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Obstacle avoidance algorithm for dual-arm robots based on task switching

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***Abstract* - With the gradual popularization of robots, safety in operation has attracted more and more attention. Due to the existence of real-time obstacles, the safe workspace of robots is gradually compressed, and the original planned path will also lead to failure. In order to ensure that the robot will not be affected in operation, an online obstacle avoidance algorithm based on the off-line trajectory is proposed in this paper. The algorithm divides the operation of the manipulator into two parts, one is to attract the main motion along the off-line trajectory, the other is to avoid obstacles. By choosing obstacle avoidance parameters, the robot can switch between primary and secondary movements in real-time to avoid obstacles. Two special examples are selected in the post-simulation. One is the robot avoiding the fist model of the person fitted to the sphere, and the other is the simulation experiment of the self-avoidance obstacle of the dual-arm robot. Simulation experiments and data results show that the algorithm proposed in this paper has strong practicability.**

Keywords: Collision avoidance, Collaborative robotics, manipulator

I. INTRODUCTION

Looking back at the development history of robots, in just a few decades, the scope of application of robots has been expanding[1]. From a large point of view, there are automation industry, manufacturing industry, deep-sea and cosmic exploration, nuclear power plant maintenance and disposal of nuclear waste and so on. From a small point of view, there are medical industry and even family services. Robots have played a great role and been increasingly widely used[2]. With the increasing application of robots, it is difficult for mobile robots and low-degree-of-freedom robots to complete complex operational tasks, such as equipment maintenance in dangerous environments, air target acquisition and so on. For redundant robots, the number of degrees of freedom of their joints is larger than the number of degrees of freedom limited by the end pose. Each joint can move from an initial joint position to the desired joint position while keeping the position and attitude of the end effector unchanged in the joint space[3]. Because of this feature, redundant robots can improve the joint configuration of low-degree-of-freedom robots, overcome the shortcomings of general robots, such as poor flexibility, low obstacle avoidance ability, joint overrun and poor dynamic performance. Because of this redundancy characteristic, which is different from traditional low-degree-of-freedom robots, redundant robots are superior to general low-degree-of-freedom robots and become the focus of attention.

An important technology in the application of redundant robots is obstacle avoidance path planning. A good obstacle avoidance planning method can reduce a lot of working time, protect the robot from damage, and save manpower and capital investment, so as to lay a good foundation for the application of redundant robots in more fields[5][6]. Robot dynamic obstacle avoidance path planning means that the robot itself is moving, and obstacles are also moving, path planning, without encountering any moving obstacles at the same time the end of the robot reaches the endpoint. In various unknown dynamic environments, redundant robots must have the ability to perceive the environment and move autonomously towards the endpoint. The uncertainty of obstacles greatly increases the complexity of task completion. Therefore, the research of dynamic obstacle avoidance path planning for redundant robots has far-reaching significance.

At present, there are many methods for obstacle avoidance path planning of redundant robots. Among them, for global obstacle avoidance path planning, there is a C-space method, and for local obstacle avoidance path planning, there is an artificial force field method.

Lazona Perzze proposed a free space method with C space as its core. A C-space is established with the joint axis of the robot as the coordinate system, and the obstacles are mapped to the local C-space to form the local obstacle C-space. Then, the complement set of obstacle C space in local space is free space. The point in free space represents the robot configuration that does not collide with an obstacle, while the point in C obstacle space represents the robot configuration that collides with an obstacle[7]. Using a hairpin search algorithm, obstacle avoidance planning is transformed into finding the path between the initial point and the endpoint in free space[8]. Other scientists have put forward many innovative theories on this basis.

Compared with the free space method, the artificial potential field method is more suitable for a dynamic environment and obstacle avoidance path planning of multi-joint robots[9]. But the main problems are as follows: when the robot is in the position of local minimum, it will stop. The so-called local minimum point is due to the simultaneous distribution of the attracting force field and the repulsive force field in space. In some areas, the local minimum point is caused by the combined action of multiple forces. The local method only considers the end and the collision point, and the collision point is constantly changing when the articulated

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manipulator moves, which causes the phenomenon of jitter near multiple obstacles.

Liegeois proposed the gradient projection method. This is an algorithm based on the generalized inverse matrix. The basic idea of this method is to decompose the inverse kinematics problem into two parts: the minimum norm solution and the homogeneous solution. The homogeneous solution, also known as zero-space pose solution, means that the decomposed pose will not affect the terminal[10][11]. Redundant robots can use the corresponding task index to calculate the zero-space solution to optimize the obstacle avoidance trajectory. The gradient projection method ensures the first task (satisfying the end trajectory) and can easily and quickly obtain the local optimal solution of an index. Different judgment indexes can accomplish different second tasks, such as avoiding obstacles, increasing flexibility, avoiding singularities, preventing joint speed from exceeding the limit, reducing joint torque, etc. Because of these advantages, the gradient projection method becomes the most important method to solve the real-time path planning of redundant robots by inverse kinematics.

Artificial Neural Network (ANN) is used to fit the inverse solution of the robot, which solves the problem of singular points[12]. However, this method is still only planning for obstacle avoidance at the endpoint, without considering the problem of arm-end obstacle avoidance. The iteration strategy avoids obstacles and determines the target point, and then searches for the next adjacent joint angle to move. The selection of a joint angle after collision detection requires no collision, and the sum of the error with the target point and the displacement of each joint of the manipulator is the smallest. This method has the characteristics of a simple algorithm and can avoid obstacles dynamically. But the safe obstacle avoidance should keep a certain distance from the obstacle. This method will make the manipulator move along the boundary of the obstacle. If there are errors, it is likely to collide, which will make the manipulator control and scene modeling difficult.

Based on the research of many scientists, this paper proposes a redundant robot obstacle avoidance algorithm for real-time moving obstacles. This algorithm relies on sensors to recognize the real-time spatial coordinates of moving obstacles and project them on each arm segment of the manipulator to find the key points of projection on each arm segment. A reverse velocity is applied in the direction between the obstacles and the key points to keep the manipulator away from the obstacles, while the end continues to move in the specified direction until the endpoint is reached. The reliability of the algorithm is verified by simulation experiments. The algorithm can also be used in self-collision avoidance of dual-arm robots.

II. ESTABLISHMENT OF ROBOT KINEMATICS MODEL

The redundant robot is a kind of robot whose joint space dimension n is larger than task space dimension m. Common redundant robots have four or five joint planar palletizing robots, or seven or eight joint space mobile robots, which are usually used in space or service industries. A person's single-arm has seven degrees of freedom(DOF), three in shoulders, one in wrist, and three in elbows. The extra degree of freedom enables a person to have flexible operation mode and realize various complex tasks. At present, humanoid robots in the market or in the laboratory usually have 7 degrees of freedom. If they are double-arm robots, they have 14 degrees of freedom showed in Fig.1. Data in Table.1 shows the parameters of the robot.

2.1 Building Model

There are usually D-H method or the theory of the screw to build the kinematic model of robots. The simulation analysis in this paper is based on the toolbox of MATLAB robotics system tool (RST). The default modeling method is the screw theory. Therefore, the screw theory will be used to build the robot model in this paper.

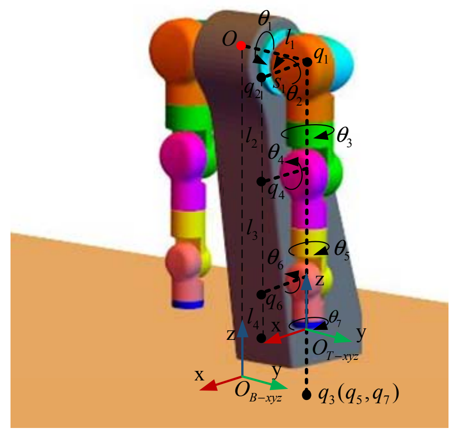

Fig.1 Model of the redundant dual-arm robot

Table 1.
Rotation Parameters of Redundant Manipulators

i	ω_i	q_i
1	$[0\ \ 1\ \ 0]$	$[0\ \ l_1\ \ l_0]$
2	$[1\ \ 0\ \ 0]$	$[s_1\ \ l_1\ \ l_0]$
3	$[0\ \ 0\ \ \text{-}1]$	$[0\ \ l_1\ \ 0]$
4	$[1\ \ 0\ \ 0]$	$[s_1\ \ l_1\ \ l_0-l_2]$
5	$[0\ \ 0\ \ \text{-}1]$	$[0\ \ l_1\ \ 0]$
6	$[1\ \ 0\ \ 0]$	$[s_1\ \ l_1\ \ l_0-l_2-l_3]$
7	$[0\ \ 0\ \ \text{-}1]$	$[0\ \ l_1\ \ 0]$

$\hat{\xi}$ is a spinor of motion, $\xi=(v^{\mathrm{T}};\omega^{\mathrm{T}})^{\mathrm{T}} \in R^6$.

When each joint rotates at the corresponding angle, the position and posture of the end of the left arm of the robot are as follows:

$$g_{st}(\theta)=e^{\hat{\xi}_1\theta_1}e^{\hat{\xi}_2\theta_2}e^{\hat{\xi}_3\theta_3}e^{\hat{\xi}_4\theta_4}e^{\hat{\xi}_5\theta_5}e^{\hat{\xi}_6\theta_6}e^{\hat{\xi}_7\theta_7}g_{st}(0) \tag{1}$$

$g_{st}(0)$ is the initial posture of the end. Based on the above, the forward kinematic model of the robot has been established.

2.2 Obstacle Detection

For a manipulator, it is generally regarded as a capsule between two adjacent joints. For some small obstacles, it is generally regarded as a sphere. The spatial position of the sphere needs to be measured by sensors. So, for the above robots, one of his robotic arms can be regarded as a combination of three capsules. Among them, 2nd-4th joints form a capsule body as well as the 4th-6th joints and 6th-7th joints. During the actual operation, the length of the last capsule body needs to be calculated from the 6th joint to the end effector.

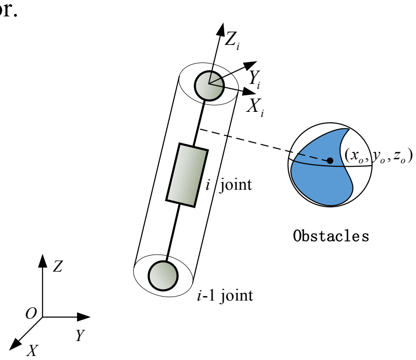

Fig.2 Space relative position of mechanical arm and obstacle

We use T_i to represent the spatial posture of the end of the first joint. T_i is a 4*4 matrix. The coordinates of known obstacles in the world coordinate system are ${}^{0}_{OB}P = (x_o \quad y_o \quad z_o \quad 1)^{\mathrm{T}}$.

Then the projection relation of obstacle O relative to the base coordinate system of the bounding box in section i can be expressed as:

$$ {}^{i}_{OB}P = \begin{pmatrix} x_{oi} & y_{oi} & z_{oi} & 1 \end{pmatrix}^{\mathrm{T}} = {}^{0}_{i}T \bullet {}^{0}_{OB}P \tag{2}$$

The projection coordinate of the z-axis in the base coordinate system of the bounding box in the first paragraph is $P_i = \begin{pmatrix} 0 & 0 & z_{Oi} \end{pmatrix}$, and the distance between the key point and the center of the obstacle is $d_i = \sqrt{x_{Oi}^2 + y_{Oi}^2}$.

2.3 Collision Detection Between Arms

For a manipulator, every three even joints and the end joints can be regarded as a new virtual link, such as the virtual link composed of joint 2nd-4th, joint 4th-6th, and joint 6th-7th. Therefore, a single-arm can be regarded as a virtual link system composed of three rotating joints. Because the virtual link between joint 1 and joint 2 is in the body of the robot, the possibility of collision is neglected.

Arbitrarily take one connecting rod for the left arm and one connecting rod for the right arm, as shown in Fig.3.

Therefore, for a line which is collinear with the line segment connected from the i-1 (i = 3,5) joint to the i + 1 joint of the left arm, the coordinates of any point a on the line can be defined as:

$$P_A = P_{L_{i-1}} + m(P_{L_{i+1}} - P_{L_{i-1}}) \tag{3}$$

Similarly, the coordinates of any point B on a line which is collinear with the line segment connecting the j-1 (j=3,5) joint to the j+1 joint of the right arm can be defined as:

$$P_B = P_{R_{j-1}} + n(P_{R_{j+1}} - P_{R_{j-1}}) \tag{4}$$

The line L_A can be expressed as a vector $\overrightarrow{P_{L_{i-1}}P_{L_{i+1}}}$, the line R_B can be expressed as a vector $\overrightarrow{P_{R_{j-1}}P_{R_{j+1}}}$, and the direction vector between point A and point B can be recorded as a vector $\overrightarrow{AB}$.

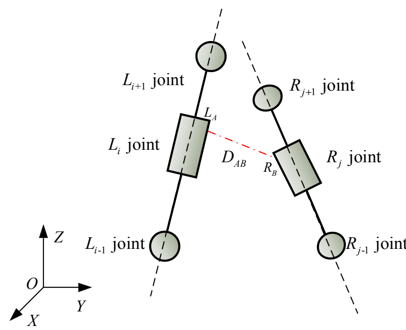

Fig.3 The distance between two arms.

The shortest distance D_{AB} between two different straight lines L_A and R_B in space is:

$$D_{AB} = \frac{\overrightarrow{P_{L_{i-1}}P_{L_{i+1}}} \times \overrightarrow{P_{R_{j-1}}P_{R_{j+1}}} \bullet \overrightarrow{AB}}{\left| \overrightarrow{P_{L_{i-1}}P_{L_{i+1}}} \times \overrightarrow{P_{R_{j-1}}P_{R_{j+1}}} \right|} \tag{5}$$

At this time, the coordinate variable m of the nearest point A is:

$$m = \frac{((P_{R_{j-1}} - P_{L_{i-1}}) \times (P_{R_{j+1}} - P_{R_{j-1}})) \bullet ((P_{L_{i+1}} - P_{L_{i-1}}) \times (P_{R_{j+1}} - P_{R_{j-1}}))}{\left\| (P_{L_{i+1}} - P_{L_{i-1}}) \times (P_{R_{j+1}} - P_{R_{j-1}}) \right\|^2}$$

(6)

The coordinate variable n of the nearest point B is :

$$n = \frac{((P_{R_{j-1}} - P_{L_{i-1}}) \times (P_{L_{i+1}} - P_{L_{i-1}})) \bullet ((P_{L_{i+1}} - P_{L_{i-1}}) \times (P_{R_{j+1}} - P_{R_{j-1}}))}{\left\| (P_{L_{i+1}} - P_{L_{i-1}}) \times (P_{R_{j+1}} - P_{R_{j-1}}) \right\|^2}$$

(7)

But because the manipulator can only be processed according to the line segment, different m and n will lead to different results of distance, showed in Fig.4.

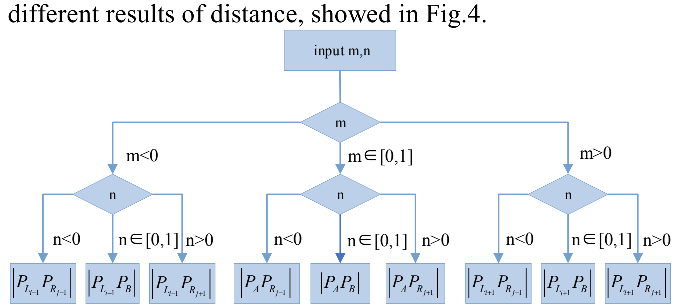

Fig.4 The distance is decided by m,n.

III. Kinematics Based on Obstacle Avoidance

The kinematics equation of the robot can be understood as the mapping between joint space $\boldsymbol{q}$ and terminal operation space $\boldsymbol{x}$:

$$x = f(q) \tag{8}$$

By calculating the derivative of time on both sides of the equal sign, we can get that:

$$\dot{q} = J^{+}\dot{x} + \left(I - J^{+}J\right)a \tag{9}$$

The first part of the right equations(9) is the robot minimum norm solution of the motion. J is the Jacobian matrix of the end motion of the robot. J_{d_0} is the Jacobian matrix of the most rear point in the robot.

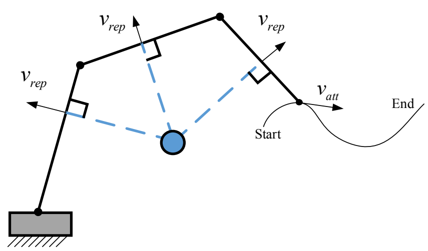

Fig.5 Effect of Obstacles on the Speed of Manipulator Link

Therefore, a new inverse kinematics equation is constructed in this paper.

$$\dot{q} = \left(I - \alpha J_{d_0}^{+} J_{d_0}\right) \cdot J^{+}\dot{x} + \beta (J_{d_0} N)^{+} (\dot{x}_0 - J_{d_0} J^{+}\dot{x}) \tag{10}$$

$$\alpha = \begin{cases} 0 & d_m > d_2 \\ \left(\dfrac{d_2 - d_m}{d_m}\right)^2 & d_2 > d_m \end{cases} \tag{11}$$

$$\beta = \begin{cases} 0 & d_m > d_2 \\ \left(1 + \cos\left(\pi \cdot \dfrac{d_{\min} - d_1}{d_2 - d_1}\right)\right)/2 & d_2 > d_m > d_1 \\ 1 & d_1 > d_m \end{cases} \tag{12}$$

α, β is a function of minimum distance dm, collectively known as obstacle avoidance gain.

When $d_m > d_2$, there is no collision risk, only the main motion, $\dot{q} = J^{+}\dot{x}$. When $d_2 > d_m > d$ it is in the stage of obstacle avoidance, attraction motion and deviation velocity are both. When $d_1 > d_m$ there is already a great risk of collision, $\beta = 1$ is mainly deviation motion.

IV SIMULATION VERIFICATION.

4.1 Situation 1

We assume the following situation during the operation of the manipulator: given an initial angle q of the manipulator, a workpiece is picked up, then it moves uniformly in the negative direction of the Y-axis for 0.8m, and then the workpiece is put down, and the task ends. We can easily calculate the inverse answer of joints.

In this case, a spherical obstacle that simulates the size of a worker's fist suddenly appears on the original trajectory during the operation. In the actual process, the operator mistakenly put his hand into the manipulation space of the robot.

The obstacle is 0.24m away from the starting point. If the obstacle avoidance operation is not carried out, then the manipulator and the workpiece will inevitably collide with the obstacle, which may lead to the damage of the manipulator or the worker.

At this time, according to the above equation(10), the obstacle avoidance trajectory of the manipulator is re-planned showed in Fig.6. changes of joints showed in Fig.7. In the simulation model, the capsule radius of the manipulator is 0.05m and the spherical obstacle radius is 0.05m.

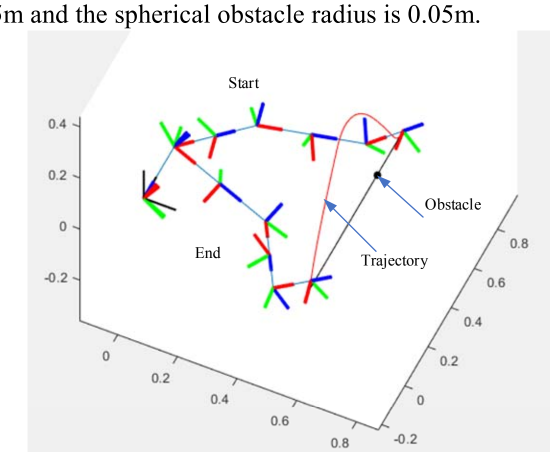

Fig.6 Simulation of obstacle avoidance motion of a manipulator in a situation

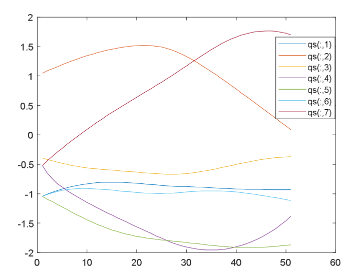

Fig.7 Angles of joints in the simulation process

The shortest distance between the obstacle and the capsules of the manipulator showed in Fig.8:

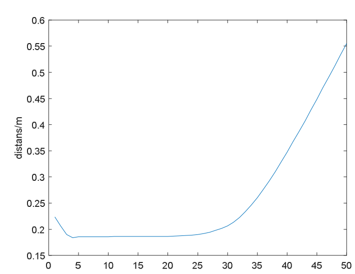

Fig.8 The shortest distance between the obstacle and the manipulator

It can be found that the minimum distance between the third capsule and the obstacle is greater than 0.18m, while the sum of the capsule radius and the obstacle sphere radius is

0.1m and the minimum distance is greater than 0.1m, so the manipulator will not collide with the obstacle. The simulation, Fig.9, also shows that there is a large distance between the obstacle and the manipulator.

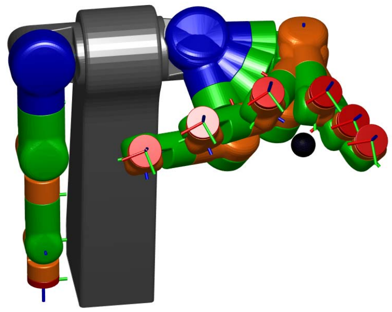

Fig.9 Entity simulation of obstacle avoidance motion

4.2 *Situation 2*

For dual-arm robots, there is a problem of cooperation between them. For example, at a certain moment, the right manipulator holds an object in a fixed position and waits for the workpiece to be processed. At this time, the left manipulator needs to move a workpiece from the left to the right. Because there is an overlap between the operating space of the two manipulators, there will be the possibility of collision between the two arms.

It is assumed that the joint angle of the right arm is qR=[pi/8 pi/8 pi/8 pi/8 pi/8 0 0 0], and the initial angle of the left arm is qL=[-pi/3 pi/3 pi/8 -pi/2 pi/2 -pi/4 -pi/6]. The right arm remains motionless and the left arm moves 0.6m to the left. When the collision is not calculated, the minimum distance between the left and right arms is detected. As it is shown in Fig.10 and Fig.11.

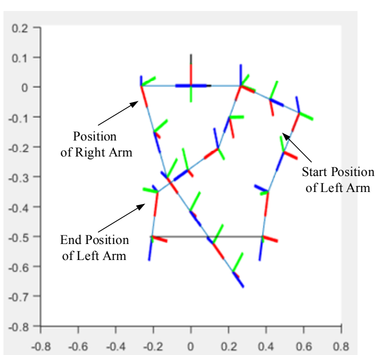

Fig.10 Two arms collide with each other

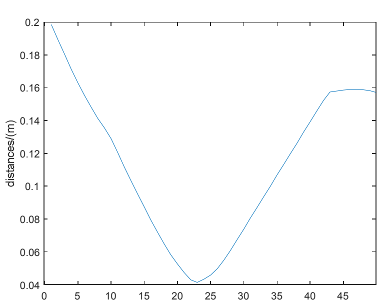

Fig.11 Distance between two manipulators without obstacle avoidance.

It can be found that the minimum distance between the left and right arms is close to 0. And it is less than 0.1m for a long time, which indicates that the collision has occurred. After the obstacle avoidance operation using the proposed algorithm, the simulation results are as Fig12-Fig15.

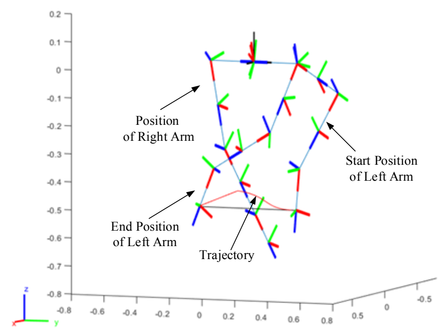

Fig.12 Simulation between two manipulators using obstacle avoidance algorithm

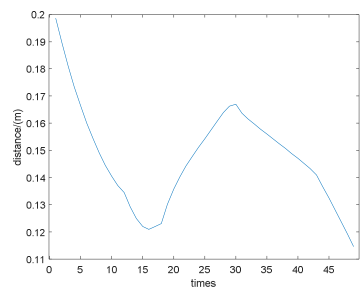

Fig.13 Distance between two manipulators after using obstacle avoidance algorithm

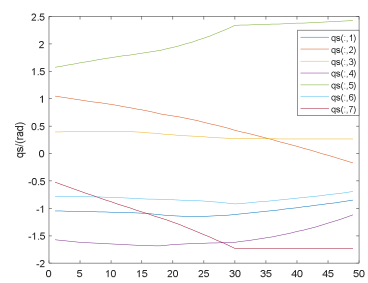

Fig.14 Change of left arm joint after using obstacle avoidance algorithm

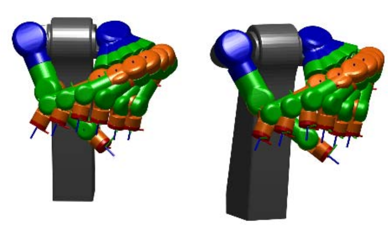

Fig.15 Motion model of the redundant dual-arm robot based on obstacle avoidance algorithm

V. The Conclusion

In an ideal environment, the space position of an obstacle, whether moving or stationary, should be real-time detected by sensors. On this premise, the relative position between the obstacle and the robot can also be calculated in real-time. By calculating the projection coordinates and the shortest distance between the obstacles and the capsules of the robot, two motion functions are constructed. One is the attraction motion along the pre-planned path direction, the other is the deviation motion of the manipulator along the shortest distance direction. The parameters between the two motion functions are also functions in the direction of the shortest distance and the shortest distance. In the two situations envisaged in this paper, the spherical obstacle fitted by the operator's fist and the other stationary arm of the two-arm robot is placed in the motion space of the left arm. The real-time distance between the manipulator and the obstacle can be calculated by calculating the joint angle of the left arm based on the inverse kinematics function constructed in this paper. This distance is larger than the pre-given warning value, which shows that there is no possibility of collision between the robot and the obstacle. It also verifies the reliability of the obstacle avoidance algorithm proposed in this paper. In future work, we will also study the coordinated obstacle avoidance method between two moving manipulators.

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