유연성 구조를 가지는 2 자유도 매니퓰레이터의 힘과 위치 제어

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Hybrid Position/Force Control of 2 DOF Flexible Manipulator

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Abstract.-A Hybrid technique is introduced in this paper for a manipulator with 2 DOF flexible links. The manipulator dynamics plus the actuator dynamics is controlled by taking force feedback for the end-effector of the link 2 while controlling the position of link 1 to control the position of the end-effector.

I. Introduction

In the last thirty years great attention has been paid to the dynamics and control of flexible robot arms due to the requirements of high-speed performance and low energy consumption. Modeling and vibration control of flexible systems have received a great deal of attention in recent years[2][3][7]. This problem has arisen, in particular, in the area of space and industrial robots with lightweighting and flexible links. When large structures are constructed by using space robot manipulators, it is necessary to control not only the position and vibration of the manipulators but also the contact force with an object. Hybrid control of manipulators has been studied by many researchers [2][4][5[7]. The dynamic stability of the force-controlled two-link flexible manipulator was analyzed in [6].

This paper proposes a method for the hybrid position/force control of planar manipulator with two flexible links. Since the tip of the flexible manipulator contact with a given constraint surface, a constraint condition should be satisfied.

II. Kinematics of Flexible Links

Fig. 1 depicts two links belonging to a kinematic chain. Link i + 1 is connected to link i by the revoulte joint i + 1. Attactched to each link is a coordinate frame C_i which is placed according to the rules developed by Denavit and Hartenberg[1]. Let A_{i+1} be the homogeneous transformation which maps the (i + 1)th frame to the ith frame. Now suppose that the links are not rigid, causing the joints to move to new position P_i^* and P_{i+1}^*. This deformation can cause both a translation and rotation of the coordinate frame. Let E_i and E_{i+1} represent this transformation, that is, E_i maps C_i^* to C_i and C_{i+1}^* to C_{i+1}, respectively. If the flexing motion is small, then E_i $(i=1,2)$ can be represented by the differential transformation defined in (1) and with Roll-Pitch-Yaw representaion [1] in sequence of Yaw, Pitch, and Roll.

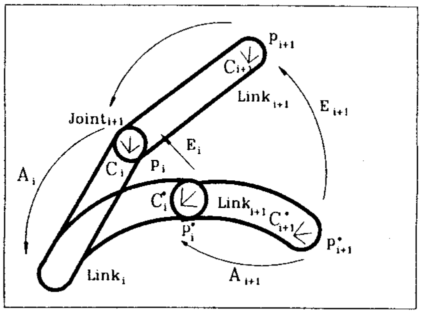

Fig. 1. Link geometry

$$E_i = \begin{bmatrix} 1 & -\phi_{i3} & \phi_{i2} & \varepsilon_{i1} \\ \phi_{i3} & 1 & -\phi_{i1} & \varepsilon_{i2} \\ -\phi_{i2} & \phi_{i1} & 1 & \varepsilon_{13} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Here the ε's represent the relative translation between C_i^* and C_i, while the ϕ's establish the rotaion between these two frames. Following the standard procedure for expressing the transformation from the ith link to the base frame and incorporating the additional transformations due to deformation, we write

$$T_i = A_1E_1A_2E_2 \cdots A_{i-1}E_{i-1}A_iE_i \quad (2)$$

Standard dynamic analysis leads to the following expression for the kinematic energy:

$$KE = \frac{1}{2} \sum_i \text{tr} [\; \dot{T}_i I_i \dot{T}_i^{\prime} \;] \quad (3)$$

where I_i is the generalized moment of inertia of link i measured in the link coordinate frame.

The potential energy of the system is composed of two parts. The first of these is the gravitational potential energy (GPE) which depends upon the displacement of the center of mass, measured with respect to the base frame, in a direction opposite to the gravitaional force field:

$$GPE_i = -m_i g' T_i d^i \quad (4)$$

Here d^i is a vector locating the mass center of the link with respect to the local frame C_i and g is the vector representing the gravitational field.

The second component of the potential energy arises from the starin energy due to the flexure of the link. The deformation of link i is defined by (1) and consists of three translational ε_{ij} and three rotational ϕ_{ij} components. Let us collect these components into the displacement vector $e_i = [\ \varepsilon_{i1},\ \varepsilon_{i2},\ \varepsilon_{i3},\ \phi_{i1},\ \phi_{i2},\ \phi_{i3}\ ]'$ Then the strain energy stored in link i is expressed by

$$SPE_i = \frac{1}{2}\ e_i'\ K_i'\ e_i \tag{5}$$

where K_i is the generalized spring constant for link i. Finally, the Lagrangian for the manipulator can be constructed from (3)-(5):

$$L=\sum_i \mathrm{tr}\ [\ \frac{1}{2}\ \dot{T}_i J_i \dot{T}_i'\ ]\ + m_i g' T^i d^i - \frac{1}{2}\ e_i'\ K_i\ e_i \tag{6}$$

Thee Euler-Lagrange equation relate the generalized firces F_i to the generalized coordinates θ_i (joint angles) and e_{ij} (deformations):

$$F_i = \frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}_i} - \frac{\partial L}{\partial \theta_i} \tag{7a}$$

$$0 = \frac{d}{dt}\frac{\partial L}{\partial \dot{e}_{ij}} - \frac{\partial L}{\partial e_{ij}} \tag{7b}$$

Substituing the Lagrangian (6) into (7a), we obtain a differential equation describing the gross motion of the manipulator:

$$\begin{aligned} F_p = & \sum_j D_{pj}\ddot{\theta}_j + \sum_{kl} D_{pkl}\ddot{e}_{kl} + \sum_{jk} D_{pjk}\dot{\theta}_j\dot{\theta}_k \\ & + \sum_{jkl} \dot{\theta}_j \dot{e}_{kl} + \sum_{jklm} D_{pjklm}\dot{e}_{jk}\dot{e}_{lm} + D_p \end{aligned} \tag{8}$$

$$\begin{aligned} 0 = & \sum_{jk} C_{mnjk}\ddot{e}_{jk} + \sum_j C_{mnj}\ddot{\theta}_j + \sum_{jklo} C_{mnjklo}\dot{e}_{jk}\dot{e}_{lo} \\ & + \sum_{jkl} C_{mnjkl}\dot{e}_{jk}\dot{\theta}_l + \sum_{jklm} C_{mnjl}\dot{\theta}_j\dot{\theta}_l \\ & + C_{mn} + \sum_j k_{mnj}\ e_{mj} \end{aligned} \tag{9}$$

The end point position vector $(X, Y)^T$ of the manipulator is given by

$$\begin{aligned} X= & L_1\cos\theta_1 - u_{iE}\sin\theta_1 + L_2\cos(\theta_1 + \dot{u}_{iE} + \theta_2\ ) \\ & - u_{2E}\sin(\theta_1 + \dot{u}_{1E} + \theta_2\ ), \\ Y= & L_1\sin\theta_1 + u_{1E}\cos\theta_1 + L_2\sin(\theta_1 + \dot{u}_{1E} + \theta_2\ ) \\ & + u_{2E}\cos(\theta_1 + \dot{u}_{iE} + \theta_2\ ) \end{aligned} \tag{10}$$

The constraint condition has a form as follows:

$$\phi(\theta_1, \theta_2, u_{1E}, \dot{u}_{1E}, u_{2E}\ ) = 0 \tag{11}$$

Let λ be a Lagrange multiplier associated with the costraint (11). The constraint force for the end point of the manipulator, i.e., the contact force between the end-effector and the constraint surface, can be expressed in terms of the Lagrange multiplier λ.

Assumption 1: $\dot{u}_{1E}$ is negligibly small compared to θ_2

Now, we consider the relation between the constraint normal for f_n and the Lagrange multiplier λ. Using Assumption 1, the raaction force from the constraint surface is given by

$$f_n n = \lambda \begin{bmatrix} b(\theta_1, \theta_2) \\ c(\theta_1, \theta_2) \end{bmatrix} \tag{12}$$

where

$$\begin{aligned} b(\theta_1, \theta_2) = & \frac{\partial \Phi}{\partial X}(L_1\cos\theta_1 + L_2\cos(\theta_1+\theta_2), \\ & L_1\sin\theta_1 + L_2\cos(\theta_1, \theta_2)), \\ c(\theta_1, \theta_2) = & \frac{\partial \Phi}{\partial Y}(L_1\cos\theta_1 + L_2\cos(\theta_1+\theta_2), \\ & L_1\sin\theta_1 + L_2\sin(\theta_1+\theta_2)). \end{aligned} \tag{13}$$

Since the unit normal vector of the constraint surface is given as

$$n = \frac{1}{\sqrt{b^2(\theta_1, \theta_2)+c^2(\theta_1, \theta_2)}}\begin{bmatrix} b(\theta_1, \theta_2) \\ c(\theta_1, \theta_2) \end{bmatrix} \tag{14}$$

we see that

$$f_n = \lambda\sqrt{b^2(\theta_1, \theta_2)+c^2(\theta_1, \theta_2)} \tag{15}$$

Since the axial compressive force Q_i is the orthogonal projection of the reaction force f_n on the unit vector

$$\begin{aligned} i_1 &= [\ \cos\theta_1, \sin\theta_2]\ ^T, \\ i_2 &= [\ \cos(\theta_1+\phi_{12}+\theta_2), \sin(\theta_2+\phi_{12}+\theta_2)]'\ ^T \end{aligned} \tag{16}$$

it can be represented as

$$Q_i = -f_n\, i_i^T n, \quad (i=1, 2) \tag{17}$$

Using (12), (17), and Assumption 2 give

$$\lambda = -\frac{Q_2}{b(\theta_1, \theta_2)\cos(\theta_1+\theta_2)+c(\theta_1, \theta_2)\sin(\theta_1, \theta_2)}. \tag{18}$$

Because the axial compressive force Q_2 can be measured by using a force sensor that is mounted at the tip of the second link, it is possible to obtain the value of the Lagrange multiplier from (18). When the direction i_2 of the link 2 is orthogonal to the normal direction n of the constraint surface at the contact point, the axial compressive force Q_2 is zero ($Q_2 = 0$), from (17). Since we cannot determine the value of the Lagrange multiplier on the basis of (18), this configuration is singular.

Let θ_{1d} and θ_{2d} be the desired angles of θ_1 and θ_2, respectively. The standard inverse kinematic technique is used to derive the desired angles θ_{1d} and θ_{2d} from the dsired position. Let f_{nd} be the desired contact force, and λ_d be the desired Lagrange multiplier corresponding to the desired fonce f_{nd}. From (15) λ_d is represented as

$$\lambda_d = \frac{f_{nd}}{\sqrt{b^2(\theta_{1d}, \theta_{2d})+c^2(\theta_{1d}, \theta_{2d})}} \tag{19}$$

III. Two-Link Planar Mechanism

Let us consider the two-link planar system illustrated in Fig. 1. We will futhermore assume that link 1 exhibits deformations ε_{12} and ϕ_{12}, ant that link 2 exhibits deformations ε_{22} and ϕ_{22}. The homegeneous transformation T_1 and T_2 are given below. Using $S_1 = \sin\theta_1$, $C_1 = \cos\theta_1$, $S_{12} = \sin(\theta_1 + \theta_2)$, and $C_{12} = \cos(\theta_1 + \theta_2)$, we obtain

$$T_1 = A_1E_1 = \begin{vmatrix} C_1 & -S_1 & C_1\phi_{12} & L1S_1 \\ S_1 & C_1 & S_1\phi_{12} & C_1\varepsilon_{12}+L1S_1 \\ -\phi_{12} & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{20}$$

$T_2 = A_1E_1A_2E_2$ (21)

Each of the links will be assumed to be a slender rod having a moment of inertia I_i. It has been aaumed that all deformatins except ϕ_{12}, ϵ_{12}, ϕ_{22}, and ϵ_{22} zre zeros. The matrix of spring constants K involves Young's modulus E and the second moment of area I of the link section about the bending axis:

The dynamic equations (8), and (9) contain product coupling of the states. Using the Lagrange equation, we obtain the following set of equations:

$$M(q)\ddot{q} + V(q, \dot{q}) + F(q) + G(q) = \tau, \quad (22)$$

where $q \in R^n$ is the arm joint variable. The dynamics of the armature-controlled dc motors that drive the links given by the n decoupled equations:

$$J_M \ddot{q}_M + B\dot{q}_M + F_M + R\tau = K_M v, \quad (23)$$

where J_M, B, F_M, R represent the motor inertia, damping, friction, gear reduction matrix respectively, and K_M is a constant expressed as K_t/R_a, in which K_t is the motor torque constant, and R_a is armature resistance. Sustituting (22) into (23), we obtain the manipulator-plus-actuator dynamics as below.

$$(M'(q)\ddot{q} + V'(q, \dot{q})\dot{q} + F'(\dot{q}) + G'(q) = K'v \quad (24)$$

Control Input

$$v_1 = \ddot{\theta}_{1d} + k_{p1}(\dot{\theta}_{1d} - \dot{\theta}_1) + k_{v1}(\theta_{1d} - \theta_1)$$
$$v_2 = \ddot{\theta}_{2d} + k_{p2}(\dot{\theta}_{1d} - \dot{\theta}_2) + k_{v2}(\theta_{2d} - \theta_2) + k_f(\lambda_d - \lambda) \quad (25)$$

IV. Case Study

For a 2 DOF flexible manipulator shown in Fig. 1, the manipulator dynamics plus actuator dynamics is given in (24). The simulation results of the each joint angle are shown below with the motor control input in (25). Let $\theta_{1d} = 0.5$, and $\theta_{2d} = 1$ for fixed positions of respective link, then Fig. 2, and Fig. 3. show that a good transient response with no initial position error for each link.

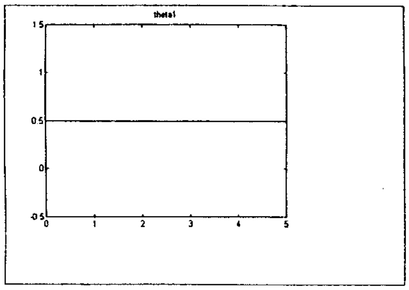

Fig. 2. Trajectory of θ_1

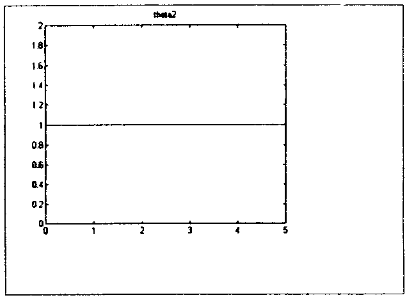

Fig. 3. Trajectory of θ_2

V. Conclusion

We have considered the problem of hybrid position/force control of a 2 DOF flexible manipulator. We have derived the force feedback dynamics of the constrained flexible manipulator by introducing the Lagrange multiplier and the manipulator dynamics using Roll-Pitch-Yaw representation taking into account the deformations of the manipulator,

VI. References

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