Sensors & Transducers, Vol. 174, Issue 7, July 2014, pp. 109-114

Sensors & Transducers

Design of a WSN-Based Monitoring System for Avoiding Collision of Tower Cranes

Jiannong Wang
Changzhou Institute of Technology, Changzhou, Jiangsu, 213002, China
Tel.: +86-0519-85567950
E-mail: wangjn@czu.cn

Received: 20 April 2014 /Accepted: 30 June 2014 /Published: 31 July 2014

Abstract: Tower cranes in large construction projects are likely to collide with other cranes close to them during the operation, which is a severe hazard to the security of the staff. Thus, a WSN-based monitoring system for avoiding collision of tower cranes is proposed. The 3D data positioning technology is used to install angle and position sensors at intervals in the cranes in order to collect position data in real time. After the data are sent to the upper computer, the computer calculates the distance using the 3D positioning technique and sets a proper threshold for alarm. When the measured distance is smaller than the threshold, the alarm is set off to prevent collision. In the experiment, three pairs of cranes 15-22 m in height that are located separately are tested in terms of errors in data collection and in alarms. The experimental results show that the proposed system has an alarm accuracy of 99.3 %, and thus, is highly applicable. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: WSN, Collision avoidance of cranes, 3D positioning, ZigBee, Node.

1. Introduction

The tower crane is important equipment for large construction projects, and is mostly used to transfer the construction materials and objects horizontally and vertically. It is widely used because it is easy to install and has no limits on the space for normal operation. Recent years have witnessed a growing number of infrastructural development projects and of tower cranes. More than one crane is required to operate in some large projects. Thus, it is necessary to carefully schedule the operations of these cranes to avoid collision and casualties. Currently, the world's advanced cranes are equipped with security monitoring systems. Our country began to develop the system for avoiding collision of tower cranes very late, but achieved technical advancement quickly, because the WSN technique has been adopted for collision avoidance. Enormous as the market is, the system is not widely used [1-2].

2. Structure of the System

The proposed system is modularized and defines the functional units of sensor nodes (terminals), aggregation nodes (routers, coordinators) and upper computer nodes [3]. The system structure is presented in Fig. 1. The sensor nodes are located at different places as required. Via WSN, the sensor nodes transmit, router and aggregate the data collected by sensors at the beams of the cranes. The upper computer nodes process the data about the positions of different cranes to obtain their 3D locations, and provide the interface for human-computer interaction in order to trigger alarms, or display and store the monitoring data in real time.

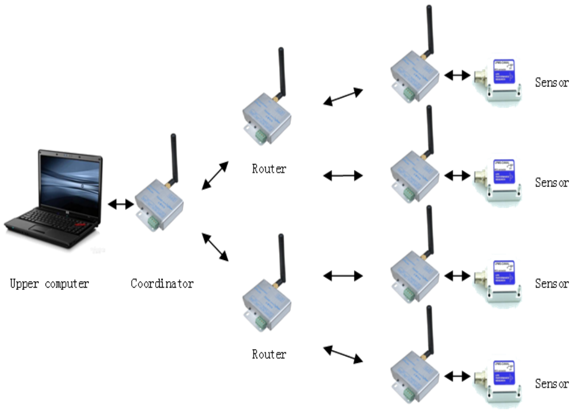


Fig. 1. The system structure.

The sensor nodes at the beams of the cranes include the angle sensors, wind velocity sensors, and inclination angle sensors. Sensors are used to obtain real-time information about the cranes transporting objects. During its operation, the crane's rotation angle is random, so two neighboring cranes should communicate with one another, imposing a high demand on the distance of the crane arms. Hence, the angles must be measured accurately. After data about the area surrounding the crane is measured with these sensors, the 3D positioning technique is employed to locate the cranes.

3. Design of the System Hardware

The CC2530 wireless transmission module is used in the system to support ZigBee. This chip is the most classic WSN solution with many interior circuits, enabling a ZigBee node (coordinator node, router node, and sensor node) to be established and wireless signals to be received and sent with fewer peripheral circuits.

3.1. CC2530 Wireless Transmission Module

The wireless transmission module is the core of the system design. The CC2530 is a second-generation SoC chip from TI that supports the ZigBee / IEEE 802. 15. 4 protocols for the 2.4 GHz ISM frequency band. It integrates the enhanced 8051 core, the 8-input 12-bit ADC and the watchdog timer.

The radiofrequency front end CC2591 from TI, which features high cost-effectiveness and high integration density, is selected to achieve better quality of transmission over the network and wider network coverage. It is appropriate for the low-power, low-voltage wireless transmission system. The built-in power amplifier (PA) can generate an output power of +22 dBm to ensure that signals are output at a high power. Moreover, it integrates the low-noise amplifier (LNA) with a receiving sensitivity of 6 dB. Based on the features above, the ZigBee nodes using CC2591 can transmit across a distance of 500-800 m when there are no obstacles, over 10 times the original range, achieving enormously widened network coverage. The connection between the hardware of CC2530 and CC2591 is shown in Fig. 2.

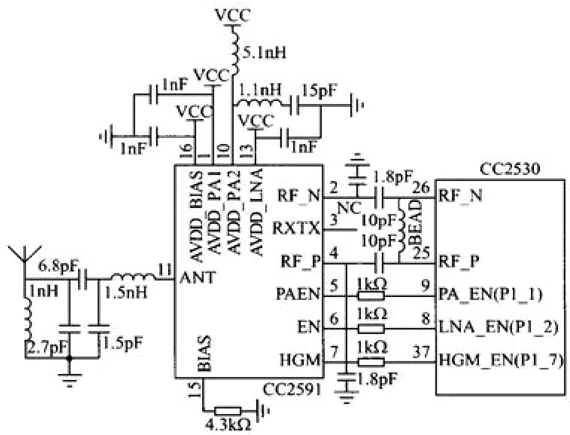


Fig. 2. Hardware interfacing between the CC2530 and CC2591.

The four digital pins of PAEN, EN, HGM and RXTX in CC2591 are used to control the state of the chip. For signal reception, the high-gain mode of 11 dB is used when HGM=1, and the low-gain mode of 1 dB is used when HGM=0. For signal transmission, signals are amplified when HGM is 1, 0, or idle. In addition, the pins of RF_P and RF_N in CC2591 should be connected with RF_P and RF_N of CC2530, respectively, to ensure that RF_P and RF_N can output the positive/negative going RF signals from the PA while sending signals, and can input positive/negative going RF signals into LNA while receiving signals.

In addition to transferring the data wirelessly, the CC2530 module used by the sensor nodes are also responsible for collecting data about the angles, inclinations and wind velocities of the tower cranes.

3.2. Data Collection Module

The crane's data collection module is deeply dependent on the ZigBee sensor nodes, which are installed at the beam of the crane to collect, exchange, and process data. Each sensor node is connected with the angle sensor, wind velocity sensor, and inclination angle sensor.

The absolute rotary optical-electricity encoder ANGTRON-RE-38-RS232/485-08-LITE is adopted in the proposed system to collect data about the crane's deflection angle. The slotting angle and position of the aluminum sheet in the sensor is used to determine whether there is deflection of angle. The angle is measured via the decoding of the electric signals. This approach to angle measurement is accurate, robust, and reliable.

The major reason for overturning or collision of cranes is that the load and force moment exceeds the limits, or the inclination angle falls outside the range. The two-axle sensor WITLINK SIS426 is employed to accurately measure the inclination angles in the X and Y directions. This sensor obtains the object's acceleration based on Newton's second law. After high-accuracy A/D conversion, the output signal of the acceleration sensor is delivered to the composite signal processor to be amplified, filtered, and least-square smoothed. This sensor is powered by 12 V DC and directly outputs the digital signal.

The data of angles collected in real time is sent to the router nodes via sensor nodes, aggregated at the coordinators, and finally arrives at the upper computer, where the short-distance positioning algorithm is used to compute the interval between cranes and to trigger alarm if necessary.

The four-wire systems of RS-485 are used for the outputs of the remotely installed sensors for measuring the angles, wind velocities and inclinations. Sensors are isolated photoelectrically from the CC2530 wireless transmission module. The photoelectric isolation circuit is shown in Fig. 3.

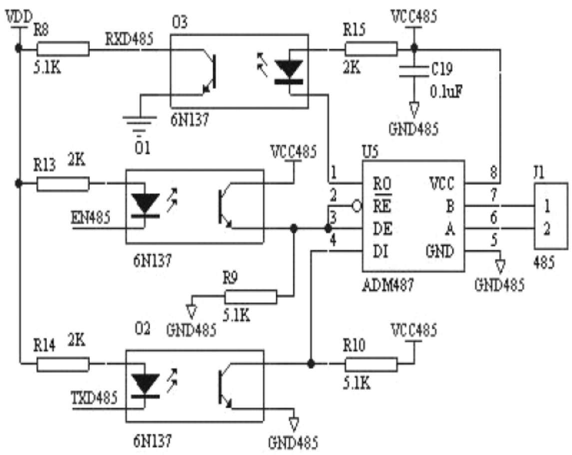


Fig. 3. Photoelectric isolation circuit.

In the circuit presented in Fig. 3, the power supply VDD (+3.3 V) is independent of VCC485 (+12 V). The former powers the wireless transmission module, and the latter powers the sensors. To achieve this, the isolation DC-DC is adopted. Optically coupled isolation is used to achieve isolated transmission of signals. ADM487 is altogether isolated from ground wires of CC2530, thus effectively preventing the generation of high common-mode voltages, reducing the failure rates of 485, and improving the system reliability.

In Fig. 3, RXD485 is connected to the P0_5 pin of CC2530 (UART1 RX). TXD485 is connected to the P0_4 pin of CC2530 (UART1 TX). The P1_7 pin of CC2530 is connected to EN485 to control the reception and sending of the RS485 port.

The communication network that involves the CC2530 module and the RS-485 components of the sensors for measuring the angles, wind velocities and inclinations is presented in Fig. 4. The master/slave mode is adopted for communications, with the CC2530 module serving as the master and the three sensors serving as the slave.

In the RS485 communication network, sensors play the role of the slave, accepting data requests from the CC2530 master and sending data to the bus immediately. The communication protocol is defined as follows:

By ending a 6-byte command (AAH, BBH, IDH, CCH, CCH, CCH) to the bus of RS485, the CC2530 host makes the data requests for data feedback from the sensor with the specified ID. AAH and BBH signal the start of the communications. Sensor IDs are in the range 0x00～0xFF.

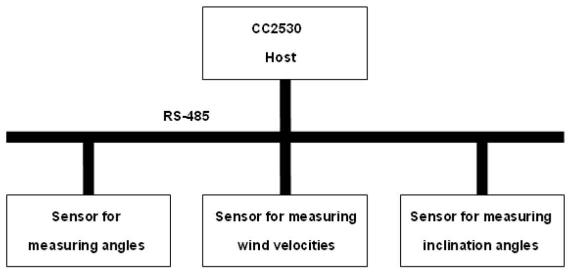


Fig. 4. RS-485 networking.

After receiving the data requests, the sensors (slave) with the right ID send the 6-byte data (AAH, BBH, IDH, DDH, DDH, DDH) to the bus immediately. The first three bytes are identical to those of the master's command, and the last three bytes are the returned data.

In addition, the height of the hook is measured using the MS5611-01BA sensor which is installed on the hook as a separate ZigBee sensor node.

4. Design of the System Software

4.1. Computation of the Distance and Location in the 3D Space

The identification of the distance that poses the risks of crane collision is a precise 3D positioning technique. The procedures for positioning include spatial modelling, compensation for computed distance, and position locating.

Spatial modelling forms the foundation for spatial locating. Making the models based on needs is essential to the accuracy of spatial positioning. The space rectangular coordinate system is developed first, and the model for special positioning is shown in Fig. 5.

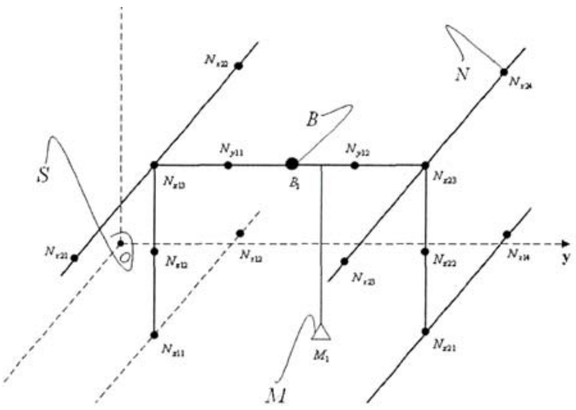


Fig. 5. The Model for special positioning.

The B in Fig. 3 denotes a standard reference node. N_{xmn}, N_{ymn}, N_{zmn} are the 3D reference coordinates of the node *mn*. The reference points are distributed along the coordinate axis. *M* represents the unknown nodes. Nodes are distributed in different directions for ease of node management. $\{N_{x11}, N_{x12}, N_{x13}\}$, $\{N_{y11}, N_{y12}, N_{y13}\}$ and $\{N_{z11}, N_{z12}, N_{z13}\}$ represent the nodes in the coordinate axes of *x*, *y*, *z*, respectively. The sets of the coordinates are represented by L_{x1}, L_{y1}, L_{z1}. In the sets of coordinates of this paper, each coordinate system distributes a collection of nodes which are parallel to each other. For example, the set in the *x* axis can be represented by $\{L_{x1}, L_{x2}, L_{x3}, \cdots, L_{xn},\}, n \in \mathbb{N}^*$. For any node *M* that moves freely in the space *S*, it can be mapped to the line formed by the nodes of a certain axis. The mapped value of the node's coordinates in this direction can be obtained in this way. A set of components $X=\{x_1,x_2,x_3,\cdots x_n\}$ is obtained after the component x_i at each axis is mapped. The components of coordinates are computed by averaging values. The 3D coordinate of the point, $p=\{x,y,z\}$, is obtained after three coordinates are processed as above. The crane's positioning accuracy is largely dependent on the accuracy of the distance measurement for spatial positioning. In this work, based on real-time network analysis, the positioning accuracy of the node is compensated using the comparison method. Each reference node has a sensor of its own to buffer the private communication data. Then, a correspondence is established between the measured distance and the reference node's information. This relates the distance measurement of the nodes to the communication information of all nodes in the space. For the reference node B, it stores the communication information of all nodes in S that arrive at it, which is denoted by D_{cal}. The actual distance is:

$$D_{real}(i,j)=\sqrt{(x_i-x_j)^2+(y_i-y_j)^2+(z_i-z_j)^2} \qquad (1)$$

On this basis, the model for compensating the actual distance of the actual measuring point is computed. After the node starts the positioning procedures, the reference point buffers the communication information of the actual nodes. In this case, the reference point I_{ref}(i, j) begins to produce the model. The functional relation that has D_{cal} as the independent variable and $\triangle D_{ij}$ as the dependent variable is presented as follows:

$$y = \Delta D = f(D_{cal}) \qquad (2)$$

By performing curve fitting on the relation above, the environmental models of each node are obtained to compensate for measurements. All anchor nodes exchange their data first after special modelling in order to produce the data model that can represent environmental characteristics. Then, the moving unknown node computes the location of the reference point and makes compensation. Finally, the unknown node obtains the location. The procedures for computing the distance and location in the 3D space are shown in Fig. 6.

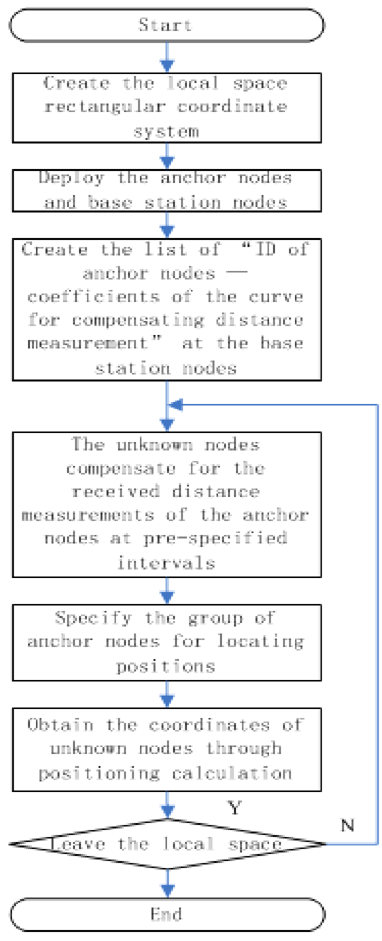


Fig. 6. Procedures for computing the spatial locations.

Three groups of all nodes in the set P along the directions of *x,y,z* can be computed based on the coordinate values. The set of points that can form a line along a certain coordinate can be expressed as $A=\{\{N_{a1b1}, N_{a1b2} ..., N_{a_1bm}\}, \{N_{a_2b_1}, N_{a_2b_2} ... N_{a2bn}\}...\}$. By computing the nodes above, three *Group* sets are obtained: *Group* (*x*), *Group* (*y*), *Group* (*z*). The finally obtained distance measurements of the reference node's coordinates are *c1*, *c2*. Coordinates of unknown nodes can be mapped to the line of both reference nodes, and the coordinate components are:

$$p = \frac{c_1^2 - c_2^2}{2(p_1 - p_2)} + \frac{p_1 + p_2}{2} \quad (3)$$

The distance of the node is finally achieved after the three coordinate components are computed as above.

4.2. ZigBee Software Design

The creation and operation of the ZigBee network is critical to the entire WSN system, data reliability, and system stability. The system's working flows are shown in Fig. 7.

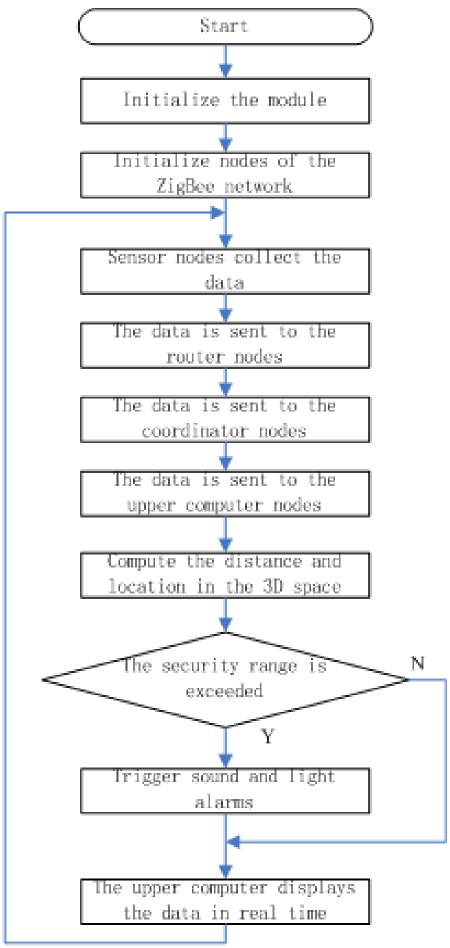


Fig. 7. The system's working flows.

After it is powered, it first initializes the hardware and network. CC2530 uses the ZigBee2007 protocol stack, whose initialization can be accomplished by Z-Stack from TI. Z-Stack is a hub polling operating system and provides most functions, including the initialization of hardware and network. The ZigBee network is established by the binding of coordinators with other sub-nodes (router nodes, terminal nodes). First, the network is created by the coordinator via the network layer function NLME_Network FormationRequest(). And, the function zb_Allow Bind() is used to enter the mode that allows binding. After the sub-node sends the request for binding, zb_BindDevice(), the coordinator creates the binding table in response. If the binding succeeds, it means that the communication is established. The same steps are followed when other nodes are added to the network, and the binding table should be updated continuously. In the binding table are the node's 16-bit network address, 64-bit IEEE address and the port number. The network address can be used for router and data transmission. The IEEE address is the unique identification of the node. The creation of the ZigBee network is presented in Fig. 8.

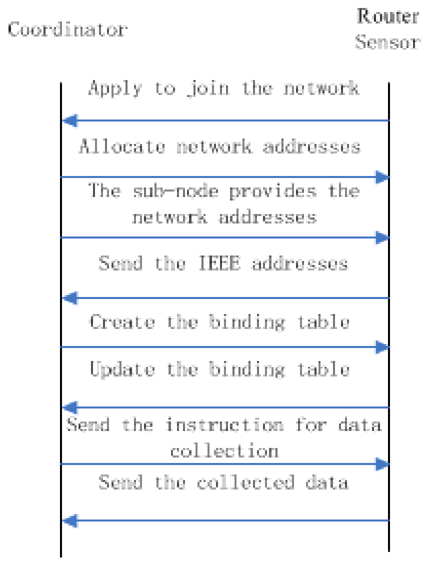


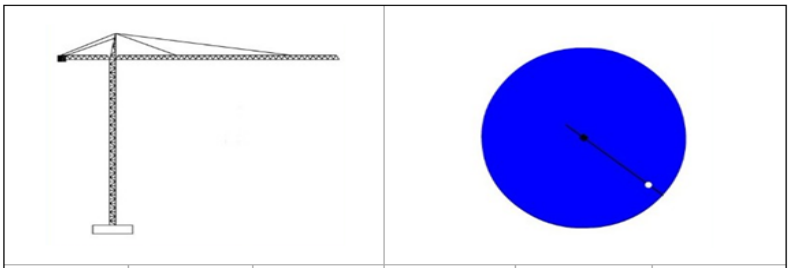
Fig. 8. The creation of the ZigBee network.

After the system is initialized, the sensor nodes begin to collect data, which is then aggregated at the coordinator via the router nodes and sent to the upper computer for real-time display. The positions of the cranes are located and compared using the 3D positioning technique, and the sound and light alarms are triggered if necessary.

5. Test of the Proposed System

5.1. Parameter Settings of the Experimental System

The parameters of the experimental system are shown in Fig. 9.

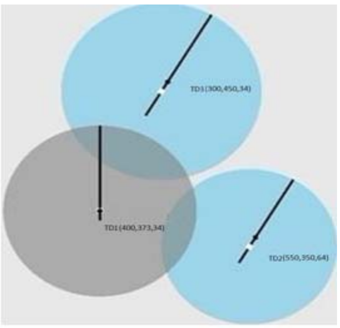


Distance that the hanger covers	Height of the hook	Swivel angle	Operating state	Reasons for Warning	Serial number of the cranes
36.8 m	4 m	129.4 °	Normal	Normal	3
Update time		Weight of the object	Wind velocity	Inclination angle	Serial number of the construction sites
2013-3-26 09 :20:36		0 t	0 m/s	0 °	GD0008

Fig. 9. Parameter settings for system tests.

5.2. Analysis of Experimental Results

In order to better test and correct the performance of the proposed system, three cranes are tested at different heights and in different environments. Data collection errors and alarm errors are measured. Experimental results are shown in Fig. 10.



Distance that the banger covers	23.1 m	Update time	2013-3-26 10:31:51
Height of the hook	22.6 m	Weight of the object	3.25 t
Swivel angle	241.2°	Wind velocity	2.7 m/s
Operating state	Normal	Inclination angle	72.4°
Reasons for Warning	Normal	Serial number of the construction sites	GD0008
Serial number of the cranes	3		

Fig. 10. Experimental results.

6. Conclusions

A method based on the 3D positioning technique is presented to avoid collisions among tower cranes that are close to one another while they are operating for large construction projects. The data sensors located at different places collect data, which is sent to the control center of the upper computer via WSN. The 3D positioning technique is then used to mathematically process the sensor information. The anti-collision alarm is sent set off or not based on the accurate mathematic model, preventing human misjudgment due to visual errors. The ground-truth tests show that the proposed system has an accuracy of 99.3 % and is highly applicable.

References

[1]. Xibo Lu, Yufeng Yin, Wireless Remote Monitoring System of Tower Crane Based on Internet of Things Technology, *Journal of Taiyuan University of Science and Technology*, Vol. 5, Issue 1, 2002, pp. 362-366.

[2]. Xu Shufang, Wang Jinha, Research and design of intelligent home control system based on ZigBee, *Application of Electronic Technique*, Vol. 5, Issue 2, 2012, pp. 80-83.

[3]. Shi Fanrong, Huang Yuqing, Ren Zhenwen, The multi-sensor Internet of Things wireless monitor system based on ZigBee, *Application of Electronic Technique*, Vol. 3, Issue 13, 2013, pp. 96-99.