Performance Assessment of Wireless Data Capture in Construction

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Abstract -

The tenet of TQM is the use of measurements to monitor an operation in order to avoid poor quality outputs. The construction faces unique barriers to utilize effective technologies to capture critical process data in real time. This paper presents the results of extensive field testing of wireless systems to study the effect of the "noisy" environment on sensing and signal propagation. The findings confirmed the hypothesis that construction activities and equipment impact the performance of such networks. In an experimental application on site, ZigBee network to collect data about temperature at pre-designed locations was integrated with an off-site station. Working with the system led to the conclusion that ZigBee is a viable technology to be implemented on the construction site, reliable and easy to use. The concrete crew receiving real time data on temperature from the embedded sensors were delighted as they have never been provided with such new and important information before.

Keywords -

Sensing and Communication; ZigBee Thermocouple; Signal Propagation Pattern; Information Hub

1 Introduction

The 1980's brought the first comprehensive concept to manage quality within a large organization that was referred to as Total Quality Management (TQM). The central tenet of TQM was the drive for continuous improvement of the operation while delivering high-quality products and services to customers. Lean manufacturing was another concept that received a lot of attention in the 1980's and depended on the availability of data. Maguad [1] summarized that: "Implementing lean production is facilitated by a focus on measurement." Of course, the preventive approach to reduce waste (=lean) requires in-process measurements instead of final product inspection. For example, the traditional concrete quality control procedures, like many other construction processes, are completed well after they have ended. For example, while curing temperature and moisture content affects the mechanical properties of concrete [2], limited data in project databases particularly in BIM records is associated to construction of concrete elements. The advances in sensing as well as communication technologies are the backbone of the transition toward a real-time process oriented quality approach. Boyer and Swink [3] articulated that "… the advent of low cost data collection technologies opens opportunities for improved observations of phenomena." In particular embedded sensors have been introduced to monitor long-term serviceability of concrete structures [4]. Akinci et al. [5] developed a "formalism" for active quality control on construction sites using embedded sensing systems. Gordon and Akinci [6] put emphasis on mobility of implemented technology in order to collect data from the point of interest with limited access during construction. However, the quality of wireless link between nodes is affected by many factors such as: a) communication protocol, b) network configuration, c) site activities and d) weather conditions. The experiments presented in this paper aim to identify the practical challenges of implementing wireless data capture technologies such as ZigBee sensor network to collect selected process data.

2 Process Quality Measurement: The Path to Eliminating Supply-Chain Waste

Bellah et al. [7], between others, reminded us that:" TQM is a philosophy and set of practices that aim to eliminate all forms of waste from all product manufacturing and service delivery processes." How can waste elimination lead to quality while improve performance? The connection becomes clear when one equates waste to lack of quality not only of the final product but also during production because waste requires resources and adds to the cost of the product thus reducing its value. Canel et al. [8] defined waste as: "… anything other than the minimum amount of equipment, materials, parts, space, and workers' time, which are absolutely essential to add value to the product or service …" Thus the systematic elimination of waste is also a systematic assault on the factors underlying poor quality and fundamental managerial problems. Robinson and Malhotra [9] highlighted this fact: "… quality practices must advance from traditional and product-based mindsets to an inter-organizational supply chain orientation involving customers, suppliers, and other partners." Perhaps the most essential difference in this transition of traditional activities is a shift from a product to a process orientation.

3 Wireless Sensing Technologies for Construction

Present implementations of ambient environment sensors on the construction process level are limited to on-board instrumentation (OBI). The agile, rugged and ever changing spatial locations of operation require hardened and flexible sets of electronic sensors to read temperature, pressure, wind, accelerations, vibration, humidity, barcodes etc. Furthermore, the extensive number of supply chains, depending heavily on truck-based delivery methods, created the need for embedding monitoring technologies into construction equipment like trucks, drilling rigs or tower cranes, or even the construction material enabled to communicate data about workflow, quality and safety. Of course, the mobility of embedded sensors not only requires mobile power-supplies but also a wireless communication network. Bae et al. [10] provided guidelines for optimal design of wireless sensor network (WSN) topology in order to maximize the performance of a ZigBee based bridge health monitoring system. They asserted that the WSN performance depends on the material type and object thickness through which the electronic signals have to travel. However, many barriers have to be overcome in order to wirelessly connect many "islands of information" at construction site are: a) Technical hardware and power, b) interoperability problems, c) security issues, d) ownership of data, e) user-friendliness, f) cost and g) ruggedized housing against dust, heat and rain [11]. Attempts to wirelessly collect data at field level started by the introduction of IEEE wireless protocols like 802.11b [12]. Although wireless conduits were backbone of information flow, the communicated data was collected manually using mobile devices [13]. Research has been done to measure capability of available wireless technologies to transfer construction specific information on-site [14] and off-site [15]. While limited in number and scope, results of feasibility tests showed the lack of knowledge regarding propagation pattern of radio signals on construction work areas [16].

Kim et al. [17] divided applications of WSN into two main categories: a) Environmental monitoring and b) identification of a mechanical system through measured system responses. We add the third category as "process waste control" through monitoring key physical variables in order to diagnose any deficiency from specifications in real time.

4 Performance Features of a Site-Based Wireless Sensor Network

As mentioned, establishing an effective wireless data collection system covering a construction site requires knowledge about the behavior of spatially distributed sensors and electronic signal propagation. Site activities affect WSN performance in two principal ways: a) Interference from electromagnetic fields generated by operating engines and b) blockage of line of sight between sender and receiver. In order to mitigate such negative effects, many wireless systems, such as ZigBee, are employing Received Signal Strength Indicator (RSSI) technology. However, fluctuations of RSSI due to signal fading significantly affect various applications' accuracy [18]. Experiments presented in this section aim to quantify ZigBee signal's decay in relation to its "root causes" providing critical knowledge to design any ZigBee based on-site tracking and control application.

The root causes have been studied by monitoring quality of a wireless link between a fixed central data logger and a portable node. National Instruments WSN Link Quality Logger is a, virtual instrument (VI), programmed in LabVIEW to determine link quality of WSN nodes in an application environment (http://www.ni.com/example/31346/en/). A snapshot of the program interface is provided in Figure 1. The interface can be used to set the sampling frequency, monitoring battery life, and more importantly recording the Link Quality Index (LQI) – a number out of 100.

4.1 Electromagnetic Emission on Site

An accelerating electrically charged object emits packet of electromagnetic (EM) energy in a fixed frequency that creates the so-called EM field. Theoretically, frequency and intensity of the EM fields at site are the two key factors affecting the performance of WSN. However, because of ZigBee's position in the radio frequency spectrum, the frequency based inference of EM sources with wireless signals is less contingent. But, the undesirable electromagnetic radiation (EMR) still can interrupt network performance through other mechanisms such as: a) Causing network components specifically the sensitive electronic chipsets to malfunction, b) increasing signal to noise ratio in the environment especially in antenna proximity, and c)

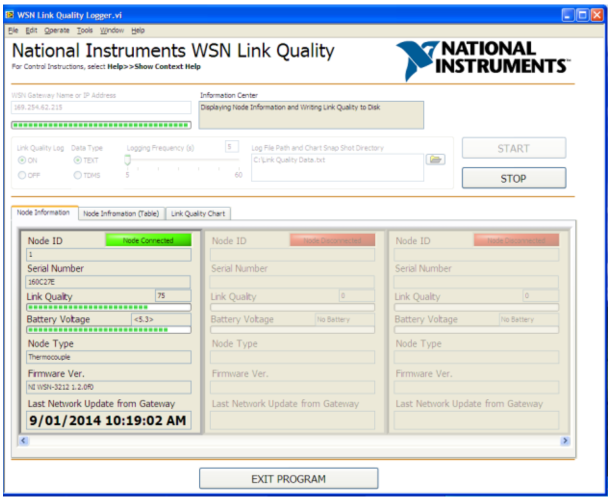

Figure 1. Interface of link quality measurement software

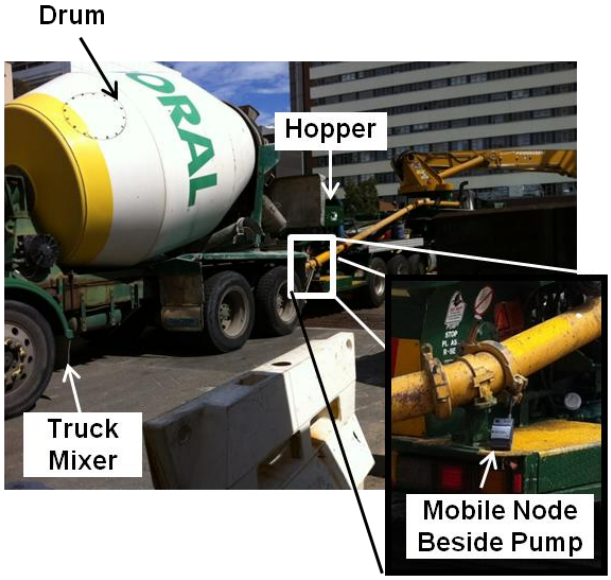

Figure 2. Experimental set up to measure concrete pump's effect

signal attenuation in a weakly ionized medium. Noise emission regulations such as FCC docket 20780 in United States and VDE 0871 and 75 in Germany have provided guidelines to protect digital and electronic equipment against a broad range of 10 KHz to 1 GHz. In particular, focus of VDE 0875 on low-frequency devices up to 150 KHz shows that network gears are potential victim of EMR of the power lines feeding tower crane as well as the heavy equipment engines.

4.1.1 Concrete Pump

First step to field deployment of a wireless monitoring system is to ensure that operation of the equipment required for the process does not threaten network's reliability. Concrete pump is one of the equipment with potential destructive EM emission. Figure 2 demonstrates test configuration where a mobile node is fixed beside the pump hopper and a truck mixer discharges the concert. The first design of experiment included recording of LQI in two different conditions a) Idle pump and b) pumping in progress. The design was later modified to examine the third treatment when pumping and feeding the hopper happened simultaneously. It was observed that mixer's engine that runs the hydraulic drives of the drum created higher noise in reverse rotation. That was enough to question whether the change in the direction of the drum rotation to "discharge" the concrete introduces different situation than "charging" rotation of the mixer. Three explained conditions comprise the treatments of the ANOVA. Link quality data for each treatment obtained from the field test is documented in Table 1. The test statistic f_o=3.82 is bigger than the critical threshold $f_{0.05,2,15}$=3.68 thus supports the rejection of the null hypothesis of equal means. Although the ANOVA says that there is significant difference among means but it doesn't say which means differ. The procedure of finding the specific differences is built upon the fact that while similar treatment means are close enough to be covered by the bell curve of normal distribution with $\sigma = \sqrt{\frac{Mean\ Square\ Error}{Nubmer\ of\ Re\ plications}} = \sqrt{\frac{52.8}{6}} = 3.0$, the dissimilar treatment means will fall out. In another word if the difference between two means is larger than the width of the normal curve, those two treatments are "different". That is common to estimate the width of normal curve with 6σ for practical purposes. However,

Table 1. Data captured in order to investigate effect of concrete pump's operation on SQI

		Readings (Link Quality)							
		1	2	3	4	5	6	Mean	Standard Deviation
Treatments	Idle Pump	54	60	63	50	55	53	55.8	4.8
	Pumping in Press	54	47	36	41	44	56	46.3	7.7
	Pumping and Feeding	49	39	36	56	38	54	45.3	8.8

because the P-value of the ANOVA (0.046) is very close to test significance level of 0.05, it would be reasonable to consider a smaller fraction of the normal curve for example 3σ. Note, that selected width still contains fairly high percentage (87%) of the area under the normal curve. Now, the difference between treatment means can be compared to indentify similar treatments. Following the described procedure, signal performance is similar around an operating pump either fed with concrete or not but is different when pump is idle. The mean signal quality index is 9.5 units larger than working pump's mean, a difference slightly larger than 3σ (=9) that confirms the effect of the pump operation on the link quality.

5 Deploying Attained Knowledge to Collect Process Data

Development of advanced information management systems in construction promises improved process coordination [19]. However, current practices of manually acquiring field data needs to be automated in order to fully deploy work-integrated information management models [20]. A wireless climatic information system for construction sites developed by [21] is a proper combination of automated collection and wireless dissemination of critical data. Still, WSN is not widely implemented to gather "process" data. Embedded measurement of concrete maturity using thermocouples is a potential application that needs extra investigation.

Heat evolution of concrete mixtures not only affects material properties such as strength [22] and yield stresses [23] but also may cause thermal cracking leading to disqualification of hardened concrete [24]. Furthermore, if available during the construction process, temperature development is an indicator of formwork striking time for concrete structures [25] as well as traffic opening criterion for concrete pavements [26]. Calorimetry test has widely been used to model hydration properties of early-age concrete [27]. However, due to equipment limitations in-situ concrete strength development cannot fully be modeled at the laboratory. For example, while it's believed that isothermal test has advantages over adiabatic test; Xu et al. [28] showed that hydration parameters calculated from semi-adiabatic test better match actual measurements. Moreover, other construction specific factors such as a) framework, b) workmanship, c) thickness of concrete element, d) heat exchange of concrete with the surrounding environment, e) weather conditions and etc. affecting hardening rate are not included in practical models. Therefore, if possible, field measurement is the most appropriate method to determine temperature development of cast in place concrete.

5.1 Instrumentation and Methodology

As pictured in Figure 3 a programmable NI3212 wireless node at work-front locally interprets T-thermocouple voltages into temperature and sent the measurements to the central NI9792 wireless sensor network (WSN) gateway. However, because concrete pump was the desired central point of the network a careful design was required to wirelessly link the end note to the central data logger. ZigBee was selected as the communication protocol because of its low power consumption and secure networking. Based on the knowledge acquired during the field surveys, a relay node was placed beside the crane to ruggedize the "information conduit" off the work-front. Figure 3 also shows the mobile multifunctional user interface (*e*CKiosk) developed to provide live temperature data to the job foreman. After pouring, data logging frequency was lowered to one measurement per 10 minutes to save battery life of wireless nodes until the formwork was removed two days later. Real time weather condition was also recorded using data provided on Australian Bureau of Metrology's website.

A distributed node can be set either as an "end node" or a "mesh router" node. Deployment of IEEE 802.15.4 radio in selected devices facilitates low power communication among as many as 64000 nodes in a network. Router configuration let the end nodes find new path back to the central gateway when existing rout is blocked or signal is lost. However, a router configuration keeps the node continuously awake synonym to higher power consumption. NI Measurement & Automation Explorer (MAX) was utilized to arrange nodes to extend network's distance as well as tune up reliability versus power consumption. The typical network configuration used during field test is presented in Figure 4. An NI9792 coordinates the network by managing node authentication, buffering

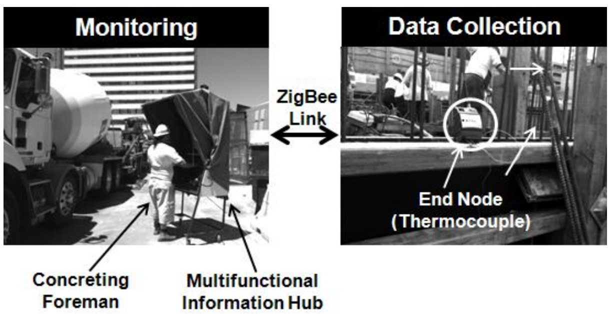

Figure 3. Architecture of live temperature control platform for concreting

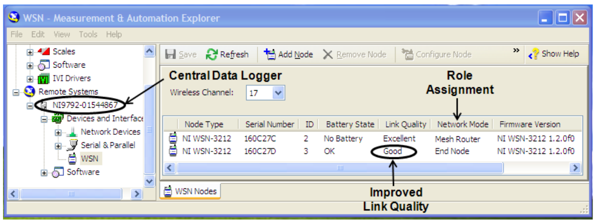

Figure 4. Role assignment to the mobile nodes

transmitted packets of data on top of bridging WSN to the internet for information sharing purposes. During preliminary tests the link reliability between NI3212 end node at pouring spot and network gateway beside the pump truck significantly dropped when rebar mesh was installed in the formwork and the node was tied to a wooden timber supporting the formwork in order to be protected against any unpredicted stroke during the process (See Figure 5a). Furthermore, selected concrete pour was inside a three meter deep foundation pit surrounded by in-situ concrete sheet piles supporting the vertical excavation. Prediction of rain for the period of data collection in addition to the confined space with significant height difference which was proven to decay signal strength [29], forced the research team to add a router node in order to enhance reliability of the system. As shown in Figure 4, install of the additional node enhanced end node's link quality from mostly "Poor" and "no signal" to "Good". Because of the access to the power outlet, the intermediate node was supposed to work on external power in the initial plan. But, according to safety rules a powered device was not allowed unattended over the night. Therefore, router node was also powered by battery during the experiment. In particular, switching to battery did not affect performance of the network at all. Figure 5b) depicts the T-type thermocouple with operating range of -10^{o}C to 400^{o}C fixed in the geometric centre of a ready-to-pour wall formwork with the aim of measuring adiabatic hydration temperature trend of the concrete in its early

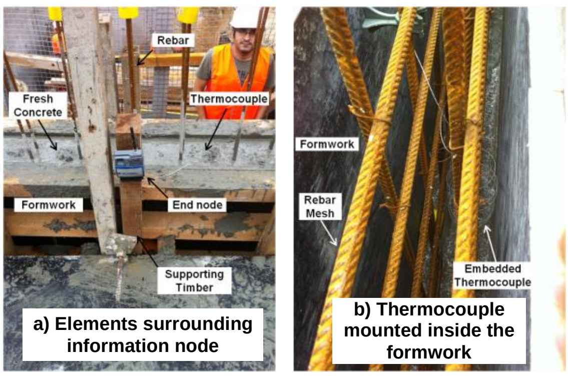

Figure 5. Fixing a wireless thermocouple node at work front

ages. A thermocouple is made by joining two different metals while the contact point may be simply twisted or welded. Any change in joint temperature produces a small thermoelectric voltage in millivolt range that is converted to the temperature using Seebeck coefficient. That coefficient is a function of materials composing the thermocouple and determines the operating range of a specific thermocouple. For example, the T thermocouple embedded in the formwork is made from cooper and as one conductor and constantan (copper-nickel alloy) as another. Similarly, a T type thermocouple with operating range of -50^{o}C to +250^{o}C from another manufacturer was used to measure surface temperature of freshly poured concrete. With typical accuracy of 1^{o}C the thermocouple was a proper choice for fresh concrete quality monitoring purposes. Compatible with selected hardware, the LabVIEW was proper system design software for our measurement and control application. The graphical programming environment of LabVIEW made creating custom software solutions dramatically simple. The code developed to acquire, analyze, display and store the concrete temperature is presented in Figure 6. Adiabatic and surface embedded thermocouples were connected to TC0 (+/-) and TC03 (+/-) terminals of NI3212 correspondingly. The NI3212 thermocouple input node is mentioned as Node3 in the network tree rooted to NI9792 as central data logger. Collected data was written on a hard disk as well as shown simultaneously to the concrete crew through *e*CKiosk. While regular waveform chart displayed the measurements in real time, two temperature meters were also added to facilitate fast reading of the data. Furthermore, two indictors were considered to notify concrete foreman when each monitored variable exceeded pre-defined thresholds. As mentioned in the methodology, the sampling frequency was set to 0.1 in pouring and then decreased to one measurement per every ten minutes in curing period. A higher sampling rate during pouring was to catch the sudden changes of temperature because of frequent drizzling. Figure 7 depicts the data presented to the crew during pouring process.

6 Summary and Conclusion

Total Quality Management (TQM) depends on proactive measurements to ensure a flawless production with high quality outputs. Poor quality supplies and processes not only lead to break downs and low productivity but can also result in costly repairs when the product does not pass final inspection. However, real time monitoring of construction processes requires a secure stream of data from the work-front collected by

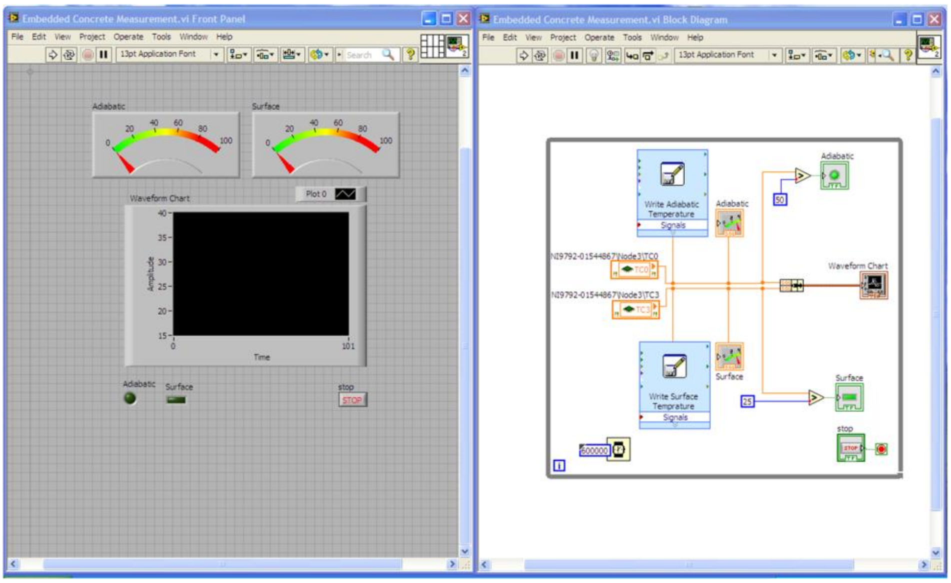

Figure 6. Developed LabView application to record and display the measurements

a sensor system. The goal of this paper was to assess the effectiveness of such wireless systems through the experimental deployment of a set of wireless thermocouples to record temperature variation inside as well as on the surface of recently poured concrete. Because the behavior of wireless signals across an active construction site was unknown, a series of pre-tests were conducted to understand the extend of possible interferences with the communication signals. For example, the effects of a pump under different operating conditions were statistically analyzed. This was followed by field testing an entire Wireless Sensor Network (WSN) coupled to a mobile and multi-purpose hub interfaced with the internet. Designed to monitor concrete construction, it enabled a more flexible condition-based control of the process especially when pouring was frequently stopped and resumed because of rain. Continuous data capturing for three days showed the robustness of the predicted signal propagation patterns used in designing the wireless network. Observations confirmed that ZigBee's data rate of 250 kbit/s was sufficient for the single transmission from sensor to gateway. On the ever changing construction site, its capability to transmit data through intermediate nodes was effective in overcoming signal attenuation. The experimental field test also demonstrated the potentials of such measurement technologies still novel in construction. The availability of new information about ambient and peak adiabatic temperatures or other weather conditions provides a proactive and nondestructive quality control of the concrete curing process. However, the value of collecting process data is not limited to quality management. While the test focused on temperature data other valuable information can be gained "for no extra cost." Examples are idleness of resources, or surface drying can indirectly be interpreted from the same data. Of course, there are a myriad of other electronic sensors that would drastically expand the possibilities to ensure high quality of processes and final products.

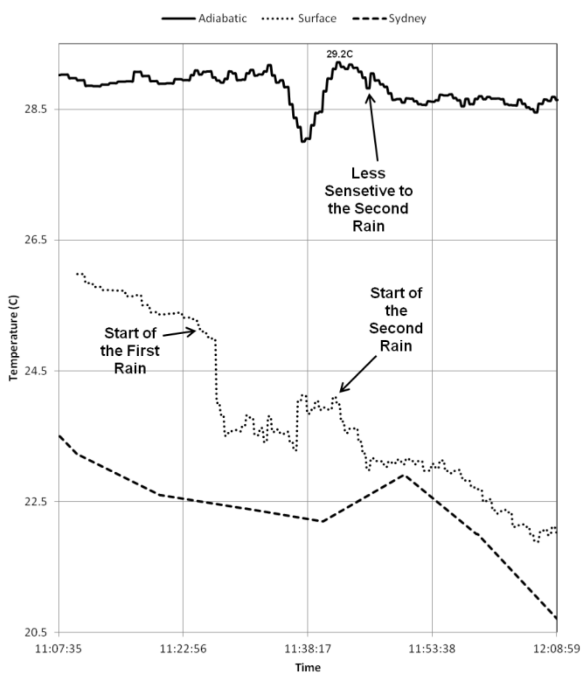

Figure 7. High frequency sampling during pouring process

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