GNSS-Based High-Precision Fixed-Point and Lofting of Hoisting Operation for Construction Tower Crane

Mingduan Zhou, Zhengyang Lu, Jiaxing Wang, Chengsi Zhao, and Yuan Zhao

***Abstract*—GNSS receiver is one of novel sensors applied to accurate management and control technology for the construction tower crane. Since the low-precision of m-level navigation application based on GNSS pseudo-range observations, it is insatiable to develop requirements of intelligent command for the construction tower crane. To improve the monitoring accuracy for construction tower crane based on GNSS method, a high-precision monitoring approach applied to fixed-point and lofting of hoisting operation by GNSS carrier phase observations is proposed. It is applied to the intelligent command of hoisting operation for the construction tower crane, and a set of GNSS-based fixed-point and lofting of hoisting operation system, named as GNSS_PLS, is designed and developed. The experimental results show that, for 6 minutes (360 epochs) of the monitor station installed on the top of the construction tower crane, the minimum error of North-RMS is 0.009m, the maximum error of North-RMS is 0.015m and the average error of North-RMS is 0.013m; the minimum error of East-RMS is 0.008m, the maximum error of East-RMS is 0.014m and the average value of East-RMS is 0.011m; the minimum error of Up-RMS is 0.021m, the maximum error of Up-RMS is 0.036m and the average value of Up-RMS is 0.030m. The monitoring accuracy of intelligent command of the GNSS_PLS system is obtained to cm-level and the effectiveness and feasibility of the proposed solutions are verified.**

***Index Terms*—Global satellite navigation system, fixed-point, lofting, hoisting operation, intelligent command.**

I. Introduction

The construction tower crane is an indispensable lifting type of equipment for large-scale construction engineering. Since the characteristics of variable amplitude, tower height, lifting weight, square circle, and high efficiency, they have been widely applied in modern assembly constructions [1]. It needs to be installed in narrow construction sites with high-density, heavy-intensity, heavy-load bearing and full square circle. It is a kind of lifting equipments with high-probability of safety accidents [2], [3]. To meet the safety requirements of hoisting operation for the construction tower crane, safety monitoring and early warning have become an important means and research hotspot to ensure the reliable hoisting operation for the construction tower crane in recent years [4], [5]. With the rise of super or high-rise buildings or structures engineering, the construction tower crane is developed toward large-scale and intelligent directions. Therefore, it will put forward higher requirements for GNSS-based high-precision monitoring of safety guarantee of monitor points and operation states for the construction tower cane [6].

GNSS receiver is one of the important novel sensors for state safety monitoring and warning of construction tower crane. The low-accuracy positioning of the monitor point based on GNSS pseudo-range observations will not meet the development requirements of intelligent command of construction tower crane. However, the precise positioning of the monitor point is one of the key techniques in the establishment of safety state monitoring and early warning applied to accurate management and control system for the construction tower crane [7], [8]. Besides, the GNSS-based method has innate unique advantages [9]. Therefore, In the light of the complex working environment of state safety monitoring and early warning for construction tower crane, to further improve the monitoring accuracy and the reliability of construction tower crane, a high-precision monitoring solution of construction tower crane based on GNSS carrier phase observations is discussed, which is applied to fixed-point and lofting of hoisting operation for construction tower crane, and the corresponding function modules are designed and developed. The proposed solutions are adapted to the development needs of intelligent command the construction tower crane, and improve the modern level of intelligent safety management of tower cranes, which part an important role in promoting the construction tower crane.

This paper is divided into five sections. The first section is the “Introduction”. In “GNSS method of precision fixed-point and lofting” section, the four-step procedure of the GNSS method is described. In “GNSS-based fixed-point and lofting system” section. The designed and developed system is discussed. In “Experimental testing and result analysis” section, the monitoring accuracy in a real engineering testing is analyzed. Finally, “Conclusion” section draws the conclusions.

II. GNSS Method of Precision Fixed-Point and Lofting

A precise monitoring method based on GNSS carrier phase observations is proposed in this paper, which is applied to precision fixed-point and lofting of hoisting operation for the construction tower crane. The flowchart of the method is shown in Fig. 1, and the four-step of the method is listed in detail as follows.

Step S1: According to the observations of navigation satellite collected by the GNSS monitor station itself and the comprehensive error correction signal transmitted by the GNSS base station on the ground through the communication chain of data after differential processing between navigation satellites, the centimeter results of 3D-coordinates of the

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phase center of the antenna of the GNSS monitor station are carried out. The positioning principle of this step is shown in the references [9], [10].

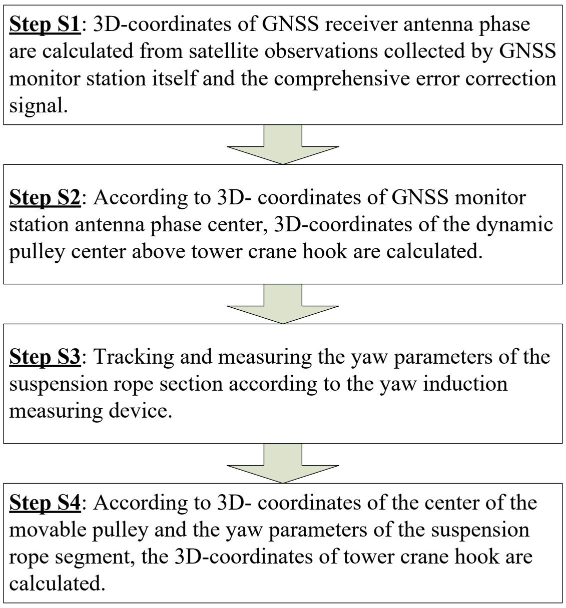

Fig. 1. Flowchart of the GNSS method.

Step S2: According to the cm-level of 3D-coordinates of the antenna phase center of the GNSS monitor station, the 3D-coordinates of the movable pulley center above the hook of tower cranes are calculated. The calculation formula of the 3D-coordinates of the movable pulley center is listed in equation (1).

$$\begin{cases} X = X_G + X_N \\ Y = Y_G + Y_E \\ H = H_G + H_U + f(\alpha_1, A) - H_1 - r \end{cases} \quad (1)$$

where (X, Y, H) is the 3D-coordinates of the center of the movable pulley, (X_G, Y_G, H_G) is the 3D-coordinates of the antenna phase center of the GNSS monitor station, (X_N, Y_E, H_U) is the deviation between the antenna phase center and the antenna geometric center of the GNSS monitor station. It is a grid antenna model provided by the Antenna Calibration Mechanism of GNSS receivers, which is calibrated according to the azimuth angle with every 5 degrees and altitude angle with every 5 degrees of navigation satellites respectively. Then the interpolation functions $f(\cdot)$ were carried out by bilinear interpolation algorithm with the actual azimuth angle α_1 and altitude angle A of navigation satellites [11]. H_1 is the vertical height from the antenna geometric center of the GNSS monitor station to the corresponding top of the center of the movable pulley, and r is the radius of the movable pulley.

Step S3: Setting up a pendulum induction measuring device on the sling section to track and measure the pendulum parameters of the sling section, and the device including a laser signal transmitter and a horizontal circular pendulum measurement unit, such as Indium Watt Bar Code Digital Horizontal Disk. The laser signal transmitter is arranged at a length calculated from the head of the suspension rope section, and the center of the horizontal circular yaw measuring unit is connected with the head of the suspension rope section. The horizontal circular yaw measuring unit is arranged at the bottom of the support frame. When the hook of tower cranes oscillates, the laser signal transmitter senses the swing of the suspension rope section, and the suspension is connected with the center of the horizontal circular yaw measuring unit. The horizontal circular yaw measuring unit transmits the laser signal vertically upward to the horizontal circular yaw measuring unit when the rope section swings. According to the laser signal, the horizontal circular yaw measuring unit transmits the calibration point such as S of the horizontal circular yaw measuring unit, and automatically meantime measures the horizontal yaw angle such as α and the horizontal yaw distance of the laser signal transmitter such as R . The process of laser signal received by the horizontal circular is shown in Fig. 2.

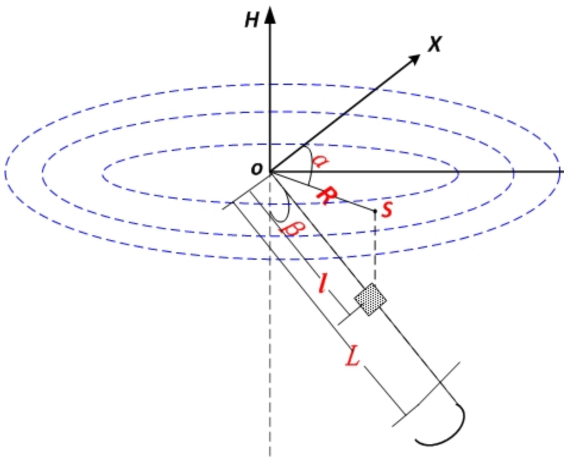

Fig. 2. Process of laser signal received by horizontal circular.

As shown in Fig. 2, the radius of the horizontal yaw measuring unit c , the length l , and the radius of the movable pulley r should satisfy the relationship as shown in equation (2).

$$c - l \cdot \sin\left(k \cdot \frac{\pi}{6} \cdot \frac{l}{L}\right) = 0, where\ c \le r \quad (2)$$

where, L is the length of the suspension rope section, and k is the safety factor of the suspension rope section, in generally k =0.7~1.0.

As shown in Fig. 2, it is judged whether the yaw angle of the suspension rope section exceeds the warning angle, and if so, an alarm signal for prompting the suspension of operation is issued. The equation for calculating the yaw angle of the suspension rope section and the early warning angle is shown in equation (3).

$$\begin{cases} \beta = \arcsin\left(\frac{R}{l}\right) \\ \chi = \arcsin\left(\frac{c}{l}\right) \end{cases} \quad (3)$$

where, R is the horizontal yaw distance of the laser signal transmitter, l is the length from the position of the laser signal transmitter to the end of the sling section, and c is the radius of the horizontal circular yaw measuring unit are used.

Step S4: According to the 3D-coordinates of the center of the movable pulley and the yaw parameters of the suspension rope segment, the 3D-coordinates of the tower crane hook are calculated. The calculation formula of the 3D-coordinates of the tower crane hook is shown in equation (4).

$$\begin{cases} X_g = X + L \cdot \cos\alpha \\ Y_g = Y + L \cdot \sin\alpha \\ H_g = H - r - H_2 - L \cdot \sqrt{1 - \left(\frac{R}{l}\right)^2} \end{cases} \tag{4}$$

where, (X_g, Y_g, H_g) is the 3D-coordinates of the tower crane hook, (X, Y, H) is the 3D-coordinates of the center of the moving pulley, L is the length of the sling section, l is the length from the position of the laser signal transmitter to the end of the sling section, r is the radius of movable pulley, H_2 is the vertical height from the bottom corresponding to the center of the movable pulley to the horizontal circular yaw measuring unit, α and R are the horizontal yaw angle and the horizontal yaw distance of the laser signal transmitter respectively.

III. GNSS-Based Fixed-Point and Lofting System

The GNSS-based fixed-point and lofting system for construction tower crane, named as the GNSS_PLS system, is one of the main functional modules of GNSS-based accurate management and control system for construction tower crane (GNSS_TCIAC) [10].

A. System Composition

The GNSS_PLS system includes six parts as follows.

1) GNSS base station

It is set in a wide-field view of the ground observation satellite to receive the GNSS signal and transmit the comprehensive error correction signal processed by the differential of satellites to GNSS monitor station through the data communication chain.

2) GNSS monitor station

The GNSS monitor station is comprised of a positioning device and a coordinate calculating device. The positioning device is used to collect the satellite observations, and the coordinate calculating device is used to calculate the 3D-coordinates of the antenna phase center of the GNSS monitor station.

3) Laser signal transmitter

It is arranged on the second suspension rope section for inducing the swing of the second suspension rope section and transmitting the laser signal vertically upward when the second suspension rope section swings.

4) Deflection measuring device

It is connected with the bottom of the tower crane support frame, and is used to receive laser signal and measure and calculate the deflection parameters of the laser signal transmitter according to the laser signal, and includes an indium watt bar code digital level plate connected to the bottom of the support frame, and the indium watt bar code digital level plate is composed of the laser signal. The laser signal is triggered and transmitted to the calibration point S of the indium watt bar code digital horizontal dial according to the laser signal, and the horizontal yaw angle alpha and the horizontal yaw distance of the laser signal transmitter are automatically measured.

5) Data processing device

The 3D-coordinates of the dynamic pulley center are calculated according to the 3D-coordinates of the antenna phase center of the GNSS monitor station, and the 3D-coordinates of the hook are calculated according to the 3D-coordinates of the dynamic pulley center and the yaw parameters of the laser signal transmitter.

6) Alarm device

It is a sound alarm device for sounding according to the alarm signal, and a light alarm device for flashing light according to the alarm signal.

B. Development IDEAS

For a tower crane, the development ideas of the GNSS_PLS system are shown in Fig. 3. From Fig. 3, the GNSS base station is erected in the open field-vision of the construction site. At the same time, a GNSS monitor station is installed on the top of the moving pulley directly below the tower arm mobile vehicle. The ground hoisters both of A and B hold an observation manual each other for the positioning of a high-precision GNSS monitor station. Three GNSS monitor stations receive the comprehensive error correction signals from the GNSS base station in real-time. It is forming a "1+3" GNSS RTK mode to achieve the cm-level high-precision monitoring function. When the tower crane is in working state, a hoister A uses a hoisting fixed-point handbook to locate the hook position accurately and obtains the hoisting fixed-point coordinates information, and sends the fixed-point coordinates information to the monitoring platform through the real-time communication server for recording and displaying, and then prompts and informs the driver of the tower crane the exact location of the hoisting hook. The monitoring platform calculates the fixed-point elements of the hoisting hook, and implements and completes the positioning-point hooking task of the hoisting object according to the fixed-point elements displayed on the monitoring platform. At the same time, a hoister B uses the hoisting lofting handbook to locate the location of the hoisting hook accurately, and obtains the hoisting lofting coordinates information, and sends the lofting coordinates information to the monitoring platform through the real-time communication server for recording and displaying, and then prompts and informs the driver of the tower crane for the exact location of the hoisting hook. The monitoring platform calculates the lofting elements of the hook, and carries out and completes the lofting and unloading tasks of the lifting and lofting objects according to the hoisting lofting elements displayed on the monitoring platform.

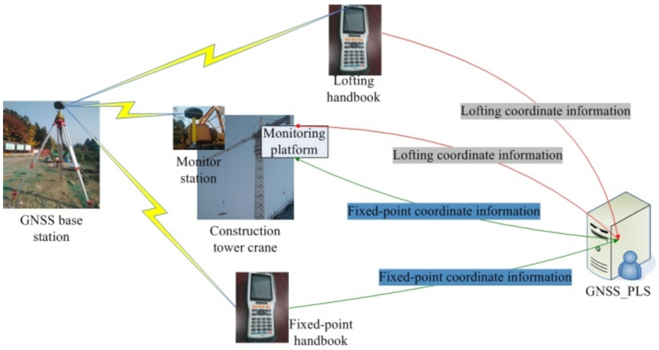

Fig. 3. Development ideas of the GNSS_PLS system.

C. The Elements Calculation of Fixed-Point and Lofting

The elements calculation method of hoisting fixed-point is similar to that of hoisting lofting [10]. Take the calculation method of hoisting fixed-point as an example. During the hoisting operation of construction tower crane, the elements of hoisting fixed-point are implemented in two steps.

1) Rough fixed-point work

It includes plane-distance elements between the tower crane hook real-time position (N,E,U) and fixed-point coordinates (N_P,E_P,U_P) of lifting the object, and vertical elevation difference elements between hook real-time position and fixed-point coordinates of lifting the object. The calculation formula is shown in equation (5).

$$\begin{cases} \Delta D = \sqrt{(N-N_P)^2+(E-E_P)^2} \\ \Delta H = U - U_P \end{cases} \tag{5}$$

2) Fine fixed-point work

It includes the transverse coordinate elements ΔE, the longitudinal coordinate elements ΔH, and the vertical elevation difference elements between the real-time position (N,E,U) of the hook and the fixed-point coordinates (N_P,E_P,U_P) of the lifting object. The calculation formula is shown in equation (6).

$$\begin{cases} \Delta E = E - E_P \\ \Delta N = N - N_P \\ \Delta H = U - U_P \end{cases} \tag{6}$$

The monitoring platform real-time displays the plane-distance element ΔD and the vertical elevation difference element ΔH of rough fixed-point work, and then the driver of the construction tower crane carries out the hoisting of the rough fixed-point work according to the plane distance element ΔD and the vertical elevation difference element ΔH. When the monitoring platform indicates that the plane-distance element ΔD of the rough fixed-point work is less than 1 meter, which would switch the display page of rough fixed-point element to the display page of the fine fixed-point element in real time. At this time, the monitoring platform real-time displays the east-coordinate element ΔE, the north-coordinate element ΔN and the vertical elevation difference element ΔH of the fine fixed-point work, and then the driver of the construction tower crane carries out the hoisting of fine fixed-point work according to the east-coordinate element ΔE, the north-coordinate element ΔN and the vertical elevation difference element ΔH.

D. System Implementation

The set of GNSS_PLS system is designed and implemented using the C# programming language of the VS2010 development platform based on GNSS high-precision single-epoch technology, which is using for carrying out the high-sampling rate (such as 1Hz) carrier phase observation data.

The main interface design view of the GNSS_PLS system is divided as two kinds, one is an interface design based on Baidu Map into shown in Fig. 4, and the other is an interface design based on human-computer interaction monitoring as shown in Fig. 5.

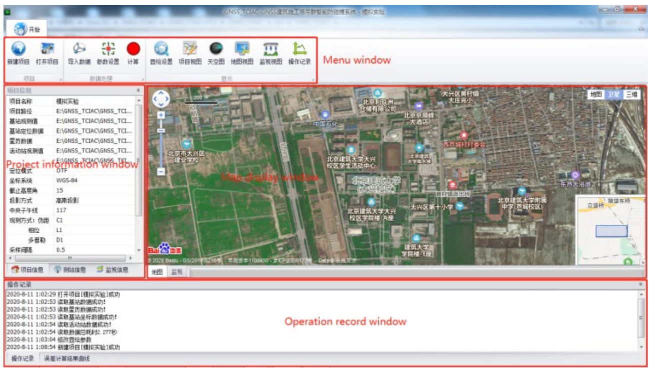

Fig. 4. Interface design based on Baidu Map.

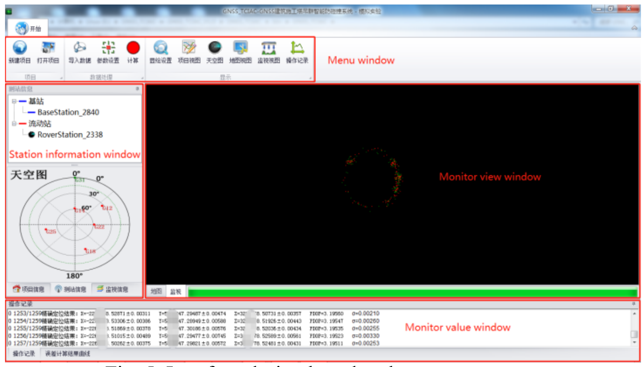

Fig. 5. Interface design based on human-computer.

IV. Experimental Testing and Result Analysis

To verified and analyze the effectiveness and the feasibility of intelligent command of GNSS_PLS system consists of fixed-point and lofting functions, the GNSS_PLS system is applied to the hoisting operation of the construction tower crane. A real engineering testing was carried out on a large tower crane served for the site protection construction project in Beijing. Fig. 6 shows that the tower crane is going on the process of hoisting operation. Fig. 7 shows the installation location of the base station and monitor station.

To analyze the accuracy of intelligent command of the GNSS_PLS system consists of fixed-point and lofting functions, the dataset of monitor-station with 6 minutes (360 epochs) form the GNSS_PLS system was used for the accuracy analysis, the RMS results as shown in Fig. 8.

Fig. 6. Hoisting operation.

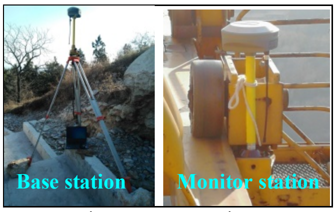

Fig. 7. GNSS station.

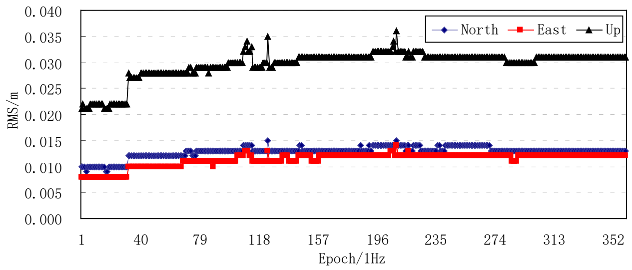

Fig. 8. RMS of the monitor station in North, East and Up directions.

In Fig. 8, for 360 epochs of the monitor-station, the minimum error of North-RMS is 0.009m, the maximum error of North-RMS is 0.015m and the average error of North-RMS is 0.013m; the minimum error of East-RMS is 0.008m, the maximum error of East-RMS is 0.014m and the average value of East-RMS is 0.011m; the minimum error of Up-RMS is 0.021m, the maximum error of Up-RMS is 0.036m and the average value of Up-RMS is 0.030m. The results of the numerical analysis show that the precision of the intelligent command of the GNSS_PLS system consists of fixed-point and lofting monitoring functions is cm-level. It shows that the solutions proposed can provide a high-precision real-time method for fixed-point and lofting of hoisting operation forthe construction tower crane.

V. Conclusion

In view of the application with complex-working environments of hoisting operation for construction tower crane, aim to improve the monitoring accuracy and the reliability of monitor points of the tower crane, a high-precision monitoring method based on GNSS carrier phase observations applied into fixed-point and lofting of hoisting operation for construction tower crane is proposed. The ideas and equations of high-precision monitoring solutions of hoisting operation are given in detail. C# programming language based on the VS2010 development platform is used for establishing function modules of the proposed solutions. A set of GNSS-based fixed-point and lofting system for construction tower crane, named as the GNSS_PLS system, is designed and developed. The effectiveness of intelligent command of the GNSS_PLS system is verified in real engineering testing. For the monitoring accuracy of GNSS_PLS system given for 6 minutes (360 epochs) of the monitor station, the minimum error of North-RMS is 0.009m, the maximum error of North-RMS is 0.015m and the average error of North-RMS is 0.013m; the minimum error of East-RMS is 0.008m, the maximum error of East-RMS is 0.014m and the average value of East-RMS is 0.011m; the minimum error of Up-RMS is 0.021m, the maximum error of Up-RMS is 0.036m and the average value of Up-RMS is 0.030m. It is obtained to cm-level which verifies the effectiveness and feasibility of the proposed solutions. It is worth mentioning that the solutions have been granted two China invention patents listed as ZL201610460375.5 and ZL201710371802.7, which can provide the effective technical support for GNSS-based high-precision fixed-out and lofting of hoisting operation for the construction tower crane. The research direction of the next stage is the design of intelligent anti-collision monitoring and warning model for construction tower crane group based on high-sample rate GNSS sensors.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mingduan Zhou proposed the idea; Zhengyang Lu, Jiaxing Wang carried out the programming; Chengsi Zhao and Yuan Zhao analyzed the data; Zhengyang Lu wrote the draft; Mingduan Zhou edited and revised the manuscript. All authors read and approved the final manuscript.

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