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A Novel Visual Servoing Approach involving Disturbance Observer

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Abstract

To improve the visual servoing performance, several strategies have been proposed by using redundant feature points, by using a point with different height, and by a weighted selection of image features. The performance of these visual servoing methods depends on the configuration between the camera and objects. And redundant feature points require much computational efforts.

This paper proposes a visual servoing method based on disturbance observer, which compensates the effect of the off-diagonal component of image feature Jacobian to be null. The performance indices such as measurement sensitivity of visual features, sensitivity of the control to noise, and controllability are improved when an image feature Jacobian is given as a block diagonal matrix. The proposed approach is applied to PUMA560 and Samsung FARAMAN 6-axis industrial robot manipulator successfully.

1. Introduction

There has been a growing interest on visual servoing since there are a lot of robotic applications if a robot manipulator can be controlled using visual information like human being [1][2][3]. The visual servoing is classified into either position-based control [4] or image-based control. The image-based control has received much attention since there is no need for three-dimensional reconstruction of visual information and one can reduce unavoidable errors, which are resulted from sensor modeling and camera calibration, by feedback control. The concept of image Jacobian was introduced by Weiss [5] in order to define a relationship between differential changes in robot joints and image feature variations for implementing image-based control. And, several schemes have been proposed to find the image Jacobian by using linear and angular velocity of a rigid target object [6], by learning based on a neural net using fuzzy membership function [7], or by differentiating a mathematical relationship of image features [8].

However, the observability and sensitivity of image features as well as the controllabilty and stability of a robot manipulator should be exposed to the front of reliable image-based control. Thus, some measures to evaluate the performance of visual servoing are introduced by using singular values of image Jacobian matrix [9][10][11][12]. In [9], feature points are selected in such a way that condition number of the image Jacobian matrix is computed as small as possible to improve not only the observability of image features but also the controllability and sensitivity of the robot manipulator. Hashimoto and Noritsugu selected image features whose minimum singular value becomes large to improve the control sensitivity of image-based control [10]. Sharma and Huchinson adopted the product of singular values of image Jacobian matrix as a measure of manipulability in [11] while a visual resolvability ellipsoid is used for representing the ability of a vision sensor to resolve object positions and orientations [12]. The ellipsoid is generated by using singular values of image Jacobian matrix and eigenvectors of the product of the transpose of image Jacobian matrix and itself. The introduced performance measures were used for selecting image feature sets or changing the location and structure of visual sensors in order to enhance control performance of visual servoing.

In this paper, a novel visual servoing approach is proposed to improve control performance by using disturbance observer and by using only block diagonal part of image Jacobian matrix when the image feature Jacobian matrix can be described by a block triangular matrix. For this, it is shown that the minimum (maximum) singular value of the image Jacobian matrix increases (decreases) and thus its condition number becomes smaller than that of block triangular image Jacobian matrix. An upper block triangular image Jacobian matrix is proposed by using vanishing points invariant to the positions of image features [13]. The disturbance observer [14][15] is used for the compensation of errors due to canceling the off-diagonal part of the block triangular image Jacobian matrix, and for the rejection of external disturbances. The proposed approach is applied to PUMA560 and Samsung FARAMAN 6-axis industrial robot manipulator successfully.

This paper is organized as follows; section 2 includes a mathematical proof of the fact that characteristics of singular values are improved when a block-diagonal matrix is used. The image Jacobian matrix using vanishing points is proposed in section 3. A new visual servoing control law using disturbance observer and block diagonal image Jacobian is described in section 4 while computer simulation for PUMA560 and experimental results for Samsung FARAMAN robot is shown in section 5. Finally, the paper is concluded in section 6.

2. Performance measures for visual servoing

Condition number and the minimum singular value has been used for performance measures of image Jacobian. The condition number, κ, is defined as

$$\kappa = \frac{\sigma_{\max}}{\sigma_{\min}} \geq 1 \qquad (1)$$

where $\sigma_{\max}$ is the maximum singular value, and $\sigma_{\min}$ is the minimum singular value of the image Jacobian. And κ is used to represent pose controllability and control sensitivity. The controllability $c(\mathbf{J})$ of an image feature Jacobian $\mathbf{J}$ is expressed as

$$c(\mathbf{J}) = \|\mathbf{J}\| \cdot \|\mathbf{J}^{-1}\| \qquad (2)$$

where $\|\mathbf{J}\|$ is the norm of $\mathbf{J}$, and $\|\mathbf{J}^{-1}\|$ is the norm of $\mathbf{J}^{-1}$. The matrix norm and the condition number are defined by spectral radius theorem in [16]. For thus let $\sigma_1 \cdots \sigma_p$ be singular values of $\mathbf{J}$. Then, we obtain that

$$\|\mathbf{J}\| = \max\{\sigma_1, \cdots, \sigma_p\}, \qquad (3)$$

$$\|\mathbf{J}^{-1}\| = 1/\min\{\sigma_1, \cdots, \sigma_p\}, \qquad (4)$$

$$\kappa = \|\mathbf{J}\| \cdot \|\mathbf{J}^{-1}\| = \frac{\sigma_{\max}}{\sigma_{\min}}. \qquad (5)$$

Here, it is noted that $\|\mathbf{J}^{-1}\|$ is a measure of differential changes of robot motion with respect to differential changes of image features. When the norm is large, i.e., the minimum singular value of $\mathbf{J}$ is small, slight changes in image features invoke an abrupt large motion of a robot. On the contrary, the differential changes of image features become sensitive to noise in case that the maximum singular value, $\|\mathbf{J}\|$, is large. Thus, a stable control of the robot can be obtained when the condition number becomes near 1. Also, the control sensitivity of the robot becomes insensitive with respect to input noise, as the condition number is near 1. On the other hand, the minimum singular value is used as a measure of insensitivity of image features relative to robot motions. It becomes easier to obtain reliable image features as the measure becomes larger.

The above performance measures are here shown to be improved when an image Jacobian is expressed as a block triangular matrix by the following theorem;

(Theorem 1)
Let $\mathbf{A}$ and $C(\mathbf{A})$ be a block triangular matrix and a block diagonal matrix given by

$$\mathbf{A} = \begin{bmatrix} A_{11} & A_{12} \\ 0 & A_{22} \end{bmatrix}, \quad C(\mathbf{A}) = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix}. \qquad (6)$$

Then,

$$\sigma_{\max, C(\mathbf{A})} \leq \sigma_{\max, \mathbf{A}}, \qquad (7)$$

and

$$\sigma_{\min, C(\mathbf{A})} \geq \sigma_{\min, \mathbf{A}}. \qquad (8)$$

proof)
The block diagonal matrix $C(\mathbf{A})$ can be written as

$$C(\mathbf{A}) = \frac{1}{2}\left(\mathbf{A} + \mathbf{U}\mathbf{A}\mathbf{U}^{-1}\right),$$

where

$$\mathbf{U} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & -\mathbf{I} \end{bmatrix}.$$

Then, by triangular inequality [16][17],

$$\|C(\mathbf{A})\| \leq \frac{1}{2}\|\mathbf{A}\| + \frac{1}{2}\|\mathbf{U}\mathbf{A}\mathbf{U}^{-1}\|,$$

and

$$\|C(\mathbf{A})\| \leq \|\mathbf{A}\|, \qquad (9)$$

since $\mathbf{A}$ and $\mathbf{U}\mathbf{A}\mathbf{U}^{-1}$ are similar and their eigenvalues and singular values are same. Therefore,

$$\sigma_{\max, C(\mathbf{A})} \leq \sigma_{\max, \mathbf{A}}.$$

For the inverse matrix of $\mathbf{A}$ [18],

$$\mathbf{A}^{-1} = \begin{bmatrix} A_{11}^{-1} & -A_{11}^{-1}A_{12}A_{22}^{-1} \\ 0 & A_{22}^{-1} \end{bmatrix}, \qquad (10)$$

and

$$C(\mathbf{A}^{-1}) = \begin{bmatrix} A_{11}^{-1} & 0 \\ 0 & A_{22}^{-1} \end{bmatrix}.$$

By using (9),

$$\frac{1}{\sigma_{\min, C(\mathbf{A})}} \leq \frac{1}{\sigma_{\min, \mathbf{A}}}.$$

This implies that

$$\sigma_{\min, C(\mathbf{A})} \geq \sigma_{\min, \mathbf{A}}.$$

In consequence, the sensitivity of $C(\mathbf{A})$ increases comparing with that of $\mathbf{A}$. For lower block triangular matrices, the Theorem can be easily proved in a similar way to the case of upper block triangular matrices.

(Q.E.D.)

3. Image Jacobian based on Vanishing Points

In this section, a block triangular image Jacobian is proposed using vanishing points of a planar rectangle shown in Fig. 1 since only rotational component can be extracted from the vanishing points independently of the position of the rectangle. Let

u, v : x- and y-coordinate of COG of the object,

a : area of the object,

x_v : x- coordinate of vertical vanishing point,

x_h, y_h : x- and y-coordinate of horizontal vanishing point.

Also, consider a coordinate frame as shown in Fig. 2. $\{x, y, z\}$ represents a reference coordinate, $\{x', y', z'\}$ is a translated coordinate frame of $\{x, y, z\}$ in the direction of x-axis, $\{x'', y'', z''\}$ is a rotated coordinate frame of $\{x', y', z'\}$ with pitch angle of β, yaw angle of α and roll angle of γ. $\{x_i, y_i, z_i\}$ is an image coordinate while f is focal length of a lens. Then, the coordinates of vanishing points and the area of the planar rectangle are described as follows:

$$x_v = f\frac{\cos\gamma}{\tan\beta} \tag{11}$$

$$x_h = -f\frac{\sin\gamma}{\tan\alpha\cos\beta} - f\tan\beta\cos\gamma \tag{12}$$

$$y_h = f\frac{-\cos\gamma}{\tan\alpha\cos\beta} + f\tan\beta\sin\gamma \tag{13}$$

$$a \cong cf^2\cos\alpha\cos\beta / z^2 \tag{14}$$

Therefore, the block triangular image Jacobian can be obtained by differentiating (11), (12), (13) and (14) and by combining translational components of image Jacobian given as

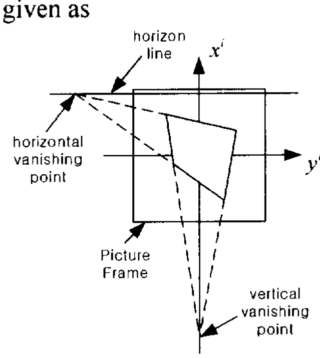

Fig 1. Vanishing Points

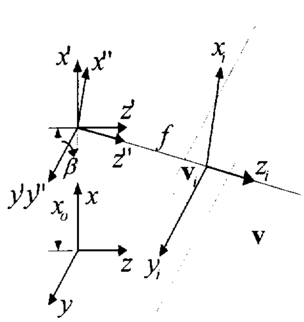

Fig 2. Coordinate Frames

$$\begin{bmatrix}\dot{u}\\ \dot{v}\end{bmatrix} = \begin{bmatrix}\frac{f}{z} & 0 & -\frac{u}{z} & -\frac{uv}{f} & \frac{\lambda^2+u^2}{f} & -v\\ 0 & \frac{f}{z} & -\frac{v}{z} & -\frac{\lambda^2+v^2}{f} & \frac{uv}{f} & u\end{bmatrix}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\\ \dot{\alpha}\\ \dot{\beta}\\ \dot{\gamma}\end{bmatrix}. \tag{15}$$

Specifically, we can obtain that

$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{a}\\ \dot{x}_v\\ \dot{x}_h\\ \dot{y}_h\end{bmatrix} = \mathbf{J}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\\ \dot{\alpha}\\ \dot{\beta}\\ \dot{\gamma}\end{bmatrix} = \begin{bmatrix}J_{11} & J_{12}\\ 0 & J_{22}\end{bmatrix}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\\ \dot{\alpha}\\ \dot{\beta}\\ \dot{\gamma}\end{bmatrix}, \tag{16}$$

where

$$J_{11} = \begin{bmatrix}\frac{f}{z} & 0 & -\frac{u}{z}\\ 0 & \frac{f}{z} & -\frac{v}{z}\\ 0 & 0 & -\frac{2cf^2}{z^3}\cos\alpha\cos\beta\end{bmatrix},$$

$$J_{12} = \begin{bmatrix}-\frac{uv}{f} & \frac{f^2+u^2}{f} & -v\\ -\frac{f^2+v^2}{f} & \frac{uv}{f} & u\\ -\frac{cf^2}{z^2}\sin\alpha\cos\beta & -\frac{cf^2}{z^2}\cos\alpha\sin\beta & 0\end{bmatrix},$$

and

$$J_{22} = f\begin{bmatrix}0 & -\frac{\cos\gamma}{\sin^2\beta} & -\frac{\sin\gamma}{\tan\beta}\\ \frac{\sin\gamma}{\sin^2\alpha\cos\beta} & -\frac{\tan\beta\sin\gamma}{\tan\alpha\cos\beta} - \frac{\cos\gamma}{\cos^2\beta} & -\frac{\cos\gamma}{\tan\alpha\cos\beta} + \tan\beta\sin\gamma\\ \frac{\cos\gamma}{\sin^2\alpha\cos\beta} & -\frac{\tan\beta\cos\gamma}{\tan\alpha\cos\beta} + \frac{\sin\gamma}{\cos^2\beta} & \frac{\sin\gamma}{\tan\alpha\cos\beta} + \tan\beta\cos\gamma\end{bmatrix}.$$

4. Visual servoing control law using disturbance observer

Disturbance observer is used for the compensation of errors due to canceling the off-diagonal part of the block triangular image Jacobian matrix, and for the rejection of external disturbances. General visual servoing method using complete inverse image feature Jacobian matrix is shown in Fig. 3, where

$\dot{\xi}_{ref}$: velocity reference of image feature,

C_{fv} : image feature PID controller,

J_f^{-1} : inverse image feature Jacobian,

P : real robot,

J_r : robot Jacobian

J_f : image feature Jacobian

$\dot{\xi}_a$: measured image feature velocity.

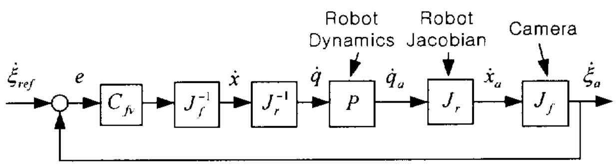

Fig. 3. The block diagram of general visual servoing method

If the image Jacobian matrix is upper-triangular, then (10) can be used. Fig. 4 shows the block diagram of our proposed visual servoing method using disturbance observer. The following notations are used.

$\dot{\xi}_{ref}$: velocity reference of image feature,

C_{fv} : image feature PID controller,

J_f : upper-block triangular type image feature Jacobian ,

$\tilde{J}_f^{-1}$: block diagonal type inverse feature Jacobian,

J_r, J_r^{-1} : Jacobian and inverse Jacobian of robot,

P_n : nominal robot model with joint speed controller using disturbance observer,

$\bar{J}_r$: robot Jacobian by real robot,

$\bar{J}_f$: image feature Jacobian by real CCD camera,

$\dot{\xi}_d$, noise : external image feature disturbance and noise,

$\dot{\xi}_a$: measured image feature velocity,

Q_f : low pass filter.

The block diagonal type inverse feature jacobian is given as

$$\tilde{J}_f^{-1} = \begin{bmatrix} J_{11}^{-1} & 0 \\ 0 & J_{22}^{-1} \end{bmatrix}.$$

The block A of Fig. 4 can be shown to become equivalent to the nominal model F_n given by

$$F_n = \tilde{J}_f J_r P_n J_r^{-1} J_f^{-1}. \tag{17}$$

And with the multiplication of terms, J_f and $\tilde{J}_f^{-1}$, the visual servoing system is converted to the block diagonal image feature Jacobian system. Fig. 5 shows the equivalent system of the proposed visual servoing system in Fig. 4.

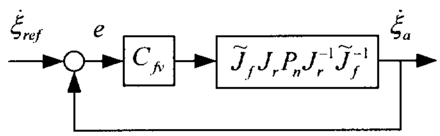

Fig. 5. The block diagram of equivalent visual servoing system of the system in Fig. 4

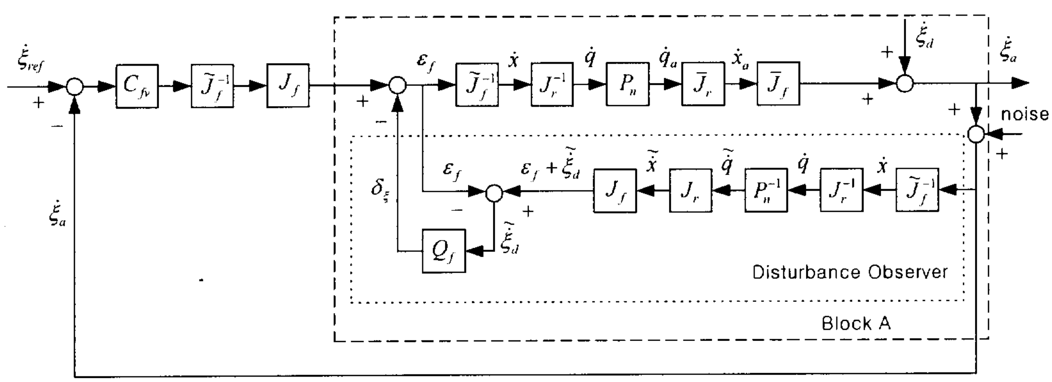

Fig. 4. The block diagram of proposed visual servoing method using disturbance observer

5. Experimental Results

To show the validity and usefulness of the proposed approach, computer simulations for PUMA560 and experiments are carried out using a Samsung FARAMAN 6-DOF industrial robot and a B/W CCD camera. The object is given as a 16cm x 16cm white square on black backgrounds. The sampling time for the control of the visual servoing is chosen as 100msec and the following 2nd order low pass filter Q-filter, whose cut-off frequency is 10 times of the sampling time, is used for disturbance observer in Fig. 4.

$$Q_f = \frac{39.48}{s^2 + 12.57s + 39.48}$$

For velocity control of the robot, we applied dynamic control with disturbance observer that compensates system non-linearity and simplifies computations.

Fig. 6, 7, 8 show the computer simulation results of maximum and singular value, condition number, respectively, when the robot is servoing with viewing posture of target object from (100, 100, 300 mm, 30, 30, 5 degree) to (50, 50, 100 mm, 45, 45, 5 degree). In these figures, maximum(minimum) singular value of the image Jacobian matrix decreases(increases) and thus its condition number becomes smaller than that of the case without disturbance observer. Fig. 9 shows characteristics of noise immunity of the block-diagonal image feature Jacobian matrix.

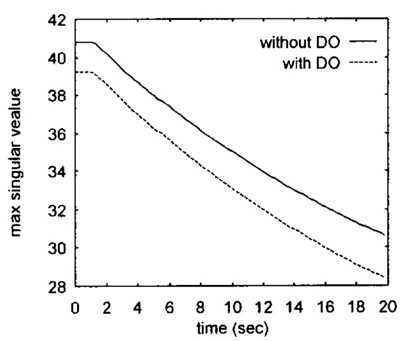

Fig. 6. Maximum singular values

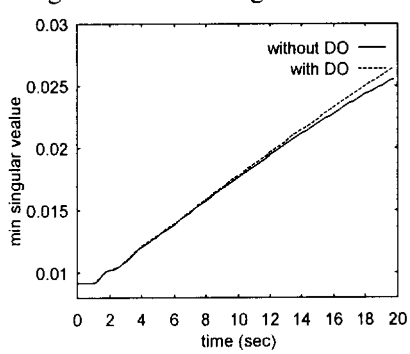

Fig. 7. Minimum singular values

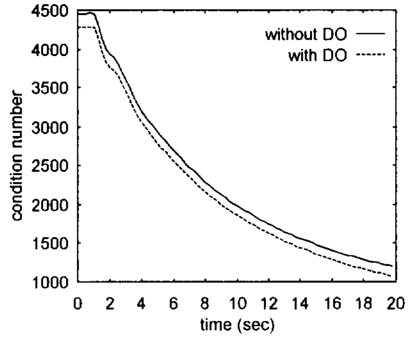

Fig. 8. Condition number

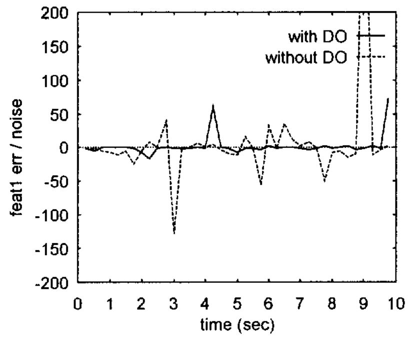

Fig. 9. The ratio of image feature noise and error

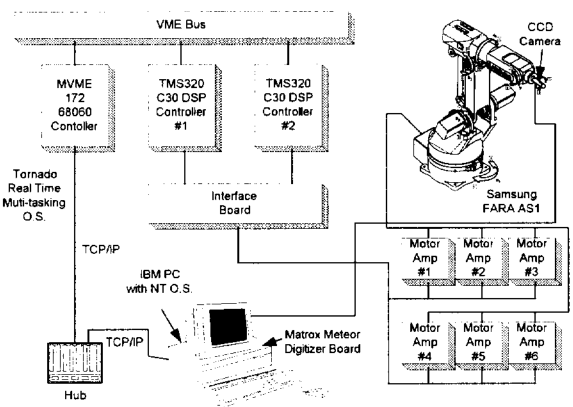

Fig. 10. Experimental Setup

Fig. 10 shows our experimental system. The nominal model of FARAMAN is obtained by experiments. And sampling time of robot velocity control loop is 1msec and that of visual servoing loop is 100msec.

Fig. 11 and Fig. 12 show experimental results for visual servoing of FARAMAN with the disturbance observer(DO) and without DO, when the robot is moving by visual servoing from a feature reference (-0.62, -0.22, 1.91, -41.76, -5.57, 22.99) to a target feature reference (-0.16, -0.018, 6.37, -34.21, 2.60, 33.17). These results show that very similar visual servoing results are obtained for both cases because the disturbance observer compensates the effect by off-diagonal term.

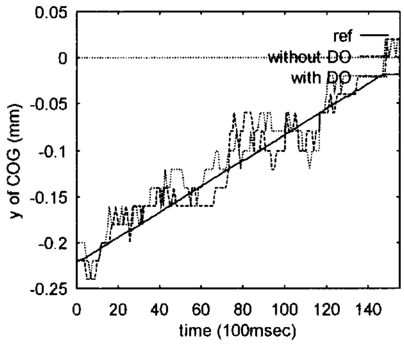

Fig. 11. y-coordinate of COG of visual target

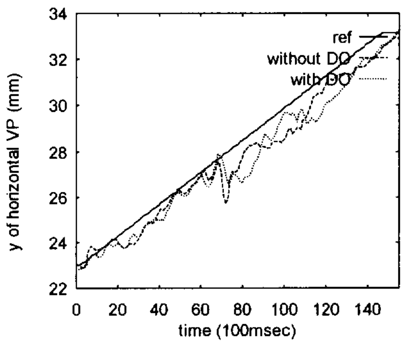

Fig. 12. y-coordinate of horizontal vanishing point

6. Conclusions

This paper proposes a novel visual servoing method using an upper block diagonal image Jacobian and disturbance observer. The disturbance observer is used for the compensation of errors due to canceling the off-diagonal part of the image Jacobian, and for the rejection of external disturbances. It is shown mathematically that performance indices such as measurement sensitivity of image features, control sensitivity and controllability are improved and simulation and experimental results show that the proposed approach is working successfully.

References

[1] S. Hutchinson, G. D. Hager and Peter I. Corke, "A tutorial on visual servo control," IEEE Trans. Robot. and Automat., vol. 12, no. 5, Oct., pp. 651-670, 1996

[2] K. Hashimoto, T. Ebine, and H. Kimura, "Visual servoing with hand-eye manipulator-optimal approach", IEEE Trans. Robot. Automat., vol. 12, no. 5, Oct., pp. 766-774, 1996

[3] J. T. Feddema, C. S. G. Lee, "Adaptive image feature prediction and control for visual tracking with a hand-eye coordinated camera," IEEE Trans. Sys., Man, Cyb., vol. 20, no. 5, Sep/Oct. 1990

[4] W. J. Wilson, C. C. W. Julls, and G. S. Bell, "Relative end-effector control using cartesian position based visual servoing," IEEE Trans. Robot. and Automat., vol. 12, no. 5, Oct., pp. 684-696, 1996

[5] L. E. Weiss, A. C. Sanderson, and C. P. Neuman, "Dynamics sensor-based control of robots with visual feedback," IEEE J. Robot. Automat., vol. RA-3, no. 5, pp. 404-417, Oct., 1987

[6] K. Hashimoto, T. Kimoto, T. Ebine, and H. Kimura, "Manipulator control with image-based visual servo," Proc. IEEE Int. Conf. Robot. Automat., pp. 2267-2272, 1991

[7] I. H. Suh and T. W. Kim, "Fuzzy membership function based neural networks with applications to the visual servoing of robot manipulators," IEEE Tans. Fuzzy Systems, vol. 2, no. 3, pp. 203-220, Aug. 1994

[8] W. Jang and Z. Bien, and J. Park, "Characterization and use of feature-Jacobian matrix for visual servoing," Visual Servoing: Real-Time Control of Robot Manipulators Based on Visual Sensory Feedback, K. Hashimoto, Ed. London: World Scientific, pp. 317-363, 1993

[9] J. T. Feddema, C. S. G. Lee, O. R. Mitchell, "Weighted selection of image features for resolved rate visual feedback control," IEEE Tans. Robot. Automat., vol. 7, no. 1, pp. 31-47, Feb., 1991

[10] K. Hashimoto and T. Noritsugu, "Performance and sensitivity in visual servoing," Proc. IEEE Int. Conf. Robot. Automat., pp. 2321- 2326, 1998

[11] R. Sharma and S. Hutchinson, "Motion perceptibility and its application to active vision-based servo control," IEEE Tans. Robot. Automat., vol. 13, no. 4, pp. 607-617, Aug., 1997

[12] B. J. Nelson and P. K. Khosla, "Force and vision resolvability for assimilating disparate sensory feedback", IEEE Tans. Robot. Automat., vol. 12, no. 5, pp. 714-731, Oct., 1996

[13] R. O. Duda and P. E. Hart, *Pattern Classification and Scene Analysis*, A Wiley-Interscience Pub., 1973

[14] K. Kaneko, K. Ohnishi, and Kiyoshi Komoriya, "A design method for manipulator control based on disturbance observer," Proc. Int. Conf. Intl. Robot and Systems, pp. 1405-1412, 1994

[15] K. S. Eom, I. H. Suh, W. K. Chung, and S. R. Oh, "Disturbance observer based force control of robot manipulator without force sensor, " Proc. IEEE Int. Conf. Robot. Automat., pp. 3012-3017, 1998

[16] M. J. Maron, *Numerical analysis*, Macmillan Publishing Co., Inc. 1982

[17] R. Bhatia, *Matrix Analysis*, Springer, 1997

[18] S. Skogestad and I. Postlethwaite, *Multivariable Feedback Control*, John Wiley & Sons, 1995