Human-Machine Interaction Impedance Control Method with Force Tracking

Zhipeng Wang [1], Haixin Xu [2], Rong Jiang [3], Jiahang Liu [4]

***Abstract*— One of the challenges in applying robotics technology to the healthcare domain is achieving safe and comfortable human-robot interaction. Impedance control is a simple and effective approach to address this issue. However, traditional impedance control fails to exhibit consistent force control in response to external environments, limiting its applicability in many human-robot interaction scenarios. In this paper, we propose a control method that combines impedance control with force control, enabling constant force tracking along a selected axis while maintaining traditional impedance control effects in other axes. This method is suitable for a wider range of interactive scenarios. We validate the proposed method through collaborative tabletop wiping tasks.**

I. INTRODUCTION

Applying robotics technology to the healthcare field has been a hot topic in recent years [1], and one important area of research is focused on enhancing interaction between humans and robots to improve patient comfort and trust in healthcare institutions. In many human-robot interaction scenarios, close physical contact between robots and humans is required [2][3]. In these cases, it is not reasonable to rely solely on motion control strategies to regulate contact forces. When the robot interacts with humans or the environment, it is necessary to generate appropriate contact reactions while closely following the desired trajectory, and sometimes even maintaining the desired force [4]. In the past few decades, force control has attracted considerable attention from researchers, leading to the development of classical force control techniques such as impedance control [5] and force-position hybrid control [6]. Hybrid force/position control is based on partitioning the control problem into position constraints along the normals of a generalized surface and force constraints along the tangents [7]. Impedance control utilizes a virtual mass-spring-damper system to achieve dynamic response at the contact point, so it is adaptable to the transition between free motion and constrained motion, and it shows satisfied tracking capability when the external constraints are known. Impedance control can be broadly classified into two types: admittance control and impedance control [8].

This paper extends the traditional impedance control approach by incorporating a constant force tracking mechanism. It enables achieving constant force tracking effect on certain axes while maintaining traditional impedance control effect on other axes. Moreover, the decoupling between different axes is ensured. Additionally, the introduction of virtual limits provides a more comfortable and safe human-robot interaction experience. The proposed method has been implemented and tested in a desktop wiping task.

II. METHODOLOGY

Impedance with Force Tracking Control

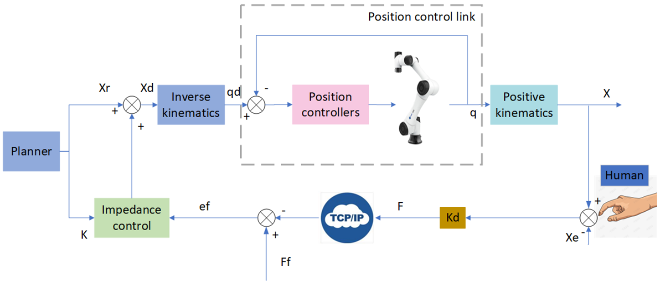

Fig. 1: Diagram of impedance control

Impedance control is an indirect force control method that aims to emulate mechanical impedance behavior. It achieves force control by establishing a dynamic relationship between force and position. This approach closely resembles the behavioral patterns observed in humans during various contact tasks. The core equation is shown below:

$$M_d(\ddot{x}_d - \ddot{x}_0) + D_d(\dot{x}_d - \dot{x}_0) + K_d(x_d - x_0) = F_{ext} - F_d \tag{1}$$

In the equation, Fext represents the actual applied force, Fd represents the desired contact force, x_0, $\dot{x}_0$, $\ddot{x}_0$ denote the actual position, velocity, and acceleration of the end effector of the robot arm, while x_d, $\dot{x}_d$, $\ddot{x}_d$ refer to the desired position, velocity, and acceleration of the end effector. M_d、D_d, and K_d correspond to the desired virtual mass matrix, damping matrix, and stiffness matrix, respectively.

In many task scenarios, it is required for a robot to achieve constant force tracking in a specific direction while maintaining impedance control in other directions. To achieve this, we will modify the formula of impedance control to attain a constant force tracking effect in a fixed direction.

First, we need to analyze the relationship between the desired contact force and the contact position. For simplicity, we will consider a one-dimensional interaction force in the subsequent analysis. Let's assume that the position of the contact surface when no force is applied is denoted as x_e. The position deviation e can be written as $e = x_d - x_e$, where x_c represents the desired contact position. (1) can be expressed as

$$\Delta f = f_e - f_d = m\ddot{e} + b\dot{e} + ke \tag{2}$$

In the steady state, to achieve consistency between the contact force and the desired force, i.e., $\Delta f = f_e - f_d = 0$, there are two main cases that need to be discussed:

Case 1: When $f_d = 0$, there is no interaction force between the robotic end effector and the environment as they are just in contact. In this case, $e \equiv 0$ regardless of the chosen value of k, and the steady state condition is always satisfied.

Case 2: When $f_d \neq 0$, the robot needs to apply a force on the environment, i.e., $e \neq 0$. In order to achieve $\Delta f = 0$ in the steady state, k needs to be set as 0. Therefore, the formula (2) becomes

$$\Delta f = f_e - f_d = m\ddot{e} + b\dot{e} \tag{3}$$

It can be observed that by setting appropriate values for m and b, when the system reaches a steady state with $\dot{e}$ and $\ddot{e}$ both equal to 0, $\Delta f = 0$, which means $f_e = f_d$

III. EXPERIMENTATION AND RESULTS

Many patients may struggle to independently perform simple household chores, such as wiping a tabletop. However, with the assistance of collaborative robots, their burden can be significantly reduced. To validate the effectiveness of the proposed algorithm in a human-robot collaboration scenario, we conducted experiments focusing on the collaborative wiping task between humans and robots. In the wiping task, we applied a constant tracking force of 5N in the vertical direction of the robot arm with respect to the table. This ensured a stable interaction force of 5N between the arm and the table when they came into contact. Additionally, we set the damping coefficient, dz, for this axis to 200 N·s /m to achieve smooth contact between the wiping surface and the table. The height of the wiping motion was manually controlled by an operator.

Next, we set the stiffness values kx = ky = 0 N/m and the damping coefficients dx = dy = 100 N·s /m for the horizontal (xy) axes in contact with the table. Under no external force, the arm remained stationary in the xy plane. However, when an operator applied a force in the xy plane, the arm responded and moved accordingly. This enabled collaborative wiping tasks to be performed.

To enable the robotic arm to perform wiping tasks on an unknown plane, the rotational stiffness of the arm is maintained at krot = 50 Nm/rad on all axes. Additionally, to ensure the safety of the operator, virtual limits are implemented on the xyz axes, preventing the end effector of the arm from moving beyond the specified positions. This enhances the operator's trust in the robot and improves the comfort of interaction.

Experiments were conducted using the test-bed as shown in Fig.2.

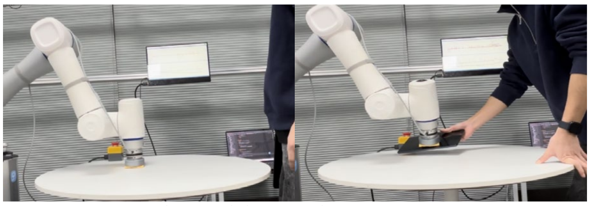

Fig. 2: Wiping experiment scene

During the experiment, we set a wiping trajectory for the robotic arm to move back and forth along the y-axis. The end effector trajectory and the force acting on the z-axis are shown in Fig. 3. As we can observe, when the robotic arm is not subjected to human forces, it follows the designated trajectory. However, when a force is applied by a person along the x-axis, the robotic arm deviates from its original trajectory to adapt to the movement imposed by the person. It then continues the wiping task at the new position.

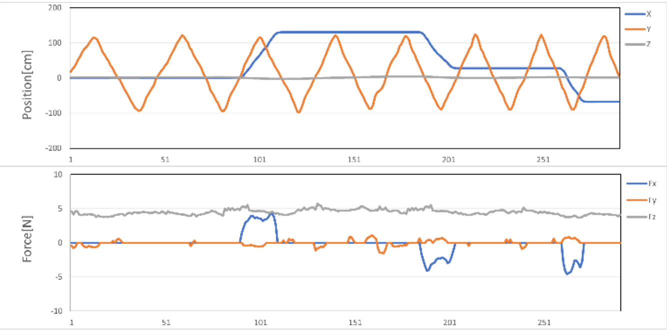

Fig. 3: Position and force variation during horizontal tabletop wiping

Later, we used an inclined plane to verify the algorithm's ability to maintain a constant force on an unknown plane. The operator holds the inclined surface and adjusts the inclination angle as desired, while the robotic arm adapts and adjusts the inclination angle accordingly, enabling human-robot collaboration in the wiping task. The end effector trajectory and the corresponding end effector force during the wiping are shown in the Fig. 4.

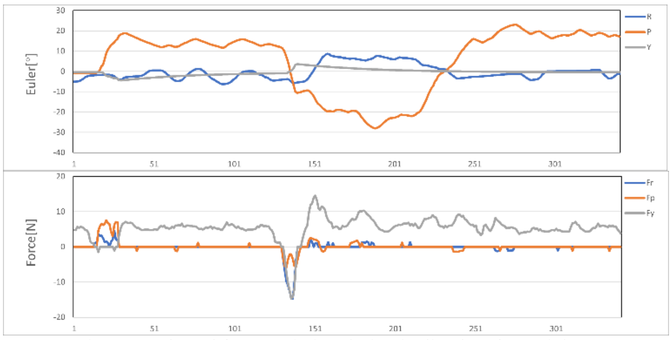

Fig. 4: Angle and force variation during inclined surface wiping

It can be observed that as we adjust the angle of the wiping plane, the robotic arm also adjusts the end effector angle accordingly to adapt to the wiping surface. Throughout the wiping process, it consistently maintains an interaction force of 5N with the contact surface.

Throughout the entire experiment, there is some fluctuation in the contact force. This is mainly due to a certain amount of delay in the network communication process, which results in a time delay between the force information received by the computer and the actual force.

IV. CONCLUSION AND FUTURE WORK

Impedance control is a crucial approach for achieving safe human-robot interaction. It allows for real-time response and trajectory adjustments when humans make physical contact with robots. This article proposes a constant force tracking impedance control method that incorporates constant force tracking control onto traditional impedance control. This method achieves constant force tracking in specific axes, thereby expanding the application scope of traditional impedance control in human-robot interaction scenarios.

Promising results have been obtained in the collaborative task of wiping a desktop.

In the future, we will introduce a variable impedance parameter mechanism that can infer intentions based on the patient's electromyographic (EMG) signals. By dynamically adjusting impedance parameters in real-time, we aim to achieve a more diverse and safe human-robot interaction.

REFERENCES

[1] Riek, Laurel D. "Healthcare robotics." Communications of the ACM 60.11 (2017): 68-78.

[2] V. Duchaine and C. Gosselin, "Safe, Stable and Intuitive Control for Physical Human-Robot Interaction," 2009 IEEE International Conference on Robotics and Automation, Kobe, Japan, 2009, pp. 3383-3388.

[3] F. Ficuciello, L. Villani and B. Siciliano, "Variable Impedance Control of Redundant Manipulators for Intuitive Human–Robot Physical Interaction," in *IEEE Transactions on Robotics*, vol. 31, no. 4, pp. 850-863, Aug. 2015.

[4] Ke, Xiaolong, et al. "Review on robot-assisted polishing: Status and future trends." Robotics and Computer-integrated manufacturing 80 (2023): 102482.

[5] Hogan, Neville. "Impedance control: An approach to manipulation: Part II—Implementation." (1985): 8-16.

[6] Yang, Chenguang, et al. "Human-like adaptation of force and impedance in stable and unstable interactions." IEEE transactions on robotics 27.5 (2011): 918-930.

[7] J. Craig and M. Raibert, ‘‘A systematic method of hybrid position/force control of a manipulator,’’ in Proc. COMPSAC 79. Comput. Softw. IEEE Comput. Soc. 3d Int. Appl. Conf., Aug. 2005, pp. 446–451.

[8] Wen, Kang, Dan Necsulescu, and G. Basic. "Development system for a haptic interface based on impedance/admittance control." The 3rd IEEE International Workshop on Haptic, Audio and Visual Environments and Their Applications. IEEE, 2004.