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# Picking up a Towel by Cooperation of Functional Finger Actions

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***Abstract*— A grasping and manipulation with a multi-fingered hand is comprised of one or more functional finger actions. We define a functional finger action as a "primitive action," and fingers that are used in separate primitive actions in a grasping and manipulation as "functional finger isolation." Various grasping and manipulations can be realized by assigning different primitive actions to the functional finger isolation form. This paper presents a towel picking task with a multi-fingered hand by assigning different primitive actions to fingers. In this paper, we describe the towel picking task by a series of primitive actions applied to the towel. Experimental results are given, and we also show that the specification of a hand for the towel picking can be derived by analyzing the primitive actions assigned to the fingers. By describing a grasping and manipulation task with primitive actions, it can be used with other type of robot hands.**

## I. INTRODUCTION

A human grasps various objects and dexterously manipulates them by cooperation of his/her fingers. Observation of human grasping brings important knowledge for describing the grasping and manipulation task with a robot hand[1]-[3]. In general, the ability of fingers to move independently is called "finger isolation." Kamakura showed that human can realize various manipulations with his/her hand by assigning some finger movements to a few finger isolation patterns [4]. If the configuration of a robot hand resembles a human hand, such as humanoid hands, the robot hand can achieve various type of grasping and dexterous manipulations by observing human finger movements and reproducing them with robot fingers [5]. So far, various robot hands have been developed which have different numbers of fingers, different degrees of freedom, and different finger configurations. If we describe grasping and manipulations by finger movements, they do not apply to other types of robot hands. In contrast, the functional finger actions constituting a grasping and manipulation can often apply to other types of robot hands. For example, "pinch" is a functional finger action that can be realized with humanoid hands and other types of robot hands. Therefore, we should describe grasping and manipulations by functional finger actions.

Various studies relating to manipulation with a multi-fingered hand have been done in the past[6]-[10]. In the studies, typical motions such as rotating or translating an object are defined as primitives, and complicated tasks are achieved by combining these primitives [7]-[9]. For example, Speeter defined a motion primitive that is a sequence of joint positions changing to execute a special task [7]. Michelman defined a cooperated task of fingers for rotating and translating a grasped object as a primitive task, and demonstrated opening the lid of a childproof medicine bottle with the Utah/MIT Dexterous Hand by combining these primitives [8]. Omata et al. studied motion planning for regrasp primitives [9].

One can observe that some typical motions (primitive motions) are composed by cooperation of several functional finger actions. For example, striking a lighter involves grasping the lighter in the index, middle, ring, and little fingers while flicking the friction switch with the thumb. The two finger actions of "grasping the lighter" and "flicking the friction switch" are independent actions in function. In other words, a lighter is lit by combining two functional finger actions, i.e., "grasping" and "flicking." In another example, using a cell-phone single-handedly involves grasping the phone in the index, middle, ring, and little fingers and pressing keys with the thumb. The operation of using a cell-phone is achieved by cooperation of the "grasping" and "pressing." In these two examples, separate functional finger actions are assigned to the thumb and other fingers, and "lighting a lighter" and "using a cell-phone single-handedly" are done by having the thumb conduct two different functional finger actions. We define such a functional finger action as a "primitive action." Various grasping and manipulations can be realized by assigning different primitive actions to the fingers [11].

As an example of task description by cooperation of the primitive actions, this paper presents a towel picking task which picks up the top towel from a towel stack. One feature of manipulating a deformable object is that the different manipulations are applied to different parts of the same object. The towel picking task is realized by applying different primitive actions to different parts of the towel. Some prior research on handling a fabric has been done. Ono tried to pick up a fabric from layers with a 3-fingered hand [12]. Shibata developed a mechanical system for picking up a messy fabric, unfolding it and placing it on a table [13]. In this paper, we describe the towel picking task by a series of primitive actions applied to the towel. Experimental results are shown, and we also show that the specification of a hand for the towel picking task can be derived by analyzing the primitive actions assigned to the fingers.

## II. PRIMITIVE ACTION

"Finger isolation" means the ability of fingers to move independently [4]. We focus on functional finger actions constituting grasping and manipulations, rather than on individual finger movements. We define a functional finger action as a "primitive action." When a grasping and manipulation

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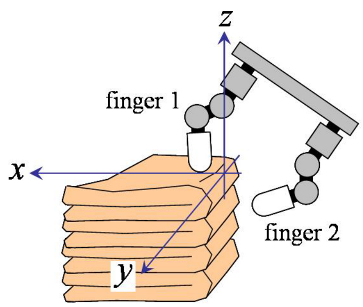



Fig. 1. Picking up a towel from a towel stack.

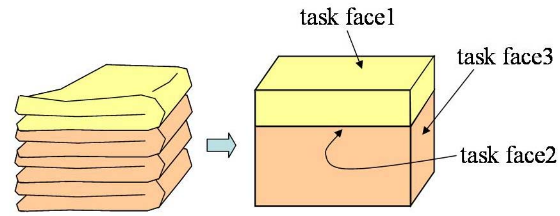



Fig. 2. Model of a towel stack.

consists of two or more primitive actions and fingers are used in separate primitive actions, we term this "functional finger isolation [11]." Michelman partitioned fingers by the finger roles in a task primitive and derived the control law of the fingers [8]. Kang assigned human fingers to virtual fingers according to the finger function in a grasp, and mapped the virtual fingers to robot fingers [14]. They discussed the individual finger function in a primitive action. The "functional finger isolation" shows that the grasping and manipulation can be functionally partitioned into primitive actions. Primitive actions are further classified by the number of fingers involved, e.g. one-fingered, two-fingered, and n-fingered primitive actions. We call a combination form of these primitive actions a "functional finger isolation form." Various grasping and manipulations can be realized by assigning different primitive actions to appropriate functional finger isolation form. A series of tasks with a multi-fingered hand can be executed by changing the functional finger isolation form and primitive actions that are assigned to the functional finger isolation form.

## III. Towel picking task

### A. Object constraint states in picking

There are three types of object constraint states in a picking task:

State A: Target object is constrained by the environment.
State B: Target object is constrained by the environment and the fingers.
State C: Target object is constrained by the fingers.

We can consider a picking task to be a state transition from State A to C. The robot actions in State A and C are mainly achieved by arm motions. The actions in State B are mainly achieved by finger motions, and arm motions are subsidiary. The picking task is characterized by the finger actions in State B. The actions in State A and C are almost identical among various types of pickings. In a simple picking task, the action in State B is only closing the fingers. But in some complex picking tasks such as picking up an object from a stack, the actions in State B involve graspless manipulations [15][16]. Maeda studied motion planning for graspless manipulation while considering the contact state transition between object and environment [16]. While a picking task is a state transition from State A to C, we should consider not only the contact state between the object and the environment, but also the contact state between the object and the fingers.

### B. Task specification of towel picking

The towel picking task is picking up the top towel from a towel stack. The folded towels are stacked as shown in Fig. 1. A robot approaches the towel stack from the back side (right side in Fig. 1), picks up the top towel, and brings it to a destination point. In order to describe the task, a task coordinate system is introduced as shown in Fig, 1. The origin of the task coordinate system is set at the center of the upper right edge of the towel stack. The finger IDs are also set as shown in Fig, 1. The towel picking is described under the following conditions:

- The position in the horizontal direction (y-axis) and orientation of the towel stack are known.
- The position in the depth direction (x-axis) and height of the towel stack are roughly known.
- The task is described by the robot actions in the $x$-$z$ plane.

### C. Description of primitive action

A finger contacts with the face of the towel or side of the towel stack, and applies functional actions to the faces. As shown in Fig 2, a towel stack is modeled as a rectangular parallelepiped, and three task faces are defined to describe the towel picking task. Task faces 1 and 2 are the upper and lower faces of the top towel and task face 3 is the back side of the towel stack. We describe the towel picking task by a series of primitive actions applied to the task faces. The towel picking task can be realized by the following five primitive actions:

Support: The support action is a functional action to support an object with a position-controlled finger. The finger passively generates force according to the force received from the object. The constraint of an object by the environment is considered to be a support action.
Press: The press action is a functional action to press an object with a force-controlled finger. The finger actively exerts force on the object.
Grasp: The grasp action is a functional action to grasp an object.

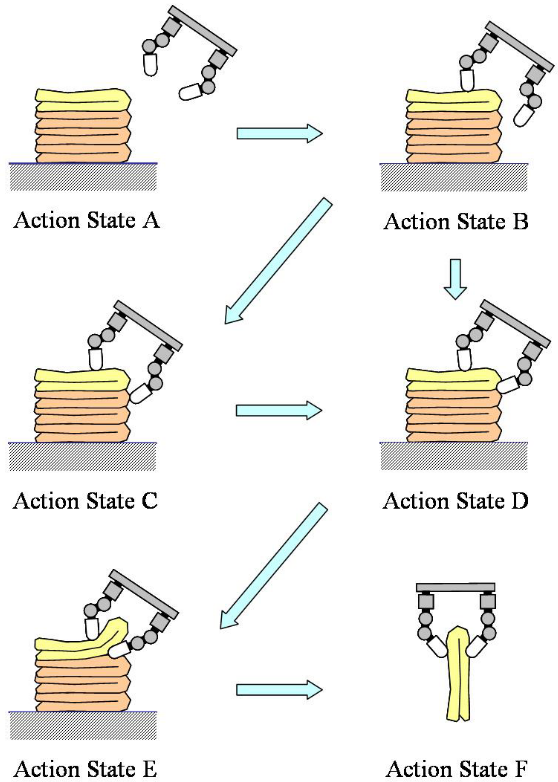


Fig. 3. Action state transition of the towel picking task.

Search: The search action is a functional action to search for a gap between towels by force or tactile sensing.

Insert: The insert action is a functional action to insert a finger between towels.

Here, any objects not the target object are considered to be the environment.

We describe a grasping and manipulation in the towel picking task as:

$$Pn(a)$$

where $P, n, a$ represent the name of primitive action, ID of task face, and actor, respectively. Actor is $a = \{f1, f2, env\}$, where $f1, f2, env$ represent finger 1, finger 2, and the environment, respectively. If a primitive action applies to a number of task faces, all IDs of the task faces are written. If a primitive action is realized with a number of actors, all symbols of the actors are written. For example, if the robot grasps the task face 1 and 2 with fingers 1 and 2, then the primitive action is described as $Grasp12(f1, f2)$. When a grasping and manipulation consists of two or more primitive actions, the primitive actions are separated by a slash, "/".

### *D. Task model of the towel picking task*

The towel picking task is modeled based on functional contact between object-environment, and object-fingers. As shown in Fig. 3, a task model of the towel picking task can be described by action state transitions. Each action state is as follows:

**Action State A (AS. A)**

Towels are stacked on a table. The top towel (the target) is supported by the lower towels. We can consider the top towel to be grasped by the environment. The grasping and manipulation in Action State A can be described as

$$Grasp2(env) \quad \text{or} \quad Support2(env)$$

**Action State B (AS. B)**

Finger 1 presses on the upper face of the top towel. The top towel is held by finger 1 and the environment. The grasping and manipulation in Action State B can be described as

$$Grasp12(f1, env)$$

The action state is only controlled by finger actions. Hence, the grasping and manipulation can also be explicitly described by finger actions as

$$Press1(f1), Support2(env)$$

**Action State C (AS. C)**

Finger 2 searches for the gap between top and lower towels by force or tactile sensing, while finger 1 presses on the upper face of the top towel. Finger 2 strokes on the back side of the towel stack. If the gap is detected by vision, etc, in advance, this action can be skipped. The grasping and manipulation in Action State C can be described as

$$Grasp12(f1, env)/Search3(f2)$$
$$\text{or}$$
$$Press1(f1), Support2(env)/Search3(f2)$$

**Action State D (AS. D)**

Insert finger 2 between top and lower towels, while finger 1 presses on the upper face of the top towel. The grasping and manipulation in Action State D can be described as

$$Grasp12(f1, env)/Insert2(f2)$$
$$\text{or}$$
$$Press1(f1), Support2(env)/Insert2(f2)$$

**Action State E (AS. E)**

The top towel is grasped by finger 1 and finger 2. The top towel is still on the towel stack. The grasping and manipulation in Action State E can be described as

$$Grasp12(f1, f2)/Support2(env)$$

**Action State F (AS. F)**

The top towel is picked up from the towel stack. The grasping and manipulation in Action State F can be described as

$$Grasp12(f1, f2)$$

A subsidiary action for state transition is executed between action states. A touch action which brings the finger into contact with a towel is executed between AS. A-B and B-C. Moving finger 2 to the gap between the top and lower towels on task face 3 is executed between AS. B-D and C-D, moving finger 1 or 2 in the vicinity of the grasp point is executed between AS. D-E, and lifting up the grasped towel is executed between AS. E-F. These state transition actions can be easily derived from the previous or next action states.

Actions in AS. A are actions in the constraint state State A, namely the object is constrained only by the environment. The actions in AS. A are mainly realized by arm motions. In the towel picking task, the following actions are executed in AS. A: 1) the hand approaches the towel stack, 2) pre-shape the hand and arm, and 3) explore the precise position of the towel stack. Actions in AS. B $\sim$ E are actions in constraint state State B, namely the object is constrained by the environment and the fingers. These actions are mainly realized by finger motions. Actions in AS. F are actions in constraint state State C, namely the object is constrained only by the fingers. The actions in AS. F are mainly realized by arm motions. In the towel picking task, the grasped towel is moved to a destination point. The actions in the towel picking task are:

**A. 1:** Move the hand to the starting point
**A. 2:** Pre-shape the hand and arm
**A. 3:** Explore the position of the towel stack
**A. 4:** Touch task face 1 with finger 1
**A. 5:** Press on task face 1 with finger 1
**A. 6:** Touch task face 3 with finger 2
**A. 7:** Search for a gap between the top and lower towels with finger 2
**A. 8:** Move finger 2 to the gap on task face 3
**A. 9:** Insert finger 2 between the top and lower towels
**A. 10:** Move finger 1 or 2 in the vicinity of the grasp point
**A. 11:** Grasp the top towel with fingers 1 and 2
**A. 12:** Lift up the grasped towel
**A. 13:** Move the grasped towel to the destination point

Here, A. 5, 7, 9 and 11 are actions in AS. B, C, D, and E, respectively. A. 4, 6, 8, 10 and 12 are subsidiary actions for state transition. A. 1 $\sim$ A. 3 are actions in AS. A, and A. 13 is a action in AS. F.

### *E. Implementation of actions*

The actions are implemented according to the hardware of the robot and system configuration. We use a Pa-10 (Mitsubishi Heavy Industries, LTD.) robot arm which has seven degrees of freedom, and a four fingered hand (Yasukawa Electric Corporation, LTD.). The fingers are arranged equally in a circle. Each finger has three degrees of freedom, one DOF of adduction/abduction and two DOFs of flexion/extension. A six-axis force torque sensor (NANO-sensor: BL Autotec, LTS.) is attached to each fingertip. Each finger is controlled by an impedance control law. The details of each action are as follows:

**A. 1: Move the hand to the starting point**

This action moves the hand to the starting point of the towel picking task with arm motion.

**A. 2: Pre-shape the hand and arm**

Pre-shape the fingers and arm posture for towel picking.

**A. 3: Explore the position of the towel stack**

The system roughly knows the position in the depth direction (x-axis) and height of the towel stack, but the system doesn't know the precise position of the towel stack. This action searches for the precise position by detecting the contact between the finger and the towel stack. The contact is detected by using the force sensor at the fingertip. The procedure of exploring the towel position is as follows:

1) The hand is moved in the depth direction (+$x$ direction) by arm motion until the finger contacts with the back side of the towel stack.
2) If finger 1 contacts with the towel stack, the arm pulls the hand away, and moves upward a fixed distance.
3) Steps (1) to (3) are repeated until finger 2 contacts with the back side of the towel stack.
4) If finger 2 contacts with the back side of the towel stack, the system sets the contact point between finger 2 and the towel stack as the origin of the x-axis of the task coordinate system.
5) The arm moves the hand to the starting point of the next exploration motion for acquiring the height of the towel stack.
6) Finger 1 moves downward until it contacts with the top of towels.
7) If finger 1 contacts with the top towel, the system sets the contact point as the origin of the z-axis of the task coordinate system.

**A. 4: Touch task face 1 with finger 1**

Finger 1 moves to contact with the upper face (task face 1) of the top towel.

**A. 5: Press on task face 1 with finger 1**

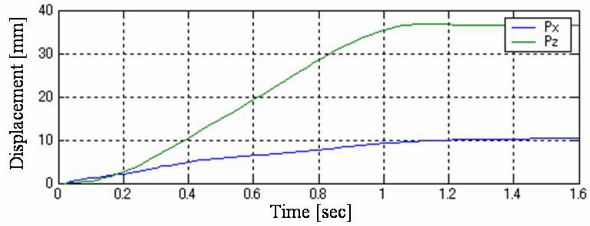
Finger 1 press down on the upper face of the top towel by constant force.

**A. 6: Touch task face 3 with finger 2**

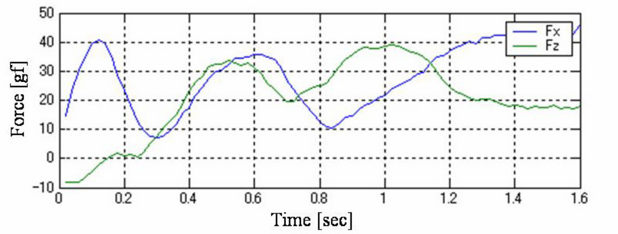
Finger 2 moves to contact with the back side (task face 3) of the towel stack.

**A. 7: Search for a gap between the top and lower towels with finger 2**

This action searches for the gap between the top and lower towels. The back side of the towel stack forms a concavo-convex shape where the gaps between towels are concave. Finger 2 strokes up the back side (task face 3) of the towel stack, while the stiffness parameter of the impedance control in the pushing direction (x-axis) is set to be small, then the contact force appears as a concavo-convex pattern according to the shape of the back side of the towel stack. The gap between towels can be detected by monitoring the contact force pattern. Fig. 4 shows displacement of the finger from the stroke starting point and contact force when the reference force for impedance control is (0.5, 0.0, 0.0)[N], the stiffness parameter is (0.02, 0.2, 0.2)[N/mm], the dumping parameter




(a) Displacement of the finger




(b) Contact force

Fig. 4. Displacement and contact force when a finger strokes the back side of a towel stack.

is (0.05, 0.05, 0.05)[N/(mm/sec)], the mass parameter is (0.002, 0.002, 0.002)[g]. By observing the $x$ component of the contact force, the concavo-convex pattern representing the shape of the back side of the towel stack is found. The last concave is the position of the gap between the top and lower towels.

### A. 8: Move finger 2 to the gap on task face 3

Finger 2 moves to the gap position on task face 3 for the next insert action.

### A. 9: Insert finger 2 between the top and lower towels

This action inserts finger 2 between the top and lower towels. If the finger is merely inserted in the depth direction (+$x$ direction), the finger rolls the towel and the finger may not be inserted into the gap between towels. An up-and-down motion is added to the insertion motion. The direction of the up-and-down motion is the opposite direction of the z component of the contact force. The gap between towels can be widened by adding the up-and-down motion, and the finger can be inserted into the gap robustly.

### A. 10: Move finger 1 or 2 in the vicinity of the grasp point

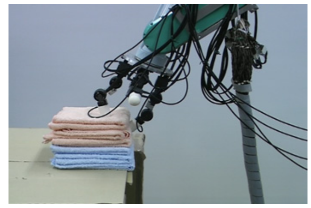
Finger 1 or 2 moves in the vicinity of the grasp point for the next 2-fingered grasp. The grasp point is set so that the distance between the fingertips is minimized.

### A. 11: Grasp the top towel with fingers 1 and 2

This action grasps the top towel with two fingers. The movement of an object grasped with two fingers can be described by the movement of one segment which connects the fingertips. Control of the position and orientation of the grasped object is realized by controlling the midpoint and orientation of the segment. The grasping force is controlled so that the internal forces are equal and opposing along a line connecting the contact points between fingertip and towel.

(a)

(b)

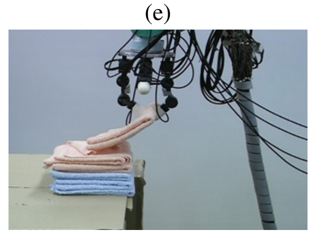


(c)

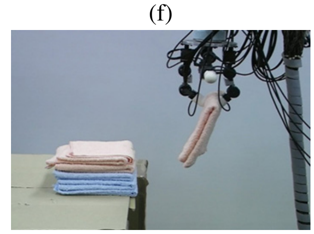
(d)

(e)

(f)



(g)



(h)

Fig. 5. Experimental scene.

### A. 12: Lift up the grasped towel

The robot lifts up the grasped towel.

### A. 13: Move the grasped towel to the destination point

The robot brings the towel to the destination point.

## IV. Experiment

We conducted experiments on towel picking using a four-fingered robot hand. Fig. 5 shows the experimental scene for the towel picking task. Fig. 5 (a) shows the hand approaching the towel stack (A. 3), (b) shows finger 1 pressing the upper face of the top towel (A. 5), (c) shows finger 2 touching the back side of the towel stack (A. 6), (d) shows finger 2 searching for the gap between towels (A. 7), (e) shows finger 2 inserting into the gap between towels (A. 9), (f) shows the fingers grasping the top towel (A. 11), (g) shows the robot lifting up the towel (A. 12), (h) shows the robot bringing the towel to the destination point (A. 13). We experimented over

TABLE I

PRIMITIVE ACTIONS ASSIGNED TO FINGER ISOLATION FORM

| Action State | Finger 1 | Finger 2 |
|---|---|---|
| Action State A | None | None |
| Action State B | $Press1$ | None |
| Action State C | $Press1$ | $Search3$ |
| Action State D | $Press1$ | $Insert2$ |
| Action State E,F | $Grasp12$ | |

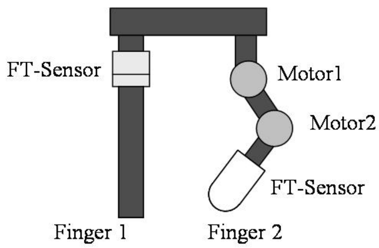



Fig. 6. Specification of a hand for the towel picking task.

twenty times. It takes about one minute and twenty seconds for one experiment. The success rate is greater than 95%.

## V. SPECIFICATION OF A HAND FOR THE TOWEL PICKING TASK

The specification of a hand for the towel picking task can be derived by analyzing the primitive actions assigned to the functional finger isolation form. Table I shows primitive actions assigned to the fingers at each action state. The AS. B $\sim$ D are realized by two one-fingered primitive actions, while AS. E and F are realized by one two-fingered primitive action. Therefore a hand for the towel picking task should have two fingers which can move independently. The primitive actions “Press”, “Search”, and “Insert” need force information, hence each finger should have a force sensor.

We first consider the primitive actions assigned to finger 1. The “Press” and “Grasp” primitive actions are assigned to finger 1. The “Press” action can be realized by arm motion without finger motion. The “Grasp” action can be achieved with a one-way hand where only one of the two fingers can move and the other is fixed to the palm [17]. Finger 1 may therefore be composed of a fixed finger with 0-DOF. Then the state transition action A. 10 is realized by the motion of finger 2.

Next we consider the primitive actions assigned to finger 2. The “Search”, “Insert” and “Grasp” primitive actions are assigned to finger 2. The “Search” and “Insert” actions are realized by 2-DOF motion in a plane, and “Grasp” action also needs 2-DOF motion, if finger 1 is a fixed finger. Hence finger 2 should have 2-DOF in a plane.

Therefore the hand for towel picking can be constructed by two fingers, one finger is a fixed finger having a force sensor, the other has 2-DOF and force sensor as shown in Fig. 6.

## VI. CONCLUSIONS

This paper presented a towel picking task which picks up the top towel from a towel stack. One feature of manipulating a deformable object is that the different manipulations are applied to different parts of the same object. The towel picking task is realized by applying different primitive actions to different parts of the towel. The towel stack is modeled as a rectangular parallelepiped, and three task faces are defined. The towel picking task was described by a series of primitive actions applied to the task faces based on functional contact between object-environment and object-fingers. We showed experimental results and that a specification of a hand for a special task could be derived by analyzing the primitive actions assigned to the fingers. A task described by primitive actions can be used by other types of robot hands.

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