Shaping the future of Structural Health Monitoring with IOT sensors

Damon PARSY
App. Engineer, Beanair GmbH
Berlin, Germany

Mohamed-Yosri Jaouadi
CTO of Beanair GmbH
Berlin, Germany

Abstract— Structural health monitoring (SHM) is an innovative method of monitoring structural safety, integrity, and performance without affecting the structure itself. Wireless sensor Networks (WSN) have demonstrated their potential for structural Health Monitoring: flexible, easy to deploy, lightweight and cost-effective. However, in many monitoring system, the conventional usages of WSNs are cases with low data rate, small data size, low duty cycle, and low power consumption. Structural health monitoring requires high data rate, time-synchronization, large data size, measurement stability and a relatively high sampling rate. There are few studies about clock distribution in WSN for data fusion and modal analysis.

In this study, we outline the synchronization requirements of wireless sensor networks and present how clock-drift, network aggregation capacity and measurement stability issues are solved.

Keywords—Wireless Sensor Networks (WSN), Structural Health Monitoring (SHM), Deterministic data transmission, Modal analysis

I. INTRODUCTION

SHM (Structural Health Monitoring) is the continuous, autonomous in-service monitoring of the physical condition of a structure by means of embedded or attached sensors with a minimum manual intervention, to monitor the structural integrity of any kind of structure (Aircraft, Bridge, Dam, Tunnel, Stadium…). The basic is the application of permanent mounted sensors on the structure. SHM includes all monitoring aspects related to damages, loads, conditions, etc., which have a direct influence on the structure. The sources are resulting from fatigue, corrosion, impacts, excessive loads, unforeseen conditions, etc. Structural health monitoring should give answers to the following questions:

• Is there damage present in the structure?
• What is the location of the damage?
• What is the severity of the damage?
• What is the remaining useful lifetime of the structure?

The complexity of the monitoring task increases with each question. Much research is focused on the development of methods to answer these questions. Among other techniques, vibration based techniques are widely studied for this purpose. However, large structures require a sensor network with a large amount of sensors for vibration/tilt/deformation monitoring. Traditional approaches with wired sensors and a central processing unit can raise scaling problems with respect to data processing and cabling. Wireless sensors solve the cabling issues, but due to limited communication bandwidth not all the data can be communicated, so the data processing has to be decentralized. Important work progress was done on energy management (mostly energy harvesting), wireless range (LoraWan and Sigfox are used as Metropolitan Network), operation frequencies (from sub-Ghz to 5GHz), Network topology (Mesh, Cluster-Tree, Star). Time-synchronized data collection for a data fusion and modal analysis is still not reliable on WSN.

Section 1 introduces challenges of WSN for SHM, section 2 describes vibration monitoring in SHM, section 3 describes two SHM case studies where WSN were deployed. The paper ends with discussion and conclusions.
energy consumption requirements of different applications to that of each different device.

Figure 1: Typical deployment of WSN on a bridge structure

A. Why bringing time-synchronisation over a Wireless Sensor Network?
In structural health monitoring, there are many requirements regarding synchronous and real-time data acquisition of the vibration information, which are distributed over different parts of an installation. It is especially important for the vibration model analysis of bridge structures, structural stability, and life assessments, which contain many sensor nodes that are distributed over different positions, with different topology structures. The signals must be sampled synchronously by the nodes; otherwise there will be incorrect information (due to samples grouped together coming from different times) of the vibration phase, resulting in an incorrect vibration model judgement. In applications in which sampling frequencies usually exceed 1 KHz, the delay of the sensor nodes synchronization is usually required to be less than 10 μs. This results in a higher requirement of synchronization in an SHM WSN.

B. Accurate technique of clock synchronisation
An extreme accuracy on clock-synchronization is achievable by bringing a two-way ranging (TWR) mechanism:
- No need of common clock reference
- Two-way ranging eliminates the error due to imperfect synchronization between nodes, relative clock drift still affects ranging accuracy. (function of $t_{\text{replyB}}$ duration because of the clock drift error accumulation)
  - $t_{\text{p}}$ is in ns unit
  - $t_{\text{replyB}}$ should be in μs unit

In this scheme ranging capable device A (RDEV) begins the session by sending a range request packet to device B. Then device B waits a time $t_{\text{replyB}}$, known to both devices, to send a request back to device A. Based on that packet, device A can measure the round-trip time $t_{\text{roundA}} = 2t_{\text{p}} + t_{\text{replyB}}$ and extract the one-way time-of-flight, $t_{\text{p}}$, with respect to its own reference time.

When implemented over IR-UWB (Impulse-Radio Ultra-Wide-Band), the large bandwidth of the UWB signals enable accurate ranging estimations of less than 3 ns.

Clock source can be based on NTP (Net Time Protocol, a networking protocol for clock synchronization between computer systems over packet-switched, variable-latency data network) or GPS Clock implemented on the backbone network or WSN coordinator.

During the WSN operation, clock-drift can be observed, a re-synchronization will be needed.

It can be managed by bringing a time-triggered on-demand synchronization, it allows to obtain sensor data from multiple sensor nodes for a specific time. This means that there is no event that triggers the sensor nodes, but the nodes should take a sample at precisely the right time. This can be achieved via immediate synchronization (where sensor nodes receive the order to immediately take a sample and time-stamp it) or anticipated synchronization (where the order is to take the sample at some future time, the target time). Anticipated synchronization is necessary if it cannot be guaranteed that the order can be transmitted rapidly and simultaneously to all involved sensor nodes. This is especially the case if sensor nodes are more than one hop away from the node giving the order (mesh or cluster-tree networks).

C. Network bottleneck and aggregation capacity of a wireless sensor networks
A review of recent wireless sensor deployments for structural health monitoring of bridges [1-3] reveals that the networks have generally relied on either local data logging and post-sampling transmission of sensor data or on low sampling rates and limited numbers of sensors in order to address WSN bandwidth limitations. Such concessions severely limit the versatility and capability of a structural health monitoring system in terms of sampling duration, data acquisition rates, and spatial resolution as well as quality of the derived mode shapes.

This problem was solved by bringing several WSN operating at the same time and managed by a unique supervision system.
Figure 3: A network architecture with several WSN operating at the same time.

Beanair WSN was deployed for assessing the impact of construction-related activities and evaluating the effect of structural retrofitting. Additionally, inherent monitoring of environmental loads and influences, operational loads, and traffic patterns and densities were used to collect a database of field measurements for providing feedback during the interchange structure extension.

A total of 280-300 wireless sensors were deployed for monitoring vibration, inclination and deformation on the interchange structure:

- Vibration response of the bridge from ambient excitation was measured by using an accurate wireless accelerometer mounted on the interchange pillar. A sampling rate of 100 Hz was configured on concrete structure and 400 Hz on the steel structure;
- Wireless inclinometers with an accuracy of±0.05° and a measurement range of±15° were used to monitor structure sinking during the construction work.
- Several wireless crack meters (LVDT technology) with a maximum stroke of 20mm were mounted on interchange pillars. Crack meter can only be used on existing cracks and cracks evolution were compared to the resonance frequencies observed on the interchange pillars.

More than 25 wireless networks with the same NTP clock source (provided by a 3G/4G modem) were deployed on the monitoring site. Wireless Sensor nodes were synchronized by using a two-way ranging technique.

Figure 4: Underside of the various overpasses comprising the Turcot Interchange.

III. CASE STUDIES: DIFFERENT SHM CHALLENGES

A. Solving the problem of aggregation capacity: Example of SHM on a Freeway Interchange in Montreal (Canada)

The Turcot Interchange is a three-level stack freeway interchange within the city of Montreal, Quebec, Canada. Located southwest of downtown, the interchange provides access to the Champlain Bridge. Turcot is the largest interchange in the province and the third busiest interchange of Montreal (after Décarie and Anjou Interchanges, respectively) as of 2010, with numbers averaging a north-southbound flow of 278,000 approximate daily drivers, and over 350,000 west-eastbound in total. Moreover, Turcot is an occasional spot for road accidents as speed is only limited to 70 km/h on any of the interchange’s directions (and the limit is often likely to be disregarded by the night drivers going over 100 km/h).

In June 2007, the Quebec government announced the demolition and reconstruction of the structure, projected to be complete in 2016. The announcement came four years after a study on the interchange showed the Turcot structure was crumbling, with reports of concrete slabs up to one square metre falling from the overpasses. In addition to a new interchange built lower to the ground, a large segment of Autoroute 20 would be rebuilt more to the north.

Reconstruction of the interchange is expected to cost between $1.2 billion and $1.5 billion.
B. Managing Clock-drift: Example of SHM on the Great Mosque of Mecca (Saudi Arabia)

The Great Mosque of Mecca, also called Grand Mosque, is the largest mosque in the world and surrounds holiest place, the Kabaa, in the city of Mecca, Saudi Arabia.

In 2007, the mosque underwent a fourth extension project which is estimated to last until 2020. King Abdullah Ibn Abdulaziz planned to increase the mosque's capacity to 2 million; although the King died in 2015, his successor, King Salman, is likely to continue renovations. In 2016 it was estimated that Great Mosque had cost 100 billion dollars.

Northern expansion of the mosque began in August 2011 and was expected to be completed in one and a half years. The area of the mosque will be expanded from the current 356,000 m² (3,830,000 sq ft) to 400,000 m² (4,300,000 sq ft). A new gate named after King Abdullah will be built together with two new minarets, bringing their total to eleven. The cost of the project is $10.6 billion and after completion the mosque will house over 2.5 million worshipers.

On 11 September 2015, at least 111 people died and 394 were injured when a crane collapsed onto the mosque.

A total of 120 wireless sensors were deployed on different structures:
- Wireless inclinometers were deployed on cranes for preventing from collapse
- Wireless accelerometers were used for vibration monitoring on the Maataf soil and the surrounding wall during the construction. DIN4150-3 (German standard for ground vibration on construction) method was used to build automatic weekly reports for the end-user.

Due to the high diurnal temperature variation, a clock-drift of 2-3 minutes/week was observed on the WSN.

A NTP server was implemented on the backbone network and a time-triggered on-demand synchronization function was
implemented on the wireless sensors. Most of the time the sensors are in sleep mode, and clock was synchronized during the wake up process.

C. Wireless Sensor network for monitoring a launch vehicle structure. Example of the European Launch vehicle Program - Ariane 6

The clear majority of existing wireless protocols are not designed to meet avionics and spacecraft design specifications. Factors such as low bandwidth, non-self-synchronized wireless network, non-existing lost data recovery mechanisms, overlapping band frequencies (2.4Ghz) and non-adapted modulation techniques to spacecraft environment call for the introduction of innovative technological platforms based on newer standards. Such platforms are already being designed and tested by Beanair Research laboratories in conjunction with major partners and operators. The main task of the newly designed SpaceWireless® technology is to challenge existing technologies by introducing a reliable, ultra-low power and time-synchronized (accuracy < 5 μs) wireless network particularly adapted to dynamic measurement (10-32 KHz).

Thanks to UWB Radio Technology and Time-of-Flight algorithms developed by Beanair, Spacewireless® can reach a time-synchronization less than 5 μs over the WSN.

Clock source is provided by the GNSS (time precision ±20ns) module available on the Wireless coordinator.

IV. CONCLUSIONS

Wireless sensor networks are one of the supporting technologies in structural health monitoring. Through intelligent, self-organizing means, they connect sensor nodes, with a variety of different test objects and working principles into a network along with functions of data processing and integration. Structural health monitoring is a convergence area, with a variety of sensor and information processing technologies. In this study, we considered clock-synchronization over a WSN and how clock-drift issue was solved on the monitoring site.

REFERENCES