An Experimental Study of Dynamic Visual Feedback Control with a Fixed Camera

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Abstract: This paper deals with the control and the estimation of dynamic visual feedback systems with a fixed camera. The model of the visual feedback system with four coordinate frames is established by using the homogeneous representation and the adjoint transformation. Secondly we derive the passivity of the dynamic visual feedback system by combining the manipulator dynamics and the visual feedback system. Based on the passivity, stability and L_2-gain performance analysis are discussed. Finally experimental results on SICE–DD arm are reported to confirm the effectiveness of the visual feedback control law.

Keywords: Visual Feedback Control, SICE–DD Arm, Passivity, Lyapunov Stability, L_2–Gain Performance Analysis

1. Introduction

Vision based control of robotic systems involves the fusion of robot kinematics, dynamics, and computer vision system to control the position of the robot end-effector in an efficient manner. The combination of mechanical control with visual information, so-called visual feedback control or visual servo, should become extremely important, when we consider a mechanical system working under dynamical environments[1, 2]. Recently, the autonomous injection of biological cells has been discussed using visual feedback control[3] and fields which need visual feedback control are increasing.

Our previous works[4, 5] deal with a robot motion control with visual information in the eye-in-hand configuration which has only three coordinate frames. However, the system can not be represented in this configuration, such as the autonomous injection of biological cells.

This paper deals with the control and the estimation of dynamic visual feedback systems with a fixed camera which have the four coordinate frames. The main contribution of this paper is that the dynamic visual feedback system with SICE–DD arm[6] is constructed in order to confirm the effectiveness of the visual feedback control law.

2. Passivity-Based Visual Feedback System

2.1 Fundamental Representation for Visual Feedback System

We consider the fixed-camera robotic system[1] is shown in Fig. 1, where the coordinate frame Σ_w represents

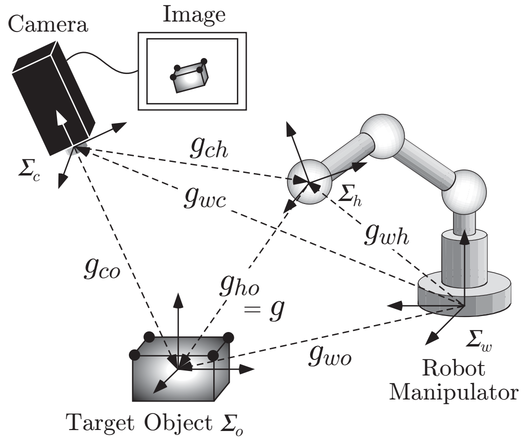


Figure 1: Visual feedback system

the world frame, Σ_h represents the hand (end-effector) frame, Σ_c represents the camera frame, Σ_o represents the object frame, respectively. Let $p_{co} \in \mathcal{R}^3$ and $e^{\hat{\xi}\theta_{co}} \in \mathcal{R}^{3\times 3}$ denote the position vector and the rotation matrix from the camera frame Σ_c to the object frame Σ_o. Then, the relative rigid body motion from Σ_c to Σ_o can be represented by $g_{co} = (p_{co}, e^{\hat{\xi}\theta_{co}})$, and $g_{ho} = (p_{ho}, e^{\hat{\xi}\theta_{ho}})$ from Σ_h to Σ_o, and $g_{ch} = (p_{ch}, e^{\hat{\xi}\theta_{ch}})$ from Σ_c to Σ_h. Similarly, we will define the rigid body motion $g_{wh} = (p_{wh}, e^{\hat{\xi}\theta_{wh}})$ from Σ_w to Σ_h, and $g_{wc} = (p_{wc}, e^{\hat{\xi}\theta_{wc}})$ from Σ_w to Σ_c, and $g_{wo} = (p_{wo}, e^{\hat{\xi}\theta_{wo}})$ from Σ_w to Σ_o, respectively, as in Fig. 1. The homogeneous representation of $g_{ab} = (p_{ab}, e^{\hat{\xi}\theta_{ab}})$ and the notation '$\wedge$' (wedge) are given in reference[7].

The objective of the visual feedback control is to bring the actual relative rigid body motion $g_{ho} = (p_{ho}, e^{\hat{\xi}\theta_{ho}})$ to a given reference $g_d = (p_d, e^{\hat{\xi}\theta_d})$. Our goal is to determine the robot motion using the visual information for this purpose. The reference $g_d = (p_d, e^{\hat{\xi}\theta_d})$ for the rigid body motion $g_{ho} = (p_{ho}, e^{\hat{\xi}\theta_{ho}})$ is assumed to be constant throughout this paper, because the end of the hand can track the moving target object in this case.

In this subsection, let us derive a fundamental representation for the three coordinate frames of the visual feedback system. Using the notation g_{ab}^{-1} as the inverse of g_{ab}, the relative rigid body motion $g_{co} = (p_{co}, e^{\hat{\xi}\theta_{co}})$ of the target object, relative to the camera frame Σ_c in Fig. 1, is given by

$$g_{co} = g_{wc}^{-1} g_{wo} \tag{1}$$

which is obtained from the composition rule for rigid body transformations[7].

The relative rigid body motion involves the velocity of each rigid body. To this aid, let us consider the velocity of a rigid body as described in reference[7]. Now, we define the body velocity of the camera relative to the world frame Σ_w as $V_{wc}^b = [v_{wc}^T \ \omega_{wc}^T] \in \mathcal{R}^6$. Similarly, the body velocity of the target object relative to Σ_w will be denoted as $V_{wo}^b = [v_{wo}^T \ \omega_{wo}^T] \in \mathcal{R}^6$.

Differentiating (1) with respect to time, the fundamental representation of the relative rigid body motion g_{co} is described as follows[4, 5].

$$V_{co}^b = -\mathrm{Ad}_{(g_{co}^{-1})} V_{wc}^b + V_{wo}^b \tag{2}$$

where $V_{co}^b := [v_{co}^T \ \omega_{co}^T]^T$. The notation $\mathrm{Ad}_{(g_{ab})}$ means the adjoint transformation associated with g_{ab} [7].

2.2 Nonlinear Observer and Estimation Error System

The visual feedback control task should require the information of the relative rigid body motion g_{co}. Since the measurable information is only the image information in the visual feedback systems, we consider a nonlinear observer in order to estimate the relative rigid body motion from the image information.

In the case of the fixed camera configuration, i.e. $V_{wc}^b = 0$, the fundamental representation of the relative rigid body motion g_{co} can be rewritten as

$$V_{co}^b = V_{wo}^b. \tag{3}$$

We shall consider the following model which is reproduced from the fundamental representation (3) just as Luenberger observer for linear systems.

$$\bar{V}_{co}^b = u_e \tag{4}$$

where $\bar{g}_{co} = (\bar{p}_{co}, e^{\hat{\bar{\xi}}\bar{\theta}_{co}})$ and $\bar{V}_{co}^b$ are the estimated value of the relative rigid body motion and the estimated body velocity, respectively. The new input u_e is to be determined in order to converge the estimated value to the actual relative rigid body motion. Because the design of u_e needs a property of the whole visual feedback system, we will propose u_e in Section 3.2.

In order to establish the estimation error system, we define the estimation error $g_{ee} = (p_{ee}, e^{\hat{\xi}\theta_{ee}})$ between the estimated value $\bar{g}_{co}$ and the actual relative rigid body motion g_{co} as

$$g_{ee} = \bar{g}_{co}^{-1} g_{co}, \tag{5}$$

in other words, $p_{ee} = e^{-\hat{\bar{\xi}}\bar{\theta}_{co}}(p_{co} - \bar{p}_{co})$ and $e^{\hat{\xi}\theta_{ee}} = e^{-\hat{\bar{\xi}}\bar{\theta}_{co}} e^{\hat{\xi}\theta_{co}}$. Note that $p_{co} = \bar{p}_{co}$ and $e^{\hat{\xi}\theta}_{co} = e^{-\hat{\bar{\xi}}\bar{\theta}_{co}}$ iff $g_{ee} = I_4$, i.e. $p_{ee} = 0$ and $e^{\hat{\xi}\theta_{ee}} = I_3$. Using the notation $e_R(e^{\hat{\xi}\theta})$, the vector of the estimation error is given by $e_e := [p_{ee}^T \ e_R^T(e^{\hat{\xi}\theta_{ee}})]^T$. Hence, $e_e = 0$ iff $p_{ee} = 0$ and $e^{\hat{\xi}\theta_{ee}} = I_3$. Therefore, if the vector of the estimation error is equal to zero, then the estimated relative rigid body motion $\bar{g}_{co}$ equals the actual relative rigid body motion g_{co}. The vector of the estimation error e_e can be obtained from the actual image information and the estimated one[4, 5].

Next, we will derive an estimation error system. The estimation error system will be derived in the same way as the fundamental representation for the visual feedback system. Differentiating (5) with respect to time, and combining (3) and (4), we can obtain

$$V_{ee}^b = -\mathrm{Ad}_{(g_{ee}^{-1})} u_e + V_{wo}^b. \tag{6}$$

Eq. (6) represents the estimation error system.

2.3 Control Error System

Let us derive the control error system in the same way as the estimation error system in order to establish the visual feedback system. Similarly to (1), the relative rigid body motion $g_{ho} = (p_{ho}, e^{\hat{\xi}\theta_{ho}})$ of the target object, relative to the hand frame Σ_h in Fig. 1, is given by

$$g_{ho} = g_{ch}^{-1} g_{co}. \tag{7}$$

Because g_{co} can not be obtained directly, we represent the relative rigid body motion g_{ho} with the estimated one $\bar{g}_{co}$ as

$$\bar{g}_{ho} = g_{ch}^{-1} \bar{g}_{co}. \tag{8}$$

Here $g_{ch} = g_{wc}^{-1} g_{wh}$ can be obtained directly, because the rigid body motion $g_{wc} = (p_{wc}, e^{\hat{\xi}\theta_{wc}})$ from Σ_w to Σ_c and $g_{wh} = (p_{wh}, e^{\hat{\xi}\theta_{wh}})$ from Σ_w to Σ_h is known by the structure of the system and the angle of the manipulator. It is supposed that the relative rigid body motion g_{ch} can be measured exactly. Since the problem of the camera calibration is one of important research topics and good solutions to it are reported in some papers (see, e.g. reference[8]), we will not consider the error of the camera calibration in this paper.

Then, the fundamental representation of the relative rigid body motion $\bar{g}_{ho}$ will be obtained in the same way as (2).

$$\begin{aligned} \bar{V}_{ho}^b &= -\mathrm{Ad}_{(\bar{g}_{ho}^{-1})} V_{ch}^b + \bar{V}_{co}^b \\ &= -\mathrm{Ad}_{(\bar{g}_{ho}^{-1})} V_{wh}^b + u_e \end{aligned} \tag{9}$$

where we exploit (4) and $V^b_{ch} = V^b_{wh}$ which is derived from $g_{ch} = g_{wc}^{-1} g_{wh}$. Here we define the control error between the estimated value $\bar{g}_{ho}$ and the reference of the relative rigid body motion g_d as

$$g_{ec} = g_d^{-1} \bar{g}_{ho}. \tag{10}$$

It should be remarked that the estimated relative rigid body motion equals the reference one if and only if the control error is equal to the identity matrix in matrix form, i.e. $p_d = \bar{p}_{ho}$ and $e^{\hat{\xi}\theta_d} = e^{\hat{\bar{\xi}}\bar{\theta}_{ho}}$ iff $g_{ec} = I_4$. Using the notation $e_R(e^{\hat{\xi}\theta})$, the vector of the control error is defined as $e_c := [p_{ec}^T \ e_R^T(e^{\hat{\xi}\theta_{ec}})]^T$. Note that $e_c = 0$ iff $p_{ec} = 0$ and $e^{\hat{\xi}\theta_{ec}} = I_3$. Similarly to (6), the control error system can be obtained as

$$V^b_{ec} = -\mathrm{Ad}_{(\bar{g}_{ho}^{-1})} V^b_{wh} + u_e. \tag{11}$$

This is dual to the estimation error system.

2.4 Property of Visual Feedback System

Combining (6) and (11), we construct the visual feedback system as follows.

$$\begin{bmatrix} V^b_{ec} \\ V^b_{ee} \end{bmatrix} = \begin{bmatrix} -\mathrm{Ad}_{(\bar{g}_{ho}^{-1})} & I \\ 0 & -\mathrm{Ad}_{(g_{ee}^{-1})} \end{bmatrix} u_{ce} + \begin{bmatrix} 0 \\ I \end{bmatrix} V^b_{wo} \tag{12}$$

where $u_{ce} := [(V^b_{wh})^T \ u_e^T]^T$ denotes the control input for the visual feedback system. Let us define the error vector of the visual feedback system as $e := \left[e_c^T \ e_e^T\right]^T$ which contains of the control error vector e_c and the estimation error vector e_e. It should be noted that if the vectors of the control error and the estimation error are equal to zero, then the estimated relative rigid body motion $\bar{g}_{ho}$ equals the reference one g_d and the estimated one $\bar{g}_{co}$ equals the actual one g_{co}, respectively. Moreover, the error and the error vector between $\bar{g}_{ho}$ and g_{ho} can be also represented as g_{ee} and e_e by (5), (7) and (8), while g_{ee} and e_e are defined as the error and the error vector between $\bar{g}_{co}$ and g_{co} in (5). Therefore, the actual relative rigid body motion g_{ho} tends to the reference one g_d when $e \to 0$.

Now, we show an important lemma concerning a relation between the input and the output of the visual feedback system.

Lemma 1 If $V^b_{wo} = 0$, then the visual feedback system (12) satisfies

$$\int_0^T u_{ce}^T \nu_{ce} d\tau \geq -\beta_{ce}, \quad \forall T > 0 \tag{13}$$

where ν_{ce} is defined as

$$\nu_{ce} := \begin{bmatrix} -\mathrm{Ad}^T_{(g_d^{-1})} & 0 \\ \mathrm{Ad}_{(e^{-\hat{\xi}\theta_{ec}})} & -I \end{bmatrix} e \tag{14}$$

and β_{ce} is a positive scalar.

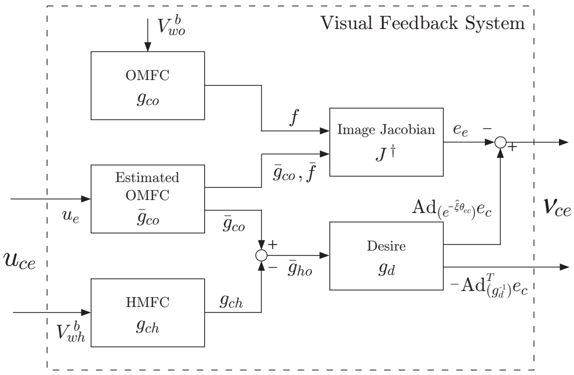


Figure 2: Block diagram of the visual feedback system

Lemma 1 is proved by considering the following positive definite function

$$V_{ce}(e) = \frac{1}{2}\|p_{ec}\|^2 + \phi(e^{\hat{\xi}\theta_{ec}}) + \frac{1}{2}\|p_{ee}\|^2 + \phi(e^{\hat{\xi}\theta_{ee}}) \tag{15}$$

where $\phi(e^{\hat{\xi}\theta}) := \frac{1}{2}\mathrm{tr}(I - e^{\hat{\xi}\theta})$ is the error function of the rotation matrix (see, e.g. reference[9]).

The block diagram of the visual feedback system is shown in Fig. 2. In Fig. 2, let us take u_{ce} as the input and ν_{ce} as its output. Then, Lemma 1 would suggest that the visual feedback system (12) is passive from the input u_{ce} to the output ν_{ce}.

3. Passivity-based Control of Dynamic Visual Feedback System

3.1 Property of Dynamic Visual Feedback System

The manipulator dynamics can be written as

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau + \tau_d \tag{16}$$

where q, $\dot{q}$ and $\ddot{q}$ are the joint angles, velocities and accelerations, respectively. τ is the vector of the input torques and τ_d represents a disturbance input.

The body velocity of the hand V^b_{wh} is given by

$$V^b_{wh} = J_b(q)\dot{q} \tag{17}$$

where $J_b(q)$ is the manipulator body Jacobian[7]. We define the reference of the joint velocities as $\dot{q}_d := J_b^\dagger(q) u_d$ where u_d represents the desired body velocity of the hand.

Let us define the error vector with respect to the joint velocities of the manipulator dynamics as $\xi := \dot{q} - \dot{q}_d$. Here, we define the weight matrices $W_c := \mathrm{diag}\{w_{pc}I_3, w_{rc}I_3\} \in \mathcal{R}^{6\times 6}$ and $W_e := \mathrm{diag}\{w_{pe}I_3, w_{re}I_3\} \in \mathcal{R}^{6\times 6}$ where w_{pc}, w_{rc}, w_{pe}, $w_{re} \in \mathcal{R}$ are positive. Now, we consider the passivity–based dynamic visual feedback control law as follows.

$$\begin{aligned} \tau = {} & M(q)\ddot{q}_d + C(q,\dot{q})\dot{q}_d + g(q) \\ & + J_b^T(q)\mathrm{Ad}^T_{(g_d^{-1})} W_c e_c + u_\xi. \end{aligned} \tag{18}$$

The new input u_ξ is to be determined in order to achieve the control objectives.

Using (12), (16) and (18), the visual feedback system with manipulator dynamics (we call the dynamic visual feedback system) can be derived as follows

$$\begin{bmatrix} \dot{\xi} \\ V_{ec}^b \\ V_{ee}^b \end{bmatrix} = \begin{bmatrix} -M^{-1}C\xi + M^{-1}J_b^T \mathrm{Ad}_{(g_d^{-1})}^T W_c e_c \\ -\mathrm{Ad}_{(\bar{g}_{ho}^{-1})} J_b \xi \\ 0 \end{bmatrix}$$
$$+ \begin{bmatrix} M^{-1} & 0 & 0 \\ 0 & -\mathrm{Ad}_{(\bar{g}_{ho}^{-1})} & I \\ 0 & 0 & -\mathrm{Ad}_{(g_{ee}^{-1})} \end{bmatrix} u + \begin{bmatrix} M^{-1} & 0 \\ 0 & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \tau_d \\ V_{wo}^b \end{bmatrix}$$
$$z = \begin{bmatrix} \varepsilon x \\ \rho u \end{bmatrix} \tag{19}$$

where $x := [\xi^T \ e_c^T \ e_e^T]^T$ and $u := [u_\xi^T \ u_d^T \ u_e^T]^T$. ε and ρ are weight matrices for the state and the input, respectively. We define the disturbance of the dynamic visual feedback system as $w := \left[\tau_d^T \ (V_{wo}^b)^T\right]^T$. Before constructing the dynamic visual feedback control law, we derive an important lemma.

Lemma 2 If $w = 0$, then the dynamic visual feedback system (19) satisfies

$$\int_0^T u^T \nu d\tau \geq -\beta, \quad \forall T > 0 \tag{20}$$

where

$$\nu := Nx, \ N := \begin{bmatrix} I & 0 & 0 \\ 0 & -\mathrm{Ad}_{(g_d^{-1})}^T W_c & 0 \\ 0 & \mathrm{Ad}_{(e^{-\hat{\xi}\theta_{ec}})} W_c & -W_e \end{bmatrix} \tag{21}$$

and β is a positive scalar.

Lemma 2 is proved by considering the following positive definite function

$$V(x) = \frac{1}{2}\xi^T M \xi + \frac{1}{2} w_{pc} \|p_{ec}\|^2 + w_{rc}\phi(e^{\hat{\xi}\theta_{ec}}) + \frac{1}{2} w_{pe}\|p_{ee}\|^2 + w_{re}\phi(e^{\hat{\xi}\theta_{ee}}). \tag{22}$$

The visual feedback system (12) satisfies the passivity property as described in (13). It is well known that the manipulator dynamics (16) also has the passivity. These passivity properties are connected by the manipulator Jacobian (17). In Lemma 2, the inequality (20) would suggest that the dynamic visual feedback system (19) is passive from the input u to the output ν.

3.2 Stability Analysis for Dynamic Visual Feedback System

It is well known that there is a direct link between passivity and Lyapunov stability. Thus, we propose the following control input.

$$u = -K\nu = -KNx, \ K := \begin{bmatrix} K_\xi & 0 & 0 \\ 0 & K_c & 0 \\ 0 & 0 & K_e \end{bmatrix} \tag{23}$$

where K_ξ:=diag$\{k_{\xi 1}, \cdots, k_{\xi n}\}$ denotes the positive gain matrix for each joint axis. $K_c :=$ diag$\{k_{c1}, \cdots, k_{c6}\}$ and K_e:= diag$\{k_{e1}, \cdots, k_{e6}\}$ are the positive gain matrices of x, y and z axes of the translation and the rotation for the control error and the estimation error, respectively. The result with respect to asymptotic stability of the proposed control input (23) can be established as follows.

Theorem 1 If $w = 0$, then the equilibrium point $x = 0$ for the closed-loop system (19) and (23) is asymptotic stable.

(Proof) Omitted due to space limitations. □

The block diagram of the dynamic visual feedback system is shown in Fig. 3.

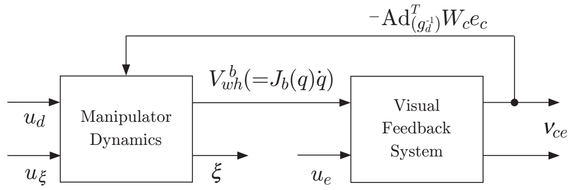


Figure 3: Block diagram of the dynamic visual feedback system

3.3 L_2-gain Performance Analysis for Dynamic Visual Feedback System

Next, we consider L_2-gain performance analysis for the dynamic visual feedback system. Now, let us define

$$P := N^T K N - \frac{1}{2\gamma^2} W - \frac{1}{2}\|\varepsilon\|^2 - \frac{1}{2}\|\rho K N\|^2 \tag{24}$$

where $\gamma \in \mathcal{R}$ is positive and $W :=$ diag$\{I, 0, W_e^2\}$. Then we have the following theorem.

Theorem 2 Given a positive scalar γ and consider the control input (23) with the weight matrices ε, ρ, W_c and W_e and the gains K_ξ, K_c and K_e such that the matrix P is positive semi-definite, then the closed-loop system (19) and (23) has L_2-gain $\leq \gamma$.

(Proof) By differentiating the positive definite function V defined in (22) along the trajectory of the closed-loop system and completing the squares, it holds that

$$\dot{V} + \frac{1}{2}\|z\|^2 - \frac{\gamma^2}{2}\|w\|^2 \leq -x^T P x \leq 0 \tag{25}$$

if P is positive semi-definite. Integrating (25) from 0 to T and noticing $V(T) \geq 0$, we have

$$\int_0^T \|z\|^2 dt \leq \gamma^2 \int_0^T \|w\|^2 dt + 2V(0), \ \forall T > 0. \tag{26}$$

This completes the proof. □

γ represents a disturbance attenuation level for the dynamic visual feedback system. Theorem 1 and 2 can be proved using the energy function (22) as a Lyapunov function and a storage function, respectively.

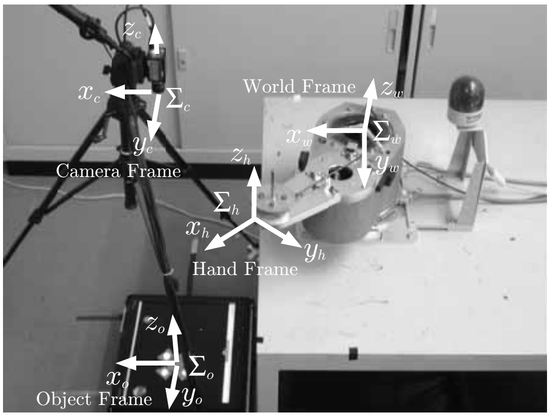
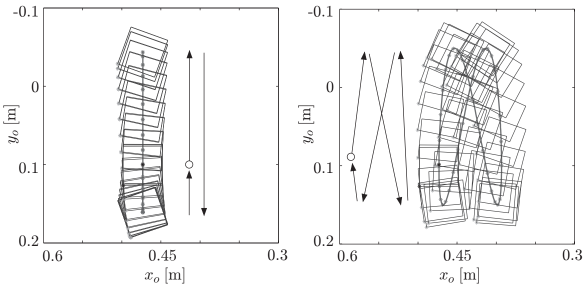


Figure 4: Experimental arm



($0 \leq t < 4$ [s]) ($4 \leq t \leq 9.6$ [s])

Figure 5: Trajectory of the target object

4. Experimental Case Study

The manipulator use in the study, known as SICE-DD arm (see Fig. 4), is controlled by a digital signal processor(DSP) from DSPACE Inc., which utilize a powerPC 750 running at 480 MHz. Control problem is written in MATLAB and SIMULINK, and implemented on the DSP using the Real-Time Workshop and dSPACE Software which includes ControlDesk, Real-Time Interface and so on. A PULNiX TM-7EX camera is mounted on $[0.47\ 0.10\ 0.19]^T$ [m]. The video signals is acquired by a frame graver board PicPort-Stereo-H4D and a image processing software HALCON.

We define the four coordinates which are described in Fig. 4. Let the target object have four feature points which are projected on the display. The object moves along a straight line ($0 \leq t < 4$) and a "Figure 8" motion ($4 \leq t \leq 9.6$) as depicted in Fig. 5.

The experimental tests were carried out with the following initial configuration: $e_c(0) = e_e(0) = 0$, $q_1(0) = 30°$, $q_2(0) = -30°$, and $\dot{q}_1(0) = \dot{q}_2(0) = 0$. The objective of the visual feedback control is to bring the actual relative rigid body motion $g_{ho} = (p_{ho}, e^{\hat{\xi}\theta_{ho}})$ to a given reference $g_d = (p_d, e^{\hat{\xi}\theta_d})$. In this study, we set a reference of position and rotation as $p_d = [0\ 0\ -0.81]^T$, $e^{\hat{\xi}\theta_d} = I$.

Firstly, we confirm the effectiveness of the weight matrices W_c and W_e. The control gain of the manipulator is chosen as $K_e = 15I$ and $K_\xi = \mathrm{diag}\{10, 10\}$. K_c and the weight matrices W_c and W_e are chosen as follows

$$\begin{aligned} \text{Gain A} : K_c &= \mathrm{diag}\{10, 10, 5, 5, 5, 10\}, \\ W_c &= I,\ W_e = I \\ \text{Gain B} : K_c &= \mathrm{diag}\{100, 100, 50, 50, 50, 100\}, \\ W_c &= 0.1I,\ W_e = I. \end{aligned}$$

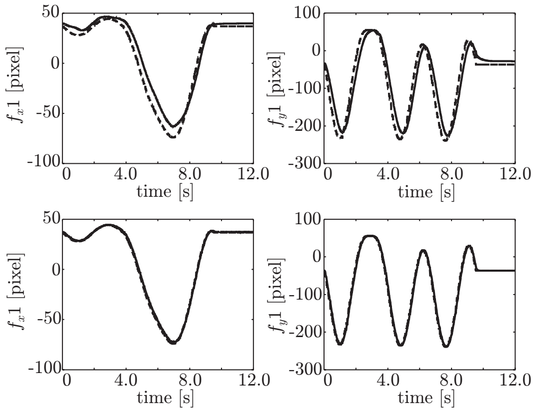


Figure 6: Estimated feature points
(top: Gain A, bottom: Gain B)

Fig. 6 presents one of the four estimated feature points. The top graph and the bottom one show the case of Gain A and Gain B, respectively. In this figure, the dashed lines denote the feature points obtained by the actual image information and the solid lines denote the feature points obtained by the estimated one. The estimation error of the feature points can be decreased by using the weight matrices as Gain B. Thus, we consider that the weight matrices play the role of the design parameter for the estimation.

Next, we verify the stability and L_2-gain performance of the dynamic visual feedback system. We design the weight matrices concerning controlled output as $\varepsilon = \mathrm{diag}\{0.4,\ 0.4,\ 1,\ 1,\ 0.25,\ 0.25,\ 0.25,\ 1,\ 2.5,\ 2.5,\ 0.025,\ 0.025,\ 0.025,\ 2.5\}$, $\rho = \mathrm{diag}\{0.02,\ 0.02,\ 2,\ 2,\ 1,\ 1,\ 1,\ 2,\ 10,\ 10,\ 0.1,\ 0.1,\ 0.1,\ 10\} \times 10^{-3}$. Also we select Gain C as follows

$$\begin{aligned} \text{Gain C} : K_c &= \mathrm{diag}\{240, 240, 120, 120, 120, 240\}, \\ K_e &= 30I,\ K_\xi = \mathrm{diag}\{10, 10\},\ W_c = 0.1I,\ W_e = I \end{aligned}$$

Then, the closed-loop system (19) and (23) with Gain B has $\gamma = 0.269$ and with Gain C has $\gamma = 0.225$.

Fig. 7 and 8 present the control error vectors e_c and the estimation error vectors e_e, the top graph, the middle one and the bottom one show the error of the translation of the x axis, the error of the translation of the y axis and the error of the rotation of the z axis, respectively. In these figures, the left graphs denote the error of the case of $\gamma = 0.269$ and the right ones denote the error of the case of $\gamma = 0.225$. In Fig. 9, the top graph and the bottom one show the norm of z in the case of $\gamma = 0.269$ and $\gamma = 0.225$, respectively. In the

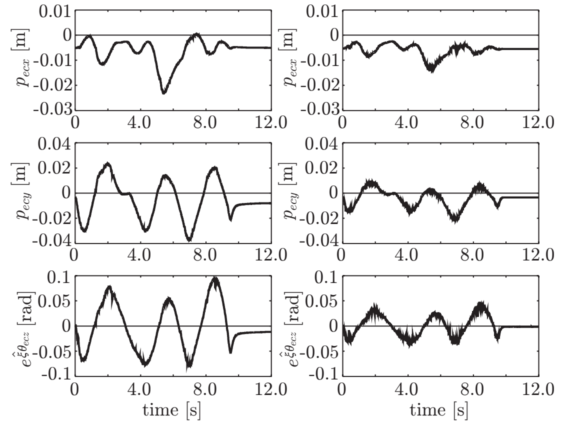


Figure 7: Control errors
(left: Gain B, right: Gain C)

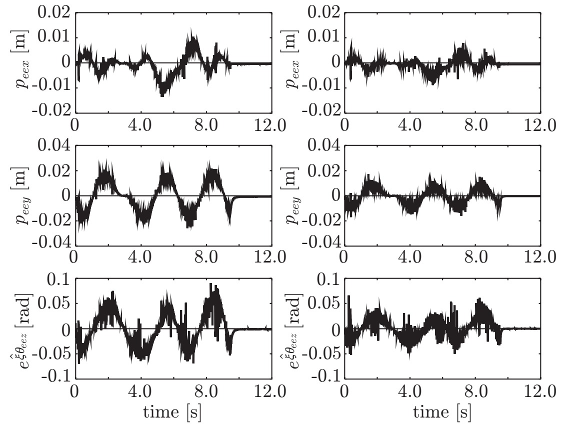


Figure 8: Estimation errors
(left: Gain B, right: Gain C)

case of the static target object, i.e. after $t = 9.6$ [s], all errors in Fig. 9 tend to zero. It can be concluded that the equilibrium point is asymptotically stable if the target object is static. In the case of $\gamma = 0.225$, the performance is improved as compared to the case of $\gamma = 0.269$. After all, the experimental results show that L_2-gain is adequate for the performance measure of the dynamic visual feedback control.

5. Conclusion

This paper dealt with the control and the estimation of dynamic visual feedback systems with a fixed camera. Firstly the fundamental representation of the relative rigid body motion and the nonlinear observer are described in order to derive the dynamic visual feedback system. Secondly we proposed the dynamic visual feedback control law which is based on passivity. Stability and L_2-gain performance analysis for the dynamic visual feedback system has been discussed using the energy function. Finally experimental results on SICE–DD arm have been shown to verify the stability

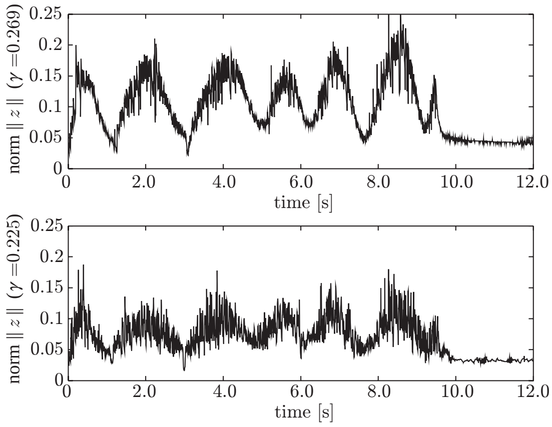


Figure 9: Euclid norms of z
(top: Gain B, bottom: Gain C)

and L_2-gain performance of the dynamic visual feedback system.

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