AN INTELLIGENT SYSTEM FOR MONITORING TOWER CRANES ON CONSTRUCTION SITES

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ABSTRACT

Harsh and dynamic construction sites are generally equipped with cranes in order to rapidly and conveniently move heavy loads from one location to the other. If not properly inspected and managed, this operation can be very hazardous and lead to accidents. As such, a reliable and self-contained monitoring system that can update construction and safety personnel about the status of the crane, the weight of the load lifted, the location of the boom with respect to nearby buildings and other tower cranes, and the weather conditions under which the crane is operating, is deemed necessary. This can lead to significant time and cost savings as well as safety and productivity improvement due to the accuracy and immediacy of relevant on-site crane information delivery. This paper takes the initial steps and presents research targeted at evaluating the capability of wireless sensor networks (WSN) for monitoring tower crane operations in construction environments. A reliable long range WSN system is implemented and information is obtained from various special-purpose sensors (temperature, wind, proximity, etc.) mounted on special motes that relay data to and from each other and a central hub. The latter continuously monitors and manages network performance and relays incoming data to the host application. This application, in turn, displays the received data, and maps it onto a user-friendly visualization scheme, triggering alarms when a set of pre-programmed rules and safety conditions are crossed. The components of the proposed system have been tested through proof of concept experiments and preliminary results highlighted the potential of WSN systems for improving monitoring of tower cranes and reducing related accidents on construction sites, especially in Lebanon and the Middle East region where safety precautions are usually not properly implemented.

KEYWORDS

Tower crane accidents, Construction safety, Tower crane monitoring, WSN

INTRODUCTION

It has been long known that monitoring and control of rotating or highly mobile devices on construction sites such as tower cranes is of paramount importance (Shapira & Glascock, 1996). A study by Neitzel (Neitzel, 2001) revealed that over a 1,000 construction injuries involving cranes and hoisting equipment happened in a single year in 23 states in U.S.A. For instance, failure to monitor specific areas on site covered by tower cranes and eliminate unsafe conditions can expose construction field personnel to a higher risk of accidents and injury (Irizarry & Karan, 2012; Shapira et al., 2009). Injuries happen not just to the personnel operating the cranes, but also to the workers on the ground, even those who are believed to be a safe distance from the site of the crane work. The related causes for such accidents have been studied by several different individuals and administrations over the years. The Occupational Safety & Health Administration (OSHA) reported that most crane accidents involving a collapse happen when the crane boom malfunctions (Isherwood, 2010). The frequency and severity of crane accidents can thereby directly impact the success of a project by causing job delays and operator downtime, which can negatively impact a project's profitability (Irizarry & Karan, 2012).

In an attempt to reduce crane accidents on site and provide a safe environment, a need emerged to look for ways to use intelligent wireless mobile units for monitoring tower cranes on construction sites.

Wireless communication makes an automation environment setup and modification easier, cheaper and more flexible. It enables new applications where wireless transmission is the only option (Bal et al., 2009). Some work targeted improving tower crane operation and productivity using technological tools such as 1) radio frequency identification technology (RFID) tags (Lee et al., 2006) or ZigBee (Zheng et al., 2011a) to give needed information required about load being lifted (type, weight, required work procedure) and 2) solar powered video cameras to transmit real-time images to the operator's cabin, in order to minimize misunderstanding between crane operator and riggers and avoid accidents (Irizarry & Karan, 2012; Guo & Zhan, 2011). As a consequence of recent developments in wireless communication technologies, the use of wireless sensor networks (WSN) is becoming increasingly widespread for a variety of monitoring and control applications (Czubak & Wojtanowski, 2009). The low-cost and energy efficient aspects of WSN, successfully reported from its implementation in indoor and building environments (Jang & Healy, 2010; Shen et al., 2008; Schmid et al., 2005), motivated its use towards monitoring tower crane operations (Zheng et al., 2011b). Installed at a critical location on the crane, each field device forms part of a mesh network, acting as both a sensor or node and a relay device to exchange data in brief, coordinated radio transmissions (Cisco, 2008). Each node joins the network to forward data collected by its own sensor or others nearby. The mesh, in turn, communicates with a wireless LAN (WLAN) that sends data to the main hub for monitoring and analysis. This mesh network is self-organizing and self-healing, i.e. if one node goes down, the system finds an alternative path for sensor traffic. The more devices are attached, the more resilient the network becomes. This network can thereby efficiently send the signals coming from all sensors located in difficult and critical access places, which provides huge potential for monitoring on-site tower crane operations.

However, to the best knowledge of the authors, none of the previous research efforts targeted monitoring of crane operations on construction sites at a low cost using WSN while visualizing in real-time the whole process. There is thus a clear and critical need to develop a new cost-effective and intelligent WSN system for monitoring on-site tower crane operations and reducing the occurrence of related accidents, especially in Lebanon and the Middle East region where safe practices are not properly followed.

METHODS

System Hardware

The monitoring system hardware consists of commercially-available WSN namely SmartMesh technology by Dust Networks (Linear Technology, 2013) and a set of proximity, temperature, and wind sensors. The SmartMesh network (Figure 1) consists of network nodes, called motes, which are ultra low-power wireless transceivers relaying data to and from each other and the manager. This latter monitors and manages network performance and relays data to the host application.

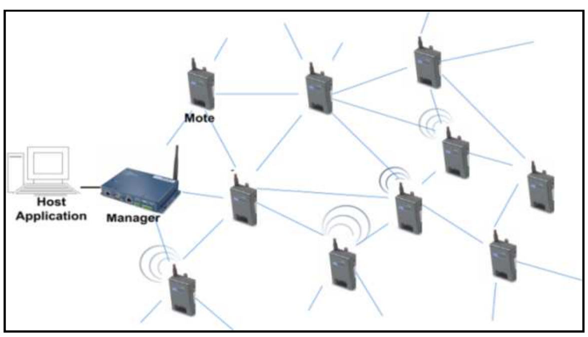

Figure 1 – SmartMesh WSN Components

It is worth mentioning that the above network is not functional without sensors attached to motes. In this case, motes transfer data to and from attached sensors and use an onboard radio to send the packets to neighboring motes. In this research work, photoelectric, temperature, and wind sensors were first considered as a way to detect anomalies and alert the safety personnel. For instance, photoelectric proximity sensors (Figure 2) are mainly used to detect nearby objects, i.e. proximity of the hook to lifting loads or proximity of the jib to nearby construction objects or other cranes' parts. Their sensing range is up to 3 meters, with diffused type ranging up to 50 meters. Precision temperature sensors (Figure 3), having a wide operating scale, are used to set the temperature range and warning signal discretionarily in case the threshold temperatures are approached or exceeded. The wind speed sensor or anemometer (Figure 4) is a four-blade propeller, which by rotating, generates an AC sine wave voltage signal that is transmitted by the mote to notify the operator of severe weather conditions.

Figure 2 – Proximity sensors

Figure 3 – Temperature Sensor

Figure 4 – Anemometer

The whole hardware system is a reliable, cost-effective tool that enables wireless monitoring and control, saves time and money on installation, provides greater flexibility, and reaches deeper into operations than possible with a wired system. Additionally, being a WSN, it's a self-healing network system. Therefore, if one of the motes seizes from functioning, the mote that was using it as a trail (called "parent") to deliver its data will automatically choose another nearby mote to do the job.

System Software and Algorithm

The Smartmesh kit comes with an application called 'Smartmesh Console 1.6' (Figure 5) that allows the user to view all the information needed related to the motes and the manager. The program allows the user to view the communication map, i.e. which signal is being sent where and by which mote. It gives, as well, an overview of how the information is reaching the manager. The software also shows the sensor voltages received, and the time that this information was received, which allows accurate analysis of the data. Smartmesh Console allows, as well, to attach alarms to certain events, which means that an alarm will go out when a certain sensor exceeds a pre-set value, or if a certain mote stops working.

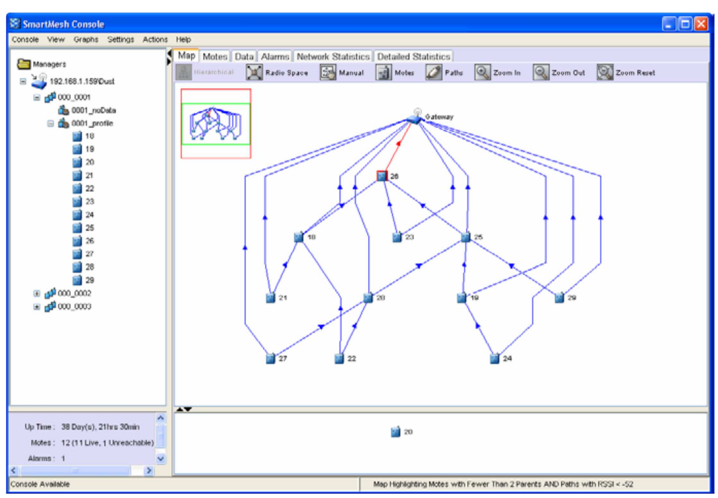

Figure 5 – Smartmesh Console 1.6

In order to manipulate the data as needed, a serial communication is set up between the manager and a laptop. MATLAB is being used to receive the information, process it, and convert the voltage values received to actual temperature, distance, and wind speed values. The relationship between the voltage values and the respective sensor physical values is determined from the sensors' datasheets. For instance, in the case of the temperature sensor used, since 0.23 volts is equivalent to 23 degrees Celsius, the voltage values received are multiplied by 100 as shown below for one mote only:

```
switch read
   case '1'  % If a 1 is received, data received is for Mote 1
   i=i+1;
      if(i<=1000)
        Volt_Mote1(i) = fread(s1,1,'float'); % Read voltage value
        TemperatureCelsius_Mote1(i) = Volt_Mote1(i) * 100 ;
      else
        Volt_Mote1(1)=[];
        TemperatureCelsius_Mote1(1)= [ ];
        Volt_Mote1(1000) = fread(s1,1,'float');
        TemperatureCelsius_Mote1(1000) = Volt_Mote1(1000) * 100;
      End
```

Once all voltage values are received then converted to sensor physical values, resulting actions are executed and displayed through the system user interface presented below in the following subsection.

System User Interface

The user interface has been designed and implemented using MATLAB as well (Figure 6). In its current form, the interface includes four different sections and displays the incoming data from the motes in real-time by visualizing physical parameters change and updating different charts.

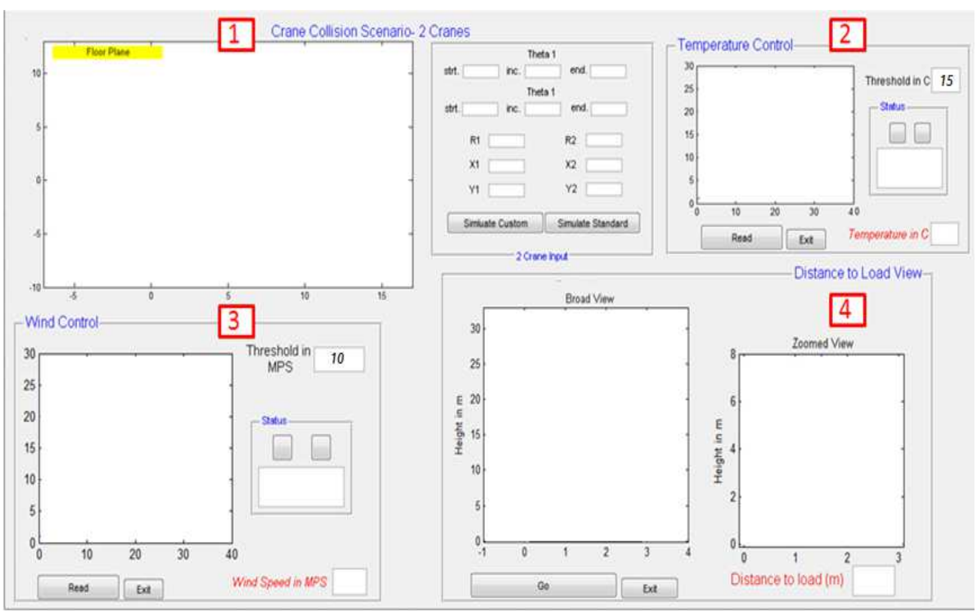

Figure 6 – System User Interface

More specifically, the first section is allocated to display the 2D movement of a crane for zoning purposes and can visualize simultaneously another crane's movements for anti-collision purposes. In other words, if the tower crane is approaching the zone limit or a nearby crane, the operator is warned and the cranes should start to move at a slower speed. If, however, the distance surpasses the allowable threshold, automatic braking of the tower should occur.

The second section is the interface for the temperature. In general, tower crane operations must stop when the ambient temperature drops below -18°C (0°F) or goes above 38°C (100°F) or as otherwise specified by the crane manufacturer or a professional engineer. Restrictions apply on operator's cabins as well. For instance, cabins and remote control stations for tower cranes shall be heated to a temperature of at least 15°C (60°F) during cold weather whenever occupied.

The third section shows the interface for the wind speed. Each crane manufacturer has specified certain wind speeds that could cause an accident or damage to the crane. In general, wind speeds less than 11 meters per sec or MPS (25 miles per hour, MPH) are considered safe, depending on the manufacturer's specifications. A value of 10 MPS was considered in this study and set as a threshold for wind speed. Both second and third panels feature a status group box that indicates unsafe conditions by turning red whenever a predetermined limit is reached on temperature or wind, and turning green otherwise.

The fourth section is currently allocated to display the distance between the hook and load. The exact value is displayed in the bottom right corner, in addition to two windows allowing the engineer or safety personnel to visualize the distances involved from close and far views.

RESULTS AND DISCUSSION

In order to certify the effectiveness of the communication network and the user interface for future application on a real tower crane as shown in Figure 7, proof of concept experiments were conducted in a laboratory environment at the American University of Beirut (AUB).

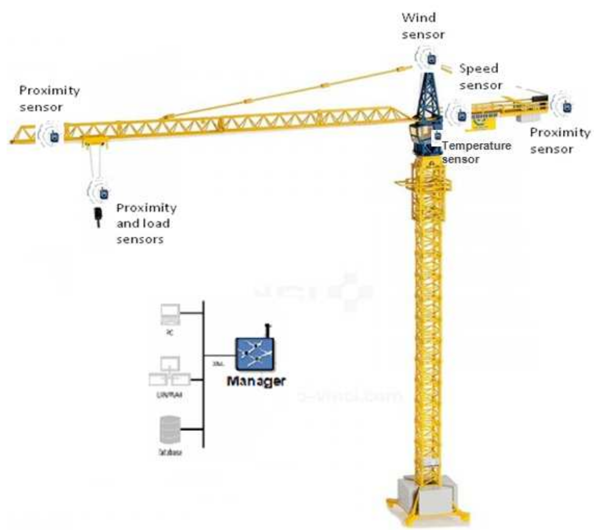

Figure 7 – Sample Sensor-Euipped Tower Crane

In this case, proximity, temperature, and wind sensor-equipped motes were spread apart by distances that reached up to 25 meters and placed at different heights to simulate a standard tower crane occupied area and related scenarios. Some experiments were carried out under certain weather conditions or involved manually moving some proximity sensor-equipped motes to check the validity of the system, in particular its alarming part. Sensor voltage values were fed to the analog and digital inputs of the motes and the manager was able to accurately read these voltages over a long period of time. The Smartmesh console responded well by displaying the data and showing information about the wireless signals and general network performance. MATLAB performed well in converting the incoming values and quickly sending them to the user interface to reflect the updated conditions and trigger warning signals if needed. The preliminary results of experiments are visually illustrated in Figure 8 that depicts the resulting user interface.

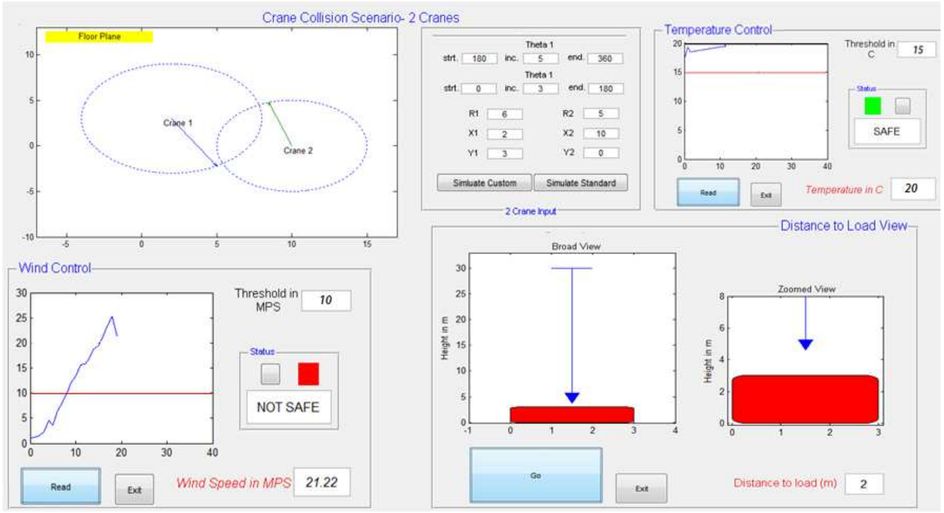

Figure 8- Experimental System User Interface

The results are promising and are not beyond refinement, by means of hardware and software development. The anti-collision scenario, in particular, was addressed in a simple way using the proximity sensors to demonstrate their feasibility in sensing a nearby crane operating at the same height. However, this process is more complicated in real-life and besides proximity, other factors such as boom speed and orientation, etc, should be taken into consideration. Similarly, the temperature interface did generate the right results given the set threshold; however, many other values should be set as well to account for different thermal conditions.

CONCLUSIONS

Construction sites are always prone to accidents especially when tower cranes are involved. The proposed system, through the deployment of a wireless sensor network, aims at helping construction or safety personnel in making rapid decisions to avoid or minimize these accidents. The preliminary results put forth by this paper serve as a proof of concept– a demonstration that a relatively low-cost intelligent system can be used to monitor tower crane operations on harsh and dynamic construction sites, in particular those in Lebanon and the region where safety precautions are not properly adopted.

Further work will seek to improve the whole system by upgrading current sensors and getting other low-cost sensors, especially if the zoning and anti-collision scenarios have to be handled effectively. A combined wind transmitter has been recently acquired for measuring both wind speed and wind direction. Three-degrees-of-freedom (3DOF) orientation trackers or inertial measurement units (IMU) to track boom rotation, vibration and speed will be obtained as well. Load sensors on the hook will be needed as well to verify that the crane’s maximum allowable load is not exceeded. On the other hand, the interface will be upgraded to include more interactive panels capable of rapidly triggering a set of alarms that can be programmed to sound and thereby automatically aid the engineers, cabin’s operator or construction field personnel in properly reacting to events and if needed, stopping the crane from operating. Therefore, the next steps encompass testing the whole system, with all current and new sensors, on two different scaled specimens of a tower crane. A number of experiments will be conducted to try out different combinations of sensors and identify their optimal locations on the cranes in order to account for all scenarios and reach favorable results. The performance of the system will then be assessed on a real tower crane located on one of AUB campus construction sites. Naturally, such improvements, or any other future work on this system for that matter, will be geared towards ultimately providing automation of some of the many monitoring tasks and processes in the field of construction.

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