Adaptive coordinated motion constraint control for cooperative multi-manipulator systems

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Abstract
Constrained motion and redundant degrees of freedom control exist in a multi-manipulator collaboration system. In other words, the multi-manipulator collaboration technology must solve the problems of uncertain environment interaction and coordinated control. Few studies have been conducted on the coordination control of a multi-manipulator, and the control effect is not good. To solve the coordinated motion problem of the multi-manipulator cooperative system, this study divides the multi-manipulator coordinated motion into two forms, namely coupled and superimposed motions, and proposes an adaptive coordinated motion constraint scheme under different motion forms. The coupled and superimposed motions are investigated through coordinated handling and coordinated drawing circle tasks, respectively. The proposed coordinated control scheme has a good effect. Without position detection and positioning, the kinematic constraint algorithm can maintain the relative motion relationship between end-effectors. When an external disturbance occurs, the slave manipulator can automatically adjust based on the position of the main manipulator, avoiding error accumulation. The experimental results show a maximum trajectory tracking error of 2.131 mm and maximum attitude error of 0.176°, indicating that the proposed control scheme has strong adaptive ability and high control accuracy.

Keywords Multi-manipulator cooperation · Collaboration system · Adaptive coordination · Kinematic constraints

1 Introduction
One of the trending topics in manipulator research is the coordinated motion of multiple manipulators [1, 2]. The emergence of cooperative multi-manipulator systems overcomes the working limit of a single manipulator system by providing larger working space, greater working ability, a more flexible system structure and greater load capacity compared with a single manipulator. Cooperative multi-manipulator systems can accomplish many difficult tasks that cannot be accomplished by a single manipulator through coordinated movement [3, 4], such as coordinated handling and welding. Multi-manipulator cooperation has many advantages over a single manipulator; however, it also introduces many control issues. Compared with a single manipulator, a cooperative multi-manipulator system has a more complex organisational structure, which is not a simple combination of multiple manipulators. It needs to address the problems of uncertain environment interaction, feasible control methods and coordinated planning [2]. Multi-manipulator coordination involves the cross-integration of multiple disciplines and is extremely complicated to implement. When multiple manipulators operate an object together, a closed-chain system will be formed, which inevitably leads to control problems such as redundant degrees of freedom and motion limitation. Therefore, research into the motion coordination of multiple manipulators is required [5–8].

Currently, single manipulator control has various control schemes, including PID control [9–11], robust control [12], adaptive control and fuzzy neural network control [13], and these control schemes are relatively mature. To extend the application of single manipulator to coordinate operation of multiple manipulator, the coordination control problem of multiple manipulator must be solved first. The traditional control scheme of single manipulator can hardly meet the control requirements of multi-manipulator cooperative system. Therefore, it is necessary to study the coordinated motion control of multi-manipulator. Using external instruments to detect the multi-manipulator position
can solve the problem of the environmental interaction of multi-manipulator and realize the coordinated motion control of the multi-manipulator. In [14], the indoor GPS (IGPS) technology was used to realize real-time feedback and control of the multi-manipulator cooperation system, thus solving the problems of positioning and motion control of the cooperative manipulator. In [15], a web-based cooperative manipulator monitoring and coordination control scheme that avoids the interference between manipulators through real-time calculation and adjustment of the kinematics model and sensor data was proposed. The coordinated motion control of the multi-manipulator cooperative system maintains the desired motion trajectory of the multi-manipulator end-effector and realizes the correspondence of the multi-manipulator end-effector in time and space. A coordinated path-planning algorithm for spatial multi-manipulators was proposed in [16] based on whether or not a relative motion exists in the process of the coordinated motion of multiple manipulators. Ref. [17] studied the effective use of ECTS motion variables to manipulate the coordinated motion of dual manipulators. Ref. [18] proposed a dual-manipulator coordinated motion planning method based on the combination of evolutionary and local search algorithms. In [19], the specific target object recognition process was analysed and solved from the perspective of visual information processing through theoretical derivation and experimental research on the coordinated motion of a dual manipulator, and a complete coordinated motion control scheme was proposed on this basis. In [20], a two-layer control scheme combining a model prediction strategy and an extended state observer was proposed for the trajectory tracking coordination problem of multiple manipulators with parameter uncertainties. Then, the visual servo error model was deduced using an image-based visual servo strategy. In [21], a novel online neighbour selection policy was proposed in the control of nonlinear networked multi-manipulator systems, in which the manipulator joint signals were subjected to varying noise levels.

Most of the above-mentioned researches achieve coordinated movement among multiple manipulators via target identification, position detection and positioning and motion planning. The effect of motion control depends on the position positioning accuracy. Specific kinematic constraints between end-effectors can be found during the coordinated operation of the multi-manipulator cooperative system. The relative position relationship between the end-effectors of multiple manipulators can be determined through kinematic constraints to realize the coordinated motion control of the multi-manipulator cooperative system. In [22], the optimization problem was formulated considering the workspace volume as the objective function. Constraints were added to guarantee the envelope regularity and force the workspace to occupy a pre-established area. Furthermore, [23] proposed a method to optimize the manipulability index of cooperative manipulation for a free-floating multi-manipulator space robot. The manipulability optimization was formulated as a nonlinear optimize problem at the position level, which is hard to be solved online. By redefining the constraint equation and manipulability index, it was transformed to a constrained quadratic program problem at the velocity-level incorporating joint velocity physical limits, generating joint velocity commands to control the multi-manipulator to complete predefined tasks. Although some researchers have applied kinematic constraints to the motion control of a multi-manipulator, their studies were relatively superficial, and realizing the motion coordination of multi-manipulator end-effectors through the kinematic constraint analysis was difficult.

Through coordinated motion, the multi-manipulator cooperative system can perform complex tasks that cannot be performed by a single manipulator. A part of this study involves some specific cases of multi-manipulator collaboration. For example, the welding coordination problem of two manipulators with complex curve welds was studied in [24]. The master/slave scheme was used to perform coordinated motion planning, and the motion trajectory of the ends of the two manipulators was automatically calculated through a kinematic relationship. In [25], a welding path-planning method was proposed by studying the path-planning problems of the multi-manipulator coordinated welding of complex spatial welds based on a multi-objective genetic algorithm. Ref. [26] proposed a novel methodology of dual-robot welding for intersecting pipes through motion planning and offline programming. This method utilizes the redundancy of the multi-manipulator system to obtain alternative paths for the collaborative welding task. In [27], a collaborative machining method was proposed by establishing a relative pose relationship between the cutter and the supporting head. In this method, the cutter trajectory of the machining manipulator is generated in real time according to the end trajectory of the offline planning supporting manipulator and the preset machining parameters. There are few case studies on coordinated motion control of multi-manipulator, and the motion form is relatively single, so the control scheme is difficult to meet the requirements of other cooperative motion forms.

Existing control schemes have poor coordination effects for performing complex collaborative tasks [28, 29], and external positioning methods, such as position detection, are required to determine the positional relationship between the end executions of multiple manipulators. The control accuracy is easily affected by the detection equipment accuracy, and the anti-interference ability is poor. An adaptive coordinated motion constraint control scheme is proposed in this paper based on the existing research. The relative motion relationship of end-effectors can be determined by establishing a motion constraint algorithm for multi-manipulator.
end-effectors through kinematic analysis, thus avoiding the detection of the relative position of the end-effectors. The proposed control scheme can automatically adjust the position and attitude of the slave manipulator based on the position and attitude of the master manipulator when the system is disturbed by the outside world. It always maintains a specific motion relationship in the motion process and exhibits a strong adaptive ability. In addition, this control scheme is suitable for multi-manipulator cooperative tasks with different motion forms.

Aiming at the problem of the coordinated motion of cooperative multi-manipulator systems, this study divides the coordinated motion of multi-manipulator systems into two motion forms: coupling and superposition motions. An adaptive coordinated motion constraint scheme is proposed for the two different motion forms. The coupling and superposition motions are investigated by coordinating transportation and circle drawing tasks, respectively. A robot toolbox is used to verify two kinematic constraint control schemes. To simulate the process of multi-manipulator coordinated motion more realistically, the MATLAB–ADAMS Co-simulation analysis of multi-manipulator coordinated motion is conducted, and the dynamic simulation of coupling and superposition motions of cooperative multi-manipulator systems is realised. Finally, the correctness of the algorithm is verified by experimenting with two 6R manipulators for coordinated motion.

2 Adaptive trajectory coordination motion constraint control of multi-manipulator

Multi-manipulator cooperation has many advantages, such as large workspace, low load performance requirements and the ability to complete more complex operation tasks, and the coordinated movement of multi-manipulators is the key to realise multi-manipulator cooperation [30, 31]. Before the trajectory coordination planning of a cooperative multi-manipulator system, the kinematics constraint relations of the cooperative multi-manipulator system should be classified, and different constraint relations have different trajectory coordination methods. According to different kinematics constraint relations of the cooperative multi-manipulator system, the coordinated motion of multi-manipulator system is divided into two categories and defined as follows:

1. Coupled motion of multi-manipulators: there is a specific pose constraint relationship between the reference points of the end-effector of multi-manipulators, and through this specific kinematic constraint relationship, the pose between the end-effector of the manipulators remains unchanged.

2. Multi-manipulator superposition motion: there is not only a specific pose constraint relationship between the end-effector reference points of multi-manipulators but also a relative motion constraint relationship, and the final motion trajectory is the superposition of the two parts.

2.1 Coordinated constraint control of multi-manipulator coupling motion

Multi-manipulator handling is the most typical type of multi-manipulator coupling motion. When multi-manipulator coupling motion planning is conducted for two manipulators, one of the manipulators is determined as the master manipulator, and the other as the slave manipulator. The relative pose between the slave manipulator and the end-effector of the master manipulator should be kept unchanged during movement. Since the slave manipulator follows the master manipulator, it is not necessary to perform separate trajectory planning for the slave manipulator. After the trajectory of the end-effector reference point of the master manipulator is determined, the unique trajectory of the slave manipulator can be obtained according to the coupling kinematics relationship.

2.1.1 Coupled motion constraint algorithm

Two reference points \( T_1 \) and \( T_2 \) at different positions were selected on the trajectory of the main manipulator, \( A T_1 \) and \( A T_2 \) represent the coordinates of the trajectory point and the trajectory point in the base coordinate system of the multi-manipulator. Assuming that the main manipulator moves from track points \( T_1 \) to \( T_2 \), the slave manipulator must move from track points \( T_1 \) to \( T_2 \). According to the definition of coupling motion, the relative pose relation between track points \( T_1 \) and \( T_2 \) is equal to that between track points \( T_1 \) and \( T_2 \). Let \( B T_1 \) and \( B T_2 \) be the coordinates of track points \( T_1 \) and \( T_2 \) in the slave manipulator coordinate system. The homogeneous transformation matrix \( aT_\beta \) of \( 4 \times 4 \) represents point coordinates in rectangular coordinates as follows:

\[
aT_\beta = \begin{bmatrix} R & E \\ 0 & 1 \end{bmatrix}, \quad a = A, B, \beta = 1, 2, I, \Pi
\]

where \( R \in \mathbb{R}^{3 \times 3} \) represents the rotation transformation matrix, and \( E \in \mathbb{R}^{3 \times 1} \) represents the translation transformation matrix.

The relative pose constraint relation between track points \( T_1 \) and \( T_2 \) is equal to that between track points \( T_2 \) and \( T_1 \), so \( B T_1 \) can be calculated according to \( A T_1, A T_2 \) and \( B T_2 \). Let the homogeneous transformation matrix from the \( T_1 \) manipulator base coordinate system to the main manipulator base coordinate system be \( 9 \). Let the homogeneous transformation
matrix from the $T_I$ manipulator base coordinate system to the main manipulator base coordinate system be $^A U_B$. The results are as follows:

$$^A T_I = ^A U_B \cdot ^B T_I$$

(2)

$$^A T_{II} = ^A U_B \cdot ^B T_{II}$$

(3)

$^A T_I$ and $^A T_{II}$ represent the coordinate representations of track points $T_I$ and $T_{II}$ in the base coordinate system of the main manipulator. In the base coordinate system of the main manipulator, $T_I$ and $T_{II}$ are expressed as $^A T_I$ and $^A T_{II}$. Let $^A U_1$ be the homogeneous transformation matrix of $T_I$ to $T_{II}$, then

$$^A T_I = ^A U_1 \cdot ^A T_{II}$$

(4)

which can be obtained from Eq. (4):

$$^A U_1 = ^A T_1 \cdot (^A T_{I})^{-1}$$

(5)

Substituting Eq. (2) into Eq. (5), we can obtain

$$^A U_1 = ^A T_1 \cdot (^A T_{I})^{-1} \cdot ^B U_A$$

(6)

where $^b H_{mb}$ represents the inverse matrix of $^m H_{sb}$:

$$^B U_A = (^A U_B)^{-1}$$

(7)

In the base coordinate system of the main manipulator, the coordinates of track points $T_2$ and $T_{II}$ can be expressed as $^A T_2$ and $^A T_{II}$. Set $^A U_2$ as the homogeneous change matrix of $T_2$ to $T_{II}$, then

$$^A T_2 = ^A U_2 \cdot ^A T_{II}$$

(8)

Substituting Eq. (3) into Eq. (8), we can obtain

$$^A T_2 = ^A U_2 \cdot ^A T_{II} = ^A U_2 \cdot ^A U_B \cdot ^B T_{II}$$

(9)

Since the pose constraint equation of $T_I$ and $T_{II}$ is equal to that of $T_2$ and $T_{II}$, we can obtain

$$^A U_1 = ^A U_2$$

(10)

Substituting Eqs. (6) and (10) into Eq. (9), we can obtain

$$^A T_2 = ^A U_2 \cdot ^A U_B \cdot ^B T_{II}$$

$$= ^A T_1 \cdot (^A T_{I})^{-1} \cdot ^B U_A \cdot ^A U_B \cdot ^B T_{II}$$

$$= ^A T_1 \cdot (^A T_{I})^{-1} \cdot ^B T_{II}$$

(11)

Equation (12) shows that for any two points $T_I$ and $T_{II}$ on the main manipulator trajectory, under a specified coupling motion mode, the corresponding two points $T_I$ and $T_{II}$ on the slave manipulator trajectory and $T_{II}$ on the slave manipulator trajectory can be calculated by $^A T_I$ and $^A T_{II}$ in the main manipulator base coordinate system and $^A T_I$ in the slave manipulator base coordinate system, respectively.

### 2.1.2 Coupled motion coordination control

Coupling motion control of multi-manipulators is investigated through a cooperative multi-manipulator handling task. In our double manipulator coordinated handling experiment, Robot2 was set as the main manipulator and Robot1 as the slave manipulator.

Assume that the main manipulator, Robot2, moves in a straight line from $T_I$ to $T_{II}$ and then to $T_{III}$ in its base coordinate system:

$$^A T_{III} = ^A T_{II} \cdot (^A T_{I})^{-1} \cdot ^A T_I$$

(12)

Then, the first point of the trajectory of Robot1 can be determined as

$$K = \begin{bmatrix}
1 & 0 & 0 & 1700 \\
0 & -1 & 0 & 50 \\
0 & 0 & -1 & 30 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

The trajectory point matrix of the slave manipulator can be obtained by Eq. (12), and there is no need to plan the slave manipulator’s trajectory separately.

Figure 1 shows the four positions and postures in the handling process.

Figure 2 shows that the simulation trajectory of the coupled motion of the two manipulator is consistent with the planned trajectory, and the relative pose of the ends of the two manipulators always remains unchanged, indicating the correctness of the coupled motion algorithm.

### 2.2 Multi-manipulator superposition motion coordination and constraint control

#### 2.2.1 Superposition motion constraint algorithm

In the main manipulator’s base coordinate system, the coordinates of any point on the trajectory of the main manipulator are expressed as $^A T_I$, and $^m U_A(t)$ is the transformation
matrix from the base coordinate system of the main manipulator to the reference coordinate system of the end-effector. \( ^AT_1 \) is the exact value of \( ^mUA(t) \) at time \( t_0 \), i.e.,

\[
^AT_1 = ^mUA(t_0)
\]  \hspace{1cm} (13)

\[
^mUA(t) = ^mf(\theta(t)) \cdot ^mfU_m = ^AT(t)
\]  \hspace{1cm} (14)

where \( \theta(t) \) represents the joint coordinate value vector of the manipulator at time \( t \), \( ^mf(\theta(t)) \) represents the positive solution of the kinematics of the main manipulator, and \( ^mfU_m \) represents the transformation matrix from the reference coordinate system of the end-effector of the main manipulator to the flange coordinate system of the main manipulator.
Suppose $^A T_i$ is the pose of any point on the trajectory of the slave manipulator in the base coordinate system of the master manipulator, then

$$m T_i = ^A U_A (t_0) \cdot ^A T_i$$

(15)

$$m U_A (t) = \left(^A U_m (t)\right)^{-1}$$

(16)

$m U_A (t)$ is the time-varying matrix from the main manipulator’s base coordinate system to the end-effector’s reference coordinate system of the main manipulator. Substituting Eq. (2) into Eq. (15), we can obtain

$$m T_i = m U_A (t_0) \cdot ^A U_B \cdot ^B T_i$$

(17)

$m T_i$ represents the trajectory of the slave manipulator in the reference coordinate system of the end-effector of the main manipulator. Equation (17) applies to any point on the trajectory of the slave manipulator within the entire cooperation cycle $\Delta t$ of the cooperative multi-manipulator system, namely,

$$m T(t) = m U_A (t) \cdot ^A U_B \cdot ^B T(t)$$

(18)

It can be obtained from Eq. (18):

$$^B T(t) = ^B U_A \cdot ^A U_m (t) \cdot m T(t)$$

(19)

Equation (19) indicates that given the known motion trajectory of the master manipulator in its base coordinate system and the relative motion trajectory of the slave manipulator in the reference coordinate system of the end-effector of the master manipulator, the motion trajectory of the slave manipulator in its base coordinate system can be solved.

### 2.2.2 Superimposed motion coordination control

Superposition motion control is investigated by performing a cooperative multi-manipulator circle drawing task. Task requirements for coordinating circle drawing are as follows: a manipulator follows another manipulator and forms a certain relative motion trajectory, whose relative motion trajectory is three circles with a radius of 200 mm. Set Robot2 as the master manipulator and its base coordinates as (1500, 0, 0). It moves from $T_1$ to $T_2$ in its base coordinate system:

$$T_1 = \begin{bmatrix} 0 & 0 & -1 & -100 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 700 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2 = \begin{bmatrix} 0 & 0 & -1 & 180 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 760 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Set Robot1 as the slave manipulator and its base coordinates as (−1200, 800, 0). This coordination circle drawing task requires that the relative motion trajectory of the end-effector of Robot1 on the reference plane of the end-effector of Robot2 be a circle. Therefore, Robot1 maintains the distance between the end-effector reference point and the end-effector of the main manipulator constant in its base coordinate system, and the x-axis of the end-effector of the slave manipulator Robot1 is always perpendicular to the x–y plane of the end-effector of Robot2.
the main manipulator Robot2. The actual motion of Robot1 consists of the following motion at a certain distance from the end-effector of Robot2 and the relative motion in the reference plane of the end-effector of Robot2.

Because the collaborative task revealed that the relative distance between the end-effector of Robot1 and the end-effector of Robot2 is constant, the parametric equation of its relative motion trajectory is

\[
\begin{align*}
    y &= 200 \cos \alpha \\
    z &= 200 \sin \alpha
\end{align*}
\]

The trajectories of the two manipulators in Cartesian space were divided into 200 parts, and the relative trajectories of the manipulator Robot1 during this period were three circles.

Figure 3 shows the base coordinate system of the two manipulators.

Figure 3 shows that the base coordinate system of the slave manipulator rotates 180° around the z-axis, the negative movement along the y-axis is 800 mm, and the x-axis moves a distance of +2700 mm to complete the transformation to the base coordinate system of the main manipulator. The homogeneous transformation matrix $M$ of the coordinate system relative to the base coordinate system of the main manipulator is as follows:

\[
M = \begin{bmatrix}
    -1 & 0 & 0 & 2700 \\
    0 & -1 & 0 & -800 \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

According to the equation above, the corresponding trajectory matrix of the manipulator in its base coordinate system can be obtained.

Then, inverse kinematics was used to solve the joint coordinates of the manipulators so that the joint coordinates of each point could be obtained. Trajectory simulation was conducted using MATLAB-Robot Toolbox. Figure 4 shows the four groups of poses in the task of drawing circles with dual manipulators.

In the circle drawing task of the master/slave manipulators, the slave manipulator moves with the master manipulator and draws a circle on a reference plane of the end-effector of the master manipulator. The relative trajectory is a circle, the actual trajectory of the master manipulator is a straight line, and the actual trajectory of the slave manipulator is a spiral curve. Figure 5 shows an actual motion track of the master and slave manipulators.

According to Fig. 5, the actual trajectory of the manipulator obtained through trajectory simulation is a three-loop spiral, which conforms to the trajectory planning result and verifies the correctness of the multi-manipulator superposition motion algorithm.

### 3 Co-simulation of adaptive coordinated motion of a cooperative multi-manipulator system

Through MATLAB and ADAMS Co-simulation, the coordinated motion process of a multi-manipulator can be simulated more realistically. According to the multi-manipulator coupling and superposition motion coordination algorithm, trajectory planning is performed using MATLAB, and joint data are derived. A multi-manipulator simulation model is established in ADAMS, and then, the joint data are input into the model to create a spline curve, and the spline curve is used as the joint driving function to drive the virtual multi-manipulator model for coordinated movement.

#### 3.1 Coordinated handling simulation analysis

The cooperative coupling motion of the multi-manipulator expands the manipulator’s working range, allowing it to carry a large mass and volume of a workpiece, and its application prospect is broad. In this section, coupling motion simulation analysis is conducted through the cooperative handling of a cuboid load by multiple manipulators. Coordinated handling task requirements are as follows: the centre of mass of the load coordinated by multiple manipulators moves in accordance with the specified trajectory, and its attitude always remains unchanged in the process of load movement. According to the multi-manipulator trajectory coordination method, the trajectory coordination planning of the two manipulators is simulated in MATLAB, and the joint angle is calculated every 0.005 s. In this simulation, the two manipulators act similarly when performing the coupled motion, so the angles of the joints corresponding to the two manipulators are also the same. Table 1 shows the joints of a manipulator at 2, 4, 6, 8 and 10 s. For the rotation angle value, the unit of change angle of each joint in the table is degree.

Spline curves were generated numerically for each joint, and spline curves were used as joint driving functions for the virtual multi-manipulator model. The simulation time is set as 10 s. When the simulation begins,

---

**Fig. 3** Master/slave manipulator base coordinate system
the two manipulators jointly carry the cuboid load, and the centroid of the cuboid moves from Point A to B and then to Point C. Figure 6 shows the simulation process is smooth without any delay. Four pose groups in the simulation process.

Figure 7 shows the angle changes of each joint of the two manipulators during the coupling motion simulation, where a illustrates the angle changes of each joint of the manipulator Robot1 and b depicts the angle changes of each joint of the manipulator Robot2.

Figure 8 shows the velocity changes of each joint during the coupling motion simulation of two manipulators. a depicts the velocity changes of each joint of the manipulator Robot1, and b depicts the velocity changes of each joint of the manipulator Robot2.

Figures 7 and 8 depict that the angle and velocity curve changes of each joint are relatively smooth, indicating that during the simulation, the running speed of each joint of the two manipulators is relatively stable and the trajectory coordination effect is good.
3.2 Simulation and analysis of coordinated circle drawing

In this section, the simulation analysis of superposition motion is performed by drawing a circle through the collaboration of multiple manipulators. Coordinating the circle drawing task requires the end-effector of the manipulator Robot2 to connect the drawing board. The drawing board moves in a straight line along the x-axis, whereas the posture remains the same. It moves from Point D (−100, 1490, 1250) to E (100, 1490, 1250). The end-effector of another manipulator, Robot1, is connected with the brush, which is always perpendicular to the drawing board. Draw a 330-mm-diameter circle on the drawing board by following the manipulator Robot2.

The spline curve was also used as the driving function in the superposition motion simulation. The trajectory coordination planning of the two manipulators was simulated in MATLAB, and the joint rotation angle was calculated every 0.005 s. Table 2 shows the joint angle values of manipulator R1 at 2, 4, 6, 8 and 10 s; Table 3 shows the joint angle values of manipulator R2 at 2, 4, 6, 8 and 10 s. The unit of the change angle of each joint in the table is degree.

The spline curve is generated from the numerical value of each joint, and the spline curve is used as the joint driving function of the virtual multi-manipulator model. The simulation time was set to 10 s. After the simulation started, the manipulator Robot2 held the drawing board and moved the drawing board from Point D (−100, 1490, 1250) to E (100, 1490, 1250). The manipulator Robot1 held the paintbrush to draw a circle on the drawing board. The entire simulation process is smooth and free of lag. Figure 9 shows four pose groups in the simulation process.

Figure 10 shows the angle changes of each joint of the two manipulators during the superposition motion simulation, where a depicts the angle changes of each joint of the manipulator Robot1 and b depicts the angle changes of each joint of the manipulator Robot2.

Figure 11 shows the velocity changes of each joint in the superposition motion simulation process of the two manipulators. a depicts the velocity changes of each joint of the manipulator Robot1, and b depicts the velocity changes of each joint of the manipulator Robot2.

Figures 10 and 11 show that the change of angle and velocity curves of each joint of the two manipulators is relatively smooth, indicating that during the superposition motion simulation process, the running speed of each joint of the two manipulators is relatively stable, and the trajectory coordination effect is good.

Table 1 Coupling motion joint angle value

| Time | 2   | 4   | 6   | 8   | 10  |
|------|-----|-----|-----|-----|-----|
| a    | 9.3727 | 27.009 | 27.602 | 21.381 | 19.264 |
| b    | 0.9312 | 8.4967 | 10.952 | 33.623 | 48.513 |
| c    | −0.9390 | −9.1465 | −11.065 | −30.482 | −49.643 |
| d    | 0 | 0 | 0 | 0 | 0 |
| e    | −0.0078 | −0.6498 | −0.1128 | 3.1404 | −1.1303 |
| f    | 9.3727 | 27.009 | 27.602 | 21.381 | 19.264 |
Experimental and analysis

To verify the feasibility and accuracy of the coordinated motion algorithm of the cooperative multi-manipulator system, an experimental platform for the cooperative multi-manipulator system was developed to conduct experimental research on cooperative multi-manipulator circle drawing tasks. The cooperative multi-manipulator system’s coordinated motion experiment platform is primarily composed of an upper computer (computer), a lower computer (speed-goat controller), servo drives and two mechanicals. As shown in Fig. 12, two 6-degree-of-freedom manipulators are used as experimental objects in the coordinated motion experiment of multi-manipulators.

In this study, the coordinated motion algorithm of the multi-manipulator is verified by the multi-manipulator coordinated circle drawing experiment. During the experiment, the end-effector of a manipulator, Robot2, was

Fig. 7 Angle change curve of coupled motion joint. R1 and R2 represent manipulator ROBOT1 and manipulator ROBOT2 respectively, and abcdef represents six different joints in turn
connected to the drawing board, which moved along a straight line with the same posture. The end-effector of another manipulator, Robot1, was connected with a brush following the movement of the manipulator, Robot2, and two circles with a diameter of 400 mm were drawn on the drawing board.

Before the experiment, the base coordinate system of the two manipulators should be calibrated first, and the homogeneous pose transformation matrix between the two manipulators base coordinate systems should be determined:

$$R_1^{T_{R_2}} = \begin{bmatrix}
-0.22494 & -0.97432 & 0.00959 & 886.610 \\
0.974365 & -0.22488 & -0.00698 & -1365.32 \\
0.004644 & -0.010914 & 0.99930 & 10.3318 \\
0 & 0 & 0 & 1
\end{bmatrix}$$

Then, trajectory planning is performed according to the coordinated motion method of the multi-manipulator. The servo driver is controlled by the controller to drive the joint of the manipulator, and the multi-manipulator is coordinated to draw a circle. After several experiments and debugging, the multi-manipulator coordinated circle drawing result is obtained, as shown in Fig. 13.

Figure 13 shows that after several experiments and debugging, the actual trajectory is consistent with the expected trajectory and can produce the basic shape required by the task, indicating the feasibility of the coordinated motion algorithm.

The experimental results will inevitably be affected by various factors, resulting in experimental errors. There were some trajectory tracking errors in the multi-manipulator coordinated circle drawing experiment, and the task curve was not sufficiently smooth. Therefore, this section analysed the experimental errors through the experimental results and investigated the accuracy of the coordination algorithm.

In the experiment of the multi-manipulator coordinated circular motion, the relative trajectory between the brush at the end-effector of manipulator R1 and the sketchpad clamped at the end-effector of manipulator R2 is circular. Because the actual motion trajectory at the end-effector of manipulator R2 is a straight line, whereas the actual motion trajectory at the end-effector of manipulator R1 is a spiral curve, the change of joint rotation angle is more complex, and the end-effector trajectory error is larger. Thus, the error of this experiment mainly comes from the error of manipulator R1. This section focuses on the analysis of the end-effector trajectory error of manipulator R1.

| Table 2 Joint angle value of R1 superposition motion |
| --- |
| Time | The joints | 2 | 4 | 6 | 8 | 10 |
| a | -6.8409 | -29.381 | -37.607 | -31.065 | -28.256 |
| b | 1.7508 | 11.323 | 17.111 | 10.629 | 9.3865 |
| c | -7.4187 | -16.956 | -5.6284 | -4.5118 | -10.126 |
| d | -20.202 | -49.232 | -41.117 | -17.228 | 0 |
| e | -7.4209 | -25.708 | -19.549 | -4.1893 | -0.7876 |
| f | -4.5143 | -15.040 | -34.467 | -31.358 | -28.256 |

| Table 3 Joint angle value of R2 superposition motion |
| --- |
| Time | The joints | 2 | 4 | 6 | 8 | 10 |
| a-2 | 1.5759 | 9.3727 | 20.415 | 27.008 | 28.245 |
| b-2 | 0.0275 | 0.9312 | 4.6155 | 8.4967 | 9.4032 |
| c-2 | -0.0275 | -0.9390 | -4.8074 | -9.1465 | -10.198 |
| d-2 | 0 | 0 | 0 | 0 | 0 |
| e-2 | 0 | -0.0078 | -0.1918 | -0.6498 | -0.7957 |
| f-2 | 1.5759 | 9.3727 | 20.415 | 27.008 | 28.245 |
In the coordinated circular drawing movement, the eight groups of error values corresponding to the moment when the terminal position error of manipulator R1 varies greatly are shown in Table 4. The maximum position error in the x-axis direction appears during the start-up phase, with a maximum error value of $-1.52 \text{ mm}$. The maximum position error value in the y-axis direction appears at approximately 7.3 s, with a maximum error value of approximately $1.58 \text{ mm}$. The maximum position error value in the z-axis direction also appears at approximately 7.3 s, with a maximum error value of approximately $2.13 \text{ mm}$.

Figure 14 shows the position tracking error of the endpoint of manipulator R1. Comparing the actual position of the endpoint of the manipulator R1 with the expected position, the maximum errors in the x-, y-, and z-axis directions...
in Cartesian space are $-1.523, 1.579$ and $2.131$ mm, respectively. The end-effector position error of the manipulator R1 can meet the accuracy requirements in this coordinated circle drawing task.

In this multi-manipulator coordinated motion experiment, there are also certain requirements for the posture of the end-effector of the manipulator. The brush at the end-effector of manipulator R1 and the drawing board at the end-effector of manipulator R2 always maintain a certain angle. When the posture error of the end-effector of manipulator R1 varies greatly, the corresponding eight groups of error values are shown in Table 5, and the unit of the angle of the change of each joint is degree. The maximum error of the rolling angle appears in the start-up stage, and the maximum error is approximately $0.176^\circ$. The maximum error of the pitch angle is approximately $5.3$ s, and the maximum error is approximately $0.067^\circ$. The maximum error of the yaw angle is approximately $5.3$ s, and the maximum error is approximately $-0.053^\circ$.

Figure 15 shows the terminal attitude error of manipulator R1. Comparing the actual and expected attitude of the endpoint of manipulator R1, the maximum errors of the rolling angle, pitch angle and yaw angle are $0.1761^\circ, 0.0674^\circ$ and $-0.0526^\circ$, respectively. In this coordinated circle drawing task, the terminal attitude error of manipulator R1 meets the accuracy requirements.

Figures 14 and 15 show that there is a large error value in the start phase of the manipulator. The main reason for the
error at this stage is the start delay. Additionally, the error value varies significantly between 5 and 8 s, and the cause of the error at this stage is more complicated. Analysing the error peak value, the maximum position error and the maximum attitude error can meet the requirements of coordinated motion accuracy.

Although error always exists in the entire coordinated motion and the error value varies frequently, the error value can be controlled in a certain range to meet the accuracy requirements, demonstrating the feasibility and accuracy of the adaptive coordinated motion algorithm of the multi-manipulator.

5 Conclusion

In this paper, an adaptive coordinated motion constraint control scheme is proposed for the multi-manipulator coordination system. Considering the kinematic constraint relation of the multi-manipulator coordination motion, the coordinated motion of the multi-manipulator is divided into coupling and superposition motions. The coupling and superposition motions are studied through coordinated handling and circular drawing of multiple manipulators, respectively. The simulation results show that the proposed adaptive trajectory coordinated motion constraint control scheme exhibits a good coordination effect, and the multi-manipulator can always maintain the coordinated motion relationship during the motion process. Finally, the multi-manipulator coordination circle drawing experiment is performed on the multi-manipulator coordination motion experimental platform. The experimental results show that the proposed control scheme has a good coordination control effect and strong adaptive ability.

The adaptive coordinated motion constraint control scheme of the multi-manipulator cooperative system proposed herein does not require position detection and positioning like those in existing research. The relative motion relationship between the end actuators can be maintained using the kinematic constraint algorithm. In case of an
external disturbance, the slave manipulator can automatically adjust based on the master manipulator’s position to avoid a cumulative error. The motion coordination method of the multi-manipulator cooperative system is considered here. Furthermore, the corresponding relationship between time and space of multiple-manipulator end-effectors is solved. However, in some cooperative tasks, the task requirements can hardly be met through only motion control; hence, internal force control must be performed on the basis of motion control. The proposed control scheme does not involve internal force control. Therefore, in the future, we will conduct a mechanical coordination control research on the basis of the adaptive coordinated motion of the multi-manipulator cooperative system and further enhance the control performance of the system through the synchronous control of position and internal force.

**Author contribution** In this study, the coordinated motion of a multi-manipulator is divided into two types: coupling and superposition motions. An adaptive coordinated motion constraint scheme is proposed for the two different motion forms. Solve the problem of coordinated motion control of multi-manipulator cooperation system.

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**Availability of data and material** The data of this study cannot be shared publicly.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

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**Competing interests** The authors declare have no competing interests.

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