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High-Speed Batting Using a Multi-Jointed Manipulator

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Abstract— **In this paper a robotic batting algorithm using a high-speed arm and high-speed stereo vision is proposed. With this strategy, the desired trajectory of the manipulator is generated so that both high-speed swing motion and tracking motion combine to meet the ball squarely with the bat. As a result the manipulator can follow the ball while swinging the bat at high speed even if it is difficult to predict the trajectory of a ball. Experimental results are shown in which a high-speed manipulator hits a ball thrown by a human.**

I. Introduction

Human beings can instantly execute motion control with excellent judgment. Most artificial robots currently are less flexible and have less sophisticated ability than human beings. In order to produce a robot as flexible as a human, however, it is not necessary to apply human processing architecture including mechanisms, materials, or computing architecture to an artificial robot. For example, in human processing an efference of copy (feedforward signal) compensates for the delay in visual processing. On the other hand in robots visual feedback is more important than feedforward, because visual processing in robots can be much faster than in humans.

Our group has developed massively-parallel digital vision chip systems with a sampling rate higher than 1 kHz [1],[2]. This technique was applied to a sensory-motor fusion system to produce high-speed grasping and manipulation [2],[3], catching [4]. This shows that the speed of robotic visual recognition will soon become higher than that of a human. In such a situation visual feedback becomes more important than the predictor, and the robotic system will be able to act in non-predictable conditions.

Based on this work in this paper we propose a baseball batting algorithm using high-speed visual feedback. In the algorithm, in order to achieve both rapidity of swing and accuracy of hitting, a hybrid trajectory generator of both visual information and the time variable function is proposed. In addition, the generated trajectory is modified by visual feedback in realtime. The experimental result using a 4-axis high-speed manipulator is shown.

II. Related Works

Sports provide examples of situations where fast motion is needed. Human beings have excellent ability to process visual information and athletic skills at sports, and these skills are useful to achieve trajectory planning and motion control for a robot which moves at high speed.

There have been several studies in which a robot tried to acquire a sport skill. Zheng et al. proposed a batting algorithm [5]. In this algorithm a two-dimensional model is geometrized. Moreover, it was verified only by computer simulation. Therefore, it is difficult to adapt the algorithm to a real robot without modification. Miyamoto et al. proposed a tennis algorithm [6], in which a trajectory generator is acquired based on neural network learning. In this method, feedforward control is emphasized rather than feedback control. For this reason, the robot cannot respond to movement of the target if learning is not accomplished. There are several robotic ping-pong machines [7],[8]. In their work the prediction of the target trajectory is focused on. In some cases the robot may not follow the target if errors in the target trajectory occur. Ming et al. proposed a golf swing algorithm [9], in which a high-speed swing is achieved. In the golf task, however, the motion of the target is static until contact. This method cannot be applied to a task requiring dynamic constraint with respect to the motion of the target. In addition, there is little previous work where a task is achieved with a general-purpose manipulator.

Thus we focused on visual feedback in particular and experimented on robotic batting with a manipulator. As a result, the utility of high-speed visual feedback was confirmed.

III. System Configuration

This section describes components and performance of the whole system. The experimental system is shown in Fig.1.

The processing system consists of sixteen DSPs (TMS320

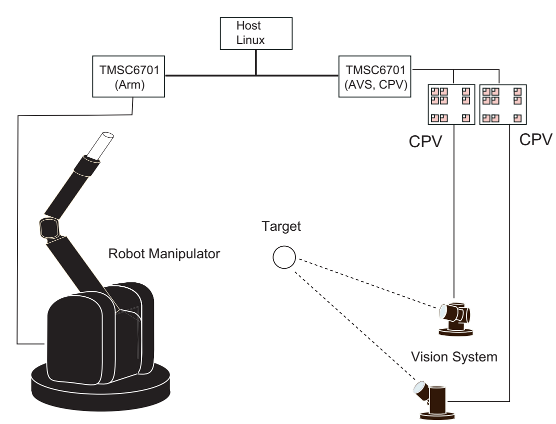
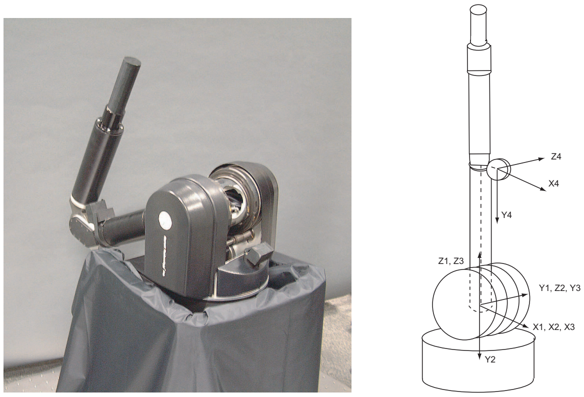


Fig. 1. System configuration



(a) Picture of a manipulator (b) Manipulator Kinematics

Fig. 2. Manipulator

C6701:Texas Instruments Inc.), whose structure is hierarchically parallel. Each DSP has the ability to calculate general-purpose floating-point arithmetic at 1 GHz. This is the main component necessary to achieve high-speed sensor information processing with a cycle time of 1 ms. In addition, as many as possible I/Os are dispersed to plural DSPs in order to decrease the I/O bottleneck.

The vision system consists of the 2-DOF (tilt and pan) active vision which is a column parallel vision system (CPV) [1]. Inside the CPV system, there are two modules composed of a PD (photo detector) array and a PE (processing element) array. The resolution of the PD array is 128×128 pixel with 8-bits gray scale, and the output image data is transmitted to the PE array in 128 lines column parallel. Since the CPV system is able to deal with image processing in parallel, various visual processing such as the segmentation or moment detection can be executed with a cycle time more than 1 kHz. The actuator is composed of a DD (direct-drive) motor, and is sufficient to follow a fast moving target. Three dimensional visual information is calculated by means of stereovision with two active visions.

The kinetic system consists of a wire-drive manipulator (Barrett Technology Inc.). A picture of the manipulator is shown in Fig.2(a), and the kinematics of the arm is shown in Fig.2(b). The manipulator has 4-DOF consisting of revolution and bending motion at shoulder joint and elbow joint. The inertia of the end-effector is low because all actuators, which have high power and low reduction ratio, are placed on the pedestal. Therefore, high-speed movement with maximum velocity of the end-effector of 6 m/s and maximum acceleration of 58 m/s^2 is achieved. Since the velocity of a human arm (elbow) is 6∼10 m/s, motion of the manipulator is as fast and flexible as human motion.

IV. Batting Motion

A. Batting Strategy

Fig.3 shows a batting task. It is important to meet the ball squarely with the bat and to impart a high-speed to the ball. To swing a bat at high speed requires rapidity and to hit a ball solidly requires accuracy, and there is a tradeoff between rapidity and accuracy. To achieve both rapidity and accuracy the trajectory of the manipulator plays an important role.

Since visual processing and movement of the manipulator typically have been slow, in order to compensate for the delay, prediction of the target trajectory has been used [10],[11]. This prediction method means that the desired trajectory is represented by a function of time t,

$$\boldsymbol{q} = \boldsymbol{f}(t) \ . \tag{1}$$

Human beings use high level prediction because the throughput of human visual processing is low. In this method, however, the task may not be achieved if the target trajectory is difficult to predict.

On the other hand, recently the trajectory of the manipulator has been generated by sensor information $\boldsymbol{\xi}$ directly, in which the time variable is not used explicitly [4],[12],[13]. This method means that the desired trajectory is represented as

$$\boldsymbol{q} = \boldsymbol{f}(\boldsymbol{\xi}) \ . \tag{2}$$

The position, the velocity, and the like are mentioned as examples of $\boldsymbol{\xi}$. In several studies the task has been achieved by mapping the end-effector position to the target position $\boldsymbol{r}_o$ one by one. This approach has the advantage that it is easy to express the robotic trajectory, but high-speed visual processing and high-speed movement of the arm are required.

If there is only one condition that a ball is hit at the core of the bat precisely, the desired trajectory is sufficiently represented by a function of the target position $\boldsymbol{r}_o$. However, in order to swing the bat at high speed regardless of the velocity of the ball, it is difficult to express the desired trajectory by Eq.(2). Thus we define the desired trajectory of the arm as

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

to pursue not only accuracy, but also rapidity of robotic motion, and suggest that the algorithm for the batting task be divided into swinging a bat at high speed and hitting a ball solidly.

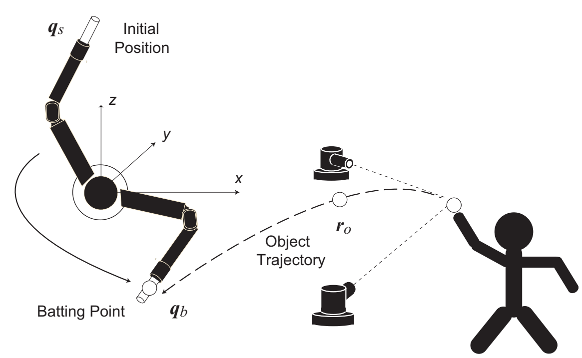


Fig. 3. Batting task

B. Batting Algorithm

To simplify the problem, suppose that the bat is fixed to the robotic arm. That is, it is equivalent to hitting a ball at the head of the arm.

Three dimensional position of the ball $\boldsymbol{r}_o \in \mathbb{R}^3$ is recognized by vision, and the vector of desired joint angles $\boldsymbol{q}_d \in \mathbb{R}^4$ is calculated by Eq.(3). The vector of joint angles $\boldsymbol{q} \in \mathbb{R}^4$ is controlled to track $\boldsymbol{q}_d$ using an appropriate controller. Fig.4 shows the block diagram. After this, we assume $\boldsymbol{q} = \boldsymbol{q}_d$ and describe how to decide the function $\boldsymbol{f}$.

Upper arm vector and front arm vector are represented as $\boldsymbol{r}_u \in \mathbb{R}^3, \boldsymbol{r}_f \in \mathbb{R}^3$ respectively. Here $L_u = \|\boldsymbol{r}_u\|$ is the upper arm length, and $L_f = \|\boldsymbol{r}_f\|$ is the length from the elbow to the core of the bat. In the batting task, the desired condition is that the bat collides with the ball at the desired batting point $\boldsymbol{r}_b \in \mathbb{R}^3$ at a certain time $t = t_b$, and is represented as

$$\boldsymbol{r}_u + \boldsymbol{r}_f = \boldsymbol{r}_b \ , \tag{4}$$

where t_b is the time of hitting. Moreover, the condition at the time of hitting is set up such that the direction where the ball is thrown (x direction) is perpendicular to the front arm vector, and expressed as the following formula:

$$\boldsymbol{r}_f \cdot \boldsymbol{e}_x = 0 \ , \tag{5}$$

where $\boldsymbol{e}_x \in \mathbb{R}^3$ represents the x-axis unit vector. That is, the bat collides with the ball on the following plane

$$x = \boldsymbol{r}_b \cdot \boldsymbol{e}_x \ . \tag{6}$$

From Eq.(5), the space S where the core of the bat at the time of hitting can exist is computed as

$$C = \{\boldsymbol{r} \mid \|\boldsymbol{r}\| = L_f \ , \ x = 0\} \tag{7}$$

$$S = \{\boldsymbol{r} \mid \|\boldsymbol{r} - \boldsymbol{r}'\| = L_u \ , \ \boldsymbol{r}' \in C\} \ , \tag{8}$$

where C is the circle, centered at the origin, with radius L_f on the plane $x = 0$ and S is the space occupied by spherical surfaces with radius L_u, centered around the periphery of the circle C. Afterwards, we decided to call this space "Batting space." It is possible to hit the ball at any position where the ball trajectory intersects the batting space; however, only one batting point $\boldsymbol{r}_b$ must be selected from this intersection. Fig.5 shows the positional relationship of batting space and batting point.

1) swing motion: In fact, the ball speed cannot be ignored in comparison to the speed of the arm; therefore, the bat must start to swing before the ball arrives at the batting point. Suppose that the batting point $\boldsymbol{r}_b$ is decided by the intersection

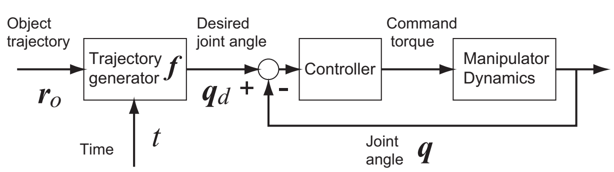


Fig. 4. Block diagram

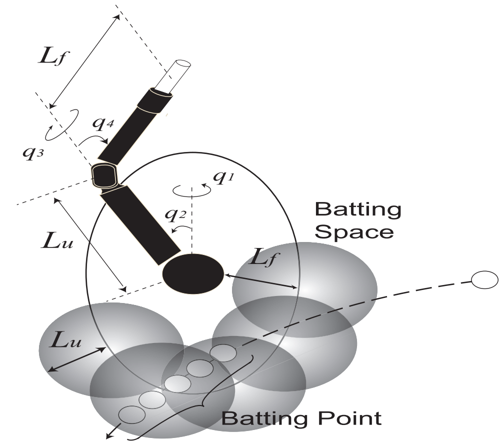


Fig. 5. Batting space and batting point

between the simple predicted trajectory of the ball and batting space, and the constraint

$$g(\boldsymbol{q}, \boldsymbol{r}_b) = 0 \ . \tag{9}$$

The function g might be any function as long as one batting point is decided by some condition with respect to joint angles of the arm, batting point and all from the above-mentioned intersection.

If the batting point is decided, the vector of joint angles at the time of hitting $\boldsymbol{q}_b \in \mathbb{R}^4$ is uniquely computed by Eqs.(4) and (5). Moreover, the predicted time when the ball reaches the batting point at $t = t_p$ is decided by batting point and predicted trajectory. Then, the manipulator begins to swing the bat if $t_p \le t_b$, otherwise calculation of $\boldsymbol{r}_o, \boldsymbol{r}_b, \boldsymbol{q}_b$ is repeated until $t_p \le t_b$ is satisfied.

The desired trajectory of the manipulator is expressed by a fifth order polynomial so as to continuously control the position, velocity, and acceleration of the bat:

$$\boldsymbol{q}(t) = \sum_{i=0}^{5} \ \boldsymbol{k}_i \, t^i \ , \tag{10}$$

where $\boldsymbol{k}_i \in \mathbb{R}^4$ is the coefficient vector satisfying the following conditions. Suppose that the starting time of the swing is at $t = 0$ and boundary conditions are written as

$$\boldsymbol{q}(0) = \boldsymbol{q}_s \quad , \quad \boldsymbol{q}(t_b) = \boldsymbol{q}_b \ , \tag{11}$$

where $\boldsymbol{q}_s \in \mathbb{R}^4$ is the vector of initial joint angles.

2) hitting by visual feedback: The batting point $\boldsymbol{r}_b$ is updated by visual feedback from the moment the manipulator begins to swing till the time of hitting. Therefore, the batting task is completed in spite of some prediction errors.

Since the inertia of the front arm is lower than the upper arm, it is easy to modify the trajectory of the front arm during the swing. For this reason, only the desired trajectory of the elbow joint can be modified. The new batting point $\boldsymbol{r}_{b'} \in \mathbb{R}^3$ is defined as the cross point between the modified predicted trajectory of the ball and the plane expressed by Eq.(6). The trajectory of the manipulator is modified so that it will pass through this point. That is, $\boldsymbol{k}_i$ is modified so as to satisfy $\boldsymbol{q}(t_b) = \boldsymbol{q}_{b'}$, where $\boldsymbol{q}_{b'} \in \mathbb{R}^4$ is the vector of joint angles corresponding to $\boldsymbol{r}_{b'}$. As a result, it is represented as

$$\boldsymbol{k}_i = \begin{cases} \boldsymbol{k}_i(\boldsymbol{r}_{b'}) & \text{elbow-joint} \\ constant & \text{shoulder-joint} \end{cases}, \tag{12}$$

and $\boldsymbol{q}$ is written as

$$\boldsymbol{q} = \begin{cases} \boldsymbol{f}(\boldsymbol{r}_{b'}, t) & \text{elbow-joint} \\ \boldsymbol{f}(t) & \text{shoulder-joint} \end{cases}. \tag{13}$$

Since the desired angles of only the elbow joint are modified so that Eq.(5) may be satisfied, the ball is not precisely hit at the core of the bat in case $\boldsymbol{r}_b \neq \boldsymbol{r}_{b'}$. Thus suppose that the distance within $\pm\delta$ from the core of the bat is within the permissible level, the manipulator can hit the ball in case $\boldsymbol{r}_{b'} \in W$:

$$W = \{\boldsymbol{r} | \ -\delta \leq \|\boldsymbol{r} - \boldsymbol{r}_u\| - L_f \leq \delta, \ x = \boldsymbol{r}_b \cdot \boldsymbol{e}_x\} \ , \tag{14}$$

where W is the space surrounded by each circle with radius $L_f \pm \delta$ centered on the position of the elbow joint at the time of hitting on the plane expressed by Eq.(6).

Fig.6 shows the modified batting point and space W. From Eq.(13), it turns out that the motion of the shoulder joint contributes to swinging the bat at high speed and the motion of the elbow joint contributes to tracking, by visual feedback, so as to meet the ball with the bat.

The desired trajectory after hitting is generated by a fifth order polynomial, the same as the one before hitting so that the manipulator can stop smoothly, and it satisfies

$$\boldsymbol{q}(t_e) = \boldsymbol{q}_e \ , \tag{15}$$

where t_e represents the time just as the arm stops and $\boldsymbol{q}_e \in \mathbb{R}^4$ is the vector of terminal joint angles. In Fig.7 the flow chart of the batting algorithm is shown.

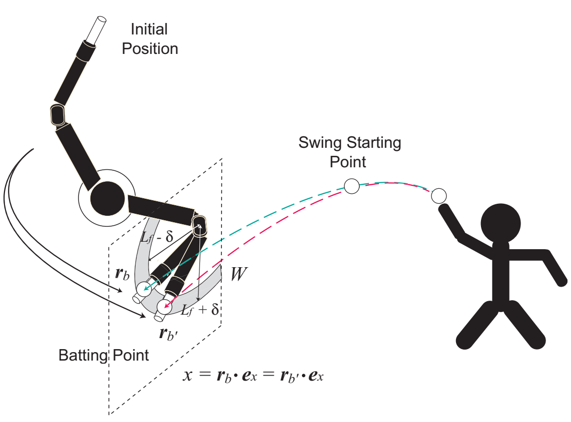


Fig. 6. Modified batting point

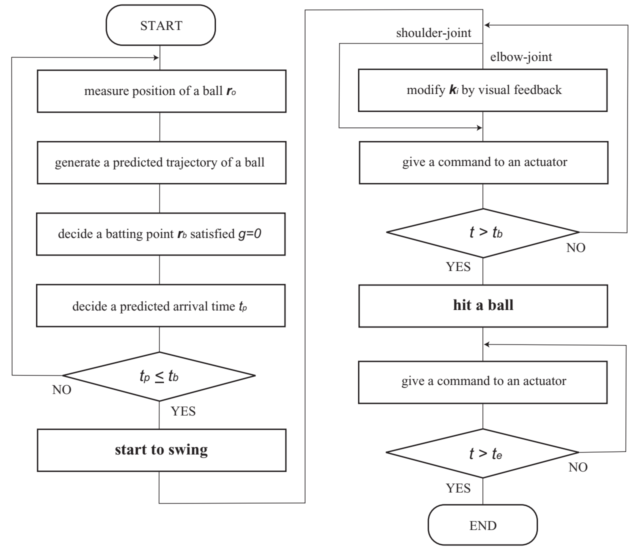


Fig. 7. Flow chart of a batting algorithm

V. Experiment

A. Experimental Setting

A human threw a styrofoam ball with radius 4.5 cm towards the manipulator from about 2.5 m away. It takes about 0.3∼0.4 s for the ball to reach the batting point from the moment the vision system finds the ball. The velocity of the ball is about 6∼8 m/s, and the velocity of the bat is about 5 m/s. The experimental configuration is shown in Fig.8.

In this experiment, the predicted trajectory was generated by fitting a function using successive least-squares estimations. Its function is approximated with a first order polynomial in x and y direction, and second order polynomial in z direction. In addition, we set the constraint $g = q_2 - q_{s2}$. This means that the second joint is fixed during the swing. The cycle time of visual and control processing is set at 1 ms. As for other parameters, we set the length of upper arm vector as $L_u = 0.55$ m, the length of front arm vector as $L_f = 0.55$ m, initial joint angles as $\boldsymbol{q}_s = (-\frac{\pi}{2}, \frac{\pi}{5}, -\frac{3\pi}{4}, \frac{7\pi}{12})$, terminal joints angles as $\boldsymbol{q}_e = (\frac{\pi}{2}, \frac{\pi}{5}, \frac{\pi}{6}, \frac{\pi}{12})$, permissible level as $\delta = 5$ cm, the time until hitting as $t_b = 0.23$ s, and the whole swing time as $t_e = 0.83$ s.

B. Experimental Result

Fig.9 shows the positional relationship of the batting point $\boldsymbol{r}_b$, final modified batting point $\boldsymbol{r}_{b'}$, and space W on the plane expressed by Eq.(6). Because $\boldsymbol{r}_{b'} \in W$, it is possible to hit the ball.

The time response of the joint angles is shown in Fig.10. At elbow joint (3rd, 4th-joint), it turns out that the desired trajectory based on $\boldsymbol{r}_b$ is modified to the one based on $\boldsymbol{r}_{b'}$ by high-speed visual feedback and the observed trajectory of the arm follows it.

Fig.11 shows the motion of the arm and the ball from various angles. The ball is hit squarely on the batting point by means of the modification using visual feedback. Moreover, in

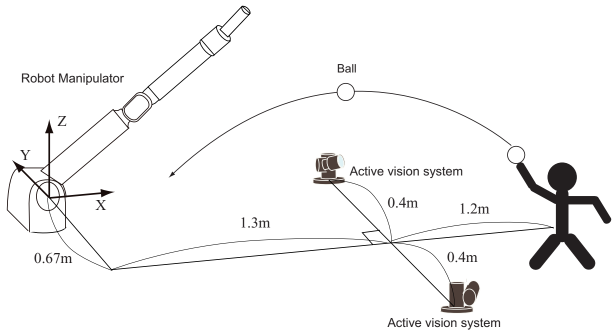


Fig. 8. Experimental configuration

Fig.12 the batting motion is shown as a continuous sequence of pictures taken at intervals of 20 ms.

The trajectory of the arm can be modified even after the manipulator begins to swing, and the swing time can be shortened using the rapidity property of the arm. The latter means that the distance between the ball position at the starting time of the swing and the batting point can be shortened. So, the time to recognize the ball till the beginning of the swing can be lengthened. In addition, many samples of the target position can be observed at a high sampling rate. Therefore, errors in the predicted trajectory can be reduced dramatically.

In summary, at first a simple prediction generates a rough batting point and timing when the swing is to be started. Next high-speed swing motion and tracking motion to hit the ball are executed in the shoulder joint and elbow joint respectively. As a result, the manipulator can hit the ball near the core of the bat using high-speed visual feedback. In this experiment, the batting task was achieved under the severe condition that the manipulator must immediately start to swing 0.1 s after the vision sensor recognized the ball.

The success rate was about 90 %. This experimental result is shown as a movie on the web site [14].

VI. Conclusion

In this paper we proposed a batting algorithm using a high-speed system. The effectiveness was verified by experiments. Our future work will concentrate on trajectory planning considering the dynamics of the arm, control of the ball right after

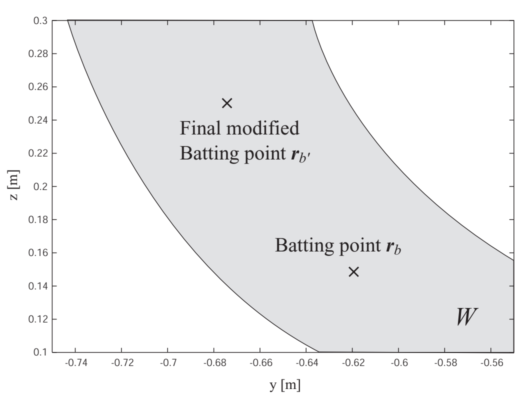
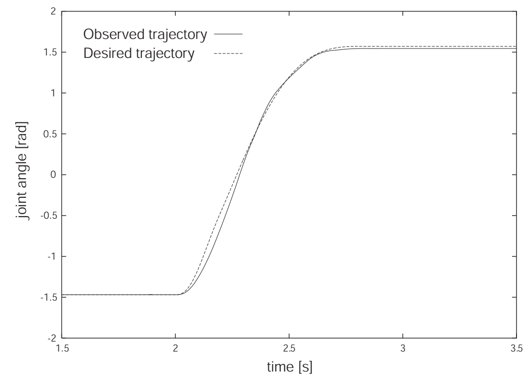
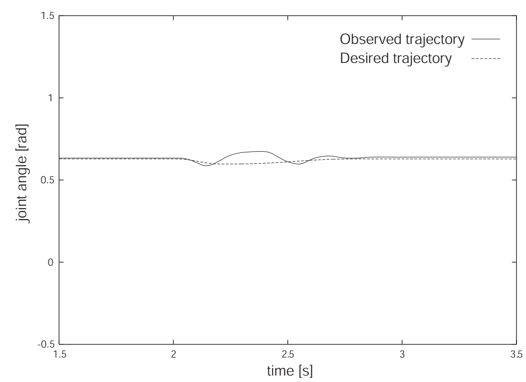


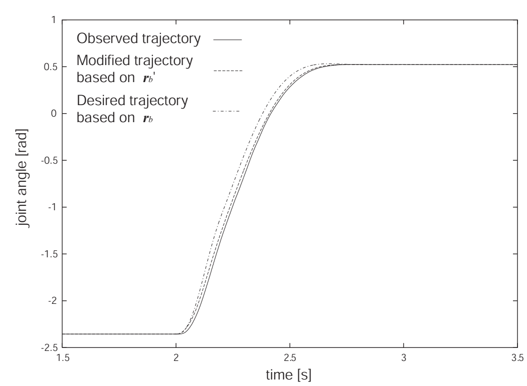
Fig. 9. Positional relationship of $\boldsymbol{r}_b$, $\boldsymbol{r}_{b'}$, W



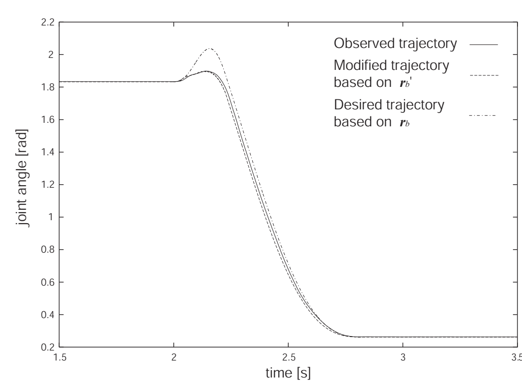
(a) joint 1



(b) joint 2

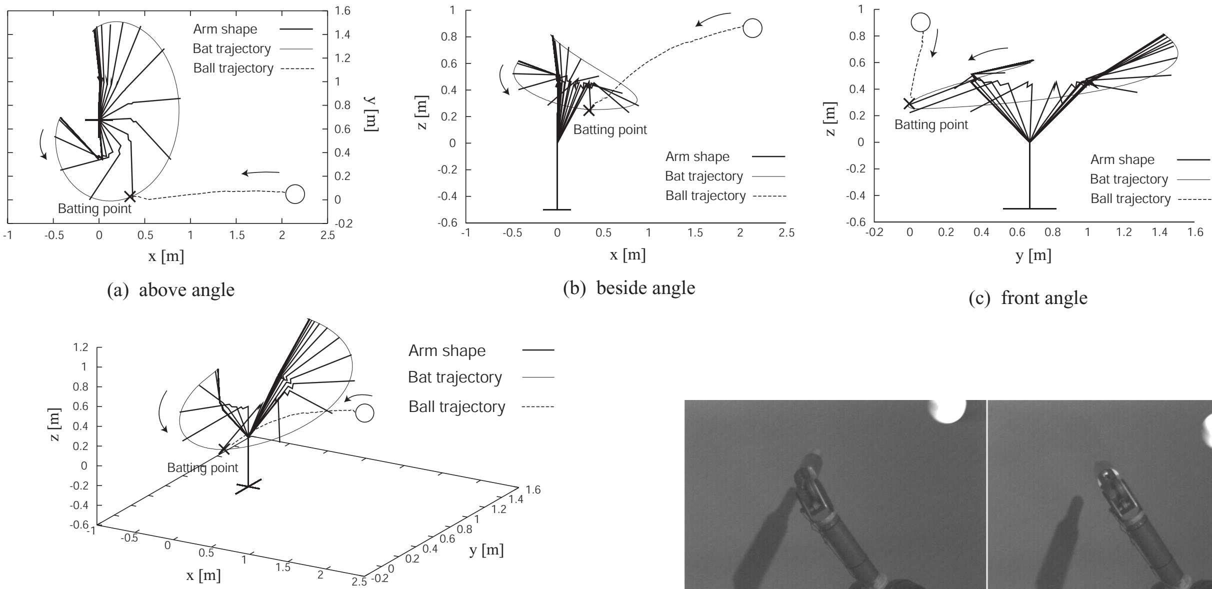


(c) joint 3



(d) joint 4

Fig. 10. Time response of joint angles



(a) above angle

(b) beside angle

(c) front angle

(d) 3-dimensional angle

Fig. 11. Batting motion

hitting, experiments using a robotic hand fixed to the arm, and applications to other tasks requiring high-speed manipulation.

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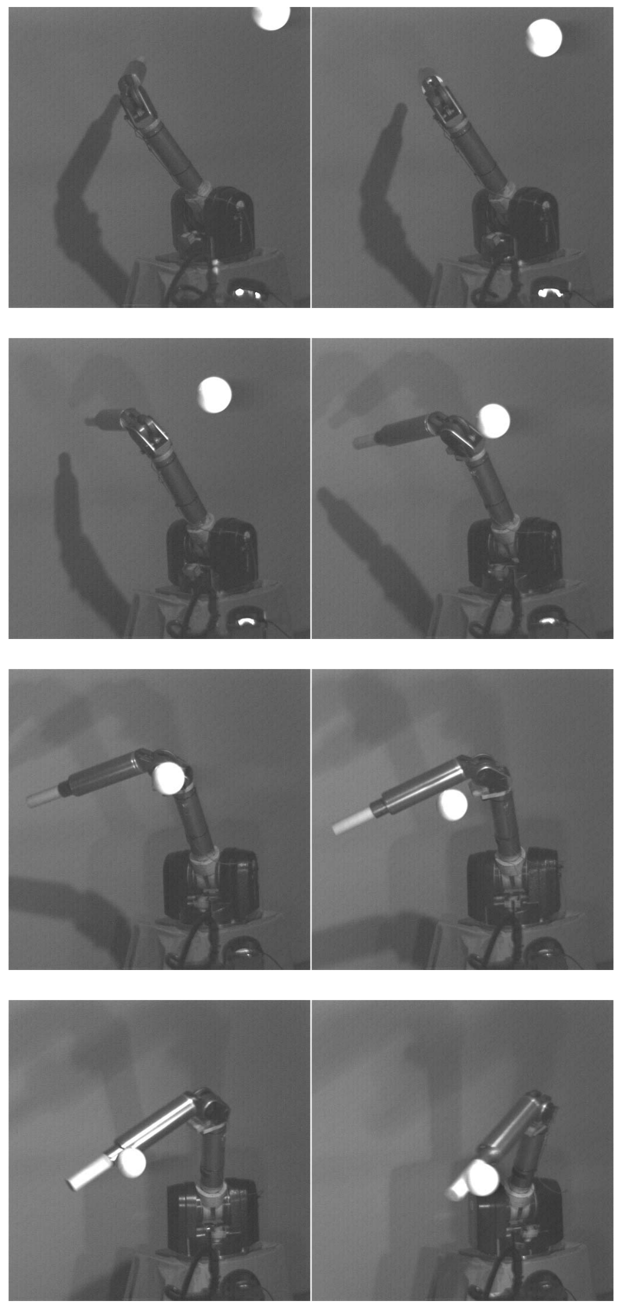

Fig. 12. Continuous sequence of pictures