Visual Servoing to 3D Pose by Evolutionary Recognition Based on Quaternion and Feedforward Compensation

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Abstract— This paper deals with visual servoing to a 3D pose (6 degree of freedom) of a target object, whose pose is expressed by unit quaternion. We propose a motion-feedforward (MFF) method to improve visual recognition dynamics, which is worsened by being disturbed hand-eye motion during visual servoing of the robot manipulator.

Key Words: Pose measurement, Unit quaternion, GA, Motion-feedforward compensation

1. Introduction

In recent years, object recognition and visual tracking and servoing have been studied intensively in the field of robotics and in other research areas [1]. Most visual servo systems use an hand-eye configuration, having the camera mounted on the robot's end-effector, so the dynamics of the manipulator will cause the recognition dynamics to deteriorate directly. It is common sense that the time-delay of recognition existing in feedback largely decreases the stability of whole control system. In this paper, we proposed a motion-feedforward (MFF) method to improve the recognition dynamics by distinguishing the motion of the target object in real world from the affected motion by compensating the dynamic motion of the robot end-effector with camera.

In this paper,unit quaternion is used to represent the orientation of the target object, which has a advantage that can represent the orientation of a rigid body without singularities. Moreover, using quaternion errors can make the control system exponentially stable [2], on the contrary, the system can not be converged by using Euler angle errors and angle/axis errors and desired tracking can not be achieved.

2. Motion-Feedforward (MFF) [3]

In Fig. 1, the target coordinate system is represented as Σ_M, the right camera coordinate system is represented as Σ_{CR}, and the reference coordinate is represented as Σ_W.

The motion of the target seeing from the camera ${}^{CR}\dot{\boldsymbol{\psi}}_M$ will be affected by both the motion of the target in the real world ${}^{W}\dot{\boldsymbol{\psi}}_M$ and the motion of the camera $\dot{\boldsymbol{q}}$ in hand-eye system. Here we describe such a relationship by the following mathematical function,

$$
\begin{aligned}
{}^{CR}\dot{\boldsymbol{\psi}}_M &= \begin{bmatrix} {}^{CR}\dot{\boldsymbol{p}}_M \\ {}^{CR}\dot{\boldsymbol{\epsilon}}_M \end{bmatrix} \\
&= \begin{bmatrix} -{}^{CR}\boldsymbol{R}_W(\boldsymbol{q})\boldsymbol{J}_P(\boldsymbol{q}) + {}^{CR}\boldsymbol{R}_W(\boldsymbol{q}) \\ \qquad \boldsymbol{S}({}^{W}\boldsymbol{R}_{CR}(\boldsymbol{q}){}^{CR}\boldsymbol{p}_M)\boldsymbol{J}_O(\boldsymbol{q}) \\ -\frac{1}{2}({}^{CR}\eta_M\boldsymbol{I} - \boldsymbol{S}({}^{CR}\boldsymbol{\epsilon}_M)){}^{CR}\boldsymbol{R}_W(\boldsymbol{q})\boldsymbol{J}_O(\boldsymbol{q}) \end{bmatrix} \dot{\boldsymbol{q}} \\
&\quad + \begin{bmatrix} {}^{CR}\boldsymbol{R}_W(\boldsymbol{q}) & 0 \\ 0 & {}^{CR}\boldsymbol{R}_W(\boldsymbol{q}) \end{bmatrix} \begin{bmatrix} {}^{W}\dot{\boldsymbol{p}}_M \\ {}^{W}\dot{\boldsymbol{\epsilon}}_M \end{bmatrix} \\
&= \boldsymbol{J}_M(\boldsymbol{q}, {}^{CR}\boldsymbol{p}_M, {}^{CR}\boldsymbol{\epsilon}_M)\dot{\boldsymbol{q}} + \boldsymbol{J}_N(\boldsymbol{q}){}^{W}\dot{\boldsymbol{\psi}}_M. \qquad (1)
\end{aligned}
$$

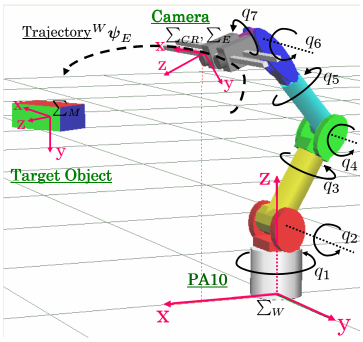

Fig.1 Visual servo system of PA-10

The matrix $\boldsymbol{J}_M$ in (1) describes how target pose change in Σ_{CR} with respect to changing manipulator pose in Σ_{CR}. The matrix $\boldsymbol{J}_N$ in (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, so let $\boldsymbol{J}_N = 0$.

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

$$
{}^{CR}\hat{\boldsymbol{\psi}}_M(t + \Delta t) = {}^{CR}\boldsymbol{\psi}_M(t) + {}^{CR}\dot{\boldsymbol{\psi}}_M\Delta t. \qquad (2)
$$

Here, ${}^{CR}\boldsymbol{\psi}_M(t)$ represents the target object's pose in Σ_{CR}, which can be recognized in real time by cameras using model-based method and "1-Step GA" [3].

3. Controller

3·1 Desired-trajectory generation

The task in visual servoing is to use visual information to control the pose of the robot's end-effecter relative to a target object. In Fig. 2, suppose the motion of the target object ${}^{W}\boldsymbol{T}_M(t)$ (Homogeneous Transformation) is given, and the relative relationship

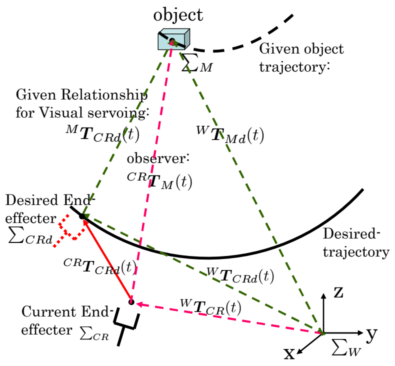

Fig.2 End-effector's motion trajectory

of Σ_M and Σ_{CR} denoted by ${}^{CRd}\boldsymbol{T}_M(t)$ is also given, then a desired-trajectory of the robot's end-effecter is determined by

$$ {}^{W}\boldsymbol{T}_{CRd}(t) = {}^{W}\boldsymbol{T}_M(t) {}^{CRd}\boldsymbol{T}_M{}^{-1}(t). \tag{3} $$

Denote the controlled end-effeter's coordinate as Σ_{CR}, and the relative relationship ${}^{CR}\boldsymbol{T}_M(t)$ can be observed by cameras, so the actual-trajectory of end-effecter is expressed by

$$ {}^{W}\boldsymbol{T}_{CR}(t) = {}^{W}\boldsymbol{T}_M(t) {}^{CR}\boldsymbol{T}_M{}^{-1}(t). \tag{4} $$

By using Eq. (3), (4) the difference of Σ_{CRd} and Σ_{CR} denoted as ${}^{CR}\boldsymbol{T}_{CRd}$ can be deduced as

$$ \begin{aligned} {}^{CR}\boldsymbol{T}_{CRd} &= {}^{W}\boldsymbol{T}_{CR}^{-1}(t) {}^{W}\boldsymbol{T}_{CRd}(t) && (5) \\ &= ({}^{W}\boldsymbol{T}_M(t) {}^{CR}\boldsymbol{T}_M^{-1}(t))^{-1} \, {}^{W}\boldsymbol{T}_M(t) \; {}^{CRd}\boldsymbol{T}_M^{-1}(t) \\ &= {}^{CR}\boldsymbol{T}_M(t) \; {}^{M}\boldsymbol{T}_{CRd}(t), && (6) \end{aligned} $$

Notice that Eq. (6) is a general deduction that satisfies arbitrary object motion ${}^{W}\boldsymbol{T}_M(t)$ and objective of visual servoing ${}^{CRd}\boldsymbol{T}_M(t)$.

Differentiating Eq. (6) with respect to time yields

$$ {}^{CR}\dot{\boldsymbol{T}}_{CRd} = {}^{CR}\dot{\boldsymbol{T}}_M {}^{M}\boldsymbol{T}_{CRd} + {}^{CR}\boldsymbol{T}_M {}^{M}\dot{\boldsymbol{T}}_{CRd}. \tag{7} $$

Differentiating Eq. (7) with respect to time again

$$ {}^{CR}\ddot{\boldsymbol{T}}_{CRd} = {}^{CR}\ddot{\boldsymbol{T}}_M {}^{M}\boldsymbol{T}_{CRd} + 2 {}^{CR}\dot{\boldsymbol{T}}_M {}^{M}\dot{\boldsymbol{T}}_{CRd} + {}^{CR}\boldsymbol{T}_M {}^{M}\ddot{\boldsymbol{T}}_{CRd}. \tag{8} $$

Here, ${}^{M}\boldsymbol{T}_{CRd}$, ${}^{M}\dot{\boldsymbol{T}}_{CRd}$, ${}^{M}\ddot{\boldsymbol{T}}_{CRd}$ are given by the desired visual servoing objective. ${}^{CR}\boldsymbol{T}_M$, ${}^{CR}\dot{\boldsymbol{T}}_M$, ${}^{CR}\ddot{\boldsymbol{T}}_M$ can be assumed to be recognized by cameras. So ${}^{CR}\boldsymbol{T}_{CRd}$, ${}^{CR}\dot{\boldsymbol{T}}_{CRd}$, ${}^{CR}\ddot{\boldsymbol{T}}_{CRd}$ can be calculated.

3·2 Servoing controller

The block diagram of our proposed controller is shown in Fig. 3. The controller used in our visual servoing is proposed by B.Siciliano [2]. Here, we just show main equations of the controller to calculate $\boldsymbol{\tau}$, which is output to control the robot manipulator.

$$ \boldsymbol{a}_p = {}^{W}\ddot{\boldsymbol{p}}_{CRd} + \boldsymbol{K}_D {}^{W}\dot{\boldsymbol{p}}_{CR,CRd} + \boldsymbol{K}_P {}^{W}\boldsymbol{p}_{CR,CRd}, \tag{9} $$

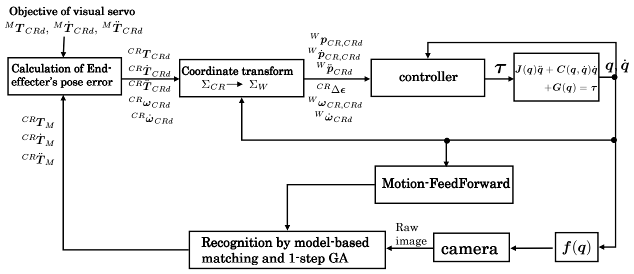

Fig.3 block diagram of the controller

$$ \boldsymbol{a}_o = {}^{W}\dot{\boldsymbol{\omega}}_{CRd} + \boldsymbol{K}_D {}^{W}\boldsymbol{\omega}_{CR,CRd} + \boldsymbol{K}_P {}^{W}\boldsymbol{R}_{CR} {}^{CR}\Delta\boldsymbol{\epsilon}, \tag{10} $$

$$ \ddot{\boldsymbol{q}} = \boldsymbol{J}^T(\boldsymbol{q})\left(\begin{bmatrix} \boldsymbol{a}_p \\ \boldsymbol{a}_o \end{bmatrix} - \dot{\boldsymbol{J}}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}}\right), \tag{11} $$

$$ \boldsymbol{\tau} = \boldsymbol{J}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}). \tag{12} $$

Here, the vectors in Eq. (9), (10) is expressed in Σ_W, which can be obtained from the vectors in Σ_{CR} deduced in 3·1 by coordinate transformation as follows.

It has been proved in [2] that the system must be exponentially stable for any choice of positive definite $\boldsymbol{K}_D$ and $\boldsymbol{K}_P$, thus

$$ \lim_{t \to 0} {}^{W}\boldsymbol{p}_{CR,CRd} = \boldsymbol{0} \qquad \lim_{t \to 0} {}^{W}\dot{\boldsymbol{p}}_{CR,CRd} = \boldsymbol{0} \tag{13} $$

$$ \lim_{t \to 0} {}^{CR}\Delta\boldsymbol{\epsilon} = \boldsymbol{0} \qquad \lim_{t \to 0} {}^{W}\boldsymbol{\omega}_{CR,CRd} = \boldsymbol{0}. \tag{14} $$

Substituting Eq. (13), (14) to Eq. (5), we have

$$ \lim_{t \to 0} {}^{CR}\boldsymbol{T}_{CRd} = \boldsymbol{I} \qquad \lim_{t \to 0} {}^{CR}\dot{\boldsymbol{T}}_{CRd} = \boldsymbol{0} \tag{15} $$

Substituting Eq. (15) to Eq. (6), we have

$$ \lim_{t \to 0} {}^{CR}\boldsymbol{T}_M = \lim_{t \to 0} {}^{CRd}\boldsymbol{T}_M \tag{16} $$

Eq. (16) proves stable convergence of visual servoing.

4. Conclusion

We have proposed a system of visual servoing to a 3D pose (6 degree of freedom) of a target object whose pose is expressed by unit quaternion. A proposed motion-feedforward compensation method can improve the visual recognition dynamics, which become worse by disturbing hand-eye motion during visual servoing of the robot manipulator. Simulation of visual servoing to a 3D pose will be shown at the conference.

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