Research on Position-based impedance control in Cartesian space of robot manipulators

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***Abstract*—The dexterous manipulability of robot manipulators depend on its manipulative dexterity, grasp robustness, and human operability, which greatly influences the ability of humanoid robots for dexterous tasks. Consequently, the control system design and control strategies for dexterous robot manipulators become one of the hot spots in humanoid robots field. In this paper, a compliant control algorithm is proposed for the dexterous hand system. The theoretical analysis of the position-based impedance control algorithm in Cartesian space is carried out. The control structure is established and dynamic model of the algorithm is given. Finally, feasibility and effectiveness of the algorithm are verified by designing an impedance control simulation experiment.**

Keywords- impedance control; robot manipulators; force and position hybrid control; control strategy.

I. INTRODUCTION

In the process of engaging in complex and refined operations, dexterous hands inevitably come into contact with the external environment. The main problem that will be faced at this time is contradictory relationship between flexibility requirement of the dexterous hand in constrained space and high stiffness requirement of position servo system along with mechanical structure of end effector in free space. The key to solve the problem is improving mechanical structure or adopting an effective control strategy, so that the end of dexterous hand has certain compliance ability to the external environment, and the dexterous hand's compliant control is an important feature that reflects the level of intelligence.

The two main methods of compliant control strategy are passive compliance with flexible materials and active compliance with control algorithms. In this paper, a compliant control algorithm is proposed for the dexterous hand system. By adjusting the impedance parameters including inertia matrix, damping matrix, stiffness matrix of the end, contact force and target position meet the desired dynamic characteristics, instead of directly controlling the expected force and position, thus achieving active compliance of finger control in consequence.

II. PRINCIPLE OF IMPEDANCE CONTROL ALGORITHM

In position-based Cartesian impedance control, the contact force is measured by six-dimensional force sensor, and the detected force is fed back to the impedance filter, then a corrected position vector is generated by the impedance filter $X_f = (x_f, y_f, z_f)^T$.

Corrected position vector meets the following relationship

$$F = M_d \ddot{X}_f + B_d \dot{X}_f + K_d X_f \tag{1}$$

Therefore

$$X_f(s) = \frac{F(s)}{M_d s^2 + B_d s + K_d} \tag{2}$$

As K_d, B_d, M_d are diagonal matrix, the above equation is similar to a second-order low-pass filter. Filtering each F, corrected position vector X_f is obtained as filtered result. Corrected position vector is added to the reference position vector X_r generated by the trajectory planning to obtain a expected position control command $X_d = (x_d, y_d, z_d)^T$.

$$X_d = X_r + X_f \tag{3}$$

When dexterous hand moves in free space and there is no contact with the external environment, obviously $F \equiv 0$. In consequence, $X_f \equiv 0$, $X_r = X_d$. After dexterous hand comes into contact with the external environment, if the position controller is accurate, where $X = X_d$, then

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$$X_f = X_r - X \tag{4}$$

Therefore, it can be seen that the position-based impedance control in Cartesian space is completely dependent on the position controller of the inner ring.

The position-based impedance control strategy in Cartesian space belongs to operation space control, and final control variable also needs to use Jacobian transpose method to associate operation space with joint space, as shown in Fig. 1. First, Cartesian space requires a high-gain position controller to compensate for the nonlinear effects of the system and improve control accuracy. Second, the required Cartesian force F in control process also needs to be calculated by Jacobian matrix. The relationship between Cartesian force and joint torque is $F = J^{-T}\tau$. The joint position controller in Fig. 1 represents the Cartesian space position control law, which can be used in the position control algorithm of general rigid robots, such as PD control, calculation of torque and so on. The reference position of the position controller can be calculated from desired impedance relationship and end Cartesian force as follows.

$$x_f = x_d - \frac{F}{M_t s^2 + B_t s + K_t} \tag{5}$$

Where x_d represents desired position in Cartesian space

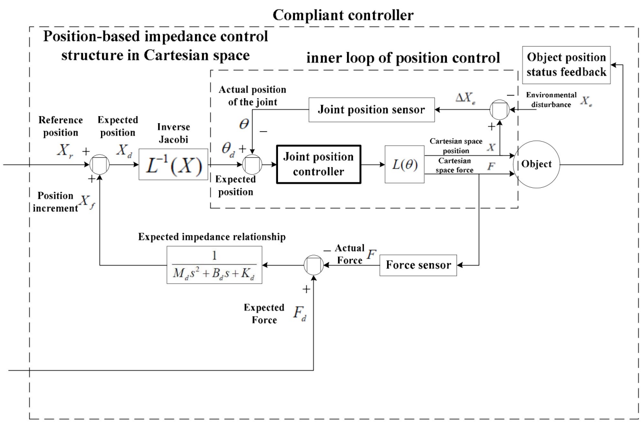


Fig. 1 Position-based impedance control strategy in Cartesian space

x_d can be obtained by using the desired joint position q_d by positive kinematics, or through the Cartesian space trajectory planner.

III. SIMULATION EXPERIMENT OF CARTESIAN SPACE IMPEDANCE CONTROL ALGORITHM

Force-based impedance control strategy in Cartesian space, because its inner loop controller is torque control, it requires high measurement accuracy and dynamic characteristics on force sensor. Position-based impedance control strategy in Cartesian space, which converts the desired force into a position compensation through a second-order impedance filter and then sent to the position controller of inner loop. This method is robust to measurement error and noise signal of force sensor. Therefore, the position-based impedance control strategy in Cartesian space is presented in this paper. Single-finger simulation model is established based on ADAMS and Simulink. Through impedance control simulation experiment, active compliance of the finger to external environment during movement process is realized.

A single finger impedance physical model is created as shown in Figure 2. An obstacle baffle is set in the effective working space, and the desired target position is set behind the baffle. The path is planned in the Cartesian space, so that the finger first tracks the joint position trajectory in the free space. After contacting the obstacle baffle, finger impedance control is performed on the contact surface.

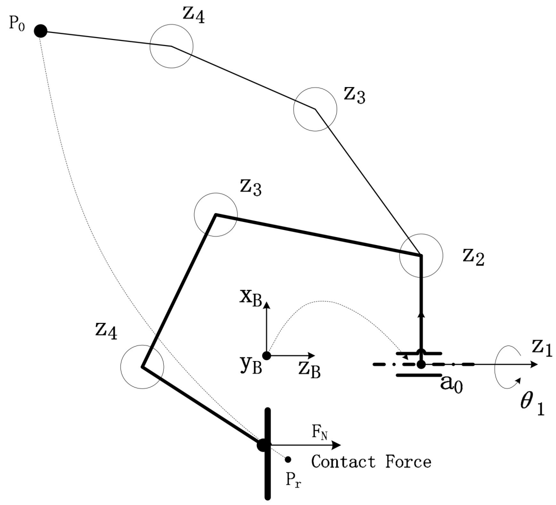
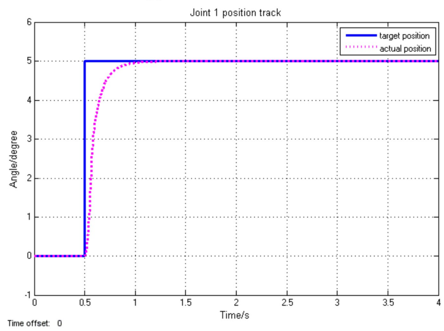
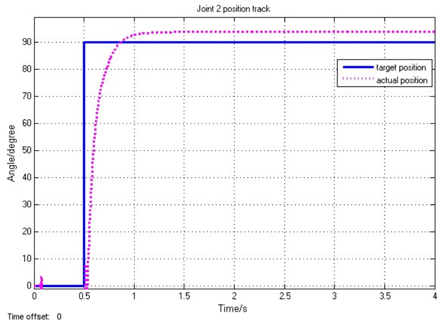


Fig 2 single finger impedance physical model in Cartesian space

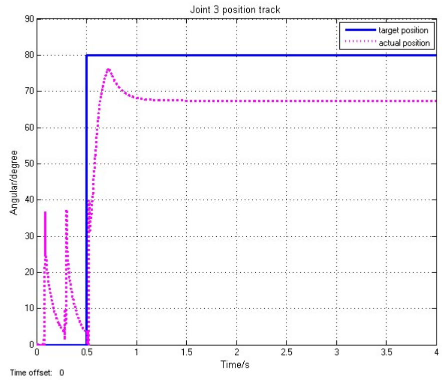
During the simulation experiment, because dynamic response of the finger is not high, the influence of inertial force on dynamic characteristics of the system is weakened, where inertia matrix $M_d = [0, 0, 0]'$. The end of finger is simplified to a spring-damped system, assuming damping matrix of the system $B_d = [1, 1, 1]'$ and stiffness matrix $K_d = [20, 20, 5]'$. The fingertip end contact force is fed back to the impedance filter, and the calculated position compensation amount is sent to the inner loop position controller, so that finger has a certain flexibility in the process of contacting the obstacle baffle. The simulation results are shown in Fig. 3.



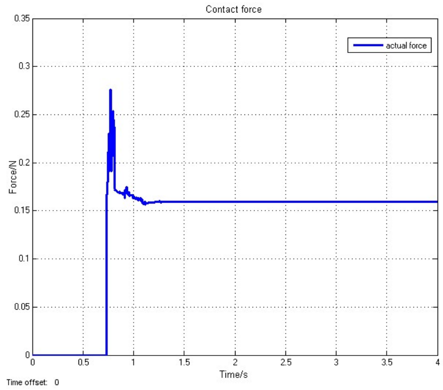
（a）Position response of joint No.1



(b) Position response of joint No.2



(c) Position response of joint No.3



(d) Contact force response of fingertips

Fig. 3 Simulation results of position-based impedance control in Cartesian space

According to the simulation results of impedance control, it can be seen that when finger moves in the free space, the force sensor has an output value of approximately 0 due to the presence of certain noise. When fingertip is in contact with the obstacle baffle, output value of the force sensor rapidly increases. At this time, the impedance controller compensates and adjusts the reference trajectory through the contact force information of the outer loop, and quickly stabilizes. The contact force between finger and the baffle is prevented from further increasing. It can be seen contact force is automatically adjusted and stabilized quickly, and finally active compliance of the finger to external environment is achieved.

IV. Conclusion

In this paper, the control structure and control strategy of robot manipulators are studied in detail. The theoretical analysis of the position-based impedance control algorithm in Cartesian space is carried out. The control structure is established and dynamic model of the algorithm is given. By designing impedance control simulation experiment, position trajectory tracking and force control of the three-degree-of-freedom finger are realized, which lays an important theoretical foundation for robot manipulators to realize position trajectory tracking in free space and force control in constrained space.

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