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Coordinated Motion Control of Dual Manipulators For Handling a Rigid Object with Non-negligible Deformation

Kazuhiro Kosuge, Kentaro Kamei and Takashi Nammoto

Abstract— **In this paper, we propose a coordinated motion control algorithm of dual manipulators for handling of an almost rigid object but with non-negligible deformation. By the proposed algorithm, an almost rigid object with non-negligible deformation, such as a cardboard box, a plastic case, etc., is held and manipulated by dual manipulators stably without producing any vibrations. By defining apparent dynamics of dual manipulators for the interface force between the object and its environment and the dissipative dynamics for the internal force applied by the manipulators to the object independently, stable manipulation is achieved. Experimental results illustrate that the vibratory motion of the manipulated object caused by non-negligible deformation is eliminated by the proposed control algorithm while the apparent dynamics of the manipulated object is realized.**

I. Introduction

A lot of industrial robots have been used in factories and have replaced human workforce for various tasks, but human workers are still doing many tasks, which are too complicated for a robot to realize, such as inspection of inside of assembled products, packing of different kinds of products, etc. Human workers execute such complicated tasks using both arms in coordination in a dexterous manner. Handling of a single object in coordination has been one of the key issues for robots to execute such tasks like human workers.

Much research has been done for the coordinated motion control of multiple manipulators for handling of a single object in coordination, and many control schemes have been proposed so far. To control internal force that is applied on the object has been validated when the object is grasped by multiple manipulators. For example, Uchiyama et al. applied hybrid position/force control scheme for coordinated motion control of dual manipulators, where the motion of dual manipulators is decoupled into the absolute motion and the relative motion using a "Virtual Stick" concept [1]. Hsia et al. applied impedance control scheme based on the internal force to control cooperating manipulators without knowing the dynamics of the object [2][3]. Khatib et al. discussed the coordinate system describing the dynamics of the object for the internal force and proposed a concept of a virtual linkage [4].

On the other hand, the object that is grasped by multiple manipulators should be moved to a certain position and orientation even though it is passively controlled by using compliant motion control depending on external force that is caused between the object and its environment when the multiple manipulators are used for the tasks such as a peg-in-hole. To meet the requirement, the motion of each manipulator should be generated by decomposing compliant motion of the object that is specifically designed for the task considering its environment [9]. In the design of the compliant motion of the object, rotation center should be located on tip of the peg to complete the task by using remote center compliance (RCC) concept [6]. Kosuge proposed a coordinated motion control algorithm of manipulators based on impedance control of each manipulator, which controls the apparent dynamics of the object for external force applied to the object and the pose of the manipulated object [6][5].

To realize both of stable grasping of the object and accurate positioning of the object by using compliant motion control, a framework that simultaneously controls both of the internal force and the external force has been presented [10]. The framework is effective, however, it cannot be employed for the complicated task such as a peg-in-hole because design of compliant motion of the object such as the location of the rotation cetner has not been discussed.

Although many control schemes have been proposed so far, most of the control methods for handling a single object by multiple manipulators assume that the manipulated object is completely rigid. Several control algorithms also have been proposed for handling a flexible object assuming that the flexibility of the object could be modeled precisely. The modeling scheme, however, could be applied to a certain class of objects [7]. In reality, most of objects, which we need to handle, is not so flexible but is not completely rigid. Although it is not easy to model the deformation of such objects, the deformation is not negligible for stable handling of an object. In many cases, the deformation of the object induces vibratory motions of the manipulators and often makes the system unstable for a certain class of control parameters. Actually, it is not an easy task to select appropriate control parameters for stable object manipulation.

In this paper, we propose an alternative coordinated motion control algorithm of dual manipulators that simultaneously controls both of the internal force and the external force, where compliant motion can be designed flexibly. Besides, the proposed algorithm has a capability to handle an almost rigid object with non-negligible deformation.

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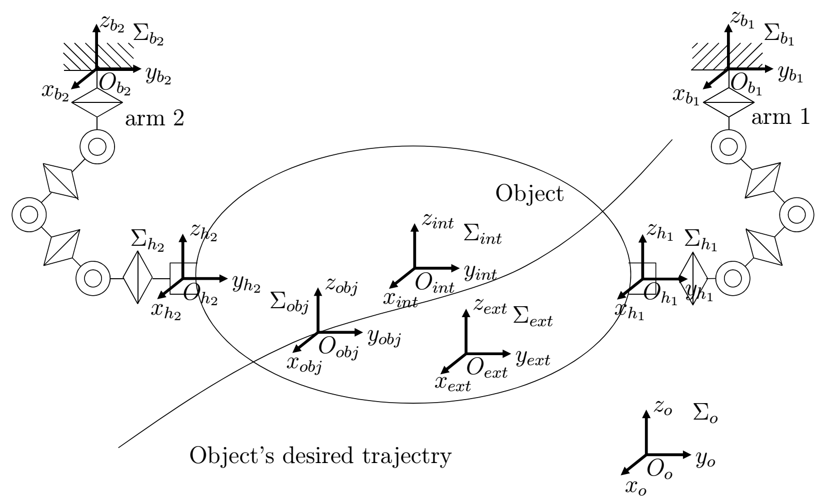


Fig. 1. Coordinate Systems for Coordinated Motion Control of Dual Manipulators for Handling a Single Object

II. CONTROL STRATEGY

In this section, we discuss a control strategy of dual manipulators for handling of an almost rigid object with non-negligible deformation. Let us consider packing of small cardboard boxes into a large cardboard box. This is a typical example of dual arms coordination for shipping products such as electronic devices. Automatization of the task is strongly desired, because it is a typical task required for the final step of a production line.

Let us consider a task to put small cardboard boxes into a large cardboard box. To do so, consider a peg-in-hole task first, since this packing task requires a similar strategy to that of the peg-in-hole problem. In the peg-in-hole task, the peg needs to move passively against the external force applied to the peg, which is caused by the interaction between the peg and the hole, to avoid jamming of the peg during the insertion. Usually force control or compliant motion control scheme, such as impedance control, stiffness control, etc., is used for the peg-in-hole task. For successful execution of the task, both the apparent dynamics of the motion of the peg for the external force and the position of the compliance center of the peg need to be selected appropriately. Going back to our original problem, this means that appropriate selection of both the apparent dynamics of the small cardboard box and the position of the compliance center of the small cardboard box are necessary for the box to be inserted to the larger box without jamming.

Let us consider squeezing of a cardboard box next. Since the small(er) cardboard box for packing (an) electronic device(s) is not small and relatively large, manipulators could handle it by squeezing it in a coordinated manner. At this time, deformation of the box, which is caused by the internal force applied to the cardboard box by the manipulators, could not be negligible, because the squeeze could cause vibratory motion of the manipulators and thus the vibratory deformation of the box. In order to realize vibration-free/stable manipulation of the deformable object, we consider to specify dissipative apparent dynamics to the relative motion of the manipulators against the internal force appropriately.

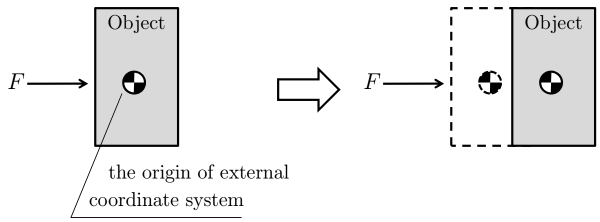
With these two requirements mentioned above, the proposed control algorithm is based on two coordinate systems; one is a coordinate system describing the relative motion of manipulators for the internal force applied to the object and the other is a coordinate system describing the absolute motion of the object against the external force applied to the object. The motion of each manipulator is decoupled into the absolute motion for the external force and the relative motion for the internal force by defining these coordinate systems appropriately.

Similarly to some of the conventional control algorithms, the proposed control algorithm controls the apparent dynamics of the manipulated object, for external force applied to the object from its environment. But in addition to the control of the apparent dynamics of the object to the external force, the proposed control algorithm controls the dynamics of manipulators for the internal force applied to manipulators in the coordinate system, which is different from the coordinate system for the external force applied the object, to control the dynamics of manipulators relating to the internal force applied to the object. That is, to reduce/eliminate the vibratory motion of the manipulators caused by the deformation of the object, dissipative dynamics of manipulators for the internal force applied to manipulators is specified.

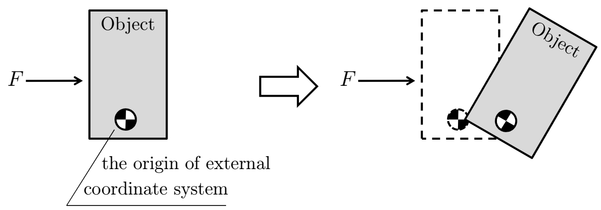
In this way, the proposed algorithm could specify both the apparent dynamics of the object against the external force and the dissipative property of the object deformation against the internal force, and the object is manipulated more stably by the dual manipulators. Note that the dynamics of the manipulated object are not required for the control algorithm.

III. COORDINATE SYSTEMS

First, let us consider a problem of handling an almost rigid object with non-negligible deformation by dual manipulators in coordination. We define coordinate systems as shown in



(a) When The Origin of The Coordinate System is attached to The Center of The Object



(b) The Case that The Origin of The Coordinate System is attached to The Lower of The Object

Fig. 2. Examples of The Motion of The Object around The Origin of The Coordinate System

Fig. 1. The absolute coordinate system $O_o - x_o y_o z_o$ is fixed to the environment. Let Σ_o represent the absolute coordinate system $O_o - x_o y_o z_o$. Let Σ_{b_i} represent the i-th base coordinate system attached to the base of i-th manipulator $O_{b_i} - x_{b_i} y_{b_i} z_{b_i}$. Their orientations correspond to that of the absolute coordinate system. The i-th hand coordinate system $O_{h_i} - x_{h_i} y_{h_i} z_{h_i}$, in which the motion of the i-th manipulator is described, is attached to the tip of the end-effector of i-th manipulator. The object coordinate system $O_{obj} - x_{obj} y_{obj} z_{obj}$, in which the motion of the object is described, is fixed to the object being held by the dual manipulators. Let Σ_{h_i} and Σ_{obj} represent $O_{h_i} - x_{h_i} y_{h_i} z_{h_i}$ and $O_{obj} - x_{obj} y_{obj} z_{obj}$, respectively.

We assume that the orientation of the hand coordinate systems and the object coordinate system are parallel that of the absolute coordinate system when the object is held by the dual manipulators.

A. Coordinate Systems for Force Control

When external force is applied to the object and the end-effector of the manipulator grasping the object is controlled by the force control, its motion depends on the definition of the coordinate system used the force control, i.e., the position and the orientation of the coordinate system used for the control. For instance, in Fig. 2, let consider a case when the object is pushed by the external force from the left hand side of the object. Consider the case in which the origin of the coordinate system for the force control is specified at the center of the object and the case in which the origin of the coordinate system for the force control is specified at the bottom of the object.

When the coordinate system is located at the center of the object, because the origin of the coordinate system for force control is on the extended line of the external force vector, the object moves along that line as shown in Fig. 2 (a). On the other hand, as shown in Fig. 2 (b), when the coordinate

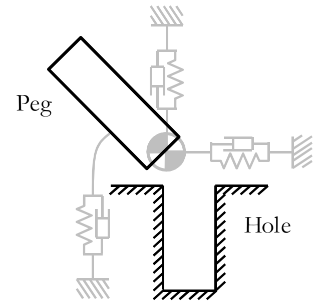


Fig. 3. Plane Model of Virtual Mechanism for Peg-in-Hole Task

system is located at the bottom of the object, moment around the origin of the coordinate system is generated and causes rotation around it, although the external force is applied to the object in the same manner as the previous case. These two figures show that the motion of the object depends on the specification of the coordinate system for the force control.

In this paper, a framework of force control system including definition of the coordinate systems for force control is based on the virtual mechanism [8]. According to the virtual mechanism concept, the dynamics of the object or end-effector, which executes a task, is represented by a mechanical tool, such as a slider mechanism, a rolling mechanism, a spring, etc. The motion of the object depending on the force applied to the object corresponds to the displacement of the mechanical tool. The axes of the displacement of the mechanical tool correspond to the axes of the coordinate system for the force control. In addition, the dynamics of the object for the force applied to the object corresponds to the dynamics of the mechanical tool. Fig. 3 shows an example of the planar model of the virtual mechanism for the peg-in-hole task.

We apply the virtual mechanism to both the apparent dynamics of the object for the external force applied to the object, that is, the absolute motion of the object, and the dynamics for relative motion of the end-effectors, that is, the deformation of the object. We define the coordinate system with respect to the virtual mechanism to describe the absolute motion of the object based on the force applied to the object in an external force coordinate system $O_{ext} - x_{ext} y_{ext} z_{ext}$. $O_{ext} - x_{ext} y_{ext} z_{ext}$ is represented by Σ_{ext}. To simplify discussions, the external force coordinate system is assumed to be parallel to the absolute coordinate system. The resultant force applied to the object in the external force coordinate system is defined as the external force.

Similar to the external force coordinate system, we define the internal force coordinate system $O_{int} - x_{int} y_{int} z_{int}$, in which the relative motion of the end-effectors, or the deformation of the object, is described. Σ_{int} represents the internal force coordinate system $O_{int} - x_{int} y_{int} z_{int}$. The force applied to the end-effector in the internal force coordinate system is defined as the internal force. The virtual mechanism corresponding to the internal force coordinate system is designed in the same way as the virtual mechanism corresponding to

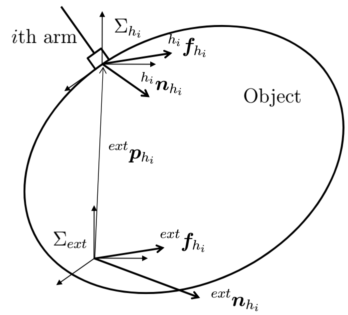


Fig. 4. Equivalent Force and Moment Applied to The Object by Each Manipulator at The Origin of The External Force Coordinate System

the external force coordinate system. The relative motion of the end-effector caused by the internal force is based on the absolute motion of the object caused by the external force.

IV. Coordinated motion control

A. Assumptions

To design the control algorithm for coordinated motion of dual manipulators, the following assumptions are made.

- The relative motion between the end-effectors of dual manipulators and the object being manipulated by dual manipulators is negligible, i.e., dual manipulators hold the object firmly.
- The deformation of the object is generated only by the internal force, i.e., the relative position of both end-effectors is unaffected by the external force applied to the object.
- The position and orientation of the base coordinate system of each manipulator with respect to the absolute coordinate system are known, and the position and orientation of the hand coordinate system of each end-effector in the absolute coordinate system can be calculated based on forward kinematics of the manipulators.
- The external force coordinate system is identical to the object coordinate system.

B. External Force

The apparent dynamics of the manipulated object for the external force applied to the object has to be specified. To calculate the external force applied to the object, the force applied to each end-effector should be considered. Generally, the force sensor is attached to the wrist of a manipulator and we can measure the force applied to the end-effector. Therefore, we assume that the force sensor is attached to the wrist of a manipulator and the force applied to force sensor can be measured.

The force applied to end-effector with respect to the hand coordinate system can be calculated from the force measured by the force sensor with respect to the sensor coordinate system. Let ${}^{ext}\boldsymbol{p}_{h_i} = \left[{}^{ext}p_{h_ix} \ {}^{ext}p_{h_iy} \ {}^{ext}p_{h_iz}\right]^T$ and ${}^{ext}R_{h_i} \in \boldsymbol{R}^{3\times 3}$ be a position vector of the origin and a rotation matrix of i-th hand coordinate system with respect to the external force coordinate system, respectively. ${}^{ext}p_{h_ix}$, ${}^{ext}p_{h_iy}$ and ${}^{ext}p_{h_iz}$ are scalar variables. Let ${}^{h_i}\boldsymbol{F}_{h_i} = [{}^{h_i}\boldsymbol{f}_{h_i}^T \ {}^{h_i}\boldsymbol{n}_{h_i}^T]^T \in \boldsymbol{R}^6$ be the force and the moment applied to the end-effector, where ${}^{h_i}\boldsymbol{f}_{h_i} \in \boldsymbol{R}^3$ and ${}^{h_i}\boldsymbol{n}_{h_i} \in \boldsymbol{R}^3$ are the force and the moment applied to the end-effector of i-th manipulator with respect to i-th hand coordinate system, respectively.

The equivalent force at the origin of the external force coordinate system applied by each manipulator with respect to the external force coordinate system is

$$ {}^{ext}\boldsymbol{F}_{h_i} = {}^{ext}W_{h_i} {}^{h_i}\boldsymbol{F}_{h_i} \tag{1} $$

where

$$ {}^{ext}W_{h_i} = \begin{bmatrix} {}^{ext}R_{h_i} & \boldsymbol{0} \\ {}^{ext}P_{h_i} {}^{ext}R_{h_i} & {}^{ext}R_{h_i} \end{bmatrix} \tag{2} $$

and

$$ \begin{aligned} {}^{ext}P_{h_i} &= \left[{}^{ext}\boldsymbol{p}_{h_i} \times\right] \\ &= \begin{bmatrix} 0 & -{}^{ext}p_{h_iz} & {}^{ext}p_{h_iy} \\ {}^{ext}p_{h_iz} & 0 & -{}^{ext}p_{h_ix} \\ -{}^{ext}p_{h_iy} & {}^{ext}p_{h_ix} & 0 \end{bmatrix}. \end{aligned} \tag{3} $$

The external force applied to the object is calculated as the sum of the equivalent force ${}^{ext}\boldsymbol{F}_{h_i}$. Thus, the external force applied to the object is described as follows:

$$ \begin{aligned} {}^{ext}\boldsymbol{F}_{ext} &= {}^{ext}\boldsymbol{F}_{h_1} + {}^{ext}\boldsymbol{F}_{h_2} \\ &= {}^{ext}W_{h_1} {}^{h_1}\boldsymbol{F}_{h_1} + {}^{ext}W_{h_2} {}^{h_2}\boldsymbol{F}_{h_2}. \end{aligned} \tag{4} $$

C. Control of Apparent Dynamics

We control the apparent dynamics of the manipulated object for the external force as the following dynamic model, that is an impedance model:

$$ M_{ext}\Delta\ddot{\boldsymbol{x}}_{ext} + D_{ext}\Delta\dot{\boldsymbol{x}}_{ext} + K_{ext}\Delta\boldsymbol{x}_{ext} = {}^{ext}\boldsymbol{F}_{ext} \tag{5} $$

where

$$ \Delta\boldsymbol{x}_{ext} = {}^{ext}\boldsymbol{x}_{ext} - {}^{ext}\boldsymbol{x}_{ext}^d \tag{6} $$

and $M_{ext} \in \boldsymbol{R}^{6\times 6}$, $D_{ext} \in \boldsymbol{R}^{6\times 6}$ and $K_{ext} \in \boldsymbol{R}^{6\times 6}$ are the positive definite matrices. ${}^{ext}\boldsymbol{x}_{ext} \in \boldsymbol{R}^6$ represents the current trajectory of the virtual mechanism describing the motion of the object to which the external force is applied. ${}^{ext}\boldsymbol{x}_{ext}^d \in \boldsymbol{R}^6$ is its desired trajectory. By the apparent dynamics of the manipulated object for the external force, we can prevent excessive force applied to the object, which is caused by the interaction between the object and its environment.

D. Internal Force

The equivalent force applied to the end-effector with respect to the external force coordinate system is decoupled as follows:

$$ {}^{ext}\boldsymbol{F}_{h_i} = {}^{ext}\boldsymbol{F}_{ext_i} + {}^{ext}\boldsymbol{F}_{int_i} \tag{7} $$

where, ${}^{ext}\boldsymbol{F}_{ext_i}$ and ${}^{ext}\boldsymbol{F}_{int_i}$ are the external component and the internal component of the force applied by i-th end-effector with respect to the external force coordinate system, respectively. The external force applied to the object is distributed to each manipulator according to the impedance dynamics of each manipulator[6], and then, we define the external force distribution to each manipulator as the external component of the force applied to the end-effector as follows:

$$^{ext}\boldsymbol{F}_{ext_i} = \rho_i {}^{ext}\boldsymbol{F}_{ext} \tag{8}$$

where ρ_i is the load distribution factor for i-th manipulator[6], and

$$\begin{cases} 0 < \rho_i < 1 \\ \rho_1 + \rho_2 = 1 \end{cases}. \tag{9}$$

The internal component with respect to external force coordinate system can be obtained by

$$\begin{aligned} ^{ext}\boldsymbol{F}_{int_i} &= {}^{ext}\boldsymbol{F}_{h_i} - {}^{ext}\boldsymbol{F}_{ext_i} \\ &= {}^{ext}\boldsymbol{F}_{h_i} - \rho_i {}^{ext}\boldsymbol{F}_{ext} \end{aligned} \tag{10}$$

To describe the motion of the end-effector depending on the internal force, the internal component has to be represented with respect to the internal force coordinate system.

$$\begin{aligned} ^{int}\boldsymbol{F}_{int_i} &= {}^{int}R_{h_i} {}^{h_i}\boldsymbol{F}_{int_i} \\ &= {}^{int}R_{h_i} {}^{ext}W_{h_i}^{-1} {}^{ext}\boldsymbol{F}_{int_i} \end{aligned} \tag{11}$$

where $^{int}R_{h_i} \in \boldsymbol{R}^{3\times 3}$ is the rotation matrix describing the orientation of i-th hand coordinate system with respect to the internal force coordinate system. The internal force applied to the end-effector can be obtained by

$$^{int}\boldsymbol{F}_{int} = \frac{1}{2} {}^{int}\boldsymbol{F}_{int_1} - \frac{1}{2} {}^{int}\boldsymbol{F}_{int_2}. \tag{12}$$

E. Damping Control

We design the dynamics of the virtual mechanism for the internal force applied to the end-effector as a dissipative dynamics described as follows:

$$M_{int}\Delta\ddot{\boldsymbol{x}}_{int} + D_{int}\Delta\dot{\boldsymbol{x}}_{int} = {}^{int}\boldsymbol{F}_{int} \tag{13}$$

where

$$\Delta\boldsymbol{x}_{int} = {}^{int}\boldsymbol{x}_{int} - {}^{int}\boldsymbol{x}^d_{int}. \tag{14}$$

and $^{int}\boldsymbol{F}_{int} \in \boldsymbol{R}^6$ is a vector of desired internal force and moment. $M_{int} \in \boldsymbol{R}^{6\times 6}$ and $D_{int} \in \boldsymbol{R}^{6\times 6}$ are the positive definite matrices. $^{int}\boldsymbol{x}_{int} \in \boldsymbol{R}^6$ is current trajectory of the virtual mechanism describing the motion of the end-effector applied the internal force. $^{int}\boldsymbol{x}^d_{int} \in \boldsymbol{R}^6$ is its desired trajectory. Because the internal force coordinate system is designed based on the external force coordinate system, the relative motion of the end-effector is based on the motion of the object with respect to the external force coordinate system. The dynamics of the virtual mechanism for the internal force is designed so that the relative motion of the end-effectors is induced depending on the internal force. By designing damping parameters of the dynamics properly, the object can be handled by manipulators, without causing vibratory motion, even without modeling the dynamics of the object, assuming that the object dynamics is passive.

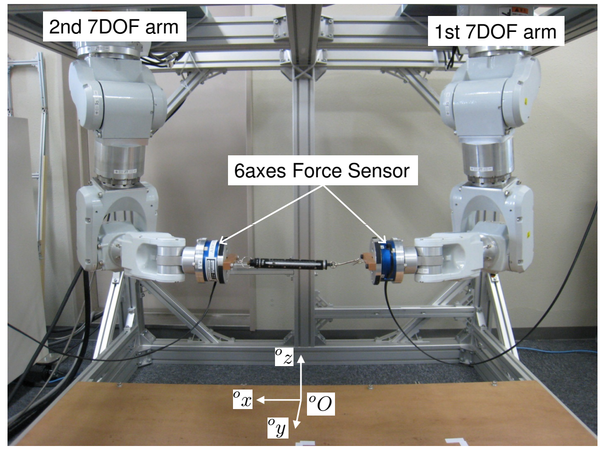


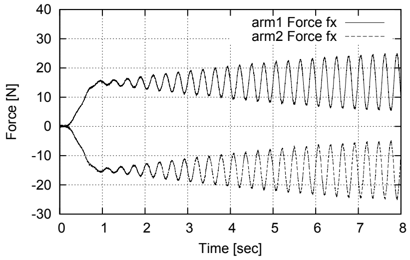
Fig. 6. Experimental System

V. Experiment

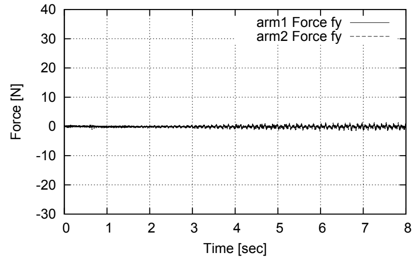
The proposed control algorithm and the conventional control algorithm proposed in [6] were implemented in the the experimental system, which consists of dual seven degree of freedom manipulators as shown in Fig. 6. The force sensor is attached to the wrist of each manipulator. The origin of the absolute coordinate system is located at the intersection between the table and the bisector of the line between the origin of the hand coordinate systems. The spring scale, whose stiffness coefficient is 1307.6[N/m], was manipulated by the dual manipulators in coordination. The direction of the desired internal force is along x axis of the absolute coordinate system. The internal force was applied to the spring scale from 0[N] to 15[N] for 2[sec] calculated by a fifth order polynomial function of time. In continuation, internal force 15[N] for 6[sec] was applied to the spring scale. The impedance and damping parameters used for the experiments are shown in Table I. In the conventional control, the same impedance parameters of the apparent dynamics of the object for the external force are used as the case of the proposed control method. The experimental results of the conventional control algorithm are shown in Fig. 5 and that of the proposed control algorithm are shown in Fig. 7. The measured position of the conventional control algorithm case (Fig. 5(d)-(f)) is represented equivalent to the case of the proposed control algorithm's case. As shown in Fig. 5, the vibratory force caused by the dynamics of the spring scale, which is held by each end-effector, is seen in the case of

TABLE I
Impedance parameter of the proposed control

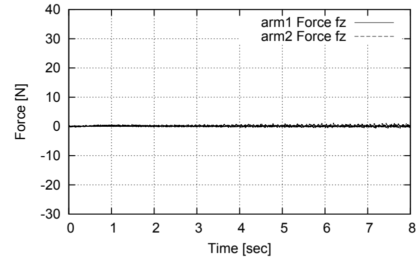
Parameter	Value
M_{ext}	$diag(5,10,10,10,10,10)$
D_{ext}	$diag(12,100,100,25,25,25)$
K_{ext}	$diag(12,120,120,25,25,25)$
M_{int}	$diag(50,50,50,50,50,50)$
D_{int}	$diag(500,500,500,500,500,500)$



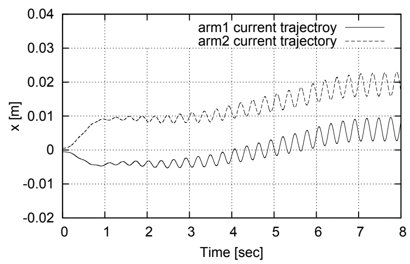
(a) Force along x Axis of Absolute Coordinate System



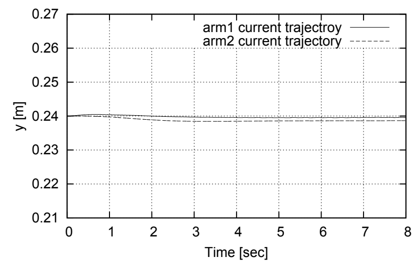
(b) Force along y Axis of Absolute Coordinate System



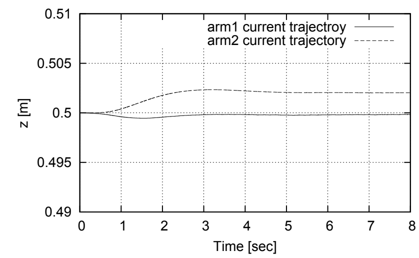
(c) Force along z Axis of Absolute Coordinate System



(d) Position of End-Effector along x Axis of Absolute Coordinate System

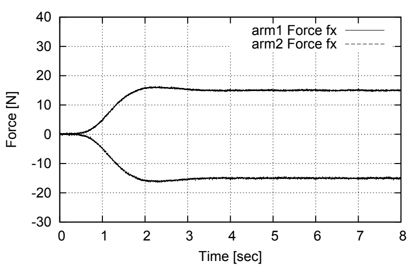


(e) Position of End-Effector along y Axis of Absolute Coordinate System

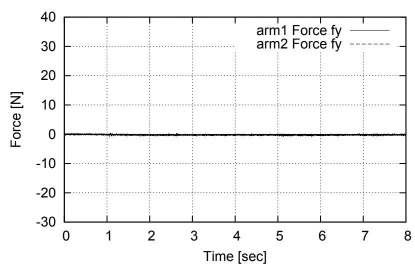


(f) Position of End-Effector along z Axis of Absolute Coordinate System

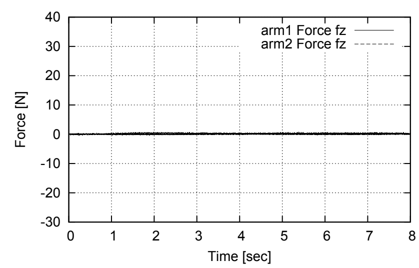
Fig. 5. Experimental Result Using Conventional Control Algorithm



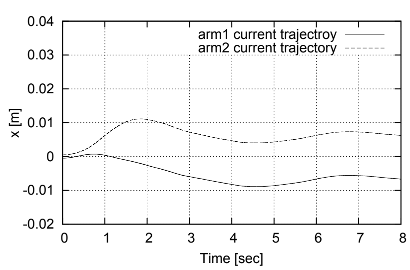
(a) Force along x Axis of Absolute Coordinate System



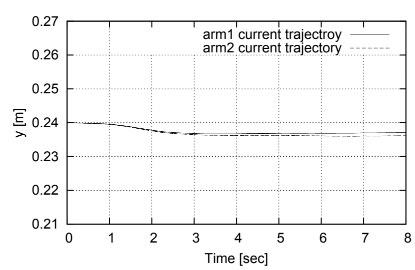
(b) Force along y Axis of Absolute Coordinate System



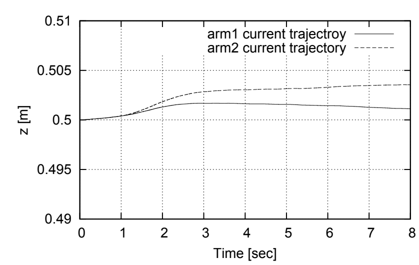
(c) Force along z Axis of Absolute Coordinate System



(d) Position of End-Effector along x Axis of Absolute Coordinate System



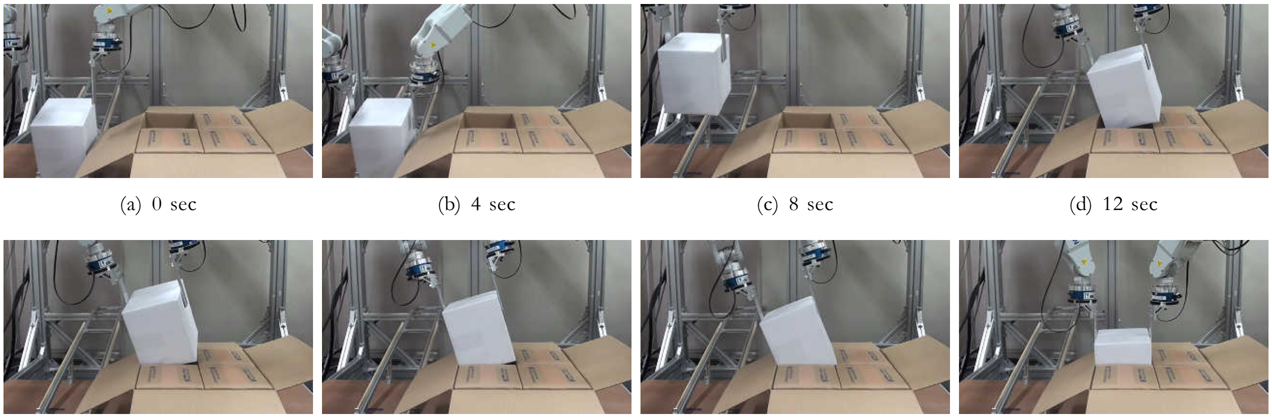
(e) Position of End-Effector along y Axis of Absolute Coordinate System



(f) Position of End-Effector along z Axis of Absolute Coordinate System

Fig. 7. Experimental Result Using Proposed Control Algorithm

the conventional control algorithm. In contrast, as shown in Fig. 7, the force applied to each end-effector is not vibratory in the case of the proposed control algorithm. You can see that the proposed control algorithm is more stable than the



(a) 0 sec (b) 4 sec (c) 8 sec (d) 12 sec

(e) 16 sec (f) 20 sec (g) 24 sec (h) 28 sec

Fig. 8. Sequential Images of Box Insertion

conventional control algorithm.

By using the proposed control algorithm, packing of small cardboard boxes into a large cardboard box is realized. Sequential images of the task are shown in Fig. 8. You can see that the algorithm can be applied such a real industrial task which is taken an example when control strategy is discussed.

VI. Conclusion

In this paper, we have proposed a coordinated motion control algorithm of dual manipulators for handling of an almost rigid object with non-negligible deformation. The virtual mechanism was used for specifying the coordinate system for the force control. The motion of the manipulators has been decoupled into to the absolute motion of the object corresponding to the external force and the deformable motion of the object corresponding to the internal force by designing the internal force coordinate system and the external force coordinate system appropriately.

Apparent dynamics of the manipulated object to the external force applied to the object from its environment is controlled by the impedance controller, and the dynamics of relative motion of the end-effectors for the internal force applied to the end-effector is controlled by a dissipative dynamics. By designing the parameters of the dissipative dynamics appropriately, the vibratory motion of end-effector caused by the dynamics of the manipulated object is suppressed. Note that this control algorithm does not require the dynamics of the manipulated object as long as the internal dynamics of the object is passive.

Finally, we implemented the proposed control algorithm and the conventional control algorithm to an experimental dual manipulators system and carried our an experiment of handling a spring scale. Using the proposed algorithm, the vibratory motion observed with the conventional control scheme was suppressed and the effectiveness was illustrated for handling the object with non-negligible deformation by dual manipulators in coordination.

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