effectively reduces size of data to be stored and transmitted by 70%.

There are many Wi-Fi modules designed for IoT-type application. These modules typically could interface to a microcontroller (MCU) via UART or SPI. These Wi-Fi modules tend to have their own MCU to run their protocol stack. We are not aware of any such modules that could support mesh protocol. They also tend to have limited RF power (under 20 dBm) that is not suitable for the kind of long-range outdoor application we have in mind. We found success with Wi-Fi USB dongles that support 27–30 dBm output power, with Linux kernel drivers that support mesh networking. Even with omnidirectional antenna, we were able to achieve close to 400 m range between adjacent BMUs.

For 3G connectivity we found many 3G USB dongles designed for consumer or industrial uses.

These connectivity device choices would necessitate use of a Linux single-board computer (SBC) due to the driver and network protocol stack that is required for operation.

40.3.3 Protocol Considerations

While not part of the requirement from customer, we wanted to be able to *ssh* over Virtual Private Network (VPN) into the BMU for miscellaneous services, mainly to update application and MCU firmware as needed. This is not mere convenience as the deployment sites are thousands of miles away from us physically. Requiring on-site work by field engineer that is familiar with embedded computer is inefficient and costly. This meant we would want the field devices to support TCP/IP networking on Linux. Linux would also afford us ample choice of open-source tools for application development and deployment.

We had planned simple Web server on each BMU so that we could directly monitor status of BMU's operation during development and deployment. It could also evolve to support a RESTful API.

We used an asynchronous message queue to transmit compressed data files from BMUs in the field to server. The asynchronous message queue provides us the required robustness against connectivity disruptions.

40.3.4 Architectural Choice

We wanted a SBC-based on ARM microprocessor. ARM-based SBCs are known to have low power consumption. They are available from several suppliers, with Linux OS. Most importantly, growing number of open-source SBC was starting to be available at low prices. When we were making the SBC decision, BeagleBoard had already been introduced for a few years and BeagleBone was just released. We liked the active developer community and were very attracted by the large number of peripherals exposed on the 92-pin headers.

Linux is not a real-time operating system and is not an ideal platform for low-latency tasks such as data acquisition. We said “not an ideal platform” because there existed patched versions of the Linux kernel that could make it more suited for real-time applications. Nevertheless, we needed many ADC ports that are usually available in MCUs but not in Linux SBCs. While we could use external ADC IC that interfaces to Linux SBC via SPI or I2C, MCU could offer far more flexibility in addition to cost and performance advantages. We decided it would be easier to use a combination of MPU and MCU.

To accommodate large variety of possible sensor interfaces, we decided to use two ARM Cortex M3 class MCUs as dedicated data acquisition processors, DAQ1 and DAQ2. Their function could be implemented in firmware. MCU firmware could be updated in the field from the Linux SBC, offering us a convenient way to fix bugs or add new functionality after field deployment. Two UART channels could be utilized to interface with these two DAQ processors.

40.3.5 Data Acquisition

The critical aspect of data acquisition is the timing for sampling dynamic parameters. The sensor interfaces to be utilized and sampling rate, set by customer for the particular site, would be transmitted from a software application on Linux SBC to DAQ processors. Our MCU firmware would set a hardware timer based on the specified sampling rate. On timer overflow, data would be sampled from the specified interfaces and passed to SBC.

To ensure correct timestamping of sampled data, we use ntpd and GPS to set time on each BMU [4, 5].

40.4 IMPLEMENTATION

We designed and assembled a printed circuit board for our BMU design. It contains:

1. Two ARM Cortex M3 MCUs (with the necessary passive parts and clock sources)

2. GPS module
3. Terminal blocks to connect:
   a. Temperature sensor
   b. 3D accelerometer
   c. Two inclinometers
   d. Power supply
   e. SDI-12 bus for water velocity and water level sensors
4. Headers to mount the BeagleBone SBC
5. Many extra signal pins for future expansion

The USB host port on SBC provides the wireless interface, either 3G or Wi-Fi.

The BeagleBone SBC was mounted on the PCB and loaded with Debian Distribution, ntpd, VPN client, openSSH server, and application software that

FIGURE 40.1 BMU mounted on a pilot site in Taiwan.

FIGURE 40.2 Yuan Shan Bridge in Taipei where two BMUs have been operating since 2014.

manages the DAQ processors as well as data file compression–storage transmissions.

The PCB is mounted on a rigid stainless steel plate inside an IP67 enclosure, with flanges to facilitate mounting to the target structure. Field deployment usually takes only a couple of hours (Figures 40.1, 40.2, 40.3, and 40.4).

Although the requirement is to transmit sampled data to server for analysis and archive, we have demonstrated doing FFT on the data immediately after sampling. We could identify frequency peaks corresponding to vibration nodes and track their deviation over time.

40.5 CONCLUSION

The underlying technology for SHM is still evolving rapidly. New protocols are still being proposed to help achieve standardization and accelerate wider adoption. We recommend developing your SHM system with loosely coupled functional modules, using open standards as much as possible, so that individual modules could be upgraded without reengineering the whole solution.

We believe it makes sense to utilize computation on the edge to analyze data for anomaly before transmitting it to servers. Vast majority of the sampled data in SHM applications will not indicate a significant event and thus is not worth transmitting and archiving. Long-term analysis using snippets of periodical data is sufficient to monitor a structure's health over time. Event detection on the edge sensor could

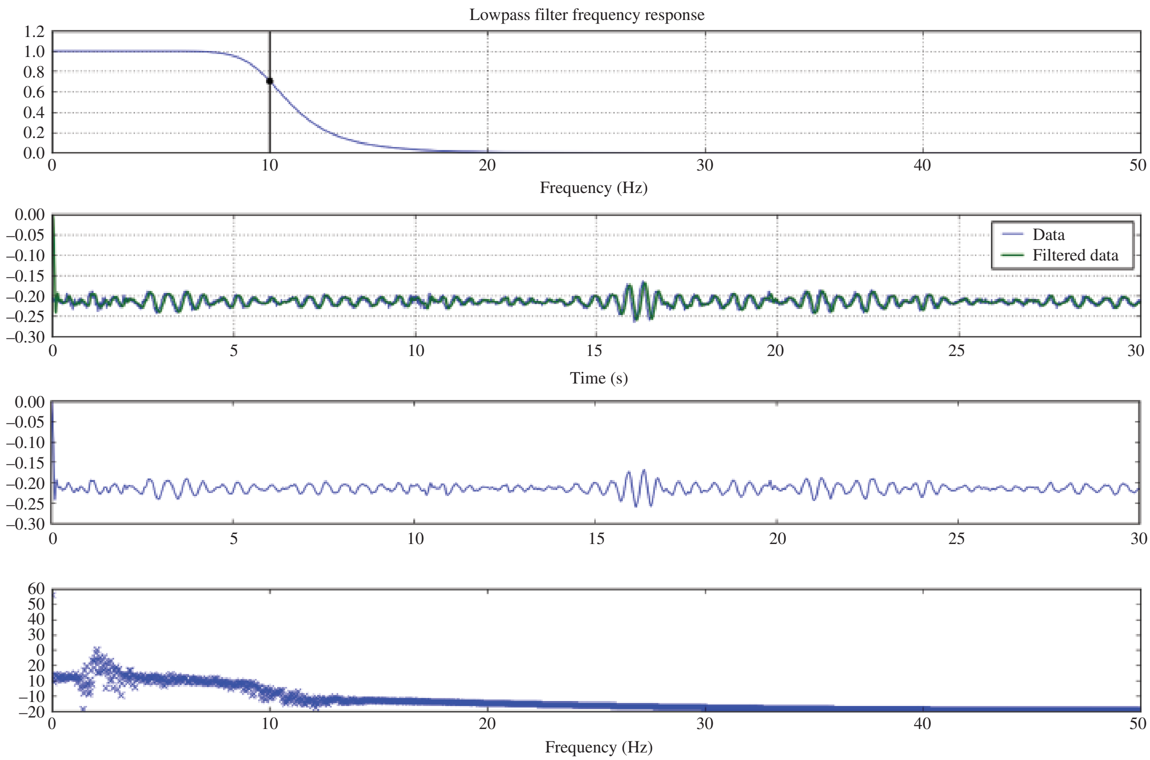

FIGURE 40.3 Data from a dynamic inclinometer processed to show clearly identifiable peak on the frequency spectrum. Shifts of frequency peaks are important indicators in SHM.

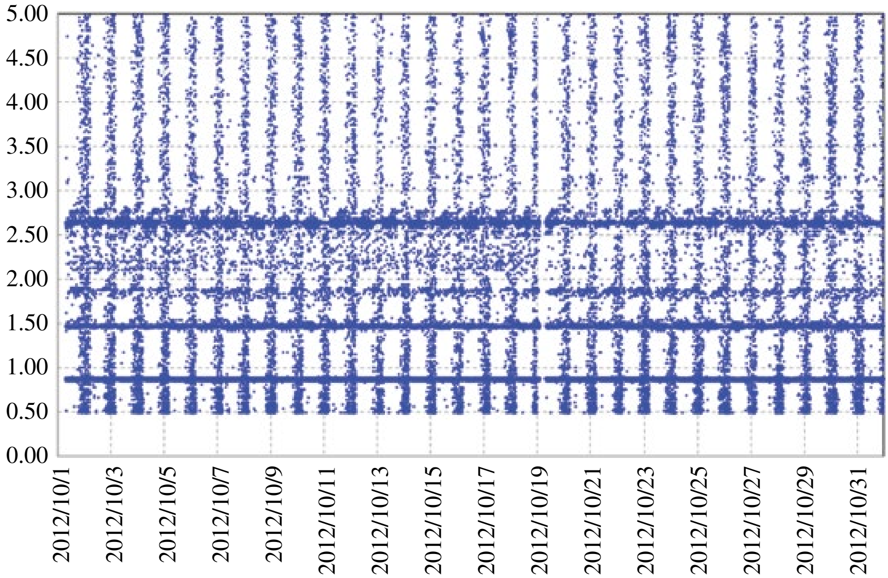

FIGURE 40.4 Spectrum of one of the dynamic inclinometers over time. The darker bands indicate the vibration nodes of the structure.

significantly reduce latency to event detection and reduce the bandwidth to transmit data indicating routine conditions. Such bandwidth reduction could make it practical to take advantage of nascent low-power wide-area networking technologies, such as LoRaWAN, for efficient connectivity for SHM applications.

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FURTHER READING

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