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Experimental Approach on Grasping and Manipulating Multiple Objects

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Abstract: This paper discusses grasping and manipulating multiple objects by an enveloping style. We formulate the motion constraint for enveloping multiple objects under rolling contacts. We further provide a sufficient condition for producing a relative motion between objects. We show that a three-fingered robot hand experimentally succeeds in lifting up two cylindrical objects from a table and in changing their relative positions within the hand.

1. Introduction

Multifingered robot hands have a potential advantage to perform various skillful tasks like human hands. So far, much research has been done on multifingered robot hands focusing on the grasp of an object such as the stability of the grasp, the equilibrium grasp, the force closure grasp, and the manipulation of an object by utilizing either the rolling or the sliding contact. Most of works have implicitly assumed that a multifingered hand treats only one object. In this paper, we relax the assumption of single object, and discuss the manipulation of multiple objects by a multifingered robot hand. While there have been a couple of works [1, 2, 3, 4] discussing the grasp of multiple objects, as far as we know, there has been no work on the manipulation of multiple objects within the hand.

The goal of this paper is to realize the manipulation of multiple objects by a multi-fingered robot hand. For grasping and manipulating an object, there are two grasp styles, finger-tip grasp and enveloping grasp. While we can expect a dexterous manipulation through a finger-tip grasp, it may easily fail in grasping multiple objects under a small disturbance. On the other hand, an enveloping grasp may ensure even more robustness for grasping multiple objects than a finger-tip grasp, due to a large number of distributed contacts on the grasped objects, while we can not expect a dexterous manipulation for enveloped objects. Taking advantage of the robustness of enveloping grasp, we focus on the enveloping grasp for handling multiple objects. One big problem for manipulating enveloped objects is, however, that the manipulating force cannot be obtained uniquely for a given set of torque commands and it generally spans a bounded space. As a result, each object motion is not uniquely determined either. Knowing of such basic properties of the manipulation of enveloped objects, we provide a sufficient condition for producing a relative motion between objects.

The highlight of this work is the experimental validation. For two cylindrical objects placed on a table, the specially developed robot hand first approaches and lifts up them with a simple pushing motion by finger tips. After two objects are fully enveloped by the hand, it starts the manipulation mode composed of four phases where torque commands are appropriately switched depending upon the relative position of objects. By switching torque commands step by step, we succeeded in manipulation two cylindrical objects within the hand.

2. Related Works

Enveloping Grasp:

There have been a number of works concerning the enveloping grasp. Especially, Salisbury et al.[5] has proposed the Whole-Arm Manipulation(WAM) capable of treating a big and heavy object by using one arm which allows multiple contacts with an object. Bicchi[6], Zhang et al.[7] and Omata et al.[8] analyzed the grasp force of the enveloping grasp. In our previous work, we have proposed the grasping strategies for achieving enveloping grasp for cylindrical objects[9].

Grasp and Manipulation of Multiple Objects:

Dauchez et al.[1] and Kosuge et al.[2] used two manipulators holding two objects independently and tried to apply to an assembly task. However, they have not considered that two manipulators grasp and manipulate two common objects simultaneously. Recently, Aiyama et al.[3] studied a scheme for grasping multiple box type objects stably by using two manipulators. For an assembly task, Mattikalli et al.[10] proposed a stable alignments of multiple objects under the gravitational field. While these works treated multiple objects, they have not considered any manipulation of objects.

Grasp by Rolling Contacts:

Kerr et al.[11] and Montana[12] formulated the kinematics of manipulation of objects under rolling contacts with the fingertip. Li et al.[13] proposed a motion planning method with nonholonomic constraint. Howard et al.[14] and Maekawa et al.[15] studied the stiffness effect for the object motion with rolling. Cole et al.[16] and Paljug et al.[17] proposed a control scheme for achieving a rolling motion for a grasped object.

3. Modeling

Fig.1 shows the hand system enveloping m objects by n fingers, where finger j contacts with object i, and additionally object i has a common contact point with object l. Σ_R, Σ_{Bi} $(i = 1, \cdots, m)$ and Σ_{Fjk} $(j = 1, \cdots, n, \quad k = 1, \cdots, c_j)$ denote the coordinate systems fixed at the base, at the center of gravity of the object i and at the finger link including the kth contact of finger j, respectively. Let $\boldsymbol{p}_{Bi}$ and $\boldsymbol{R}_{Bi}$ be the position vector and the rotation matrix of Σ_{Bi}, and $\boldsymbol{p}_{Fjk}$ and $\boldsymbol{R}_{Fjk}$ be those of Σ_{Fjk}, with respect to Σ_R, respectively. ${}^{Bi}\boldsymbol{p}_{Cjk}$

and ${}^{Fjk}\boldsymbol{p}_{Cjk}$ are the position vectors of the kth contact point of finger j with respect to Σ_{Bi} and Σ_{Fjk}, respectively. ${}^{Bi}\boldsymbol{p}_{COt}(t = 1, \cdots, r)$ is the position vector of the common contact point between object i and object l with respect to Σ_{Bi}.

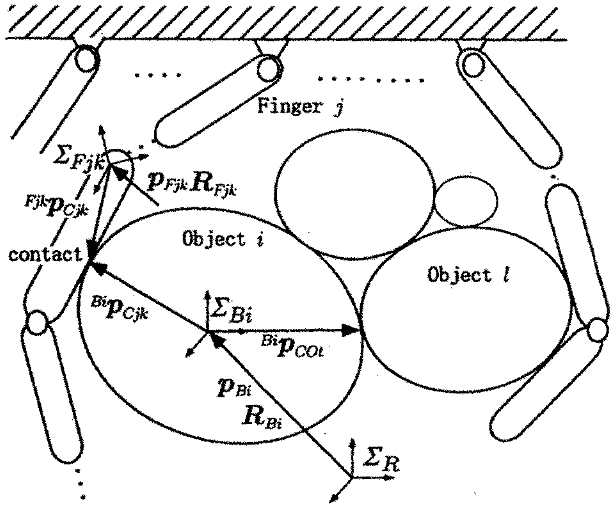


Fig. 1. Model of the System

3.1. Basic Formulation

In this subsection, we derive the constraint condition. The contact point between object i and the kth contact of finger j can be expressed by Σ_{Bi} and Σ_{Fjk}. Similarly, the contact point between object i and object l can be expressed by Σ_{Bi} and Σ_{Bl}. As a result, we have the following relationships:

$$\boldsymbol{p}_{Bi} + \boldsymbol{R}_{Bi}{}^{Bi}\boldsymbol{p}_{Cjk} = \boldsymbol{p}_{Fjk} + \boldsymbol{R}_{Fjk}{}^{Fjk}\boldsymbol{p}_{Cjk}, \tag{1}$$

$$\boldsymbol{p}_{Bi} + \boldsymbol{R}_{Bi}{}^{Bi}\boldsymbol{p}_{COt} = \boldsymbol{p}_{Bl} + \boldsymbol{R}_{Bl}{}^{Bl}\boldsymbol{p}_{COt}. \tag{2}$$

Suppose the rolling contact at each contact point. The velocity of object i and the finger j should be same at the contact point. Also, the velocity of two objects should be same at the common contact point between them. These constraints lead to the following equations[11]:

$$\boldsymbol{D}_{Bjk}\begin{bmatrix} \dot{\boldsymbol{p}}_{Bi} \\ \boldsymbol{\omega}_{Bi} \end{bmatrix} = \boldsymbol{D}_{Fjk}\begin{bmatrix} \dot{\boldsymbol{p}}_{Fjk} \\ \boldsymbol{\omega}_{Fjk} \end{bmatrix}, \tag{3}$$

$$\boldsymbol{D}_{Oit}\begin{bmatrix} \dot{\boldsymbol{p}}_{Bi} \\ \boldsymbol{\omega}_{Bi} \end{bmatrix} = \boldsymbol{D}_{Olt}\begin{bmatrix} \dot{\boldsymbol{p}}_{Bl} \\ \boldsymbol{\omega}_{Bl} \end{bmatrix}, \tag{4}$$

$$\boldsymbol{D}_{Bjk} = [I \ \ -(\boldsymbol{R}_{Bi}{}^{Bi}\boldsymbol{p}_{Cjk}\times)], \tag{5}$$

$$\boldsymbol{D}_{Fjk} = [I \ \ -(\boldsymbol{R}_{Fjk}{}^{Fjk}\boldsymbol{p}_{Cjk}\times)], \tag{6}$$

$$\boldsymbol{D}_{Oit} = [I \ \ -(\boldsymbol{R}_{Bi}{}^{Bi}\boldsymbol{p}_{COt}\times)], \tag{7}$$

where I, $(\boldsymbol{R}_{Bi}{}^{Bi}\boldsymbol{p}_{Cjk}\times)$, $(\boldsymbol{R}_{Fjk}{}^{Fjk}\boldsymbol{p}_{Cjk}\times)$ and $(\boldsymbol{R}_{Bi}{}^{Bi}\boldsymbol{p}_{COt}\times)$ denote the identity and the skew-symmetric matrices which are equivalent to the vector product, respectively, and ω_{Bi} and ω_{Fjk} denote the angular velocity vectors of Σ_{Bi} and Σ_{Fjk} with respect to Σ_R, respectively. Since the velocity of the finger link including the kth contact point of finger j can also be expressed by utilizing the joint velocity of finger j, we obtain the following relationships:

$$\begin{bmatrix} \dot{\boldsymbol{p}}_{Fjk} \\ \boldsymbol{\omega}_{Fjk} \end{bmatrix} = \boldsymbol{J}_{jk}\dot{\boldsymbol{\theta}}_j, \tag{8}$$

where $\boldsymbol{J}_{jk}$ is the jacobian matrix of the finger link with respect to the joint velocity. Substituting eq.(8) into eq.(3) and aggregating for $j = 1, \cdots, n$ and $k = 1, \cdots, c_j$, and aggregating eq.(4) for $t = 1, \cdots, r$, the the relationship between joint velocity and object velocity can be derived as follows:

$$\boldsymbol{D}_F\dot{\boldsymbol{\theta}} = \boldsymbol{D}_B\dot{\boldsymbol{p}}_B, \tag{9}$$

where

$$\begin{aligned}
\boldsymbol{D}_F &= \begin{bmatrix} \boldsymbol{D}_{F1} & \cdots & \mathrm{o} \\ \vdots & \ddots & \vdots \\ \mathrm{o} & \cdots & \boldsymbol{D}_{Fn} \\ \mathrm{o} & \cdots & \mathrm{o} \end{bmatrix}, \\
\dot{\boldsymbol{\theta}} &= [\dot{\boldsymbol{\theta}}_1^T \cdots \dot{\boldsymbol{\theta}}_n^T]^T, \\
\boldsymbol{D}_B &= [\boldsymbol{D}_{B1}^T \cdots \boldsymbol{D}_{Bn}^T\ \boldsymbol{D}_O^T]^T, \\
\dot{\boldsymbol{p}}_B &= [\dot{\boldsymbol{p}}_{B1}^T\ \boldsymbol{\omega}_{B1}^T \cdots \dot{\boldsymbol{p}}_{Bm}^T\ \boldsymbol{\omega}_{Bm}^T]^T.
\end{aligned}$$

Definition of $\boldsymbol{D}_{Fj}$ $(j = 1, \cdots, n)$, $\boldsymbol{D}_{Bj}$ $(j = 1, \cdots, n)$ and $\boldsymbol{D}_O$ are shown in [4], and an example for a grasp of two objects by two fingers will be shown in the next section. In eq.(9), $\boldsymbol{D}_B \in R^{(\sum_{j=1}^n 3c_j+3r)\times 6m}$ and $\boldsymbol{D}_F \in R^{(\sum_{j=1}^n 3c_j+3r)\times \sum_{j=1}^n s_j}$, where s_j shows the number of joints of finger j.

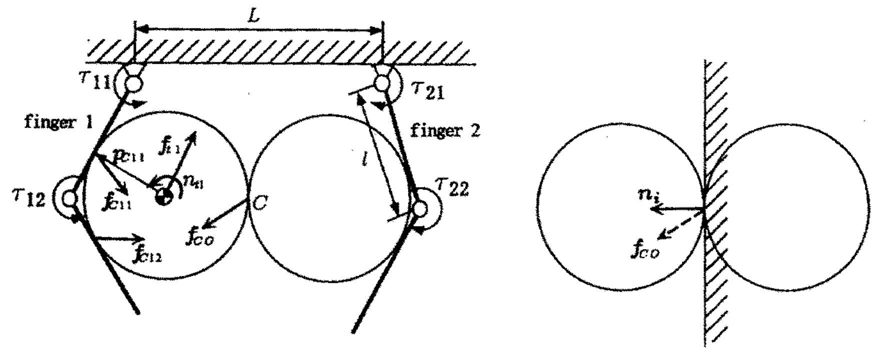
Note that, while the kinematics for a 3D model is discussed so far, for a 2D model, the skew-symmetric matrix equivalent to the vector product $\boldsymbol{a}\times$ is redefined as $(\boldsymbol{a}\times) = [-a_y\ \ a_x]$, and $\boldsymbol{D}_B \in R^{(\sum_{j=1}^n 2c_j+2r)\times 3m}$.

4. A Sufficient Condition for Producing a Relative Motion for Two Objects

Fig. 2 shows the 2D model of the grasp system, where τ_{ij}, $\boldsymbol{f}_{Cik}$, $\boldsymbol{p}_{Cik}$, $\boldsymbol{f}_{ti}$, n_{ti} and $\boldsymbol{f}_{CO}$ denote the torque of the jth joint of the ith finger, the kth contact force of the ith object, the total force and moment of the ith object, and the contact force between two objects, respectively. Let $\boldsymbol{f}_{CB}$ and $\boldsymbol{\tau}$ be the contact force vector from each finger to the object and the joint torque vector, where $\boldsymbol{f}_{CB} = [\boldsymbol{f}_{C11}^T \cdots \boldsymbol{f}_{C22}^T]^T$ and $\boldsymbol{\tau} = [\tau_{11} \cdots \tau_{22}]^T$. We have the following relationship between $\boldsymbol{f}_{CB}$ and $\boldsymbol{\tau}$

$$\boldsymbol{\tau} = \boldsymbol{J}^T\boldsymbol{f}_{CB}, \tag{10}$$

where $\boldsymbol{J}$ is the Jacobian matrix for two fingers. Assuming a friction cone at



(a) (b)

Fig. 2. Model of the Grasp System

each point of contact, we can express the contact force $\boldsymbol{f}_{CB}$ in the following form:

$$\boldsymbol{f}_{CB} = \boldsymbol{V}\boldsymbol{\lambda}, \quad \boldsymbol{\lambda} \geq \mathbf{o}, \tag{11}$$

where

$$\begin{aligned}
\boldsymbol{\lambda} &= [\lambda_{11}^1 \ \lambda_{11}^2 \ \lambda_{12}^1 \ \cdots \ \lambda_{22}^2]^T \in R^{8\times1}, \\
\boldsymbol{V} &= \begin{bmatrix} \boldsymbol{V}_{11} & \mathbf{o} & \cdots & \mathbf{o} \\ \mathbf{o} & \boldsymbol{V}_{12} & \ddots & \vdots \\ \vdots & \ddots & \boldsymbol{V}_{21} & \mathbf{o} \\ \mathbf{o} & \cdots & \mathbf{o} & \boldsymbol{V}_{22} \end{bmatrix}, \\
\boldsymbol{V}_{ij} &= [\boldsymbol{v}_{ij}^1 \ \boldsymbol{v}_{ij}^2] \in R^{2\times2}.
\end{aligned}$$

Substituting eq.(11) into eq.(10) yields

$$\boldsymbol{\tau} = \boldsymbol{J}^T\boldsymbol{V}\boldsymbol{\lambda}. \tag{12}$$

By solving eq.(12) with respect to $\boldsymbol{\lambda}$, we finally obtain

$$\boldsymbol{f}_{CB} = \boldsymbol{V}\left[(\boldsymbol{J}^T\boldsymbol{V})^\sharp\boldsymbol{\tau} + \{\boldsymbol{I} - (\boldsymbol{J}^T\boldsymbol{V})^\sharp\boldsymbol{J}^T\boldsymbol{V}\}\boldsymbol{k}\right], \tag{13}$$

where $(\boldsymbol{J}^T\boldsymbol{V})^\sharp$, $\boldsymbol{I}$ and $\boldsymbol{k}$ denote the pseudo-inverse matrix of $\boldsymbol{J}^T\boldsymbol{V}$, unit matrix, and an arbitrary vector whose dimension is same as $\boldsymbol{\lambda}$.

In order to introduce the contact force $\boldsymbol{f}_{CO}$, we first consider the equation of motion for two objects

$$\boldsymbol{M}_B\ddot{\boldsymbol{p}}_B + \boldsymbol{h}_B = \boldsymbol{D}_{CB}^T\boldsymbol{f}_{CB} + \boldsymbol{D}_O\boldsymbol{f}_{CO}, \tag{14}$$

where $\boldsymbol{M}_B = \mathrm{diag}[m_{B1}\boldsymbol{I} \ H_{B1} \ m_{B2}\boldsymbol{I} \ H_{B2}]$, $\ddot{\boldsymbol{p}}_B = [\ddot{\boldsymbol{p}}_{B1}^T \ \ddot{\phi}_{B1} \ \ddot{\boldsymbol{p}}_{B2}^T \ \ddot{\phi}_{B2}]^T$, $\boldsymbol{h}_B$, m_{Bi}, and H_{Bi} denote the inertia matrix, acceleration vector at the center of object, various forces(such as gravitational force, centrifugal and Colioris force), mass and inertia of the ith object, respectively. $\boldsymbol{D}_{CB}$ and $\boldsymbol{D}_O$ are given by

$$\begin{aligned} \boldsymbol{D}_{CB} &= [\boldsymbol{D}_{B1}^T \ \boldsymbol{D}_{B2}^T]^T, & (15)\\ \boldsymbol{D}_{B1} &= [\boldsymbol{D}_{B11} \ \mathbf{o}], & (16)\\ \boldsymbol{D}_{B2} &= [\mathbf{o} \ \boldsymbol{D}_{B21}], & (17)\\ \boldsymbol{D}_O &= [\boldsymbol{D}_{O11} \ \ -\boldsymbol{D}_{O21}]. & (18) \end{aligned}$$

The constraint condition for keeping contact at point C is expressed by

$$\boldsymbol{D}_O \dot{\boldsymbol{p}}_B = \mathbf{o}. \qquad (19)$$

From both eqs.(14) and (19), we can obtain $\boldsymbol{f}_{CO}$ in the following form:

$$\boldsymbol{f}_{CO} = (\boldsymbol{D}_O \boldsymbol{M}_B^{-1} \boldsymbol{D}_O^T)^{-1}(-\boldsymbol{D}_O \boldsymbol{M}_B^{-1} \boldsymbol{D}_{CB}^T \boldsymbol{f}_{CB} + \boldsymbol{D}_O \boldsymbol{M}_B^{-1} \boldsymbol{h}_B - \dot{\boldsymbol{D}}_O \dot{\boldsymbol{p}}_B). \quad (20)$$

Note that $\boldsymbol{f}_{CO}$ cannot be uniquely determined since $\boldsymbol{f}_{CB}$ includes an arbitrary vector $\boldsymbol{k}$. As a result, $\boldsymbol{f}_{CO}$ spans a contact force space $\mathcal{F}_C$. Now, let us consider the total force $\boldsymbol{f}_{ti}$ summing up all contact forces for the ith object:

$$\begin{aligned} \boldsymbol{f}_{t1} &= \boldsymbol{f}_{C11} + \boldsymbol{f}_{C12} + \boldsymbol{f}_{CO}, & (21)\\ \boldsymbol{f}_{t2} &= \boldsymbol{f}_{C21} + \boldsymbol{f}_{C22} - \boldsymbol{f}_{CO}. & (22) \end{aligned}$$

A sufficient condition for moving the ith object in the direction given by a unit vector $\boldsymbol{a}_i$ is shown by the following condition:

$$\begin{aligned} \boldsymbol{a}_i^T \boldsymbol{f}_{ti} &> 0, & (23)\\ \boldsymbol{n}_i^T \boldsymbol{f}_{ti} &> 0, & (24) \end{aligned}$$

where $\boldsymbol{n}_i$ denotes the unit vector expressing the normal direction of object i at C.

Now, let us consider an example. Two fingers with $l = L = 1.0$[m] initially grasp two cylindrical objects whose diameter and mass is $R = 0.45$[m] and $M = 1.0$[kg], respectively. Consider the problem computing the command torque, so that the object 1 and 2 may move upward and downward, respectively. In order to reduce the number of parameters, we assume the following relationship between τ_{i1} and τ_{i2}.

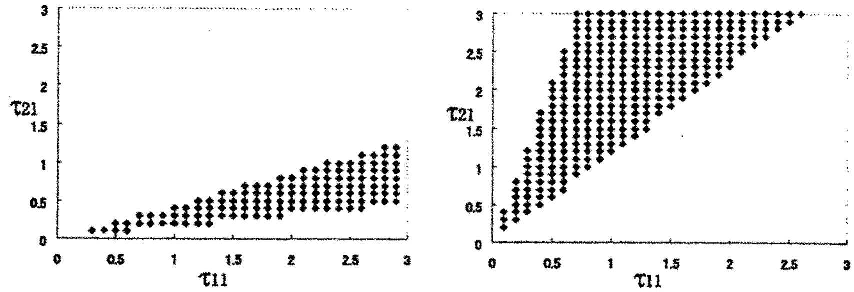
$$\tau_{i2} = k_i \tau_{i1}, \ (i = 1, 2). \qquad (25)$$

Also, we assume the maximum torque of $\tau_{max} = 3.0$[Nm]. Fig. 3 shows the simulation results where (a) $k_1 = 0.9$, $k_2 = 0.1$, and (b) $k_1 = 1.2$, $k_2 = 0.5$, respectively. When choosing the torque commands from the region computed, it is guaranteed that the object 1 and 2 moves upward and downward respectively, although we cannot specify that either rolling or sliding motion may happen.

5. Experiments

5.1. Manipulating Two Cylindrical Objects by Human

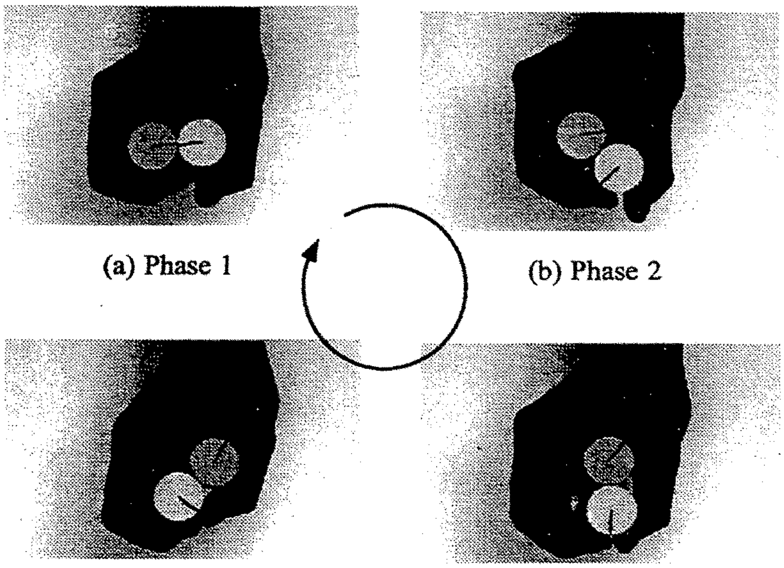
Fig. 4 shows a grasp experiment by human, where Phase 1 through 4 denote a series of continuous photos taken when the line connecting each center of objects



(a) k_1=0. 9, k_2=0. 1 (b) k_1=1. 2, k_2=0. 5

Fig. 3. Computed Torque Set

rotates in every 45[deg]. Human can achieve such a manipulating motion easily and quickly. We would note that, in most phase, a slipping contact is kept between two objects, while rolling is a dominant motion between each object and hand.



(a) Phase 1 (b) Phase 2

(d) Phase 4 (c) Phase 3

Fig. 4. Manipulating Two Cylinders by Human

5.2. Manipulating Two Cylindrical Objects by a Robot Hand

We execute a whole grasping experiment for two objects initially placed on a table, where there is no interaction between the hand and objects. For this experiment, we utilize the Hiroshima-Hand[18], where each finger unit has three rotational joints. Each joint is driven by tendon whose end is fixed at the drive pully connected to the shaft of actuator. Tension Differential type Torque sensor (TDT sensor) is mounted in each joint for joint torque control. Fig.5 shows an experimental result, where each finger first approaches and grasps two objects placed on the table, and starts to manipulate them by changing the torque commands step by step. During manipulation of two objects, we prepared four set of torque commands depending upon the relative position of objects. Each torque command is chosen so that it is enough for producing a slipping motion at the point of contact between objects. We believe that this is the first experiment of the manipulation of multiple objects within the hand.

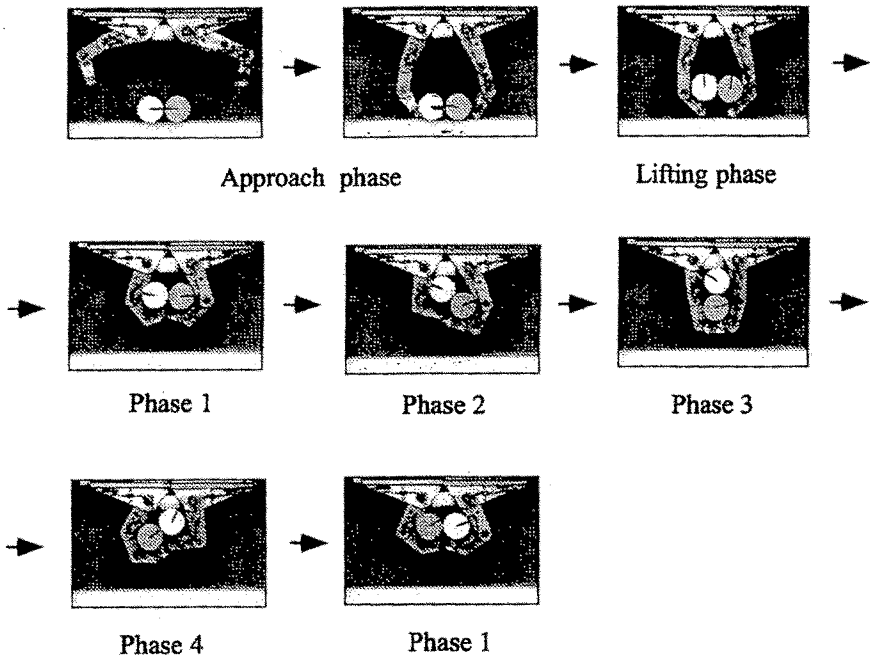


Fig. 5. An Experimental Result

6. Conclusions

In this paper, we discussed the manipulation of multiple objects. We formulated the motion constraint for enveloping multiple objects under rolling contacts. We showed a sufficient condition for changing the relative position of two objects. For two cylindrical objects placed on a table, we succeeded in grasping and manipulating them within a robot hand.

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