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Visual Servoing with Redundant Features

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Abstract

This paper presents how the control performance of the visual servo system is improved by utilizing the redundant features. We use the minimum singular value of the image Jacobian as a measure of the control accuracy (sensitivity) and we show that the sensitivity is strictly decreased by increasing the number of redundant features. Effectiveness of the control scheme with redundant features are verified by real time experiments on a PUMA 560 manipulator.

I Introduction

Visual servoing problem can be considered as a nonlinear control problem with the gray level of two dimensional pixel array being an observation. The size of the observation is larger than ten thousands, and it has nonlinear interaction with each pixel elements. Though it is not easy to solve the nonlinear interaction analytically, the problem size can be reduced to a proper level by using feature points. The number of the feature points necessary to achieve a specified task can be computed based on the calibration technique, however there is no paper which discusses the sufficient number to satisfy a specified accuracy. In this paper, accuracy improvement by increasing the number of features is discussed. We show that the singular value of the image Jacobian becomes a sensitivity of the controlled error against the error of the features in the image. Also, we show that the sensitivity is strictly decreased by adding redundant features to the necessary features. To investigate the accuracy, real time experiments on the PUMA 560 are carried out. Translational step responses with three (minimum) and five (redundant) features are examined. The results exhibit the effectiveness of the control scheme utilizing the redundant features.

II Image Jacobian

Let ξ be a $2n$ dimensional vector of image coordinates of n feature points; θ be an m dimensional vector of joint angles; $\mathcal{M}_\theta \subset \mathbf{R}^m$ be the work area of the robot; and $\mathcal{M} \subset \mathbf{R}^{2n}$ be the range of the feature vector. Then the *system model* for n feature points is defined by the map $\iota : \mathcal{M}_\theta \to \mathcal{M}$ as follows:

$$\iota(\theta) \stackrel{\text{def}}{=} \xi, \tag{1}$$

which is composed of kinematic model of the robot followed by perspective projection of the camera. This definition is somewhat abstract but the interpretation is simple: *the object image moves with the joint angle smoothly; once the joint angle is given, then the object image is determined uniquely.* Differentiation of the camera model yields

$$\dot{\xi} = J\dot{\theta}, \tag{2}$$

where J is called *image Jacobian* [1].

III Sensitivity

It is useful to discuss the ratio of the joint angle error to the feature vector error for evaluating the performance of the feature-based visual servo system. The following theorem shows that increasing the number of the feature point is an effective way to improve the ratio of the joint/feature errors.

Theorem 1 *Let the joint error be $\Delta\theta = \theta - \theta_d$ and the feature error be $\Delta\xi = \xi - \xi_d$. Define the worst joint/feature error ratio β, called sensitivity, as follows:*

$$\beta = \sup_{\|\Delta\xi\| \neq 0} \frac{\|\Delta\theta\|}{\|\Delta\xi\|} = \frac{1}{\sigma_{min}(J)}. \tag{3}$$

Then the sensitivity β decreases strictly by increasing the number of non-degenerated features.

IV Controller

Linearizing the model (2) with the feature vector being the state vector yields an uncontrollable model because ξ can not move arbitrarily in $\mathbf{R}^{2n}$. A simple way to avoid this problem is to map $\xi \in \mathcal{M}$ onto the tangent space of $\mathcal{M}$ by using the following transformation

$$z \stackrel{\text{def}}{=} J_d^T(\xi - \xi_d), \tag{4}$$

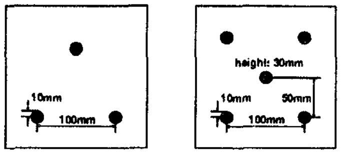

Figure 1: Configuration of Feature Points

where $J_d \stackrel{\text{def}}{=} J(\theta_d)$ is the image Jacobian at the desired point [2]. Note that z and θ are one-to-one in the neighborhood of θ_d. The dynamics of the feature error on the tangent space of the feature manifold $\mathcal{M}$ is as follows

$$\dot{z} = J_d^T J(\theta)\dot{\theta}. \tag{5}$$

Thus, for a simple continuous time control law $\dot{\theta} = -Kz$ with a positive definite constant matrix K yields asymptotical stability if $J_d^T J(\theta)$ is positive definite. This is satisfied in the neighborhood of $\xi = \xi_d$.

V Experiments

Real time experiments on PUMA 560 were carried out. PUMA tracks an object based on the information from the camera mounted on the hand. As shown in Fig.1, the objects are white boards with three and five black marks. For five points, four points are on corners of a square with edge length 100mm and an extra point with height 30mm is added at the center of the square. The initial camera position is in front of the object and the distance is about 1000mm. The features are x and y coordinates of the center of the image of each mark. At the initial position, the minimum singular values for three and five feature points are 0.339 and 3.55, respectively. The object motion is a step of 100mm in vertical axis. The object motion is considered as a disturbance for the plots of the features in the image plane. On the other hand, the object motion becomes the step change of the reference position for the position of the camera in the world coordinate system.

Three Points Fig.2 (top) has six curves which show the x and y coordinates of the feature point in the image plane. The horizontal axis is the time. The curves of y are disturbed by the step motion of the object. The response in the image plane is very good. However the plots in Fig.2 (middle), which depicts the position errors of the camera in the world coordinate system, are not stable. Fig.2 (bottom) shows the orientation errors of the camera expressed in the Euler angles, say ψ, η, ϕ. The plot of ψ is also unstable. The middle and bottom figures show that the hand goes right and the wrist rotates left to keep the features in the neighborhood of the reference position.

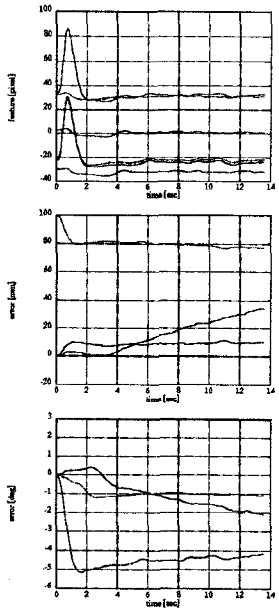

Figure 2: 3 Points

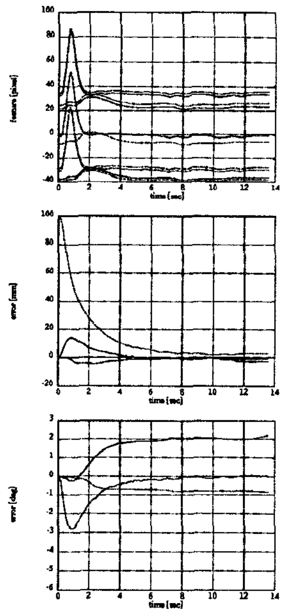

Figure 3: 5 Points

Five Points Fig.3 (top) depicts the features in the image plane for the experiment with five points. The response of the camera position (Fig.3, middle) is improved considerably. The steady state errors are smaller than 5mm for all directions. The camera orientation errors (Fig.3, bottom) shows quick stabilization.

VI Conclusions

Discussions on the performance improvement of the feature-based visual servoing due to redundant features were presented. We have shown that the minimum singular value of the extended image Jacobian plays an important role for performance improvement. Real time experiments on PUMA 560 were carried out to evaluate the improvement of the accuracy and speed by utilizing the redundant features.

References

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[2] K. Hashimoto, T. Ebine, K. Sakamoto, and H. Kimura. Full 3D visual tracking with nonlinear model-based control. In *American Control Conference*, pages 3180–3184, San Francisco, Calif., 1993.