Position-based Visual Servoing to 3D Pose with Feedforward Compensation

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Abstract: This paper deals with position-based 6-DoF visual servoing. With a common sense of feedback control, we stress that improvement of the dynamics of the sensing feedback unit is important for a stable visual servoing system. We propose a method to improve dynamics in visual recognition of model-based matching, with the on-line matching compensating the fictional motion of the target in the hand-eye camera images caused by the ego motion of the manipulator, by extracting the real motion of the target. We named it as hand-eye motion feedforword (MFF) method. The enhanced dynamics of recognition gave further stability and precision to the total visual servoing system, evaluated by full 6-DoF actual manipulator.

Keywords: visual servoing; hand-eye motion feedforword.

1 Introduction

Tasks in which visual information are used to direct a manipulator toward a target object are referred to visual servoing in [1]. Generally, visual servoing can be described as a feedback control (Fig.1), where hand-eye motion disturbs recognition in H, and incorrect recognition will cause hand motion Y to be unstable, and the disturbed Y amplifies servoing error. This repeating connection in feedback loop may lead to dangerous unstable motion. Such an undesirable circulation is preferably cut down by improving the recognition dynamics to make the system be robust against the hand-eye motion. However, it looks like that the researches concerning the sensing dynamics for visual servoing have not been concentrated energetically so far. In this paper, we propose a method to compensate the effect on recognition from the robot manipulator's motion. We named it as hand-eye motion feedforword (MFF) method.

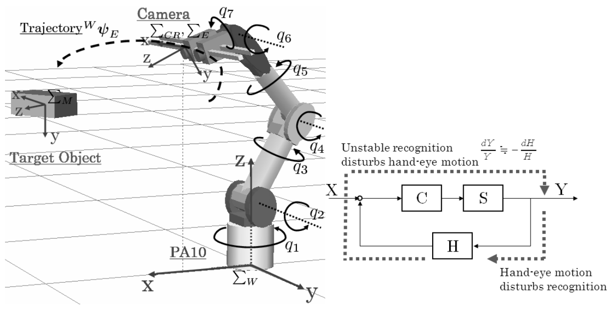


Fig. 1 Visual servo system of PA-10

Visual servoing methodologies can be classified into two major groups: position-based and image-based visual servoing. Position-based visual servoing is to determine the object pose in Cartesian coordinate frame and lead to Cartesian robot motion planning, [2]. On the other hand, in an image-based visual servoing, image features are measured in the 2-D image space, and the robot is controlled directly to servo the image features to a set of desired locations [3], without recognizing the target pose in 3-D space. Comparing image-based visual servoing with position-based visual servoing, the latter is more understandable, since the way of the visual servo is more like human-beings, who always perceive their poses in Cartesian space and the perception is effectively important during dynamical action like sports.

We use a model-based matching method and genetic algorithm (GA) to recognize a target object in a 3-D searching area, [4]. To recognize a target input by CCD camera in real-time, and to avoid time lag waiting for the convergence to a target, we used GA in dynamic image recognition [5] with proposed MFF and the effectiveness was confirmed by actual experiment.

2 Motion-Feedforward (MFF) Compensation

The motion of the target seeing from the camera will be affected by both the motion of the target in the real world and the motion of the camera in a eye-in-hand system. Here we describe such a relationship by a mathematical function, which can distinguish these two motions.

$$
\begin{aligned}
{}^{CR}\dot{\psi}_M &= \begin{bmatrix} {}^{CR}\dot{r}_M \\ {}^{CR}\dot{\epsilon}_M \end{bmatrix} \\
&= \begin{bmatrix} -{}^{CR}R_W(q)J_p(q) + {}^{CR}R_W(q) \\ S({}^{W}R_{CR}(q)\,{}^{CR}r_M)J_o(q) \\ -\frac{1}{2}({}^{CR}\eta_M I - S({}^{CR}\epsilon_M))\,{}^{CR}R_W(q)J_o(q) \end{bmatrix} \dot{q} \\
&+ \begin{bmatrix} {}^{CR}R_W(q) & 0 \\ 0 & {}^{CR}R_W(q) \end{bmatrix} \begin{bmatrix} {}^{W}\dot{r}_M \\ {}^{W}\dot{\epsilon}_M \end{bmatrix} \\
&= J_M(q, {}^{CR}\psi_M)\dot{q} + J_N(q)\,{}^{W}\dot{\psi}_M . \qquad (1)
\end{aligned}
$$

Please refer to [4] for a detailed deduction procedural of Eq. (1). Here, the target's orientation is represented by unit quaternion [6], which has a advantage that can represent the orientation of a rigid body without singularities.

The matrix J_M in Eq. (1) describes how target pose change in camera coordinate Σ_{CR} with respect to changing manipulator pose in Σ_{CR}. The matrix J_N in Eq. (1) describes how target pose change in Σ_{CR} with respect to the pose changing of itself in real word.

In this paper, we do not deal with the prediction of the target's motion in the real world, we take account of the prediction of the target velocity in Σ_{CR} based on the joint velocity $\dot{q}$ of the manipulator, so we can rewrite Eq. (1) as

$$ {}^{CR}\dot{\psi}_M = J_M(q, {}^{CR}\psi_M)\dot{q}. \qquad (2) $$

Then the 3-D pose of the target at time $t+\Delta t$ can be predicted based on the motion of the end-effecter at time t, presented by

$$ {}^{CR}\hat{\psi}_M(t+\Delta t) = {}^{CR}\hat{\psi}_M(t) + \hat{J}_M(q(t), {}^{CR}\hat{\psi}_M(t))\dot{q}(t)\Delta t. \qquad (3) $$

We consider that the recognition ability will be improved by using Eq. (3) to predict the future pose of the target based on the ego motion of the robot manipulator. Thus, the target model will move together with the object in Σ_{CR}, never loose it even under a high-speed moving of robot manipulator, which will improve the stability of visual servoing.

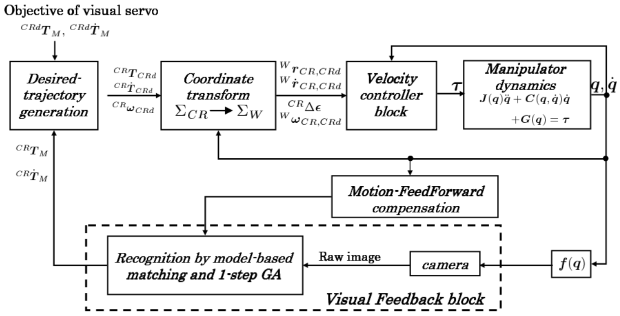


Fig. 2 Block diagram of the visual servoing system

3 Servoing Controller

The block diagram of the visual servoing system in Fig.2. Based on the above analysis of the desired-trajectory generation, the desired hand velocity ${}^{W}\dot{r}_d$ is calculated as,

$$ {}^{W}\dot{r}_d = K_{P_p}\,{}^{W}r_{CR,CRd} + K_{V_p}\,{}^{W}\dot{r}_{CR,CRd}, \qquad (4) $$

Where ${}^{W}r_{CR,CRd}, {}^{W}\dot{r}_{CR,CRd}$ are given by transforming ${}^{CR}T_{CRd}$ and ${}^{CR}\dot{T}_{CRd}$ from Σ_{CR} to Σ_W. K_{P_p} and K_{V_p} are positive definite matrix to determine PD gain.

The desired hand velocity ${}^{W}\omega_d$ is calculated as,

$$ {}^{W}\omega_d = K_{P_o}\,{}^{W}R_{CR}\,{}^{CR}\Delta\epsilon + K_{V_o}\,{}^{W}\omega_{CR,CRd}, \qquad (5) $$

where ${}^{CR}\Delta\epsilon$ is the quaternion error that from the recognition result directly, and ${}^{W}\omega_{CR,CRd}$ can be calculated by transforming ${}^{CR}T_{CRd}$ and ${}^{CR}\dot{T}_{CRd}$ from Σ_{CR} to Σ_W. Also, K_{P_o} and K_{V_o} are suitable feedback matrix gains.

The desired joint variable $\dot{q}_d$ is obtained by

$$ \dot{q}_d = J^{+}(q) \begin{bmatrix} {}^{W}\dot{p}_d \\ {}^{W}\omega_d \end{bmatrix}. \qquad (6) $$

where $J^{+}(q)$ is the pseudoinverse matrix of $J(q)$, and $J^{+}(q) = J^T(JJ^T)^{-1}$. The control system, based on a PI control is expressed as

$$\tau = K_{SP}(\dot{q}_d - \dot{q}) + K_{SI}\int_0^t (\dot{q}_d - \dot{q})dt \quad (7)$$

where $\dot{q}_d - \dot{q}$ is the velocity error of the joint angle, K_{SP} and K_{SI} are symmetric positive definite matrix to determine PI gain.

4 Visual Servoing Experiment

To verify the effectiveness of the proposed visual servoing system, we conduct the experiment of visual servoing to a 3D marker that is composed of a red ball, a green ball and a blue ball. The radiuses of these three balls are set as 30[mm].

4.1 Experimental Condition

A photograph of our experimental system is shown in Fig. 3. The robot used in this experimental system is a 7-Link manipulator, Mitsubishi Heavy Industries PA-10 robot. Two cameras are mounted on the robot manipulator's end-effecter.

4.2 Step Response Experiment

Here, a static object is set as,

${}^{CR}\psi_M = [-70[mm], 70[mm], 1000[mm], 0.1, -0.2, 0.12]^T$,

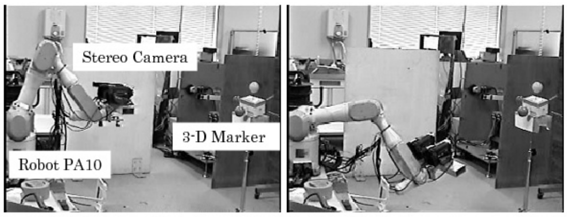
where the value of orientation 0.1 in quaternion expression is about 12[deg].

The objective of visual servoing is given by a fixed relation between Σ_{CR} and Σ_M, as

${}^{CR}\psi_{Md} = [0[mm], 10[mm], 900[mm], 0, 0, 0]^T$.

The initial pose of the robot manipulator is shown in Fig.3 (a), and the moved robot manipulator to satisfy ${}^{CR}\psi_{Md}$ is shown in Fig.3(b). The initial pose of the end-effecter is defined as Σ_{E_0}.

To show the effectiveness of the proposed MFF method, we perform the step response experiment with MFF method and without MFF method separately. Fig 4 shows the difference of the desired hand pose and the actual hand pose in Σ_{E_0} without using MFF method. Fig 5 shows the hand difference with using MFF method. In Fig.4, the end-effecter is unstable from 6[s] to 28[s]. Since the hand began to move, the object in camera frame was moving together with the end-effecter, then the recognition dynamics became worse, which cause the vibration in this period. The end-effecter cost 30[s] to be converged to the desired pose in the case of not using MFF compensation.



(a) (b)

Fig. 3 Step response experiment. (a) Initial pose of Pa10. (b) Visual servoing to a static 3-D marker.

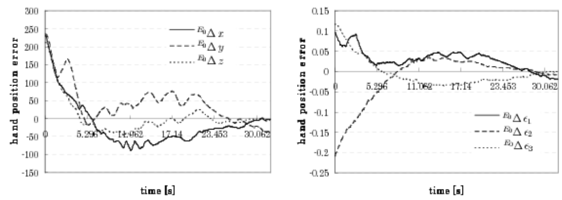


Fig. 4 Hand pose error of step response without using MFF

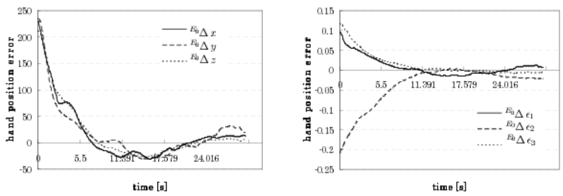


Fig. 5 Hand pose error of step response by using MFF

On the other hand, as shown in Fig 5, such vibrations existing in Fig 4 had been suppressed, and the end-effecter cost about 10[s] to converge to the desired pose by using MFF method.

4.3 Visual Servoing To A Moving Object

In this experiment, the target object is fixed on a mobile robot, as shown in Fig.6. The coordinate system of the mobile robot is represented as Σ_R.

Here, the motion of the mobile robot is rotation around the z axis of Σ_R by

$$\theta_d[deg] = a\sin(\frac{2\pi}{T})t; \quad (8)$$

where we set a=8[deg], T=40[s].

The voltage of the right and left wheel is given by

$$V_R = kp(\theta_d - \theta) + kv(\dot{\theta}_d - \dot{\theta}); \quad V_L = -V_R; \quad (9)$$

where k_p and k_v are feedback PD control gains.

The objective of visual servoing is given by

${}^{CR}\psi_{Md} = [0[mm], 10[mm], 700[mm], 0, 0, 0]^T$.

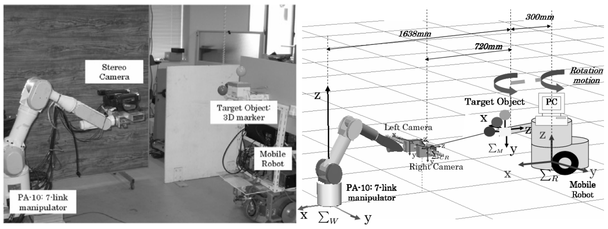


Fig. 6 A photograph of visual servo system (left) and its coordinate frames(right)

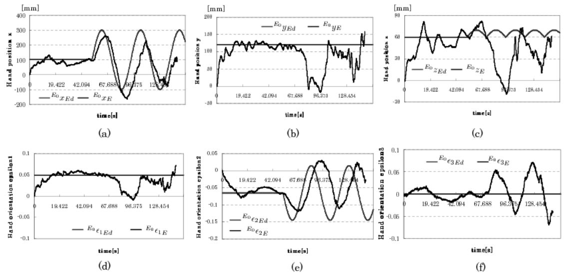


Fig. 7 Hand pose error of visual servoing without MFF. method

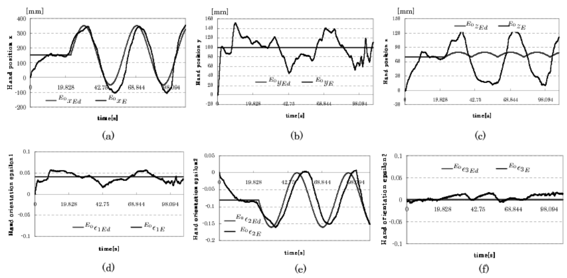


Fig. 8 Hand pose error of visual servoing with MFF. method

Figs 7(a) to (f) is the experimental results in the case of not using MFF method, which show the actual motion of the end-effecter with respect to the fixed frame of $Ü_{E0}$, defined as $^{E0}†_{E}$, compared with the desired hand pose $^{E0}†_{Ed}$. Figs 8(a) to (f) show the experimental results in the case of using MFF method. In the period of the trajectory of $^{E0}†_{Ed}$ is a straight line, the mobile robot did not move, visual servoing to a static object was performed firstly. Then the desired trajectory in Fig 7 and Fig 8 (a),(e) began to turn to curved line of sin/cos function,the mobile robot started to move.

Comparing Figs 7(a), (e) with Fig 8(a), (e), the time-delay of hand motion in the case of using MFF method was smaller than that without using MFF method. The errors of hand motion in the other (b),(c),(d),(f) figures were also smaller in the case of using MFF method. This experiment of visual servoing to a moving object has also confirmed the effectiveness of the proposed MFF method and the stability improvement of the visual servoing system.

5 Conclusion

This paper deals with position-based 6-DoF visual servoing. We propose a MFF method to compensate the fictional motion of the target based on the joint velocity of manipulator, and extract the real motion of the target for the robot to recognize during visual servoing.Thus, visual recognition preciseness is improved, and the visual servoing become more stable. The effectiveness of our proposed visual servoing system has been confirmed by experiments.

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