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Adaptive Hybrid Control for Visual and Force Servoing in an Unknown Environment

An adaptive robot controller is proposed to achieve a contacting task with an unknown environment, while the robot is visually guided. Since the proposed controller has on-line estimators for the parameters of the camera-manipulator system and the unknown constraint surface, the controller needs no *a priori* knowledge besides the manipulator kinematics. Experimental results validate the proposed scheme.

Keywords: Visual servoing, hybrid control, unknown environment, adaptive servoing controllers

To build an autonomous robot that can act in unknown dynamic environments, it is imperative to make the robot adaptive and calibration-free. Especially when the robot is equipped with multiple external sensors, on-line calibration is crucial because information from sensory interaction is not available through unknown dynamic environments.

Existing control schemes for robots usually need calibration, because it is common for a robot to accomplish a task defined in a Cartesian coordinate frame in 3D space. A human operator usually defines the frame, which is different from that of robot's own sensors. Therefore, the sensors must be carefully calibrated with respect to the Cartesian frame so that the robot can observe its own performance in it. Because of this procedure, task performance is prone to be affected by calibration errors and disturbances.

On the other hand, when the task is defined in the sensor coordinate frame, the robot becomes calibration-tolerant and robust against disturbances. One good example of this is image-based visual servoing [1] in which image information is directly used for feedback. In most of the previous work on image-based visual servoing, however, they still need calibration to determine the feedback gains. There have been some attempts to make the system calibration-free [2, 3, 4], but these are still cases with one external sensor, while with multiple external sensors the situation becomes even more difficult.

To build an adaptive controller for a robot with multiple sensors, one solution is to design a hybrid controller consisting of adaptive controllers corresponding to sensors. The task is also defined as a conjunction of subtasks, each of which is defined in an external sensor coordinate independently. Nelson et al. have proposed hybrid visual servoing/force servoing control based on two external (vision and force) sensors in [5], but the task for each sensor is carefully designed beforehand so that it can be independent of the other. To the best of our knowledge, there has been no research on such a hybrid structure of adaptive controllers.

In this paper, focusing on control of a robot with a visual sensor and a force sensor, a hybrid controller consisting of two adaptive external sensor-based controllers is proposed. The task given for the robot consists of a visual servoing task and a force exerting one, and they are not coordinated beforehand.

The visual servoing controller has an on-line estimator for the parameters of the cam-

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era-manipulator system, which has been already proposed and validated by the authors' group [4]. The force controller also has an on-line estimator for the parameters of the unknown constraint surface, therefore, the proposed hybrid controller only needs knowledge on the manipulator kinematics. However, since these controllers estimate their own parameters independently, there is interference between these controllers if one does not coordinate the estimated results. The proposed hybrid controller can deal with this interference by on-line coordination.

The remainder of this article is organized as follows. First, we propose an estimator for the image Jacobian matrix that describes the relation between image features and the tip position and orientation of the manipulator. Second, a method to estimate the normal vector of an unknown constraint surface is introduced. Then, an adaptive hybrid controller for visual servoing and force servoing is proposed. Finally an experiment demonstrates the effectiveness of the proposed estimators and controller.

TASK AND ASSUMPTIONS FOR THE CAMERA-MANIPULATOR SYSTEM

A camera-manipulator system consisting of a manipulator, a force sensor, and a camera is shown in Figure 1. Utilizing the camera, one can observe quantities of image features such as position, line length, contour length, and/or area of certain image regions. The image features are on the tip of the manipulator. The manipulator has a force sensor at the tip.

The task consists of a visual servoing task: to make the image features converge to given desired trajectories, and a force servoing task: to make force at the tip of the manipulator converge to the desired value. We assume that:

A1. The only knowledge that the controller needs is position and orientation of the manipulator tip with respect to the manipulator base frame. That is, it does not have any *a priori* knowledge of the translation and rotation between the manipulator base frame and the camera frame, of the camera model, of the constraint surface, nor of the relation between the manipulator and the constraint surface.

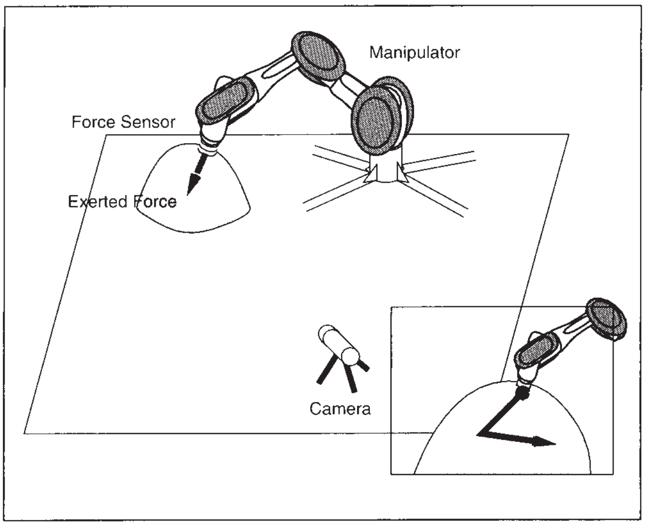

Figure 1. Camera-manipulator system.

A2. The number of constraint surfaces is one, but its equation is unknown. This means that the end-effector position is constrained on an unknown smooth 2-D curved surface. The constraint surface is assumed in the C_1 class.

ESTIMATION OF IMAGE JACOBIAN MATRIX

Let $x \in \Re^n$ and $x_{img} \in \Re^m$ denote the position and orientation vector with respect to the manipulator base frame on the manipulator base and the image feature vector obtained from the camera, respectively. The velocity relation between $\dot{x}$ and $\dot{x}_{img}$ is

$$\dot{x}_{img} = E_{img}(x)\dot{x}, \tag{1}$$

where $E_{img}(x) = \partial x_{img} / \partial x^T \in \Re^{m \times n}$ is an image Jacobian matrix that describes the relation between time-derivatives of the quantities of image features and those of the position/orientation of the tip of the manipulator. This Jacobian matrix depends on the internal camera parameters such as focal length, aspect ratio, distortion coefficients, and the relative position and orientation of the camera with respect to the manipulator base frame.

Assuming that movement of the camera-manipulator system is slow enough to consider the image Jacobian matrix E_{img} as constant during the sampling time, we get

$$x_{img}(k+1) = x_{img}(k) + E_{img}(k)u(k), \tag{2}$$

as a discrete model of the image features, where $E_{img}(k)$ and $u(k)(=T\dot{x})$ denote the constant Jacobian matrix and a control input vector in k^{th} step during sampling rate T, respectively.

So to obtain $\hat{E}_{img}$, the estimation of E_{img} which satisfies Eq. (2), we utilize a kind of least squares method[6]:

$$\begin{aligned} E_{img}(k+1) = E_{img}(k) \\ +\left\{x_{img}(k+1) - x_{img}(k) - \hat{E}_{img}(k)u(k)\right\} \\ \frac{u(k)^T W(k)}{\rho + u(k)^T W(k)u(k)} \end{aligned} \tag{3}$$

where $W(k)$ and ρ denote a weighting matrix and an appropriate positive constant that ensures stability of Eq.(3), respectively. The proposed estimator is intended not to estimate the true Jacobian matrix, but to estimate a matrix that satisfies Eq.(2). By utilizing this estimated image Jacobian matrix, the authors' group has already shown that visual servoing control can be applied to uncalibrated camera-manipulator systems [4].

ESTIMATION OF UNKNOWN CONSTRAINT SURFACE [7]

According to assumption **A2**, the constraint surface is represented as $S(x) = 0$, and differentiating it we can get

$$e_f^T\dot{x} = 0. \tag{4}$$

Because the controller does not have any *a priori* knowledge on the constraint surface (assumption **A1**), the normal vector of the surface e_f has to be estimated from the sensory data.

Suppose that the tip of the manipulator keeps contact with the surface, and we can observe force f from the force sensor as the sum of the frictional force and the normal force. By assuming that the frictional force is in the direction of end-effector motion, we can calculate the estimated unit normal vector $\hat{e}_f$. Let Dx be the end effector motion during sampling rate T. Then the estimated vector $\hat{e}_f$ becomes

$$\hat{e}_f = \tilde{f} / \| \tilde{f} \| , \tag{5}$$

where

$$\tilde{f} \underline{\underline{\Delta}} f - \left(f^T \Delta x \right) \Delta x / \| \Delta x \| .$$

HYBRID CONTROL OF ADAPTIVE VISUAL SERVOING AND FORCE SERVOING

Coordination of Controllers

To build an adaptive controller for a robot with multiple sensors, one solution is to design a hybrid controller consisting of adaptive controllers corresponding to the sensors. The task is defined as a conjunction of subtasks each of which is defined in an external sensor coordinate frame independently. One must consider the coordination between the external sensor-based controllers, because:

R1 the given subtasks depend on each other because the subtasks are given in different frames independently.

R2 Even if the subtasks are carefully designed beforehand so that they can be independent of each other, they tend to suffer from noise and disturbances, and they cannot remain independent of each other.

In [5], Nelson et al. assume that all the parameters of the robot and the environment are known so that one can calculate the selection matrices which describe directions of force servoing and visual servoing before the tasks are accomplished. Consequently, force servoing and visual servoing can be applied independently, and they do not coordinate two controllers. In their case, however, the subtasks for the visual servoing and the force one must be carefully designed beforehand so that they can be independent of each other, and the resultant controller is sensitive to disturbances.

When the parameters are unknown, one can estimate the image Jacobian matrix and the normal unit vector of the unknown constraint surface from the proposed estimators described in the last two sections. However, because of the reasons **R1** and **R2**, the outputs of the visual servoing are no longer independent of those from force servoing. In such a case, we must coordinate these two outputs. There may be two ways to coordinate, one is weighting on outputs and adding them, and the other is setting a priority (order). Here, we choose setting a priority, because quantitative evaluation is difficult by weighting and adding the outputs.

There may be many ways to determine the priority. Here, we set a priority to the force servoing task over the visual one because an output of the visual servoing control without considering the contact may result in breaking the constraint surface and/or the manipulator. Based on the priority, one must eliminate the force control direction $\hat{e}_f$ from the image Jacobian matrix $\hat{E}_{img}$. The orthogonal matrix $\hat{E}'_{img}$ becomes

$$\hat{e}'_{img,j} = \hat{e}_{img,j} - \hat{e}_f^T \hat{e}_{img,j} \hat{e}_f , \tag{6}$$

where $\hat{e}'_{img,j}$, $j = 1, \cdots, m$ denotes the row vectors of $\hat{E}'_{img}$. By utilizing Eq.(6), the direction of the force control becomes perpendicular to that of the visual servoing control, and therefore, one can coordinate the force servoing control with the visual one.

Adaptive Hybrid Controller

In this paper, a P+ feed forward controller and a PI controller are applied for visual servoing and force servoing, respectively. Supposing that the joint velocity controllers control the manipulator, the proposed hybrid controller is

$$\dot{\theta} = J^{-1}(u_f + u_{img}) , \tag{7}$$

where

$$u_f = \hat{e}_f \left\{ K_{fp} \left(f_d - \hat{e}_f^T f \right) + K_{fi} \int \left(f_d - \hat{e}_f^T f \right) dt \right\} , \tag{8}$$

and

$$u_{img} = \hat{E}_{img}^{'+} \left\{ \dot{x}_{img,d} + K_p \left(x_{img,d} - x_{img} \right) \right\} . \tag{9}$$

Vectors f_d and $x_{img,d}$ denote the desired force along the normal vector of the constraint surface and the desired image feature vector, respectively. Note that the robot Jacobian matrix J is known from assumption **A1**. The adaptive hybrid control for visual servoing and force servoing is shown in Figure 2.

EXPERIMENT

To show the effectiveness of the proposed estimators and the hybrid controller, we present an experimental result.

Experimental Equipment

Video signals from a CCD camera are sent are a tracking module equipped with a high-speed correlation processor by Fujitsu (image size: 512[pixel] x 512[pixel]). We specify a certain region in the image (called a template) to be tracked before starting an experiment. During the experiments the module feeds coordinates, where the correlation measure (it uses a SAD measure, Sum of Absolute Difference) is the smallest with respect to the template, to the main control board MVME167 (CPU:68040, 33MHz, Motorola). Force signals obtained by a 6-axis force/torque sensor (BL Autotech Ltd.) are also fed to the control board through a parallel I/O port. The control board calculates control signals for the manipulator by the proposed scheme and sends them to the manipulator controller via network (5Mbps). We use a 7 DOF manipulator PA-10 (Mitsubishi Heavy Industry Co.) as a 3 DOF manipulator, maintaining fixed desired orientation of the tip of the manipulator. Using this experimental equipment and programs in C language on VxWorks (Wind River)™, the sampling rate of the visual servoing and that of the force servoing are 33[ms] and 4[ms], respectively.

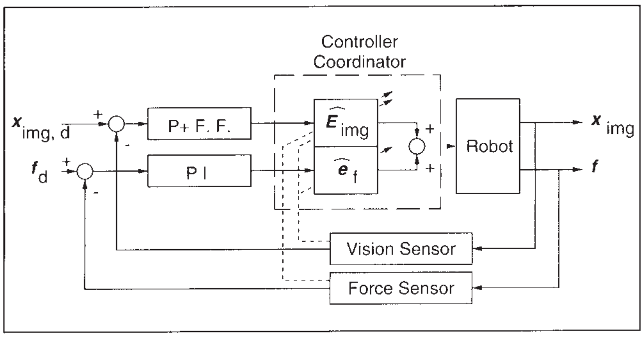

Figure 2. Adaptive hybrid control for visual servoing and force servoing.

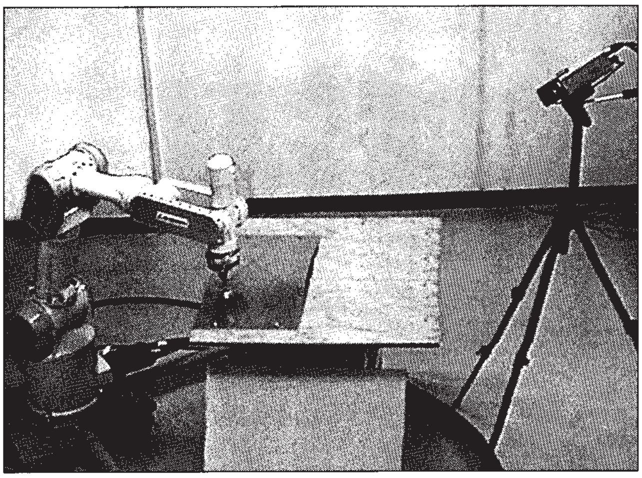

Figure 3. Overview of the manipulator, the camera, and the constraint surface.

An Experiment on a Curved Surface

An overview of the manipulator, the camera, and the constraint surface is shown in Figure 3. The constraint surface is a curved one whose shape is unknown. The image feature vector consists of the coordinates of a template in the image plain (indicated as a rectangle in Figure 4). A desired image trajectory, given for the experiment, is also shown in Figure 4. The desired image feature is moving from point A to B in 5 [sec], B to C in 5[sec], and C to A in 5[sec] according to trapezoidal velocity curves. The desired force along the normal of the surface is 19.6[N]. The weighting matrix $W(k)$ and the forgetting factor ρ are selected as $0.01I$ (I is the identity matrix) and 0.3, respectively, by trial and error. By simple movements along x, y, z-axes, the initial value of the image Jacobian $\hat{E}_{img}$ is roughly estimated:

$$\hat{E}_{img}(0) = \begin{bmatrix} -0.03 & 0.4 & -0.02 \\ 0.15 & 0.1 & -0.2 \end{bmatrix}.$$

As for gains, $K_{fp} = 29.0$, $K_{fi} = 0.075$, and $K_p = \mathrm{diag}\,[2.0\ 2.0\ 2.0]$. To estimate the normal vector, $\hat{e}_f$ force signal is filtered by a 5th order digital low pass filter.

The experimental result is shown in Figures 5, 6, and 7. In Figure 5, estimated normal vectors of the constraint surface are shown, in which we can find that the estimates of the normal vectors appear to be perpendicular to the curved constraint surface. In Figure 6, exerted normal force is shown, in which we can find that the proposed force control scheme can realize a good force response. The force error becomes small when the speed of the manipulator becomes small.

A realized trajectory on the image plane is shown in Figure 7, in which we can find that the proposed controller realizes a good response on the image plane. The tracking error on the image plane is less than 4 [pixels].

We have also done an experiment without the coordination of force and visual servoing, and found that the resultant controller hits the constraint surface and almost breaks the manipulator. From this fact and these experimental results, we have shown the effectiveness of the proposed method.

DISCUSSIONS AND SUMMARY

To control a robot system with multiple external sensors, the hybrid structure of external sensor-based controllers makes it possible to make the system adaptive. In such a case, the coordination between the controllers is important because they have interference with each other through an unknown and dynamic environment. In this paper, we prove the effectiveness of the hybrid controller and the importance of eliminating the interference through an example.

The meaning of the word "hybrid" is essentially different from that used in the previous papers [7], [8], and [9], in which they used the term as hybridness of a joint controller and a force servoing controller. They had only one external sensor and did not have to deal with the interaction between sensor signals. Unlike these works, the word means hybridness of controllers in this paper, in which the interaction between them through an unknown and dynamic environment is an essential problem to be solved.

As we indicated in this paper, to deal with such interactions, it is important to determine how to give the task priority. The priority of force control is intuitively introduced in this paper, but in other cases, we have not yet found the general principle to derive the task priority.

To coordinate multiple external sensor-based controllers, one must have a common coordinate frame where schemes are coordinated. It is necessary also for the coordination of visual servoing and the force servoing. This is the reason why we have made the image features on the tip of the manipulator, and why we have made the assumption **A1**. In this case, the manipulator base frame becomes the common frame between two control schemes. When other sensors are applied,

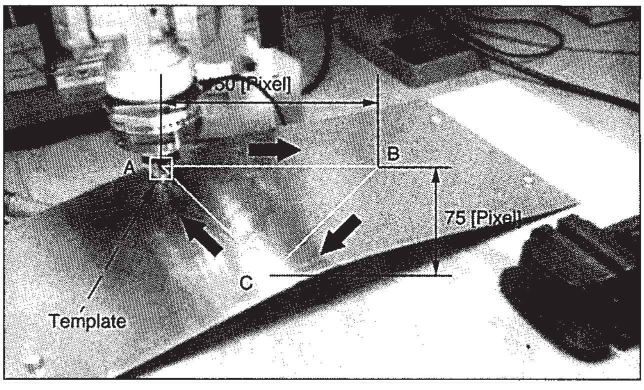

Figure 4. Desired image trajectory on the image plane.

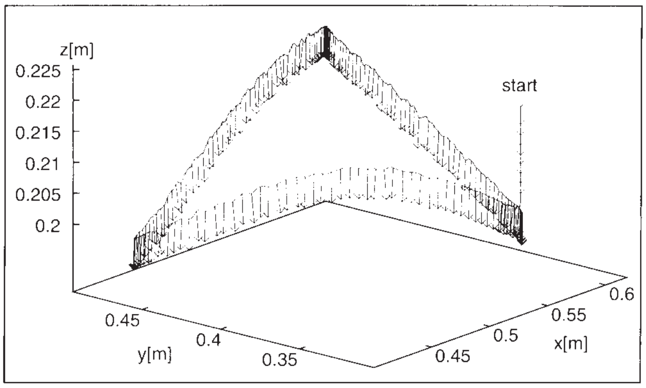

Figure 5. Experimental result 1: estimated normal vectors of the constraint surface.

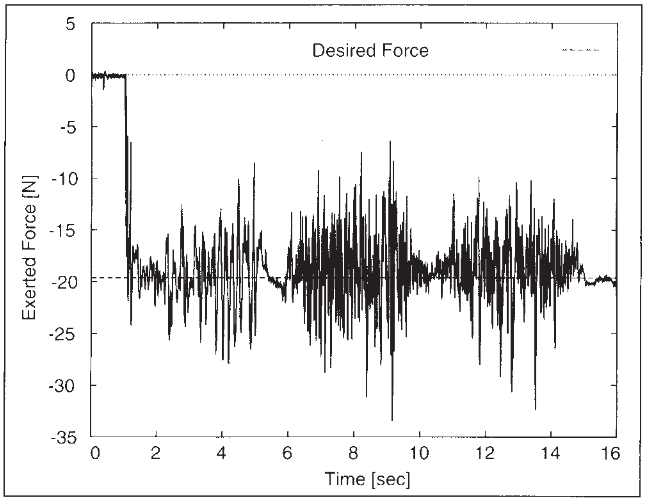

Figure 6. Experimental result 2: exerted normal force.

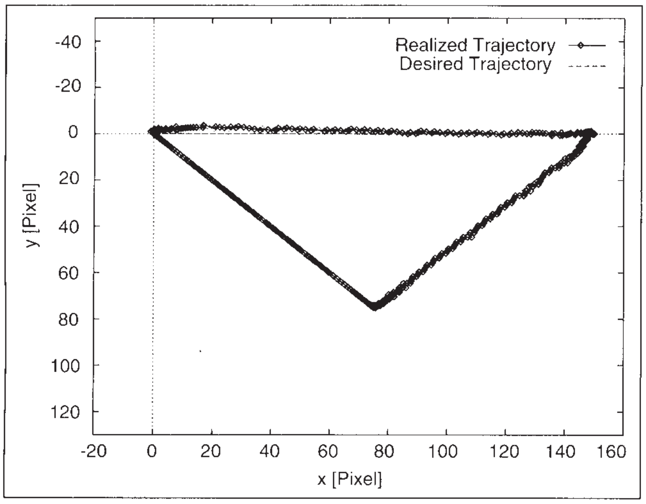

Figure 7. Experimental result 3: trajectory on the image plane.

one will have to consider the common frame to coordinate.

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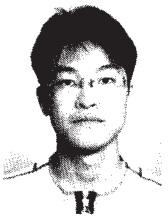

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