Safety Monitoring of Construction Equipment based on Multi-sensor Technology

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Abstract –

The growth in the size and the level of complexity of construction equipment imposes tremendous hazards in construction sites. Any breakdown or failure of such systems may not only cause the delay in construction but also lead to the loss of life and properties. To address these issues, this paper proposes an intelligent monitoring system based on multi-sensor technology, which consists of multiple sensor clusters, signal transmission and data acquisition systems, condition evaluation, identification and alerting systems, assisted by Wifi or Zigbee wireless transmission technology to obtain the real-time state data from various parts of construction equipment. The center computer can manage and analyze the relevant parameters to reveal the safety reserve of the tower crane, scaffolds, self-climbing platform and other construction equipment in a visual image. In addition, the alerting alerts can be sent directly to security officers and operators to respond to and avoid accidents. Lastly, the intelligent multi-sensor monitoring system is simulated tested in 6013 flat crane, which is shown the workflow of whole technology and demonstrates this technology is fast, accurate and valid for the safety management of construction.

Keywords –

Construction equipment; High-rise buildings; Intelligent safety monitoring system; Multi-sensor technology.

1 Introduction

Because of the high casualty rate, site safety is one of the most concerned issues in the construction industry. Statistics data from Ministry of Construction suggests that, in china, there have been 637 safety accidents and 736 deaths in the first ten months of 2018, with 6.52% and 4.69% increased, respectively, compared to 2017.

Although the construction technology is constantly updated and upgraded, the management of construction site safety still primarily relies on the manual approaches, such as the daily patrol and regular inspections by the safety officers. With the gradual introduction of Industry 4.0 technology[1] into the construction industry, some construction robots and large-scale integrated construction platforms have emerged[2], which enhance the size and the level of complexity of construction equipment. Traditional safety monitoring methods may not be applicable to such complex construction environments and many unexpected causes of risks may render faults or failure, even with the tight security control measures[3]. For instance, the long-term environmental exposition, the inappropriate use and maintenance, the installation tolerances and their growth may all give rise to the unpredictable risks, which may eventually cause the bucking or collapse of scaffolds and the toppling of the tower cranes.

This safety matter is especially challenging in the construction industry and requires intelligent methods to monitor the stiffness, strength and stability of these complex construction equipment and temporary structures, such as scaffolds, in order to eliminate potential hazards. Literature review suggests that a wide range of studies have looked at the intelligent monitoring system or technology used for construction sites. Moon[4] studied an automated data acquisition system and appliance based on the Ubiquitous Sensor Network (USN) technology to collect structural responses. Zhu and Roh[5-6] introduced a method based on multi-sensors, visualization technology and computer vision technology for updating 3D equipment movements in order to prevent the collision between equipment, workers and other objects on the construction site. Son[7] proposes an efficient, automated 3D structural component recognition and modeling method that employs color and 3D data acquired from a stereo vision system for use in construction progress monitoring.

To address these issues, this paper proposes an intelligent monitoring system based on multi-sensor technology, consisting of multiple sensor clusters, signal transmission and data management systems, condition evaluation, identification and alerting systems. Assisted by Wifi or Zigbee wireless transmission technology[8], the structural parameters of key parts of construction equipment are received by the central server, which are used to monitor the working status of equipment structure in the real time. For instance, taking the data from the wind speed meter to measure wind velocity, inclination and displacement sensors to monitor deformation and movements, strain sensors to capture the stress/strain conditions and accelerometers to understand the dynamic properties, the data processing center can collect and analyze the relevant parameters to reveal the safety reserve of the tower crane, scaffolds, self-climbing platform and other construction equipment.

Safety monitoring of construction equipment technology is an intelligent and automated technology that the original data collected by multiple sensor clusters are automatically processed and converted to structural parameters in accordance with a predetermined programme and the damage degree of the equipment is shown by visualization. This paper mainly introduces the working principle and integration mechanism of systems, with the key focus on how to integrate, transmit and process data in each system.

2 Safety monitoring system

The intelligent monitoring system can automatically transform the original data collected by multiple sensors and feed to the evaluation modules[9] revealing and monitoring the structural health state of construction equipment in real time seen in Figure 1. The process entails the following steps: 1) data collection and acquisition by utilizing different types of sensors or multiple sensor clusters; 2) data analysis and modelling; 3) damage identification and health evaluation. The final step can be revealed by visual representation together with some alerting systems[10].

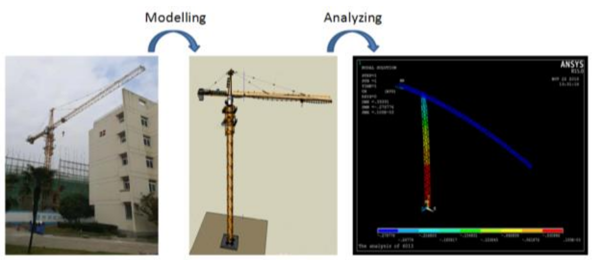

Figure 1. Data-driven modelling of tower cranes

The above process can be presented in the workflow as shown in Figure 2, which can be generally divided into four subsystems, namely multiple sensor clusters, signal transmission and data management subsystems, condition evaluation and identification an alerting subsystem. The data from various sensors, often in differing formats and output signals, are integrated so that the data, resources and process states can be shared across the system. Pre-alerting of impeding faults or failure of those construction equipment structures can be alerted. The key of this type of system is the stability and timeliness of wireless transmission[11] and the optimization of data processing[12]. The massive data will be accumulated in the data center and the big data analysis technology can be employed so that the minimal size of them should be stored and feed into the structural modelling.

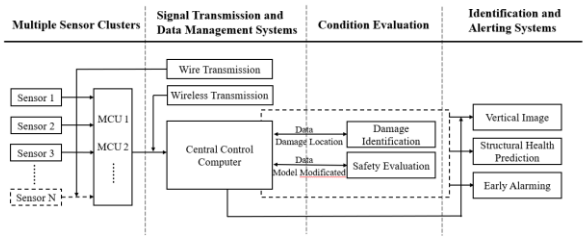

Figure 2. Workflow of safety monitoring system

2.1 Multiple sensor clusters

Multiple sensor clusters are the first tier in the intelligent monitoring system[13]. The common sensors used include the wind speed sensor to measure wind velocity, inclination and displacement sensor to record the movements, strain sensor to acquire the strain condition and accelerators to capture the dynamic properties. The locations of sensors are properly designed and selected, so are the acquisition frequencies.

In order to reduce the amount of data for transmission and storage, the initial processing of the original data is required so that the unimportant or redundant data are filtered out in the first instance. Kalman filter is usually used to preprocess the original data, which is an algorithm to extract the real value of the dynamic system in a series of measure data with noise. And then, feature selection of the initial preprocessed array is carried out to manifest the principal and precise characteristics in one set period. Common feature extraction methods are principal component analysis (PCA), linear singular analysis (LDA)[14], independent component analysis (ICA)[15], neural network, etc. The method of feature selection is properly selected on the basis of structural characteristics and monitoring requirements. In general, the application of feature selection is beneficial to reduce the amount of calculation and improve the accuracy of structural analysis in the process of condition evaluation.

In the collection process, it is assumed that cycle of the sensor data collection is 2s and the cycle of central computer operation is 30s. So, within 30 seconds, the sensor-1 will gain 15 pieces of data: $[X]_1 = [X_1, X_2, X_3, \dots, X_{15}]$. Before feature selection, simple preprocessing should be carried out on the original data to delete the data with large errors. In the end, the eigenvalue X_1 will be calculated by single-chip microcomputer (MCU) and transmitted to the central control computer.

2.2 Signal transmission and data management systems

Signal and data transmission can be regarded as the logistics support for the whole system[16]. Only with stable transmission technology can the whole system be sampled synchronously and the structural data of each part at the same time point can be obtained. Otherwise, if data in different cycles arrive at the central computer and be processed simultaneously, it will yield data chaos[17].

In this present system, there are two transmission modes, wired transmission and wireless transmission. Wired transmission is used to transmit data from sensors to microcomputers, which is the front-end data transmission of the whole system. Due to the space limitation of wired transmission, the locations of both sensors and microcomputers need to be considered and a single-chip microcomputer (MCU) can process data up to 8 sensors at the same time. Wireless transmission, such as Wifi or Zigbee wireless transmission technology, transfers the data preprocessed from MCU to the central computer for the further data analysis. In the construction environment, due to the signal reception blocking of the concrete or metal, the wireless transmission signal is usually weak. In order to establish a wireless network for real-time data acquisition, the system uses ZigBee technology to receive data by using radio frequency (RF) signal transmission, which can connect up to 65,000 sensor nodes and transmit data at 250 kbps[18].

Data collection from multiple sensors is usually synchronized. In the real applications, such synchronization can be compromised due the delay in the data transmission (see Figure 3). To address this problem, step by step filtering (SSF) fusion algorithm is adopted. Compared with centralized fusion algorithm (CFA), SSF (see Figure 4) has fewer requirements for calculation efforts and the number of central processors and network bandwidth, but stronger system survivability[19-20].

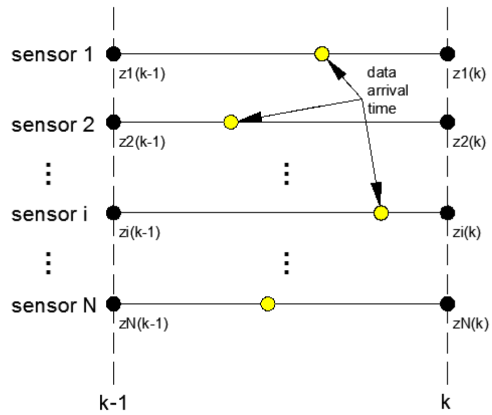

Figure 3. Simultaneous sampling with transmission delay[17]

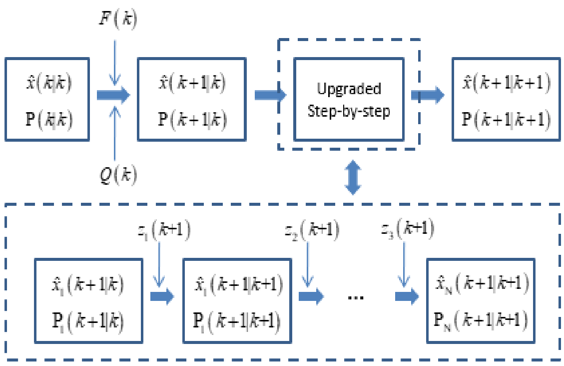

Figure 4. SSF Fusion Algorithms[20]

Table 1. Definition of mathematical expression

No.	Mathematical Expressions	Definition
1	k	A certain moment
2	$k+1$	The moment of one cycle after k moment
3	$x(k)$	State function
4	$x(k+1)$	State function in k+1 moment. $x(k+1) = F(x)x(k) + v(k)$
5	$\hat{x}(k\|k)$	The global estimated value
6	$\hat{x}(k+1\|k+1)$	The global information-based estimated value
7	$P(k\|k)$	The corresponding estimated error covariance
8	$P(k+1\|k+1)$	The corresponding error covariance
9	$z_1^k(i)$	The set of measurement sequences of the i-th (i =1,2, ⋯ ,N) sensor at

		1,2, ⋯ ,k moments. $Z_1^k(i) = [z_i(1)^T, z_i(1)^T, \ldots, z_i(k)^T]$
10	Z_1^k	The set of measurement sequences of all N sensor at time 1,2,⋯,k moments.$Z_1^k = [Z_1^k(1), Z_2^k(2), \ldots, Z_2^k(k)\ ]$
11	$F(k)$	Distribution function of X,X is random variable and k is any real. $F(k) = P\ (x < k)$
12	$Q(k)$	Covariance function. $Q(k) = E[v(k)v(k)^T]$
13	$v(k)$	White noise sequence of zero mean gauss process

In the actual monitoring process, due to the instability of data transmission, it is difficult to ensure that all sensor data can reach the computing platform synchronously. To solve this problem, the database store method is adopted. If a value X_n fails to reach the computing platform synchronously, the X_{n-1} of the previous array is retrieved. And if the value fails to reach the computing platform for three processing cycles, the warning system would started to report the error.

The subsystem involves both hardware and software. The hardware includes transmission cables, optical cables, RF transmitters, RF receivers, digital-to-analog conversion cards (A/D), etc. The software is used to store and manage the digital signals, using a common software platform such as C++.

In a real-time monitoring system, even in the case of data pre-processing, there are thousands of data collected every day, which requires a robust data management system and program. The data management system is not only responsible for managing the preprocessed data, but also managing all information in each subsystem, including materials, geometric information, and structural analysis results of devices. Should any accident strike, this type of data can be traced for the forensic analysis purpose.

2.3 Condition Evaluation

In this subsystem, the structural software is used to model the system based on the collected real-time data so that the health condition of the equipment can be assessed.

To this end, the first step is to transform the preprocessed data from multi-sensors clusters into physical data [Vm], such as strain or movements, and then check with the specified threshold value [Vd] to identify the any damages. If there's a big difference between the value [Vm] and value [Vd], the structure must be secure and there is no point to expand extra unnecessary computations. Once any damage is identified, a reliability analysis can be conducted to evaluate the severity of damage, based on which due alerting is released for the management purpose.

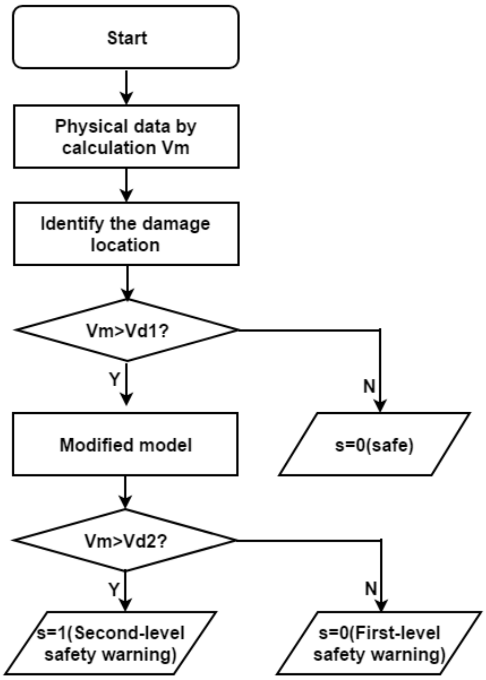

Figure 5. Workflow of condition evaluation

1. Safety assessment

Safety assessment consists of serviceability limit state assessment and ultimate limit states assessment. The evaluation indicators of serviceability limit state are the deformation of structure, cracking growth acceleration, etc. And the ultimate limit states can be assessed by structural analysis software. The simplest method of evaluation is to analyze the development trends shown by the measured stress, deflection, acceleration and other indicators.

2. Damage identification

At present, an increasing number of damage identification methods have been applied in engineering projects, such as structural modal parameter identification based on wavelet transform[21], damage sensitivity analysis based on structural modal parameters[22], structural damage detection based on neural network, structural damage detection based on improved genetic algorithm[23], etc. These methods mainly perform modal analysis of structural dynamic response, and then calculate the damage indicators with different damage identification methods.

2.4 Identification and alerting systems

Through data processing and mining, the system will eventually be able to obtain real-time visualized structural health monitoring images, structural health predictions and early warnings.

1. Visual monitoring image

The final structural health state can be showed by a visual image. Construction workers and manager can quickly and accurately monitor the structural health status of the equipment remotely, and then find problems in time and take measures.

2. Structural health predictions

Through sufficient data mining, state estimation and prediction of the structural state of the construction equipment can be performed. A large amount of data collected and the simulated force model can be used to detect the weak places of the equipment structure for focal monitoring. the weak points can be predicted by well-rounded algorithm, including linear regression method, nonlinear model method, unsupervised supervised learning method and other methods, so as to prevent risks in advance.

3. Early warming

The identified damages with its location and size are systemized for formulating the alerting information, which can be circulated via mobile electronically devices or other type overall alerting system. Due measures can be taken to respond to such alerting information.

3 Case Study

The intelligent monitoring system is employed for the real-time supervision of the construction equipment and temporary structures used in the construction site. Four subsystems are instrumented to collect, transmit and process the data. A visualization program is to reveal the data and work status of the monitored systems.

The system is mounted into a tower crane, which is presented below to show the entire process of coordinated work and data processing of each subsystem. In the simulated test, 6013-flat-head tower crane is selected as the experimental tower crane with 800KN*m load moment, 46 meters maximum free height, 60 meters maximum radius of revolution and lifting 6 tons materials at most

According to the specifications for tower crane design, there are five key performance indicators for the overall structure safety operation, namely, temperature $[T]$, the bending strength $[\sigma_1]$ and deflection $[v_1]$ of crane jib, the vibrational frequency $[f]$,the deformation of crane column$[v_2]$. For each indicator, one or more sensors are placed to obtain the corresponding structural parameters directly or indirectly. By data fusion, calculation and estimation, the large amount of original data are processed to the structural parameters to realize the visual monitoring of the loading state of the tower crane.

It is worth noting that the working stress of crane tower is constantly changing due to the moving load during the lifting operation. Under different loading scenarios, the maximum stress points change, and, therefore, the sensors need to be placed in some crucial places. According to the "Tower crane design specification (GBT 13752-2017)", the layout of the sensors should follow the following principles:

a) The places with significant stress changes or large stress, which can be calculated by the finite element analysis;

b) Important component of the structure, such as structural cross-middle rod parts and suspension rod parts, etc;

c) Representative and regular places, such as fatigue-prone and corrosion-prone positions, etc.

3.1 Multiple sensor clusters

In this simulated case, five types of sensors are mounted in selected locations, i.e. temperature sensors, wind speed sensors, accelerometers, displacement and strain sensors. Ten sensors were placed in the simulated experiment (shown in Figure 6)and the original data obtained were named as $[A_1]$, $[A_2]$, $[B]$, $[C]$, $[D_1]$, $[D_2]$, $[D_3]$, $[E_1]$, $[E_2]$, $[E_3]$, $[F_1]$, $[F_2]$, $[F_3]$, $[F_4]$, as shown in Table. Among them, the displacement sensor consists of a transmitter and a receiver. It can simultaneously collect the displacement in X, Y, Z directions, and the data are all collected by the receiver.

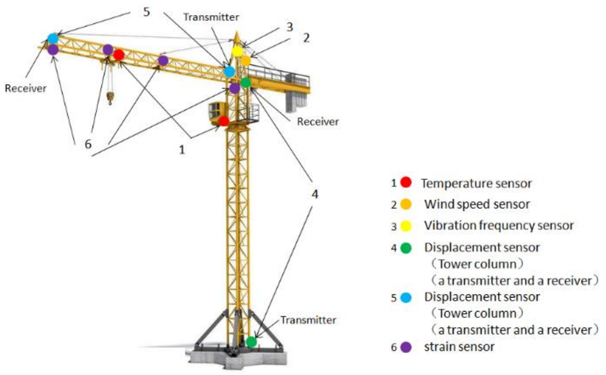

Figure 6. Diagram of the location of multiple sensor clusters

Table 2. Types of sensors and corresponding dataset

No	Sensors	Data Set	Note
1	Temperature sensor	$[A_1]$, $[A_2]$	Environment temperature $[A_1]$ and engine

			temperature $[A_2]$
2	Wind speed sensor	$[B]$	Wind velocity
3	Accelerometers	$[C]$	
4	Displacement sensor（Tower column）	$[D_1]$-X Direction $[D_2]$-Y Direction $[D_3]$-Z Direction	A transmitter and a receiver
5	Displacement sensor（Tower jib）	$[E_1]$-X Direction $[E_2]$-Y Direction $[E_3]$-Z Direction	A transmitter and a receiver
6	Strain sensor	$[F_1], [F_2], [F_3], [F_4]$	Key position

3.2 Signal transmission and data management systems

Through wired transmission, the original data will be transmitted to MCU for initial processing, and then the mathematical sets$[A_1]$, $[A_2]$, $[B]$, ⋯, $[F_4]$ acquired by multiple sensor clusters will gain the corresponding values A_{1i}, A_{2i} , B_i ⋯, F_{4i}.Since the wired transmission is limited by space, an MCU connected up to 8 sensors is to process data at the same time. In installing MCU, the quantity and locations of MCU shall be determined by the relationship between the sensor clusters and MCU.

In this case, three single-chip microcomputers are placed in the tower crane (Figure 7). The first one is on the top of tower column, which is used to collect the engine temperature $[A_2]$, the displacement of tower column $[D_1]$, $[D_2]$, $[D_3]$, the stain of tower column $[F_1]$; the second one is at the junction of tower column and jib, which is used to collect wind velocity $[B]$, vibration frequency $[C]$ and stain of tower jib $[F_2]$; the third one is at the end of tower jib, which is used to collect the environment temperature $[A_2]$, the displacement $[E_1]$, $[E_2]$, $[E_3]$ and the stain of tower jib $[F_3]$, $[F_4]$.

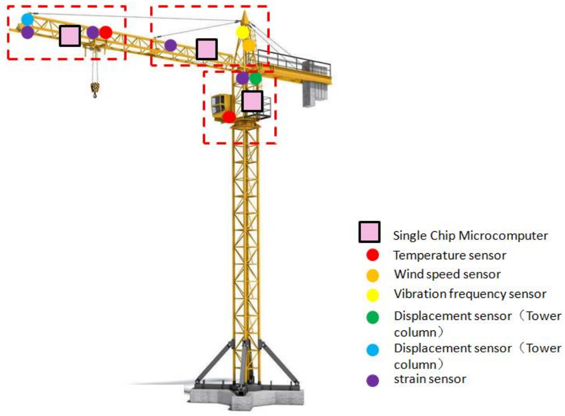

Figure 7. Diagram of the location of MCU

The preprocessed data (A_{1i}, A_{2i} , B_i ⋯, F_{4i}.) are transmitted wirelessly to the central control computer, using the robust and fast wireless transmission technology, Zigbee. The central control computers not only are responsible for data processing, but also for date management and storage. Date management subsystem is responsible for storing the pre-processed data, the modelled structural parameters, and the structural images at certain intervals, which is used for continuous system inspection and identification and analyzing the cause of failure if the tower crane collapses.

3.3 Risk assessment

The obtained values are analyzed by using MATLAB software to determine the presence, the location and size estimation of damages. Furthermore, the safety evaluation can be conducted and reported.

3.4 Identification and alerting systems

ANSYS software is used to simulate the component response of tower crane based on the collected data. The displacement of x-component, y-component and z-component, the rotation of x-component, y-component and z-component, elastic strain and plastic strain can be calculated for the entire structure (Fig. 8).

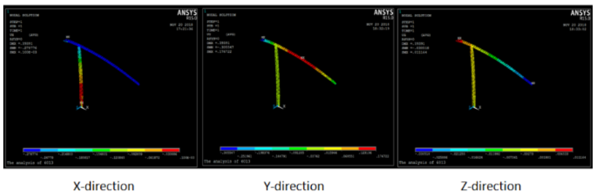

Figure 8. Diagram of modelled deformation

4 Conclusion

The safety monitoring system can intelligently monitor the working status of construction equipment in real time, establish visual model for the strength and deflection of the entire structure, and inform the safety state of construction site in the visualized way. By means of data collection of sensors and step-by-step processing of computers, security officers can obtain real-time structural state of construction equipment or temporary structures to avoid accidents, especially in severe environment. Such system possesses the following features:

1. **Fully automation.** Except installation and regular system inspections, the system can archive data collection, multi-software interactive data processing, and identification of the location and size of damage, visual representation and producing alerting messages to the related personnel.
2. **High timeliness**. The sensor collects data in the real time, and the data is processed by program in automatic way, so the final structural state can be obtained in a nearly synchronized manner.
3. **Visualization.** The displacement and stress of the structure can be visualized.
4. **Other applications**. A large number of environmental and structural parameters collected in the data management subsystem can provide detailed experimental data for equipment structural design, from which the correlation relationship between the environmental action and vibration frequency can be established.

The safety monitor system can replace the traditional methods of maintaining construction equipment, such as tower crane, which provides improved accuracy and enhanced safety level.

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