Hybrid Position/Force Control of Flexible-Macro/Rigid-Micro Manipulator Systems

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Abstract—In this paper, hybrid position/force control algorithms of combined flexible-macro/rigid-micro manipulator systems are proposed. In the proposed system, the micro manipulator is attached at the tip of the flexible macro manipulator. The macro manipulator can move widely, but cannot realize fast and precise motion because of its flexibility. On the contrary, the micro manipulator cannot move widely, but can move fast and precisely. By taking advantage of both the macro/micro system, both the end point position and the force exerted by its end effector can be easily controlled in spite of the flexibility in the macro part.

This paper first discusses trajectory planning for the macro/micro system. Second, a quasi-static hybrid control algorithm and a dynamic hybrid control algorithm are developed. In our control algorithms, the macro part is controlled roughly to realize the desired trajectory, and suppress vibration. The micro part is controlled to compensate for the position and force errors due to the elasticity in the macro part. Finally, to verify the effectiveness of the proposed control algorithms, experimental results are shown.

I. INTRODUCTION

In recent years, need for light-weight and high-mobility structures for industrial robots has developed. In space applications, long arms are needed that are light in comparison to their load. The elasticity in such arms demands compensation for arm deformation and vibration.

The main body of research of flexible manipulators performed so far has been in the area of position control [1], [2]. The amount of research addressing both the position and force control of flexible manipulators is limited.

In many applications of flexible manipulators, a small rigid manipulator is attached at the tip of the flexible arm to obtain local mobility at the end point of the system. The large flexible arm is called a macro manipulator, and the small manipulator is called a micro manipulator. This kind of system can be regarded as a macro/micro manipulator system. In the macro/micro system, the macro part can move widely, but cannot realize fast and precise motion because of its flexibility. On the contrary, the micro part cannot move widely, but can move fast and precisely. By taking advantage of both the macro/micro system, both the end point position and the force exerted by its end effector can be easily controlled in spite of the flexibility in the macro part.

Hybrid position/force control of rigid manipulators has been proposed and developed by several researchers, such as Raibert et al. [3], Khatib [4], Yoshikawa [5], and McClamroch et al. [6]. Recently, the following work on the force control of flexible manipulators has been done. Chiou et al. [7] studied stability of constrained flexible manipulators. Matsuno et al. [8], [9], Mills et al. [10] and Hu et al. [11] proposed position/force controllers for flexible manipulators. Spong [12] and ElMaraghy et al. [13], [14] studied force control of flexible joint manipulators. However, the performance of force controlled flexible manipulators is limited since the response of the tip of flexible manipulators is generally slow, and simultaneous position and force control at the tip is difficult.

In the research of macro/micro systems, Yamada [15] mentioned the merit of using the macro/micro system. Khatib [16], [17], and Sharon et al. [18] have studied rigid-macro/rigid-micro systems. Chiang et al. [19] and Ballhaus et al. [20] proposed PTP control of flexible-macro/rigid-micro manipulator systems. Yoshikawa et al. [21], [22] have proposed the trajectory tracking control of flexible-macro/rigid-micro systems. They also discussed hybrid control [23]. Lew and Book [24] also proposed hybrid control of flexible-macro/rigid-micro systems. However, Lew and Book proposed only quasi-static hybrid control, and the merits of using the macro/micro system are not reflected in their formulation. Furthermore, their control algorithm does not have any terms suppressing residual vibration in the macro part.

In this paper, two hybrid position/force control algorithms for flexible-macro/rigid-micro systems are proposed. The paper first describes the construction of the flexible-macro/rigid-micro manipulator systems under consideration. Second, considering the redundancy and the elasticity of the system, trajectory planning to make the manipulator roughly track the desired trajectory is discussed. Third, two hybrid position/force control algorithms are proposed, one is quasi-static and the other is dynamic. In our hybrid control algorithms, the macro manipulator is controlled to track the planned trajectory, and suppress vibration due to the flexibility. The micro manipulator is controlled to realize the desired end point position and force. Finally, the effectiveness of these algorithms are verified by experimental results.

II. CONSTRUCTION OF MACRO/MICRO MANIPULATOR SYSTEM

A. Kinematic Equations

Let us consider a macro/micro system consisting of a macro part with $A$ degrees of freedom and a micro part with $\lambda$ degrees of freedom (Fig. 1). $p (\in \mathbb{R}^6)$ denotes the end point vector with respect to the inertial coordinate frame $\Sigma_o$, where $n (\leq 6)$ is the dimension of the task coordinate system, and $\mathbb{R}^n$ denotes $n$-dimensional Euclidean space. $\theta (\in \mathbb{R}^{A+\lambda})$ denotes the joint displacement vector. The joint displacement vector $\theta$ consists of joint displacement of the macro part $\theta_M (\in \mathbb{R}^A)$ and that of the micro part $\theta_m (\in \mathbb{R}^\lambda)$:

$$\theta = [\theta_M^T \quad \theta_m^T]^T.$$ (1)

Let $e (\in \mathbb{R}^6)$ denote the generalized coordinates to describe the elastic deformation of flexible links of the macro part, where $g$ is the degree of freedom of deformation.
The end point vector \( \mathbf{p} \) is expressed as a nonlinear function of joint vector \( \mathbf{\theta} \) and deformation \( \mathbf{e} \) as

\[
\mathbf{p} = s(\mathbf{\theta}, \mathbf{e}).
\]

Differentiating (2) and neglecting the second and higher order terms of infinitesimal displacement, infinitesimal displacement of the end point vector \( \Delta \mathbf{p} \) is derived as

\[
\Delta \mathbf{p} = \mathbf{J}_{m} \Delta \mathbf{\theta} + \mathbf{J}_{e} \Delta \mathbf{e},
\]

where \( \mathbf{J}_{m} \) and \( \mathbf{J}_{e} \) are Jacobian matrices of \( \mathbf{p} \) with respect to \( \mathbf{\theta} \) and \( \mathbf{e} \), respectively. We assume that the macro part and the micro part have enough degrees of freedom to move in the \( n \) dimensional task space. This means that \( \Lambda \geq n \) and rank \( \mathbf{J}_{m} = n \) for macro part, and \( \Lambda \geq n \) and rank \( \mathbf{J}_{e} = n \) for micro part. In the following, we consider the special case that \( \Lambda = n \) and \( \Lambda = n \). However, the result can be extended to more general cases.

B. Equation of Motion

In this subsection, the equation of motion of the macro/micro system is derived. We model the flexibility by spring-mass model [25]. Using this model, the equation of motion is relatively easy to derive. This model is simple and thought to be suitable for the real-time control of flexible manipulators. The relation between the force and deformation is given by

\[
\mathbf{f} = \mathbf{K}_{1} \delta_{1} + \mathbf{K}_{2} \delta_{2} + \mathbf{K}_{3} \delta_{3},
\]

where \( \mathbf{f} \) and \( \mathbf{n}_{i} \) are the force and moment at the tip of link \( i \), \( \delta_{i} \) and \( \phi_{i} \) are the vectors of deformation and angular deformation due to the link elasticity, and \( \mathbf{K}_{1} \), \( \mathbf{K}_{2} \), and \( \mathbf{K}_{3} \) are the matrices of the spring constant. Using this model, the vector \( \mathbf{e} \) in (2) is defined by

\[
\mathbf{e} = [\delta_{1}^{T} \delta_{2}^{T} \ldots \delta_{\Lambda}^{T} \phi_{1}^{T} \ldots \phi_{\Lambda}^{T}]^{T}.
\]

Using Lagrange's method [25], the equation of motion is derived as follows:

\[
\mathbf{M} \ddot{\mathbf{\theta}}_{m} + \mathbf{h} = \mathbf{\tau}_{m} - \mathbf{J}_{e}^{T} \mathbf{f}.
\]

III. TRAJECTORY PLANNING

In this section, trajectory planning is discussed. We calculate the desired joint trajectory and the desired trajectory of elastic displacements off-line in advance of the actual manipulator motion. This is because the macro/micro system has redundancy and flexibility, and it is not easy to obtain the desired joint trajectory and desired trajectory of elastic displacements. The method of trajectory planning is described as follows:

1) Step 1: The desired joint displacement \( \mathbf{\theta}_{d} \) is determined so as to realize the desired end point position without considering the elastic displacement \( (\mathbf{e} = 0) \) [Fig. 2(a)].

2) Step 2: The joint displacement is assumed to coincide with \( \mathbf{\theta}_{d} \). So we determine the amount of elastic displacement \( \Delta \mathbf{e}_{d} \) that is caused when the desired force \( \mathbf{f}_{d} \) is exerted by the end effector [Fig. 2(b)].

3) Step 3: \( \mathbf{\theta}_{d} \) is modified so as to compensate the end point position error due to the elastic displacement \( \Delta \mathbf{e}_{d} \). So the final desired joint displacement \( \mathbf{\theta}_{d} \) is obtained [Fig. 2(c)].

Each step is explained in more detail in the following:

Step 1: In this step, we do not consider the steady state deformation, \( \mathbf{e} = 0 \). And substituting \( \mathbf{e} = 0 \) into (2), the tip vector \( \mathbf{p} \) becomes a function of \( \mathbf{\theta} \), such as

\[
\mathbf{p} = s(\mathbf{\theta}, 0).
\]
Differentiating (7), we obtain

$$\dot{p} = J_d \theta$$

where the Jacobian matrix $J_d \in \mathbb{R}^{n \times (n+1)}$ is equal to the matrix $J_{Mm}$ substituting $e = 0$.

For the case of the macro/micro system, the number of actuators is more than that of the given task space. When the desired trajectory of end point $p_d$ is given, the trajectory is planned so as to make a certain performance index $V(\theta)$ as large as possible. The desired joint velocity $\theta_d$ is given as

$$\theta_d = J_d^T \xi_d + (I - J_d^T J_d) \xi_k p$$

where $\xi_k$ is given as

$$\xi = [\xi_{M1}, \xi_{M2}, \ldots, \xi_{Mn}, \xi_{m1}, \xi_{m2}, \ldots, \xi_{m3}]^T,$$

and

$$\xi_{ki} = \frac{\partial V(\theta)}{\partial \theta_{ki}}.$$

Here the constant $k_p$ is chosen so as to make the performance index, $V(\theta)$, increase as quickly as possible under the condition that $\theta_d$ does not become excessively large. Various candidates for $V(\theta)$ can be considered.

**Step 2:** In this step, we assume that the joint displacement coincides with that derived in Step 1. We determine the amount of elastic displacement $A_{ed}$, which is caused when the desired force $f$ is exerted. The elastic displacement $A_{ed}$ is given by

$$A_{ed} = F f_d.$$  

Here, $F$ is the stiffness matrix which is derived neglecting dynamic terms in the equation of motion (6). Though $F$ is a function of $\theta_d$ and $e$, we assume that the change of $e$ is small and can be neglected. If the gravity force exists, this is considered in this step.

**Step 3:** In this step, $\theta_d = [\theta_{M,Rd}^T, \theta_{M,Md}^T]^T$ is modified so as to compensate the end point position error due to the elastic displacement $A_{ed}$. Let $\Delta A_{ed}$ be 0, (3) is transformed as

$$J_M \Delta \theta_M + J_m \Delta \theta_m + J_e \Delta e = 0.$$  

Using $\Delta \theta_M$ and $\Delta \theta_m$, which satisfy (13), $\theta_{M,Rd}$ and $\theta_{M,Md}$ are determined, such as $\theta_{M,Rd} = \theta_{M,Rd} + \Delta \theta_{M,Rd}$ and $\theta_{M,Md} = \theta_{M,Md} + \Delta \theta_{M,Md}$. In this case, $\Delta \theta_M$ and $\Delta \theta_m$ have redundancy. To ensure the work space of the micro part, $\Delta \theta_m$ is fixed to be 0 and the desired joint displacement of the macro part $\theta_{M,Rd}$ is determined to change following the change of $A_{ed}$, such as

$$\Delta \theta_{M,Rd} = -J_{M,Rd}^T J_e \Delta e_d.$$  

So we obtain the final desired joint trajectory and the desired trajectory of elastic displacement as

$$\theta_{M,Rd} = \theta_{M,Rd} + \Delta \theta_{M,Rd}$$

$$\theta_{M,Md} = \theta_{M,Md}$$

$$e_d = \Delta e_d.$$  

In this planning method, dynamics of the arm is not considered. Although we can take the dynamic effect into consideration more accurately by using the planning method proposed by Pfeiffer and Gebler [27], we consider that our method is enough in usual cases.

**IV. CONTROLLER FOR THE MACRO PART**

In this section, the controller for the macro part is derived. Since the macro part cannot realize fast and precise motion because of its flexibility, the macro part is controlled to track the planned trajectory as developed in the previous section, and roughly realizes the desired end point trajectory. In the case of force control of flexible manipulators, unexpected vibration due to unexpected disturbance and large acceleration may occur. So, the macro part is controlled to suppress vibration.

First, we rewrite the equation of motion (6) as follows:

$$M_M \ddot{\theta}_M + B_M \dot{\theta}_M + C_M \theta_M + D_M \theta_m = K \Delta f_d + \Delta h_m + \Delta h_d.$$  

Here, $K$ is the stiffness matrix. From the first and third rows of (16), We derive the state equation of the macro part as

$$\dot{\theta}_M = A_M \dot{\theta}_M + B_M \tau_M + K \Delta f_d,$$  

In (17), $A_M$, $B_M$, and $H_M$ change following the change of configuration. However, if the change is small, we can fix $A_M$, $B_M$, and $H_M$ to certain values. In our experiment, we fixed $A_M$, $B_M$, and $H_M$ to the values at the final configuration of the desired trajectory. We also omitted the effect of $u$. We apply the optimal regulator to the linearized (17). Let the performance index be given by

$$J = \int_{0}^{\infty} \left( z - z_d \right)^T Q \left( z - z_d \right) + R \dot{\tau}_M \dot{\tau}_M \ dt$$  

where $Q$ and $R$ are positive-definite symmetric matrices. The optimal state feedback that minimizes the performance index is described as follows:

$$\tau_M = K_M (z_d - \hat{z}) + K_M (z_d - \hat{z}).$$  

Equation (19) is a controller of the macro part, where $z_d$ is defined as

$$z_d = [\theta_{M,Rd}^T, e_d^T]^T.$$

$\theta_{M,Rd}$ and $e_d$ are derived in the previous trajectory planning. Using this controller, the vibration in the macro part is suppressed, and the macro part roughly tracks the desired trajectory.

**V. CONTROLLER FOR THE MICRO PART**

**A. Quasi-Static Hybrid Control**

In this subsection, a quasi-static hybrid position/force control algorithm for the micro part is proposed. The complex dynamics
Position and force errors that include consideration of the direction in the constraint frame $\Sigma_c$ are described as

$$p_e = S(p_d - p),$$

$$f_e = (I_n - S)(f_d - f),$$

where $S$ is given by

$$S = \text{diag}[s_1, s_2, \ldots, s_n].$$

The matrix $S$ is called the selection matrix (of the position control directions). The value of $s_j (j = 1, 2, \ldots, n)$ is 1 in the directions of position control and 0 in the directions of force control.

Letting $J_m(^{\Sigma_c}T_{\Sigma_c}J_m)$ denotes the Jacobian matrix of the micro part with respect to the constrained coordinate frame $\Sigma_c$, we have

$$J_m = ^{\Sigma_c}T_{\Sigma_c}J_m$$

where $^{\Sigma_c}T_{\Sigma_c}$ is the transformation matrix between $\Sigma_c$ and $\Sigma_m$. We can transform the above errors back to the joint coordinate of the micro part using the following equations:

$$\theta_m = ^{\Sigma_c}J_m^{-1}\theta_c$$

$$\dot{\theta}_m = ^{\Sigma_c}J_m^{-1}\dot{\theta}_c$$

$$\tau_m = ^{\Sigma_c}J_m^{-1}f_c.$$

On the basis of these error expressions, we now calculate two joint driving forces of the micro part, $\tau_{mp}$ and $\tau_{mf}$. Although a variety of position and force control laws of the micro part are applicable, we use the PD position control law:

$$\tau_{mp} = K_{mpd}\theta_{me} + K_{mpf}\theta_{me}$$

and the feed forward and PI force control law:

$$\tau_{mf} = ^{\Sigma_c}J_m^{-1}f_d + K_{mpf}\tau_{me} + K_{mf}\int_0^t \tau_{me}(t') dt'$$

where $K_{mpd}$, $K_{mpf}$, $K_{mpf}$, and $K_{mf}$ are feedback gain matrices.

Finally, the joint driving force of the micro part is given by

$$\tau_m = \tau_{mp} + \tau_{mf}.$$
propose a dynamic hybrid position/force control for the micro part based on [5].

1) Basic Equations for Dynamic Hybrid Control: In this subsection, we obtain basic equations for dynamic hybrid control. Differentiating (2) with respect to time yields:

\[ \dot{p} = J_M \dot{\theta}_M + J_m \dot{\theta}_m + J_e \dot{e} \]

where \( J = [J_M \quad J_m \quad J_e] \), and \( J_M, J_m, \) and \( J_e \) are Jacobian matrices of \( p \), with respect to \( \theta_M, \theta_m, \) and \( e, \) respectively. Differentiating (27) again, the following relation is derived:

\[ \ddot{p} = J[\dot{\theta}_M \quad \dot{\theta}_m \quad \dot{\theta}_e]^T + J[\ddot{\theta}_M \quad \ddot{\theta}_m \quad \ddot{\theta}_e]^T + e. \]  

The equation of motion (6) is transformed as

\[ -M^{-1}h - M^{-1}J^T f. \]

Using (28), (29) is transformed to the following relation between the end point acceleration and the joint driving force, such as

\[ \ddot{p} = N_M \tau_M + N_m \tau_m - JM^{-1}h - J^T f + a \]  

where

\[ N_M = JM^{-1} \begin{bmatrix} I_A \\ 0 \\ 0 \end{bmatrix}, \]

\[ N_m = JM^{-1} \begin{bmatrix} 0 \\ I_A \\ 0 \end{bmatrix}, \]

\[ J^T = JM^{-1}J^T. \]

2) Dynamic Hybrid Control Algorithm: Using the equations derived in the previous subsection, we propose a dynamic hybrid position/force control for the micro part. Using (30), a dynamic hybrid position/force control law for the micro part is described as follows:

\[ \tau_m = N_m^{-1} \left\{ E^{-1} \left( \mathbf{u}_{p_m} - \mathbf{E} \ddot{p} \right) - N_M \tau_M \\ + JM^{-1}h - a + J^T E_F \mathbf{u}_{F_m} \right\}, \]

where

\[ E = [E_F^T, E_F^T]^T. \]

Here, the constraint on the end point position is expressed as a set of \( n_F \) hyper surfaces given by

\[ \mathbf{p}_F(p) = 0. \]

\( (n - n_F) \)-dimensional vector, \( \mathbf{p}_F(p) \), is selected such that the elements of \( \{ \mathbf{p}_F(p), \mathbf{p}_F(p) \} \) are mutually independent. So \( E_F \) and \( E_F \) are given by

\[ E_F = \frac{\partial \mathbf{p}_F}{\partial \mathbf{p}_F}, \]

\[ E_F = \frac{\partial \mathbf{p}_F}{\partial \mathbf{p}_F}. \]

VI. EXPERIMENTS

A. Robot System

The macro/micro system used for experiment is shown in Figs. 3 and 4. A flexible manipulator with two rotational joints is used as the macro part. The micro part has one rotational joint and one prismatic
joint. The physical parameters of the robot are shown in Tables I and II. In this manipulator system, variables are set as

\[
\begin{align*}
\theta &= [\theta_1, \theta_2, \theta_3, \theta_4] \quad (\text{rad}) \\
\dot{\theta} &= [\dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3, \dot{\theta}_4] \\
e &= [\varepsilon_1, \varepsilon_2, \phi_1, \phi_2] \quad (\text{rad})
\end{align*}
\]

where \(\varepsilon_1\) and \(\varepsilon_2\) are the elastic deformation at the tip of link 1 and 2, and \(\phi_1\) and \(\phi_2\) are the angular deformation at the tip of link 1 and 2, respectively.

All joints of the macro/micro system are equipped with optical encoders, enabling the displacement of all joints, both rotational and prismatic, to be measured. The velocity of each joint displacement is derived by finite-differentiation of each joint's displacement data. Strain gauges are attached to each link of the macro part to measure elastic displacements. A 2-axis force sensor is attached at the tip of the micro part to measure the force exerted by the end effector. In our experiments, the end point position is not directly measured. It is calculated using the kinematic equation (2). We used a PC with a i486DX2 66 Mhz as a host computer. We wrote the control program using Assembly and C. The sampling period is set as 1.88 msec in all experiments.

B. Experimental Results

In this subsection, experimental results are shown. We performed experiments as follows:

1) Quasi-static hybrid control.
   a. The end point goes back and forth in 4 seconds.
   b. The end point goes back and forth in 0.8 seconds.

2) Dynamic hybrid control.
   a. The end point goes back and forth in 4 seconds.
   b. The end point goes back and forth in 0.8 seconds.

In all experiments, the end point is constrained to the surface \(y = -0.35(m)\) with respect to the inertial coordinate system. Using this constrained surface, the matrix \(S\) in (20a) and (20b), the matrix \(T_e\) in (22) and the matrix \(E\) in (31) are given by

\[
\begin{align*}
S &= \text{diag} [5] \\
T_e &= \text{diag} [1, 0] \\
E &= \text{diag} [1, 1]
\end{align*}
\]

The feedback gain matrices in (24), (25), and (35) are chosen as

\[
\begin{align*}
K_{mp} &= \text{diag} [1] \\
K_{mp} &= \text{diag} [0.003, 0.003] \\
K_{mfp} &= \text{diag} [0.0005, 0.0005] \\
K_{infi} &= \text{diag} [9, 9] \\
K_{mp} &= 9000 \\
K_{mp} &= 30 \\
K_{mp} &= 1 \\
K_{mp} &= 2
\end{align*}
\]

The weighting matrices in the optimal regulator in (18) are chosen as

\[
Q = \text{diag} [5 \times 10^7, 5 \times 10^7, 1 \times 10^7, 1 \times 10^7, 1 \times 10^7, 1 \times 10^7, 1 \times 10^5, 1 \times 10^5, 1 \times 10^5, 1 \times 10^5]
\]

\[
R = \text{diag} [1, 1]
\]

Fig. 7. Results of experiment (1-2).

Fig. 8. Results of experiment (2-1).
We derived the optimal gain using MATLAB. Copyright MathWorks, Inc.

The desired end point trajectory \( p_{Fd} \) in (35) is shown in Figs. 6(a), 7(a), 8(a), and 9(a). The desired force \( f_{Fd} \) in (35) is set as

\[
f_{Fd}(t) = \begin{cases} 
3.5(N) & \text{for} \ 0 \leq t (sec) \leq 5 \\
2.5 & \text{for} \ 5 < t \leq 10 
\end{cases}
\]  

(37)

In all experiments, the desired trajectory is planned in advance of the macro/micro system actually controlled. In this case, the performance index \( V(\theta) \) in (9) is set as

\[
V(\theta) = 1 - \left( \frac{2}{\pi} \left( \theta_{M1} + \theta_{M2} + \theta_{M3} \right) - 1 \right)^{2}
\]

and \( k_p \) is set as \( k_p = 10 \) by trial and error. The planned trajectory is shown in Fig. 5.

Experimental results are shown in Figs. 6-9. Figs. 6 and 7 are the results of the quasi-static hybrid control, and Figs. 8 and 9 are those of the dynamic hybrid control. Comparing Figs. 6 and 8, it can be seen that there is little difference between quasi-static control and dynamic control when the manipulator moves slowly. This is because the effect of inertia at the tip of the macro/micro system is small [16]. However, comparing Figs. 7 and 9, position and force errors of the dynamic control are much smaller than those of the quasi-static control. So we can say that the dynamic control is more effective when the manipulator moves fast.

VII. CONCLUSIONS

In this paper, hybrid position/force control of flexible-macro/rigid-micro manipulator systems was proposed. First, trajectory planning was discussed. Second, a quasi-static hybrid position/force control algorithm and a dynamic hybrid position/force control algorithm were proposed. Then, to verify the effectiveness of the proposed control algorithm, experimental results were presented. Experimental results showed that the dynamic hybrid control is more effective than the quasi-static one when the manipulator moves fast, and that the vibration suppression in the macro part works well.

We modeled the elasticity of the arm using the spring-mass model. As the second or higher modes of vibration was not modeled in the spring-mass model, comparison of the models of elasticity and analyzing the effect of the omitted modes is considered to be a future topic. In order to improve the robustness of the proposed controller for the omitted \( H_M \) and fixed \( A_M \) and \( B_M \) in (17), applying some robust controller is also considered to be one of our future topics.

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Composite Adaptive Control of Constrained Robots

Jing Yuan

Abstract— Force control is the main challenge in force/motion control of constrained robots. This paper presents a composite adaptive controller to deal with the force error. The proposed controller is designed and analyzed in two steps. In the first step, the force error is shown to be asymptotically proportional to the residual force. A force feedback signal is introduced to reduce the force error. The second step presents an analytical study on a composite adaptive controller with a focus on the convergence of the residual force. It is proven that the proposed adaptive controller is able to achieve zero tracking and force errors without the persistent excitations.

I. INTRODUCTION

A robot is known to be in constrained motion when its end-effector contacts or interacts with the environment as the robot arm moves [1]. The control objectives, in this case, are trajectory tracking and force regulation. Typical examples of constrained robots include grinding, cutting, drilling, inserting, fastening, contour following, etc. [1]. Force/motion control of constrained robots was first addressed by assuming exact knowledge of the robot dynamic model. Controllers were proposed by Raibert and Craig [2], Yoshikawa [3], Yun [4], Mills and Goldenberg [5], McClamroch and Wang [6] to cancel the nonlinear robot dynamics, and ensure zero tracking and force errors.

More recently, the research is extended to force/motion control of constrained robots with parameter uncertainties. Carelli and Kelly [7] proposed a direct adaptive controller with a feed-forward force control signal. Su et al. [8,9] present a reduced dynamic model and apply adaptive and variable structure controller, respectively, to suppress the effect of dynamic uncertainties. Motion control of a constrained robot is not a difficult task. It can be shown to be equivalent to free-motion control of a robot with less degrees of freedom. Almost every available robot controller can be modified to meet the requirement. The main challenge, however, is how to achieve a desired constraint force in the presence of parameter uncertainty. A zero tracking error and a bounded force error seem to be a common feature shared by many recently proposed methods such as those reported in [7]-[10]. One possible way to achieve zero tracking and force errors is to apply a nonlinear coordinate transformation [11], such that the robot dynamic model can be written in a form with no accelerations in certain curvilinear directions. The corresponding regressor may become complicated and difficult to implement. Another approach is the parallel regulation proposed by Chaiverini et al. [12], which guarantees zero force error at the expense of a steady-state position error. The method was extended to an adaptive force/position regulator by Siciliano and Villani [13] to deal with robot dynamic parameter uncertainties. Recently, Siciliano and Villani [14] proposed a passivity-based controller for force/position control of constrained robots. Their method achieves zero force error when the desired path has a constant component in the norm of contact surface. In this study, a composite adaptive controller is shown able to achieve zero force error for a robot in an arbitrary constrained motion. The force control objective is achieved without a nonlinear coordinate transformation.

The force error bound of an adaptive controller can be shown proportional to the residual force $Y\ddot{\theta}$, which is the product of the robot regressor $Y$ and the parameter adaptation error $\dot{\theta}$. (Detailed definitions of $Y$ and $\theta$ are provided in the text.) Forcing the convergence of $\dot{\theta} \to 0$ seems to be a reasonable direction to obtain a zero force error. It is therefore proposed here to incorporate an indirect adaptive law to improve the adaptation of $\dot{\theta}$, as suggested by Slotine and Li for free-motion robot control [15]. The Slotine and Li composite adaptive controller forces the convergence of $W\ddot{\theta} \to 0$ [15] via a properly low-pass filtered regressor $W$. The convergence of $\dot{\theta} \to 0$, however, depends on the persistent excitations. This study by-passes $\dot{\theta}$ to establish a new analytical link that $W\ddot{\theta} \to 0$ implies $Y\dot{\theta} \to 0$. It proves the existence of an asymptotic intersection between the null spaces of $Y$ and $W$, even though the two regressors have different definitions and different differential orders. The proposed method forces $\dot{\theta}$ to converge to the common null space of $Y$ and $W$ without the persistent excitations. The convergence of $\dot{\theta} \to 0$ becomes relatively immaterial.

For adaptive control of a constrained robot, the convergence of $Y\dot{\theta} \to 0$ implies a zero force error. An integral force feedback is also proposed to reduce the force error for a direct adaptive control law. When combined with a composite adaptive controller, the integral force feedback helps to reduce the effect of potential disturbances due to numerical inaccuracies. To the best of the author's knowledge, this is the first adaptive controller to achieve zero force error. It is therefore an important improvement to the results of...