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Target tracking using the efficient estimation of the image Jacobian with large residual

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SUMMARY
An efficient calibration-free visual servoing method is presented. The nonlinear optimization problem is formulated with the residual term for tracking a target. The residual term is estimated based on the secant approximation method. The image Jacobian is estimated using the affine model of the end-effector feature. Some experimental results are presented for a moving target.

KEYWORDS: Image Jacobian; Unconstrained optimization; Calibration-free visual servoing; Target tracking.

I. INTRODUCTION

Visual-feedback control is generally referred to as visual servoing.[1] In image-based visual servoing, the image error is used to control the robot manipulator with the image Jacobian.[2] The nonlinear least squares optimization method is used for visual servoing. Previous works[3,4] have not considered the residual term due to the difficulty in finding the closed form (zero residual). In this paper, the estimation of the residual term has been carried out using the secant approximation method (large residual).

Calibration-free visual servoing also requires the estimation of the image Jacobian.[2,5] Instead of utilizing the image error, an affine model is proposed in estimating the image Jacobian, which is independent of the target motion.

II. UNCONSTRAINED OPTIMIZATION METHOD FOR TARGET TRACKING

The control problem in target tracking (Fig. 1) is defined as the minimization of the image error between the end-effector, $f_r(q)$, and the target, f_t. The image error is denoted as $e(q) = f_r(q) - f_t$ in the image plane. The nonlinear least squares optimization problem is then defined as:

$$\min_{q \in R^n} E(q) = \min_{q \in R^n} \frac{1}{2} e^T(q) e(q) \tag{1}$$

We define the composite image Jacobian of the robot as $J_q(q) = \partial f_r(q)/\partial q$. Then the iterative form of the joint value to minimize $E(q)$ becomes:

$$q_{k+1} = q_k - (J_q(q_k)^T J_q(q_k) + R(q_k))^{-1} J_q(q_k)^T e(q_k) \tag{2}$$

where

$$R(q) \equiv \sum_{l=1}^{n} e_i(q) \cdot \nabla^2 e_i(q) = \nabla (J_q(q))^T e(q)$$

The residual term in (2), $R(q)$, is estimated using the secant approximation method. Using the composite image Jacobian, we estimate the Hessian matrix of the end-effector feature vector as $H(q) = \nabla^2 f_r(q)$. An approximation model is adopted for the Hessian matrix as $H_k \approx \nabla^2 f_r(q_k)$ at q_k. The iterative form of the residual term is then estimated as:

$$R(q_k) = \frac{(J_q(q_k) - J_q(q_{k-1}))^T e(q_k)(q_k - q_{k-1})^T}{(q_k - q_{k-1})^T (q_k - q_{k-1})} \tag{3}$$

III. ESTIMATION OF THE IMAGE JACOBIAN

For eye-to-hand visual servoing, we define the affine model of the end-effector feature as:

$$l_k(q) = f_r(q_k) + \nabla f_r(q_k)(q - q_k) \tag{4}$$

If the kth affine model correctly specifies the error at the $(k-1)$th increment, we have:

$$\begin{aligned} &(\hat{J}_q(q_k) - \hat{J}_q(q_{k-1}))\Delta q \\ &\quad = (f_r(q_k) - f_r(q_{k-1})) - \hat{J}_q(q_{k-1})\Delta q \end{aligned} \tag{5}$$

Then we estimate the image Jacobian as:

$$\begin{aligned} \hat{J}_q(q_k) &= \hat{J}_q(q_{k-1}) \\ &+ \frac{((f_r(q_k) - f_r(q_{k-1})) - \hat{J}_q(q_{k-1})(q_k - q_{k-1}))(q_k - q_{k-1})^T}{(q_k - q_{k-1})^T (q_k - q_{k-1})} \end{aligned} \tag{6}$$

IV. EXPERIMENTAL RESULTS

The location of the target in the image plane was assumed to be $(320 - 200\sin(2\pi\omega t),\ 240 + 100\cos(2\pi\omega t))$ with the Gaussian noise. We evaluated the performance of the proposed image Jacobian in (6). The results show the

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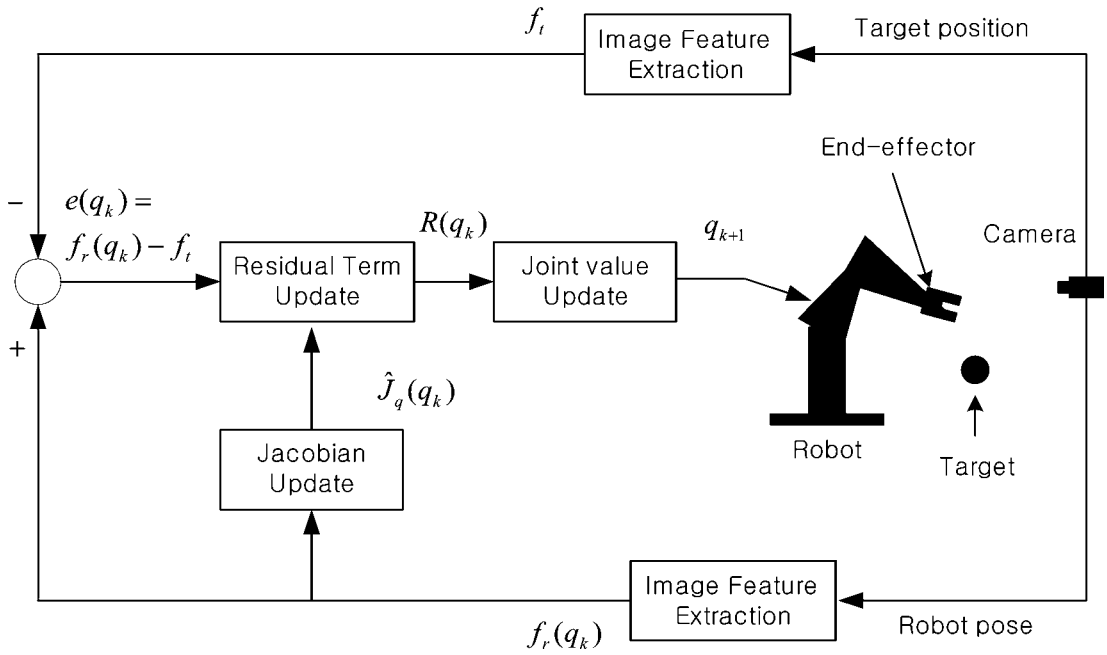
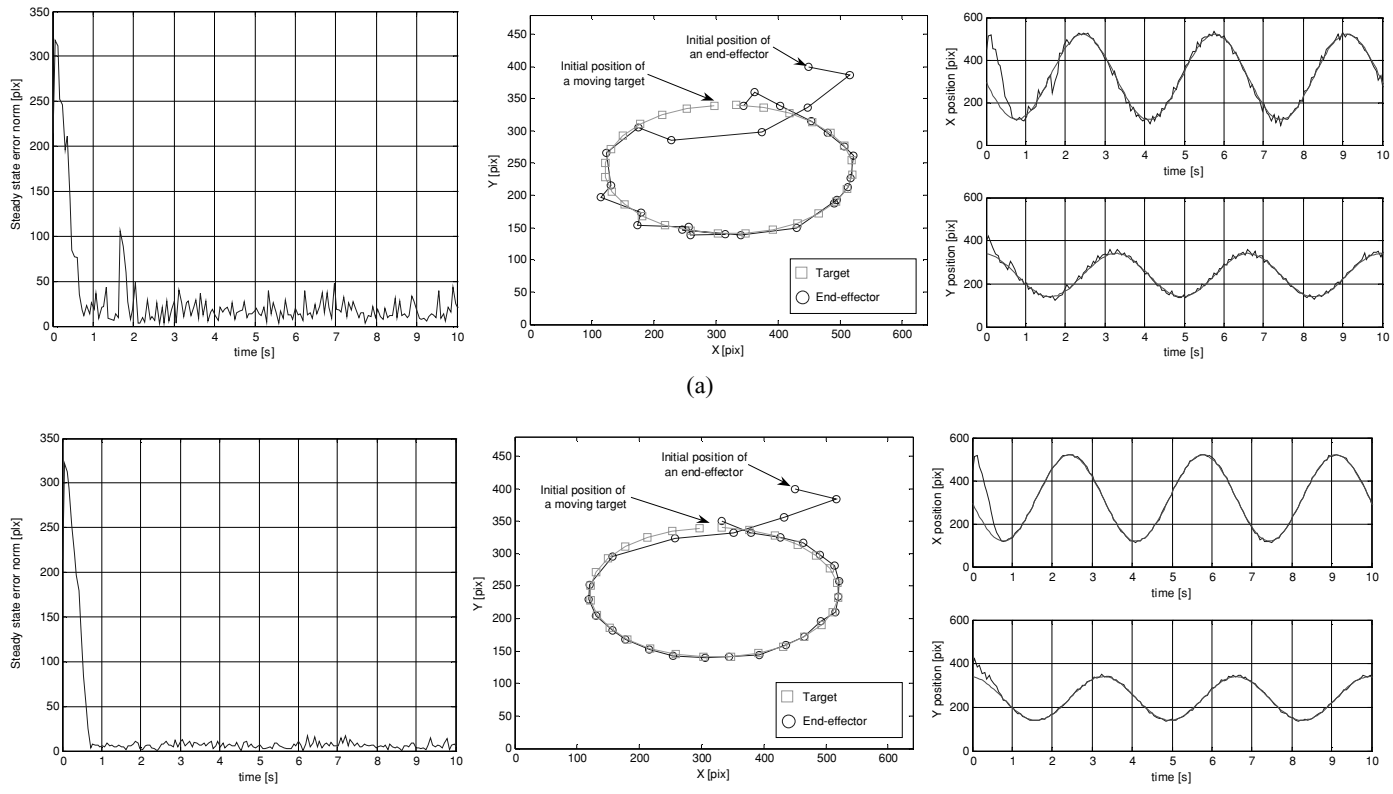


Fig. 1. The schematic control architecture for eye-to-hand visual servo control system.



(a)

(b)

Fig. 2. Experimental results at $\omega = 0.3$ rad/s: (a) Estimated image Jacobian using the image error. (b) Estimated image Jacobian using the proposed affine model.

improved performance of the affine model in Fig. 2(b) compared to the conventional error based model in Fig. 2(a). The convergence time of the affine model and the error model was 0.78 and 2.16 sec, respectively. The average error norm of the affine model and the error model was 6.4906 and 16.926 pixel as shown in Fig. 2.

V. CONCLUSIONS

Calibration-free visual servoing is achieved using the affine model. The proposed estimation of the image Jacobian was found to be efficient for tracking a moving target in eye-to-hand configuration. The performance of the affine model is notable in terms of the convergence time and the average

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error. The average error using the affine model was found to be smaller than that of the conventional method.

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