Characterisation of Wireless Sensor Platforms for Vibration Monitoring of Wind Turbine Blades

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Abstract — Three different wireless sensor platforms and a wired accelerometer have been used to measure the acceleration response of a 2.5kW wind turbine blade subject to a uniaxial white noise excitation. The acquired data has been analysed using Fast Fourier Transform (FFT) analysis and the resonant frequency of the blade has been determined by each hardware platform. The results show excellent performance from all three wireless sensor systems. Individual wireless sensor accuracy is discussed, and an assessment of the functional capabilities of each platform is provided.

Keywords — Wireless Sensors, Damage Detection, Vibration Monitoring

I Introduction

Wired sensing and communication solutions for Structural Health Monitoring (SHM) applications can be both expensive and complex for large wind turbines. The presence of rotating elements, the increasing size of structural components and the considerable length of cabling required, make the installation of wired sensors difficult, expensive and time consuming. The use of cheap, commodity Wireless Sensors (WS) for the remote monitoring of large structures offers a convenient, cable-free alternative to wired-based acquisition systems [1]. There are now numerous low cost WS platforms on the market which are relatively straightforward to deploy with respect to their wired counterparts. However, the performance of these new platforms, when subjected to dynamic load conditions, must be assessed relative to conventional sensors and their long-term potential must be demonstrated in field applications. Through experimental investigation, the preliminary study presented in this paper provides a comparison of different WS platforms in order to benchmark their performance and reliability in wind turbine applications.

II Related Work

Over the past decade researchers have explored the use of Wireless Sensors for Structural Health Monitoring. An overview of research and commercial WS platforms used for structural monitoring applications can be found in [2]. In that work the authors note that the wireless nodes are increasingly computational capable and may be used to locally process data without the need to transmit them to a base station. To demonstrate the computational capabilities offered by WS nodes, Lynch et al. [3] describe a wireless sensing unit intended to perform the Fast Fourier Transform and Autoregressive Time-Series modeling locally on the node itself. The cost-effectiveness of wireless systems in such environments is emphasized in [2]. Higher sensor densities are instrumental for reliable implementation of robust damage detection algorithms. In [4], the authors perform a preliminary study on the effect of operating rotating machinery on wireless transmission, and they stress the need for implementing reliable communication protocols and robust data processing tools. They also report a
number of prior studies in literature in which researchers noticed data loss during the testing of the Crossbow MICA family [5] platform for SHM applications. Packet loss in wireless transmission was also observed in [2]. In [6], the design and the test of a Wireless Sensor Network (WSN) of 64 nodes (based on MICAz motes [5]) deployed on the Golden Gate Bridge was presented. WSN communication and routing challenges, such as time synchronization, jitter, power consumption and data reliability, were considered in pursuit of reliable data collection in a harsh real-life environment. Active wireless devices can also be used for actuating or exciting a structure according to a prescribed control or monitoring strategy. In [7], a damage detection algorithm based on system identification techniques is tested on an aluminum plate equipped with piezoelectric active transducers, which are controlled by the wireless active sensing unit to excite and record the plate. The use of wireless sensors for the SHM of wind turbines has been recently investigated in [1], [8]. In [8], wireless accelerometers are installed on a Micon 65/13 wind turbine. It is observed that a considerable number of packets are lost during the wireless data transmission and low pass filtering techniques are used in order to mitigate the issue of data loss. Swartz et al. [1] explore the performance of the low-cost Stanford WiMMS WS against that provided by a wired-based system using PCB 3701 accelerometers. The sensors have been installed on two different wind turbine structures: a 40 m tall NEG-Micon 250 turbine (250 kW) and 78 m tall Vestas V-80 turbine (2 MW). Results show a high level of agreement between the wired and wireless obtained data. In this paper, a comparative analysis of a number of wireless sensing platforms has been carried out in order to assess the reliability of the WS and to establish their effectiveness in wind turbine applications. The results presented in later sections show that data acquired from low-cost WS are functionally equivalent to data sensed using a traditional cable-based infrastructure.

III INSTRUMENTATION

Three wireless accelerometers were installed on a 2.5kW Wind Turbine Blade (WTB) alongside an Entran EGCS 2G wired accelerometer. The Agile-Link [9] is a commercially available tri-axial 2G wireless accelerometer packaged with a software application to configure, stream or datalog using a point-to-point link with the sensor. The other two wireless sensor devices are the SunSPOT [10] and the MICAz [5](note), which are small devices with an integrated microprocessor, memory modules, sensors, accelerometer and a radio transceiver capable of forming wireless sensor networks.

a) Entran EGCS Wired Accelerometer

The Entran accelerometer, model number EGCS-A2-2 [11], was powered via the recommended Entran PS-30 combined power supply/amplifier module. The output of this amplifier was recorded using a StrainSmart® System 7000 data acquisition system. An acquisition rate of 128 samples/second was used as this was the closest multiple of 64 available on the system. This enabled every second point to be extracted to ensure the data matched the 64 samples/second used for the other sensors.

b) G-Link Wireless Sensor

The MicroStrain Agile-Link G-Link® [9] contains two 2g orthogonally mounted, dual-axis MEMS accelerometers for measuring acceleration in the X, Y and Z axes. It also has an on-board temperature sensor and employs a 12 bit A/D converter to digitize the accelerometer voltage. The accelerometer digital data is passed to the on-board microprocessor, processed with an embedded algorithm, and in turn either passed to it’s radio for immediate transmission or saved to the 2MB on-board flash memory for later download. Using the proprietary software the sensor was configured to datalog at 64 samples/second rather than streaming at the fixed preset of 617 samples/second.

c) SunSPOT Wireless Sensor

The SunSPOT (Sun Small Programmable Object Technology) [10] wireless sensor has been developed by Sun Microsystems, now Oracle Labs. The first SunSPOT model, known as rev.6, is the version employed in these experiments. It incorporates a 180 MHz 32-bit Atmel ARM920T microprocessor with 512KB of RAM and 4MB of flash memory. The SunSPOT runs a Java ME (Micro Edition) virtual machine called Squawk which is capable of running Java bytecode on embedded devices. It is powered by a rechargeable 3.6V Lithium-Ion battery.

The SunSPOT integrates the Texas Instruments Chipcon CC2420 transceiver which conforms to the IEEE 802.15.4 PHY/MAC specification and has an effective data rate of 250 Kbps. IEEE802.15.4 establishes the maximum packet size as 128 bytes. The available payload size falls to 79 bytes when provision is made for the header, header size and CRC error check. The CC2420 operates in the unlicensed ISM 2.4 GHz band with a typical indoor range of 20-30 meters and outdoor range of up to 100 meters.

Each SunSPOT processor board has two Atmel AT91 Timer/Counter, part of the ARM920T system-on-a-chip, which are clocked by the MCK with a speed of 59,904 KHz. The AT91 Counter provides access to a set of different clock speed
ranges and associated maximum duration times, from 2.188 ms to 2 seconds.

The SunSPOT comes with temperature and light sensors integrates, in addition to the 2G/6G 3-axes LIS3L02AQ linear accelerometer [12] with an effective sample ratio of 160 Hz.

SunSPOT Vibration Monitoring Configuration

A SunSPOT mote is programmed to continuously send raw accelerometer data from its point of attachment on the blade to a SunSPOT base station. The SunSPOT base station relays data between the gateway PC device and a SunSPOT that is part of the local Wireless Sensor Network. An application runs on the gateway PC device which connects to the base station and performs a broadcast scan for all the SunSPOT devices in range. It also instructs the SunSPOT on when to start streaming, i.e. to continuously send accelerometer packets to the base station and log this information in a file for subsequent processing and analysis.

In order to allow for fast sampling of accelerometer data while minimizing packet drop, a mechanism which employs a transmission queue of 100 payload packets is employed. A packet is assembled with a predefined number of accelerometer values and then the packet is queued for radio transmission. A variety of mechanisms are employed to increase the reliability of the communication. For instance, the CC2420 transceiver is instructed to acknowledge (ACK) the packet on reception. If an ACK is not received for a transmitted packet, up to 4 retransmissions are attempted before the packet is dropped - thereby increasing the packet delivery ratio. The achievable delivery ratio, as well as the time to transmit a packet, depends on the number and activity of the nodes in the neighbourhood and the backoff time after each retransmission. Once the packet outcome is determined (transmitted or dropped) the packet is removed from the queue.

For the purpose of our experiments, a 64 Hz sample ratio was chosen to capture the acceleration of the blade. In order to achieve a sampling rate of 64 Hz, i.e. sample period of 15.625 ms, the closest available clock source is selected (i.e MCK/32). This clock source supports a maximum duration of 35.009 ms with a tick of duration of 0.5342 us. Thus 29249 clock ticks of the MCK/32 clock source equates to an actual 64,0008 Hz rate. At the end of each 15.625 ms period, a task is invoked which gathers the current acceleration value for each of the 3 axes and appends the values into the current packet. When the packet is fully assembled, the packet is moved to the transmission queue and population of a new packet begins.

As previously noted, the available payload size is 79 bytes. 73 bytes are occupied in accordance with IEEE802.15.4. Each packet contains the wireless sensor’s local time for its first sample (8 bytes) and the number of samples stored in the packet (1 byte). In addition, each acceleration sample occupies 8 bytes i.e 2 bytes for each value of the tuple <d,x,y,z>, where “d” is an offset from the first accelerometer sample time of the packet and “x,y,z” are acceleration units for each axis. Thus, a maximum of 8 tuples can be accommodated per packet, i.e. 8 samples per packet for each axis with a resolution of 16 bits each.

d) MICAz Wireless Sensor

The MICAz [5] mote was originally developed by Crossbow Technology Inc. and is now being commercialized by Memsic Corporation. A MICAz mote incorporates an 8 MHz 8-bit Atmel Atmega128L microcontroller with 4 KB SRAM, 128 KB flash memory for program code and 512 KB flash memory for measurement/data storage. It is powered by two AA batteries. The MICAz is programmed in nesC, a programming language which is derived from C and targeted towards embedded wireless sensor devices. A small footprint operating system written in nesC, known as TinyOS, underpins the development and deployment of applications and protocols. TinyOS is an event-based operating system which supports the concurrency required for interrupt-based sensor applications. For these experiments the latest version of TinyOS (v.2.1.1) has been employed. The MICAz mote uses the same radio transceiver, the 2.4 GHz Texas Instruments Chipcon CC2420, as is used in the SunSPOT.

The 128L microcontroller integrates two 8-bit Timer/Counter with a single channel counter and a 10-bit clock prescaler. It is clocked directly from an external 32 KHz (32768 Hz) crystal oscillator. The timer component call used in TinyOS for the periodic sampling of the accelerometer values is known as TimerMilliC. This provides millisecond precision and is built on top of the hardware Timer/Counter 0. The component prescales the Timer/Counter 0 to CLK/32 and therefore 1 second is considered as 1024 binary units.

The MICAz mote comes with a 51-pin UART expansion connector for communicating with expansion and gateway interfacing boards e.g. the MIBS20CB board [5] used for programming and gateway connectivity purposes. The MICAz sensing boards interface through the 51-pin expansion connector to provide add-on sensing capabilities. The sensor board employed in these experiments, the MTS310CB [5], integrates a range of sensors: dual-axis magnetometer, light, temperature, acoustic (microphone), sounder and a dual-axis accelerometer. The accelerometer is
an ADXL202JE [13] package - a MEMS surface micro-machined 2-axis, 2 g device, providing an offset and sensitivity of 1 % in an inversion test and claiming a theoretical sample ratio of 6 KHz with 10-bit resolution.

**MICAz Vibration Monitoring Configuration**

The MICAz mote has been programmed to continuously send raw accelerometer data from its point of attachment on the blade to a base station comprising a MICAz MIB520CB programmer-gateway board which itself is connected to a logging/analysis computer. In the computer, an application connects to the base station mote creating a bi-directional data relay connection for transmitting and receiving packets. The base MICAz mote and the sensing motes are configured with the same Personal Area Network (PAN) identifier - thereby allowing them to communicate with each other.

The accelerometer data streaming application uses TinyHop [14], a reactive routing protocol for wireless sensor networks. By employing a reliable routing protocol the system incorporates the capability to deliver the MICAz packet stream from the blade to the base station across multiple intermediate MICAz motes. The protocol implements reliable routing mechanisms such as retries and acknowledgements. However, for the set of experiments presented in this paper, motes are at 1 hop distance, therefore routing is not performed. Moreover, the application incorporates a 6 packet transmission queue, which serves as a packet buffer prior to the current packet being delivered. In the event of the queue being full, for instance due to a high packet sample rate in tandem with a low or impaired packet delivery rate, then packets are dropped until the transmission queue again has available capacity. The reduced SRAM memory size of the MICAz mote (4 KB), only accommodates the routing protocol and a queue of 6 packets.

For the purpose of our experiments, a 64 Hz sample frequency was chosen to capture the flapwise and edgewise acceleration of the blade. In order to account for a sample ratio of 64 Hz, the timer had to be set to fire at exactly 16 binary units, i.e. 1024/64. At the end of each 16 binary units (15.625 ms) period, a task is invoked which gathers the current acceleration value for each of the 2 axes and populates a buffer. When the maximum number of accelerometer samples per packet is reached, the packet is moved to the transmission queue and population of a new packet begins.

The effective payload size is established as a maximum of 52 bytes, which allows for the headers and control bytes of the IEEE802.15.4 specification. Each packet contains a timestamp value corresponding to the acquisition time of the first sample in the packet (4 bytes, i.e. 48.5 days to rollover), a count-sequence value which indicates the number of packets generated (4 byte) and the sample period value (1 byte). In addition each acceleration sample is comprised of the tuple $<x,y>$ with 2 bytes for each axis value, i.e. each $<x,y>$ sample occupies 4 bytes. In each packet 8 tuples are transported (16 bytes), i.e. 8 samples per packet for each axis with a resolution of 16 bits each. In addition to this, the 11 bytes for routing are added to achieve a final payload size of 36. At 64 Hz sample ratio, a throughput of 8 packets per second is required to maintain the real-time stream.

**IV Experimental Procedure**

The 1.4m long WTB utilised for the test is made from a polypropylene/glass fibre composite with a weight of 1.7kg. The instrumentation attachment points, as shown Figure 1, were prepared by scoring the surface with 40 grit sandpaper then cleaning with alcohol. This exposed the glass fibre within the matrix to which a two-part epoxy adhesive readily adhered. The blade was fixed to a shake table using a purpose built clamp at the root to simulate fixing at a nacelle. Base excitations were applied using a uni-axial LDS electrodynamic shaker to which the desired excitation signal was inputted via an amplifier.

Before attaching the sensors for the sequence of tests, a 2g inversion calibration test was carried out for each sensor by observing the output of the accelerometer as it pointed downwards in the gravitational plane (+1g) then inverting so that it now sensed a negative g-value (-1g). The Agile link WS has an onboard "G-link" calibration tool which uses the tri-axial property of the sensor to self-calibrate. The Agile-Link and Entran sensors were fixed to drilled and threaded plates that were bonded to the surface of the WTB. This ensures secure anchorage with no damage to the surface of the blade. Instrumentation can easily be recovered after the test. A lightweight aluminium platform was fabricated and attached to secure the
SunSPOT and MICAz sensors as shown in Figure 1. This arrangement ensured all sensors were located within a 100mm x 100mm area of the blade to minimise the difference in acceleration due to the multiple attachment points necessary for this experiment.

V Results and Discussion

Sine sweep tests (by gradually varying the frequency of a sinusoidal signal) were conducted with a sweep from 3 to 5 Hz. The data in Figure 2 shows a segment of data from a single sine sweep and demonstrates the excellent agreement between the four sensors.

For the sine sweep tests the amplitude of the input excitation was chosen such that, at resonance, the response exceeded the nominal range of the sensors. This enabled assessment of their performance when subjected to dynamic loads within and beyond their acceleration limits in a single test. Sine sweep data demonstrated that the SunSPOT exhibited an over-range threshold of 2.5g when configured on its 2g setting, while the other nominally 2g sensors perform well up to the +/-4g response acceleration. This confirms there is a factor of two over-range tolerance on the Agile-Link, MICAz and Entran. Figure 3 shows the FFT analysis of an entire 3 to 5 Hz test with over-range accelerations up to +/-4g. This analysis was carried out to investigate if a response history with incomplete amplitude data, as obtained with the SunSPOT in this case, could be used to determine the natural frequency of the structure.

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It can be observed that in these tests the MICAz and SunSPOT FFT plots exhibit more noise than those of the Agile-Link WS and the wired Entran. In the case of the SunSPOT this is not surprising giving the over range accelerations induced in the system and the loss of amplitude data due to saturation of the sensor. Nonetheless, the average natural frequency of the WTB could be determined from the peak of each of these FFT plots with an average of 3.93 Hz and a standard deviation of 0.098.

In addition to the sine sweep tests a white noise excitation was applied to the WTB and the response was measured as shown in Figure 4.

Again, all four sensors performed well and FFT analysis was performed as shown in Figure 5. FFT analysis was employed for each of the white noise tests and a maximum standard deviation of 0.06 was observed in the fundamental frequency peak of the WTB. A second harmonic was observed close to 23 Hz. Table 1 shows the peak FFT values for the fundamental and second harmonic frequencies, in addition to the averages and standard deviation for each test. The results demonstrate that the sensors are in excellent agreement throughout, although the standard deviation is larger for the second harmonic.
VI Conclusions

Vibrational data has been collected using wireless accelerometers installed on a small wind turbine test blade. Different input excitations and response analysis has been performed under laboratory conditions. Inexpensive, commodity wireless sensors have been shown to perform when compared with both a commercially available wireless sensing device and a wired sensor. The quality of the data has demonstrated that the wireless sensors, with their onboard sensing, embedded DSP and output capabilities, have great potential for detection, estimation and control applications for Structural Health Monitoring of structures including wind turbines. The implementation of a smart network of wireless sensors over many locations on a wind turbine can be made feasible at low cost using the devices benchmarked in this study.

VII Acknowledgements

This research is carried out under the EU FP7 funding for the ITN Marie Curie project SYSWIND (Grant No. 238325).

Table 1: FFT peak values for the 3 white noise experiments. Average and standard deviation quoted for each experiment.

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References


