Embedded Wireless Communication Platform Addresses Crane Safety and Efficiency

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ABSTRACT

Boosting the communication at the process level has been identified as promising strategy to improve construction productivity, safety and quality. However, the capacity of classic paper-based information flow at work-front limits the transformation towards construction paradigm able to access to a ubiquitous data network. For this reason, “information superhighways” have to be constructed to connect the many information sources and sinks to enable highly productive practices supported by built in smart agents. IT is not only an essential tool to linking islands-of-information but opens opportunities for processing the data in real time using sophisticated processes. Included in the discussion are the lessons learned on the site-readiness to accommodate IT and incentives to foster collaboration, creation of rugged interfaces and interoperability. The paper will end with an analysis of the data collected during the experimental testing of innovative prototype systems that encompassed the use of RFID tags, GPS, the Electronic Construction Kiosk (eCKiosk), wireless IP camera and Bluetooth intercom. Results confirmed the importance of involving the site personnel in the implementation of new concepts and the positive impact of well-designed IT system to improve significantly process productivity and quality. Practical challenges caused by the nature of construction are highlighted.

INTRODUCTION

Construction operations intensively rely on requests for information to build what has been designed. Faulty or missing information lead to waste of resources such as idleness, rework, excessive order, low quality work and incidents. However, limited capacity of traditional manual information dissemination hinders the timely access to accurate and complete information required for waste-free field operation. Therefore, reliable infrastructure is needed to autonomously collect, process and communicate information through project life cycle in both managerial and field levels. Interoperability of implemented technology and its alignment with field functions are practical barriers against integrated project control which significantly depends on real time communication. On the other hand, miscommunication between entities may cause wasteful consequences such as fatal accidents and low efficiency.

Streamlined lifting and positioning of heavy loads are the key requirement to build which was even indentified and addressed in the construction of ancient monuments such as Persepolis and pyramids. Not surprisingly, omnipresent tower cranes have become commonplace within construction sites. The increase in
workload and complexity of the task demands for enhanced communication and consequently gives the potential for undesirable event. Tower cranes, without doubt, are the heart of construction site sustaining site alive by delivering physical resources to the work-front and removing scrap from work place. However, safe operation of tower crane is one of the most challenging tasks in site management. Communication wise, crane operator is fully dependent on spotter’s guiding commands specifically in “blind” lifts and in the micro-scale movements like holding formwork in place to be precisely assembled. Furthermore, crane operator has to trust slinger’s (rigger) competency in hitching the object to the hook block while legally the operator is also responsible in a case of falling load. In current practice, coordination among crane operator and slingers establishes based on only one of human senses – listening to two-way radio or observing hand-signals. When suspended load is a potential risk, crane operate can’t view the load in blind lifts. That is why a senior crane operator is paid 90000 AU$ per annum while other construction and mining laborers in average are paid 50500 AU$ per annum (2011 data from Open Universities Australia Career Advice - [http://www.open.edu.au/careers/mining-resources-energy](http://www.open.edu.au/careers/mining-resources-energy)). Based on safe Work Australia (SWA) statistics reported at December 2012, with 39 fatalities, construction industry placed the third after transportation and agriculture. The construction industry recorded 3.77 deaths per 100,000 workers which is almost two times the overall fatality rate of 1.93. The report adds that “The number of fatalities in the Construction industry has remained relatively stable over the past few years.” Also, eight years average from 2003 to 2011 shows 5% of total notified worker fatalities in Australia comprises "workers who died when they were hit by a heavy object being lifted with cranes or forklifts" as well as 17 bystanders fatalities. On the other hand, injuries significantly hurt the industry. For example, from 2001 till 2009, median time lost from work in the construction industry averaged 4.0 working weeks. In addition, the median payment for claims in the construction industry was 9400 AU$ in 2009. Similarly, other researches from Singapore (Ling et al. 2009), Israel (Shapira and Lyachin 2009), USA (Beavers et al. 2006, Bernold 2013, and Bernold et al. 1997), UK (Sertysilisik 2010), Hong Kong (Tam and Fung 2011), and Netherland (Swuste 2013) emphasized the importance of crane related incidents in the construction. As a whole, it’s hypothesized that establishment of a robust communication corridor between crane hook and crane cabin to provide video of action scene to the operator re-assures safety, increase crane crew coordination and reduces crane operator’s dependency on spotter.

According to the elaborated demand for new communication means to support crane operation, this paper proposes a process oriented application of IT to supply crane operator with real-time stream of rich information. The novel system aims primarily to prevent misunderstanding of signaling/radio communication from spotter in order to reinforce safe operation and secondarily eases blind lifts. Although the core function of innovative system is about safety reassurance, other sorts of data are also communicated to the crane crew to facilitate process management.

COMMUNICATION GAP IN CRANE OPERATION

People receive and decode communicated message by combinations of human senses and store it in sensory memory. Then, selective data is processed leading to cognition of message which is followed by an action or semantic transformation to
respond the message. Encoded response is transmitted to the sender and above cycle may repeat as many times as required (Bernold and AbouRizk 2010). Explained path and example potential source of misunderstanding/miscommunication in a blind lift is provided in Table 1. “Blind” lift in Table 1 refers to situations that crane operator can’t see the load, load’s landing area, load’s path of travel, crane’s path of travel, or can’t accurately estimate the distance because of sunlight, reflection or far distance. Given that 60% of accidents in lifting operations are caused by human error (Beavers et al. 2005), communicating live video of undergoing lift to the operator will compensate for lack of communication. Watching video compliments operator’s perception gained by solely listening to the slinger. Extra information enabled by video includes but is not limited to object size, available space, proper orientation of load, appropriateness of slings, safe tying, temporary obstacles, readiness of dropping area, and presence of unpermitted labor below the load. Crane crew coordination is also improved because operator can watch while dialoguing with the spotter. It will be explained later how proposed system goes beyond the internal coordination and streamlines coordinating of unloading with its predecessor (delivery) and successor processes such as rebar placement.

Table 1. Communication during a blind lift

<table>
<thead>
<tr>
<th>Command/Action Path</th>
<th>Example of Blind Lift</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sender</strong></td>
<td><strong>Two-Way Radio</strong></td>
</tr>
<tr>
<td>Encoding</td>
<td>Voice to radio wave</td>
</tr>
<tr>
<td>Transmitting</td>
<td>Travelling radio wave</td>
</tr>
<tr>
<td><strong>Receiver</strong></td>
<td><strong>Crane operator</strong></td>
</tr>
<tr>
<td>Decoding</td>
<td>Radio wave to voice</td>
</tr>
<tr>
<td>Processing</td>
<td>Listening</td>
</tr>
<tr>
<td>Cognition</td>
<td>Interpreting message</td>
</tr>
<tr>
<td>Action</td>
<td>Joystick control</td>
</tr>
<tr>
<td>Semantic Transformation</td>
<td>Talking to Slinger</td>
</tr>
</tbody>
</table>

SYSTEM ARCHITECTURE AND PRELIMINARY TEST RESULTS

The main objective of developed Embedded Wireless Communication Platform (EWCP) is to serve as a modulated mobile communication node rapidly embedded into various pieces of equipment. Very similar to development of telephone from landlines, to analogue mobile phones and then Smartphone working over 4G networks, attempts to increase range of visually accessible distance in crane operation started with CRANIUM – a wired camera mounted on the tip of crane
boom and transfers real-time picture of the loads to the television monitor in the crane cabin (Everett and Slocum, 1993). Later, Shapira et al. (2008) tested a wireless vision system installed on the crane trolley. Analogous to fast networks like 4G that enabled capabilities like “Face time”, recently developed 802.11/n protocol with improved amount of bandwidth supports faster speed and more signal range. Establishing wireless-n network with a set of high gain antennas and equipping wireless camera with signal booster will reduce delay and error of wireless communication. However, all of previous applications only worked as stand-alone systems and never integrated with project network. Like the early mobile handsets that were only functioning as wireless two-way communication tools. But later Smartphones were equipped with embedded technologies like GPS, Bluetooth and scanners to work beyond just a phone. Similar trend has been witnessed in crane safety research. Lee et al. (2012) projected laser and video camera data on a BIM model passively to develop a navigation system for blind area. In particular, EWCP is believed to be last generation of its own type incorporating GPS, Bluetooth and RFID technologies. It goes far beyond static integration of information by efficiently sharing dynamic information through project network. In this case, wireless camera is directly connected to the site WiFi network. Wireless camera acts as an independent entity and establishes a visual connection upon request from an authorized agent. As mentioned, because of limited capability of older wireless standards to stream video reliably, adding an active wireless entity wasn’t feasible until recently. Furthermore, the mounting location of previously deployed systems was very far from the object causing difficulties in interpreting hand signals. Even utilizing a motorized lens was not convenient enough and “it was difficult to produce a satisfactory image on the monitor” (Everett and Slocum, 1993). System prototyped in this study is attached to crane hook block to be close enough to the work spot. Figure 1 shows different technologies, the reason to use them, affected task and the predicted outcome. Details of implemented technologies and preliminary test results are elaborated in following sections.

**Bluetoot h Intercom to Secure Verbal Communication**

Safety regulations highlight the necessity of robust communication link between crane operator and spotter. For example Code of Practice for Cranes published by Safe Work Australia implies that “A reliable method of signalling between the crane operator and dogger (or rigger) is essential for safe crane operation. Failure to implement a reliable method of communication may lead to unsafe crane operations and contribute to injury to persons” Similarly, Singaporean Code of Practice for Safe Use of Tower Cranes issued by Occupational safety and Health Brach of Labour Department stresses consideration of “the effectiveness of communication among relevant parties, such as that between the operator and the signaller(s)” when it describes planning of lift operation. Currently in use two-way radios have two main issues: a) All crane crew use the same frequency which increases risk of interruption and misunderstanding. For the crane under study, crane foreman, operator, two slingers, three traffic controllers, lift-truck operator and
Figure 1. Technologies used in developing EWCP

lift-truck chaser, use the same frequency. b) Slingers can’t use both hands when using radio. Figure 2a) shows how slinger’s right hand is engaged with radio when he needs to use both hand to control the rebar bundle. Two-way communication interface used in EWCP (Figure 2b) secures a private communication channel between slinger and crane operator. Furthermore, two paired devices are connected by pushing the “interphone” key once letting the slinger use both hands. Product manual claims half kilometer of Bluetooth intercom range in straight line of sight. Research team tested Bluetooth interphone successfully in blind rebar unloading process. The average straight distance between slinger and operator was estimate to be 60 meter but obstructed by an uncompleted five story building.

Figure 2. a) Dangerous control of suspended rebar bundle by leg when right hand is engaged to the radio, b) Bluetooth interphone improvised on hardhat

Bridging the Visibility Gap Using Wireless Camera
Considering ambient environment effects like intense sunlight, shade, and reflection, even regular lifts lacks clear visibility especially in working at the margins of crane’s coverage area. The authors witnessed near-miss accident at the studied construction site where crane operator tried to speed up the process by lowering the hook block in a blind area without waiting for the spotter to arrive to the point and steer the operator. Problem initiated from the crooked design of the façade which resulted in zigzag scaffolding at western face of the site. Western face of the site located adjacent to university walkway and very rarely a lift has been done at that area. Crane operator moved trolley far enough to avoid straight-lined scaffolding as he perceived from working at northern façade where he usually performs the blind unloading. Unfortunately, crane hook impacted the scaffold and was stuck. Hook released from the scaffold with a strong shock wave made whole scaffolding vibrate for a while. One can predict the catastrophic injuries to the pedestrians if any piece of scaffolding fell to the ground.

Figure 3, shows how limited crane operator’s visibility field is watching the work-face from crane cabin. According to identified lack of visibility, main function of EWCP set to challenge this problem. A wireless network camera powered by a 12V DC battery was securely attached to the crane hook block (Figure 4). To ensure connectivity, a signal booster was implemented to empower transmitted signals. Performance of signal booster was tested using a 3-axis radio frequency strength meter and showed that emitted signals were 20 times stronger when booster was in action. An eight dbi omnidirectional antenna was used to set up host wireless-n network over the site. Authorized users access to video streamed by the camera at real time using any IP-enabled screen such as laptop, tablet, Smartphone, or specially designed site electronic communication hub -the eCKiosk.

In the preliminary set of experiments, crane operator used a laptop to watch the point of activity. Bird’s eye view provided to the crane operator is depicted in Figure 5.

**Figure 3. Limited and far view from the crane cabin (regular lift)**

**Adopting GPS for Process-Oriented Positioning**

Positioning of objects in EWCP is organized in two scales. External use of GPS to coordinate supply logistics with site activities reaches way out of site to the supply chain. On the other hand, internal use of GPS addresses the need to know the exact position of recorded frame to enable secondary applications such as live as-built linked to BIM, autonomous work progress measurement, and autonomous safety
threats detection. Apparently accuracy of positioning is more important in the latter application. In the preliminary test scenario the position of rebar delivery truck was communicated live to the crane foreman via eCKiosk to let him adjust crane allocation timetable to serve the truck upon delivery. While previous time study on crane operation revealed significant wait time of 104 minutes with standard deviation of 30 minutes, at the day of study unloading started with five minutes delay from the scheduled start time. Truck waited 39 minutes before service started but because it arrived to the site 34 minutes earlier than the appointed time. The interface of online GPS tracking website is presented in Figure 6a). The GPS receiver used for crane hook position tracking, the PDA used to log data and sample outcome file with frequency of one is shown in Figure 6b) and 6c).

Figure 4. Wireless camera housing attached to hook block.

Figure 5. Plan view of operation using EWCP: a) stabilizing the load, b) hoisting, c) slewing, and d) lowering the load
Electronic Construction Kiosk
As a wireless hub, is designed in a way to be able to be moved wherever the crews are working. Although it basically works as information delivery tool but it also provides a data collection platform. Indeed the main advantage of eCKiosk is its interactive design. eCKiosk facilitates interaction among e-communication islands revolutionizing the conventional paper-based information delivery. Data collected from different points of interest are retrievable through the eCKiosk upon demand. In another word, eCKiosk is the interface to benefit from EWCP. For example, information regarding real-time position of rebar delivery truck is communicated to the crane operation foreman, rebar placement foreman as well as site manager right at the work-front. GPS data in combination with traffic information records provide a reliable decision making tool to coordinate on-site crews.

Figure 6. a) Interface of online GPS tracking webpage, b) Configuration of the hook tracking GPS unit, and c) Sample output

Interactive Logistics Control by Embedded RFID
Because the general contractor in charge ruled a no-storage policy, upon arrival of rebar delivery truck, one of rebar placement personnel called steely has to determine the spot on the site each bundle should be transferred to feed running placement activities taken place across the site. The identification process is done by painting bundles in different colors to guide the slinger where to unload the object. Time study shows that marking delays unloading in average 18 minutes with the standard deviation of 10 minutes. It was observed many times that steely was confused himself and had to consult with steel work foreman to decide about the destination of a bundle. Steely’s action was important because crane foreman doesn’t allowed second lift for the same bundle as he ratiocinated safety issues. That means improper decision of steely would freeze subsequent process. Delayed unloading process causes loss to all three involved players because steel sub-contractor, crane and rebar supplier work separately. The Research team hypothesized that a proper communication among three entities will make steely’s action redundant while
speeding up unloading and subsequent processes. RFID technology was accommodated in EWCP to eliminate the need to steely connecting engaged entities. An adaptive bundling equipped with the colored RFID tags composes the kernel of experiment design. Result of comparative analysis before and after use of EWCP reviled a 23% faster unloading process while presence of steely was completely redundant. Also, well coordinated rebar delivery process using EWCP enabled just-in-arrival unloading which saves time due to avoidable steely’s action. Used RFID reader and a snapshot of colored RFID tags attached to bundles are presented in Figure 7.

![Figure 7. a) Colored RFID tags and the reader, b) Tags attached to rebar bundle](image)

**SUMMARY AND CONCLUSION**

Inappropriate communication may cause safety concerns while lack of information leads to idleness of resources. Therefore, a state of the art communication mean compatible in addressing communication needs at process level is required to eliminate waiting for information in order to increase process efficiency. Continuing the work presented in CRC2012 (Zekavat and Bernold 2012), articulated in this paper were the results of a long-term investigation on a construction site to measure and find answers to two key questions: a) Is it feasible to employ Embedded Wireless Communication Platform (EWCP) to efficiently transfer/process fairly large amount of information without overflow? and b) what would IT’s impact on process performance be? Successful implementation of EWCP proved that IT can be mingled with construction process in a large-scale in order to significantly improve field safety, work quality and overall productivity. The remarkable measured impact of IT on communication at field level will make IT an impartible recourse in management of future construction. New communication corridors as well as improved conventional means tested in this study showed that still exploration is required to identify many potential areas of IT application at process level. In a nutshell, the measurements on the performance of EWCP showed significant jump in the efficiency of crane operation and its subsequent processes. Furthermore, positive feedback from field personnel and managers regarding satisfactory performance of EWCP promises a solution toward safer and more efficient construction activities by filling the communication gaps.

Challenges to implementing such an effective ubiquitous construction site communication network were organized into two main categories: a) Value-adding application and b) technological barriers. As discussed in the paper, both issues are
closely connected to available IT technologies that opening the way for new ways of communication. However, usefulness of each individual application has to be scientifically measurable to persuade diffusion of IT in site level. Furthermore, because many of technologies are adapted to become consistent with construction processes, technical barriers such as interoperability, specific ontology, unique security requirements, hardware robustness, housing, power, availability and user friendliness have to be considered when innovative applications are designed.

REFERENCES


