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Research Article

Research on Safety Control Technology for Dual Robots Based on Kinematic Models

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Abstract

The industrial robots play an important role in modern industrial manufacturing processes, and their applications are becoming increasingly widespread, greatly improving manufacturing efficiency and significantly enhancing the digitalization level of the manufacturing industry. Therefore, achieving safe control of multi robot collaborative work is of great significance for the stable and efficient operation of robot systems. This article proposes a dual robot safety control technology based on the kinematic model of industrial robots. Firstly, a mathematical model of the kinematic space of the dual robots is constructed using D-H parameters; Then, use recursive traversal algorithm to calculate the minimum distance between each joint arm of the two robots in real time; Finally, the minimum distance between each joint arm will be calculated and compared with the set safety threshold to achieve real-time assessment and control of collision risk during the movement of the dual robots. A dual robot safety control testing platform was built using two KUKA industrial robots, integrated control software was developed, and relevant algorithms were validated. Through experiments, it was verified that this method can evaluate the collision risk of dual robots in real time during motion and effectively control the collision risk during the motion of dual robots.

Keywords

Dual Robots, Safety Control, Kinematic Model, Collision Prevention

1. Introduction

With the continuous development of technology and the continuous progress and maturity of industrial robot technology, the application of industrial robots in multiple fields such as mechanical processing, aviation manufacturing, and logistics is becoming increasingly widespread. With the continuous deepening of industrial robot applications, single robot systems are no longer able to meet the requirements of special application scenarios such as large-scale component handling and aviation large component assembly. Therefore, dual robot systems have gradually emerged in the public's vision. A dual robot system can compensate for the disadvantages of a single robot system such as low load capacity and insufficient workspace, but there is also a risk of collision between the two robots during motion. Therefore, conducting research on collision prevention technology during the movement of dual robots is of great significance for improving the operational efficiency and safety of dual robot systems.

At present, domestic and foreign scholars have conducted relevant technical research on the safety control technology

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of dual robot motion. The offline path planning method (e.g., [1-8]) uses simulation software to plan the motion trajectory of the dual robots offline, and then the dual robot system strictly follows the planned path to achieve collision prevention during the dual robot motion process. This method can effectively avoid the risk of double robot collision during repetitive work in a fixed working environment, but it is not suitable for scenarios such as drilling, riveting, polishing, etc. that require real-time correction of the work path. The external sensor perception method (e.g., [9-15]) installs external sensors at critical positions of industrial robots, and the sensors collect real-time external data (including distance, images, etc.) during the movement process of industrial robots to determine whether there is a risk of collision. This method has real-time performance, but due to the installation of sensors at critical positions of industrial robots, it is impossible to achieve full domain state perception of the industrial robot body, resulting in the risk of collision omission. Therefore, this article proposes a dual robot motion safety control technology based on robot kinematics. By constructing a dual robot kinematic space model and using recursive traversal algorithm to calculate the distance between the two robots in real time, the collision risk of the two robots is evaluated and controlled. After experimental verification, this method can effectively evaluate and control the collision risk during the motion of dual robots.

2. Model Simplification

The dual robot layout is shown in Figure 1. Simplify the robot model before modeling, as shown in Figure 2.

In the simplified model of industrial robot A, the coordinate system $O_{A1}-x_{A1}y_{A1}z_{A1}$ is the robot's base coordinate system, where the Z-axis coincides with the first rotation axis of the robot; The coordinate system $O_{A2}-x_{A2}y_{A2}z_{A2}$ is the second axis coordinate system of the robot, where the axis of the second axis coincides with the X-axis; The coordinate system $O_{A3}-x_{A3}y_{A3}z_{A3}$is the third axis coordinate system of the robot, where the axis of the third axis coincides with the X axis; The coordinate system $O_{A4}-x_{A4}y_{A4}z_{A4}$ is the fourth axis coordinate system of the robot, where the axis of the fourth axis coincides with the Y axis; The coordinate system $O_{A5}-x_{A5}y_{A5}z_{A5}$ is the fifth axis coordinate system of the robot, where the axis of the fifth axis coincides with the X-axis; The coordinate system $O_{A6}-x_{A6}y_{A6}z_{A6}$ is the sixth axis coordinate system of the robot, where the axis of the sixth axis coincides with the Y-axis. At the same time, the coordinate axes of the six coordinate systems mentioned above are parallel to each other. L_{A1} represents the distance between the coordinate system $O_{A1}-x_{A1}y_{A1}z_{A1}$ and the coordinate system $O_{A2}-x_{A2}y_{A2}z_{A2}$, which is the length of the first connecting rod; L_{A2} represents the distance between the coordinate system $O_{A2}-x_{A2}y_{A2}z_{A2}$ and the coordinate system $O_{A3}-x_{A3}y_{A3}z_{A3}$, which is the length of the second connecting rod; L_{A3} represents the distance between the coordinate system $O_{A3}-x_{A3}y_{A3}z_{A3}$ and the coordinate system $O_{A4}-x_{A4}y_{A4}z_{A4}$, which is the length of the third connecting rod; L_{A4} represents the distance between the coordinate system $O_{A4}-x_{A4}y_{A4}z_{A4}$ and the coordinate system $O_{A5}-x_{A5}y_{A5}z_{A5}$, which is the length of the fourth connecting rod; L_{A5} represents the distance between the coordinate system $O_{A5}-x_{A5}y_{A5}z_{A5}$ and the coordinate system $O_{A6}-x_{A6}y_{A6}z_{A6}$, which is the length of the fifth connecting rod; L_{A6} represents the distance between the coordinate system $O_{A6}-x_{A6}y_{A6}z_{A6}$ and the end face of the robot flange, which is the length of the sixth connecting rod. θ_{A1} represents the rotation angle of the first shaft, θ_{A2} represents the rotation angle of the second shaft, θ_{A3} represents the rotation angle of the third shaft, θ_{A4} represents the rotation angle of the fourth shaft, θ_{A5} represents the rotation angle of the fifth shaft, and θ_{A6} represents the rotation angle of the sixth shaft.

Similarly, simplify the model of industrial robot B.

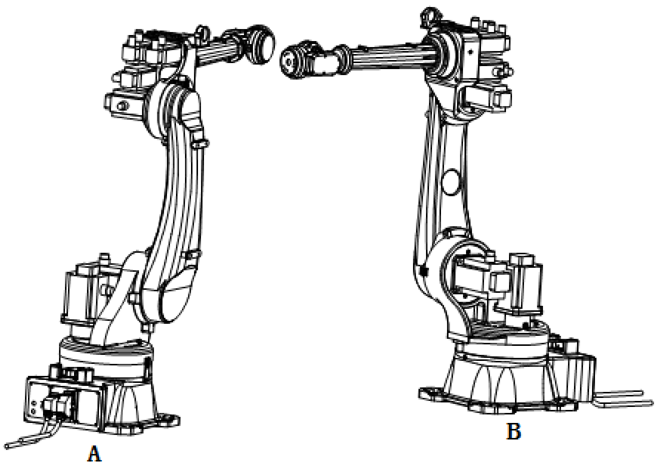

Figure 1. *Dual robot system layout.*

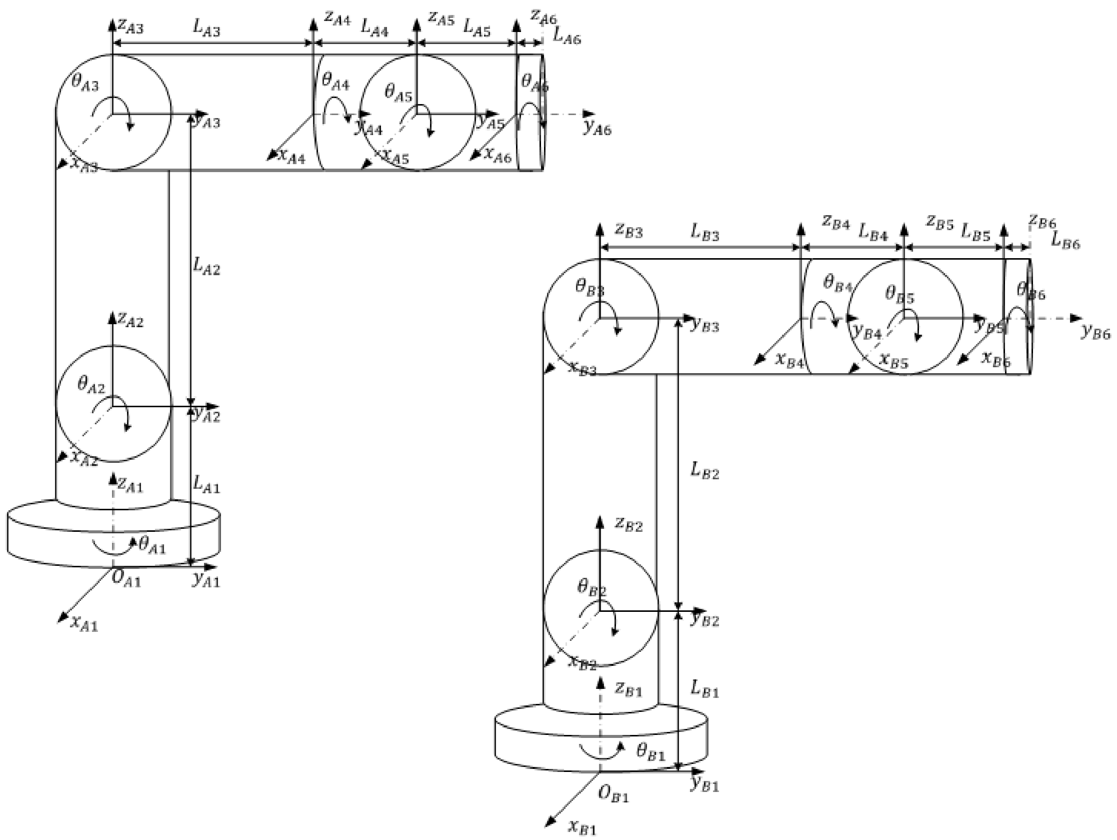

Figure 2. *Simplified model of dual robots.*

3. Establishment of Robot Kinematic Model

As shown in Figure 2, the equation for the axis of the first connecting rod of industrial robot A in the base coordinate system $O_{A1}-x_{A1}y_{A1}z_{A1}$ is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = l * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \ (0 \le l \le L_{A1}) \quad (1)$$

The equation for the axis of the second connecting rod of industrial robot A in the coordinate system $O_{A2}-x_{A2}y_{A2}z_{A2}$ is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = l * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \ (0 \le l \le L_{A2}) \quad (2)$$

Convert it to the base coordinate system $O_{A1}-x_{A1}y_{A1}z_{A1}$ z A1, and the equation is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{A1}) * R_x(\theta_{A2}) * l * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ L_{A1} \end{pmatrix} \ (0 \le l \le L_{A2}) \quad (3)$$

Among them, $R_z(\theta_{A1}) = \begin{bmatrix} \cos\theta_{A1} & -\sin\theta_{A1} & 0 \\ \sin\theta_{A1} & \cos\theta_{A1} & 0 \\ 0 & 0 & 1 \end{bmatrix}$, $R_x(\theta_{A2}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{A2} & -\sin\theta_{A2} \\ 0 & \sin\theta_{A2} & \cos\theta_{A2} \end{bmatrix}$.

The equation for the axis of the third connecting rod of industrial robot A in the coordinate system $O_{A3}-x_{A3}y_{A3}z_{A3}$ is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = l * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{A3}) \quad (4)$$

Convert it to the base coordinate system $O_{A1}-x_{A1}y_{A1}z_{A1}$ z A1, and the equation is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{A1}) * R_x(\theta_{A2}) * L_{A2} * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R_z(\theta_{A1}) * R_x(\theta_{A2}) * R_x(\theta_{A3}) * l * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{A3}) \quad (5)$$

Among them, $R_x(\theta_{A3}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{A3} & -\sin\theta_{A3} \\ 0 & \sin\theta_{A3} & \cos\theta_{A3} \end{bmatrix}$.

The equation for the axis of the fourth connecting rod of industrial robot A in the coordinate system $O_{A4}-x_{A4}y_{A4}z_{A4}$ is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = l * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{A4}) \tag{6}$$

Convert it to the base coordinate system $O_{A1}-x_{A1}y_{A1}z_{A1}$ z A1, and the equation is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{A1}) * R_x(\theta_{A2}) * L_{A2} * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R_z(\theta_{A1}) * R_x(\theta_{A2}) * R_x(\theta_{A3}) * (L_{A3} + l) * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{A4}) \tag{7}$$

The equation for the fifth link of industrial robot A in the coordinate system $O_{A5}-x_{A5}y_{A5}z_{A5}$ is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = l * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{A5}) \tag{8}$$

Convert it to the base coordinate system $O_{A1}-x_{A1}y_{A1}z_{A1}$ z A1, and the equation is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{A1}) * R_x(\theta_{A2}) * L_{A2} * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R_z(\theta_{A1}) * R_x(\theta_{A2}) * R_x(\theta_{A3}) * (L_{A3} + L_{A4}) * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} + R_z(\theta_{A1}) * R_x(\theta_{A2}) * R_x(\theta_{A3}) * R_y(\theta_{A4}) * R_x(\theta_{A5}) * l * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{A5}) \tag{9}$$

Among them, $R_y(\theta_{A4}) = \begin{bmatrix} \cos\theta_{A4} & 0 & \sin\theta_{A4} \\ 0 & 1 & 0 \\ -\sin\theta_{A4} & 0 & \cos\theta_{A4} \end{bmatrix}$, $R_x(\theta_{A5}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{A5} & -\sin\theta_{A5} \\ 0 & \sin\theta_{A5} & \cos\theta_{A5} \end{bmatrix}$.

The equation for the sixth link of industrial robot A in the coordinate system $O_{A6}-x_{A6}y_{A6}z_{A6}$ is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = l * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{A6}) \tag{10}$$

Convert it to the base coordinate system $O_{A1}-x_{A1}y_{A1}z_{A1}$ z A1, and the equation is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{A1}) * R_x(\theta_{A2}) * L_{A2} * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R_z(\theta_{A1}) * R_x(\theta_{A2}) * R_x(\theta_{A3}) * (L_{A3} + L_{A4}) * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} + R_z(\theta_{A1}) * R_x(\theta_{A2}) * R_x(\theta_{A3}) * R_y(\theta_{A4}) * R_x(\theta_{A5}) * (L_{A5} + l) * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{A6}) \tag{11}$$

Similarly, the equations for each link of industrial robot B in its base coordinate system $O_{B1}-x_{B1}y_{B1}z_{B1}$ can be obtained as follows:

The first connecting rod model is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = l * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \ (0 \le l \le L_{B1}) \tag{12}$$

The second connecting rod model is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{B1}) * R_x(\theta_{B2}) * l * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ L_{B1} \end{pmatrix} \ (0 \le l \le L_{B2}) \tag{13}$$

Among them, $R_z(\theta_{B1}) = \begin{bmatrix} \cos\theta_{B1} & -\sin\theta_{B1} & 0 \\ \sin\theta_{B1} & \cos\theta_{B1} & 0 \\ 0 & 0 & 1 \end{bmatrix}$, $R_x(\theta_{B2}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{B2} & -\sin\theta_{B2} \\ 0 & \sin\theta_{B2} & \cos\theta_{B2} \end{bmatrix}$.

The third link model is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{B1}) * R_x(\theta_{B2}) * L_{B2} * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R_z(\theta_{B1}) * R_x(\theta_{B2}) * R_x(\theta_{B3}) * l * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{B3}) \tag{14}$$

Among them, $R_x(\theta_{B3}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{B3} & -\sin\theta_{B3} \\ 0 & \sin\theta_{B3} & \cos\theta_{B3} \end{bmatrix}$.

The fourth connecting rod model is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{B1}) * R_x(\theta_{B2}) * L_{B2} * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R_z(\theta_{B1}) * R_x(\theta_{B2}) * R_x(\theta_{B3}) * (L_{B3} + l) * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{B4}) \tag{15}$$

The fifth connecting rod model is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{B1}) * R_x(\theta_{B2}) * L_{B2} * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R_z(\theta_{B1}) * R_x(\theta_{B2}) * R_x(\theta_{B3}) * (L_{B3} + L_{B4}) * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} + R_z(\theta_{B1}) * R_x(\theta_{B2}) * R_x(\theta_{B3}) * R_y(\theta_{B4}) * R_x(\theta_{B5}) * l * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{B5}) \quad (16)$$

Among them, $R_y(\theta_{B4}) = \begin{bmatrix} \cos\theta_{B4} & 0 & \sin\theta_{B4} \\ 0 & 1 & 0 \\ -\sin\theta_{B4} & 0 & \cos\theta_{B4} \end{bmatrix}$, $R_x(\theta_{B5}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{B5} & -\sin\theta_{B5} \\ 0 & \sin\theta_{B5} & \cos\theta_{B5} \end{bmatrix}$.

The sixth connecting rod model is:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = R_z(\theta_{B1}) * R_x(\theta_{B2}) * L_{B2} * \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + R_z(\theta_{B1}) * R_x(\theta_{B2}) * R_x(\theta_{B3}) * (L_{B3} + L_{B4}) * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} + R_z(\theta_{B1}) * R_x(\theta_{B2}) * R_x(\theta_{B3}) * R_y(\theta_{B4}) * R_x(\theta_{B5}) * (L_{B5} + l) * \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \ (0 \le l \le L_{B6}) \quad (17)$$

4. Security Control Strategy

After solving the equations of the connecting rods of industrial robot A and industrial robot B, the shortest distance between the connecting rods of the two industrial robots is solved. Based on the results, the collision risk of the two robots can be identified and controlled.

The general calculation method for the shortest distance between any connecting rod of industrial robot A and industrial robot B is as follows:

The general equation for a certain link of industrial robot A is:

$$\begin{cases} x_A = a_1 * l_1 + b_1 \\ y_A = c_1 * l_1 + d_1 \ (0 \le l_1 \le L_A) \\ z_A = e_1 * l_1 + f_1 \end{cases} \quad (18)$$

The general equation for a certain link of industrial robot B is:

$$\begin{cases} x_B = a_2 * l_2 + b_2 \\ y_B = c_2 * l_2 + d_2 \ (0 \le l_2 \le L_B) \\ z_B = e_2 * l_2 + f_2 \end{cases} \quad (19)$$

The distance between any two points of the two connecting rods is:

$$L = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2}$$

$$(0 \le l_1 \le L_A, 0 \le l_2 \le L_B) \quad (20)$$

Assuming a function: $f(l_1, l_2) = L^2 = (a_1 * l_1 + b_1 - a_2 * l_2 - b_2)^2 + (c_1 * l_1 + d_1 - c_2 * l_2 - d_2)^2 + (e_1 * l_1 + f_1 - e_2 * l_2 - f_2)^2 \ (0 \le l_1 \le L_A, 0 \le l_2 \le L_B)$.

To obtain the shortest distance between two connecting rods, the function $f(l_1, l_2)$ can be first calculated to obtain the minimum value.

Take the partial derivative of function $f(l_1, l_2)$ and make the derivative equal to zero.

$$\begin{cases} \frac{\partial f(l_1, l_2)}{l_1} = 0 \\ \frac{\partial f(l_1, l_2)}{l_2} = 0 \end{cases} (0 \le l_1 \le L_A, 0 \le l_2 \le L_B) \quad (21)$$

If the above equation system has a solution (l_a, l_b), then the shortest distance between the two connecting rods is:

$$L_{min} = \sqrt{\begin{matrix} (a_1 * l_A + b_1 - a_2 * l_B - b_2)^2 + \\ (c_1 * l_A + d_1 - c_2 * l_B - d_2)^2 + \\ (e_1 * l_A + f_1 - e_2 * l_B - f_2)^2 \end{matrix}} \quad (22)$$

When the above equation system has no solution, the shortest distance between two connecting rods is the minimum distance between the endpoints of the connecting rods.

5. Experiment

The experiment used two Kuka robots to build the experimental platform, as shown in Figure 3. The two robot models are KUKA KR20 R1810-2 and KR16 R1610-2, and their technical parameters are shown in Table 1.

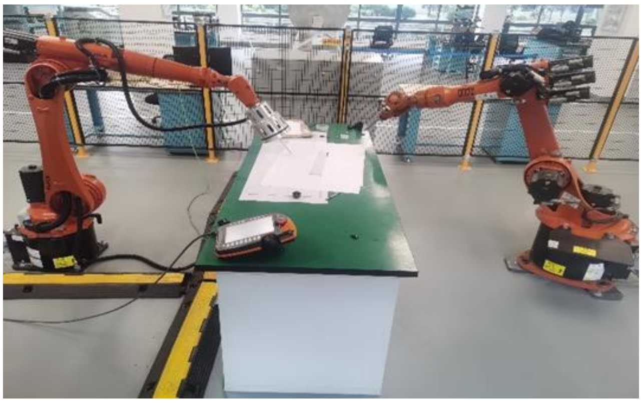

Figure 3. *Verification experiment.*

Table 1. *Main technical parameters of robots.*

model	working space	load	Repetitive positioning accuracy
KR20 R1810-2	1813mm	20kg	±0.04mm
KR16 R1610-2	1610mm	16kg	±0.04mm

A robot integrated control system was developed using C#, as shown in Figure 4. A dual robot motion safety control model was constructed. By collecting the positions of each robot joint, the relative positions between the dual robot links were calculated in real time, and the collision risk was evaluated and controlled.

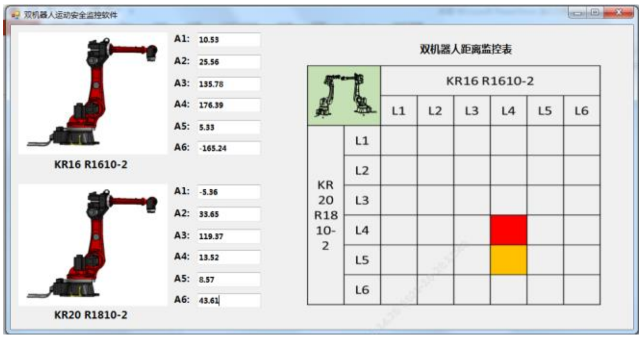

Figure 4. *The control software.*

6. Conclusions

This article proposes a safety control technology suitable for dual robot motion monitoring. By simplifying the industrial robot model and using the D-H (Denavit-Hartenberg) parameter method, a theoretical model of the robot is constructed; Build a dual robot control system, collect real-time joint angle information of the dual robots, and drive the theoretical model to use a traversal recursive algorithm to calculate the distance between the dual robot links in real time. Alarm and prompt for collision risks during the dual robot movement process. Experimental verification shows that this method can effectively prompt and predict collision risks during the motion of dual robots, achieve safe control of dual robot motion, and provide technical support for the safe application of dual robot systems.

7. Recommendations

Intelligent manufacturing is the development trend of the future manufacturing industry, subsequently, the safety control of industrial robots can be combined with artificial intelligence technology to achieve autonomous perception and decision-making of the system, in order to adapt to the development of future intelligent manufacturing.

Abbreviations

D-H Denavit-Hartenberg

Author Contributions

Qiang Chen is the sole author. The author read and approved the final manuscript.

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflicts of interest.

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