Article

TRANSACTIONS OF THE INSTITUTE OF MEASUREMENT & CONTROL

Transactions of the Institute of Measurement and Control
2019, Vol. 41(11) 3235–3247

DOI: 10.1177/0142331218822717
journals.sagepub.com/home/tim
SAGE

Research on dual-arm coordination motion control strategy for power cable mobile robot

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Abstract

Regarding the typical operation tasks in high-voltage transmission line environment, in order to effectively eliminate or reduce the disadvantageous effects on the robot operation reliability caused by the close chain internal forces. According to the motion status of manipulator operation, the dual-arm coordination control of the mobile operation robot can be divided into three different modes, which are dual-arm independent operation mode, dual-arm fully constrained mode and dual-arm partially constrained mode. The dynamic model between dual-arm and operation objects for the three different models are established, respectively. The manipulator position and force are set as the control targets, a unified dual-arm coordination controller is designed for the three operation modes. Through the mutual compensation of force error and position error, the close chain internal force can be dynamically allocated in each joints, so that the robot joints force can be balanced during the operation, and the internal force in the close chain can be minimized during the operation process so as to ensure the operation reliability and safety. Finally, the validity and engineering practicability is verified by MATLAB simulation experiment and 220 kV living damper replacement and drainage plate bolt tightening operation experiment, respectively.

Keywords

Robot, manipulator, close chain, internal force allocation, coordination control

Introduction

The high-voltage transmission line is an important equipment in the power grid system. It is characterized with overhead suspension structure, high voltage and special geographical environment, and it always experiences across rivers, mountains, and virgin forests. In order to ensure the safety and normal operation of power cable, it is necessary to regularly and irregularly conduct maintenance and construction operation on the power cable transmission lines and its corresponding fittings. Bolt tightening is a typical operation task of high-voltage transmission live operation. The bolt tightening is required for many kinds of line fittings, including fastening the deflector plates, resetting, shifting, or replacing the vibration dampers, spacer bars replacement, and so forth. Therefore, the bolt tightening operation has a strong representation for different electrification operation tasks. The research and development of mobile robots (e.g. Eibar et al., 2018; Gulzar et al., 2018; Lima et al., 2018; Pouliot, 2012; Pouliot et al., 2012, 2015) and their manipulators with dual arm coordinated operation have important theoretical and practical values for reducing operation risks, ensuring operation safety, improving operation efficiency and operation reliability. Regarding the operations such as bolt tightening, the robot dual arm is required to complete the coordination motion control of the robot arms. Different from the single-arm robot, the dual-arm robot works together during the coordinated operation between the arm and the object. There are certain kinematic and mechanical constraints between dual arms and operation objects. Regarding the complex operation process, the motion and force constraint presents high dimensions and strong coupling, especially the coupling of internal force is obvious. The purpose of dual-arm coordination control is to precisely achieve the planned position and force. In addition, the precise position control and force control of conventional applications on the dual-arm robot need to be considered; due to the existence of certain motion and force constraints between the dual arm, and the coordination control precision of the position and force so as to meet the task requirements, the dual arm can complete the

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coordinate control tasks. Therefore, it is of great theoretical significance and practical application value to study the dual-arm coordinated motion control method in the robot operation process so as to improve the operation efficiency and operation reliability.

The current study of dual-arm coordination control can be mainly divided into master-slave control method based on kinematics model and force-position hybrid control method based on dynamic model. For example, Garcia-Valdovinos et al. (2015) proposed a force control method for mastering the dual-arm coordination in the master-slave mode, which achieves the operation object grabbing, and analyzed the necessity of force control in the operation process. Zhang et al. (2013) proposed a master-slave position-force control method and it is used to realize the task of the dual-mechanical arm coordinated control for objects transfer. The master arm adopts position control and the force control of the slave arm is used to track the motion trajectory of the master arm; the force sensor installed on the slave arm joint is also used to detect the interaction force between the arms. Li et al. (2015) proposed a master-slave position control and it is used for the coordinated motion control of double industrial robots to pick up the same objects. According to the pre-planned master arm motion trajectory, the slave arm realized a coordinated tracking of the master arm motion and avoided communication delays; additionally, a position prediction was designed on the slave arm to predict the cumulative error of the slave arm motion compensation. Yamano M et al. (2004) applied the master-slave position compensation control method to double industrial robots, so as to complete the coordination operation of bolts and nuts tightening. The master arm adopts position control, the slave arm also adopts position control according to the motion constraint relationship; one of the robot wrists is installed with force-torque sensor, so as to modify the robot motion trajectory. Kesner et al. (2014) proposed a master-slave position-force compensation control method based on genetic algorithm for dual-arm coordination robots. The master arm adopts position control, and the slave arm position information can be obtained through reading the master arm posture in each motion cycle. Taking the position of the master arm and deriving it in a real-time manner through the constraint relationship of the coordinated motion, the position-force compensation control is applied to the arm, and the force at the manipulator is used as the feedback information of the position control to compensate the position error. Liu et al. (2016) proposed a dual arm coordinated control strategy combined with master-slave control method and symmetry control method, and performed collision judgment and obstacle avoidance control by detecting the motion path of dual robots. In the master-slave control mode, the slave arm tracks the movement of the master arm through the sensor or the master-slave constraint relationship. This requires a fast response speed of the slave arm; in addition, this model is based on a kinematics model control method and the influence of robot mass, inertial parameters and so forth are not taken into consideration on actual motion. In addition, for the dual-arm coordination operation, the arms need to be output at the same time. In addition to balancing the object gravity and friction, the arms also need to bear certain resistance. Therefore, it is difficult for the master arm to complete the task only using the position control.

In order to improve the performance of the master-slave control method and consider the dual characteristics of position and force control, force-position hybrid control is an effective method. The control idea is to divide the operation space into position control subspace and force control (e.g. Calanca et al., 2017; Duan et al., 2018; Kruse et al., 2015; Lee et al., 2014). The two subspaces are independently controlled, both arms are force-position controlled, and the force-position hybrid control method can better control the position and force of the coordinated operation task at the same time, but cannot act in the same direction at the same time and convert to the joint space. The position and the force control law need to be superimposed to achieve hybrid force-position control, and according to different task requirements, it is necessary to switch between position control and force control, which results in a large amount of calculation and it is difficult for the position space strict orthogonal partitioning with zero space (e.g. Dehghan et al., 2015; Kawasaki et al., 2006; Moosavian et al., 2010; Zhao et al., 2014). This paper takes force-position as the control objective, synthetically considers the robots dynamic and the objects dynamic mode, and the dynamic allocation of internal forces between the arms. This paper proposes a dual-arm coordination controller based on robot dynamic model, and applies it to the replacement and inspection of the high-voltage cable shock hammer repair robot, which effectively reduced the internal forces in the close chain of the dual-arm coordination operation and improved the operational reliability.

Entity structure and operational principle

Entity structure

The power cable robot is a 7-DOF mechanism, which basically consists of double walking wheels, double moving arms, double manipulators, clamping jaws, equipotential wheel and a control box. The terminus of the moving arm is equipped with walking wheels, which are able to walk along the transmission line and have the function of determining location. Double moving arms and double manipulators each have a stretch joint, and double manipulators share a common horizontal joint. There is sufficient margin for the two manipulators to work together on the transmission line and fit within the robot's space constraints. Figure 1(a) and Figure 1(b) are configuration and entity structure of the robot, the robot using walking positioning, body rising up and down, manipulator stretch action, and so forth, to realize clamping damper, nut alignment, bolt tightening or loosening, damper removement and installation, enter or exit operation space and so forth key actions and complete damper replacement operation functions.

Operational principle

The robot operation environment, damper orientation in the environment and the structural model of the damper are shown in Figure 2 (a), Figure 2 (b) and Figure 2 (c), respectively. The damper contacts the power transmission line

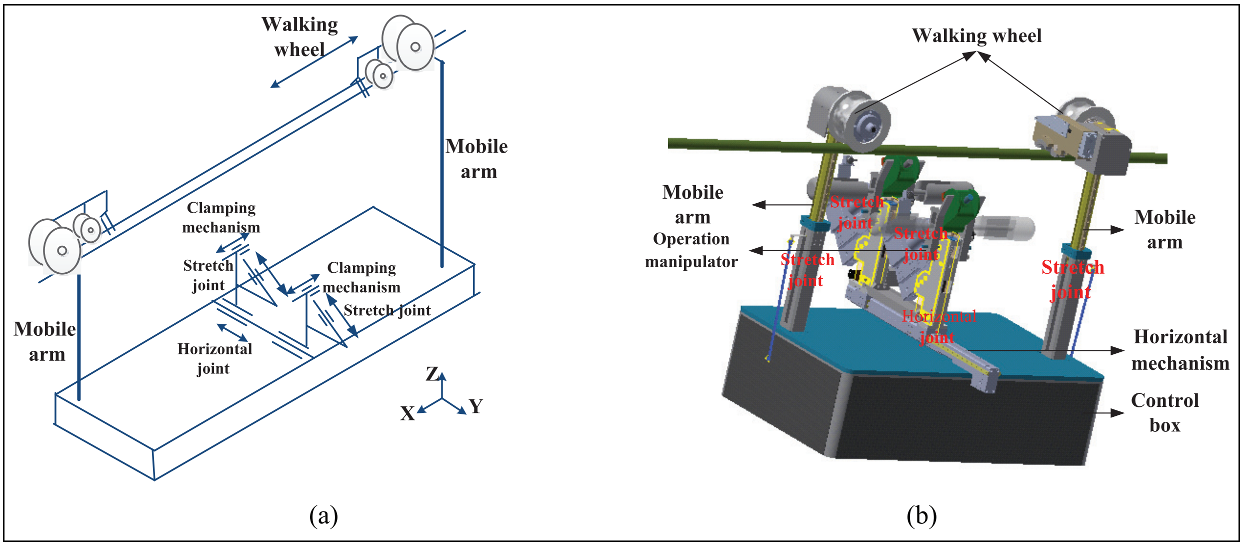

Figure 1. Robot configuration and entity structure.
(a) Configuration structure
(b) Entity structure.

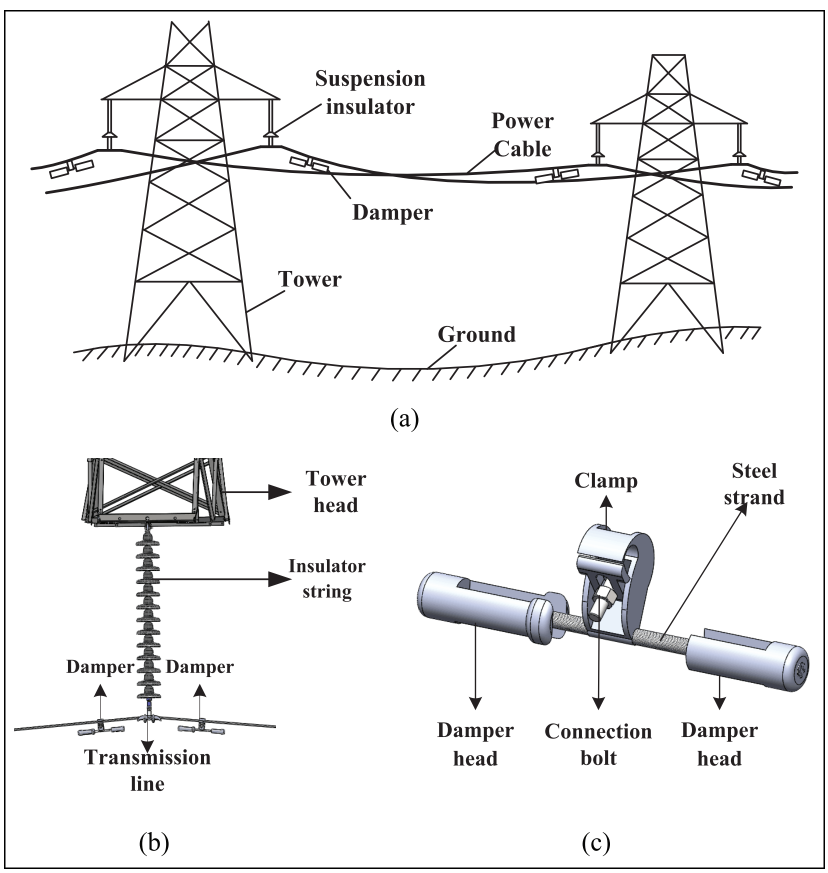

Figure 2. Operation environment and operation object.
(a) Robot operation environment.
(b) Damper orientation in the environment.
(c) Operation object.

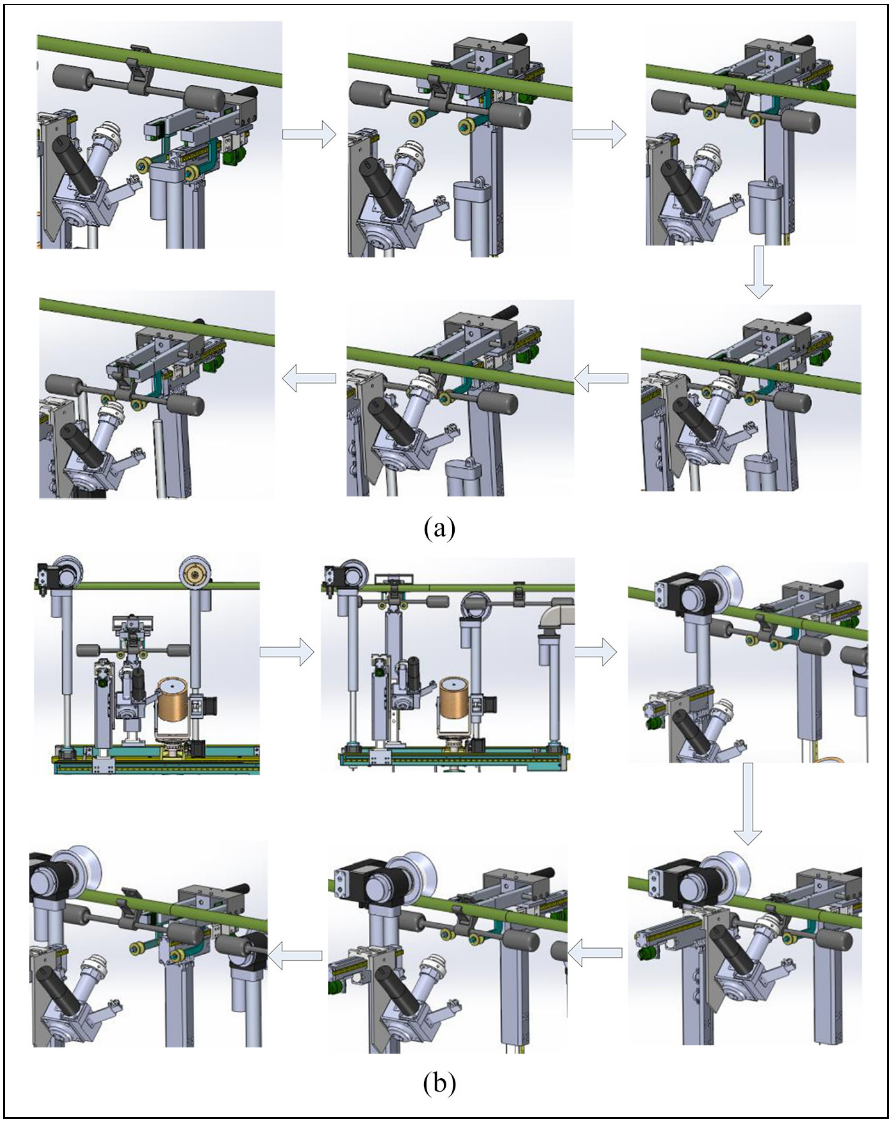

Figure 3. Motion planning of damper replacement operation.
(a) Old damper removal.
(b) New damper installation.

through the clamp, which is fastened together with power transmission line by bolts; the replacement of damper operation can be completed mainly by the bolt tightening mechanism and the damper clamping mechanism, wherein the bolt tightening mechanism is responsible for tightening (or loosening) the clamp while the damper clamping mechanism is responsible for holding the new (or old) damper and bringing it into (or out) of the working space. The damper replacement can be achieved through the coordination operation of all joints and the entire operation process can be completed by the robot without any outside manual intervention.

Operational motion planning

The damper replacement operation process includes two important aspects that can be divided into old damper removal and new damper installation. First, the robot's manipulator 1 can be adjusted to the proper posture so as to achieve the old damper clamping, then loosen the connection bolt and bring out the old damper from the working space. The operation motion simulation is shown in Figure 3(a). After that, the new damper is brought into the working space by manipulator 2, then the connection bolt is tightened so as to fix the new damper clamp onto the power transmission line and finish the installation. The operational motion simulation is shown in Figure 3(b). Finally, after finishing the operation, the robot moves out of the working area, the manipulators return to their initial postures, and the robot is removed from the line in the same way that it was placed there.

Robot force coordination control

In the process of robot operation, when the dual manipulators and the operation object have no contact with each

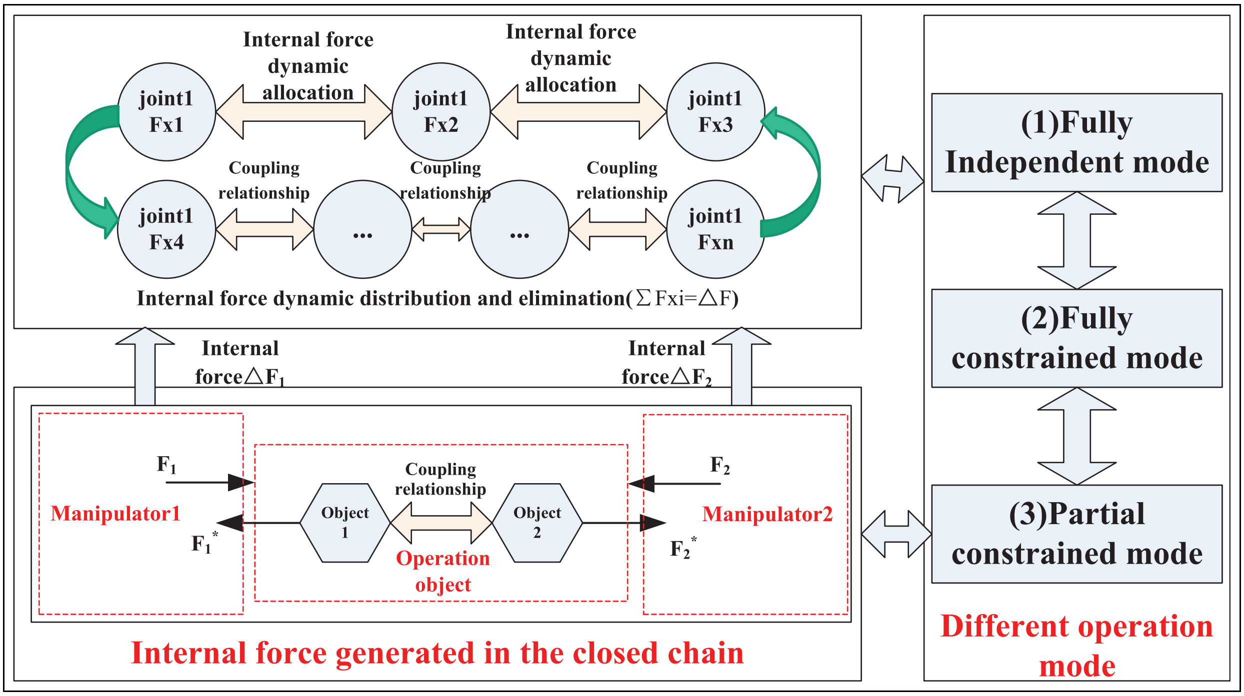

Figure 4. Structure of robot dual manipulators coordination control.

other, the control performance requirements can be satisfied with using only position control, and with its goal to bring the joint or end of the controlled robot manipulator to the desired position, it mainly involves the kinematics control method of the robot. However, when there is collision and contact between the dual manipulators and the operation object or the operation environment, the internal force will be generated between the manipulator and the operation object. In this case, the control performance requirement cannot be satisfied with only using the position control, then the internal force control is needed based on the position control, and with its goal to achieve the desired joint control torque or end of the controlled robot manipulator, it mainly involves the dynamic control method of the robot. In the process of dual manipulators coordinated movement, the dynamic allocation of the internal force generated by the dual manipulators and the operation object is the key to coordinated control according to the external loads during the operation. Therefore, it is very important to adapt suitable control strategies for different operation objects and operation processes. Regarding the power cable maintenance robot, both the robot and the damper, the clamps, the bolt head, and the nut are all make contact with each other during the damper replacement operation, which results in a certain internal force in the close chain. Only when the internal force effectively and rationally is allocated to each various joint or absorbed by them can the robot complete the operation task normally (e.g. Berlinger et al., 2018; Feng et al., 2012; Salloum et al., 2015). Taking the bolt tightening in damper replacement operation as an example, the robot manipulator force control block diagram is shown in Figure 4. The robot dual manipulators operation mode is divided into three categories, which is independent mode, full constraint mode and partial constraint mode. On the basis of the manipulator position control, the dual manipulators have been completed with the bolt or nut positioning and docking. Assuming that the force applied to the bolt by manipulator 1 is $\boldsymbol{F_1}$, the force applied to the nut by manipulator 2 is $\boldsymbol{F_2}$, the opposite reaction force by the bolt with respect to the manipulator 1 is $\boldsymbol{F_1}^*$, the opposite reaction force by the nut with the manipulator 2 is $\boldsymbol{F_2}^*$. Then the internal force generated by the robot close chain structure and the operation object is $\triangle \boldsymbol{F} = \triangle \boldsymbol{F_1} + \triangle \boldsymbol{F_2}$, additionally, $\triangle \boldsymbol{F_1} = \boldsymbol{F_1}\text{-}\boldsymbol{F_1}^*$, $\triangle \boldsymbol{F_2} = \boldsymbol{F_2}\text{-}\boldsymbol{F_2}^*$. Regarding the purpose of force coordinated control, the internal forces should be absorbed by the joints in the dual manipulators, and therefore, $\boldsymbol{F} = \boldsymbol{Fx_1} + \boldsymbol{Fx_2} + \boldsymbol{Fx_3} + \boldsymbol{Fx_4} + \boldsymbol{Fx_5} + \boldsymbol{Fx_6} + \boldsymbol{Fx_7} + \ldots + \boldsymbol{Fx_n}$, wherein, $\boldsymbol{Fx_i}$ ($i = 0\text{-}n$) is the force that manipulators apply to objects.

Dynamic modeling and model unification under typical operation

Dual arm independent operation mode

The robot dual-arm independent operation mode is shown in Figure 5. In this mode, the dual-arm completes different operation functions in the same operation space, without considering the motion and force constraints between the dual operation arm, and it only needs to ensure the dual arms no collision avoidance with the operation environment, therefore, the dynamic equation of the dual operation arm in this mode is

$$\boldsymbol{M}_i(q_i)\ddot{q}_i + \boldsymbol{C}_i(q_i, \dot{q}_i)\dot{q}_i + \boldsymbol{G}(q_i) - \boldsymbol{J}_i\boldsymbol{F}_i = \tau_i \tag{1}$$

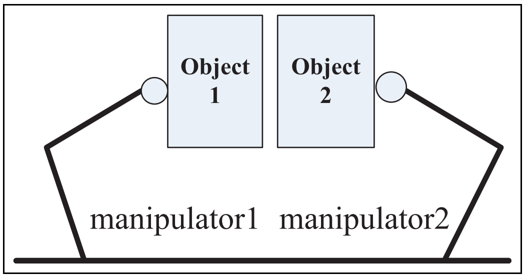

Figure 5. Independent operation mode.

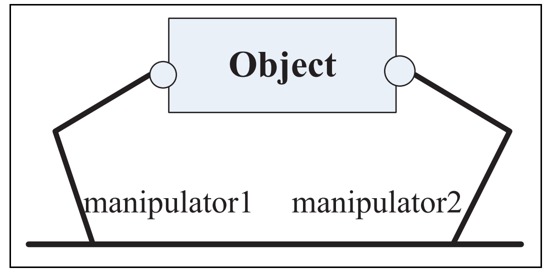

Figure 6. Full constrained coordination operation mode.

In equation (1), wherein $\boldsymbol{M}$ is the inertial matrix of the robot arm, $\boldsymbol{C/G}$ are the coriolis force, the centrifugal force and the gravity matrix, $\boldsymbol{F}$ is the generalized force vector on the manipulator by the object, and $\boldsymbol{J}$ is the Jacobian matrix of the robot arm in the world coordinate system. q_i,$\dot{q}_i$,$\ddot{q}_i$... are the joint position, velocity and acceleration of robot arm. At the same time, the dynamic model of the operation object can be expressed as equation (2)

$$\boldsymbol{M}_0\ddot{X}_0 + \boldsymbol{C}_0\dot{X}_0 + \boldsymbol{G}(q_i) + \boldsymbol{J}_i^*\boldsymbol{F}_i = F_e \tag{2}$$

In equation (1), wherein $\boldsymbol{M}_0$ is the mass matrix of the operation object, $\boldsymbol{G}$ is the gravity vector of the operation object, $\boldsymbol{X}_0$ is the position vector of the mass center of the operation object, $\boldsymbol{C}_0$ is the motion constant of the object, and so that $\boldsymbol{F}_\mathrm{i}$ in equation (1) can be obtained from equation 2. The joint kinetic equation of the robot arm is equation (3)

$$\begin{aligned}&\boldsymbol{M}_i(q_i)\ddot{q}_i + \boldsymbol{C}_i(q_i, \dot{q}_i)\dot{q}_i + \boldsymbol{G}(q_i)\\&+ J_i(J_i^*)^{-1}(\boldsymbol{M}_0\ddot{X}_0 + \boldsymbol{C}_0\dot{X}_0 + \boldsymbol{G}(q_i) - F_e) = \tau_i\end{aligned} \tag{3}$$

Dual arm full restraint coordination operation mode

The fully constrained operation mode of the robot dual-arm is shown in Figure 6. In this mode, the dual arm work together to complete an operation task (such as the manipulator 1 fixing bolt, the manipulator 2 tightening nut), a complete close chain of motion and force constraints can be formed between the arms and the objects. At this time, the motion of the dual arm will affect each other, and one arm needs to consider the coordination control force applied by the other arm to the operation object; that is, the dynamic allocation of the internal forces exerted by the dual arm on the operation object. In this mode, the dynamic model of the manipulator is shown in equation (1). Because the dual arms are fully constrained, the dynamic equation of the operation object can be corrected as equation (4), according to equation (2)

$$\boldsymbol{M}_0\ddot{X}_0 + \boldsymbol{C}_0\dot{X}_0 + \boldsymbol{G}(q_i) + \sum J_i^*F_i = \tau_e \tag{4}$$

According to equation (1), the dynamic equation of the manipulator 1 and the manipulator 2 are equation (5) and equation (6), respectively. Define the objective function of the internal force control in the close chain between arms and operation objects as equation (7), and substitute equation (5), equation (6) into equation (7), therefore, equation (8) can be obtained. In order to get the optimal $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$, we can derivative equation (8) regarding $\boldsymbol{F}_1$ and $\boldsymbol{F}_2$ respectively, and order the first derivative as zero so as to get equation (9), therefore, the optimal force exerted to operation object by the dual-arm can be obtained as equation (10)

$$\boldsymbol{M}_1\ddot{X}_1 + \boldsymbol{C}_1\dot{X}_1 + \boldsymbol{G}(q_1) + J_1^*F_1 = \tau_1 \tag{5}$$

$$\boldsymbol{M}_2\ddot{X}_2 + \boldsymbol{C}_2\dot{X}_2 + \boldsymbol{G}(q_2) + J_2^*F_2 = \tau_2 \tag{6}$$

$$f = (\tau_1)^T\tau_1 + (\tau_2)^T\tau_2 \tag{7}$$

$$\begin{aligned}f = {}&(\boldsymbol{M}_1\ddot{X}_1 + \boldsymbol{C}_1\dot{X}_1 + \boldsymbol{G}(q_1) + J_1^*F_1)^T\boldsymbol{M}_1\ddot{X}_1\\&+ \boldsymbol{C}_1\dot{X}_1 + \boldsymbol{G}(q_1) + J_1^*F_1 +\\&(\boldsymbol{M}_2\ddot{X}_2 + \boldsymbol{C}_2\dot{X}_2 + \boldsymbol{G}(q_2) + J_2^*F_2)^T\boldsymbol{M}_2\ddot{X}_2\\&+ \boldsymbol{C}_2\dot{X}_2 + \boldsymbol{G}(q_2) + J_2^*F_2\end{aligned} \tag{8}$$

$$\begin{cases}\dfrac{\partial f}{\partial F_1} = 0\\[2mm]\dfrac{\partial f}{\partial F_2} = 0\end{cases} \tag{9}$$

$$\begin{cases}F_1 = \dfrac{J_2(J_2)^T(F_1 + F_2) + J_2(\boldsymbol{M}_2\ddot{X}_2 + \boldsymbol{C}_2\dot{X}_2 + \boldsymbol{G}(q_2)) - J_1(\boldsymbol{M}_1\ddot{X}_1 + \boldsymbol{C}_1\dot{X}_1 + \boldsymbol{G}(q_1))}{J_1(J_1)^T + J_2(J_2)^T}\\[3mm]F_2 = \dfrac{J_1(J_1)^T(F_1 + F_2) + J_1(\boldsymbol{M}_1\ddot{X}_1 + \boldsymbol{C}_1\dot{X}_1 + \boldsymbol{G}(q_1)) - J_2(\boldsymbol{M}_2\ddot{X}_2 + \boldsymbol{C}_2\dot{X}_2 + \boldsymbol{G}(q_2))}{J_1(J_1)^T + J_2(J_2)^T}\end{cases} \tag{10}$$

Dual arm partial constrained coordination operation mode

Partial constrained coordination mode is shown in Figure 7. In this mode, both arms complete the same operation task, and non-close motion and force constraints can be formed between the dual operation arms. In this mode, according to whether there are contact and force constraints between the dual operation ends, it can be further subdivided into two cases. If the contact force between the operation ends and the

Table 1. Mapping relationship of dynamic behaviors and operation patterns.

	τ_A	τ_E	Mode
1	$\boldsymbol{M}_i(q_i)\ddot{q}_i + \boldsymbol{C}_i(q_i,\dot{q}_i)\dot{q}_i + \boldsymbol{G}(q_i)$	$J_i(J_i^*)^{-1}(\boldsymbol{M}_0\ddot{X}_0 + \boldsymbol{C}_0\dot{X}_0 + \boldsymbol{G}(q_i) - F_e)$	Independent
2	$\boldsymbol{M}_i(q_i)\ddot{q}_i + \boldsymbol{C}_i(q_i,\dot{q}_i)\dot{q}_i + \boldsymbol{G}(q_i)$	$J_i(J_i^*)^{-1}(\boldsymbol{M}_0\ddot{X}_0 + \boldsymbol{C}_0\dot{X}_0 + \boldsymbol{G}(q_i) + J_i^*F_i - F_e)$	Full constraint
3	$\boldsymbol{M}_i(q_i)\ddot{q}_i + \boldsymbol{C}_i(q_i,\dot{q}_i)\dot{q}_i + \boldsymbol{G}(q_i)$	$J_i(J_i^*)^{-1}(\boldsymbol{M}_0\ddot{X}_0 + \boldsymbol{C}_0\dot{X}_0 + \boldsymbol{G}(q_i) - F_e) + J_if_0$	Partially constrained

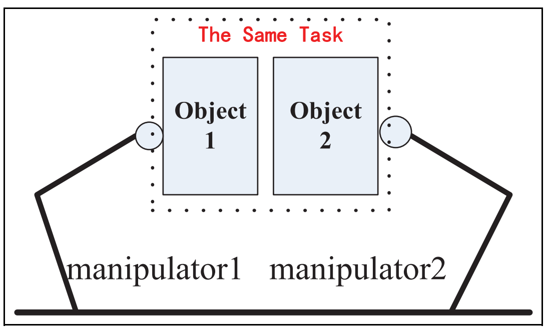

Figure 7. Partial constrained coordination mode.

dual-arms is $\boldsymbol{f}_0$, then the dual-arm dynamic model in this mode can be obtained as equation (11).

$$\begin{aligned}&\boldsymbol{M}_i(q_i)\ddot{q}_i + \boldsymbol{C}_i(q_i,\dot{q}_i)\dot{q}_i + \boldsymbol{G}(q_i)\\ &+ J_i(J_i^*)^{-1}(\boldsymbol{M}_0\ddot{X}_0 + \boldsymbol{C}_0\dot{X}_0 + \boldsymbol{G}(q_i) - F_e)\\ &+ J_if_0 = \tau_i\end{aligned} \tag{11}$$

Unified model under different operation modes

In order to facilitate the controller design, the dynamic model of the three operation modes can be abstracted as the unified form equation (12), which is the manipulator dynamic model under different operation conditions. The first part is the linear part of the manipulator dynamic model. The second part is the generalized force exerted to manipulator by the operation environment. The value of the operation force varies with different operation modes, as shown in Table 1.

$$\tau_i = \tau_A + \tau_E \tag{12}$$

Through the above kinetic equations' derivation process, it can be concluded that in the dual-arm independent operation mode there is no force constraint relationship between the dual arms. In the dual-arm partial constraint operation mode, when the dual-arm end effectors are in contact with each other, it is only necessary to consider the magnitude of the contact force of the instantaneous dual-arm interaction, which can be measured by the end force sensor, this can be done by processing the force on the dual-arm dynamics model. However, in the full-constrained operation mode, the coupling occurs between the arms, the dual arms act as mutual influence, and the dual-arm dynamic decoupling is required.

Coordinated controller design and stability analysis

Coordinated controller design

According to the basic principle of force-position hybrid control, the force-position hybrid control law consists of two parts, as shown in equation (13). Wherein τ_p is position control, τ_f is internal force control, regarding the position control, a calculating torque control can be adopted, and the control law is shown in equation (14). Wherein $\ddot{X}_d{}^i$,$\dot{X}_d{}^i$,$X_d{}^i$ are the desired position, speed, acceleration of the robot joint i, respectively. $\ddot{X}^i$,$\dot{X}^i$,X^i are the actual position, speed, acceleration of the robot joint i, respectively, K_p,K_v,K_f are position, speed and force gain matrix respectively. Regarding the ***PI*** method using internal force control, the control law is shown in equation (15), where $\boldsymbol{J}$ is the system Jacobian matrix, F_d, F are the expected internal force and the actual internal force in the close chain, K_i is integral gain matrix, according to the designed control law, the structure of the force-position hybrid control can be obtained as shown in Figure 8.

$$\tau = \tau_p + \tau_f \tag{13}$$

$$\tau_p = \ddot{X}_d{}^i + K_v(\dot{X}_d{}^i - \dot{X}^i) + K_p(X_d{}^i - X^i) \tag{14}$$

$$\tau_f = J(F_d + K_i\int(F_d - F)dt) \tag{15}$$

The key technology of the force-position coordination control is to ensure that the obtained close-loop system meets certain performance index requirements. The most basic and important criterion is the system stability, namely, when the system implements the specified motion trajectory, even if the interference is existed and under the effect of disturbance, the error can be controlled within a certain range. Define the robot joint position, velocity and acceleration errors as $e_p{}^i = X_d{}^i - X^i$,$\dot{e}_p{}^i = \dot{X}_d{}^i - \dot{X}^i$,$\ddot{e}_p{}^i = \ddot{X}_d{}^i - \ddot{X}^i$, internal force error is $e_f = F_d - F$, therefore, equation (16) can be obtained, thus, the system internal force error equation (19) can be obtained.

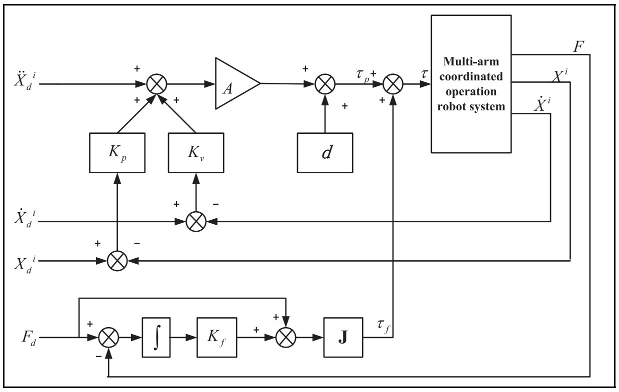

Figure 8. Structure of multi-arm robot force-position coordination control.

Stability analysis

Lyapunov theorem is an important method to analyze the stability of the system In order to conduct the stability analysis, first the definition and stability determination theorem of Lyapunov stability is given as follow. Set the system state equation as $\dot{x} = f(x, t)$, and with its balance state is $f(0, t) = 0$, suppose that the state space origin is in equilibrium and it is assumed to be in the origin field $\exists V(x, t) = 0$, and with its first derivative of x is existence, if $V(x, t)$ positive definite and $\dot{V}(x, t)$ definite negative, which means that the system energy monotonically decays with time, therefore, the system is progressively stable.

Regarding the combination dynamic model of robot and operation object, taking the proper control torque as equation (16), then the error dynamic equation can be obtained as equation (17), wherein the parameters are defined as above.

$$\tau = M_i\ddot{X}_{dr}{}^{i} + C_i(X^i{}_r, \dot{X}^i{}_r)^i + K_v(\dot{X}_{dr}{}^{i} - \dot{X}^i) + K_p(X_{dr}{}^{i} - X^i) + \tau_f \tag{16}$$

$$M_i\ddot{e} + K_v\dot{e} + K_pe = 0 \tag{17}$$

The stability of the control system is a prerequisite for the normal operation of the control system. The stability of equation (17) is discussed as below. Namely, the control system can still tend to be stable under the influence of certain external disturbances. The Lyapunov function V can be constructed as equation (18), and deriving the selected Lyapunov function, then equation (19) can be obtained. Combine with equation (17), then equation (20) can be also obtained

$$V = \frac{1}{2}\dot{X}^T{}_iM_i\dot{X}_i + \frac{1}{2}e^TK_pe \tag{18}$$

$$\dot{V} = \frac{1}{2}\dot{X}^T{}_i\dot{M}_i\dot{X}_i + \dot{X}^T{}_iM_i\ddot{X}_i - e^TK_p\dot{X}_i \tag{19}$$

$$\dot{V} = -\dot{X}_i{}^TK_v\dot{X}_i \leqslant 0 \tag{20}$$

According to Lyapunov theory, through selecting the appropriate controlled torque, it can ensure robot joint motion tracking from an arbitrary initial posture to the desired posture with motion tracking error converging to zero, and also ensure global asymptotic stability of mechanical arm motion control system. Therefore, the system can certainly be kept stable under force-position coordinated control.

Simulation and field operation experiment

Simulation experiment

Set robot dual arm bolt tightening or loosening and damper replacement as the research process, the two sets simulation experiments have been conducted, and the simulation aimed at two aspects, which are robot close chain internal force dynamic allocation and joint internal force decrease or elimination. Firstly, the internal forces of the dual arms in the close chain between the arms and operation objects during the entire operation process before and after the position control change with time, as shown in Figure 9(a). From the simulation results, it can be seen that when the position control is not applied, the internal force in the close chain of the damper replacement is obviously higher than the internal force in the close chain after the position control is applied. Under traditional control, the internal force change from 0 to 115N, and under position control, the internal force change from 0 to 95N. Therefore, the position control can effectively reduce the internal force in the close chain; that is, the position error and force error can compensate each other to a certain extent. The second set experiment is based on the position control, and continues to apply the force position hybrid control. The internal force in the close chain under the force-position hybrid control is shown in Figure 9(b). From the simulation results, it can be seen that under the force position control operation, the internal force in the close chain continues to decrease, therefore, the force position hybrid control is the optimal control algorithm in dealing with the problem of manipulation close chain internal force allocation.

Figure 10 shows the real-time torque values of the dual arms joints under traditional operation, position control and force position hybrid control. The simulation results show that under the force position control, the internal forces in the close chain can be effectively allocated to each robot joints. Comparing with the traditional control and position control, under the force-position control the joint torque fluctuates more smoothly, and it satisfies the requirement of the stability of the robot much more, thereby further improving the robot operation reliability.

Regarding the joint internal force, three times experiments are launched by using three different methods in damper bolt tightening and drainage plate bolt tightening respectively, the different joint internal force can be measured by joint force sensor as shown in Table 2, Table 3, and set damper replacement as an example; the corresponding simulation is in Figure 11. From the simulation results, we can conclude that no matter what joints, what joint actions, and what operations, the joint internal force using force-position hybrid control is the smallest, the position control is in the middle, and the traditional PID control is the biggest, therefore, the force-position hybrid coordination control can effectively reduce joint internal force and guarantee the operation safety and reliability.

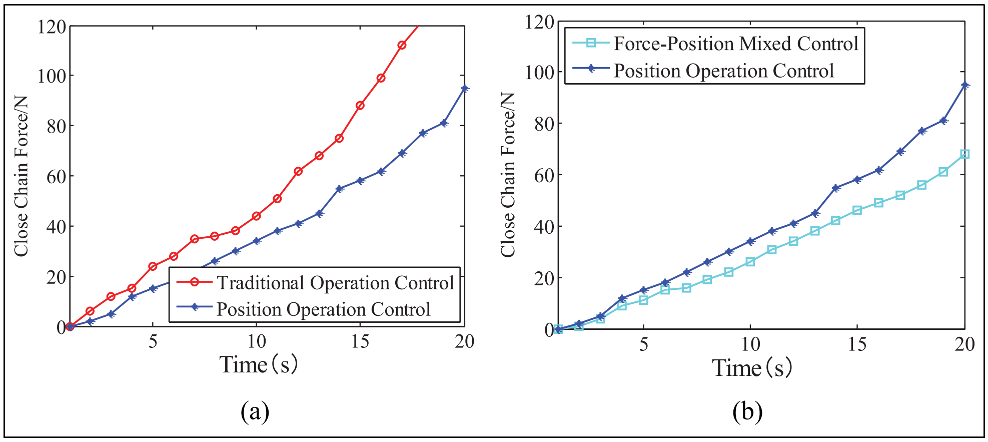

Figure 9. Robot close chain internal force curves under different control methods.
(a) The first set simulation.
(b)The second set simulation.

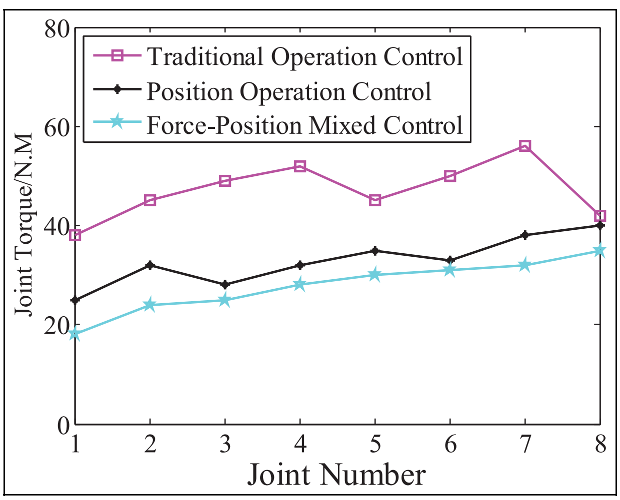

Figure 10. Robot joint internal force curves under different control methods.

Table 3. Joint internal force with different control method.(Drainage plate bolt tightening).

Joint	PID control	Position control	Force position hybrid control
Vertical	*105N*	*92N*	*80N*
Stretching	*88N*	*72N*	*65N*
Tightening	*133N*	*120N*	*112N*
Horizontal	*90N*	*82N*	*68N*

Simultaneously, the method has strong engineering applicability for different operations.

Field experiment

In order to further verify the engineering practicability of the dual-arm coordination motion control strategy for power

Table 2. Joint internal force with different control method.(Damper bolt tightening).

Joint	PID control	Position control	Force position hybrid control
Clamping	*88N*	*75N*	*56N*
Stretching	*65N*	*52N*	*46N*
Tightening	*108N*	*95N*	*86N*
Horizontal	*96N*	*85N*	*76N*

cable mobile robot, a robot damper replacement operation was tested on 220 kV power cable transmission line under the administration of the Hunan Electric Power Company live working center in Hunan Province, China. The tower type is GDDZ-18, the wire type is LGJ-240/30, the damper type is FR-3. The online field operation robot is shown in Figure 12. The robot manipulator moves from the initial posture to the damper clamping posture and bolt tightening status through the joint movement. The key process of robot damper replacement field operation test is shown in Figure 13.

In order to making a comparison among force-position hybrid control, position control and conventional PID control, three times operation tests were carried out by using three different control methods respectively in different line slopes. The robustness of robot force position hybrid control was tested in macro level. In order to dynamically monitor the macro robust stability during damper replacement process in which different motions were performed, the angle ranges, which were measured by inclination sensor carried by robot itself with three different control methods in different line slopes, are recorded in Table 4. Compared with several other actions, as rotation and tightening action are easier to influence the robot motion stability, so the two actions are taken as example to carry out simulation research in MATLAB environment. The simulation results are shown in Figure 14.

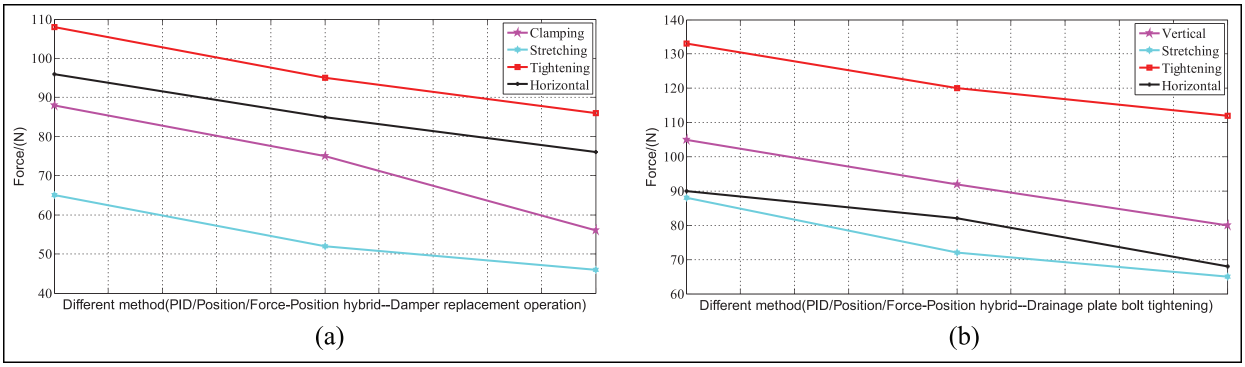

Figure 11. Different joint internal force curves under different control methods.
(a) Damper bolt tightening.
(b) Drainage plate bolt tightening.

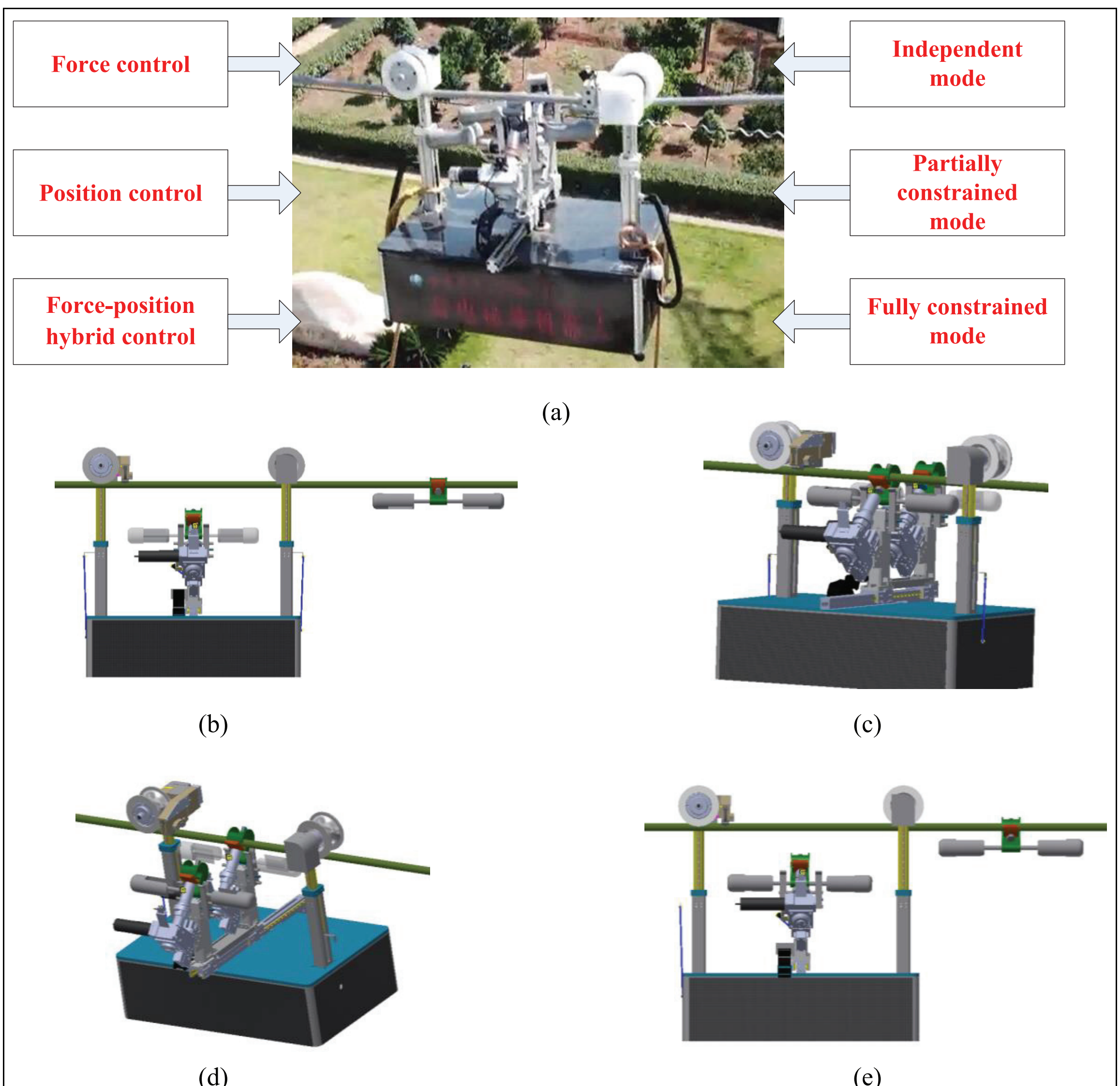

Figure 12. The field robot on 220kV transmission line and operation simulation.
(a) Field robot on 220kV transmission line (b) Initial posture (c) Operation posture (d) Bolt tightening and replacement (e) Operation finished.

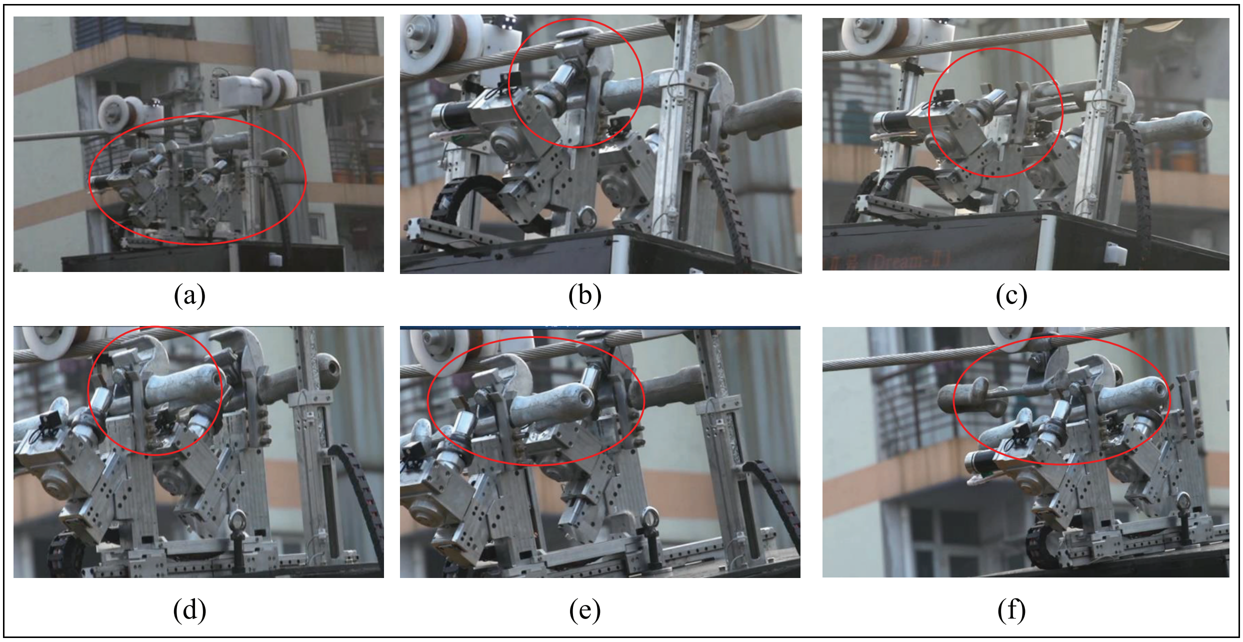

Figure 13. Field operation experiment of damper replacement.
(a) Reaching operation space.
(b) Clamping / loosing bolt.
(c) Removing old damper.
(d) New damper replacement.
(e) Clamping / tightening bolt.
(f) Exiting the operation space.

Table 4. Robot stability of manipulator different actions with different methods.(Line slope=12°& 15°).

Action	PID(12°/ 15°)	Position(12°/ 15°)	Force-position hybrid (12°/ 15°)
Clamping	9°-14°/ 13°-18°	11°-13°/ 13.8°-17°	11.6°-12.6°/ 14.2°-16.6°
Stretching	12°/ 14.5°-15.5°	12°/ 14.5°-15.5°	12°/ 14.5°-15.5°
Tightening	8.5°-14°/ 9.5°-18.5°	11°-13.2°/ 11.5°-17.8°	11.8°-12.5°/ 13.8°-16.2°
Horizontal	12°-13°/ 14.5°-15.5°	12°/ 14.8°-15.3°	12°/ 15°
Vertical	12°-13°/14.5°-15.5°	12°/ 14.8°-15.3°	12°/ 15°

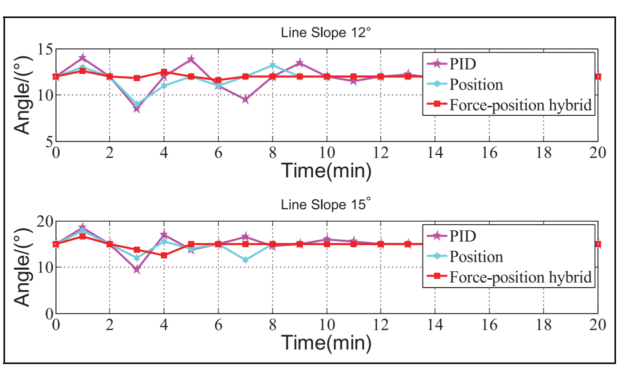

Figure 14. Performance comparison of different control methods in field operation.

According to the inclination angle range of different movements of manipulator using three different control method shown in Table 3, it can be known that the inclination angle of different movements of manipulator measured using force-position hybrid control are uniformly smaller than that measured using position control, additionally, the greater the line slope, the more obvious the advantage of force-position hybrid control method, therefore, it can conclude that the mechanical arm moves more stably using force-position hybrid control compared with position control and PID control. According to the simulation results in Figure 12, the maximum range of each joint with different control method is [8.5°, 14.5°], [11°, 13.2°], [11.6°, 12.5°], respectively, when the line slope is 12°; the maximum range of each joint with different control method is [9.5°, 18.5°], [14.8°, 17.8°], [13.8°, 16.6°], respectively, when the line slope is 15°; and after 15 min, 9 min, 7 min, the robot system tends to stable respectively when the line slope is 12°; after 12 min, 8 min, 5 min the robot system tends to stable respectively when the line slope is 15°. Therefore, we can conclude that regarding the robot system, the force-position hybrid control obtain the sound speed and stability of the control system.

It can be seen from the field operation experiment that through using the dual-arm coordinated motion control strategy, the double moving arm and the double manipulator from the initial status to the operation status, clamp positioning, damper clamping, bolt positioning and damper exit and enter etal key status, the robot manipulator shows a sound performance under the dual-arm coordinated motion control strategy, all joints run smoothly and stably, each joints internal force can be decreased and close chain internal force is effective elimination and allocated in each robot joint. Therefore, the method has a strong engineering practicability that further improves the operational efficiency, and to some extent reflects the robot operations intelligence.

Conclusion

(1) This paper has described the development of a damper replacement power cable live maintenance robot experimental prototype that greatly improves operation efficiency and deals with the safety problem of operation in a high-voltage environment.
(2) A general force-position hybrid control model of the manipulator motion control for multi-arms multi-actions robot is established, and a corresponding method of internal forces allocation in close chain is also proposed.
(3) The simulation experiment verified the effective of the force position hybrid control that can effectively reduce the internal force in close chain. The different field experiments have further confirmed the engineering practicability.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Hubei Provincial Department of Education Research Project (2019), Wuhan Textile University Funding (National Project Cultivation Plan), Hubei Natural Science Foundation of China (2018CFB273) and 2018 Opening Foundation Project for Hubei Key Laboratory of Digital Textile Equipment (Wuhan Textile University) (Project ID:DTL2018026).

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