Application of Particle Swarm Optimization in Overturning Moment of Crawler Crane

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Abstract. The rotating angle is one of the important operation parameters of jib crane, while the on-site survey of slewing angle is a difficult problem to evaluate the accuracy of angle display. This paper put forward a survey methodology based on the coordinate data around the rotation of marked points on the crane boom, and constructed the cost function by the geometric relations of marked point trajectory, used the particle swarm optimization algorithm to find the optimal solution of estimated angle. The simulation, laboratory experiment and on-site tests showed the survey methodology has the satisfied accuracy and be easy to implement.

Keywords: Slewing Angle Measurement; Particle Swarm Optimization; Cost Function.

1. Introduction

The rotating angle is one of the important parameters to the jib crane, which directly affects the safe operation of the crane. In order to increase the productivity, the luffing and slewing of the jib cranes are frequently performed with the rapid change of the lifting moment and anti-overturning moment. When the lifting moment reaches the critical value of anti-overturning moment, the jib cranes would be overturned if the safety protection devices such as lifting moment limiter do not act in time. In 2016, it is required the validity and accuracy of rotating angle displayed on the monitoring system should be verified.

In recent years, the methods and principles of measurement technology have undergone a qualitative change with the application of total station, which realizes the automatic measurement, the intelligence of data analysis and the information fusion[1]. G. Ganci et al.[2] measured the evenly distributed marks on the 300m crane rail with three total stations, obtained the rail span, horizontal and height deviation of the same sections and other parameters. Dennig D. et al.[3] developed a crane track detection system, which includes the detection trolley and external sensors. The system has the advantages of high precision with the comprehensive measurement parameters. Wen xue et al.[4] put forward a three-point angle optimum model based on the particle swarm and the genetic hybrid optimum algorithm, which greatly reduced the influence of three measuring points angle on the measurement accuracy. Shi Luqiang et al. [5] measured the inclination angle by the sensor data fusion technology, and selected the quantum Particle Swarm Optimization (PSO) algorithm to optimize the data fusion complementary filter parameters, which has the advantages of fast search speed with less parameters to be adjusted, it is easy to implement in engineering. The paper puts forward an approach based on the total station and the improved particle swarm optimization algorithm, which realizes the satisfied estimation of the rotating angle.
2. Construction of Cost Function about Rotating Angle

2.1. The Total Station Measurement
The total station is a measuring instrument integrated with the horizontal and vertical angle. Figure 1 is the schematic diagram of the total station measurement process, where \(xyz-O\) is the view-coordinate. In the survey, the total station is placed at the origin \(O\), and the line \(AB\) is rotated to the line \(A'B'\) around the rotating axis \(O\) with the rotating angle \(\alpha\). The coordinates of points \(A\) and \(B\) are marked \((x_A, y_A, z_A)\), \((x_B, y_B, z_B)\) and \((x_{A1}, y_{A1}, z_{A1})\), \((x_{B1}, y_{B1}, z_{B1})\) as the rotation positions respectively. Due to the uncertain of axis position and many factors such as the observation error, the sway error caused by the wind and external forces, the effective way to reduce the measurement errors is to make full use of measured data by the optimization algorithms. In the paper, the cost function of rotating angle is constructed, and the PSO algorithm is used to process the observation data, so as to obtain the accurate rotating angle.

![Figure 1. Schematic diagram of measurement.](image1)

![Figure 2. Survey diagram of boom mark point.](image2)

2.2. Construction of Rotating Angle Cost Function
In theory, the change of line \(AB\) coordinates is simply caused by the rotating angle \(\alpha\), that is, to establish a cost function of the rotating angle \(\alpha\). In Figure 2, the schematic diagram for measuring the rotating marked points of the crawler crane boom is shown, the marked points around rotation are labeled as \(PNT\), \(PNT\) and \(PNT\) respectively, and \(C1\), \(C2\), \(C3\), \(C4\), \(C5\) are the rotating circles. The marked points are noted as 1 to 5 for the convenience of description, thus one mark point \(i\) is labeled as \((x_{i1}, y_{i1}, z_{i1})\) and \((x_{i2}, y_{i2}, z_{i2})\) around rotating, the center coordinates of the corresponding rotating circle is \((x_{io}, y_{io}, z_{io})\).

The rotating angle cost function \(F\) is composed of the following two parts:

1. The sum of squared errors \(F_1\) between each calculated rotating angle \(\alpha_i\) and the actual rotation angle \(\alpha\) of the marked points on rotating circle is the minimum, that is

\[
F_1 = \sum_{i=1}^{5} (\cos \alpha_i - \cos \alpha)^2
\]

Where \(\cos \alpha_i = \left[\left(l_{i0}^2 + l_{i2}^2\right) - (l_{i1}^2)\right] / \left[2l_{i0}l_{i2}\right], \ l_{i2}\) is the distance between the mark point before and after the rotation, \(l_{i2} = \sqrt{(x_{i1} - x_{i2})^2 + (y_{i1} - y_{i2})^2 + (z_{i1} - z_{i2})^2}\), and \(l_{i0}, l_{i2}\) are the distances from the mark point \(i\) to the center of rotating circle around rotation respectively, where \(l_{i0} = \sqrt{(x_{i1} - x_{i0})^2 + (y_{i1} - y_{i0})^2 + (z_{i1} - z_{i0})^2}\) and \(l_{i2} = \sqrt{(x_{i2} - x_{i0})^2 + (y_{i2} - y_{i0})^2 + (z_{i2} - z_{i0})^2}\).

2. An isosceles triangle is formed with three points of \((x_{i1}, y_{i1}, z_{i1})\), \((x_{i2}, y_{i2}, z_{i2})\) and \((x_{io}, y_{io}, z_{io})\), whose base angle \(\beta\) and top angle \(\alpha\) is met \(\beta = \frac{1}{2}(\pi - \alpha)\). The sum of squared errors \(F_2\) between the
calculated angle $\beta_i$ and the real angle $\beta$ of the isosceles triangle of each rotation circle is the minimum, that is

$$F_2 = \sum_{i=1}^{5}(\cos \beta_i - \cos(\frac{\pi - \alpha}{2}))^2$$

(2)

Where $\cos \beta_i = [(l_{i0}^2 + l_{i1}^2)^2 - (l_{i20}^2)^2]/[2l_{i0}l_{i1}]$, then $F=F_1 + F_2$.

2.3. Selection of Optimization Parameters

In order to reduce the unknown parameters, the geometric relationship between these parameters is adopted to improve the performance of optimization algorithm. As the rotating axis is perpendicular to the plane of each rotating circle, the linear equation is constructed by the center point $(x_{i0}, y_{i0}, z_{i0})$ of rotating circle and the vector $(m, n, p)$ of rotating axis, meanwhile, the plane of rotating circle $i$ is considered, that is

$$m(x_{i0} - x_{i1}) + n(y_{i0} - y_{i1}) + p(z_{i0} - z_{i1}) = 0$$

$$\frac{x_{i0} - x_{i1}}{m} = \frac{y_{i0} - y_{i1}}{n} = \frac{z_{i0} - z_{i1}}{p} = t$$

(3)

Where the solution of (3) is

$$x_{i0} = x_{i1} + mt$$
$$y_{i0} = y_{i1} + nt$$
$$z_{i0} = z_{i1} + pt$$

the optimization parameters are each rotating circle center $(x_{i0}, y_{i0}, z_{i0})$, the rotating axis $(m, n, p)$ and rotating angle $\alpha$.

### 3. Improved Particle Swarm Optimization Algorithm

PSO [6, 7] is an evolutionary algorithm developed in recent years, which has the characteristics of simple, easy program and fast convergence. And genetic algorithm (GA) [8] is a random search algorithm based on the natural selection and genetic mechanism. Many scholars have studied the performance, parameter setting, convergence speed and application of particle swarm optimization algorithm, and put forward many improved particle swarm optimization (IPSO) algorithms. As to the on-site survey of slewing angle of crawler crane, PSO has good robustness and error tolerance to the measurement data, and IPSO overcomes the shortcoming of easily falling into local optimum.

3.1. PSO and GA

In PSO, the update of particles speed and position are according to the following formula as

$$\begin{align*}
\mathbf{v}_i(t+1) &= \omega(t)\mathbf{v}_i(t) + c_1 r_1 \left( \mathbf{p}_{best}(t) - \mathbf{x}_i(t) \right) + c_2 r_2 \left( \mathbf{g}_{best}(t) - \mathbf{x}_i(t) \right) \\
\mathbf{x}_i(t+1) &= \mathbf{x}_i(t) + \mathbf{v}_i(t+1)
\end{align*}$$

(4)

Where the update of inertia weight is $\omega(t) = \omega_{\text{min}} + (\omega_{\text{max}} - \omega_{\text{min}})(t_{\text{max}} - t)/(t_{\text{max}} - 1)$, and $\omega_{\text{max}}$, $\omega_{\text{min}}$ are the maximum and minimum values of inertia weight, $t_{\text{max}}$, $t_{\text{min}}$ are the current and maximum iteration, $c_1, c_2$ are the learning factors, $r_1, r_2$ are the evenly distributed random numbers between 0 and 1, $\mathbf{v}_i(t), \mathbf{x}_i(t)$ is the velocity and position of the particle $i$ in time $t$, $\mathbf{p}_{best}(t)$ is the particle local extremum position, $\mathbf{g}_{best}(t)$ is the global optimal position of the whole population.

3.2. Improved Particle Swarm Optimization (IPSO) Algorithm

PSO is easy to fall into the local extremum when the particles are too concentrated, so the direction of the particles should be reversed or reinitialized at this time. As the mutation operator of GA has ability of escaping from the local extremum, therefore, the IPSO algorithm combining PSO and GA is adopted, firstly, the best $mp$ particles in total particles are selected by PSO, and then the selected particles are copied, crossed and mutated to generated the new population by GA, which is the start of
next iteration. The algorithm flow is shown in Figure 3.

4. Experiments and Result Analysis

4.1. Simulation Test

A cylinder model is built by ADAMS software, and the observation coordinate system is established with the intersection point between the axis of the cylinder and rotating axis as the origin, seven points are marked on the cylinder model, whose coordinate data are shown in Table 1 with the rotating angle 60°.

| ordinal number | before rotation | after rotation (60°) |
|----------------|-----------------|---------------------|
|                | x   | y  | z   | x  | y  | z   |
| 1              | -225 | 0  | -250| -112.5 | 194.8557 | -250 |
| 2              | -450 | 0  | -500| -225.0 | 389.7114 | -500 |
| 3              | -675 | 0  | -750| -337.0 | 583.70112| -750 |
| 4              | -900 | 0  | -1000| -449.5 | 778.55684| -1000 |
| 5              | -1125| 0  | -1250| -561.0 | 971.6805 | -1250 |
| 6              | -1347| 0  | -1500| -673.5 | 1166.5362| -1500 |
| 7              | -1572| 0  | -1750| -786   | 1361.3919| -1750 |

The total number of particles in the algorithm is 80, and the reserved optimal particles is reserved as $m_p = 40$, the learning factors $c_1 = c_2 = 2$, the inertia weight $\omega_{\text{max}} = 0.9$, $\omega_{\text{min}} = 0.2$, the number of optimization parameters are 7, the iteration of PSO $t_{\text{max}} = 10000$, and the global iterations $g_{\text{max}} = 300$, the optimal cost function $F = 7.0081$ with the estimated rotating angle $\alpha = -60.010^\circ$, the global iteration number of the convergence curve is shown in Figure 4.
4.2. Experiment Test

The experiment is carried out in the laboratory with the devices shown in Figure 5 and Figure 6, and the tower scale is rotated by 135°, the coordinate data of nine marked points on the tower scale are listed in Table 2.

| ordinal number | before rotation | after rotation (135°) |
|----------------|-----------------|----------------------|
|                | x               | y    | z    | x               | y    | z    |
| 1              | -3.8681         | -7.7333 | 4.8998 | -3.9785         | -7.6897 | 4.8991 |
| 2              | -3.8882         | -7.8453 | 4.9871 | -4.0539         | -7.7448 | 4.9860 |
| 3              | -3.9018         | -7.9065 | 5.0437 | -4.105          | -7.7817 | 5.0420 |
| 4              | -3.9161         | -7.9750 | 5.1019 | -4.161          | -7.8233 | 5.0999 |
| 5              | -3.92725        | -8.0254 | 5.1505 | -4.2042         | -7.8536 | 5.1480 |
| 6              | -3.9483         | -8.1206 | 5.2375 | -4.2831         | -7.9104 | 5.2347 |
| 7              | -3.9641         | -8.1936 | 5.3059 | -4.3455         | -7.9541 | 5.3023 |
| 8              | -3.97955        | -8.26465| 5.3722 | -4.4045         | -7.9964 | 5.3683 |
| 9              | -4.00675        | -8.3862 | 5.48815| -4.5075         | -8.0688 | 5.4834 |

The iteration of PSO $t_{\text{max}}=15000$, the global iterations $g_{\text{max}}=500$, and other parameters are set as above, the optimal cost function $F=0.3623$ with the estimated angle $\hat{\alpha}=137.426^\circ$, the global iteration number convergence curves about the cost function and estimated angle are given in Figure 7, Figure 8 respectively, and the deviation between the estimated and real rotating angle is small.

4.3. On-site Measurement Test

A QUY700 crawler crane is selected to test the performance of IPSO algorithm, firstly, five points are marked on the main boom, and two points are marked on the side of the pulley and hook, then the slewing mechanism is approximately rotated to 60°. Meanwhile, the coordinate data of marked points are measured by the total station around the rotation.

The iteration of PSO $t_{\text{max}}=15000$, the global iterations $g_{\text{max}}=1000$, and other parameters are set as above, the optimal cost function $F=1965.1605$ with the estimated rotating angle $\hat{\alpha}=-64.296^\circ$, the global iteration number convergence curve about the cost function and estimated angle are given in Figure 9, Figure 10 respectively, the deviation between the estimated and real rotating angle is acceptable.

4.4. Analysis of Results

The estimated rotating angles obtained by the ADAMS simulation, the laboratory experiment and the on-site crawler crane slewing operation are compared with their real angles respectively, whose error rates are 0.017%, 1.80% and 7.16%. The increase of error rates is due to the external environment interference factors, because there isn’t any external factors in the ADAMS simulation, the accuracy of estimated angle is the most higher. In the laboratory experiment the connection of the tower ruler and the rotating base is no rigid fixed mode, which leads to the gravity sagging of tower ruler, therefore, there exists some deviation between the rotating trajectory of the marked point and the ideal rotating circle, the accuracy of estimated angle is good. In the on-site crawler crane slewing operation
test, the main boom is pulled by the steel wire rope, and the measured coordinate data is affected by many factors such as the wind load, the external vibration, the gravity deformation, etc., especially in the slewing operation, the assemble gap and service wear in the slewing mechanism and the flexibility of steel wire make the roundness error of the marked point trajectory larger, therefore, in this case the accuracy of estimated angle is relatively low.

![Figure 9. On-site cost function VS iteration.](image1)

![Figure 10. On-site estimated angle VS iteration.](image2)

5. Conclusion
In the paper, a survey methodology is put forward to measure the rotating angle of crawler crane, and IPSO algorithm is applied to optimize the cost function of rotating angle, which takes advantage of the high-precision measurement of total station. The methodology can also be adopt to measure the other geometric parameter of crane, and the ADAMS simulation, laboratory experiment and on-site test show that the methodology is easy to realize, and the accuracy of estimated angle is also satisfied and acceptable.

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