Application of millimeter wave radar in safety obstacle avoidance of crane in electric power construction

Wei He¹, Shenglei Hu¹, Wang Pan² and Lijuan Zhang²*

¹ Shanghai High Voltage Industry Co. Ltd, Shanghai, 200331, China
² School of Electrical and Electronic Engineering, Shanghai Institute of Technology, Shanghai, 201418, China
*Corresponding author’s e-mail: zljsmx@sit.edu.cn

Abstract. When the traditional electric construction crane safely avoids obstacles, obstacles are only detected according to the parameter estimation results, which is greatly affected by the external environment and takes a long time to avoid obstacles. Aiming at the above problems, the safety obstacle avoidance method of electric construction crane based on millimeter wave radar is studied. The millimeter wave radar is used to obtain the millimeter wave radar detection signal for crane safety obstacle avoidance. According to the impulse response of millimeter wave radar detection echo, the obstacle location mark and distance estimation are carried out, and the distance and azimuth information between the crane and the obstacle are calculated. By optimizing the safe obstacle avoidance path of electric construction cranes, the safe obstacle avoidance of electric construction cranes can be realized. Through comparative simulation experiments, it is verified that the design method takes less time to avoid obstacles, has higher efficiency, and does not collide with obstacles in the workspace in the process of movement, which verifies the effectiveness of the method.

1. Introduction
Crane is the main construction machinery widely used in electric power construction, and it is indispensable and important for electric power construction. With the wide use of the crane, its safety problem cannot be ignored[1]. The density of obstacles around electric power construction cranes is also increasing, which makes the electric power construction environment complex. There are often cross operations of multiple cranes, even close cross operations. In this case, it is easy to cause collision between cranes due to human operation errors, or collision accidents between cranes and surrounding buildings, and even fatal accidents. The traditional safety obstacle avoidance method of electric construction crane is to set ultrasonic sensor or infrared detector on the boom and hook of tower crane, and use ultrasonic or infrared to monitor the distance of surrounding obstacles. Although it can play a certain obstacle avoidance effect within a limited range, it has the problem of low obstacle avoidance rate in actual detection. Millimeter wave radar has the advantages of high resolution, high precision, high efficiency, and small antenna aperture. So millimeter wave radar is applied to the safety obstacle avoidance of electric power construction crane, and a safety obstacle avoidance method of electric power construction crane based on millimeter wave radar is designed.
2. Safety obstacle avoidance method of electric power construction crane based on millimeter wave radar

The flow chart of safety obstacle avoidance method of power construction crane based on millimeter wave radar designed in this paper is shown in figure 1. The five-step process shown in the figure will be described in detail below.

Figure 1. Safety obstacle avoidance method flow of electric construction crane based on millimeter wave radar

2.1. Obtain millimeter wave radar detection signal for crane safety obstacle avoidance

In order to realize the safety obstacle avoidance method of electric power construction crane based on millimeter wave radar, firstly, the millimeter wave radar pulse detection signal is obtained. The wireless sensor device is adopted at the bottom of the safety obstacle avoidance method of electric construction crane for signal acquisition. The spacing of millimeter wave radar signal acquisition array elements for ranging in the safety obstacle avoidance of electric construction crane in the $x$-axis direction is $d_x$, and the spacing of millimeter wave radar ranging pulse signal array elements for safety obstacle avoidance of electric construction crane in the $y$-axis direction is $d_y$. The array element spacing of safety obstacle avoidance of electric construction crane meets the requirements, as shown in equation (1).

$$d_x = d_y$$  \hspace{1cm} (1)

The correlation spectrum detection method is used to separate the electromagnetic interference factors of millimeter wave radar pulse signal, and $n(t)$ is separated. In the safety obstacle avoidance of electric power construction crane, the scattering function $R_\varphi$ of crane millimeter wave radar ranging and echo detection output is:

$$R_\varphi = R_\varphi(\varphi) + n(t)$$  \hspace{1cm} (2)

In equation (2), $R_\varphi(\varphi)$ is the angle information representing the obstacle position, and the angle information of the obstacle position after introducing the cross-correlation core detected by radar millimeter wave can be expressed as equation (3):

$$R_\varphi(\varphi) = d_x d_y \sum_{i=1}^{p} \sum_{j=1}^{p} \alpha(\theta)$$  \hspace{1cm} (3)

Where $p$ represents the total number of signal fluctuations; $i$ represents the fluctuation times of $x$-axis direction signal; $j$ represents the fluctuation times of $y$-axis direction signal; $\alpha$ represents the initial cross-correlation kernel function of radar millimeter wave detection; $\theta$ represents the termination cross-correlation kernel function of radar millimeter wave detection. The matched filter detection
method is used to process the millimeter wave radar pulse signal of crane obstacle avoidance[2]. Multi-scale feature of millimeter wave radar detection echo pulse signal is decomposed, and then crane safety obstacle avoidance is carried out according to the feature decomposition results. Assuming that the running speed of crane is \( v \), the relationship between target azimuth and expansion angle of crane safety obstacle avoidance millimeter wave radar detection signal is:

\[
g(t) = R(\varphi)\sqrt{sv(s(t - \tau))}
\]  

(4)

In equation (4), \( s \) is a two-dimensional spectral peak, abbreviated as scale; \( t \) is the termination coefficient of characteristic decomposition; \( \tau \) is the initial coefficient of characteristic decomposition. The problem of target parameter estimation for crane safety obstacle avoidance is transformed into the problem of distributed source azimuth estimation. The linear feedback equalizer is used to design the channel model of millimeter wave radar transmission data for crane safety obstacle avoidance, modulate and demodulate the transmission signal, and the scale expansion change method is used for obstacle control.

2.2. Millimeter wave radar echo detection of obstacles

Assuming that there are \( N \) obstacle distributed nodes, the detection signal of crane safety obstacle avoidance millimeter wave radar is detected under the background of interference. By estimating the scale and time delay of the millimeter wave radar detection signal for crane safety obstacle avoidance, the time scale \( W \) of the millimeter wave radar detection signal is obtained by using the signal covariance estimation method, that is:

\[
W = \sqrt{s \cdot r(t)^* (s(t - \tau))}
\]  

(5)

Where * represents complex conjugate. Combined with the minimum mean square error estimation method, the mean value of crane safety obstacle avoidance navigation control is recorded as \( D \):

\[
D = W \cdot x(t + \frac{\tau}{2})
\]  

(6)

The time domain and frequency domain of millimeter wave radar detection signal for crane safety obstacle avoidance are combined through equation (6). According to the maximum peak detection results, windowing operation is carried out. The windowing function is \( N_t \). The transmission channel pulse broadening \( T \) of millimeter wave radar for crane safety obstacle avoidance is as follows:

\[
T = N / D
\]  

(7)

According to the pulse broadening results of the transmission channel of the millimeter wave radar for crane safety obstacle avoidance, the discrete characteristic component of the millimeter wave radar detection signal for crane safety obstacle avoidance is detected. Using the spectrum separation detection method, the steep gradient function expression \( k \) of millimeter wave radar pulse signal for crane safety obstacle avoidance is obtained as follows:

\[
k = T(x^4) - 2T(x^2)
\]  

(8)

According to equation (8), the obstacle location mark and distance estimation are carried out according to the impulse response of millimeter wave radar detection echo, so as to accurately estimate the distance and azimuth information between the crane and the obstacle[3-4]. In the millimeter wave radar system for crane safety obstacle avoidance, the frequency component feature decomposition method is used for signal feature decomposition, and the transmission signal of millimeter wave radar for crane safety obstacle avoidance is sampled. The time-frequency decomposition method is used to realize the signal conversion from time domain to frequency domain, complete the millimeter wave radar echo detection of obstacles, and improve the ability of detection and obstacle avoidance.

2.3. Calculate the orientation information of electric construction crane and obstacle distance parameters

Based on millimeter wave radar echo detection of obstacles, the azimuth information of electric power
construction crane and obstacle distance parameters are calculated. The time domain characteristics of millimeter wave radar signal for crane safety obstacle avoidance are obtained by setting the array element spacing of millimeter wave radar signal sampling for crane safety obstacle avoidance. Under the quasi-stationary random detection model, the discrete characteristic component $e$ of the detection control output of millimeter wave radar is calculated by using equation (9).

$$e = \frac{\partial}{\partial u} [\mathcal{D}]$$  \hspace{1cm} (9)

Where $\mathcal{D}$ represents the probability of electric construction crane avoiding obstacles; $u$ is a discrete function. According to the relevant characteristics of obstacle avoidance millimeter wave radar detection signal, in the millimeter wave radar detection of crane safety obstacle avoidance, the obstacle location mark and distance estimation are carried out according to the impulse response of millimeter wave radar detection echo. If the objective function is $A$, there is equation (10).

$$A = \frac{f^2}{\partial u} [t_0] + \frac{t}{\gamma}$$  \hspace{1cm} (10)

Where $f$ is the frequency domain decomposition feature; $t_0$ is the time of obstacle location mark and distance estimation; $\gamma$ is the angle information component of the obstacle[5-6]. Through equation (10), the orientation information of electric construction crane and obstacle distance parameters are calculated as the key parameters for safe obstacle avoidance of electric construction crane.

2.4. Optimization of safe obstacle avoidance path for electric construction crane

According to the calculated orientation information of electric construction crane and obstacle distance parameters, plan the next travel direction of crane. Support vector machine algorithm is used to train the optional travel direction data of crane. If the training set is $U$, there is $U = \{(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)\}$, and $U \in (x \times y)^m$, $x, y$ are kernel functions; $m$ refers to the traveling direction of the crane. After obtaining the training set, the training set is defined as $C$ in the moving space of the crane. The midpoint at both ends of the $C$ space is taken as the moving control point of the crane. The potential field value of the crane obstacle avoidance space is calculated through the support vector machine algorithm, and the potential field value of the crane obstacle avoidance space is set as $j(v)$:

$$j(v) = \begin{cases} j^i_x + j^i_y + j^i_z \\ j^i_y - j^i_z \end{cases}$$  \hspace{1cm} (11)

Where $j^i_x$ refers to the number of crane moving joints; $j^i_y$ refers to the torsional linear speed of the crane moving joint; $j^i_y$ refers to the torsional linear velocity vector of the crane moving joint; $j^i_z$ refers to the torsional angle velocity vector of the crane moving joint[7-8]. Obtain the $C$ space potential field value of the crane configuration corresponding to each node through equation (11), and select the node with the smallest potential field value as the successor node of the current node. In this way, the greater the potential field value after recursive iteration, the greater the possibility of safe obstacle avoidance of the crane. Through path optimization, select the current node and subsequent nodes without collision[9]. The support vector machine algorithm is used for the path optimization of the nearest priority, that is, the RBF kernel function is obtained. If the expression of the RBF kernel function is $K(x, y)$, the equation is shown in the following.

$$K(x, y) = \exp(-r \|x - y\|^2)$$  \hspace{1cm} (12)
Where \( r \) refers to the optimal training times. The RBF kernel function can not only reduce many unnecessary calculations in the traditional crane safety obstacle avoidance method, but also obtain the optimal solution, but also effectively solve the discontinuity of crane safety obstacle avoidance path planning.

2.5. Realize safe obstacle avoidance of crane

Through the optimization of the above electric construction crane safety obstacle avoidance path, signal analysis and obstacle avoidance, it is obtained that the decision function \( H \) of crane safety obstacle avoidance.

\[
H = K(x, y)(t)
\]  \hspace{1cm} (13)

On this basis, the Internet of things for crane safety obstacle avoidance is developed and designed with Revit software, and the bus development and hardware integration design for crane safety obstacle avoidance are carried out with ADSP-BF537 as the core processor [10]. ISA/EISA/Micro Channel expansion bus is used to load the instructions of crane safety obstacle avoidance, and the program loading and cross compilation control of crane safety obstacle avoidance are carried out in the embedded environment. The JTAG debugging interface is used to read and write the real-time program of the crane safety obstacle avoidance code, ADSP-BF537BBC-5A is used to collect the original information of the crane safety obstacle avoidance system, and the collected automatic obstacle avoidance control commands are imaged and loaded. To sum up, the design method of safety obstacle avoidance of electric construction crane based on millimeter wave radar is realized.

3. Simulation experiment

3.1. Experimental preparation

In order to test the application performance of this method in realizing safe obstacle avoidance of electric construction crane, simulation experiments are carried out. The simulation experiments are carried out in INTEL (R) core (TM) i7-6820 CPU@3.60 GHz, 16 GB memory, on a computer equipped with 64-bit windows7 operating system. To obtain the accurate speed performance parameters of the obstacle avoidance method proposed in this paper, the method proposed in this paper is implemented in C++ language by using Visual Studio 2013 software platform. At the same time, considering the strong matrix operation and data visualization ability of MATLAB platform, the joint angle value sequence obtained after obstacle avoidance operation by C++ program is input into MATLAB platform and visualized to obtain reliable and intuitive results. This experiment selects an electric construction crane as the experimental object, and the top view of plane 2R crane drawn by MATLAB software. It takes about 0.15s to establish the external collision database OCQD and self-collision database SCQD of this 2R planar manipulator in Visual Studio software platform. The configuration space obstacle model can be obtained through the unit serial number index OCQD and SCQD of square obstacles in the workspace, and the color of the configuration space obstacle model corresponds to the workspace obstacle model one by one. The obstacle avoidance path planning problem of plane 2R crane in workspace is transformed into the problem of finding a path connecting the starting point and target point in the free region of configuration space.

Firstly, the traditional obstacle avoidance method is used for the safe obstacle avoidance of electric construction crane, and then the obstacle avoidance method based on millimeter wave radar is used to implement the same operation steps. The response time of millimeter wave radar ranging and echo detection is set to 0.25ms, the length of millimeter wave radar signal acquisition is 1024, the bandwidth is 24dB, and the interference signal-to-noise ratio is 10dB. According to the above simulation environment and parameter settings, millimeter wave radar ranging and echo detection are carried out to realize crane safety obstacle avoidance and obtain millimeter wave radar echo signal. The obstacle avoidance method designed in this paper is set as the experimental group, and the traditional obstacle avoidance method is the control group. At the same time, test the total obstacle avoidance time under the two obstacle avoidance methods. The shorter the total time, the higher the obstacle avoidance
efficiency of the method. According to the simulation experiment steps designed above, the experimental data under the two obstacle avoidance methods are collected, and the status of crane obstacle avoidance path planning is displayed by embedding IMU in SRTYE rendering window through human-computer interaction interface.

3.2. Analysis and conclusion of experimental results

To show the difference more intuitively in the total time of obstacle avoidance between the two methods, the experimental results under the two obstacle avoidance methods are compared together. The experimental results are shown in Table 1:

| Number of experiments | Experience group | Control group |
|-----------------------|------------------|---------------|
|                       | Obstacle avoidance path planning takes time (s) | Obstacle avoidance path search time-consuming (s) | Total time (s) | Obstacle avoidance path planning takes time (s) | Obstacle avoidance path search time-consuming (s) | Total time (s) |
| 1                     | 0.036            | 0.015         | 0.051         | 0.075 | 0.035 | 0.110 |
| 2                     | 0.035            | 0.014         | 0.049         | 0.078 | 0.036 | 0.114 |
| 3                     | 0.033            | 0.015         | 0.048         | 0.080 | 0.029 | 0.109 |

It can be seen from Table 1 that the obstacle avoidance path planning time and obstacle avoidance path search time of the design method in this paper are faster than those of the control group. Therefore, it is proved that the total obstacle avoidance time of the design method is shorter, the efficiency is higher, and there is no collision with the obstacles in the workspace during the movement, which verifies the effectiveness of the method proposed in this paper and has good application value.

4. Conclusion

In this paper, millimeter wave radar is applied to the safety obstacle avoidance design of electric construction crane, and a new safety obstacle avoidance method of electric construction crane is proposed, which improves the obstacle avoidance ability of electric construction crane. Through the above research, obstacle location and distance estimation based on millimeter wave radar detection echo impulse response is feasible and accurate. The method provides theoretical support for improving the working efficiency of electric construction crane. However, due to the limited research time, the proposed method still has some shortcomings. In the future, the method needs to be continuously optimized and improved through practical application. In addition, other equipment obstacle avoidance related contents will be further studied in the future, including the detection and optimization of crane obstacle avoidance technology and the research on crane obstacle avoidance method in three-dimensional state, to promote the scientific development of power construction.

References

[1] Zhang W, Chen H, Chen H, et al. A Time Optimal Trajectory Planning Method for Double-Pendulum Crane Systems With Obstacle Avoidance[J]. IEEE Access, 2021, (99):1.
[2] Cao C, J Gao, Liu Y C. Research on Space Fusion Method of Millimeter Wave Radar and Vision Sensor[J]. Procedia Computer Science, 2020, 166:68-72.
[3] Lingard H, Cooke T, Zelic G, et al. A qualitative analysis of crane safety incident causation in the Australian construction industry[J]. Safety Science, 2021, 133:105028.
[4] Bagheri S M, Taghaddos H, Mousaei A, et al. An A-Star algorithm for semi-optimization of crane location and configuration in modular construction[J]. Automation in Construction, 2021, 121:103-447.
[5] Zhang Z, Pan W. Virtual reality supported interactive tower crane layout planning for high-rise modular integrated construction[J]. Automation in Construction, 2021, 130:103-854.

[6] Shentu S, Xie F, Liu X J, et al. Motion Control and Trajectory Planning for Obstacle Avoidance of the Mobile Parallel Robot Driven by Three Tracked Vehicles[J]. Robotica, 2020:1-14.

[7] He Y, Wu M, Liu S. A cooperative optimization strategy for distributed multi-robot manipulation with obstacle avoidance and internal performance maximization[J]. Mechatronics, 2021, 76:102-560.

[8] Li W, Xiong R. Dynamical Obstacle Avoidance of Task-Constrained Mobile Manipulation Using Model Predictive Control[J]. IEEE Access, 2019, (99):1.

[9] Mu Z, Liu T, Xu W, et al. A Hybrid Obstacle-Avoidance Method of Spatial Hyper-Redundant Manipulators for Servicing in Confined Space[J]. Robotica, 2019, 37(6):998-1019.

[10] Xi X, Shi Y, Jin Y, et al. Obstacle avoidance path control method for agricultural machinery automatic driving based on optimized Bezier[J]. Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering, 2019, 36(19):82-88.