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Solving the Minimum Energy Consumption of a Manipulator with Constrained Redundancy

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Abstract: The exhaustive method is used to solve the maximum value of the end of the mechanical arm when the terminal angle of the mechanical armis unchanged and the end of the manipulator moves in a fixed direction, so that people can judge whether the mechanical armcan reach the target object from the current position in advance. If it can be reached, the mechanical arm will be controlled to approach the target object. If it cannot be reached, the mechanical arm platform needs to be moved so that it can finally reach the target object. The simulation results show that the algorithm proposed in this paper can quickly and accurately calculate the maximum range that can be actually reached by the mechanical arm, and it has a good application value for embedded systems with limited computing power as well as systems with high real-time requirements.

1. Introduction

A remote-control mechanical arm is widely used in anti-terror work tasks. The system is usually a mobile platform equipped with a mechanical arm, cameras, weapon system, and sensor system, and it can be used to perform reconnaissance, fetching and eod tasks, and through teleoperation, the operator can control the mobile platform to get close to the target and grab objects with the mechanical arm. Therefore, a mechanical arm is usually a redundant system, which allows it to be flexible enough to adapt to a complex environment.

Path planning and obstacle avoidance of redundant mechanical arm is a hot research topic in the current study. In an environment with constrainedmotion trajectory, in order to respond quickly, it is necessary to adopt optimization to get close to and grasp objects, and especially for the system with poor computing power and higher real-time requirements, it is very important to use a less time-consuming algorithm. As it is complex to accurately perceive the real environment and it needs to respond quickly to a large number of uncertain events, supervisory control rather than automatic control is applied in these hazardous environments. Therefore, it is necessary to plan and calculate the maximum motion path of the mechanical arm.

2. Redundant mechanical arm system

The redundant mechanical arm has six degrees of freedom and is installed on a mobile platform, through which the mechanical arm can increase its range of motion, enabling it to adapt to complex environments and perform related tasks. The mechanical arm has a coplanar four-joint redundant mechanical arm, and its related parameters and specifications are shown in Table 1.

The mechanical arm control system adopts TMS320LF2407ADSP and PC-104 mainboard to conduct real-time control. Its main functions include receiving the command data from the operator, collecting the position data of each joint, acquiring the information of obstacles, optimizing the terminal control algorithm, and adjusting the configuration of the mechanical arm.

The control system consists of six modules, including a command interaction module, trajectory planning module, motion planning module, sensor sampling module, servo control module, as well as state feedback module. The command interaction module is used to receive commands from the upper computer to decide whether to carry out trajectory planning or uniaxial motion. The trajectory planning, sensor sampling, and servo control are periodic tasks, and they are used to calculate the target position of each shaft, the data of the sample sensor, and send output signals to the servo driver, respectively. The control system adopts WindowsCE system and Microsoft Bedded VisualC++4.0 is used to program.

Table 1 Specifications and parameters of the mechanical arm

Specifications	Parameters
Weight (kg)	410
Reach range	4.109
Load (kg)	20
Length of joint (m)	L_1,1.280 L_2,1.100 L_3,1.000 L_4,0.729
Joint angle range(°)	$\theta_1, -10 \sim 90$ $\theta_2, -90 \sim 0$ $\theta_3, -130 \sim 15$ $\theta_4, -45 \sim 45$ $\theta_5, 0 \sim 270$ $\theta_6, 0 \sim 300$

3. Exhaustion Programming Algorithm

When the redundant mechanical arm approaches the target object, the terminal angle of the mechanical arm remains unchanged, and it is required to control the end of the mechanical arm to approach the target object in a fixed direction. At this point, if the extreme value range that can be reached by the mechanical arm along a fixed direction in a straight line can be calculated, and the actual distance between the end of the mechanical arm and the target object can be measured by a laser rangefinder, then it can judge whether the mechanical arm reach the target object by starting from the current position. If not, the vehicle needs to be moved, so that the mechanical arm can finally reach the target object. Therefore, pre-planning is very meaningful for the mechanical arm to approach the target object. Next, the mathematical model of manipulator motion will be analyzed and an exhaustion planning algorithm will be proposed.

As shown in Fig. 1, the end of the mechanical arm is set by starting from the initial position E.

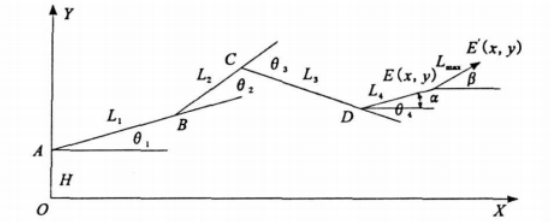

Fig. 1 Planar structure of the mechanical arm

The initial angles of the four rods are $\theta_{10}, \theta_{20}, \theta_{30}, \theta_{40}$, respectively, and the terminal angle αkeeps unchanged, and the end moves in a straight line along the fixed angle β, and the limit position is E'. At this point, the angle values of each bar of the mechanical arm areθ_1,θ_2,θ_3,θ_4, respectively, and in this process, the movement distance of the end of the mechanical arm is $L_{\max}$. Then, the terminal coordinates $E\left(f_{x0}, f_{y0}\right)$and terminal angle α are as follows:

$$\begin{cases} f_{x0} = L_1\left(\cos\theta_{10}\right) + L_2\cos\left(\sum_{i=1}^{2}\theta_{i0}\right) + \\ L3\cos\left(\sum_{i=1}^{3}\theta_{i0}\right) + L_4\cos\left(\sum_{i=1}^{4}\theta_{i0}\right) \\ f_{y0} = H + L_1\sin\left(\theta_{10}\right) + L_2\sin\left(\sum_{i=1}^{2}\theta_{i0}\right) + \\ L_3\sin\left(\sum_{i=1}^{3}\theta_{i0}\right) + L_4\sin\left(\sum_{i=1}^{4}\theta_{n}\right) \\ \alpha = \sum_{i=1}^{4}\theta_{i0} = \text{ Constant} \end{cases} \tag{1}$$

In the actual mechanical structure, the motion range of the four rods of the mechanical arm is limited by the mechanical limit, and the actual rotation angle range of each rod meets the constraint conditions as shown in Formula (2).

$$\begin{cases} \theta_{1\min} \leqslant \theta_1 \leqslant \theta_{1\max} \\ \theta_{2\min} \leqslant \theta_2 \leqslant \theta_{2\max} \\ \theta_{3\min} \leqslant \theta_3 \leqslant \theta_{3\max} \\ \theta_{4\min} \leqslant \theta_4 \leqslant \theta_{4\max} \end{cases} \tag{2}$$

Based on the analysis, it can be seen that the problem is transformed into an optimization problem satisfying the constraints of Formula (4), as shown in Formula(3).

max(L)

$$L = \left[H + L_1\sin\left(\theta_1\right) + L_2\sin\left(\sum_{i=1}^{2}\theta_i\right) + L_3\sin\left(\sum_{i=1}^{3}\theta_i\right) + L_4\sin\left(\sum_{i=1}^{4}\theta_i\right) - f_{y0} \right]^2 + \\ \left[L_1\cos\left(\theta_1\right) + L_2\cos\left(\sum_{i=1}^{2}\theta_i\right) + L_3\sin\left(\sum_{i=1}^{3}\theta_i\right) + L_4\sin\left(\sum_{i=1}^{4}\theta_i\right) - f_{x0} \right]^{2-0.5} \tag{3}$$

$$\begin{cases} \left[H + L_1\sin\left(\theta_1\right) + L_2\sin\left(\sum_{i=1}^{2}\theta_i\right) + L_3\sin\left(\sum_{i=1}^{3}\theta_i\right) + L_4\sin\left(\sum_{i=1}^{4}\theta_i\right) - f_{y0} \right] \times \\ \cos\left(\beta\right) = \left[L_1\cos\left(\theta_1\right) + L_2\cos\left(\sum_{i=1}^{2}\theta_i\right) + L_3\cos\left(\sum_{i=1}^{3}\theta_i\right) + L_4\cos\left(\sum_{i=1}^{4}\theta_i\right) - f_{x0} \right] \times \sin\left(\beta\right) \\ \sum_{i=1}^{4}\theta_i = \alpha = \text{ Constant} \\ \left[L_1\cos\left(\theta_1\right) + L_2\cos\left(\sum_{i=1}^{2}\theta_i\right) + L_3\cos\left(\sum_{i=1}^{3}\theta_i\right) + L_4\cos\left(\sum_{i=1}^{4}\theta_i\right) - f_{x0} \right] \times \cos\left(\beta\right) \geq 0 \\ \left[H + L_1\sin\left(\theta_1\right) + L_2\sin\left(\sum_{i=1}^{2}\theta_i\right) + L_3\sin\left(\sum_{i=1}^{3}\theta_i\right) + L_4\sin\left(\sum_{i=1}^{4}\theta_i\right) - f_{y0} \right] \times \sin(\beta) \geqslant 0 \\ \theta_{i\min} \leqslant \theta_i \leqslant \theta_{i\max} \left(i = 1, 2, 3, 4\right) \end{cases} \tag{4}$$

The Lagrange relaxation method can be used to obtain the solution to this problem, but it is necessary to solve the derivative value and inverse matrix when using this method. For embedded systems with limited computing power and systems with high real-time requirements, it is not practical to use the Lagrange relaxation method to solve the problem.Then according to the actual characteristics of the mechanical structure, an exhaustion planning algorithm was proposed. When meeting the constrained motion that the terminal is a straight line and the terminal angle remains unchanged, the structure's degree of freedom is 2. When moving to the limit position, at least 2 rods reach the limit position or the included angle of two adjacent barsis 0°. Therefore, when reaching the limit position, the angles of at least 2 rodsare selected from the following set of angles, $\theta_{iset} = \theta_{i\min}, 0.0, \theta_{i\max}\left(i = 1, 2, 3, 4\right)$. Thus, the total number of all possible angle choices can be obtained: $N = C_4^2 \times 3 \times 3 = 54$. By solving the result of the solution under such a situation, the solution of the optimization problem can be obtained.

If the angle is set as $\theta_1 = \theta_{1\min}, \theta_2 = \theta_{2\min}$, then Formula (4) with inequality constraint is solved. If there is no solution to the equation set, then there are no solutions to θ_3 and θ_4 when θ_1 and θ_2 are the assumed angles. If the equation set has a solution, then the solution to the system set is the angle data of θ_3 and θ_4 of the rods, and then the angle data of each rod at this time is θ_1,θ_2,θ_3,and θ_4, so the corresponding distance L can be obtained according to Formula (3).

4. Experimental results

Fig. 2 shows the maximum position that the four-rod mechanism can reach when moving along the direction of 0.65π from the starting point, and the graph of the angle of at least two rods in the set $\theta_{i\text{set}} = \theta_{\text{i}\min}, 0.0, \theta_{i\max} \left(i = 1, 2, 3, 4\right)$ during the moving process. According to the figure, the advantages of the redundant mechanical arm can be found. The maximum position reached by fixing one of the rods in a straight line is not necessarily the limit position that can be reached by the mechanical arm starting from this position. At this moment, the mechanical arm can continue to move by adjusting other rods and finally reach the actual maximum position. Meanwhile, by calculating the angle data of each rod at the maximum position in advance, the actual moving angle data of each rod can be obtained when reaching the maximum position, so as to minimize the actual moving distance of each rod.Fig. 3 shows the graph of the maximum position that can be reached when the redundant mechanical arm moves in all directions from the starting point.

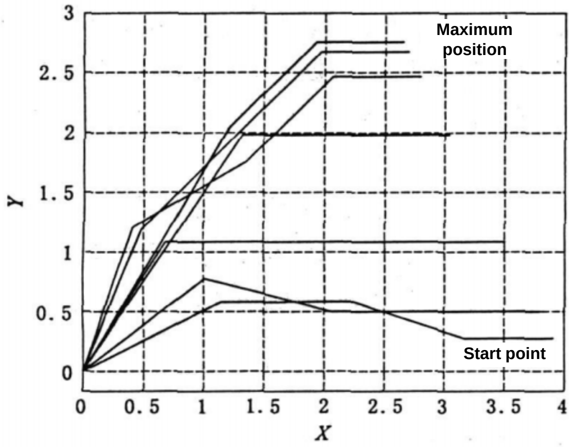

Fig. 2 Maximum distance that can be reached when the end of the redundant mechanical are moves along the fixed direction 0.65π

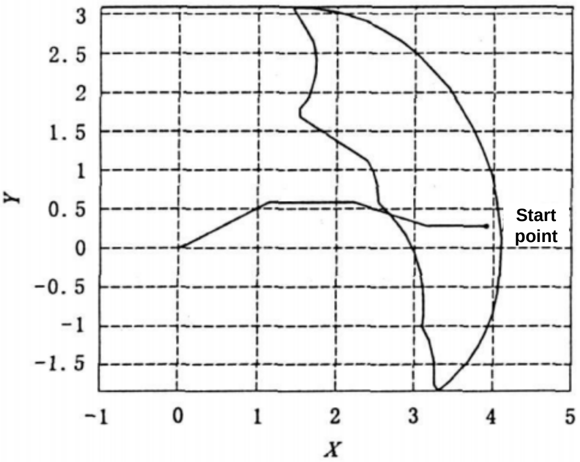

Fig. 3 The limit range that can be reached when the end of the redundant mechanical arm moves in all directions

5. Conclusion

In this paper, a method was proposed to solve the minimum energy consumption of the redundant mechanical arm which can be moved under the constraints of keeping the angle of the terminal pose unchanged and the trajectory of the terminal motion in a straight line. Transforming this problem into a mathematical model is an optimization problem with constraints. For the system with limited computing power and high demand for real-time performance, the conventional Lagrange relaxation method has poor efficiency and can not meet the practical needs. Therefore, the exhaustive method is used to solve the problem, and based on the actual calculation verification, the exhaustive method can be used to quickly solve the optimal value of the problem.

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