https://doi.org/10.20965/jrm.2014.p0287

Review:

High-Speed Vision and its Application Systems

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[Received February 19, 2014; accepted April 16, 2014]

This paper introduces high-speed vision the authors developed, together with its applications. Architecture and development examples of high-speed vision are shown first in the sections that follow, then target tracking using active vision is explained. High-speed vision applied to robot control, design guidelines, and the development system for a high-speed robot are then introduced as examples. High-speed robot tasks, including dynamic manipulation and handling of soft objects, are explained and then book flipping scanning – an image analysis application – is explained followed by 1 ms auto pan/tilt and micro visual feedback, which are optical applications.

Keywords: high-speed vision, high-speed robot, book flipping scanning, 1 ms auto pan/tilt, micro visual feedback

1. Introduction

Information devices have become widespread in today's science- and technology-led society and demand is growing for services with greater user affinity and familiarity. Most conventional mobile devices have cameras and vision-sensing functions. Because vision alone provides at least 80% of the information received by the five senses, image information is particularly important both in video recording and in advanced recognition and judgment in complex environments. Vision is also increasingly important in image analysis applications using inspection and security checking and in mechanical control such as robots and automobile driving assist systems requiring visual feedback.

Conventional CCD vision sensors using a standard sampling rate of 30 Hz were developed focusing on ways of increasing spatial resolution. Their time resolution is sufficient for presenting images but not machine-controlled image information because of the time it takes to process and transfer images. CCDs also have comparatively low reliability due to low time density making it necessary to compensate for data – they even sometimes produce uncertain estimation information.

The ultra-high-speed cameras used to shoot high-speed physical phenomena such as ball deformation in batting, a breaking process when two objects collide with each other, and wing motion have a high sampling rate and cover a wide operating bandwidth appropriate for analyzing images. Ultra-high-speed cameras store large amounts of time sequence data that are used offline, making real-time processing and feedback difficult and preventing conventional vision systems from being more useful in high-speed real-time image sensing, processing, and transfer.

Needs for high-speed real-time vision are diversified and are high in areas such as detecting parts defects on production lines, reducing tact time in robot works, and improving the operability of human-machine interfaces. Specifically, speeding up visual feedback would make both the motion and reaction faster, thereby providing distinctive characteristics to the robots. Using these high-speed features could lead to both a quantitative advantage in speed and the creation of robot skills that actively handle non-contact states and unstable areas that conventional robots cannot.

Against this background, the authors have developed a technological basis and related systems for high-speed vision. Results found in this paper are explained from various viewpoints based on their devices, systems, and applications. Section 2 introduces high-speed vision architecture and examples of development and explains the advantages of high-speed image processing [1–12]. High-speed active vision is also discussed that uses a motor to control vision direction. Section 3 introduces an application to robot control with high-speed vision, design guidelines, and an example of a high-speed robot with a goal of making a robot whose movements are so fast as to be invisible to a human being [13–16]. Tasks are explained that realize a high-speed robot including dynamic manipulation [17–21] and complex soft-object handling [22–25]. Section 4 discusses the application of high-speed vision in book flipping scanning for book digitization [27–32], a gaze control system that uses "1 ms auto pan/tilt" mirror [33, 34], and micro visual feedback for controlling microscope observation autonomously [35–40]. Section 5 summarizes conclusions and perspectives. Also see our Web site [a] for a supplement to this paper and videos [b] can be viewed there.

2. High-Speed Vision

2.1. Vision Architecture

In robot and system development, the performance of sensing, actuators, and processing must be determined based on target phenomena or task dynamics and a total design made for an ideal system. This requires high-speed vision that realizes both high-speed imaging and image processing plays an important role in determining system performance. Thanks to the development of various high-speed systems with this design concept, specifications required for versatile high-speed vision have been determined to include a variable sampling rate up to about 1 kHz, partly because the control rate of standard servo-controllers and limits on image-shooting speed of silicon photodiodes for image sensing are around 1 kHz.

One system that meets high-speed vision requirements has image-shooting and processing functions installed on an LSI [1], with a data processing module and an optical detector directly connected to each pixel. This configuration enables parallel image transfer from the image-shooting module to the processing module and realizes a processing system with the same parallelism as pixels. Systems have been developed for a versatile digital vision chip with a programmable processing function [2], dedicated to tracking [3], and dedicated to image moment calculation [4]. **Fig. 1** shows the versatile digital vision chip. Another system has the vision chip structure separated into two to increase resolution and enhance processing function [5] to accelerate data transfer and processing by transferring, in parallel, images taken with a dedicated camera to completely parallel programmable processing modules.

Systems have also been developed in which a dedicated module for dedicated processing is connected one to one to a high-speed camera to realize high-speed sensing, e.g., a versatile high-speed image-processing board for industrial use, inspection [6], and a one-board image-processing system for real-time use in robot vision [7] were developed. Another vision system with accelerated image processing and flexible functions, has dedicated ultra-parallel coprocessors installed on a versatile PC [8] enabling image moments of each of more than 1,000 individual areas to be calculated simultaneously for image analysis 1,000 times a second.

In high-speed vision, a target object moves little on image screens in sampling intervals to compensate a change in phenomena shot on an image. This eliminates the need to scan entire images to find target object motion while examining only areas identified from previous sampling step data [9]. With an appropriate sampling rate designed in advance for a changeable observation target component, the above idea can be applied to simplify high-speed vision image processing.

It has been verified that the use of these systems and image processing could accurately sense an object that changes motion quickly and randomly, including position sensing of a thrown ball [9], sensing of the rotation axis and speed of a rotating ball [10], real-time recognition of a fluid [11], and real-time detection of an object that moves 1,000 times per second [12]. **Fig. 2** shows a shape-detection system.

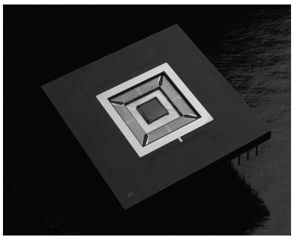


Fig. 1. Versatile digital vision chip.

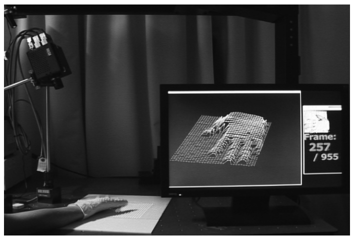


Fig. 2. Real-time 3D sensing of moving/deforming objects.

2.2. Active Vision

2.2.1. Target Tracking

Target tracking is typical image processing that utilizes high-speed vision, continuously detecting and tracking a person or automobile, for example, moving freely in space. This technology is essential for crime prevention, security, life log, and safe driving assist functions requiring image data recognition and is expected to be applied to information communication assuming an intellectual network environment.

It is important in tracking to track a target continuously to not miss information or cause inconsistencies. It is particularly effective in occlusion problems to develop a multi-eye system with multiple visions but target data from vision requires complex processing. The visual field with a single active vision for visual field problems is widened by actively driving high-speed active vision mounted on a camera platform – extremely simple and effective in the major purpose of tracking.

Below, we consider tracking with high-speed active vision that keeps the visual line in the direction of gaze similar to human eye movement.

2.2.2. High-Speed Visual Feedback

The sampling rate of an ordinary servo controller controlling an actuator is about 1 kHz, compared to conventional vision sensors working at a frame rate of 30 Hz for video signals. Feedback loop cycle time for the sensing system is thus 30 times or more longer than that of motion systems, and mechanical system motion performance cannot be fully utilized due to the vision data processing delay. Insufficient vision data is compensated for by a complex processing prediction and learning algorithm but tracking a high-speed object or live object moving randomly is difficult. Solving this problem requires high-speed visual feedback enabling tracking having a direct response to vision information.

An example of the high-speed active vision the authors developed is shown in **Fig. 3**. The system has high-speed 1 kHz image processing CPV [5] on a camera platform

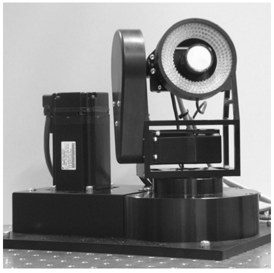


Fig. 3. AVS-III.

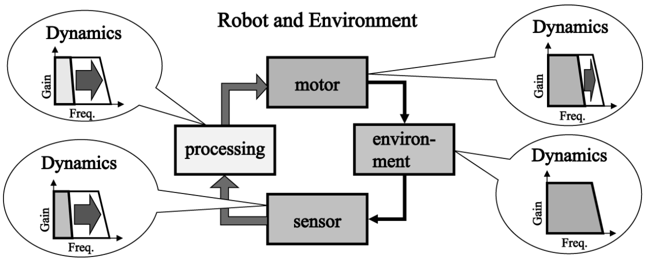


Fig. 5. Dynamics matching.

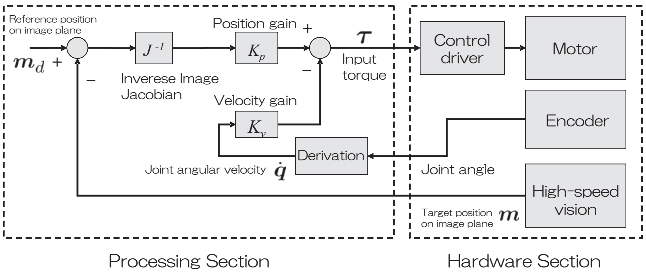


Fig. 4. Control block diagram of active vision system.

with two-degrees-of-freedom (DOF) to control tracking. High speed and high acceleration minimally influenced by response delays are realized by employing a high-output direct drive motor and a mechanism with the rotation center at the center of gravity.

An image-based visual servo controls tracking so that the target object is always at the vision center. **Fig. 4** shows a control block diagram. In 1 kHz high-speed image processing, direct visual feedback is given to the servo loop of the controller. With image Jacobian J, torque command value $\boldsymbol{\tau} = K_p J^{-1}(\boldsymbol{m}_d - \boldsymbol{m}) - K_v \dot{\boldsymbol{q}}$ is assigned to target image coordinate $\boldsymbol{m}_d$ of the target object. Encoder resolution is generally higher than vision resolution, so a fast moving object is tracked smoothly, which is realized not by conventional PD control used for image coordinates but by a control mechanism in which motor speed instead of image speed is used as D. If the target is fully tracked with active vision having sufficient time resolution, measurement accuracy is not limited only by the encoder accuracy of the active mechanism, not by the number of vision sensor pixels. That is, measurement with active object tracking achieves higher spatial accuracy than that using fixed cameras.

A verification test for tracking a color ball thrown by a pitching machine at 70 km/h was conducted and stereo vision realized with two active visions was applied to various tasks that need three-dimensional (3D) data.

3. High-Speed Robot

3.1. System Design

The authors developed a high-speed robot that reacts and moves at higher or even extremely higher speed so that human vision cannot recognize the motion. This section explains the system design concept for realizing the robot and the high-speed robot the authors developed, starting with their proposed system design concept, i.e., dynamics matching [13]. This is followed by an explanation of a high-speed robot system developed based on dynamics matching, together with high-speed robot hands, arms, high-speed vision system, and high-speed tactile sensors.

3.1.1. Dynamics Matching

Dynamics matching design concept was proposed by the authors for intellectual systems with high-speed sensor feedback. As shown in **Fig. 5**, the control target object in the real world – the robot, the object, and the environment – has its own dynamics, and the sampling theorem states that complete target understanding and control require that all system components have sufficient bandwidth for target dynamics. To fully cover target dynamics, dynamics matching establishes an intellectual system having complete consistency and maximizes system performance by enhancing all system components, i.e., sensing (sensors), processing (computers), and motion (actuators) systems and designing the dynamics of the entire system. Specifically, dynamics matching responds flexibly and robustly to high-speed random movement of the control target object.

3.1.2. High-Speed Robot System

The high-speed robot system developed by the authors based on dynamics matching explained here consists of a robot hand, robot arm, high-speed vision, active vision system (AVS), tactile sensor, and real-time controller as shown in **Fig. 6**, with all components working at 1 ms.

High-speed vision uses the vision chip and column parallel vision system (CPV) explained in Section 2. Due to the large amount of data that depends on resolution and gradation, images are processed separately from main control, and only necessary information is transferred to the real-time control system.

A system developed by dSPACE is employed for the real-time control system, which inputs sensor data every 1 ms, creates robot motion paths, calculates control algorithms, and sends output to actuators.

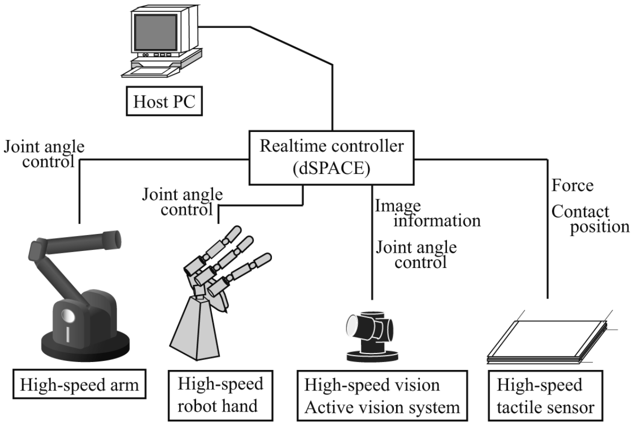


Fig. 6. High-speed robot system.

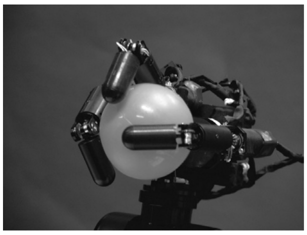


Fig. 7. Robot hand.

3.1.3. High-Speed Robot Hand [14]

Conventional robot hands have been developed to realize deft, flexible grasping but have not been designed for dynamic performance characteristics such as speed or acceleration. We thus targeted an extremely high-speed machine system from the viewpoint of dynamics matching, and designed and developed a compact high-output actuator, followed by a light-weight high-speed 3-finger robot hand with a 2 DOF wrist [14].

From a light-weight backlash-less harmonic drive®, a compact motor realizing immediate high-speed output was developed for use as an actuator. Due to winding density 1.5 times higher than that of commercially available motors, the motor achieved a 3.5 times higher ratio of instantaneous torque to weight than that of commercial motors and made 180° opening/closing motions in 0.1 seconds. **Fig. 7** shows the developed robot hand and **Tables 1** and **2** list actuator performance and robot hand specifications (IP: fingertip joint axis, MP: finger root joint axis, and TM: finger turning axis).

3.1.4. High-Speed Arm [c]

The Barrett Arm, a product of Barrett Technology established in 1989 by a research group at the Massachusetts Institute of Technology, was used as the robot arm [c] for the system shown in **Fig. 8**.

Brushless samarium-cobalt servomotors and high-output low-deceleration actuators were used. Actuators were mounted on a platform and fingertip inertia was suppressed as much as possible to realize a high speed of 6 m/s, high acceleration of 58 m/s^2, and high fingertip force of 26 N.

Table 1. Actuator specifications.

	IP	MP, TM
Type	Brushless DC	
Deceleration ratio	50	
Maximum angular speed [rad/sec]	30	
Maximum torque [Nm]	0.245	1.71
Weight [g]	25	60

Table 2. Robot hand specifications.

	IP	MP	TM
Maximum fingertip speed [m/s]	4.5		
Maximum fingertip force [N]	28.5		
Number of fingers and DOF	3 fingers, 8 DOF		
Weight [g]	Slightly less than 800		
Movable range [rad]	$-\frac{\pi}{2} \sim \frac{\pi}{2}$	$-\frac{\pi}{2} \sim \frac{\pi}{2}$	$0 \sim \pm\pi$

Fig. 8. Robot arm.

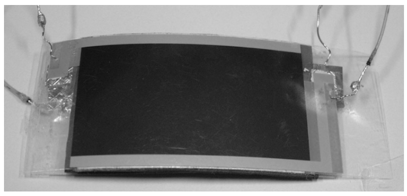


Fig. 9. High-speed tactile sensor.

3.1.5. Tactile Sensor [15]

A tactile sensor with high-speed response was developed in collaboration with Shimojo, University of Electro-Communications, under the same architecture as the vision chip above [15] as shown in **Fig. 9**. The tactile sensor features

1. Flexibility, a thin (0.8 mm thick) profile, and light weight (0.2 g/cm^2).
2. Four wires per sensor regardless of area.
3. High-speed response at a cycle time 1 ms.

4. Center and magnitude of 2D distributed load that can be measured.

The conductive 3-layer sensor consists of pressure-sensitive conductive rubber between two conductive films. The rubber is a polymer mostly of silicon rubber with uniformly distributed black lead particles. Applying pressure reduces the local rubber volume and changes the particle distribution so that particles come in contact, creating a conductive path and changing resistance. This change is used to measure the central position and magnitude of a 2D distributed load. This tactile sensor is also useful as a slip sensor [16].

The tactile sensor was wrapped around robot fingers.

3.2. Dynamic Manipulation

Dynamic manipulation is a generic term for robot manipulation in high-speed dynamic actions, unlike conventional robot manipulation, which focuses only on low-speed quasi-static motion. Dynamic manipulation targets action that is dynamic, e.g., human sports, and to push the envelope in terms of speed as mechanical systems. Specifically, robot response speed depends on the sensor information feedback rate, so high-speed vision becomes increasingly effective in acceleration tasks. This sub-section shows an example of dynamic manipulation.

3.2.1. Batting/Throwing Robots

Batting/throwing robots use two manipulators, one that throws a ball and one that hits it. The two robots do not share ball path information, so they operate independently. That is, the batting robot hits a randomly thrown ball but the throwing robot throws a ball anywhere, even into the batting robot's strike zone.

The batting robot [17] uses active vision to calculate the 3D ball position each 1 ms and adjusts batting based on ball position data each 1 ms. The robot thus hits a ball entering the strike zone even if the ball is breaking or thrown at a random point or random timing. The batting robot does not try to hit balls not entering the strike zone. Human batters usually employ feed-forward strategy in which they forecast the ball path from the pitcher's motion or based on experience. The batting robot, in contrast, uses feedback strategy to react in real time to ball motion. The robot arm's trajectory is determined by a hybrid trajectory generation algorithm in which the trajectory combines high-speed swing and hitting following ball motion. This algorithm realizes a fast swing even for slow balls, taking 0.2 seconds from when hitting starts to when the bat contacts the ball, i.e., if active vision recognizes the ball in 0.2 seconds, the robot hits the ball. Theoretically, in actual baseball action, a hitting robot on home plate would hit a ball thrown at 300 km/h by the pitcher on the pitching mound.

Unlike spring-arm or wheel pitching machines, the throwing robot [18] throws a ball using fingers and arm just as human pitchers do. To increase fingertip speed at the moment a ball is released not all joints exert maximum power, but energy from the trunk is propagated efficiently to the fingertips. A kinetic chain model is employed for the robot in which the peak speed waveform propagates over time from the trunk to the fingertips. The multi-fingered hand is controlled so that inertia generated in a high-speed swing with the ball grasped by the robot's three fingers is cancelled until the ball is released. To release the ball, the first finger is removed from the ball at an appropriate timing and the other two fingers push the ball out while controlling the throwing direction robustly to realize high-speed throw of the ball to the target direction.

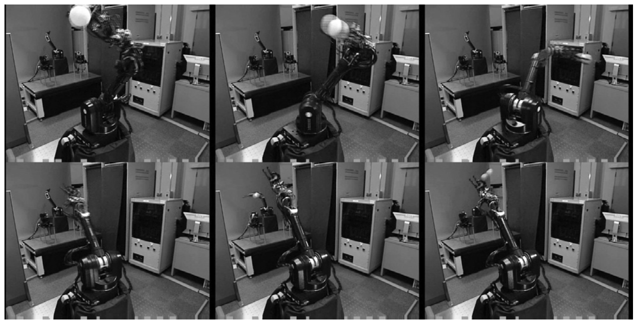


Fig. 10. Batting and throwing task.

Figure 10 shows results of experiments in which the batting and throwing robots are used. A ball thrown by the robot on the near side passes between two active visions and is hit by the other robot on the far side.

As an extension of batting study, we studied the control of direction in which the ball is hit [19]. A flat bat, rather than a round one, was used to add a DOF in controlling the direction of contact. This controls the direction in which the ball was hit. Due to the increased weight of additional DOF, the swing was 80 ms slower than that of the batting. Using this architecture, we proposed controlling the direction in which the ball was hit by introducing a collision model based on hybrid trajectory generation. In experiments, a person standing 3 m away from the manipulator threw a ball at it which the manipulator hit into a 30 cm-diameter net 2 m away, as shown in **Fig. 11**.

3.2.2. Catching Robot

Catching smoothly turns to grasping if high-speed visual information obtained before the robot arm touches the target object is utilized effectively. This sub-section introduces active catching in which the target object is guided to a stable position, soft catching – softly grasping a fragile fast-moving object without damaging it – based on visual impedance, and the catching of small objects by using tweezers.

When an object falls inconveniently and is difficult to catch, active catching is used [14] – tapping the object to guide it to a stable point where it is grasped easily. The hand trajectory is derived by integrating a finger posture change calculated to catch the falling object with high-

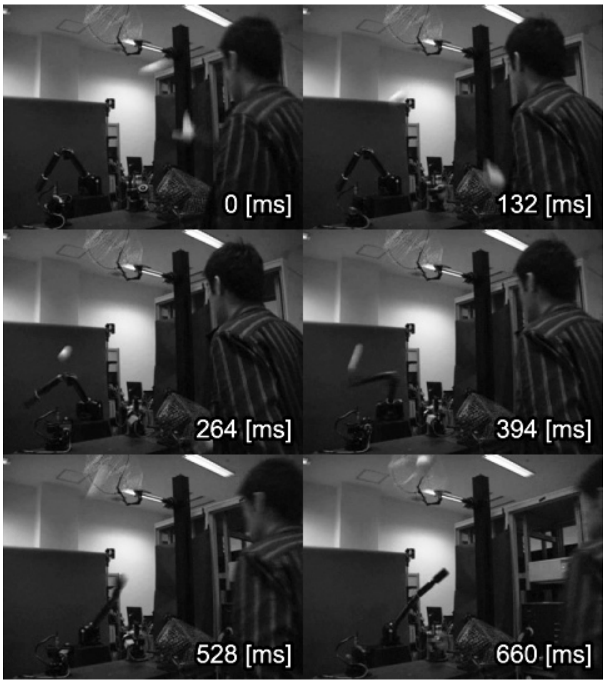
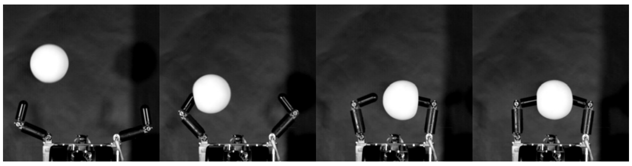
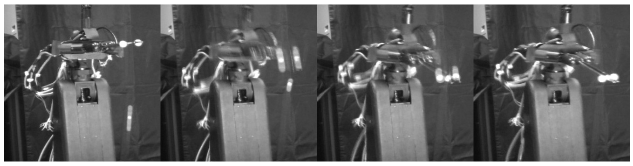


Fig. 11. Ball control in batting.



(a) active catching

(b) soft catching



(c) small object catching

Fig. 12. Catching motion.

speed vision and target-object position change calculated based on the tapping. In experiments, a ball falling from 1 m was actively tapped by one robot finger to move it to the center area between two fingers so that these fingers could grasp the ball stably. **Fig. 12(a)** shows experiments at 20 ms intervals.

A general type of soft grasping is to attach a soft cover to the robot finger to make it shock-absorbent. In high-speed operations, in contrast, force on the object is high and effects of slippage deformation and slipping of the object material cannot be ignored. Virtual impedance control with high-speed visual feedback is combined with passive shock absorption by the soft cover to catch objects whose flexibility is adjustable based on motion speed. In experiments, a raw egg was used as the fragile object and the robot caught the egg without breaking it. **Fig. 12(b)** shows experiments at 10 ms intervals.

Small objects are caught [20] by the robot hand using tweezers. These tweezers are controlled by the hand to handle small objects, not fixed on the hand. For tweezers to follow a small object and pick it up accurately, the tweezer position and posture are estimated by force sensors on the fingertips but not robustly enough, so relative coordinates between the tweezers and the object is controlled directly using high-speed vision. In experiments, a ball 6 mm in diameter moving upward in the air at an initial speed of 1.1 m/s was caught successfully. **Fig. 12(c)** shows experiments at 33 ms intervals.

3.2.3. Dynamic Regrasping [21]

Regrasping changes the form with which an object is grasped, meaning that the object already in hand is "re-held." The way chopsticks are held, for example, differs greatly between when picked up from a surface and when used to pick up food. In such a series of actions, the way chopsticks are held must be changed smoothly. Smooth control of the grasping of an object is thus an important function of the robot hand.

Due to slow motion and response, conventional robots change the form of grasping by sliding their fingers along the surface of a target object but cannot regrasp the object at high speed. The method we propose uses a strategy called dynamic regrasping, which utilizes characteristics of high-speed robots. The strategy consists of two steps – throwing an object up so that it rotates and changes its posture and grasping the falling object through the use of visual feedback control. For throwing, the object release speed of fingers is controlled based on object trajectory calculations that positions the hand appropriately for easily grasping the falling object. To compensate for errors in throwing control, the position and posture of fingers when grasping the falling object based on the object trajectory are corrected based on visual feedback at 1 ms.

Figure 13 shows results of experiments in which a cylinder is regrasped initially being held horizontally, then being thrown up into the air and regrasped vertically. The proposed method was extended to regrasping of an asymmetrical object of asymmetric shape or weight distribution. The effectiveness of dynamic regrasping was verified in tests for various objects.

3.3. Grasping Soft Objects

This sub-section explains the grasping of soft objects as a high-speed robot application. In previous experiments, solid objects were used in robot manipulation. Soft objects have also been used often as targets, but it has been difficult to use a robot to handle soft objects, except over a long operation time. There are two basic reasons for this difficulty:

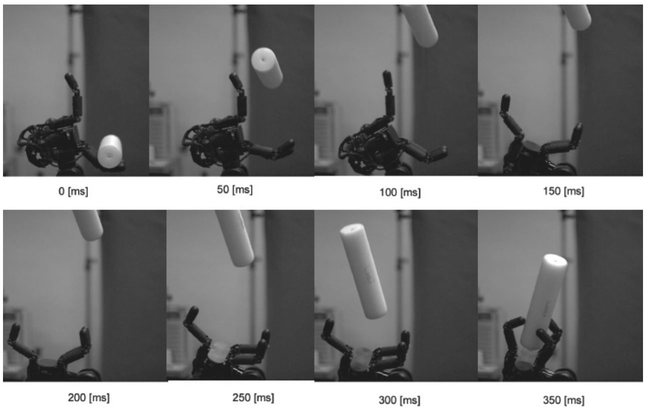


Fig. 13. Dynamic regrasping.

- The soft object changes shape when handled.
- Deformation of the soft object is difficult to estimate.

To solve the first problem, the authors employed a strategy limiting or using the deformation of the soft object. To solve the second problem, the authors used high-speed vision to find and feed back the condition of the object. They thus succeeded in tasks such as single-handed tying of soft string, dynamic handling of soft string, and folding of cloth as explained below.

3.3.1. Single-Handed Tying of Soft String [22]

Tying soft string is a typical example of soft object handling, and doing so using a robot hand is realized by limiting string deformation to prevent unpredictable deformation and using visual-tactile sensing feedback to make tying robust.

To extract the skill for tying, human single-handed string tying was analyzed and divided into three steps:

Step 1: Creating a circle of the string.

Step 2: Exchanging the string position.

Step 3: Pulling the string.

We realized single-handed string tying by consecutively executing the skills extracted in the above analysis. Visual sense feedback control and tactile sense feedback were used to create a circle and exchange string parts.

In experiment results for single-handed tying of soft string, **Figs. 14(a)–(e)** show the creation of a circle, **Figs. 14(g)–(i)** exchange of string position, and **Figs. 14(j)–(l)** pulling of the string. **Fig. 14(f)** shows holding of the string to make position exchange easier. These results show that the robot hand successfully tied the string. (For details of visual and tactile sense feedback control, see Reference [22].)

The knot made in the above single-handed tying is called an overhand knot. Combining the above skills enables different type of tyings to be performed [23].

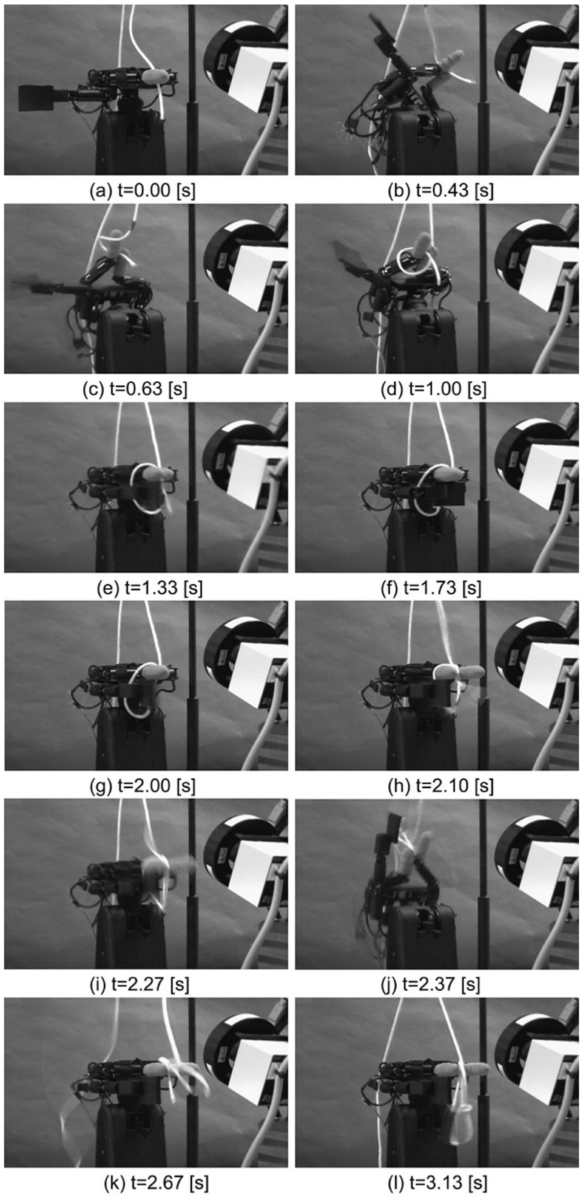


Fig. 14. One-handed knotting of flexible rope [22].

3.3.2. Dynamic Handling of Soft String [24]

Conventional dynamic models of soft objects usually use partial differential equations that describe the soft object as a continuum body and matrix differential equations that describe the soft object as a multilinked system. Many researchers studying these models found problems such as difficulty in analyzing models, in determining model parameters, and in using models to create robot trajectories.

Instead of these complex models, this section controls robot hand speed to suppress the influence of unwanted deformation in the soft object and approximates object dynamics by using algebraic equations of the hand trajectory. Creating the hand trajectory based on this model is proposed [24] and has such advantages as simplifying the model, simplifying robot trajectory creation, and operating at high-speed, and is thus expected to improve the dynamic manipulation of soft objects. In the present case, it realizes dynamic high-speed tying of soft string with a robot arm.

Discrete soft string deformation model

The robot arm is controlled as follows:

- The robot arm is controlled along the target trajectory where w is the length of an arc from the start of the trajectory to the arm. The 3D coordinates of the arm as functions of w are expressed as $\boldsymbol{r}(w) \in R^3$.
- The robot arm moves at constant speed λ from time $t = 0$ to $t = T_r$. The arc length is $w = \lambda t$.
- Hand speed λ of the robot arm shall be high enough.

A model that approximates soft string by a multilink system in which mass points are connected by constant-length links is considered. The coordinates of each mass point on the soft string are given by the following equations:

$$\boldsymbol{s}_0(t) = \boldsymbol{r}(\lambda t) \quad \ldots \ldots \ldots \ldots \quad (1)$$

$$\boldsymbol{s}_i(t) = \boldsymbol{s}_0(t) + \sum_{j=1}^{i} \Delta l \boldsymbol{e}_j \quad (i = 1, 2, \ldots, N-1) \quad . \quad (2)$$

where $\boldsymbol{s}_i$ is the coordinates of the i-th mass point from one end of the string, Δl is the distance between mass points, $\boldsymbol{e}_j$ is the unit vector to the next mass point, and N is the number of mass points.

Trajectory creation for soft string handling

An arm trajectory for creating the target shape of string using the proposed model is explained as follows:

1. Target shape $\boldsymbol{s}_0(t)$ of string is provided.
2. Based on Eq. (1), above, arm trajectory $\boldsymbol{r}(\lambda t)$ is given following target shape $\boldsymbol{s}_0(t)$ of string.

   $$\boldsymbol{r}(\lambda t) = \boldsymbol{s}_0(t) \quad (0 \leq t \leq T_r) \quad \ldots \ldots \quad (3)$$

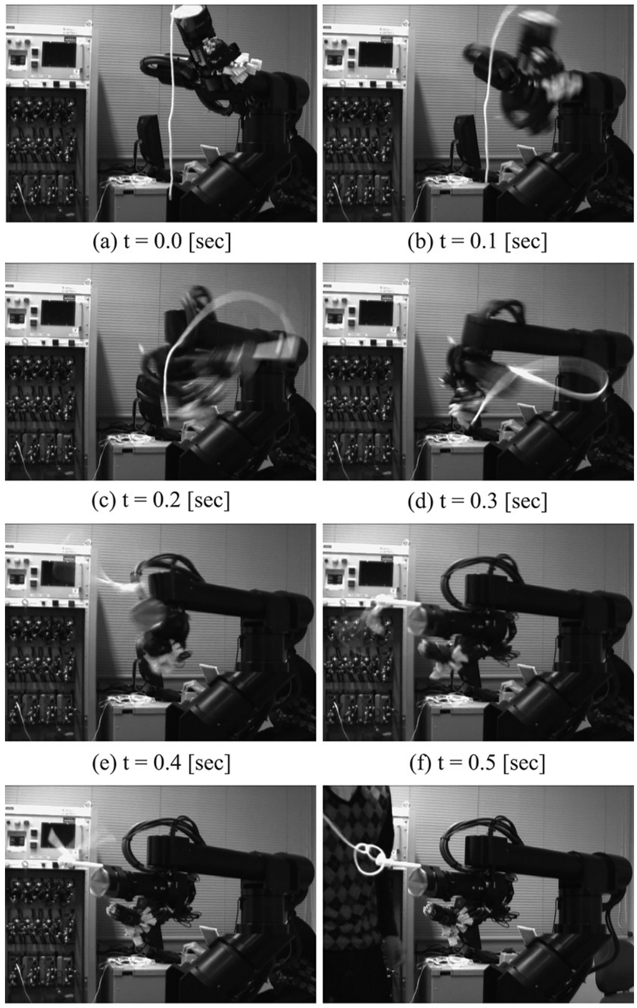
3. Inverse kinematics are solved to calculate arm joint angle trajectory $\boldsymbol{\theta}(t)$.

Robot working conditions and the approximation made to the present model (Eqs. (1) and (2)) are studied theoretically and validity is confirmed through simulation and experiment results. Although gravity must be taken into account to create the trajectory, a model and trajectory creation method with the gravity term neglected is presented here and detailed in Reference [24].

Results of dynamic string tying experiments conducted using the proposed method are shown in **Fig. 15**, with high-speed arm motion successfully deforming and tying the string at high speed.

3.3.3. Cloth Folding [25]

The last example of soft object handling is that of cloth folding by two robot hands. A hand holding one end of the cloth moves back instantly and swings the cloth upward to make it into an appropriate form. At the same time, the other free end of the cloth approaches the hand by inertia. The position of the free end is recognized using high-speed vision and grasped by the hand to dynamically fold the cloth as it is held in the air.



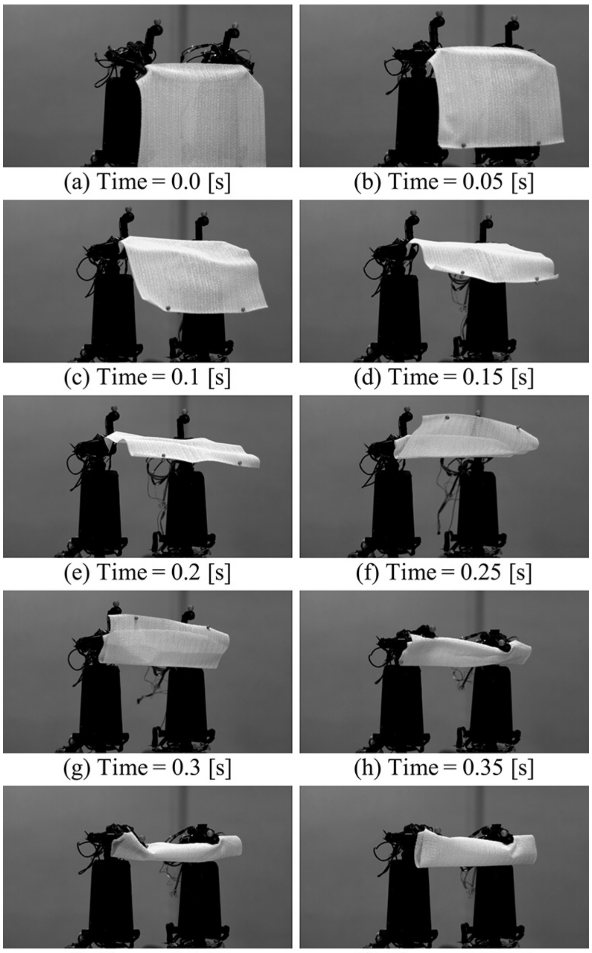
(a) t = 0.0 [sec] (b) t = 0.1 [sec] (c) t = 0.2 [sec] (d) t = 0.3 [sec] (e) t = 0.4 [sec] (f) t = 0.5 [sec] (g) t = 0.6 [sec] (h) t = 3.20 [sec]

Fig. 15. Dynamic knotting of a flexible rope [24].

The cloth deformation model was derived by extending the discrete deformation model of one-dimensional string in the previous section into a two-dimensional (2D) model. The robot trajectory is created by limiting cloth deformation the same way as is done in creating the robot hand trajectory for soft string handling. In this task, both cloth deformation due to robot motion and that due to inertia are important. Analysis based on a triplex pendulum model confirmed that cloth is folded appropriately [25].

Figure 16 shows cloth folding experiment results. The robot system took 0.2 s to deforms the cloth and visual feedback started at 0.22 s. At 0.4 s, the robot grasped the folded cloth and finished folding it. Compared to a US Berkeley research team that realized towel folding in a minute [26], our study did so in 0.4 seconds, realizing extremely high-speed folding.

As shown above, the high-speed robot system both



(a) Time = 0.0 [s] (b) Time = 0.05 [s]
(c) Time = 0.1 [s] (d) Time = 0.15 [s]
(e) Time = 0.2 [s] (f) Time = 0.25 [s]
(g) Time = 0.3 [s] (h) Time = 0.35 [s]
(i) Time = 0.4 [s] (j) Time = 0.45 [s]

Fig. 16. Dynamic folding of cloth [25].

solved the problems in the soft object handling and realized object handling tasks considered difficult several ten times faster than the conventional method. Specifically, the system responded to deformation of a soft object using high-speed visual and tactile sense feedback and simplified the soft object model by utilizing high-speed motion.

4. Application Systems

The sections that follow discuss applications of high-speed vision, an image analysis application in "book flipping scanning," and applications to optical systems called "1 ms auto pan/tilt" and "micro visual feedback."

4.1. Book Flipping Scanning

Real-time 3D sensing of a moving/deforming object with high-speed vision is expected to be utilized for many new and different applications. One such application is ultra-high-speed book digitization called "book flipping scanning" introduced below.

Book digitization is important and necessary on various business occasions in public works and for daily personal use. Conventional book digitization has not yet reached sufficient processing speed because page flipping is slow, pages are made flat, and static pages are scanned.

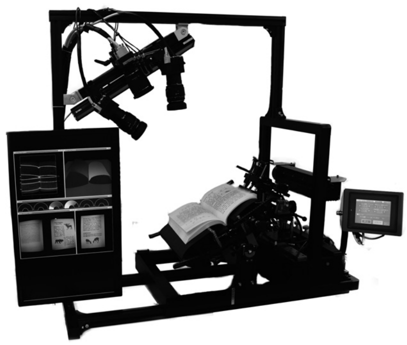


Fig. 17. BFS-Auto: high-speed high-resolution book digitization.

The proposed book flipping scanning scans a book while flipping pages but without stopping flipping each time scanning is done [27]. That is, the scanner scans an entire book by flipping pages and page flipping need not be stopped for each page or to be done accurately. All pages are scanned by high-speed vision that views a target at much higher speed than the human eye. This architecture enhances book digitization speed up to the limits of paging flipping speed.

Among the component technologies developed for realizing book flipping scanning, BFS-Auto was developed to realize speed, high resolution and automation. **Fig. 17** shows the developed system with BFS-Auto's new automatic page flipping unit for the automation and high-speed flipping [28]. This mechanism turns a page without directly touching it, which is completely different from conventional turning. To realize fast digitization and high resolution simultaneously, adaptive image shooting combines high-speed 3D sensing and high-resolution camera function in which high-speed 3D sensing captures the page that the paging flipping unit flips, detects the moment at which the page image can be shot at highest quality, and uses the high-resolution camera to shoot the page image at that moment [29]. BFS-Auto takes 250 page images of up to 500 dpi a minute.

3D correction for distorted book images [30] utilized the developable surface property of paper, i.e., the property by which paper is developed without being expanded, contracted, or torn. Technology was also developed to obtain high-resolution images by shooting a single page in multiple images with a multilens [31]. To realize mobile ultrahigh-speed book digitization, BFS-Solo reproduces a developable surface shape and its texture from monocular video [32]. Since BFS-Solo only uses motion pictures shot by a single camera, it is useful for various purposes such as for mobile or desktop use, enabling books to be digitized at any time and anywhere.

4.2. 1 ms Auto Pan/Tilt

Both conventional image media such as television and motion pictures and video distribution and video-sharing sites on the Internet are widely used, increasing the importance of image media. More people are thus involved in video shooting, making the further development of video shooing technologies important.

In conventional image shoots, the person shooting the image sets a camera at an appropriate position in an appropriate direction. A target moving at high speed or randomly makes it difficult to control the camera direction based on target motion. In sports programs of baseball or golf, for example, we may find them failing to follow the ball and thus looking for the ball, indicating one of the limitations on human camera control.

Sports broadcasting requires clear videos of scenes in which balls and people move rapidly. Specifically, ultraslow-motion videos focusing on a target athlete or ball have a tremendous impact but due to the target's rapid motion, shooting of such videos with a human being controlling the camera is extremely difficult, as is stable shooting of a target that does not move as expected, such as an animal or insect.

As stated, there is a relative motion between a camera and a target object that the camera operator cannot control. To solve this problem with the visual line of the camera, technology called "1 ms auto pan/tilt technology" was proposed and developed to control the visual line based on high-speed image processing [33]. Since this automatically controls the pan/tilt direction so that the target object remains in the center of the screen, just as in autofocus automatically focuses. Specifically, 1 ms high-speed image processing technology enables stable object tracking at extremely high speed.

4.2.1. Saccade Mirror

Conventional visual line camera control is done by mounting the camera on a platform and moving it. Due to the moment of inertia of the camera or the platform, however, it is difficult to control the visual line at high speed, i.e., on the order of milliseconds. The mechanical response of the platform is too slow to be combined with high-speed image processing and may become a bottleneck for the entire system.

To improve the slow response of the platform, we proposed the saccade mirror [34] for high-speed visual line camera control using two rotating mirrors with a small moment of inertia instead of moving the camera at a large moment of inertia. The rotation axes of the two mirrors are mutually orthogonal and control pan and tilt directions.

If mirrors are placed in front of the camera, the mirror face must be large enough to reflect the entire incident ray to the camera. In this case, the moment of inertia of mirrors is large and response is too slow to realize high-speed response. Pupil transfer optics was then used to transfer the entrance pupil, in which incoming light was most narrowed, to the front of the camera and a mirror was set at that point. With this architecture, even a small mirror could control wide beam lines. The optical visual line control unit of this architecture is called the saccade mirror.

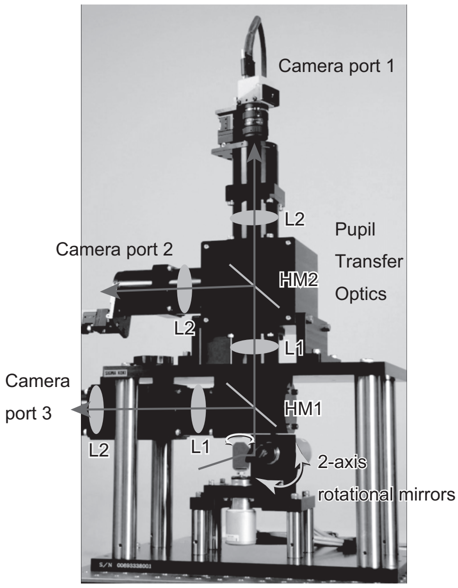


Fig. 18. Saccade mirror prototype configuration. Arrows indicate optical paths along optical axes. HM1, HM2: Half mirrors. L1, L2: Lenses.

The latest prototype controls the visual line in an angle range of 40° in 3.5 ms and transfers full HD videos as shown in **Fig. 18**.

4.2.2. Application

Figure 19 shows an example of actual applications, i.e., a 1 ms auto pan/tilt image of table tennis with a full-HD high-speed camera at 500 fps. The high-speed table tennis ball in a rally is followed stably by using the saccade mirror and 1000 fps high-speed processing, enabling 1 ms auto pan/tilt images to be taken as if the ball had stopped at the center of the screen. This technology is expected to significantly influence broadcasting technologies, for example, by shooting high-precision slow-motion videos of important moments in sportscasting. It also realizes detailed video recording and analysis of such phenomena as flying birds or insect or moving automobiles or airplanes, which are difficult when done conventionally.

4.3. Micro Visual Feedback (MVF)

Optical microscopes are widely used as important tools appropriate for noncontact minimally invasive observation to observe microscopic objects such as cells and integrated circuits. In the microscopic world, in which the typical scale is on the order of microns, the motion of an object is general faster than objects in the ordinary world. This is known as the scaling law, in which motion features change with the object's scale. Since an object may move at high speed in such microscopic environments, controlling object motion requires a high-speed measurement rate and high-speed sensor information processing. High-speed sensor vision meets these requirements and makes possible autonomous control corresponding to the

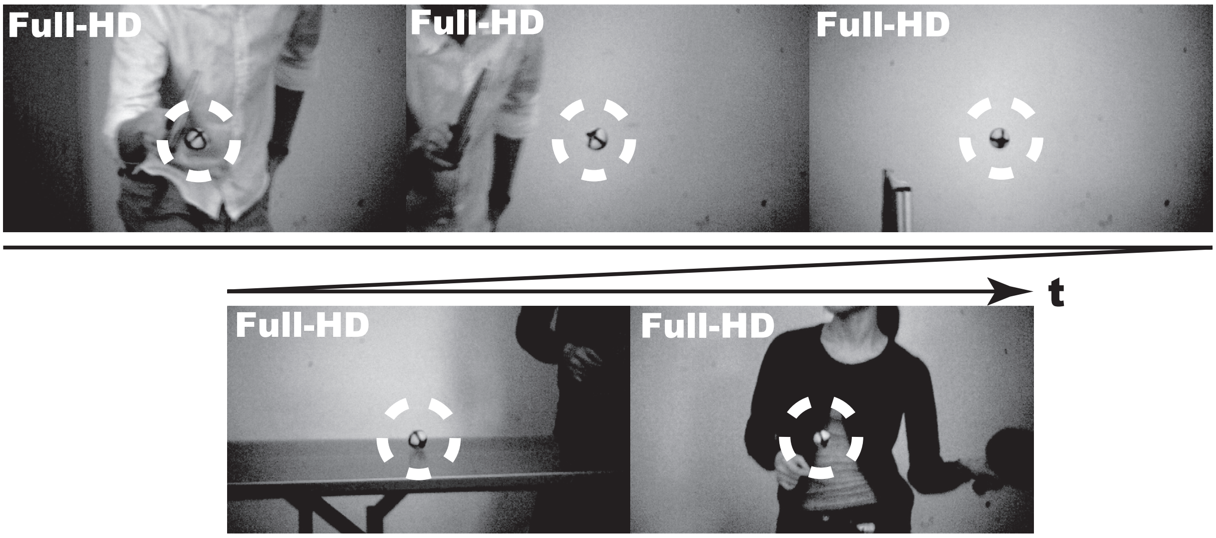


Fig. 19. Successive images of a table tennis ball in a rally taken with a full-HD high-speed 500 fps camera. In experiments, a high-speed sensor for image processing and a high-speed camera were linked on the same line, and images of the ball were taken with the high-speed camera while the ball was tracked.

microscopic environment conventionally considered difficult.

Micro visual feedback that controls a microscale object has been proposed using high-speed vision for object information feedback in the microscopic world [35]. Below, we explain the vibration suppression in vibrating objects and microorganism tracking microscopes.

4.3.1. Vibration Suppression Control of Vibrating Objects

The cantilever beam is often used to control and operate an object in the microscopic world. It is often difficult to control the object position due to resonance and the structure is so small that a sensor is attached to it and hence the vibration suppression by the high-speed visual feedback becomes necessary. We conducted experiments to suppress vibration in a beam based on visual information obtained from high-speed vision measurement of a vibrating microscopic beam [35].

The target beam has one end fixed through a jig to an actuator, with the end position controlled using an actuator. High-speed vision uses a microscope with 5-fold magnification to observe a point 35 mm away from the fixed end of the beam. The beam's one-dimensional transverse vibration is controlled based on visual information. The beam is displaced as calculated from the center of gravity of the image and the position of the actuator. Only one-dimensional transverse vibration is controlled, so only 1 DOF of the actuator is used.

Vibration was suppressed by modeling the actuator and beam as a 2D system and designing a feedback compensator of a servo system with Smith-Davison's servo design [41]. Results are shown in **Fig. 20**. Note how target object vibration was controlled and suppressed. This technology will become increasingly important in accurate efficient control of microtools in robot surgery.

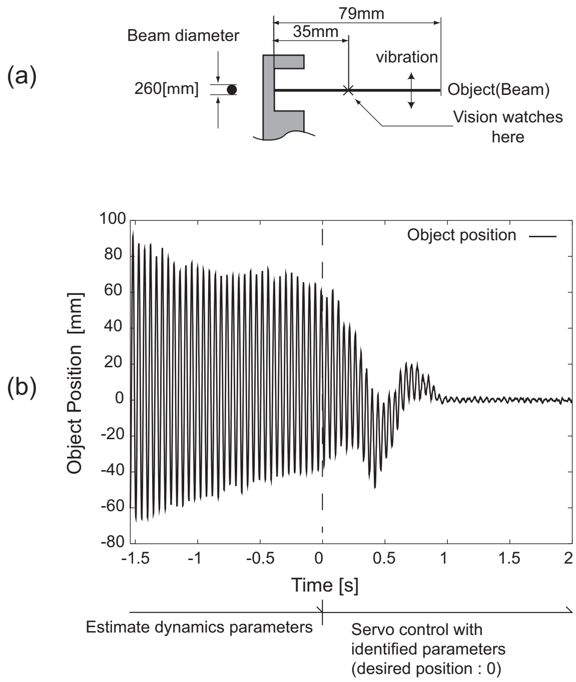


Fig. 20. Results of vibration suppression experiments of beam. (a) shows the beam used in experiments and (b) beam vibration in vibration suppression experiments [35]. Vibration suppression started at time 0. Note the rapid suppression of vibration.

4.3.2. Microorganism Tracking Microscope

The optical microscope observes dynamic activity in microscopic space without harming whatever organism is producing the activity, and this is an important measure in life sciences research. A microscope's observable range is limited by its visual field width and the depth of field depending on the magnification ratio of field lenses, which is usually given by an extremely small columnar area of

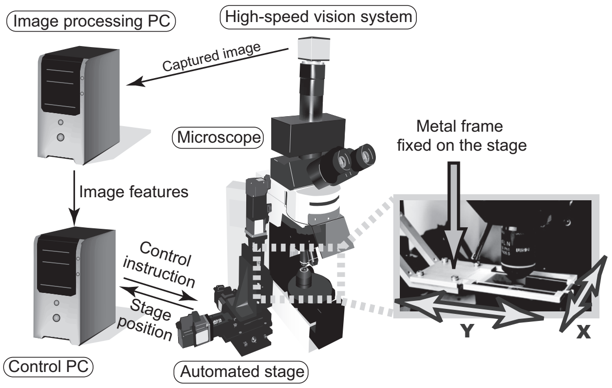


Fig. 21. Typical microorganism tracking configuration. Extracted from **Fig. 3** in Reference [36].

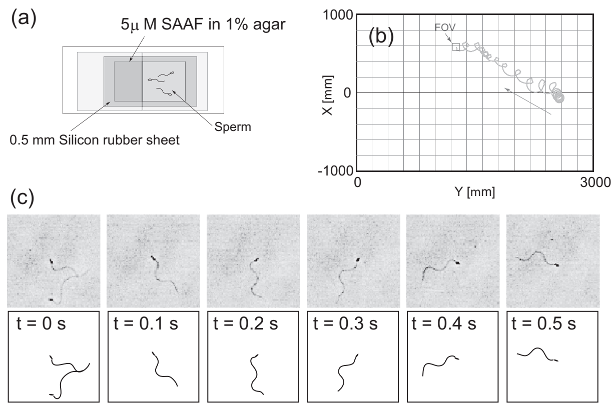


Fig. 22. Results of tracking experiments on Ciona intestinalis sperm. Extracted from **Fig. 4** in Reference [37].

a diameter of several hundred microns and of a thickness of several microns. This limit makes measurement difficult, especially when observing a moving object such as a swimming cell. The swimming observation target immediately exits the observation range and makes continuous observation difficult. In previous studies, a specific tool was used to physically fix the moving object at a particular position or mechanical, or chemical processing was applied to the object to stop its locomotion. Although these methods do not actually affect the life of the object, it is preferable to employ methods that are minimally invasive.

We applied the micro visual feedback to observation and proposed and developed a microorganism tracking microscope that tracks a swimming cell while keeping it in the center of the microscope's visual field using high-speed vision. The microorganism tracking microscope combines an ordinary optical microscope, high-speed vision, and an electric stage for controlling the position of the target object. For tracking, high-speed vision measures the position of the target and the stage is controlled to keep the target in the center of the visual field. **Fig. 21** shows the microscope. The target position is controlled by moving the prepared slide that contains the target. In the figure, the target and culture fluid are held in a container 100–150 μm deep that is then covered with a glass slide. Due to the viscosity of the culture fluid, the fluid and the cell in the container move together with the container.

For microorganism tracking microscopes, the high-speed vision is crucial, providing the following advantages:

1. High-speed control is at the same speed and same frequency as for rapidly moving microorganisms.

2. A target object observed in a visual field may quickly or suddenly exit the field, but can be observed in the visual field if tracking control is at high speed.

3. Due to the small frame interval, displacement of the target between frames is small even for multiple target objects in a visual field, since they are easily tracked individually.

The example of ascidian sperm tracking is shown here. Ascidian is a distant ancestor of vertebrates, including human beings, and is used as a model organism in development in biology. Ascidian sperm is known to swim based on the concentration gradient of a specific chemical substance. To observe this in an area wider than the visual field of a microscope, the tracking experiment of the sperm was conducted in collaboration with a group led by Manabu Yoshida, associate professor at Misaki Marine Biological Station of The University of Tokyo.

Figure 22(b) shows the trajectory of the head tracked by the system. In experiments, a diffusion source of attractant (SAAF) was placed on the left to form a one-dimensional concentration gradient toward the right side. The figure shows sperm swimming to the left where the diffusion source existed. **Fig. 22(c)** was taken during tracking experiments. Note that the sperm head remains in the center of the visual field. A motion picture of this experiment is also available. In observation of Ascidian sperm motion characteristics, experiments simultaneously measured the motion trajectory over the visual field and took detailed images of the target, including flagella.

In the target moving three-dimensionally, focusing on the target by tracking it along the optical axis (z) is needed. Ascidian sperm tended to swim along the glass slide, so 2D tracking was enough to follow it, although high-speed auto focusing would also be necessary for other targets. For the high-speed auto focusing, a method was proposed for estimating optical axis position error from defocused image characteristics of cells [38, 39]. Cells are translucent and modulate the phase of light, so the defocused image of cells blurs differently depending on the defocus direction. Analyzing blurring enables the target position in the direction of depth to be estimated from a single image.

Here we measured results for Chlamydomonas, a cell swimming with flagella and a kind of alga 10 μm in diameter. To measure flagella motion in detail by tracking, the authors obtained results in collaboration with a group led by Masahide Yoshikawa, professor of Graduate School of Medicine at The University of Tokyo. In this

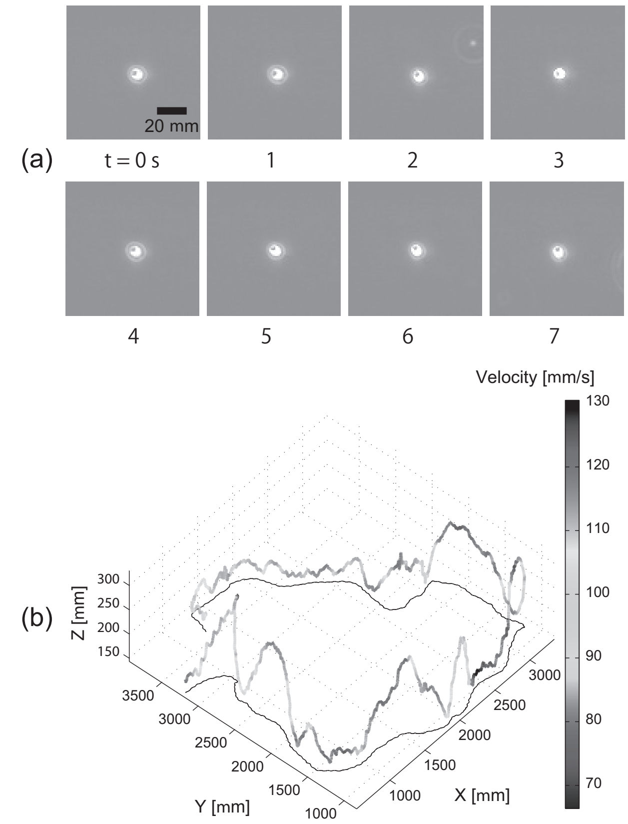


Fig. 23. Results of 3D tracking experiments on Chlamydomonas. Arranged from **Fig. 8** in Reference [40].

study, many defocused images of Chlamydomonas taken using phase contrast were prepared in advance, then the relationship between pixel strength distribution in the radial direction and optical axis position error in images of Chlamydomonas was obtained by linear regression analysis and the position in the direction of depth was estimated based on this relationship as shown in **Figs. 23(a)** and **(b)**. Tracking measured the dense trajectory of a target, so the method has advantages in easy quantitative evaluation.

5. Conclusion

We have given an overview of high-speed vision from its architectures for robots and other applications based on research results of the authors. In contrast to feed-forward data generation using prediction and learning, high-speed vision extracts useful information from high time-resolution image data in milliseconds and generates data based on this obtained information. We have developed high-speed vision and applied it to the control of mechanical systems such as robots to verify the feasibility of real-time feedback in ultra high-speed time.

High-speed vision both improves image processing throughput and work efficiency of robots and has advantages such as simplifying processing algorithms and diversifying robot performance. In other words, high-speed vision quantitatively improves speed and pursues extreme performance to create a quantitative change. Realizing recognition functions and motion performance superior to human processing by using high-speed vision opens up the following prospects:

In FA, high-speed robots reduce the number of preparatory processes, increase the number of products that robot cell production could handle, and promote the automation of expert skills, significantly improving conventional industrial robots for which further cost-cutting would otherwise be difficult. Robots can be also used for human-machine coordinated systems, virtual reality systems, medical robots, amusement systems, etc. High-speed robots developed to reach the limits of mechanical systems add to the importance of motion performance in robot R&D and influence the promotion of developing robot component technologies, the development of intellectual technologies such as error prevention and recovery, and the creation of new intellectual forms based on physical characteristics of robots.

Technological applications of high-speed vision are also possible in information communication. Developing the theoretical basis and hardware technology of high-speed vision networks based on high-speed image processing realizes multifaceted information acquisition through multi-layered wide-area/local sensing, fixed/mobile vision, and time-series/multi-viewpoint images, and enables efficient services by selecting appropriate information. Universal communication and interactive interfaces are realized through networks and other applications to information services. This would lead to innovation in information communication technologies.

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Main Works:

• dynamic manipulation, hand-arm coordination, high-speed visual feedback control, biped robot

Membership in Academic Societies:

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Main Works:
• manipulation planning and control of high-speed, dynamic manipulation of flexible objects

Membership in Academic Societies:
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Main Works:
• high-speed vision, massively parallel processor, real-time image sensing, image media, digital archive

Membership in Academic Societies:
• The Robotics Society of Japan (RSJ)
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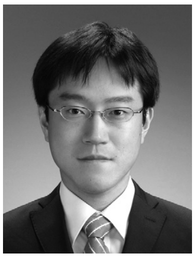

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2005-2011 Research Associate and Assistant Professor, The University of Tokyo
2011-2014 Lecturer, The University of Tokyo
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Main Works:
• high-speed image processing, high-speed optical devices, dynamic image control

Membership in Academic Societies:
• The Robotics Society of Japan (RSJ)
• The Japan Society of Applied Physics (JSAP)
• The Optical Society of Japan (OSJ)
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1999- Professor, The University of Tokyo
2004-2005 Vice-President, The University of Tokyo
2005-2006 Executive Vice-President, The University of Tokyo

Main Works:
• high speed vision, sensor fusion, high speed robot, visual feedback, vision architecture, dynamic image control, meta perception

Membership in Academic Societies:
• The Society of Instrument and Control Engineers (SICE)
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• Information Processing Society of Japan (IPSJ)
• The Institute of Electrical Engineers of Japan (IEEJ)
• The Virtual Reality Society of Japan (VRSJ)
• The Japanese Society of Mechanical Engineering (JSME)
• The Institute of Image Information and Television Engineers (ITE)