Passivity-based Visual Force Feedback Control for Planar Manipulators with Eye-in-Hand Configuration

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***Abstract*— This paper investigates visual force feedback control for planar manipulators with the eye-in-hand configuration based on passivity. The vision/force control is applied to horizontal/vertical direction for the environment which is thought as a frictionless, elastically compliant plane. We show passivity of the visual force feedback system which allows us to prove stability in the sense of Lyapunov. The L_2-gain performance analysis for the disturbance attenuation problem is considered via the dissipative systems theory. Finally simulation results are shown to verify the stability and L_2-gain performance of the visual force feedback system.**

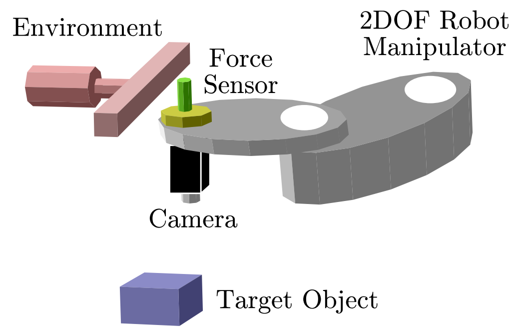

Fig. 1. Visual force feedback system with the eye-in-hand configuration.

I. Introduction

Robotics and intelligent machines need sensory information to behave autonomously in dynamical environments. Visual information is particularly suited to recognize unknown surroundings. Vision based control of robotic systems involves the fusion of robot kinematics, dynamics, and computer vision to control the motion of the robot in an efficient manner. The combination of mechanical control with visual information, so-called visual feedback control or visual servoing, is important when we consider a mechanical system working under dynamical environments [1][2].

In the visual feedback control, many practical methods are reported. In [3], the 2 1/2-D visual servoing which incorporates the advantages of both position-based and image-based visual servoing is proposed in order to guarantee robustness with respect to calibration errors. Partitioned visual servoing is considered in [4] in order to guarantee that all features remain in the image. Cowan $et\ al.$ [5] addressed the field-of-view problem for 3D dynamic visual feedback system using navigation functions. More recently, an approach based on switching between position-based visual servoing and backward motion is investigated for dealing with the field of view problem [6]. In our previous works, we discussed the dynamic visual feedback control for three dimensional target tracking based on passivity [7][8][9][10]. Recent applications of visual feedback control include the autonomous injection of biological cells [11], laparoscopic surgery [12] and others. Although visual information is necessary in order to recognize environments, visual information is inadequate to complete tasks in these applications. For example, not only visual information but also force information are needed to inject DNA to biological cells. Hence, integrating visual feedback control with force control is important for the modern robot. Most reported hybrid vision/force control considers the fixed-camera configuration with a calibrated camera [13][14][15]. In contrast to most hybrid vision/force research, Baeten $et\ al.$ [16] addressed a hybrid control structure for the eye-in-hand vision and force control. However few rigorous results have been obtained in terms of the nonlinear control aspects, although many practical methods are reported with experimental results. For example, there exist no researches that explicitly show *Lyapunov function* for the visual force feedback system.

This paper deals with visual force feedback control for planar manipulators with the eye-in-hand configuration as depicted in Fig. 1. The vision/force control is applied to horizontal/vertical direction for the environment which is thought as a frictionless, elastically compliant plane. We show passivity of the visual force feedback system which allows us to prove stability in the sense of Lyapunov. The L_2-gain performance analysis for the disturbance attenuation problem is considered via the dissipative systems theory. Finally simulation results are shown to verify the stability and L_2-gain performance of the visual force feedback system.

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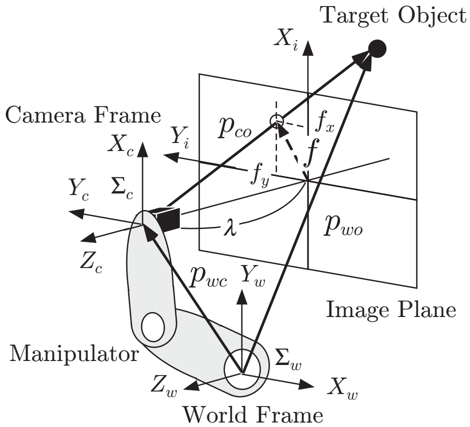

Fig. 2. Pinhole camera model with perspective projection

II. Visual Force Feedback System

A. Manipulator Model

The dynamics of n-link rigid robot manipulators can be written as

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau \tag{1}$$

where q, $\dot{q}$ and $\ddot{q}$ are the joint angle, velocity and acceleration, respectively, τ is the vector of the input torque, and τ_d represents a disturbance input. $M(q) \in \mathcal{R}^{n\times n}$ is the manipulator inertia matrix, $C(q,\dot{q}) \in \mathcal{R}^{n\times n}$ is the Coriolis matrix and $g(q) \in \mathcal{R}^{n}$ is the gravity vector. The following properties are well known [17].

Property 1: The inertia matrix $M(q)$ is positive definite.

Property 2: $\dot{M}(q) - 2C(q,\dot{q})$ is skew-symmetric.

Property 2 is concerned with the passivity property. These properties are important for the Lyapunov/passivity based control design.

The relation between the vector of generalized forces F and the vector of joint actuating generalized forces τ_F can be expressed as

$$\tau_F = J_p^T(q)F \tag{2}$$

where $J_p(q)$ is the manipulator Jacobian [18]. Then we consider generalized forces F and the disturbance forces d, the manipulator dynamics (1) can be transformed into

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + J_p^T(q)(F + d). \tag{3}$$

Throughout this paper, the above equation is used as the model of the manipulators with $n = 2$.

B. Camera Model

We consider a planar manipulator with the world frame $\Sigma_w = \{X_w\ Y_w\ Z_w\}$. It is assumed that the manipulator end-effector evolves in the $X_w - Y_w$ plane of Σ_w. Suppose that a camera with the frame $\Sigma_c = \{X_c\ Y_c\ Z_c\}$ is mounted on the manipulator end-effector as depicted in Fig. 2. Hence, the manipulator kinematics gives the camera position $p_{wc}(q) := [x_{wc}(q)\ y_{wc}(q)]^T$ and the orientation $\theta(q) := q_1 + q_2$ with respect to Σ_w. A frame $\Sigma_i = \{X_i\ Y_i\}$ is defined in the camera image plane and its origin is the intersection of the optical axis with the image plane. Here it is assumed that the axes X_i and Y_i parallel the axes X_c and Y_c respectively.

Next the object point p_{wo} is located at $[x_{wo}\ y_{wo}\ z_{wo}]^T$ with respect to the frame Σ_w. We assume that the object point motion is restricted on the $X_w - Y_w$ plane, i.e. $\dot{z}_{wo} = 0$. $p_{io} = [x_{io}\ y_{io}]^T$ is the image coordinate of p_{wo} through the perspective transformation with the frame Σ_i.

Taking the perspective transformation as the camera model (shown in Fig. 2) yields

$$f = \frac{\lambda}{z_{wo}} R^T(\theta)(p_{wo} - p_{wc}) \tag{4}$$

where $f := [f_x\ f_y]^T$ and $\lambda > 0$ is a focal length [7].

Then the differential kinematics of the manipulator gives the relationship between the manipulator joint velocities $\dot{q}$ and the velocities of the camera mounted on the end-effector. The relation can be represented using the manipulator Jacobian $J_p(q) \in \mathcal{R}^{2\times 2}$:

$$\dot{p}_{wc}(q) = J_p(q)\dot{q}. \tag{5}$$

The derivation of the equation (4) yields

$$\dot{f} = -\frac{\lambda}{z_{wo}} R^T J_p \dot{q} - R^T \dot{R} f + \frac{\lambda}{z_{wo}} R^T \dot{p}_{wo} \tag{6}$$

where $\dot{p}_{wo}$ is the unknown motion of the target object.

C. Visual Force Feedback System

Here, we define the coordinate frame Σ_F as a force frame whose direction coincides the world frame Σ_w as shown in Fig. 3. Then, the generalized forces F can be separated F_x normal and F_y tangential to the environment plane, i.e. $F = [F_x\ F_y]$. Moreover, we define the virtual image plane $c_x - c_y$ whose origin and direction coincide the image plane $X_i - Y_i$ and the force frame Σ_F, respectively.

Thus, the virtual image $c := [c_x\ c_y]^T$ can be expressed as

$$\begin{aligned} c &= Rf \\ &= \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} f_x \\ f_y \end{bmatrix}. \end{aligned} \tag{7}$$

The environment is thought of as a frictionless, elastically compliant plane. Hence the model of the contact force takes on the simple form

$$F = K_e(p_{wc} - p_{wc0}) \tag{8}$$

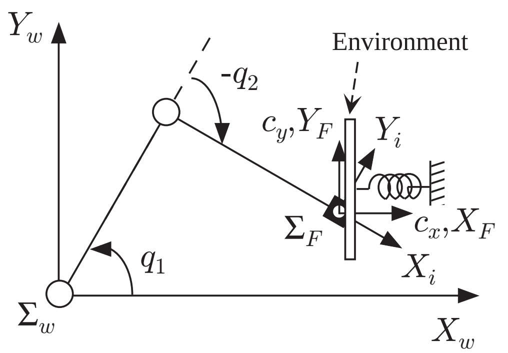

Fig. 3. Coordinate frames for planar manipulators

where p_{wc} is the position of the contact point, p_{wc0} is a point of the environment plane at rest. K_e is the constant symmetric stiffness matrix, i.e. $K_e = \mathrm{diag}\{k_{ex}, k_{ey}\}$. It is assumed that contact with the environment plane is not lost.

Let $F_d = [F_{dx}\ F_{dy}]$ be a desired force and $f_d = [0\ 0]^T$ be a desired image. By using the relation (7), the desired virtual image $c_d := [c_{dx}\ c_{dy}]^T$ satisfies $c_d = [0\ 0]^T$. We define the force error, the image error and the virturl image error as

$$F_e := F - F_d, \tag{9}$$

$$f_e := f - f_d, \tag{10}$$

$$c_e := c - c_d, \tag{11}$$

respectively. By using (4), (7) and (8), the force error F_e can be transformed into

$$\begin{aligned} F_e &= \frac{z_{wo}}{\lambda} K_e c_e \\ &= \frac{z_{wo}}{\lambda} \begin{bmatrix} k_{ex} & 0 \\ 0 & k_{ey} \end{bmatrix} \begin{bmatrix} c_{ex} \\ c_{ey} \end{bmatrix}. \end{aligned} \tag{12}$$

Our purpose is to design a stabilizing control law τ such that the force control and the visual feedback control hold for the normal direction and the tangential direction to the environment plane, respectively.

In order to consider both the force control and the visual feedback control, we define the visual force error as follows:

$$s = \begin{bmatrix} F_{ex} \\ c_{ey} \end{bmatrix}. \tag{13}$$

By using (7) and (12), the state s can be transformed into

$$\begin{aligned} s &= \begin{bmatrix} \alpha & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} c_{ex} \\ c_{ey} \end{bmatrix} \\ &= \begin{bmatrix} \alpha\cos(\theta) & -\alpha\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} f_e \end{aligned} \tag{14}$$

where $\alpha := \dfrac{z_{wo}k_{ex}}{\lambda}$. Differentiating (14) with respect to time, we obtain

$$\dot{s} = \begin{bmatrix} -\alpha S_\theta & -\alpha C_\theta \\ C_\theta & -S_\theta \end{bmatrix} \dot{\theta} f_e + \begin{bmatrix} \alpha C_\theta & -\alpha S_\theta \\ S_\theta & C_\theta \end{bmatrix} \dot{f}_e \tag{15}$$

where S_θ and C_θ represent $\sin(\theta)$ and $\cos(\theta)$ for short, respectively. Using (4), (6) and (15), we obtain

$$\begin{aligned} \dot{s} &= \begin{bmatrix} -\alpha S_\theta & -\alpha C_\theta \\ C_\theta & -S_\theta \end{bmatrix} \dot{\theta} f_e \\ &\quad - \begin{bmatrix} k_{ex}C_\theta & -k_{ex}S_\theta \\ \frac{\lambda}{z_{wo}}S_\theta & \frac{\lambda}{z_{wo}}C_\theta \end{bmatrix} \begin{bmatrix} C_\theta & S_\theta \\ -S_\theta & C_\theta \end{bmatrix} J_p \dot{q} \\ &\quad - \begin{bmatrix} \alpha C_\theta & -\alpha S_\theta \\ S_\theta & C_\theta \end{bmatrix} \begin{bmatrix} 0 & -\dot{\theta} \\ \dot{\theta} & 0 \end{bmatrix} f_e \\ &\quad + \begin{bmatrix} k_{ex}C_\theta & -k_{ex}S_\theta \\ \frac{\lambda}{z_{wo}}S_\theta & \frac{\lambda}{z_{wo}}C_\theta \end{bmatrix} \begin{bmatrix} C_\theta & S_\theta \\ -S_\theta & C_\theta \end{bmatrix} \dot{p}_{wo} \\ &= -\begin{bmatrix} k_{ex} & 0 \\ 0 & \frac{\lambda}{z_{wo}} \end{bmatrix} J_p \dot{q} + \begin{bmatrix} k_{ex} & 0 \\ 0 & \frac{\lambda}{z_{wo}} \end{bmatrix} \dot{p}_{wo}. \end{aligned} \tag{16}$$

where we exploit that $R^T\dot{R}$ is skew-symmetric, i.e.

$$R^T\dot{R} = \begin{bmatrix} 0 & -\dot{\theta} \\ \dot{\theta} & 0 \end{bmatrix}.$$

Combining (3) and (16), we construct the visual force feedback system as follows:

$$M\ddot{q} + C\dot{q} + g = \tau + J_p^T(F + d) \tag{17}$$

$$\dot{s} = -K_{xy}J_p\dot{q} + K_{xy}\dot{p}_{wo} \tag{18}$$

where

$$K_{xy} := \begin{bmatrix} k_{ex} & 0 \\ 0 & \frac{\lambda}{z_{wo}} \end{bmatrix}.$$

The following assumption will be made throughout this paper:

Assumption 1: The manipulator Jacobian J_p is nonsingular.

This assumption is required for technical reasons in the stability analysis. Under this assumption, we formulate the manipulator control problem as follows:

Control problem : For the visual force feedback system with the eye-in-hand configuration described by (17) and (18), design a control law τ such that $s \to 0$ and $\dot{q} \to 0$ as $t \to \infty$.

III. Visual Force Feedback Control

A. Passivity of Visual Force Feedback System

Now, we propose the control law for the manipulator as

$$\tau = u_\xi + J_p^T K_{Fc} s + M\dot{u}_d + Cu_d + g - J_p^T F \tag{19}$$

where

$$K_{Fc} := \begin{bmatrix} k_F & 0 \\ 0 & k_c \end{bmatrix}.$$

k_F and k_c denote the positive scalar gain for force error and image error, respectively. The new inputs u_ξ and u_d are to be determined in order to achieve the control objective. Here, we define the error vector with respect to the joint velocity of the manipulator dynamics as

$$\xi := \dot{q} - u_d. \tag{20}$$

Using (17), (18) and (19), the visual force feedback system can be derived as follows:

$$\begin{bmatrix} \dot{\xi} \\ \dot{s} \end{bmatrix} = \begin{bmatrix} -M^{-1}C\xi + M^{-1}J_P^T K_{Fc} s \\ -K_{xy}J_p\xi \end{bmatrix} + \begin{bmatrix} M^{-1} & 0 \\ 0 & -K_{xy}J_p \end{bmatrix} u + \begin{bmatrix} M^{-1}J_P^T & 0 \\ 0 & K_{xy} \end{bmatrix} w \tag{21}$$

where $u := [u_\xi^T \ u_d^T]^T$. We define the state and the disturbance of visual force feedback system as $x := [\xi^T \ s^T]^T$ and $w := [d^T \ \dot{p}_{wo}^T]^T$, respectively.

Remark 1: In the visual force feedback system, the joint angle q, velocity $\dot{q}$, normal generalized force to the environment F_x and visual information f are measurable. Then, the normal visual information to the environment c_y will be obtained by using f and $\theta = q_1 + q_2$. Because one of states s which is constructed by $F_{ex} = F_x - F_{dx}$ and $c_{ey} = [\cos(\theta) \ \sin(\theta)] f_e$ is calculated, the state of the visual force feedback system x can be exploited for the control law.

Before constructing the visual force feedback control law, we derive an important lemma.

Lemma 1: If $w = 0$, then the visual force feedback system (21) satisfies

$$\int_0^T u^T \nu d\tau \geq -\beta, \quad \forall T > 0 \tag{22}$$

where

$$\nu := Nx, \quad N := \begin{bmatrix} I & 0 \\ 0 & -J_P^T K_{Fc} \end{bmatrix}$$

and β is a positive scalar.

Proof: Consider the following positive definite function

$$V = \frac{1}{2}\xi^T M \xi + \frac{1}{2} s^T K_{Fc} K_{xy}^{-1} s. \tag{23}$$

Differentiating (23) with respect to time yields

$$\begin{aligned} \dot{V} &= \xi^T M \dot{\xi} + \frac{1}{2}\xi^T \dot{M}\xi + s^T K_{Fc} K_{xy}^{-1} \dot{s} \\ &= \xi^T \left(-C\xi + u_\xi + J_p^T K_{Fc} s\right) + \frac{1}{2}\xi^T \dot{M}\xi \\ &\quad - s^T K_{Fc} K_{xy}^{-1} K_{xy} J_p \xi - s^T K_{Fc} K_{xy}^{-1} K_{xy} J_p u_d \\ &= \xi^T u_\xi + \frac{1}{2}\xi^T(\dot{M} - 2C)\xi + \xi^T J_p^T k_{Fc} s \\ &\quad - s^T K_{Fc} J_p \xi - s^T K_{Fc} J_p u_d \\ &= u^T \nu. \end{aligned} \tag{24}$$

Integrating (24) from 0 to T, we obtain

$$\int_0^T u^T \nu d\tau = V(T) - V(0) \geq -V(0) = -\beta \tag{25}$$

where β is a positive scalar that only depends on the initial states of ξ and s. ■

Let us take u as the input and ν as its output. Thus, Lemma 1 implies that the visual force feedback system (21) is *passive* from the input u to the output ν as in the definition in [19].

B. Visual Force Feedback Control and Stability Analysis

We now propose the following control input for the interconnected system:

$$\begin{aligned} u &= -\begin{bmatrix} K_\xi & 0 \\ 0 & K_p \end{bmatrix} \begin{bmatrix} I & 0 \\ 0 & -J_P^T K_{Fc} \end{bmatrix} x \\ &= -KNx \end{aligned} \tag{26}$$

where

$$K := \begin{bmatrix} K_\xi & 0 \\ 0 & K_p \end{bmatrix}$$

and $K_\xi := \mathrm{diag}\{k_{\xi 1}, k_{\xi 2}\}$ and $K_p = \mathrm{diag}\{k_{p1}, k_{p2}\}$ denote the positive gain matrices for each joint axis. Using the control input (26), $s = 0$ and $\dot{q} = 0$ if and only if $x = 0$. Then, the stability of the visual feedback system can be described by the following theorem.

Theorem 1: If $w = 0$, then the equilibrium point $x = 0$ for the closed-loop system (21) and (26) is asymptotic stable.

Proof: In the proof of Lemma 1, we have already derived that the time derivative of V along the trajectory of the system (21) is formulated as (24). Using the control input (26), (24) can be transformed into

$$\dot{V} = u^T \nu = x^T N^T u = -x^T N^T K N x. \tag{27}$$

Because N is a nonsingular matrix and K is a positive definite matrix, this completes the proof. ■

Theorem 1 shows the stability via Lyapunov method for the visual force feedback system. It is interesting to note that stability analysis is based on the passivity as described in (22).

C. L_2-Gain Performance Analysis

In this subsection, we utilize L_2-gain performance analysis to evaluate the tracking performance of the control scheme in the presence of a moving target. The motion of the target object is regarded as an external disturbance. Here, we define the controlled outputs as

$$z := \begin{bmatrix} \varepsilon_\xi & 0 \\ 0 & \varepsilon_s \end{bmatrix} x$$

where $\varepsilon_\xi = \text{diag}\{\varepsilon_{\xi 1}, \varepsilon_{\xi 2}\} > 0$ and $\varepsilon_s = \text{diag}\{\varepsilon_{s1}, \varepsilon_{s2}\} > 0$. are weight matrices.

Here, let us define

$$P := \begin{bmatrix} K_\xi - \frac{1}{2}\varepsilon_\xi^T \varepsilon_\xi - \frac{1}{2\gamma^2} J_P^T J_P & 0 \\ 0 & K_{Fc}^T J_p K_p J_p^T K_{Fc} - \frac{1}{2}\varepsilon_s^T \varepsilon_s - \frac{1}{2\gamma^2} K_{Fc}^T K_{Fc} \end{bmatrix} \quad (28)$$

where $\gamma \in \mathcal{R}$ is positive.

Theorem 2: Given a positive scalar γ, consider the control input (26) with the weight matrices ε_ξ and ε_s and the gains K_ξ, K_p and K_{Fc} such that the matrix P is positive semi-definite. Then the closed-loop system (21) and (26) has L_2-gain $\leq \gamma$.

Proof: Differentiating the positive definite function V defined in (23) along the trajectory of the closed-loop system yields

$$\begin{aligned} \dot{V} = &-\xi^T K_\xi \xi - s^T K_{Fc}^T J_p K_p J_p^T s \\ &+ \xi^T J_p^T d + x^T K_{Fc} \dot{p}_{wo} \end{aligned} \quad (29)$$

By completing the squares, we have

$$\begin{aligned} &\dot{V} + \frac{1}{2}\|z\|^2 - \frac{\gamma^2}{2}\|w\|^2 \\ &\leq -\xi^T K_\xi \xi - s^T K_{Fc}^T J_p K_p J_p^T s + \frac{1}{2}(\varepsilon_\xi \xi)^T \varepsilon_\xi \xi \\ &\quad + \frac{1}{2}(\varepsilon_s s)^T \varepsilon_s s + \frac{1}{2\gamma^2}\xi^T J_p^T J_p \xi + \frac{1}{2\gamma^2} s^T K_{Fc}^T K_{Fc} s \\ &= -x^T P x \end{aligned} \quad (30)$$

It can be verified that the inequality

$$\dot{V} + \frac{1}{2}\|z\|^2 - \frac{\gamma^2}{2}\|w\|^2 \leq 0 \quad (31)$$

holds if P is positive semi-definite. Integrating (31) from 0 to T and noticing $V(T) \geq 0$, we have

$$\int_0^T \|z\|^2 \leq \gamma^2 \int_0^T \|w\|^2 + 2V(x(0)) \quad (32)$$

This completes the proof. ■

The L_2-gain performance analysis of the visual force feedback system is discussed via the dissipative systems theory.

IV. SIMULATION

To illustrate the behavior of the visual force feedback control, we apply the proposed control law to a two-link planar manipulator. The stiffnesses of the contact plane are $k_{ex} = 200$ [N/m] and $k_{ey} = 0$ [N/m]. The control objective is $F_x \to F_{dx}$ and $c_y \to c_{dy}$ as $t \to \infty$, i.e. F_y and c_x are not considered in this framework. We give the desired force and the desired image as $F_{dx} = 18$ [N] and $c_{dy} = 0$ [pixel], respectively.

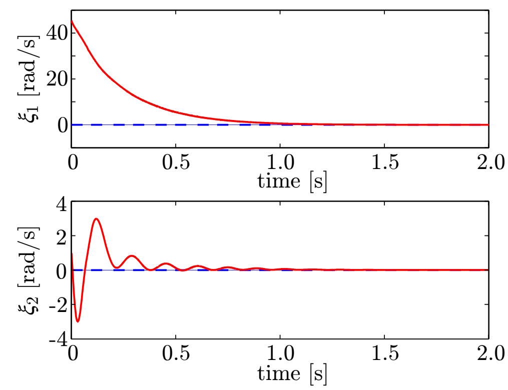

Fig. 4. Time response of $\xi(t)$

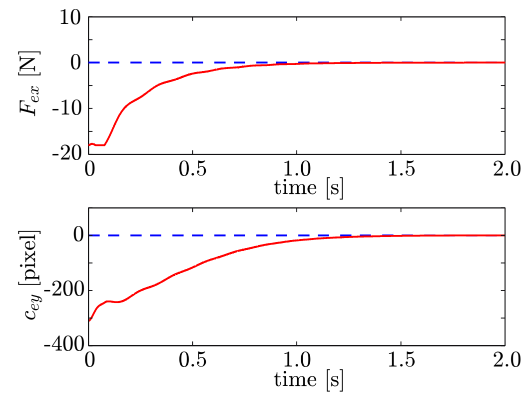

Fig. 5. Time response of $s(t)$

A. Stability Analysis

First, we present results for the stability analysis with a static target object. The initial conditions of the manipulator are set as follows: $q_1(0) = \pi/2$ [rad], $q_2(0) = -\pi/2$ [rad], $\dot{q}_1(0) = 0$ [rad/s], $\dot{q}_2(0) = 0$ [rad/s]. In this initial setting, the initial states of the visual force feedback system satisfy $\xi_1 = 0$ [rad/s], $\xi_2 = 0$ [rad/s], $F_{ex} = -18$ [N], $c_{ey} = -310$ [pixel], respectively. The controller parameters for Equation (26) were empirically selected as $K_\xi = \text{diag}\{0.1, 0.1\}$, $K_p = \text{diag}\{1, 0.1\}$ and $K_{Fc} = \text{diag}\{10, 0.1\}$. The simulation results are shown in Figs. 4 and 5. Figs. 4 and 5 illustrate the velocity error ξ and the force and image error s, respectively. From these figures, the asymptotic stability of the equilibrium point $x = 0$ can be also confirmed.

B. L_2-gain Performance Analysis

Next, we present simulation results for the L_2-gain performance analysis in the case of a moving target object. In particular, we consider the disturbance attenuation problem by regarding the target motion as the disturbance for the visual force feedback system. The target object moves along a straight line parallel to Y_w-axis. The initial states of the

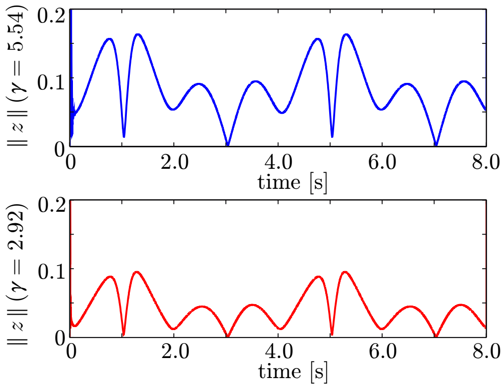

Fig. 6. Euclidean norm of the controlled output $\|z\|$

visual force feedback system is $x(0) = 0$. The weights for the states are selected as $\varepsilon_\xi = \text{diag}\{2.0, 2.0\}$ and $\varepsilon_s = \text{diag}\{0.25, 0.01\}$. The following gains were selected in order to confirm the adequacy of the L_2-gain performance for the visual force feedback system.

$$\begin{aligned}
\text{Gain A}: &\ \gamma = 5.54,\ K_\xi = \text{diag}\{5, 5\},\ K_p = \text{diag}\{80, 40\},\\
&K_{Fc} = \text{diag}\{0.5, 0.015\}\\
\text{Gain B}: &\ \gamma = 2.92,\ K_\xi = \text{diag}\{5, 5\},\ K_p = \text{diag}\{5, 2.5\},\\
&K_{Fc} = \text{diag}\{5, 0.4\}
\end{aligned}$$

In Fig. 6, the top graph and the bottom one show the norm of controlled output z in the case of $\gamma = 5.54$ and $\gamma = 2.92$, respectively. It can be verified that the disturbance attenuation is improved in the case of the smaller value of γ from Fig. 6.

V. Conclusions

This paper investigates the visual force feedback control for planar manipulators. The proposed method is regarded as an extension of the hybrid position/force control to the hybrid vision/force control. The main contribution of this paper is to show that the visual force feedback system has the passivity. Stability and L_2-gain performance analysis for the visual force feedback system are discussed based on passivity and dissipative systems theory. Finally simulation results are presented to verify the stability and L_2-gain performance of the visual force feedback system. In our future work, we will discuss the visual force feedback control for three dimensional task space based on passivity.

References

[1] S. Hutchinson, G. D. Hager and P. I. Corke, "A Tutorial on Visual Servo Control," *IEEE Trans. Robotics and Automation*, Vol. 12, No. 5, pp. 651–670, 1996.

[2] H. I. Christensen and P. Corke, "Editorial: Special Issue on Visual Servoing," *Int. Journal of Robotics Research*, Vol. 22, No. 10–11, pp. 779–780, 2003.

[3] E. Malis, F. Chaumette and S. Boudet, "2-1/2-D Visual Servoing," *IEEE Trans. on Robotics and Automation*, Vol. 15, No. 2, pp. 238–250, 1999.

[4] P. I. Corke and S. A. Hutchinson, "A New Partitioned Approach to Image-Based Visual Servo Control," *IEEE Trans. on Robotics and Automation*, Vol. 17, No. 4, pp. 507–515, 2001.

[5] N. J. Cowan, J. D. Weingarten and D. E. Koditschek, "Visual Servoing via Navigation Functions," *IEEE Trans. Robotics and Automation*, Vol. 18, No. 4, pp. 521–533, 2002.

[6] G. Chesi, K. Hashimoto, D. Prattichizzo and A. Vicino, "Keeping Features in the Field of View in Eye-In-Hand Visual Servoing: A Switching Approach," *IEEE Trans. on Robotics*, Vol. 20, No. 5, pp. 908–913, 2004.

[7] A. Maruyama and M. Fujita, "Robust Control for Planar Manipulators with Image Feature Parameter Potential," *Advanced Robotics*, Vol. 12, No. 1, pp. 67–80, 1998.

[8] T. Murao, H. Kawai and M. Fujita "Passivity-based Control of Visual Feedback Systems with Dynamic Movable Camera Configuration," *Proc. of the 44th IEEE Conference on Decision and Control*, pp. 5360–5365, Seville, 2005.

[9] H. Kawai, T. Murao and M. Fujita, "Image-based Dynamic Visual Feedback Control via Passivity Approach," *Proc. of the 2006 IEEE Conference on Control Applications*, pp. 740–745, 2006.

[10] M. Fujita, H. Kawai and M. Spong, "Passivity-based Dynamic Visual Feedback Control for Three Dimensional Target Tracking: Stability and L_2-gain Performance Analysis," *IEEE Transactions on Control Systems Technology*, Vol. 15, No. 1, pp. 40–52, 2007.

[11] S. Yu and B. J. Nelson, "Autonomous Injection of Biological Cells Using Visual Servoing," In:D. Rus and S. Singh (Eds), *Experimental Robotics VII*, Springer–Verlag, pp. 169–178, 2001.

[12] K. Omote *et al.*, "Self-Guided Robotic Camera Control for Laparoscopic Surgery Compared with Human Camera Control," *The American Journal of Surgery*, Vol. 177, No. 4, pp. 321–324, 1999.

[13] B. J. Nelson and P. K. Khosla, "Force and Vision Resolvability for Assimilating Disparate Sensory Feedback," *IEEE Trans. Robotics and Automation*, Vol. 12, No. 5, pp. 714–731, 1996.

[14] K. Hosoda, K. Igarashi and M. Asada, "Adaptive Hybrid Control for Visual and Force Servoing in an Unknown Environment," *IEEE Trans. Robotics and Automation Magazine*, Vol. 5, No. 4, pp. 39–43, 1998.

[15] D. Xiao, B. K. Ghosh, N. Xi and T. J. Tarn, "Sensor-based Hybrid Position/Force Control of a Robot Manipulator in an Uncalibrated Environment," *IEEE Transactions on Control Systems Technology*, Vol. 8, No. 4, pp. 635–645, 2000.

[16] J. Baeten, H. Bruyninckx and J. D. Schutter, "Integrated Vision/Force Robotic Servoing in the Task Frame Formalism," *International Journal of Robotics Research*, Vol. 22, No. 10–11, pp. 941–954, 2003.

[17] M. W. Spong, S. Hutchinson and M. Vidyasagar, *Robot Modeling and Control*, John Wiley & Sons, 2006.

[18] B. Siciliano and L. Villani, *Robot Force Control*, Kluwer Academic Publishers, 1999.

[19] A. van der Schaft, *L_2-Gain and Passivity Techniques in Nonlinear Control* (2nd ed.), Springer–Verlag, 2000.