Handling of an Object Exceeding Load Capacity of Dual Manipulators Using Virtually Unactuated Joints

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Abstract

The load capacity of a manipulator depends on a load capacity of a joint or load capacities of some joints of the manipulator. Even if a manipulator could not handle an object because of its load capacity, some of its joints still have enough capabilities for the handling of the object. In this paper, we proposed a method to handle an object using available joints of the manipulators by introducing virtually unactuated joints. The virtually unactuated joints are controlled so that no load will be applied to the joints. The introduction of the virtually unactuated joints makes the available degrees of freedom of the manipulator less than that of the original manipulator. In this paper, we propose a method to manipulate an object with dual manipulators having virtually unactuated joints. An experiment illustrates the validity.

1 Introduction

Various kinds of robots have been developed so far. In general, most of them have been used in an environment isolated from humans. However, with the coming of aging societies, robots are expected to execute tasks in human environments. The robots in human environments are expected to be driven by small actuators having lower outputs than the conventional ones for safety reasons. In this paper, we consider a problem to handle a heavy object by robots whose load capacities are lower than the ones required to handle it. We assume that the load capacity of a manipulator depends on a capacity of a joint or capacities of some joints. The load capacity of a manipulator usually depends on the load capacities of several joints located close to the end of the manipulator. Actuators with high output power are heavy in general and could not be used to drive joints located close to the end of the manipulator. The joints located close to the end of the manipulator are to be driven by actuators having low output power.

Several researches[1, 2, 3] for handling a heavy object have been done by introducing robots with special mechanisms. In this paper, we consider a problem to handle a heavy object by dual serial link manipulators, which consists of revolute joints and rigid links. Then, we assume that the dual manipulators grasp the object rigidly. In the rest of this paper, the word "manipulator" means a serial link manipulator.

In [4], we proposed a method to handle an object by a manipulator, whose load capacity is not enough to handle it, by introducing virtually unactuated joints. By the proposed method, the manipulator is controlled as if no load will be applied to the virtually unactuated joints by handling the object. The manipulator is to behave as if some of its joints are unactuated. We also considered a problem to handle the object by dual manipulators in coordination and derived a necessary and sufficient condition for the handling of the object by dual manipulators having virtually unactuated joints.

We described the concept of handling an object by dual manipulators with virtually unactuated joints to design the control system.

In this paper, we consider handling of an object by dual manipulators in detail. We propose a control algorithm to handle the object by controlling the force and moment applied to the center of mass of the object. Then, we consider applying the algorithm to handling of an object by dual six degrees of freedom manipulators consisting of wrist-partitioned manipulators. An experiment illustrates the validity of the method proposed in this paper.

2 Handling of an Object by Dual Manipulators with Virtually Unactuated Joints

Let us consider handling of an object by dual manipulators with virtually unactuated joints.

2.1 Dynamics of an Object

As is well known, a motion of a rigid body handled by manipulators is expressed as follows:

\[ M \ddot{x} + g(x) = F_{ext}. \]  

(1)
where $M(\in R^{6x6})$ is the inertia matrix of the object, $x(\in R^6)$ is the position and orientation of the object, $g(x)(\in R^6)$ is the gravity vector and $F_{ext}(\in R^6)$ is the external force and moment vector applied to the center of mass of the object by dual manipulators. Note that $F_{ext}$ is the resultant force and moment by the dual manipulators. The relationship of the resultant force and moment is given by

$$F_{ext} = F_L + F_R = QF_{LR},$$

where $F_L(\in R^6)$ and $F_R(\in R^6)$ are the force and moment applied to the center of mass of the object by the L-manipulator and R-manipulator, respectively as shown in Fig.1 and $E_6$ is a $6 \times 6$ identity matrix. Since $Q$ is not a square matrix and has a null space, the internal forces and moments, which do not affect the motion of the object, exist. From Eq.(2), $F_{LR}$ is solved as follows:

$$F_{LR} = Q^+ F_{ext} + (E_{12} - Q^+Q)b,$$

where $Q^+$ is a pseudo inverse matrix of $Q$, $E_{12}$ is a $12 \times 12$ identity matrix and $b(\in R^{12})$ is an arbitrary vector. In Eq.(3), the second term is the internal forces and moments. The term is expressed using $F_{int}$ as follows:

$$(E_{12} - Q^+Q)b = \begin{bmatrix} E_6 \\ -E_6 \end{bmatrix} F_{int},$$

Then elements of $Q^+$ is shown as below[7].

$$Q^+ = \begin{bmatrix} G \\ E_6 - G \end{bmatrix}$$

where $G(\in R^{6x6})$ is a load sharing matrix. The external forces and moments applied to the center of mass of the object are shared in the ratio of $G$ to $E_6 - G$ and supported by L-manipulator and R-manipulator, respectively.

From Eq.(1) and (3), we can calculate the force and moment applied to the center of mass of the object by each manipulator when handling the object. In Section 2.2, we will explain the method to calculate joint torques of the dual manipulators from $F_{LR}$ obtained in Eq.(3).

### 2.2 Static Relation of Dual Manipulators

In this section, we derive the relationship among the forces, moments applied to the center of mass of the object by the dual manipulators with virtually unactuated joints and the joint torques of them to handle the object.

In Fig.1, let joint torques of L-manipulator and R-manipulator be $\tau_L(\in R^{n_L})$ and $\tau_R(\in R^{n_R})$, respectively. $n_L$ and $n_R$ are the number of joints of L-manipulator and R-manipulator, respectively. Let $m$ be the dimension of the workspace. Both manipulators have enough degrees of freedom for the workspace, namely $m \leq n_L$ and $m \leq n_R$. Let the force and moment vectors applied to the center of mass of the object by L-manipulator and R-manipulator be $F_L(\in R^m)$ and $F_R(\in R^m)$, respectively. Let $J_L(\in R^{m \times n_L})$ and $J_R(\in R^{m \times n_R})$ be Jacobian matrices of L-manipulator and R-manipulator, respectively. Let $F_{ext}(\in R^m)$ and $F_{int}(\in R^m)$ be the external and internal force and moment vectors applied to the center of mass of the object, respectively. Let $F_{Lc}(\in R^m)$ and $F_{Rc}(\in R^m)$ be the force and moment vectors corresponding to $F_{ext}$ in $F_L$ and $F_R$, respectively. Let $F_{Lr}(\in R^m)$ and $F_{Rr}(\in R^m)$ be the force and moment vectors corresponding to $F_{int}$ in $F_L$ and $F_R$, respectively. Then we have the following relations concerned with $F_{ext}$ and $F_{int}$.

$$F_{ext} = F_{Lc} + F_{Rc}$$

(6)

$$F_{int} = -F_{Lr} = F_{Rr}$$

(7)

From the relationship among the force, moment applied to the center of mass of the object and the joint torques of the dual manipulators, we have

$$\begin{bmatrix} \tau_L \\ \tau_R \end{bmatrix} = \begin{bmatrix} J^T_L F_{Lc} \\ J^T_R F_{Rc} \end{bmatrix} + \begin{bmatrix} J^T_L F_{Lr} \\ J^T_R F_{Rr} \end{bmatrix}$$

(8)

From Eq.(6) and (7), Eq.(8) is rewritten as

$$\begin{bmatrix} \tau_L \\ \tau_R \end{bmatrix} = \begin{bmatrix} J^T_L (E - G)F_{ext} \\ J^T_R (E - G)F_{ext} \end{bmatrix} + \begin{bmatrix} J^T_L F_{int} \\ J^T_R F_{int} \end{bmatrix}$$

(9)

where $E(\in R^{m \times m})$ and $G(\in R^{m \times m})$ are an identity matrix and a load sharing matrix, respectively. The external force and moment are shared with the ratio $G : E - G$. Let $T_L(\in R^{m \times n})$ and $T_R(\in R^{m \times n})$ be poses of L-manipulator and R-manipulator at the center of mass of the object, respectively. Let $\theta_L(\in R^{n_L})$ and $\theta_R(\in R^{n_R})$ be joint angles of L-manipulator and R-manipulator, respectively. Both manipulators handling an object satisfy $T_L(\theta_L) = T_R(\theta_R)$.

From Eq.(9), we can obtain the joint torques of the dual manipulators from $F_{ext}$ and $F_{int}$. But the dual manipulators with the virtually unactuated joints cannot output torques. From the output torques of the virtually
unactuated joints are zeros, we obtain the following equation.

\[
\begin{bmatrix}
F_{ext} \\
F_{int}
\end{bmatrix} = \begin{bmatrix}
J_L^T G & -J_R^T G \\
J_L^T (E - G) & J_R^T \end{bmatrix}^+ \begin{bmatrix}
\tau_L \\
\tau_R
\end{bmatrix}
\]

\[
= S \begin{bmatrix}
\tau_L \\
\tau_R
\end{bmatrix} + \begin{bmatrix}
S_{eLa} & S_{eLa} \\
S_{eRa} & S_{eRa}
\end{bmatrix} \begin{bmatrix}
\tau_{La} \\
\tau_{Ra}
\end{bmatrix},
\] (10)

where \([\ ]^+\) is a pseudo inverse matrix of \([\ ]\), \(\tau_{La}\) and \(\tau_{Ra}\) are the joint torque vectors corresponding to the actuated joints of L-manipulator and R-manipulator, respectively, \(S_{La}\) and \(S_{Ra}\) are elements corresponding to the actuated joints of L-manipulator and R-manipulator in \(S\), respectively and subscripts \(e\) and \(i\) indicate elements corresponding to the external and internal forces and moments, respectively. In Eq.(10), if the rank of \([S_{eLa}, S_{eLa}]\) is equal to \(m\), the dual manipulators can act arbitrary external forces and moments on the center of the object. Similarly, if the rank of \([S_{iLa}, S_{iLa}]\) is equal to \(m\), the dual manipulators can act arbitrary internal forces and moments on the center of the object.

In Eq.(9), since elements of \(\tau_L\) and \(\tau_R\) corresponding to virtually unactuated joints are zeros, we can calculate \(F_{int}\) for given \(F_{ext}\).

### 2.3 Dynamics of Dual Manipulators

When we control the dual manipulators with virtually unactuated joints, we have to calculate the dynamics of the dual manipulators. Since the dual manipulators with virtually unactuated joints can be regarded as a closed link mechanism with unactuated joints, we can utilize the methods to calculate the dynamics of the closed link mechanism with unactuated joints in \([5, 6]\).

### 2.4 Control Algorithm

In this section, we explain the method to handle the object by the dual manipulators with the virtually unactuated joints.

Let the desired trajectory of the object be \(x_d(\in R^6)\). From \(x_d\), we calculate \(\ddot{x}\) expressed as follows:

\[
\ddot{x} = \ddot{x}_d + K_v(\dot{x}_d - \dot{x}) + K_p(x_d - x).
\] (11)

where \(K_v\) and \(K_p\) are the velocity and position gains, respectively. Substituting Eq.(11) into Eq.(1), we can obtain the external force and moment:

\[
F_{ext} = M(\ddot{x}_d + K_v(\dot{x}_d - \dot{x}) + K_p(x_d - x)) + g(x).
\] (12)

required to track the desired trajectory of the object. Substituting \(F_{ext}\) into Eq.(9), we can obtain the internal force and moment \(F_{int}\) applied to the center of mass of the object since the output torques of the virtually unactuated joints are zeros. Substituting the external and internal force and moment into Eq.(9), we can obtain the actuated joint torques to handle the object. Then, we can obtain the actuated joint torques to control the dual manipulators from the method in \([5, 6]\).

### 3 Handling of an Object by Dual Wrist-Partitioned Manipulators with Virtually Unactuated Joints

In this section, we consider handling of an object by dual manipulators consisting of two six degrees of freedom wrist-partitioned manipulators with virtually unactuated joints as shown in Fig.2.

#### 3.1 Static Relation of Dual Wrist-Partitioned Manipulators

In this section, since the calculation of Eq.(9) using dual six degrees of freedom manipulators is often impossible, we consider static relation from another point of view.

In general, since output torques of wrist three joints of such the manipulator are low, we control wrist three joints as virtually unactuated joints when dual manipulators handle a heavy object. Axes of wrist three joints of the wrist-partitioned manipulator intersect in a common point. Those three joints can be regarded as a spherical joint\([8]\). If we control those joints as virtually unactuated joints, we cannot specify three degrees of freedom of the wrist orientation arbitrarily. Though each link connected with a virtually unactuated joint can transmit linear force, it cannot transmit moment parallel to the joint axis. Thus, in a force and a moment applied to the wrist by three joints of the manipulator base, only the force is transmitted to the center of mass of the object. The three joints of the manipulator base can apply the forces to the wrist as long as a three degrees of freedom manipulator consisting of the three joints is not in a singular configuration. Then, the relationship among the external force, moment applied to the center of mass of the object handled by the dual manipulators and the forces applied to the wrists
Figure 3: Handling of an object by dual six degrees of freedom manipulators whose wrist three joints are virtually unactuated joints.

is shown as follows (Fig. 3):

\[
\begin{bmatrix}
  f_c \\
  n_c
\end{bmatrix} = \begin{bmatrix}
  E_3 \\
  [p_L \times] \\
  [p_R \times]
\end{bmatrix} \begin{bmatrix}
  f_L \\
  f_R
\end{bmatrix} = W_c \begin{bmatrix}
  f_L \\
  f_R
\end{bmatrix},
\]

where \( f_c (\in \mathbb{R}^3) \) and \( n_c (\in \mathbb{R}^3) \) are the external force and moment vectors applied to the center of mass of the object, respectively. \( E_3 \) is a \( 3 \times 3 \) identity matrix. \( f_l (\in \mathbb{R}^3) \) and \( f_R (\in \mathbb{R}^3) \) are the force vectors applied to the wrists of L-manipulator and R-manipulator bases, respectively. \( p_L (\in \mathbb{R}^3) \) and \( p_R (\in \mathbb{R}^3) \) are position vectors from the center of mass of the object to the wrists of L-manipulator and R-manipulator, respectively. In Eq. (13), the \( 6 \times 6 \) matrix \( W_c \) is not full rank and the rank is five generally. Hence, a direction \( df_n \) of the force and moment that the manipulators cannot apply to the center of mass of the object exists (Appendix). \( df_n \) is shown as follows:

\[
df_n = [(p_L \times p_L)^T, (p_R - p_L)^T]^T.
\]

No output torques of base three joints can apply the force and moment parallel to \( df_n \) to the center of mass of the object handled by dual manipulators whose wrist three joints are virtually unactuated joints. Since we cannot apply the force and moment parallel to \( df_n \) to the center of mass of the object even if we want to apply the force and moment including the element of \( df_n \), the direction we can control the object completely is perpendicular to \( df_n \). Therefore, when we handle the object by dual manipulators whose wrist three joints are virtually unactuated joints, we have to apply the force and moment perpendicular to \( df_n \) to the center of mass of the object.

A null space of \( W_c \) is given by

\[
[(p_L - p_R)^T, (p_R - p_L)^T]^T \in \ker W_c.
\]

From Eq. (15), an element parallel to a direction of \([(p_L - p_R)^T, (p_R - p_L)^T]^T \) in \([f_L^T, f_R^T]^T \) does not affect the external force and moment applied to the center of the object. Namely, the element in \([f_L^T, f_R^T]^T \) cause the internal force and moment at the center of the object. Note that we can control the internal force and moment caused by the element in \([f_L^T, f_R^T]^T \) using the torques of the three joints of the dual manipulators.

We show the method to calculate \([f_L^T, f_R^T]^T \) from \([f_L^T, n_L^T]^T \) perpendicular to \( df_n \). Since \( W_c \) is not a full rank matrix, we cannot calculate an inverse matrix of it. From the elementary column operation of \( W_c \), Eq. (13) is rewritten as

\[
[f_c \\
 n_c] = \begin{bmatrix}
  E_3 \\
  [p_L \times] \\
  [p_R \times]
\end{bmatrix} \begin{bmatrix}
  f_L \\
  f_R
\end{bmatrix} = W_{cc} \begin{bmatrix}
  f_L \\
  f_R
\end{bmatrix},
\]

where \( W_{cc} \) is obtained from \( W_c \) by the elementary column operation. Since \( df_n \) is perpendicular to all columns of \( W_c \), \( df_n \) is perpendicular to all columns of \( W_{cc} \), too. We can calculate an inverse matrix of \( W_{cc} \), because \( W_{cc} \) is a matrix yielded by replacing the fifth column which is a zero vector of \( W_c \) with \( df_n \) and is a nonsingular matrix. So, from the inverse matrix of \( W_{cc} \), we can obtain

\[
W_{cc}^{-1} \begin{bmatrix}
  f_c \\
  n_c
\end{bmatrix} = \begin{bmatrix}
  E_3 \\
  [p_L \times] \\
  [p_R \times]
\end{bmatrix} \begin{bmatrix}
  f_L \\
  f_R
\end{bmatrix} = \begin{bmatrix}
  f_L \\
  f_R
\end{bmatrix}.
\]

Since \( S \) in Eq. (17) is not a full rank matrix, we cannot calculate an inverse matrix of it and obtain \([f_L^T, f_R^T]^T \) uniquely. Let us consider a constraint condition satisfying that the dual manipulators do not apply the internal forces and moments to the center of mass of the object, namely \([f_L^T, f_R^T]^T \) does not have the element of the null space of \( W_c \). Then, let us add the condition to Eq. (17):

\[
[(p_L - p_R)^T, (p_R - p_L)^T]^T \begin{bmatrix}
  f_L \\
  f_R
\end{bmatrix} = 0.
\]

Let \( S' \) be a matrix yielded by replacing the fifth column of \( S \) of Eq. (17) with Eq. (18), we can calculate an inverse matrix of \( S' \) since \( S' \) is nonsingular. Thus, under the condition satisfying that the dual manipulators do not apply the internal forces and moments to the center of mass of the object, \([f_L^T, f_R^T]^T \) which cause
Figure 4: Regarding an object and parts from wrists to ends of dual manipulators as one object.

\[ [f^T, n^T] \] is given by
\[ S^{-1} W_{ee}^{-1} \begin{bmatrix} f \cr n \end{bmatrix} + \gamma \begin{bmatrix} p_L - p_R \cr p_R - p_L \end{bmatrix}. \] (19)

In Eq.(19), we can calculate \([f_L^T, f_R^T]\) from \([f^T, n^T]^T\) in cases that the dual manipulators do not apply the internal forces and moments to the center of mass of the object. If we want to specify the internal forces and moments applied to the center of mass of the object, from Eq.(15), we have to add the term of the internal forces and moments to Eq.(19) as follows:
\[ S^{-1} W_{ee}^{-1} \begin{bmatrix} f \cr n \end{bmatrix} + \gamma \begin{bmatrix} p_L - p_R \cr p_R - p_L \end{bmatrix} + \gamma \begin{bmatrix} p_L - p_R \cr p_R - p_L \end{bmatrix}. \] (20)

where \(\gamma\) is an arbitrary scalar quantity to specify the internal forces and moments applied to the center of mass of the object.

### 3.2 Dynamics of Dual Wrist-Partitioned Manipulators

As explained in Section 3.1, we can not act all directions of the force and moment on the center of mass of the object handled by dual manipulators whose wrist three joints are virtually unactuated joints. Namely, the dual manipulators cannot keep the position and orientation of the object against the force and moment of the direction \(d_{fn}\). We can not apply the method shown in [6] to such the mechanism which cannot maintain static equilibrium among the external force, moment applied to the object and the actuated joint torques.

Let us regard the object and parts from the wrists to the ends of the dual manipulators as one object. And let us regard parts from the bases to the wrists of the dual manipulators as dual manipulators(Fig.4). Then we can consider the object handled by dual manipulators whose wrist three joints are virtually unactuated joints. This system is similar to a hand handling an object. But, in the system the ends of the dual manipulators always contact with the object. Moreover, the ends of the dual manipulators can apply the forces to a surface of the object arbitrarily.

In the system the dynamics of the dual manipulators is given by
\[ M_o(\theta_o) \ddot{\theta}_o + c_o(\theta_o, \dot{\theta}_o) + g_o(\theta_o) + J_o(\theta_o)^T F = \tau_o. \] (21)

where \(M_o(\theta_o)\) is a 6 \(\times\) 6 inertial matrix, whose elements is given by
\[ M_o(\theta_o) = \begin{bmatrix} M_{Lo}(\theta_{La}) & 0 \\ 0 & M_{Ro}(\theta_{Ra}) \end{bmatrix}, \]
\[ \theta_o = [\theta^T_{La}, \theta^T_{Ra}]^T (\in \mathbb{R}^6) \] is a joint angle vector, \(c_o(\theta_o, \dot{\theta}_o) = [c_{Lo}^T(\theta_{La}), c_{Ra}^T(\theta_{Ra})]^T\) is a Coriolis and centripetal term, \(g_o(\theta_o) = [g_{Lo}(\theta_{La}), g_{Ra}(\theta_{Ra})]^T (\in \mathbb{R}^6)\) is a gravity force term, \(J_o(\theta_o)\) is a 6 \(\times\) 6 Jacobian matrix, whose elements is given by
\[ J_o(\theta_o) = \begin{bmatrix} J_{La}(\theta_{La}) & 0 \\ 0 & J_{Ra}(\theta_{Ra}) \end{bmatrix}, \]
\[ F = [f_L^T, f_R^T]^T (\in \mathbb{R}^6) \] is the forces of the ends applied to the surface of the object, and \(\tau_o = [\tau^T_{La}, \tau^T_{Ra}]^T (\in \mathbb{R}^6)\) is the joint torques of the dual manipulators, respectively.

\[ J_o(\theta_o) = \begin{bmatrix} J_{La}(\theta_{La}) & 0 \\ 0 & J_{Ra}(\theta_{Ra}) \end{bmatrix}, \]

\[ F = [f_L^T, f_R^T]^T (\in \mathbb{R}^6) \] is the forces of the ends applied to the surface of the object, and \(\tau_o = [\tau^T_{La}, \tau^T_{Ra}]^T (\in \mathbb{R}^6)\) is the joint torques of the dual manipulators, respectively.

### 3.3 Control Algorithm

In this section, we explain the method to handle the object by the dual wrist-partitioned manipulators whose wrist joints are virtually unactuated joints.

As described in Section 3.2, we consider handling of the object by the end forces \([f^T_f, f^T_k]^T\) of the dual three degrees of freedom manipulators. Let the trajectory and the desired trajectory of the object be \(x_o (\in \mathbb{R}^3)\) and \(x (\in \mathbb{R}^3)\), respectively. From Eq.(12), we can calculate the external force and moment \(F_{ext}\) to handle the object. Then, we can obtain \([f^T_f, f^T_k]^T\) from Eq.(20). Let each end position of the dual three degrees of freedom manipulators be \(T_{La}(\theta_{La}) (\in \mathbb{R}^3)\) and \(T_{Ra}(\theta_{Ra}) (\in \mathbb{R}^3)\), respectively. Then, \(T_{La}(\theta_{La})\) and \(T_{Ra}(\theta_{Ra})\) are calculated as follows:
\[ T_{La}(\theta_{La}) = r + p_L, \] (22)
\[ T_{Ra}(\theta_{Ra}) = r + p_R, \] (23)
where \(r (\in \mathbb{R}^3)\) is the position of the object. Since \(p_L\) and \(p_R\) depend on the orientation of the object, we can calculate \(\theta_o\) from \(x\) using inverse kinematics of the dual three manipulators. Thus, we can obtain the actuated joint torques \(\tau_o\) to handle the object substituting \(\theta_o\) and \([f^T_f, f^T_k]^T\) into Eq.(21).

### 4 Experiment

To show the validity of the proposed algorithm, the control algorithm was implemented in the dual manipulators consisting of the two PA-10s(Fig.5). In this experiment, we regard the dual manipulators as the six degrees of freedom manipulators by keeping the third joint angles constantly. And we handle an object by dual manipulators whose wrist three joints are virtually unactuated joints. The direction of the force and moment commanded to the dual manipulators is perpendicular to \(d_{fn}\) in Eq.(14). To realize the motion,
we control actuated joints of the dual manipulators using feedforward and feedback control. Though load capacity of the PA-10 is ten kilograms, the mass of the object handled by the dual manipulators is twenty-four kilograms. The trajectory commanded to the object is shown in Fig.6. Then, the joint torques of the dual manipulators are shown in Fig.7. From Fig.7, the base three joints are actuated within each load capacity and little torques are applied to the wrist three joints.

5 Conclusions

In this paper, we considered a problem to handle a heavy object by manipulators. In general, the load capacity of a manipulator depends on the maximum output or outputs of a joint or joints. Other joints are still available for the handling of the object even if the load exceeds the manipulator’s capacity. We proposed a method to handle an object by utilizing the available joints and introducing the virtually unactuated joints. We extended the method to the handling problem of an object by dual manipulators. We discussed the static and dynamic relations of the dual manipulators with virtually unactuated joints. An experiment illustrated the validity of the proposed method.

References


