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Research Article

Position-Based Contact Force Synchronous Control for Dual-Arm Cooperative Manipulators

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ABSTRACT

The focus of this research is to propose a method known as position-based contact force synchronous control for cooperative manipulation of an object using a dual-arm manipulator. By defining relative positional and force errors between both manipulators and the object, these errors can be utilized in conjunction with a general impedance controller to enhance contact force accuracy during operation. This unique approach guarantees coordination between both arms while minimizing internal forces exerted on the object compared to conventional impedance control techniques.

1. Introduction

With the continuous expansion of the application scope of robots, many new operational tasks and work environments have emerged, which pose higher demands on the performance of robots [1]. The dual-arm cooperative manipulator, compared to the traditional single-arm robot, has higher flexibility, operability, and load capacity, which has attracted widespread attention in both academia and industry [1], [2].

When manipulating an object by a dual-arm cooperative manipulator, it is not only necessary to coordinate the position of the manipulators in relation to each other but also to prevent damage to the object due to excessive contact forces between the manipulator and the object [3]. Dual-arm cooperative manipulation tasks impose higher levels of motion and force constraints on manipulators as opposed to single-arm manipulation tasks. The problem of cooperative control of a dual-arm manipulator is to control the motion and force of two manipulators under certain motion constraints [4].

The main control methods can be broadly divided into two categories: direct and indirect methods [5], [6]. The direct method is represented by the hybrid force/position control. This method is based on the orthogonality of the position subspace and force subspace and achieves decoupled control of force and position with high control accuracy [6]. However, the realization of this approach presupposes that the contact forces and trajectories required for the interactive manipulation are both known, which is often difficult in unstructured or dynamic environments. This also limits the further application of the method in a wider range of applications [7]. The indirect method represented by impedance control does not directly control the contact force or position but controls the relationship between the external force at the operating point and the state of motion in order to achieve the expected dynamic motion characteristics. Impedance control is widely used in practical applications because it

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enables contact forces compliant control in a constrained environment with a small computational effort and high robustness [8].

Unlike the single-arm manipulation task, when two manipulators grasp the same object at the same time, a closed-chain motion mechanism will be formed. During the impedance control of the closed chain system, the distribution of the load also needs to be considered [9]. For symmetrical bimanual tasks, achieving effective compensation of the absolute error of each manipulator and the relative error between the two manipulators is essential to achieve reasonable load distribution. This is crucial for reducing the internal forces of manipulation and ensuring the safety of the manipulated object [10]. In the existing literature, there is a lack of research on the problem of relative error compensation during the cooperative manipulation of a dual-arm cooperative manipulator.

In this paper, based on the above analysis, the relative error compensation problem in the dual-arm cooperative manipulation is studied, and a position-based contact force synchronous control method is proposed.

2. Dual-arm Cooperative Manipulation Model

This section defines the model for dual-arm cooperative manipulation, specifically the dynamics and kinematics model of the dual-arm cooperative manipulator, and the force analysis, kinematics and dynamics model of the manipulated object.

Fig. 1 presents the dual-arm cooperative manipulator that was used throughout this study.

The robotic system consists of multiple subsystems, with the dual-arm based on humanoid-inspired design. Each robotics manipulator consists of 7 rotational joints configured in a spherical-roll-spherical configuration, with three equivalent spherical joints at the shoulder and wrist, and one rotating joint at the elbow. Each joint is independent and controlled by a separate controller. Without considering the end effector, the arm span of each robotics manipulator is 1.375m.

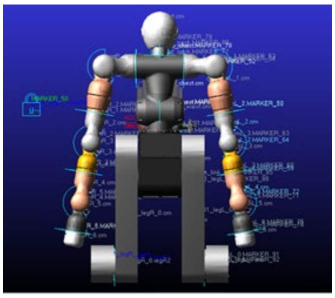

Fig. 1. The dual-arm cooperative manipulator

2.1. *Model of dual-arm cooperative manipulator*

The dynamics equations of the manipulator in a dual-arm cooperative manipulator is shown below:

$$m_i(\theta_i)\ddot{\theta}_i + c_i(\theta_i,\dot{\theta}_i) + g_i(\theta_i) = \tau_i - J_i^T f_i \qquad (1)$$

where, $i = r, l$ represents two robotic arms; $m_i \in R^{m\times n}$ is the inertia matrix and $c_i(\theta_i,\dot{\theta}_i) \in R^n$ is the vector of the force/torques due to the nonlinear terms (e.g. centrifugal, Coriolis and friction); $g_i(\theta_i) \in R^n$ is the vector of gravity; $\tau_i \in R^n$ denotes to the joint torque; $\theta_i \in R^n$ denotes to the joint angle; $J_i \in R^{m\times n}$ is the analytical Jacobian matrix; $f_i \in R^m$ denotes the contact force from the external environment. The model of the dual-arm cooperative manipulator can be expressed as

$$m(\theta)\ddot{\theta} + c(\theta,\dot{\theta}) + g(\theta) = \tau - J^T f \qquad (2)$$

where, the vectors are stacked (e.g., $g(\theta) = [g_r^T, g_l^T]^T$, $\theta = [\theta_r, \theta_l]$) and the matrices are block-diagonal (e.g., $m = blockdiag(m_r, m_l)$)

The kinematic model of the dual-arm cooperative manipulators is shown below:

$$\begin{cases} \dot{\aleph} &= J(\theta)\dot{\theta} \\ \ddot{\aleph} &= J(\theta)\ddot{\theta} + \dot{J}(\theta,\dot{\theta})\dot{\theta} \end{cases} \qquad (3)$$

where, $\aleph \in R^{2m}$ is the position and orientation of the end-effector of the dual-arm manipulator and satisfies $\aleph = [\aleph_r^T \quad \aleph_l^T]^T$.

2.2. *Model of manipulated object*

In the process of gripping an object with two arms, it is necessary to know the position of the object and to plan the expected position of the arm according to the position of the object. In order to ensure a stable gripping of the object, the planned position of the manipulator must generally intrude a certain distance into the object and achieve a certain gripping force.

Fig. 2 presents the grasp for a dual-arm cooperative manipulator manipulating a common object

Where, $\aleph_{rd}$ and $\aleph_{ld}$ denote the expected positions for the end-effector of the manipulator to grasp the object; $\aleph_r$ and $\aleph_l$ denote the actual positions of the end-effector gripping the object; f_{rd} and f_{ld} denote the expected contact forces; f_r and f_l denote the actual contact forces.

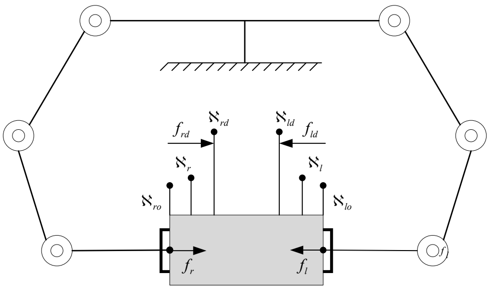

Fig. 2. The grasp for a dual-arm cooperative manipulator manipulating a common object

Let's assume that the object is clamped separately by the two manipulators, and there is no relative motion between the end-effectors and the object. Further, by invoking the virtual works principle, the relationship between the the manipulated object and the end-effector at the velocity level can easily derived

$$\dot{\aleph} = J_o \dot{z} \tag{4}$$

where, $J_o \in R^{2m\times p}$ is the grasping matrix; $z \in R^p$ denotes the position and orientation of the object.

The complete kinematic relationship is as follows:

$$\dot{z} = J_o^{\dagger} J\, \dot{\theta} \tag{5}$$

The object' motion is described as below

$$m_z(z)\ddot{z} + c_z(z,\dot{z})\dot{z} = f_z \tag{6}$$

where, m_z is the inertia matrix of the manipulated object; c_z contains the various nonlinear components of the inertial forces/moments; f_z represents the force that applied on the center of mass of the object.

When the robot grasps the object, the output forces of the manipulators is $f = [f_r^T, f_l^T]^T$, and the combined force on the manipulated object is

$$f_z = J_o^T f \tag{7}$$

3. Contact force synchronous controller Design

3.1 *Classical impedance controller*

When a robotic system interacts with an external environment, compliant behavior can be achieved by forcing the robot system to have appropriate dynamic characteristics to avoid excessive contact forces and moments. Specifically, impedance schemes are used to enforce the following mechanical impedance behavior between the object position and the forces acting on the object

$$m_d \ddot{\tilde{\aleph}} + b_d \dot{\tilde{\aleph}} + k_d \tilde{\aleph} = f_e \tag{8}$$

When the impedance control method is used to control the robot to perform a dual-arm cooperative manipulation task, the inputs and outputs of the impedance controller are defined as $\aleph_I = (\aleph_{rI}^T, \aleph_{lI}^T)^T$ and $f_I = (f_{rI}^T, f_{lI}^T)^T$, respectively, and the impedance relationship between them satisfies the following:

$$\begin{cases} m_{dr}\ddot{\tilde{\aleph}}_{rI} + b_{dr}\dot{\tilde{\aleph}}_{rI} + k_{dr}\tilde{\aleph}_{rI} = f_{rI} \\ m_{dl}\ddot{\tilde{\aleph}}_{lI} + b_{dl}\dot{\tilde{\aleph}}_{lI} + k_{dl}\tilde{\aleph}_{lI} = f_{lI} \end{cases} \tag{9}$$

The relationship between the generalized force at the output of the impedance controller and the expected generalized force is as followins:

$$\begin{cases} f_{rI} = f_r - f_{rd} \\ f_{lI} = f_l - f_{ld} \end{cases} \tag{10}$$

Based on Equation (10), the expected input poses of the left and right manipulators yield

$$\begin{cases} \aleph_{rd} = \aleph_r - \aleph_{rI} \\ \aleph_{ld} = \aleph_l - \aleph_{lI} \end{cases} \tag{11}$$

When utilizing classical impedance control for dual-arm compliance control, ensuring precise positioning of the end-effector becomes problematic, thereby increasing the difficulty in achieving cooperative motion between the two manipulators.

3.2. *Relative error and absolute error definition*

The absolute error of the dual-arm cooperative manipulation is defined as the difference between the actual and expected pose of each manipulator

$$\begin{cases} \delta_r = \aleph_{rd} - \aleph_r \\ \delta_l = \aleph_{ld} - \aleph_l \end{cases} \tag{12}$$

The definition of relative error is further given on the basis of absolute error

$$\begin{cases} \delta_{rk} \square k_{rk}(\delta_r - \delta_l) \\ \delta_{lk} \square k_{lk}(\delta_r - \delta_l) \end{cases} \tag{13}$$

where, k_{rk} and k_{lk} are proportional factors. To ensure the synchronization, the relative error needs to be compensated. After synchronous control, the posture of the manipulators meets the following relation.

$$\begin{cases} \aleph_{rk} = \aleph_r + \delta_r + \delta_{rk} \\ \aleph_{lk} = \aleph_l + \delta_l + \delta_{lk} \end{cases} \tag{14}$$

The range of variation of the proportional factor is $0 \le |k_{rk}|, |k_{lk}| \le 1$. The setting of the proportional factor should be based on the requirements of the operating task. For operations with low synchronization requirements, the proportional factor can be reduced appropriately to reduce the role of relative error, and the system relies on absolute position error to complete the operating task.

4. Contact force synchronous controller

When a dual-arm cooperative manipulator performs a task, each manipulator needs not only to have a certain of compliance, but also to maintain synchronization between the two manipulators. For this reason, we introduced the relative error into the general impedance controller to obtain a contact force synchronous controller, which is designed as follows.

At first, according to the impedance equation and the expected trajectory of the manipulated object, the generalized acceleration of impedance controller can be obtained

$$\begin{cases} \ddot{\tilde{\aleph}}_{rI} = m_{dr}^{-1}(f_{rI} - b_{dr}\dot{\tilde{\aleph}}_{rI} - k_{dr}\tilde{\aleph}_{rI}) + \ddot{\tilde{\aleph}}_{rd} \\ \ddot{\tilde{\aleph}}_{lI} = m_{dl}^{-1}(f_{lI} - b_{dl}\dot{\tilde{\aleph}}_{lI} - k_{dl}\tilde{\aleph}_{lI}) + \ddot{\tilde{\aleph}}_{ld} \end{cases} \tag{15}$$

Then, the above equations are integrated to obtain the output posture. The expected input of the contact force synchronization controller is shown below.

$$\begin{cases} \aleph_{rId} = \aleph_{rI} + {}_{l}^{r}T\chi_{lI} \\ \aleph_{lId} = \aleph_{lI} + {}_{r}^{l}T\chi_{rI} \end{cases} \tag{16}$$

where, ${}_{l}^{r}T$ and ${}_{r}^{l}T$ are mapping relationships between the position and posture of the left and right manipulators. After compensating for the relative error, the expected input of the contact force synchronous controller is shown below.

$$\begin{cases} \aleph_{rk} = \delta_{rk} + k_{rI}\aleph_{rId} \\ \aleph_{lk} = \delta_{lk} + k_{lI}\aleph_{lId} \end{cases} \tag{17}$$

where, k_{rI} and k_{lI} are proportional factors based on task requirements. By combining the kinematic equations of the dual-arm cooperative manipulators, yields the expected joint acceleration

$$\ddot{\theta}_d = J^{-1}\left[\ddot{\aleph}_k - \dot{J}^{-1}\dot{\theta}\right] + N^T\lambda \tag{18}$$

Lastly, the expected joint moment can be obtained by combining the dynamic equations

$$\tau_d = m_d J^{-1}\left[\ddot{\aleph}_k - \dot{J}^{-1}\dot{\theta}\right] + m_d N^T\lambda - J^T F \tag{19}$$

5. Simulation Analysis

In order to verify the performance of the proposed control scheme, it was tested using the combined simulation platform of Adams and Matlab. As a means of benchmarking, a classical impedance control method was also applied to the same task.

Fig. 3 shows the model of a dual-arm cooperative manipulator with the specific manipulation task that is clamping a spherical object.

Fig. 4 and Fig. 5 show the contact force changing curve of the manipulators and the combined force received by the object under different control methods.

After stabilizing, the maximum resultant force exerted on the object using the two methods mentioned above is 0.0964N and 0.0238N, respectively. The synchronization between the manipulators is significantly improved after adopting the position-based contact force synchronous control method. And the fluctuation of the combined force on the object is significantly reduced, achieving the goal of regulating the contact force on the object.

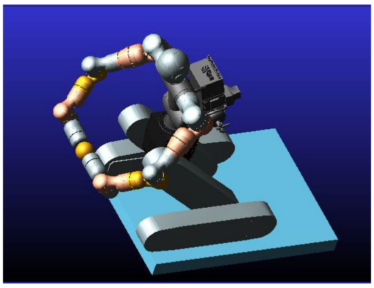

Fig. 3. The dual-arm cooperative manipulation tasks

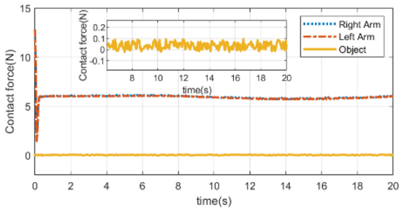

Fig. 4. Contact force changing curve based on classical impedance control method

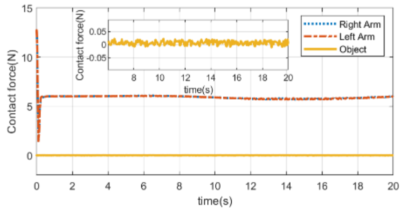

Fig. 5. Contact force changing curve based on position-based contact force synchronous control method

6. Conclusion

To address the cooperative problem in the contact force control of a dual-arm cooperative manipulator, this paper proposed a position-based contact force synchronous control method. The method first defines the relative positional error between the two manipulators, and then combines it with the impedance control scheme to compensate the synchronous error and solve the synchronous problem during the dual-arm cooperative operation. The control scheme is validated based on a simulation task that a dual-arm cooperative manipulator clamping an object. The simulation results show that the control scheme proposed in this paper can effectively reduce the contact force between the manipulator and the object as well as the combined force on the object, thus ensuring the safety of the system.

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References

1. C. Smith, et al., "Dual arm manipulation—A survey," Robot. Auton. Syst., vol. 60, no. 10, pp. 1340-1353, 2012.
2. M. Garabini, et al., "WRAPP-up: A Dual-Arm Robot for Intralogistics," IEEE Robot. Autom. Mag., vol. 28, no. 3, pp. 50-66, September, 2021.
3. F. Caccavale, P. Chiacchio, A. Marino and L. Villani, "Six-DOF Impedance Control of Dual-Arm Cooperative Manipulators," IEEE/ASME Transactions on Mechatronics, vol. 13, no. 5, pp. 576-586, October, 2008.
4. M. CostanzoG. De Maria and C. Natale, "Tactile Feedback Enabling In-Hand Pivoting and Internal Force Control for Dual-Arm Cooperative Object Carrying," IEEE Robot. Autom. Lett., vol. 7, no. 4, pp. 11466-11473, October, 2022.
5. H.F.N. Al-Shuka, S. Leonhardt, W. Zhu, R. Song, C. Ding and Y. Li, "Active Impedance Control of Bioinspired Motion Robotic Manipulators: An Overview," Appl. Bionics Biomech., vol. 2018, pp. 1-19, December, 2018.
6. C. Chen, Z. Liu, Y. Zhang and S. Xie, "Coordinated Motion/Force Control of Multiarm Robot with Unknown Sensor Nonlinearity and Manipulated Object's Uncertainty," IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 47, no. 7, pp. 1123-1134, July, 2017.
7. Z. Li, C. Xu, Q. Wei, C. Shi and C. Su, "Human-Inspired Control of Dual-Arm Exoskeleton Robots with Force and Impedance Adaptation," IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 50, no. 12, pp. 5296-5305, December, 2020.
8. G. Xiong, Y. Zhou and J. Yao, "Null-space impedance control of 7-degree-of-freedom redundant manipulators based on the arm angles," Int. J. Adv. Robot. Syst., vol. 17, no. 3, pp. 255688463, May, 2020.
9. J. Lee, P.H. Chang and R.S. Jamisola, "Relative Impedance Control for Dual-Arm Robots Performing Asymmetric Bimanual Tasks," IEEE Trans. Ind. Electron., vol. 61, no. 7, pp. 3786-3796, July, 2014.
10. D. Jinjun, G. Yahui, C. Ming and D. Xianzhong, "Symmetrical adaptive variable admittance control for position/force tracking of dual-arm cooperative manipulators with unknown trajectory deviations," Robot. Comput.-Integr. Manuf., vol. 57, pp. 357-369, 2019.

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