Visual Servo Control using Stereo Image Jacobian

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Abstract: - Visual servo is a method to control robot manipulator using both image and robot information. In this paper, stereo image Jacobian has been developed and applied to control a 5-DOF robot manipulator with two cameras mounted on it. The proposed dynamic estimation of stereo image Jacobian allows the system to achieve visual servoing without any calibration of the camera or robot and any robot kinematics. The robot trajectory can then be planned online which provides the system to work in an undetermined environment. The proposed technique can also be used to directly drive motors of the robot joints.

Key-words: -Visual Servo, robot manipulator control, calibration, stereo image jacobian

1 Introduction
Presently, human-robot interaction has become more varied. In order for the robot to interact with human accurately, it must relatively know physical positions of the target being interacted with. The method to acknowledge such positions can be varied such as using infrared or laser device with additional signal processing. Using such sensors has some disadvantages and limitations, especially when human directly involves. The development of using visual servo which employs computer vision for target localization is then one of the most suitable methods.

Visual servo is mainly composed of robotics and computer vision. It was firstly introduced in [1]. In early 80s, all related work of visual feedback can be categorized into 4 groups of methods: look and move, dynamic look and move, position and image based visual servo. In 1987, [3] proposed the method to directly use object parameters from image without having to calculate actual positions of the target. This work, however, was only presented in mathematical model and limited to only 3-DOF system. Later on, [4] presented the use of digital camera to track moving object via adaptive control. In 1996, all related concept of visual servo was summarized in [5]. Nowadays, there are various visual servo methods, e.g. cooperation of eye-in-hand and eye-to-hand cameras for visual servoing [6][7], dynamic visual servo [8][9], visual servo together with artificial intelligent techniques [10][11] etc.

Image Jacobian-based visual servo has been introduced in 1984 by [2]. The most interesting of using this method is the ability to directly use image parameters without having to calculate actual positions of the target in which the end effector is moving toward. The relationship between the image parameters and the end effector has been called image Jacobian by [12] and has been widely used ever since [13][14]. This work presents the online trajectory planning for a robot manipulator. The objective is to develop a robot system to work in an undetermined environment without having to calibrate the system. The purposed method is based on visual servo technique which does not require a priori knowledge about robot kinematics. The system has been able to apply stereo image Jacobian for controlling robot manipulator to grab single object efficiently.

2 Image Jacobian
Robot control can be defined in term of parameters of end-effector position in Cartesian space. The changes in robot joints relate to robot Jacobian [15]. These cause corresponding changes in image parameters which relate to image Jacobian [5]. Let a robot manipulator has \( n \) joints and \( n \) DOF. The control target is defined in term of \( m \) image parameters. Let \( \hat{\theta} \) be \( n \)-joint position vector and \( \hat{r} \) be a robot end-effector position vector with size of \( p \). Let \( \hat{f} \) be \( m \)-image-parameter vector. The
relationship of robot joint velocities \( \dot{\theta} \) and end-effector velocity \( \dot{r} \) can be described by

\[
\dot{r} = J \cdot \dot{\theta}
\]  

(1)

where \( J \) is the robot Jacobian and

\[
J = \begin{bmatrix}
\frac{\partial r_1}{\partial \theta_1} & \cdots & \frac{\partial r_1}{\partial \theta_n} \\
\vdots & \ddots & \vdots \\
\frac{\partial r_p}{\partial \theta_1} & \cdots & \frac{\partial r_p}{\partial \theta_n}
\end{bmatrix}
\]  

(2)

Changes in robot end-effector \( r \) provide changes in image parameters \( f \) by the relationship

\[
\dot{f} = J_r \cdot \dot{r}
\]  

(3)

where \( J_r \) is \( m \times p \) matrix and

\[
J_r = \begin{bmatrix}
\frac{\partial f_1}{\partial r_1} & \cdots & \frac{\partial f_1}{\partial r_p} \\
\vdots & \ddots & \vdots \\
\frac{\partial f_m}{\partial r_1} & \cdots & \frac{\partial f_m}{\partial r_p}
\end{bmatrix}
\]  

(4)

Consequently, relationship between \( \dot{f} \) and \( \dot{\theta} \) can be related as image Jacobian \( J_q \) which is

\[
\dot{f} = J_q \cdot \dot{\theta}
\]  

(5)

where \( J_q = J_r \cdot J \) and

\[
J_q = \begin{bmatrix}
\frac{\partial f_1}{\partial \theta_1} & \cdots & \frac{\partial f_1}{\partial \theta_n} \\
\vdots & \ddots & \vdots \\
\frac{\partial f_m}{\partial \theta_1} & \cdots & \frac{\partial f_m}{\partial \theta_n}
\end{bmatrix}
\]  

(6)

### 2.1 Dynamic Image Jacobian Estimation

Image Jacobian can be dynamically estimated from changes of robot joints and changes of image parameters using linear relationship in (5). Thus, a joint motion \( (\Delta \theta) \) that reduces the image error can be computed by

\[
\Delta \theta = J_q^{-1} \Delta f
\]  

(7)

Consider image parameter \( f^i \) and joint vector \( \theta^i \) at time index \( i \). Changes of image parameters can be computed by \( df^i = f^i - f^{i-1} \) and changes of robot joints can be obtained by \( d\theta^i = \theta^i - \theta^{i-1} \). Both can be used for image Jacobian calculation. In order to be able to control robot joints using estimated Jacobian, a number of image parameters must be greater than or equal to a number of robot joints, i.e. \( n \leq m \). There are \( n \) pairs of image parameters in total and robot joints defined by

\[
[(d\theta_1, df_1, \ldots, df^{i+1}), \ldots, (d\theta_n, df_n)]
\]  

(8)

Then \( n \times n \) matrix \( DQ \) and \( m \times n \) matrix \( DF \) can be defined by

\[
DQ = \begin{bmatrix}
d\theta_1^{n-1} & \cdots & d\theta_n \\
\vdots & \ddots & \vdots \\
d\theta_n^{n-1} & \cdots & d\theta_n
\end{bmatrix}
\]  

(9)

\[
DF = \begin{bmatrix}
df_1^{i+n-1} & \cdots & df_1 \\
\vdots & \ddots & \vdots \\
df_m^{i+n-1} & \cdots & df_m
\end{bmatrix}
\]  

(10)

where \( d\theta_i^i = [d\theta_1^i, \cdots, d\theta_n^i]^T \) and \( df_i^i = [df_1^i, \cdots, df_m^i]^T \). The image Jacobian can then be estimated by

\[
\hat{J}_q = DF \cdot DQ^{-1}
\]  

(11)

The estimated Jacobian can be used to compute \( df^{i+1} \) and \( d\theta^{i+1} \) for the next robot drive. Then, information of \( df^{i+1} \) and \( d\theta^{i+1} \) are observed and stored to employ in a new pair of \( DQ \) and \( DF \) matrix for next image Jacobian estimation.

### 2.2 Dynamic Estimation of Stereo Image Jacobian

Using image Jacobian from one camera is proved to have some limitations. For example, when the target in the image is obscured, calculation of image Jacobian might not be achieved. Consequently, stereo image Jacobian then has been developed in this work. Two cameras are used to obtain required information for each computation of image Jacobian. The main advantage of using two cameras is that if one camera fails to provide information about the target, the other camera can still be able to track the
target. Details of using stereo image Jacobian are described in the following.

Consider \( J_{r1} \) and \( J_{r2} \) as image Jacobian of each camera, they can be calculated by using 
\[
df^i_1 = J_{r1}^i \cdot dr^i \quad \text{and} \quad df^i_2 = J_{r2}^i \cdot dr^i.
\]
Obviously, both image Jacobians are related by \( dr^i \). Consequently, both equation can be combined to
\[
\begin{bmatrix}
df^i_1 \\
df^i_2
\end{bmatrix} = \begin{bmatrix}
J_{r1}^i \\
J_{r2}^i
\end{bmatrix} \cdot dr^i \quad \text{(12)}
\]

From \( J^i_q = \begin{bmatrix} J_{q1}^i & J_{q2}^i \end{bmatrix} \) which is the Jacobian of image parameters from both cameras and robot end-effector velocity, the stereo image Jacobian can then be defined by
\[
J^i_q = \begin{bmatrix} J_{q1}^i & J_{q2}^i \end{bmatrix} \quad \text{where } J^i_q \text{ is the } m \times p \text{ matrix and } J^i_{q1,2} = J^i_{q1,2} \cdot J^i \text{ is the } m \times n \text{ matrix.}
\]

3. System Configurations
In order to employ the stereo image Jacobian in the robot controller, the system is implemented on a 5-DOF SCORBOT-ER III as seen in Figure 2 in which two cameras are mounted on the robot arm as shown in Figure 3. Both cameras are aligned to cover the work space of the robot gripper. A yellow ball is used as a target. It can then be segmented and located in the image plane by using simple color segmentation. Finally, the objective of the system is to drive robot arm to reach for the target by keeping it in the center of the images of both cameras.

Once the system starts, initial values of Jacobian are computed. There are 2 methods used in this work. Firstly, robot joints are moved randomly until enough information is obtained. Secondly, each robot joint is moved and corresponding parameters are observed and employed for the next move of the robot arm. The image from each camera has a size of 320x240 pixels. The target is said to be in the center of the image if it locates within a radius of 10 pixels of the image center.

![Diagram of visual servo system using stereo image Jacobian.](image1)

![System configurations.](image2)
4. Experimental Results
Figure 4 shows a sequence of robot actions reaching the target at random position within the robot workspace. The image sequences taken from each camera are shown in Figure 5. The error distance of the target position from the image center of each camera is displayed in Figure 6. The results clearly show that the robot arm can reach the target where the final location of the target is inside the gripper. This can be seen by the target is located in the image center for both camera. The robot manipulator can reach the target within approximately 25 iterations. This also shows that the estimated stereo image Jacobian can be efficiently achieved without having to calibrate both cameras and robot manipulator.

5. Discussion and Conclusion
In this paper, stereo image Jacobian has been developed and applied to control a 5-DOF robot arm. By using two cameras mounted on the robot arm, image parameters from both camera can be achieved and used in image Jacobian calculation. The proposed dynamic estimation of stereo image Jacobian allows the system to achieve visual servoing without any calibration of the camera or robot and any robot kinematics. The robot trajectory can then be planned online which allows the system to work in an undetermined environment. The proposed technique can also be used to directly drive motors of the robot joints. The results show the accuracy of both position and direction while the robot arm moves toward the target. The implementation is also as convenient as using single image Jacobian. Due to its fast and simple characteristic, the use of stereo image Jacobian allows the system to be improved for the better control performance.

Reference:
[3] L.E. Weiss, A.C. Sanderson and C.P. Neuman, Dynamic Sensor-Based Control of...


**Fig. 6** Error distance of the target position from center of the image (a) from CCD camera #1 and (b) from CCD camera #2