Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

Dynamic Active Catching Using a High-speed Multifingered Hand and a High-speed Vision System

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***Abstract*— A new robotic hand system with high-speed finger motion of 180 [deg] per 0.1 [s] has been developed. With high-speed visual feedback at a rate of 1 [kHz], various dynamic manipulations are achieved. As examples of dynamic manipulation we describe the dynamic active catching tasks for a falling ball and a falling cylinder using a high-speed multifingered hand. We achieved these difficult tasks by utilizing high-speed motion and impact forces actively. Experimental results using active catching strategy based on visual feedback are shown.**

I. Introduction

Historically, in order to achieve a dexterous and skillful artificial hand similar to a human hand, various types of multifingered hands have been developed [1], [2]. Such hands were designed with primary attention to range of motion and accuracy, and less attention to speed of motion. For this reason it is difficult for such a hand to achieve high-speed motion.

Human manipulation consists of not only precise slow motion but also dynamic fast motion [3] in which the nature of contact between a finger and a target changes dynamically. Examples of this dynamic motions are ”pushing”, “hitting”, “throwing”, “catching”, etc. A human takes advantage of such dynamic motions for manipulation. This is one of the reasons that human hand manipulation is more dexterous and flexible than a robotic hand.

Against such a background, we have developed a high-speed multifingered hand system [4], [5], in which not only accuracy and range of motion but also speed of motion is seriously considered. In addition we have developed a hand control system with high-speed vision to achieve dynamic manipulation, and applied it to the task of catching a falling ball.

In this paper we also describe dynamic catching tasks as examples of dynamic manipulation. In this regard, we propose an “active” strategy for catching. The catching strategy in our previous study may be called “passive” in that impact forces between the target and the fingertip are kept as low as possible. However, in order to be effective in various situations, it is important to utilizing the high-speed motion of the hand and impact forces actively. This is because the hand may catch the target in the optimal position by changing the position and the orientation of the target.

We use a falling ball and a falling cylinder as catching targets. The active strategies based on visual feedback and the experimental results are shown.

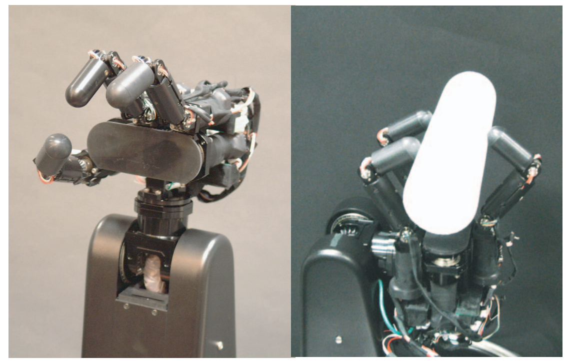

Fig. 1. High-speed multifingered hand

II. Experimental system and control algorithm

In this section, we introduce the experimental system and propose a basic control algorithm for manipulation by high-speed visual feedback.

A. High-speed multifingered hand

Fig.1 shows photos of the high-speed multifingered hand [4], [5]. The hand has eight joints and three fingers. A newly developed small harmonic drive gear and a high-power mini actuator are fitted in each finger link. The design of this actuator is based on the new concept that maximum power output should be improved rather than rated power output. As a result it can generate maximum power only for a short period of time (about 0.1 [s]), but the power output is high. The torque per weight is more than 3.5 times other products. The total weight of the hand module is only 0.8 [kg], but high-speed motion and a high-power grasp are possible. The hand can close its joints at 180 [deg] per 0.1 [s], and fingertips have an output force of about 28 [N].

For instance the Utah/M.I.T. hand also achieved high-speed motion [6], but it is difficult to use it with a robotic arm because of the traditional tendon-controlled mechanism. In that regard our robotic hand is suitable for use with a robotic arm because of the simple transmission mechanism.

B. High-speed vision system

The vision is a massively parallel vision system called CPV (column-parallel high speed vision system) [7]. The CPV has

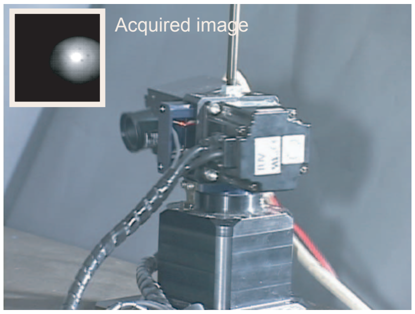

Fig. 2. Active vision (with a CPV head)

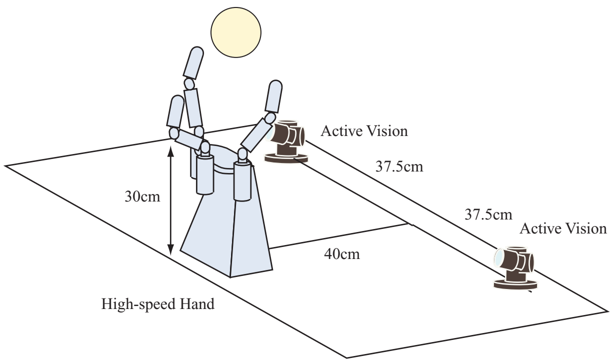

Fig. 3. Experimental system

128×128 photo detectors and an all pixel parallel processing array based on vision chip architecture and an exclusive summation circuit for calculating moment values. Since the visual processing is executed in parallel in the processing array, high-speed visual processing (moment detection, segmentation, and etc.) is achieved, within 1 [ms].

Early image processing in CPV is achieved in order: segmentation of the image, extraction of the target area, and computation of the image moments. Using two active visions equipped with CPV (Fig.2), three-dimensional position of the target and so on is computed. Fig.3 shows the experimental system.

C. Basic control algorithm using visual feedback

The image feature for visual feedback control is defined based on the virtual contact model [8]. To simplify the problem, suppose that the target is a sphere. It regards the noncontact condition as a virtual contact condition supposing that fingers are touching a virtual surface. Using the model, parameters related to contact can be computed in the noncontact phase. The virtual contact point can not be described by a unique definition, and several types of definitions can exist. Here we define it as a point on each finger link.

In Fig. 4 $\boldsymbol{r}_o \in \mathbb{R}^2$ is the target position, and $\boldsymbol{e}_i \in \mathbb{R}^2$ is the unit vector fixed on the i-th link. We define a vector $\boldsymbol{r}_{pi} \in \mathbb{R}^2$ as the virtual contact point on the i-th link according to the following constraints:

$$\boldsymbol{e}_i{}^T \left(\boldsymbol{r}_o - \boldsymbol{r}_{pi}\right) = 0, \quad (i = 1, 2). \tag{1}$$

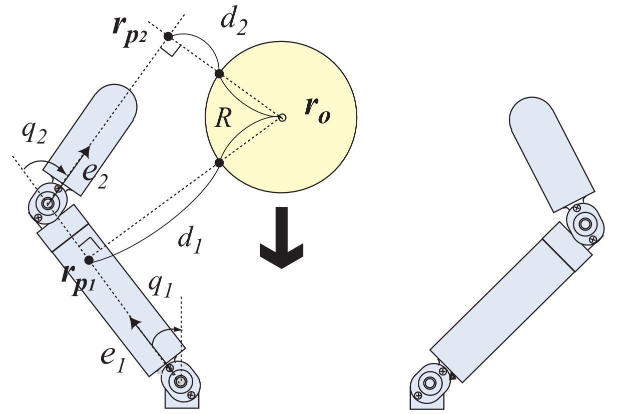

Fig. 4. Control algorithm

Then a scalar $d_i \in \mathbb{R}$ is the distance between the virtual contact point and the target position, which is computed as

$$d_i = ||\boldsymbol{r}_{pi} - \boldsymbol{r}_o|| - R, \quad (i = 1, 2). \tag{2}$$

where $R \in \mathbb{R}$ is the radius of the target.

If $\boldsymbol{q} = [q_1, q_2]^T$ represents joint angle, and $\boldsymbol{r}_o = [r_{ox}, r_{oy}]^T$ represents the target position, the vector of virtual contact distances $\boldsymbol{d} = [d_1, d_2]^T$ is computed as

$$\boldsymbol{d} = \boldsymbol{d}(\boldsymbol{q}, \boldsymbol{r}_o), \tag{3}$$

which is a function of the joint angles and the target position.

Differentiating both sides of (3),

$$\dot{\boldsymbol{d}} = J \dot{\boldsymbol{q}} + G \dot{\boldsymbol{r}}_o, \tag{4}$$

where $J \triangleq \frac{\partial \boldsymbol{d}}{\partial \boldsymbol{q}}$ is a Jacobian of the joint angles, and $G \triangleq \frac{\partial \boldsymbol{d}}{\partial \boldsymbol{r}_o}$ is a Jacobian of the target position.

Transforming (4), we obtain

$$\boldsymbol{q}_d = \boldsymbol{q} + J^{-1} \left(\Delta \boldsymbol{d} - G \Delta \boldsymbol{r}_o\right). \tag{5}$$

Using this equation, command joint angle $\boldsymbol{q}_d$ is computed from the error in the contact distance $\Delta \boldsymbol{d}$. The term $-G \Delta \boldsymbol{r}_o$ is compensation for target motion.

III. Active Catching of a Falling Ball

Catching is one of the most important tasks for dynamic manipulation. In this section dynamic catching of a falling ball using the high-speed multifingered hand and a high-speed vision system is shown.

A. Problem description

Fig.5 shows a simple kinematic model of the task. We suppose that a target and a hand are on a two-dimensional plane and the target is caught with two fingers each of which has each 2 DOF and face each other.

If the target does not always fall at the center of the two fingers but falls in a position shifted from center, it is difficult to catch stably. Therefore, the target should be driven to the stable grasp configuration by using an impact force between the finger and the target. As a result catching is successful.

Such a strategy may be called "active catching". This has several advantages when compared with "passive catching", in which the impact force between the target and the fingertip is kept as low as possible. In the active catching the hand may catch the target, which moves faster than the maximum speed of the fingertips. Furthermore, by changing the position and the orientation of the target, the hand may catch the target in the optimal position. In order to achieve active catching, precise and fast finger motion is needed. In addition, the target or the fingertip should be soft. In this paper we used only a soft rubber ball.

B. Catching strategy

In the two-dimensional plane shown in Fig.5, the dynamic active catching task using collision is analyzed. The problem which we will discuss is how a finger should give the target an impact force to change its movement in the desirable direction. To simplify the problem, suppose that the target is a sphere of radius $R \in \mathbb{R}$ and mass $M \in \mathbb{R}$. The mass of the fingertip is $m \in \mathbb{R}$. Σ_U represents the world coordinate and Σ_C represents the contact plane coordinate.

Using the velocity of the fingertip in Σ_C before collision ${}^C\boldsymbol{v} = [v_x, v_y]^T$ and after collision ${}^C\boldsymbol{v}' = [v'_x, v'_y]^T$, and the velocity of the target before collision ${}^C\boldsymbol{u} = [u_x, u_y]^T$ and after collision ${}^C\boldsymbol{u}' = [u'_x, u'_y]^T$, the law of conservation of momentum and the equation of the rebound coefficient are given as

$$\begin{aligned} \int N dt &= -m(v'_y - v_y) = M(u'_y - u_y), \\ \mu \int N dt &= -m(v'_x - v_x) = M(u'_x - u_x), \\ & -e(v_y - u_y) = v'_y - u'_y, \end{aligned} \tag{6}$$

where $N \in \mathbb{R}$ is the normal force, e is the rebound coefficient and μ is the friction coefficient between the fingertip and the target. Although e and μ depend on the relative velocity of objects by nature, we are assuming they are constant to simplify the problem. In addition we are neglecting the ball rotation for the same reason.

Assuming that finger joints are controlled rigidly so that they are not influenced by the impact force, we can introduce $m \to \infty$ and then we obtain

$$\begin{aligned} {}^C\boldsymbol{v}' &= \begin{bmatrix} v_x \\ v_y \end{bmatrix}, \\ {}^C\boldsymbol{u}' &= \begin{bmatrix} u_x + \mu(1+e)(v_y - u_y) \\ (1+e)v_y - eu_y \end{bmatrix}, \\ \int N dt &= (1+e)M(v_y - u_y). \end{aligned} \tag{7}$$

Thus we can write the argument of ${}^C\boldsymbol{u}'$ as ${}^C\alpha \in \mathbb{R}$, that is,

$$\begin{aligned} {}^C\alpha &= \tan^{-1}\left(\frac{u'_y}{u'_x}\right) \\ &= \tan^{-1}\left\{\frac{(1+e)v_y - eu_y}{u_x + \mu(1+e)(v_y - u_y)}\right\}. \end{aligned} \tag{8}$$

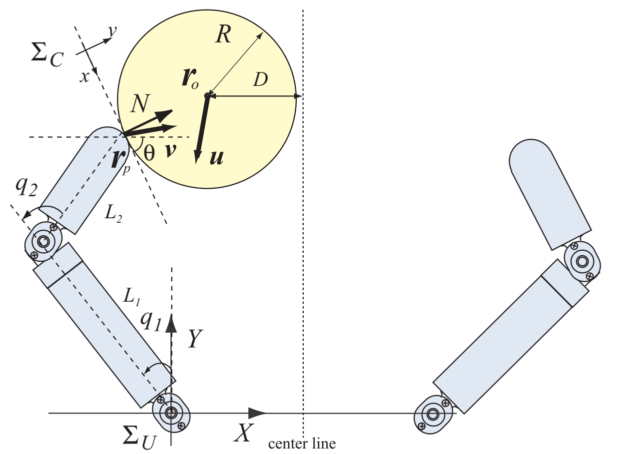

Fig. 5. Dynamic catching task

Namely, the direction of the target velocity is controlled by the fingertip velocity ${}^C\boldsymbol{v}$. Introducing the orientation of Σ_C as $\theta \in \mathbb{R}$, the argument of the velocity in Σ_U as ${}^U\alpha \in \mathbb{R}$ is given as

$${}^U\alpha = -\theta + \tan^{-1}\left\{\frac{(1+e)v_y - eu_y}{u_x + \mu(1+e)(v_y - u_y)}\right\}. \tag{9}$$

Note that θ is determined according to the position of the contact point between the fingertip and the target, that is the relative relation of the target position and the finger posture. In addition, since the fingertip velocity in Σ_C, ${}^C\boldsymbol{v}$, is also determined according to the finger posture, we can finally express ${}^U\alpha$ as a function of target position and finger posture.

To be concrete, using the argument of the vector form the contact point ${}^U\boldsymbol{r}_p = [r_{pX}, r_{pY}]^T$ to the target position ${}^U\boldsymbol{r}_o = [r_{oX}, r_{oY}]^T$, θ is given as

$$\theta = \tan^{-1}\left(\frac{r_{oX} - r_{pX}}{r_{oY} - r_{pY}}\right). \tag{10}$$

Also, the contact point ${}^U\boldsymbol{r}_p$ (equal to the fingertip position) is given as

$${}^U\boldsymbol{r}_p = L_1\begin{bmatrix} \sin q_1 \\ \cos q_1 \end{bmatrix} + L_2\begin{bmatrix} \sin(q_1 + q_2) \\ \cos(q_1 + q_2) \end{bmatrix}, \tag{11}$$

where $L_1 \in \mathbb{R}, L_2 \in \mathbb{R}$ are the length of the links and q_1, q_2 are the joint angle. Differentiating and coordinate transforming, we can obtain ${}^C\boldsymbol{v}$ from ${}^U\boldsymbol{r}_p$. Finally, using the condition $|{}^U\boldsymbol{r}_o - {}^U\boldsymbol{r}_p| = R$, ${}^U\boldsymbol{r}_p$ is given in relation to ${}^U\boldsymbol{r}_o$ and then θ is determined. On the other hand, since the posture of the finger which satisfies θ is given, ${}^C\boldsymbol{v}$ is also given, so we can control the direction of the target velocity according to (9). In addition, to simplify the problem, we assume that the fingertip joint is always controlled at 90 [deg] and the root joint is always controlled at constant velocity depending on the power of the actuator. As a result, ${}^U\alpha$ is written as a nonlinear equation:

$${}^U\alpha = f(q_1, r_{oX}). \tag{12}$$

Conversely, getting r_{oX} by vision and setting a desired target value of ${}^{U}\alpha$ and solving the equation, we can obtain the desired value of q_1 :

$$q_{1d} = f^{-1}({}^{U}\alpha_d), \tag{13}$$

where $q_{1d} \in \mathbb{R}$ is the desired joint angle and ${}^{U}\alpha_d \in \mathbb{R}$ is the desired argument of the target velocity.

Finally using the method described in section II-C, we control the hand to knock the target at the desired joint angle. Although it is desirable to set the desired contact distance by visual feedback, we set it by trial and error this time.

C. Experimental setup

We use a rubber ball whose radius is 3.5 [cm] and mass is 35 [g] as a target, and drop it from about 1 [m] height. The distance between the dropping position and the center of the fingers $D \in \mathbb{R}$ is changed from 2 [cm] to 8 [cm] in intervals of 2 [cm]. ${}^{U}\alpha_d$ is set at zero.

We respectively calculate the relation between ${}^{U}\alpha_d$ and q_{1d} according to the term stated above. The finger is controlled by setting the virtual contact distance between the fingertip and the surface of the target, so that it knocks the target at the joint angle q_{1d} which satisfies ${}^{U}\alpha_d$. Collision occurs only once, and after that the finger is simply controlled to close.

D. Experimental result

Fig.6 shows the calculated relation between ${}^{U}\alpha_d$ and q_{1d}. For example in the case of $D = 4$ [cm], q_{1d} which satisfies ${}^{U}\alpha_d = 0$, is about -37.4 [deg]. In the case of $D = 6$ [cm], q_{1d} which satisfies ${}^{U}\alpha_d = 0$ is about -54.7 [deg].

Actually catching is achieved using these values as ${}^{U}\alpha_d$ and q_{1d}. Fig.7 shows the experimental result in the case of D = 6 [cm] as a continuous sequence of pictures. The falling target is knocked by the right finger, and collides with the left finger, and is finally caught by the both fingers at the center.

IV. Active Catching of a Falling Cylinder

Next we describe the dynamic catching task for a falling cylinder. When the catching target is a cylinder instead of

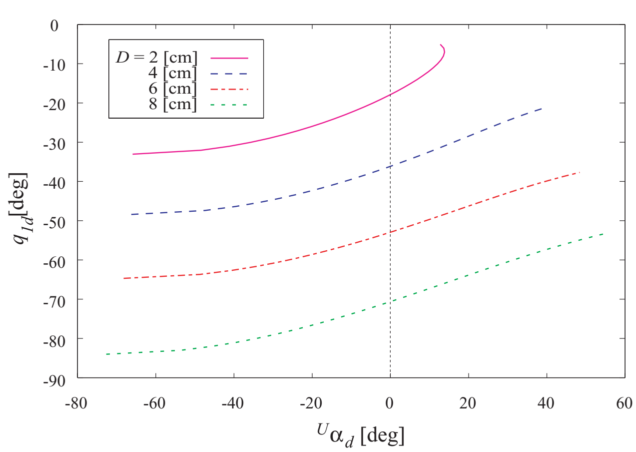

Fig. 6. Relation between ${}^{U}\alpha$ and q_1

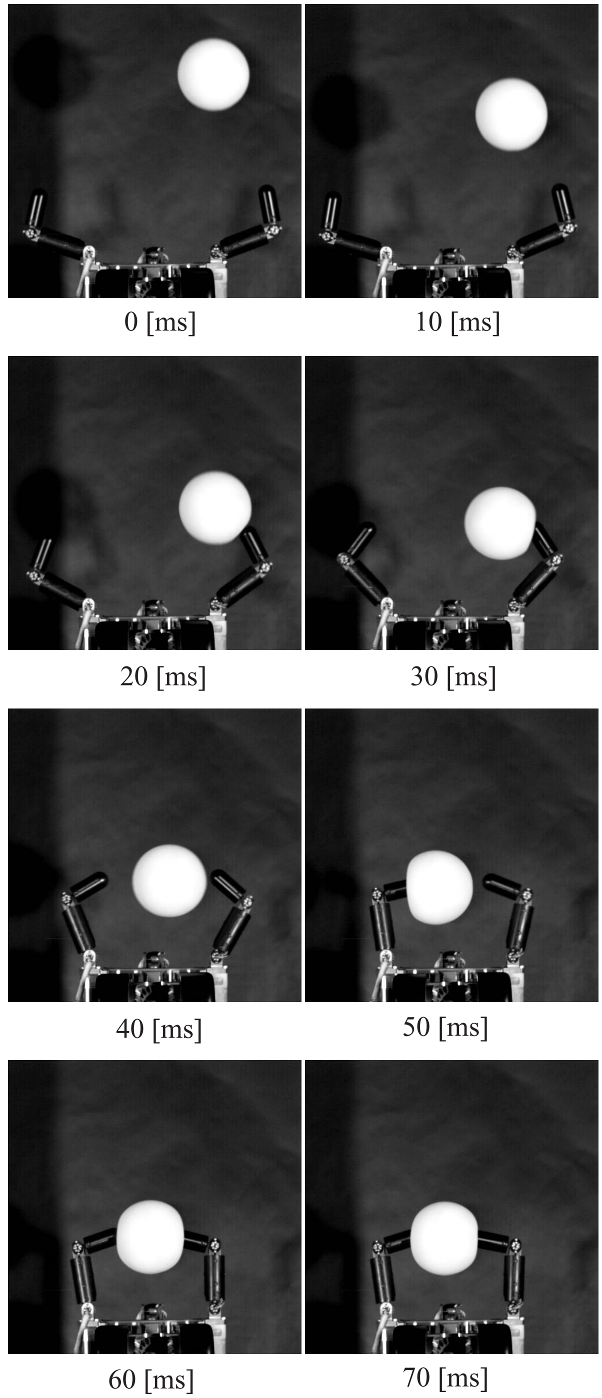

Fig. 7. Experimental result

(Movies: http://www.k2.t.u-tokyo.ac.jp/fusion/DynamicCatching/)

a ball, the stable grasp configuration changes according to its orientation. For this reason a more complicated catching strategy is required.

Here, we assume that the target orientation is computed by the vision system in addition to its three-dimensional position, and we describe an active strategy for catching a falling cylinder using three fingers.

As for the grasping form of the hand, the fingers of both sides are placed to face the middle finger. It is the result of taking the structure of the hand and balance of power into consideration.

Hereafter the catching strategy is divided into two phases : "approaching phase" (the phase until the hand contacts with the falling target) and "grasping phase" (the phase until the hand operates the target orientation in the final grasping form after contact). We describe in order of "grasping phase" to "approaching phase". To simplify the problem, we make three assumptions about the target : 1) The target radius and length are given and mass distribution is uniform, 2) The target is dropped in the orientation with a main axis level to the ground, 3) The target does not rotate during the fall, 4) The barycentric position of the target G corresponds with the center of the hand.

A. Grasping phase

Fig.8 shows a simple kinematic model of the movement in the horizontal plane. Let us consider a strategy for manipulating the target from the initial state where the orientation in the horizontal plane is $\theta \in \mathbb{R}$ [deg] to the end state.

Each finger is designated F1, F2, and F3, and it is assumed that the finger and the target make point contact. First, in order to obtain rotational velocity $\omega \in \mathbb{R}$, impulse force $P_1 \in \mathbb{R}$ is given to the target by F1. However, the target takes on not only rotational velocity but also translational velocity. In order to cancel this, it is necessary to give a impulse force $P2 \in \mathbb{R}$ by F2 from the counter side simultaneously. Then we obtain

$$\begin{aligned} Mv &= P_1 - P_2, \\ I\omega &= a\cos\theta P_1 + b\cos\theta P_2, \end{aligned} \tag{14}$$

where $v \in \mathbb{R}$ is the velocity of G, $M \in \mathbb{R}$ is the mass of the target, $I \in \mathbb{R}$ is the moment of inertia, $a \in \mathbb{R}$ and $b \in \mathbb{R}$ are the distance from G to the contact point of F1 and F2 on the main axis respectively. Next assuming $P_1 \simeq P_2 \equiv P$ and using a geometric condition $a + b = D/\cos\theta + 2R\tan\theta$ ($D \in \mathbb{R}$ is the interval of the fingers, $R \in \mathbb{R}$ is the radius of the cylinder), we can obtain

$$\begin{aligned} v &= 0, \\ \omega &= (D + 2R\sin\theta)P/I. \end{aligned} \tag{15}$$

We take the barycentric position of the target G corresponding with the center of the hand. However, even if not corresponding, the same result as (15) is obtained by calculating similarly. That is, regardless of the barycentric position, if the value of P_1 and P_2 are equal, constant angular velocity ω is obtained. However, since a rotation center is the barycentric position in this case, it is necessary to accommodate the barycentric position of the target with the hand center so that the target rotates on the center of the hand well.

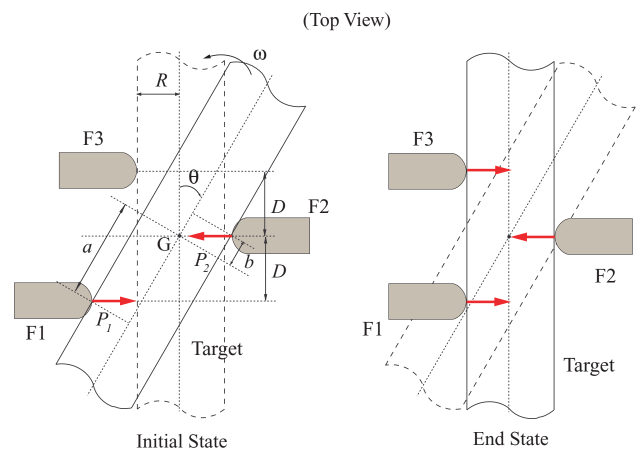

Fig. 8. Grasping phase

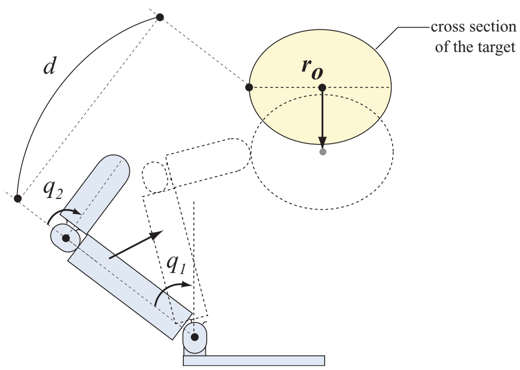

Fig. 9. Approaching phase

B. Approaching phase

Fig.9 shows a simple kinematic model on a two-dimensional plane where a finger moves. We consider such a plane about each finger. The barycentric position and the axis length of the cross section of the target are calculated by the three-dimensional position and orientation. The virtual contact distance d is defined as shown in Fig.9 and only the root joint is controlled based on visual feedback. The fingertip joint is always controlled at 90 [deg].

In this way F1 and F2 virtually simultaneously give impact forces to the target, and it obtains rotation velocity as we mentioned in section IV-A. On the other hand F3 stands ready to catch the rotation. After rotation has stopped, the target is grasped by three fingers.

C. Experimental setup

We used a styrofoam cylinder whose diameter was 5 [cm] and length 20 [cm] as a target, and dropped it from about 1 [m] height. The orientation of the target was kept flat in the vertical plane, and kept at a fixed angle in the horizontal plane throughout the fall. The orientation in the horizontal plane was changed form 0 [deg] to about 50 [deg]. The barycentric position of the target was adjusted to correspond to the center of the hand. The target position and orientation was computed by CPV.

D. Experimental result

We achieved this catching task at various conditions of the target orientation in the horizontal plane from 0 [deg] to 50 [deg]. Fig.10 shows one of the experimental results in the case of $\theta = 50$ [deg] as a continuous sequence of pictures. Each finger is moving properly to manipulate the target according to its orientation, and finally catching is achieved.

V. Conclusion

In this paper, we described the dynamic active catching tasks of a falling ball and a falling cylinder using a robotic hand system. Catching is an example of dynamic manipulation, and it is difficult for a conventional robotic hand system to achieve it. However, we achieved it by using a high-speed multifingered hand and high-speed vision system. Especially we proposed an active catching strategy in which high-speed motion and impact force are actively utilized. In the future this hand system will be mounted on a manipulator, and used for various types of dynamic manipulation.

The need for a robotic hand system that works in the real world is growing. Such a system should be able to adapt to changes of environment. Further development of a high-speed hand system with real time visual feedback is an important area for robot reserah [9]–[12].

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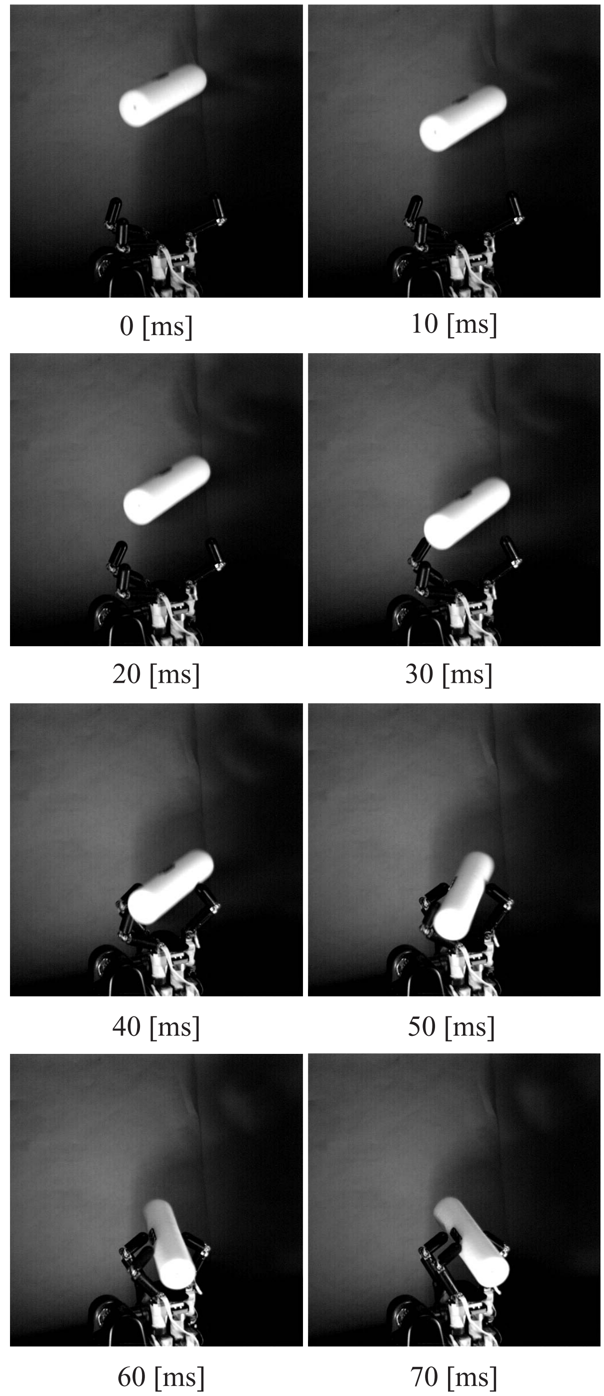

Fig. 10. Experimental result

(Movies: http://www.k2.t.u-tokyo.ac.jp/fusion/DynamicCatching/)