Design of Cooperative System Consisting of Multiple Position Controlled Robots*

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A simple strategy for carrying a large object with the cooperation of multiple position-controlled robots is proposed. In cooperative systems handling single objects, compliance is necessary for each robot to avoid excessive inner forces caused by mutual positioning errors. However, since the majority of commercial industrial robots have PID position controllers, the necessary compliance cannot be achieved by servo systems. Thus, mechanisms consisting of passive joints are installed in a cooperative system as mechanical compliance. First, the mechanical compliance required for the cooperation of position-controlled robots is derived. From the theoretical results, it is determined that the maximum number of robots that can directly support a single object is six. Second, the statics and error characteristics of cooperative systems including compliant mechanisms are analyzed. An example of the cooperation of three mobile robots is designed using passive joint mechanisms. Finally, the strategy is extended to cooperation among an arbitrary number of mobile robots by building hierarchical structures with passive joints.

Key Words: Robot, Positioning, Manipulator, Cooperation, Position Controller, Passive Joint Mechanism, Multiple Mobile Robot, Mechanical Compliance

1. Introduction

The cooperation of multiple robots will be one of the most significant technologies of future robot systems. It can improve the various performances of robotic systems, such as payload capacity and grasping function. When multiple robots grasp a single object simultaneously, geometrical constraints by closed loop structures are imposed on each robot. Thus, compliance is required for each robot to avoid excessive inner forces caused by the mutual positioning errors of robots. In order to realize compliance among robots, most cooperative algorithms proposed for manipulators have controlled forces generated by the end-effectors, assuming that the manipulators have torque controllers and do not exist in singular points⁽¹⁾⁻⁽³⁾. However, the necessary compliance can-

not be achieved by servo systems because most commercial industrial robots have PID position controllers with very high servo stiffness. Thus, very few cooperative systems have been developed that use commercial industrial robots⁽⁴⁾⁻⁽⁶⁾.

Cooperative strategies for autonomous mobile robots have been proposed recently. The cooperation of mobile robots will be one of the most effective strategies for carrying large or heavy objects in the future. However, the majority of algorithms proposed for manipulators could not be installed because of the following two characteristics:

(1) In some cases, the mutual positioning errors of robots become uncontrollable due to the unevenness of the ground or the non-holonomic constraints of wheel mechanisms.

(2) In decentralized systems, such as multiple mobile robotic systems, cooperation will be accomplished by means of communication between robots, whose transmission ratio is generally very low and not sufficient for servo level cooperation.

To solve the above problems, Hashimoto et al. installed an additional actuator on each mobile platform and designed a cooperative controller⁽⁷⁾. Kosuge

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et al. developed a cooperative controller which does not require explicit communication among robots⁽⁸⁾. However, these controllers cannot be used on uneven ground. To realize cooperative tasks in decentralized robotic systems, cooperation methods applicable to the systems with inevitable positioning errors of robots are essential. Installation of compliance measures, such as springs or passive joints, among robots is one of the simplest and most effective solutions to avoid excessive inner forces in cooperation systems with PID position controllers. Moreover, the stability problem will not be so critical for slow motion control.

The authors have proposed a method of designing cooperative systems with two position-controlled robots⁽⁹⁾⁻⁽¹¹⁾. According to the proposed method, the authors have also developed a cooperative system consisting of a crane and an industrial robot⁽¹²⁾ and a system consisting of two mobile robots⁽¹³⁾. In this paper, a general method of designing a cooperative system consisting of an arbitrary number of position-controlled robots is proposed.

In sections 2 and 3, the necessary kinematic conditions for installed passive joint mechanisms for cooperation will be shown. After demonstrating the method of analyzing error characteristics and statics of designed cooperative systems in section 4, two types of cooperative systems consisting of three mobile robots are designed and their characteristics are analyzed. As the result of the kinematic analysis, it is proved that the maximum number of robots that can simultaneously grasp a single object is 6. Hence, a way to overcome this limitation is proposed using a hierarchical structure of compliant mechanisms.

2. Kinematic Conditions for Cooperative Systems

2.1 Kinematic model of cooperative system

Figure 1 shows a kinematic model of a cooperative system of multiple robots. Each robot grasps the object rigidly at the end-effector through its passive joint mechanism. n and m_i denote the number of robots and the number of passive joints connected to Robot i , respectively. If the number of installed passive joints are not sufficient to satisfy the conditions adequately, excessive inner forces are generated due to the mutual positioning errors among robots. On the other hand, if there are too many passive joints installed, the cooperative system cannot compensate for the gravity of the object. In this chapter, the necessary kinematic conditions for installed passive joint mechanisms will be shown.

We assume that each passive joint mechanism does not exist at its singular point. This model is applicable to any type of grasping by modeling the

Fig. 1 Kinematic model of cooperative system with free joints

remaining degrees of freedom at the grasped points as passive joints. The cooperation of position-controlled robots can be achieved by designing these passive joint mechanisms in a suitable manner.

2.2 Free motion space and constraint space

First, two subspaces, Free Motion Space (F.M.S.) and Constraint Space (C.S.), are defined. Let q_i be the joint angle vector of the passive joint mechanism connected to Robot i and $x_{ti} \in R^6$ be the position and orientation vector of the tip. Then the Jacobian matrix J_i between q_i and x_{ti} is expressed as Eq. (1).

$$\Delta x_{ti} = J_i \Delta q_i \quad (1)$$

The F.M.S. of the passive joint mechanism of Robot i can be defined as the space spanned by the column vectors of the matrix P_{fi} calculated as follows:

$$\begin{aligned} m_i < 6: P_{fi} &= J_i J_i^+ \\ m_i &\geq 6: P_{fi} = I_6, \end{aligned} \quad (2)$$

where J_i^+ denotes the pseudo-inverse matrix of J_i and $I_6 \in R^{6 \times 6}$ expresses an identity matrix. When $k_i \leq 6$, the rank of P_{fi} becomes m_i because all passive joints are not at their singular points. In this space, the tips of passive joint mechanisms move according to the external forces applied to the tip. The C.S. is defined as a complementary space of F.M.S. Thus, it is obtained as the space spanned by the column vectors of the matrix P_{ci} calculated by Eq. (3).

$$P_{ci} = I_6 - P_{fi} \quad (3)$$

Let the rank of P_{ci} be k_i . Then, $k_i = 6 - m_i$, ($m_i \leq 6$) or $k_i = 0$, ($m_i > 6$) because P_{fi} is the orthogonal projection matrix into the complementary space of C.S. In this space, the tip cannot move at all and external forces at the tip are applied to Robot i directly.

Since the mutual geometrical relationships between the tips and the object do not change due to the rigid grasps, we consider that x_{ti} coincides with the position vector of the object x_o in the following analysis.

2.3 Kinematic conditions of passive joint mechanisms

We define "a geometrical constraint matrix" C as Eq. (4) to derive the kinematic condition for the cooperation of n position-controlled robots,

$$C = [p_{c1,1} \cdots p_{c1,m1} \ p_{c2,1} \cdots p_{cn,mn}], \quad (4)$$

where $p_{ci,j}$, ($j=1 \cdots k_i$) is an orthogonal basis of the C. S. of Robot i .

Condition 1: The kinematic condition to avoid excessive inner forces caused by positioning errors of robots is that all the column vectors of the matrix C are linearly independent of each other.

Proof: Let the C. S. of the passive joint mechanism of Robot i be S_{ci} and that of the passive joint mechanism consisting of all other robot be $S_{\bar{ci}}$. If all the column vectors of the matrix C are linearly independent,

$$S_{ci} \cap S_{\bar{ci}} = \phi.$$

Thus, Eq. (5) is derived.

$$\dim(S_{ci} \cap S_{\bar{ci}}) = 0 \quad (5)$$

On the other hand,

$$(S_{ci} \cap S_{\bar{ci}})^\perp = S_{ci}^\perp + S_{\bar{ci}}^\perp = S_{fi} + S_{\bar{fi}}$$

is satisfied. Thus, Eq. (6) is obtained.

$$\dim(S_{fi} + S_{\bar{fi}}) = 6 \quad (6)$$

Equation (6) shows that errors in all the directions can be absorbed by the displacements of all the passive joints.

Therefore, condition 1 is proved.

Condition 2: The kinematic condition to support external forces applied to the object is that the dimension of the matrix C is six.

Proof: If there are six linearly independent geometrical constraints, it is clear that the object is fixed in all directions. Thus, the object can generate reaction forces against external forces applied in arbitrary directions. If the rank of C is less than 6, it can be easily understood that it is impossible to generate reaction forces in the orthogonal complementary space of the space spanned by C . Therefore, theorem 2 is proved. This condition has already been proved by Kobayashi⁽¹⁴⁾.

The mechanism for the cooperation of multiple position-controlled robots must at least satisfy both the above conditions.

3. Kinematic Analysis of Cooperative System

The necessary kinematic conditions for the cooperation of position-controlled robots are presented. These conditions are essential for the cooperation process, but they are insufficient for practical use because information regarding the transmission mechanism of positioning errors or forces through the passive joint mechanisms is not clear.

The mechanism shown in Fig. 2 satisfies both the conditions mentioned above. In Fig. 2(a), the positioning error of the object generated by the rotational error of the robot is not large. On the other hand, in Fig. 2(b), a large positioning error is generated though the robot that has the same error as in Fig.

Fig. 2 Relationship between positioning error of a robot and that of the object

Fig. 3 Cooperation of two manipulators

2(a). We must design the structures of the cooperative mechanisms according to the error characteristics of each robot. The mechanism shown in Fig. 3 also satisfies the conditions mentioned above, but if the direction of gravity coincides with the y axis, the entire gravity force is concentrated on Robot 1. Thus, the cooperation cannot improve the load capacity of the control system.

We assume that $n-1$ robots are fixed at the desired positions and only Robot i has a positioning error Δx_i . The positioning error of the object Δx_o due to Δx_i can be calculated as follows. First, the passive joint mechanisms, except that of Robot i , are regarded as a single passive joint mechanism fixed to the ground as shown in Fig. 4. The passive joints of this mechanism can be modeled as one of the bases of the F. M. S., $p_{\bar{fi},1} \cdots p_{\bar{fi},k_i}$. These vectors can be obtained as linearly independent column vectors of matrix $P_{\bar{fi}}$ calculated by Eq. (7),

$$P_{\bar{fi}} = I_6 - P_{\bar{ci}}, \quad (7)$$

where

$$P_{\bar{ci}} = C_i (C_i^T C_i)^{-1} C_i^T$$

$$C_i = [p_{c1,1} \cdots p_{c(i-1),m(i-1)} \ p_{c(i+1),1} \cdots p_{cn,mn}]. \quad (8)$$

Next, we introduce two virtual manipulator models. One consists of the links from the base to the object, and the other consists of those from the base to Robot i . Let J_{oi} be the Jacobian matrix of the former manipulator and J_{ei} be that of the latter one. Then, each Jacobian matrix can be obtained by Eqs. (9) and (10).

$$J_{oi} = [p_{\bar{fi},1} \cdots p_{\bar{fi},k_i} \ 0 \cdots 0] \quad (9)$$

Fig. 4 Serial link model of the cooperative system

Fig. 5 Direction of the robot generating the largest positioning error of the object

$$J_{ei} = [\hat{p}_{fi,1} \cdots \hat{p}_{fi,k_i} \hat{p}_{fi,1} \cdots \hat{p}_{fi,m_i}] \quad (10)$$

The vectors $\hat{p}$ with the upper symbol are expressed with respect to the coordinates of Robot i . Using J_{oi} and J_{ei} , the relationship between Δx_o and Δx_i can be expressed as Eq. (11).

$$\Delta x_o = J_{oi} J_{ei}^{-1} \Delta x_i = J_{iei} \Delta x_i \quad (11)$$

Thus, if $1 \geq \Delta x_i^T \Delta x_i$, Δx_o satisfies Eq. (12).

$$1 \geq \Delta x_o^T (J_{iei}^T J_{iei}) \Delta x_o \quad (12)$$

From Eq. (12), it can be easily understood that the singular decomposition of J_{iei} implies the error characteristics of the object according to the positioning error of Robot i . The relationship between the error of Robot i and that of the object is shown in Fig. 5. When the robot has a unit norm positioning error, the error ellipsoid of the object is generated. The axes of the ellipsoid and the lengths are obtained by singular decomposition. Let the direction vector of the axis with the largest length be denoted d_{oi} . Then, the error direction of Robot i generating the largest possible positioning error of the object can be calculated as Eq. (13).

$$d_{imax} = J_{iei}^+ d_{oi} \quad (13)$$

The characteristics of the statics will be obtained as follows. If all the robots have infinitesimal displacements, the displacement of the object is calculated as Eq. (14),

$$\Delta x_o = \sum_{i=1}^n J_{oi} J_{ei}^{-1} \Delta x_i = J \Delta x, \quad (14)$$

where

$$x = [x_1^T \cdots x_n^T]^T, \quad J = [J_{o1} J_{e1}^{-1} \cdots J_{on} J_{en}^{-1}].$$

From Eq. (14), the statics can be obtained as Eq. (15).

Fig. 6 Cooperative mechanism for three mobile robots

Fig. 7 Geometrical relationship among three robots

$$F = J^T f_{ext}, \quad F = [f_1^T \cdots f_n^T]^T \quad (15)$$

f_{ext} denotes the external force applied to the object and f_i the applied force to Robot i .

4. Cooperative Mechanism for Three Mobile Robots

Figures 6(a) and (b) show the designed cooperative mechanisms for the cooperation of three mobile robots. The shape of the transported object is a regular triangle. In the Type 1 mechanism, the passive joint mechanism installed in Robot 1 consists of two rotational joints, and the mechanisms of Robots 2 and 3 consist of two ball joints which are equal to five passive joints. In the Type 2 mechanism, the same type of mechanism with four rotational joints (one ball joint and one rotational joint) is installed in all the robots.

If the geometrical relationships among robots are as shown in Fig. 7, both mechanisms satisfy Conditions 1 and 2. The results of the singular decomposition of the Type 1 mechanism for Robots 1 and 2 based on Eq. (11) are shown in Table 1 and that of the Type 2 mechanism for Robots 1 and 2 are shown in Table 2. The principal axes of the error ellipsoid of the object and the corresponding directions of the robots are shown in both Tables. The upper three elements of each column express the displacements [m] in the x , y and z directions and the lower three elements express the displacements [rad] in the rotational directions about the x , y and z axes. They are expressed with respect to the corresponding mobile robot coordinate or the object coordinate. The origin of each mobile robot coordinate is fixed at the

Table 1 Error characteristics of Type 1

Robot	r11	r12	r21	r22	r23
principal axis of object error ellipsoid with largest singular value d_{oi}	-0.96	0	-0.91	0.91	0.91
	0	0.2	-0.03	0.03	0.03
	0	0.28	-0.31	0.31	0.31
	0	0.22	0.095	0.095	0.095
	0.18	0	0	0	0
	-0.22	-0.91	-0.28	-0.28	-0.28
corresponding error direction of robot d_{ijmax}	0.0	0.43	0	0.43	-0.43
	0.0	0.25	-0.1	0.25	0.25
	0.0	0.87	-0.3	0.87	0.87
	0.0	0	0	0	0
	1.0	0	0.95	0	0
	0	0	0	0	0
singular value	5.4	0.39	1.0	1.1	0.17

Table 2 Error characteristics of Type 2

	Robot 1		Robot 2	
principal axis of error ellipsoid of the object	0.80	0	0.40	0.24
	0	-0.28	-0.68	0.14
	0	0.49	0	0.49
	0	0.82	-0.40	-0.41
	-0.46	0	-0.23	0.71
	-0.40	0	0.40	0
corresponding error direction of robot	1.0	0	0.50	0.43
	0	-0.50	-0.87	0.25
	0	0.87	0	0.87
	0	0	0	0
	0	0	0	0
singular value	0.70	0.78	0.70	0.78

midpoint of the line between both wheels. The x axis coincides with the wheel shaft and y axis with the moving direction. In both Types, the error characteristics of Robot 3 are equivalent to those of Robot 2. Thus, Robot 3 is omitted.

In Table 1, since the virtual serial link mechanism consisting of the passive joints of Robots 2 and 3 imposes two geometrical constraints on the object, 4 dimensional positioning errors are generated by the positioning errors of Robot 1. It is observed that the error of Robot 1 in the direction of the fourth vector from the left side generates the largest positioning error of the object. This situation occurs when one of the wheels of Robot 1 runs over an obstacle. On the other hand, since Robots 1 and 3 give five geometrical constraints to the object, only one dimensional error is generated by those of Robot 2. The error direction of Robot 2 with the largest positioning error of the object is obtained as the same direction of the link of the passive joint mechanism.

In Type 2, all the robots have the same type of passive joint mechanism, and the error directions due to the errors of each robot exist in two-dimensional space. In Table 2, both robots have the same error

Fig. 8 Model of cooperative mechanism

characteristics, which comes from the fact that both robots are symmetrically placed around the object coordinate. Additionally, all the singular values becomes less than 1.0, which means that the effect of the error of each robot on the object error decreases. Therefore, the Type 2 mechanism can be considered to be more suitable for cooperative transportation requiring positioning accuracy of the transported object. As for the statics, it is clear that all the robots support the same load.

5. Extension to Cooperative System Including More than Six Robots

5.1 Design method of cooperative mechanism

As shown in Conditions 1 and 2, the number of geometrical constraints imposed on the object must be six. Accordingly, we can use only six robots to directly support the object. Even if we use more than six robots for cooperation, only six of them could support the weight of the object. However, we can use as many robots as we want by constructing a mechanism with hierarchical structure.

Figure 8 illustrates the kinematic model of a passive joint mechanism with hierarchical structure. Each robot in Fig. 1 is replaced by a module consisting of n_i robots and their cooperative mechanisms. x_{oi} denotes the position and orientation vector of Module i . By modeling each module as single robot, its characteristics can easily be analyzed. The error of x_{oi} and Δx_o can be expressed as Eq. (16) in the same manner as Eq. (11).

$$\Delta x_o = J_{oi} J_{ei}^{-1} \Delta x_{oi} \quad (16)$$

Δx_{oi} is also generated by robots constructing Module i . Thus Eq. (17) is obtained.

$$\begin{aligned} \Delta x_o &= \sum_{i=1}^n J_{oi} J_{ei}^{-1} \Delta x_{oi} = \sum_{i=1}^n J_{oi} J_{ei}^{-1} \sum_{j=1}^{n_i} J_{oij} J_{eij}^{-1} \Delta x_{ij}, \\ &= J_s \Delta x_s \end{aligned} \quad (17)$$

where

$$\begin{aligned} x_s &= [x_{11}^T \cdots x_{nn}^T]^T \\ J_s &= [J_{o1} J_{e1}^{-1} J_{o11} J_{e11}^{-1} \cdots J_{on} J_{en}^{-1} J_{on1} J_{en1}^{-1} \cdots] \end{aligned}$$

Fig. 9 Cooperative structure for nine robots

$$J_{oi} J_{en}^{-1} J_{onn} J_{enn}^{-1}.$$

$\mathbf{x}_{ij}$ is the position and orientation vector of the j -th robot included in Module i (r_{ij}) and J_{oin_j} and J_{ein_j} are the Jacobian matrices of Module i corresponding to J_{oi} and J_{ei} respectively. The statics can be calculated as Eq. (18).

$$\mathbf{F}_s = \mathbf{J}_s^T \mathbf{f}_{ext}, \quad \mathbf{F}_s = [\mathbf{f}_{11}^T \cdots \mathbf{f}_{nn}^T]^T \quad (18)$$

$\mathbf{f}_{ij}$ expresses the force vector applied to the j -th robot of Module i .

5.2 Cooperative mechanism for nine mobile robots

The mechanisms shown in Figs. 9(a) and (b) consist of three modules that have three mobile robots with Type 1 and Type 2 mechanisms. The kinematic parameters of each module are the same as those shown in Fig. 6, and the sizes of the table and the supporting links are three times as large as those shown in Fig. 6. The results of error characteristics are shown in Tables 3 and 4. r_{ij} indicates the j -th robot of Module i . The vectors listed in the upper row are the principal axes corresponding to the largest singular values of each error ellipsoid of the object generated by the positioning error of each robot. The vectors in the lower row generate the positioning error of the object in the upper row. The singular values in the lowest row indicate the magnification ratio of errors.

From Table 3, it can be understood that the positioning error of Robot 11 generates a large positioning error of the object, which also means that external forces applied to the object in the corresponding direction are magnified and transmitted to Robot 11. However, for Type 2, all the singular values become less than the values in Table 2, which means that the error norm is caused to become much smaller by the hierarchical structure. This is because the error directions of each module are near the directions corresponding to the small singular values. From the results, it can be concluded that the hierarchical structure is effective not only in increasing the payload capacity of cooperative systems but also in reducing the positioning error of the transported object.

Table 3 Error characteristics of Type 1

Robot	r11	r12	r21	r22	r23
principal axis of object error ellipsoid with largest singular value	-0.96	0	-0.91	0.91	0.91
$\mathbf{d}_{oij}$	0	0.2	-0.03	0.03	0.03
	0	0.28	-0.31	0.31	0.31
	0	0.22	0.095	0.095	0.095
	0.18	0	0	0	0
	-0.22	-0.91	-0.28	-0.28	-0.28
corresponding error direction of robot	0.0	0.43	0	0.43	-0.43
$\mathbf{d}_{ijmax}$	0.0	0.25	-0.1	0.25	0.25
	0.0	0.87	-0.3	0.87	0.87
	0.0	0	0	0	0
	1.0	0	0.95	0	0
	0	0	0	0	0
singular value	5.4	0.39	1.0	1.1	0.17

Table 4 Error characteristics of Type 2

Robot	r11	r12	r21	r22	r23
principal axis of object error ellipsoid with largest singular value	0.97	0.78	0.48	0.47	-0.29
$\mathbf{d}_{oij}$	0	-0.11	-0.61	-0.36	0.73
	0	0.51	0.51	0	0.52
	0	0.32	-0.29	-0.16	-0.03
	-0.19	-0.15	0.20	-0.10	0.35
	-0.16	-0.13	0.13	0	-0.13
corresponding error direction of robot	1.0	0.66	0.77	0.50	0.11
$\mathbf{d}_{ijmax}$	0	-0.50	-0.32	-0.87	0.82
	0	0.56	0.56	0	0.56
	0	0	0	0	0
	0	0	0	0	0
	0	0	0	0	0
singular value	0.36	0.27	0.27	0.36	0.27

6. Conclusion

A simple but very practical method for cooperation of position-controlled robots was proposed, and a method of designing the mechanical compliance required for cooperation based on PID position controllers was developed.

-The essential kinematic conditions for the cooperative mechanisms were shown.

-The characteristics of the positioning error and the statics of proposed mechanisms were analyzed.

-Two cooperative mechanisms for the cooperation of three mobile manipulators were proposed and their characteristics were analyzed.

-The method of extending the proposed strategy to cooperative systems of more than six robots was shown.

The method described in this paper requires the introduction of additional mechanical compliance instead of servo compliance. A method using servo compliance seems more flexible and appears to have good performance for cooperation, but the majority of commercial robots are controlled by PID position controllers. Thus, if users want to use their robots

cooperatively, they must modify their robot controllers themselves. However, in practice, it is very difficult and almost impossible for users to achieve this due to the complexity of the controllers. On the other hand, the design of simple passive joint mechanisms and their introduction are simple and practical, and the proposed method is applicable in many industries or in future distributed autonomous robotic systems.

A feedback control method based on position control or an optimal design of mechanisms for practical use will be the next step for our future studies.

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