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Original Article

Unknown constrained mechanisms operation based on dynamic interactive control☆

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Abstract

In order to operate various constrained mechanisms with assistive robot manipulators, an interactive control algorithm is proposed in this paper. This method decouples motion and force control in the constrained frame, and modifies the motion velocity online. Firstly, the constrained frame is determined online according to previous motion direction; then the selection matrix is adjusted dynamically, the constrained motion direction is chosen as the driving-axis. Consequently, the driving-axis and non-driving-axis are decoupled; finally, velocity control and impedance control are implied on above axes respectively. The selecting threshold for driving-axis is also varying dynamically to fit different constrained mechanism. Door-opening experiments are conducted to verify the performance of the proposed method.

Keywords: Unknown constrained mechanism; Selection matrix; Constrained frame; Robot manipulator; Impedance control

1. Introduction

The application field of the assistive robot is getting increasingly wide, and the interactions between assistive robot manipulators and the environment, such as opening the door, pulling a drawer, serving the tea, is becoming more and more closely [1–3]. There are various constrained mechanisms in the interactive environment. In the situations where task descriptions of each constrained mechanism are not necessary, manipulators need a way to operate the unknown constrained mechanisms.

The operation of unknown constrained mechanisms is very complicated. For instance, opening the door, which involves a series of problems such as positioning, trajectory planning, and tracking, is a typical problem of the unknown constrained mechanism operation. Most of the traditional opening-door operation needs to model the door first to plan a trajectory, which does not provide the universal solution because different tasks need different task descriptions. For example, Nagatani modeled the door and presented a detailed analysis of the path planning to open the door [4,5]; Peterson used the smallest-model analysis to predict the parameters but the success rate of opening the door is 90% [6]; Pujas proposed a force-position hybrid control method, but the inaccurate task description model might result in positioning errors [7]; Petrovskaya adopted the laser-scanning modeling based particle filter method which also suffered from the defects of inaccuracy [8]. There are also model-free methods. Schmid installed multi-point haptic sensors on the hand claw and force/torque sensors on the wrist to open the door operation, but this kind of method increased the complexity of the controller [9]; Lutscher proposed to operate the unknown constrained mechanisms based on

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an impedance control method, which adjusted the guiding speed by impedance control to achieve two-dimensional plane operation [10]; On the basis of [10], we put forward a operation method based on impedance control and the motion prediction. By fitting the historical trajectory to estimate motion model, and then adjusting the orientation and amplitude of the guiding speed, the operating efficiency is improved [11]; Furthermore, we put forward the dynamic hybrid complaint control method [12] that online chooses traction axis and estimates constraint coordinate system. Besides, the operating space is not limited by the two-dimensional plane. However, because the threshold of the traction axis selection is fixed, this method cannot manipulate constrained mechanisms with different resistance.

This paper proposed a dynamic interacting control based method, which developed from the force/position hybrid control [13] that introduces dynamic selection matrix to dynamically choose the direction of the force and speed control. Besides, this method does not require a detailed task description. The constrained motion direction is chosen as the driving axis, and other axes as the non-driving axis. The speed-control method is adopted on the driving axis to produce active-traction effect, while the force-control method is used on the non-driving axis to adjust the position and posture of manipulator passively. Selection of the driving axis is the key point of this method. Under the precondition of the unknown constrained mechanisms moving direction, the driving axis can be selected randomly to test the moving direction of the constrained mechanisms. By selecting matrix criterion, the driving axis can be adjusted dynamically until the constrained mechanisms began to move. Then according to the moving direction of the constrained mechanisms, the dynamic constraint coordinate system can be dynamically estimated. And the decoupling of the driving axis and non-driving axis can be accomplished through the dynamic selection matrix. Through the dynamic adjustment, choose suitable driving axis is chosen to manipulate the unknown constrained mechanisms. Impedance control method is adopted on the non-driving axis, because the manipulators are moving follow the constrained mechanisms, which resulting in the position errors and the force errors. So force control alone cannot tracking the position errors of the manipulators in time. Impedance control does not directly control the desired force and position, but achieves the complaint function by controlling the dynamic relationship between position and force, which is suitable for the non-driving axis control method in this paper.

2. Controller design

This paper takes the door-opening task as an instance to introduce the dynamic interaction control based method to manipulate the on of the limited operation method to manipulate the unknown constrained mechanisms. It is assumed that the position and orientation of the door and the position of the door's axis are unknown. For simplicity, it is assumed that the end effector has grasped the doorknob as shown in Fig. 1. As shown in the figure, the robot's base frame is denoted as $\sum_b$, the end-effector frame is denoted as $\sum_e$, and the constrained frame is denoted as $\sum_c$. The origins of $\sum_c$ and $\sum_e$ are of coincidence, which are both the doorknob denoted by p_c with respect to $\sum_b$.

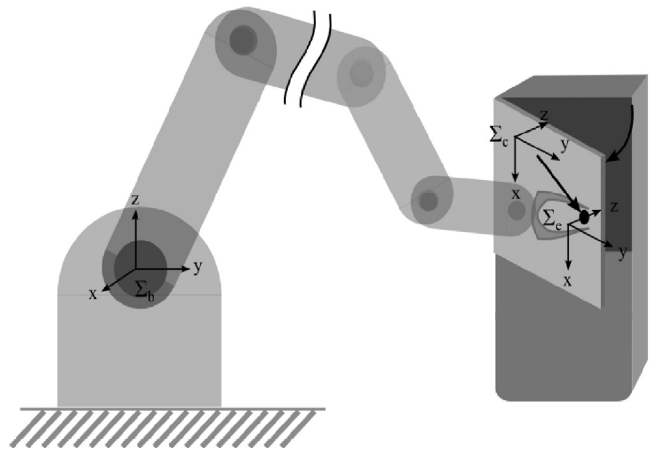

Fig. 1. The system model.

2.1. Control system design

The block diagram of the control system is shown in Fig. 2. The system can be mainly divided into operating space velocity controller and the angular velocity controller. The outputs of the linear velocity controller and the angular velocity controller are add together to produce the control velocity, after that it will be transferred to the joint space through the differential inverse kinematics. The linear velocity controller adopts the dynamic interactive control method and the angular velocity controller adopts the moment-following control method.

Under $\sum_c$, assume that $\dot{p}^c$ is the current linear velocity, $\dot{p}_d^c$ is the desired linear velocity, ω is the control angular velocity, ω is the linear velocity of the end effector, v_i is the driving linear velocity, f_d^c is the desired control force, τ_d^c is the desired control torque, $\dot{p}$ is the control velocity of the end effector. $R_e^c(v^e)$ is the rotation matrix from the end-effector frame to the constrained frame, $v^e = (v_x, v_y, v_z)$ is the end effector's velocity with respect to the end-effector frame, S is the selection matrix. The force and torque measured under $\sum_e$ by the six-dimension force/torque sensor are transferred to the constrained frame $\sum_c$ and denoted as h^c, including force f^c and torque τ^c.

As shown in the Fig. 2, $R_e^c(v^e)$ and S are changed dynamically. The former selects the dynamic constrained frame and the latter selects the driving axis, which will described in Section 2.2. Because the constrained mechanism is unknown, $\dot{p}_d^c$ is unknown. In the k th control period, define the desired velocity of the $k+1$ th control period as:

$$\dot{p}_d^c(k+1) = \dot{p}^c(k) \tag{1}$$

The control steps are as follows:

1) Give an arbitrary initial speed to the end effector to test the movement;
2) According to the moving direction of the constrained mechanisms, the constrained frame and the selection matrix are dynamically chosen;