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Flexible Object Manipulation Using Dual Manipulators

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Abstracts We propose a coordinated motion control algorithm of dual manipulators handing a flexible object. The controller is designed so that it can specify the apparent impedance of the object as well as can control its deformation. The experimental results will illustrate the validity of the proposed algorithm.

Keyword Robot, Manipulator, Flexible Object, Manipulation, Coordinated Motion Control

1 Introduction

By controlling multiple manipulators, we can improve the characteristics of a system, for example, rigidity, load capacity, and dexterity. The multiple manipulators can be applied to various works that is not suitable for single manipulator such as handling a flexible object. Many algorithms for coordinated motion of multiple manipulators have been proposed so far[1][2][3]. Most of them are designed to handling rigid object and can't apply to handling flexible object. In this paper, we propose a coordinated motion control algorithm for dual manipulators handling a flexible object. The proposed control algorithm is designed so that we can specify both the deformation and the apparent impedance of the handling object. The experimental results will illustrate the validity of the proposed algorithm.

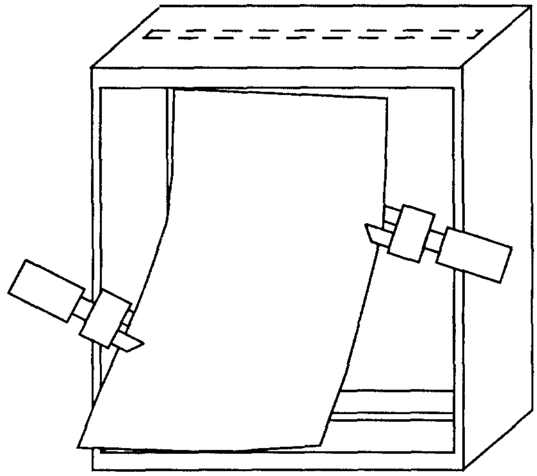


Fig 1: Parts-mating of flexible object.

2 Algorithm

To take a simple example for handling a flexible object, let us consider parts-mating of flexible object as shown in Fig 1. To insert the flexible object into the flame, we have to bend the object, and place them into appropriate position. That is to say, we would like to specify the deformation and the motion of the flexible object at the same time. We propose a control algorithm that satisfies those two requirements as follows:

1. For a given deformation of the object, calculate internal forces which realize the deformation. This step could be done preliminary.
2. Control the motion of the manipulators based on impedance control, so that manipulators apply internal forces to the object, while moving desired trajectory.

Because the deformation of the object is controlled by internal forces applied by manipulators, the control algorithm agrees with compliant motion control of the manipulator. Fig 2 shows block diagram of the algorithm.

3 Example of modeling the flexible object

To obtain internal force which realize the desired deformation, we need some mathematical model of the object which formulates the relationship between the deformation and the internal force. In this paper, we obtain the relation based on finite element method (FEM) analysis[8], because it could be applied to various shapes and materials. The object is divided into rectangular segment as shown in Fig 3, and relationship between the deformation and the forces applied to the node point is formulated. From the formulation, we could derive relationship between deformation and internal force given by the manipulators.

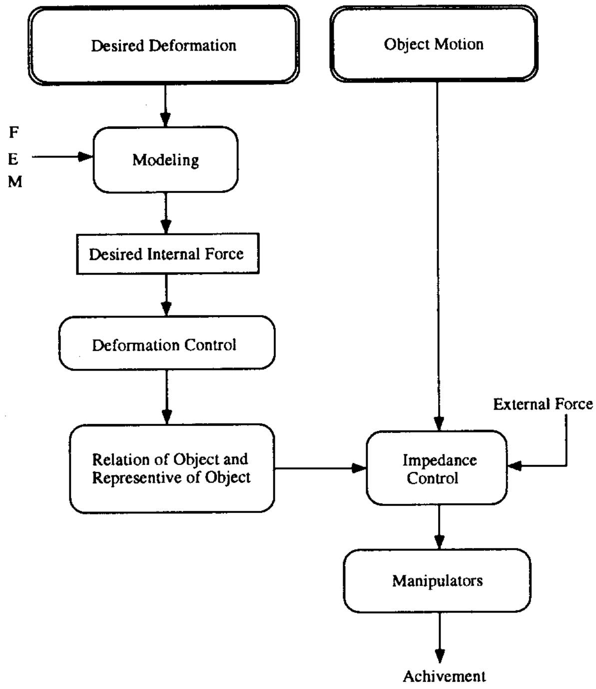


Fig 2: Manipulation algorithm.

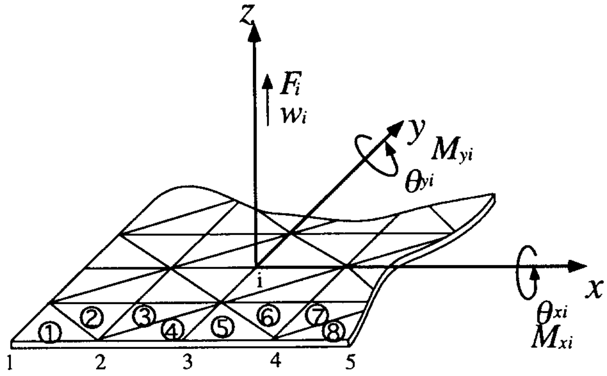


Fig 3: Thin rectangular element (non conforming) model.

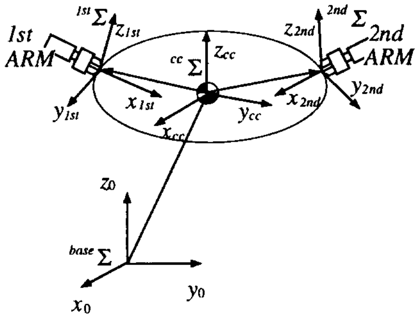
4 Controller

4.1 Definition of deformation flame

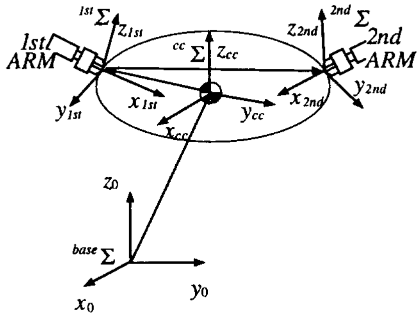
First, we have to define the coordinate system which describes the deformation task, We have following two approaches:

1. attach a coordinate system on the object and describe the motion of the manipulators with reference to the object. (Fig4-(a))
2. attach a coordinate system on one of the manipulators and describe the motion of the object and the other manipulators with reference to the manipulator. (Fig4-(b))

we chose the first approach because it is suitable for distributed control strategy.



(a) Attach a coordinate system on the object.



(b) Attach a coordinate system on one of the manipulators

Fig 4: Deformation coordinate.

4.2 Controller design

The apparent compliance of the flexible object against the external force about the compliance center (the representative of the the object) is specified as follows:

$$\boldsymbol{M}\Delta\ddot{\boldsymbol{x}} + \boldsymbol{D}\Delta\dot{\boldsymbol{x}} + \boldsymbol{K}\Delta\boldsymbol{x} = \boldsymbol{f}^{ext} \quad (1)$$

$$\Delta\boldsymbol{x} = \boldsymbol{x} - \boldsymbol{x}_d \quad (2)$$

where

$x (\in R^6)$, : generalized coordinate that represents the position and orientation of the object,

$x_d (\in R^6)$: desired generalized coordinate that represents the position and orientation of the object,

$M (\in R^{6\times6})$: inertia matrix,

$D (\in R^{6\times6})$: damping matrix,

$K (\in R^{6\times6})$: stiffness matrix,

$f^{ext} (\in R^6)$: generalized external force applied to : the object,

Let us introduce scalar constant ρ_i ($\rho_i > 0, \sum_i \rho_i = 1$), which specify the sharing ratio of external forces. Then the external force shared to i-th manipulator, f_i^{ext} is given by

$$f_i^{ext} = \rho_i F^{ext} \tag{3}$$

For the realization of the apparent impedance of object as in (1) , the compliance of each manipulator is as follows[1]:

$$M_i = \rho_i M \quad , \quad D_i = \rho_i D \quad , \quad K_i = \rho_i K \tag{4}$$

Then the external force f_i^{ext} is obtained by

$$f_i^{ext} = f_i^{sens} - f_i^{int} - f_i^0 (i = 1, 2) \tag{5}$$

where

f_i^{sens} : the force/moment detected by the force sensor of i-th manipulator

f_i^0 : the nominal nonlinear force/moment caused by the object motion

f_i^{int} : the internal force around the compliance center of each manipulator

As discussed in the previous section, from FEM model, we could calculate the internal force f_d^{int} for the desired deformation ${}^{def}\Delta_d$. Then taking the modeling error and noise into account, we design following feedback controller:

$$f^{int} = f_d^{int} + K_I \int_0^t ({}^{def}\Delta_d - {}^{def}\Delta)\, dt \tag{6}$$

where

K_I : constant matrix

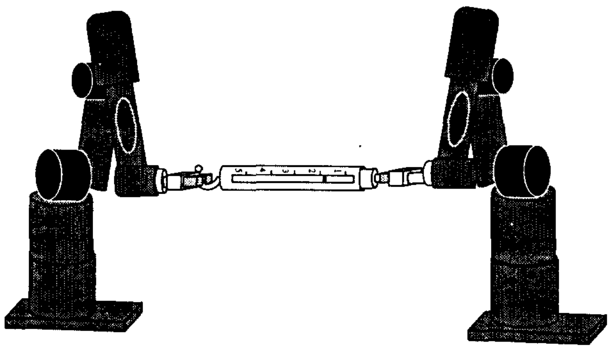


Fig 5: Experimental system.

5 Experiment

We applied the proposed control algorithm to dual industrial manipulators (Nachi, 7603-APJ), each of them has six degrees of freedom and has a force sensor at the wrist. The controller was implemented using VxWorks. Sampling rate was 500[Hz]. As a flexible object, we use a spring hand scale(1-DOF flexible object).

< conditions >

$M = \mathrm{diag}(m1, m1, m1, m2, m2, m2)$,
$m1 = 20[\mathrm{kg}], \quad m2 = 20[\mathrm{kgm}^2]$
$D = \mathrm{diag}(d1, d1, d1, d2, d2, d2)$,
$d1 = 60[\mathrm{Ns/m}], \quad d2 = 60[\mathrm{Ns/rad}]$
$K = \mathrm{diag}(k1, k1, k1, k2, k2, k2)$,
$k2 = 40[\mathrm{N/rad}], \quad k2 = 40[\mathrm{N/rad}]$
Young rate=495[N/m]

< results >

Fig 7-(a),(b) shows the result of deformation control at shared ratio 1:1. The actual trajectory follows reference trajectory. On the other hand, as shown in Fig 7-(c),(d),(e),(f), while the manipulator controlled the deformation, *i.e.*, the internal force is constant, the external force was shared to each manipulator at the specified ratio.

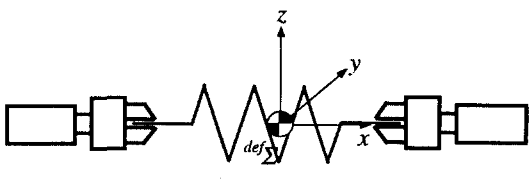
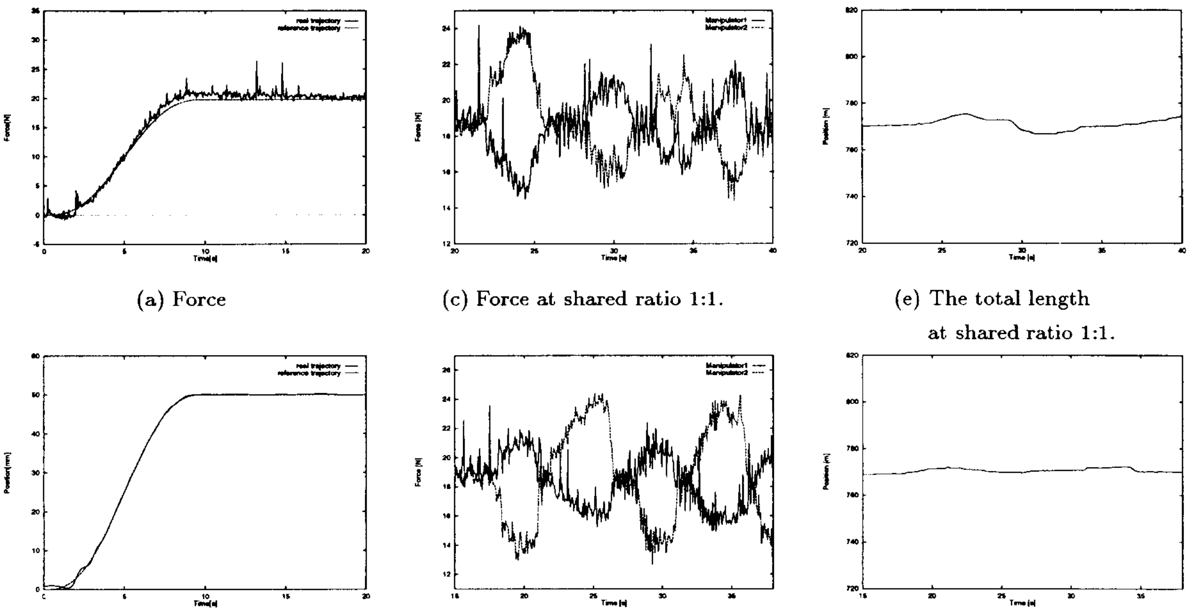


Fig 6: Coordinate system.



(a) Force (c) Force at shared ratio 1:1. (e) The total length at shared ratio 1:1.

(b) Deformation (d) Force at shared ratio 1:2. (f) The total length at shared ratio 1:2.

Fig 7: Experimental result.

6 Conclusion

In this paper, we proposed a coordinated motion control algorithm of dual manipulators handling a flexible object and the experimental results illustrate the validity of the proposed control system.

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