Image-based fuzzy control system

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A novel image-based fuzzy control (IBFC) scheme is developed to imitate the way humans use visual information to control objects. A CCD camera gathers images of the controlled plant, and a simple algorithm analyses the images. The proposed image analysis algorithm utilises image information more intuitively than visual servo control systems. The difference between a reference image and the current image is numerically expressed and directly used by a fuzzy control system using a human-like control law. To investigate the effectiveness of the proposed IBFC scheme, it is applied to control an inverted pendulum system. Simulation results show that the IBFC system can achieve favourable tracking performance without prior knowledge of the controlled plant.

Introduction: For the past decade, machine vision has attracted a lot of research, and is widely used in many industries, especially the robot and vehicle industries [1, 2]. It mimics the human sense of vision and allows for non-contact measurement of the environment. A control scheme which aims at using the information provided by machine vision to control the motion of robot or vehicle systems is called visual servo control, and is usually divided into two classes, position-based visual servo (PBVS) and image-based visual servo (IBVS) [3, 5]. The performance of PBVS control highly depends on the accuracy of image feature extraction and camera calibration. On the other hand, co-ordinate transformation in the IBVS, involving calculation of the image Jacobian, adds significant complexity to the system design as well as inducing a heavy computational burden.

Considering the drawbacks resulting from the ways that the image-type information is used in PBVS and IBVS, we decided to use the image-type information in a more intuitive way. By using the proposed algorithm, we can 'read' the images and obtain knowledge of the difference between reference and current images. Then, the image difference is directly imported into a fuzzy logic control system to derive a suitable control law. Hence, we do not need to reconstruct the 3D environment to extract information such as position and velocity, and complex co-ordination transformation is not necessary.

Image analysis algorithm: Using a CCD camera, we take an image of the controlled object in a static reference position (called the reference image), and images of the controlled object (called the current images) during the control process. We use a simple algorithm to numerically express the differences between the reference image and the current image. The fuzzy control rules are determined by an expert. A simple example of an inverted pendulum is used to illustrate the proposed algorithm. Figs. 1*a* and *b* show the reference and current images of the rod of the inverted pendulum, respectively. For simplicity, the image resolution is chosen as 10V × 10H; however, the developed algorithm can be applied to analyse images with arbitrary resolution. The image to be analysed is first translated into a transformation matrix, $M \in R^{n\times m}$ as follows:

$$\mathbf{M} = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1m} \\ m_{21} & m_{22} & \cdots & m_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nm} \end{bmatrix} \quad i = 1, 2, \ldots, n, \quad j = 1, 2, \ldots, m$$

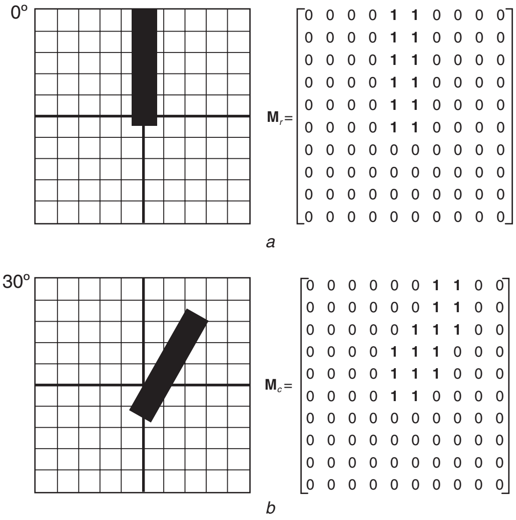
where nV × mH is the image resolution, $m_{ij} = 1$ if the corresponding pixels are partially or fully covered by the object in the image, and $m_{ij} = 0$ if the corresponding pixels are not covered. The transformation matrices of Figs. 1*a* and *b* are defined as $\mathbf{M}_r$ and $\mathbf{M}_c$, and are shown in the right sides of Figs. 1*a* and *b*.

Define $\mathbf{M}_e = \mathbf{M}_r - \mathbf{M}_c$. To confirm the difference between the reference and current images in the vertical direction, we first determine a vertical weighting vector $\mathbf{v} = [v_1 \; v_2 \ldots v_n] \in R^n$, where $0 < v_1 < \ldots < v_n$ ($\mathbf{v} = [1 \; 2 \ldots 10]$ for this example). Then, we define $\mathbf{M}_{e,v} = \mathbf{v}\mathbf{M}_e$. The Frobenius norm of $\mathbf{M}_{e,v}$ is calculated as $\|M_{e,v}\|_F = \sqrt{(\sum_{i=1}^{10} \sum_{j=1}^{10} |m_{ij}|^2)} = \sqrt{(88)}$. It is clear that a large $\|M_{e,v}\|_F$ implies a big difference between the reference and the current images in the vertical direction, and a small $\|M_{e,v}\|_F$ implies a small difference.

We are also interested in the image information in the horizontal direction. That is, if the controlled object in the static position is viewed as a reference point, we would like to confirm if the object during the control process is located to the left or right. Among the elements which equal 1 in the transformation matrix $\mathbf{M}$, we denote the leftmost and rightmost ones as m_l and m_r, respectively. Suppose that m_l is in j_lth column and m_r is in the j_rth column, then, a 'middle index' is defined as $\mathrm{I} = (j_l + j_r)/2$. Thus, the middle indices of $\mathbf{M}_r$ and $\mathbf{M}_c$, denoted as I_r and I_c, respectively, are $I_r = (5+6)/2$ and $I_c = (5+8)/2$. It is easy to see that $I_r > I_c$ implies that the controlled object is located on the left side of the object at the equilibrium, and vice versa. Combining the image information in both the vertical and horizontal direction, we can numerically express the difference between the reference and current images as

$$z = s\|M_{e,v}\|_F, \quad s = \begin{cases} 1, & \text{if } I_r < I_c \\ -1, & \text{if } I_r > I_c \end{cases}$$

Thus, we can easily express the difference between Figs. 1*a* and *b* as $z = \sqrt{(88)}$.



$$\mathbf{M}_r = \begin{bmatrix} 0&0&0&0&1&1&0&0&0&0 \\ 0&0&0&0&1&1&0&0&0&0 \\ 0&0&0&0&1&1&0&0&0&0 \\ 0&0&0&0&1&1&0&0&0&0 \\ 0&0&0&0&1&1&0&0&0&0 \\ 0&0&0&0&1&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \end{bmatrix}$$

$$\mathbf{M}_c = \begin{bmatrix} 0&0&0&0&0&0&1&1&0&0 \\ 0&0&0&0&0&0&1&1&0&0 \\ 0&0&0&0&0&1&1&1&0&0 \\ 0&0&0&0&1&1&1&0&0&0 \\ 0&0&0&0&1&1&1&0&0&0 \\ 0&0&0&0&1&1&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0 \end{bmatrix}$$

Fig. 1 *Examples of images of rod of inverted pendulum*

Remark 1: That the camera field of view should completely cover the motion of the controlled object.

Remark 2: High resolution is indispensable for precise image analysis but is computationally expensive. However, the image analysis performed with the proposed algorithm can achieve the necessary precision with a quite low resolution, e.g. 10V × 10H in Figs. 1*a* and *b*. This will be further examined in the Section 'Results'.

Remark 3: The choice of the vertical weighting vector $\mathbf{v}$ could influence the precision of the image analysis in the vertical direction, especially for low-resolution images.

Before constructing the proposed image-based fuzzy control (IBFC) scheme, we first formulate the control problem. Consider a general nth-order nonlinear system of the form $x^{(n)} = f(\mathbf{x}, u)$, where $\mathbf{x} = [x \; \dot{x} \ldots x^{(n-1)}]^T$ is the state vector of the system (which can be left unknown in our system), $f(\mathbf{x},\mathrm{u})$ is the unknown nonlinear system dynamics and u is the control input of the system. Since the system dynamics $f(\mathbf{x},\mathrm{u})$ cannot be exactly obtained, the considered system poses an interesting and challenging problem for control systems. The model-free feature of fuzzy control provides a feasible solution to this problem. Fig. 2 shows the block diagram of the proposed IBFC scheme.

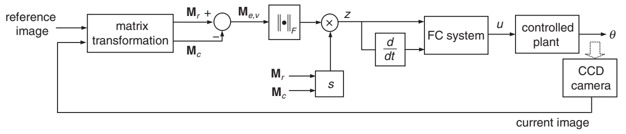
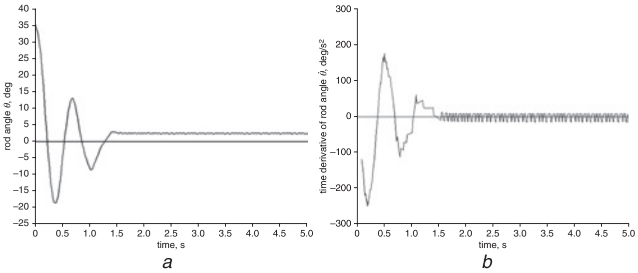


Fig. 2 *Block diagram of IFBC scheme*

Results: A simulation of an inverted pendulum is provided as an example to verify the effectiveness of the proposed IBFC scheme. The control target is to balance the rod in the upright position. To obtain a high-contrast image, we place the inverted pendulum against a white background.

The dynamics of the inverted pendulum are defined in [6]. The input of the fuzzy system is defined as $\mathbf{z} = [z\ \dot{z}]$, where $\dot{z}$ is the time derivative of z. The simulation begins with the rod tilted at a 35° angle, and a time derivative of zero. The reference trajectory is that to keep the rod in the upright position. For this simulation, rather than generating the images on the fly, we created predefined images based on the rod angle (θ). We varied θ from $-90°$ to $90°$, with a quantisation of 5° for a total of 37 images. The higher the resolution, the smaller the quantisation level should be. It should be emphasised that the quantisation and off-line matrix transformation are only necessary for the computer simulation and can be skipped in a practical implementation.

The simulation results are shown in Fig. 3, where Figs. *a* and *b* show the tracking response of θ and $\dot{\theta}$. In Fig. 3*a*, we see that θ does not converge to zero but oscillates around $\theta = 2.5°$ (half of the quantisation level), and in Fig. 3*b* that the oscillation of θ directly causes the oscillation of $\dot{\theta}$ around zero. This phenomenon clearly shows the influence of quantisation. If the resolution of the analysed image is higher, a smaller quantisation can be chosen and thus both θ and $\dot{\theta}$ will be closer to zero.



a *b*

Fig. 3 *Simulation results*

Conclusion and future work: We propose a novel image-based fuzzy control scheme (IBFC). A CCD camera is substituted for human eyes, and the images captured by the CCD camera are analysed by the proposed simple algorithm. The algorithm provides an intuitive and reasonable way to deal with the image information. Moreover, complex co-ordination transformations can be avoided. The simulation results demonstrate that even under the limit of low image resolution, it can achieve favourable tracking performance on an inverted pendulum. Having made some progress in this study, we still have some difficult problems to be solved, e.g. the lack of stability analysis may harm the reliability of the system, and the proposed image analysis algorithm is not general enough. In future, we will concentrate our work on exploring stability analysis and removing the restrictions of the proposed algorithm, making it more reliable and applicable for practical systems.

10 January 2008
Electronics Letters online no: 20080057
doi: 10.1049/el:20080057

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References

1 Trivedi, M.M., Gandhi, T., and McCall, J.: ‘Looking-in and looking-out of a vehicle: computer-vision-based enhanced vehicle safety’, *IEEE Trans. Transport. Syst.*, 2007, **8**, (1), pp. 108–120

2 Rousseau, P., Desrochers, A., and Krouglicof, N.: ‘Machine vision system for the automatic identification of robot kinematic parameters’, *IEEE Trans. Robot. Autom.*, 2001, **17**, (6), pp. 972–978

3 Hutchinson, S., Hager, G.D., and Corke, P.I.: ‘A tutorial on visual servo control’, *IEEE Trans. Robot. Autom.*, 1996, **12**, (5), pp. 651–670

4 Mezouar, Y., and Chaumette, F.: ‘Path planning for robust image-based control’, *IEEE Trans. Robot. Autom.*, 2002, **18**, (4), pp. 534–549

5 Cho, J.S., Kim, H.W., and Kweon, I.S.: ‘Image based visual servoing using position and angle of image features’, *Electron. Lett.*, 2001, **37**, (13), pp. 862–864

6 Wang, W.Y., Cheng, C.Y., and Leu, Y.G.: ‘An online GA-based output-feedback direct adaptive fuzzy-neural controller for uncertain nonlinear systems’, *IEEE Trans. Syst., Man Cybern., B*, 2004, **34**, (1), pp. 334–345