Adaptive Focus Integral Image System Design Based on Fast-Response Liquid Crystal Microlens

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***Abstract*—The discrepancy of disparity and accommodation in current 3D display systems is one source of discomfort for the audience. To solve this problem, an adaptive focus integral image (InIm) system is proposed, which could adjust the image location according to the video content. To prove concept, a fast-response liquid crystal microlens is proposed and its performance is simulated.**

***Index Terms*—Adaptive focus, fast response, integral image (InIm), microlens.**

I. INTRODUCTION

THREE-DIMENSIONAL (3D) display is commonly recognized as next-generation display system in the near future. Integral image (InIm) is one of the promising candidates for 3D display because of its advantages, such as glass-free display mode, comparably high illuminance, and compatibility with current 2D display technologies [1]–[3]. However, most 3D display systems, including InIm, face an obstacle which might prevent the widespread of 3D display. This is the discrepancy of disparity and accommodation, which arises from the basic 3D vision mechanism of humankind. The 3D feeling, or in another word, the perception of distance of human is based on several different mechanisms, including disparity and accommodation. Disparity means the same object appears as two images of different angles in the two eyes of an observer, whereas accommodation means the eyes will focus on the object to acquire a sharp image. In natural vision, these mechanisms provide the same distance feeling to the brain. But in most 3D displays developed so far, the depth effect is based only on disparity, but not accommodation. The lack of correct accommodation results in the misunderstanding of distance, eye fatigue and nausea, especially when the audience watches 3D video for a long time [4], [5].

In this paper, we propose an adaptive focus InIm system, in which each 3D pixel is covered by an adaptive lens. By adjusting the lens focus in video speed, each pixel of the video is imaged to the correct distance, so the correct accommodation effect is achieved. We also proposed a liquid crystal (LC) microlens design to meet this adaptive focus lens requirement. The performance of the LC lens and the required driving scheme is simulated and analyzed.

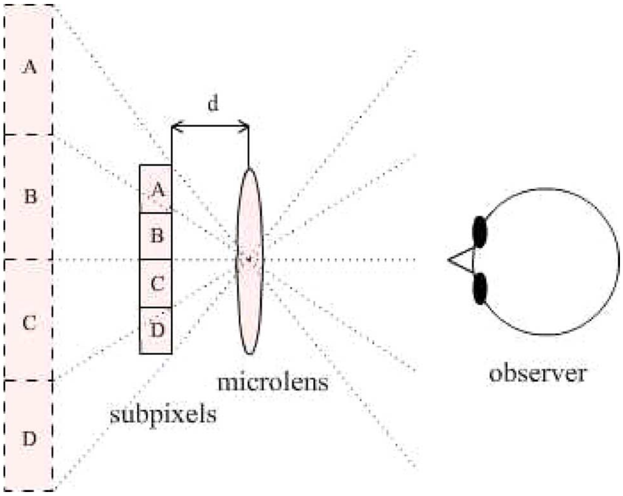

Fig. 1. Conventional InIm system.

II. ADAPTIVE FOCUS INIM SYSTEM

Fig. 1 depicts the conventional InIm system. A fixed microlens covers one integral image pixel, which includes multiple subpixels (4 subpixels in Fig. 1). The subpixels are imaged by the microlens to a certain location. The microlens also performs as the aperture stop, so the eye at each angle could only see the image of one subpixel, and two eyes of an observer acquires the image signals from two different subpixels. Multiple subpixels' images "integrate" into a whole image, from which the name "integral image" originates [6].

In order to achieve large viewing angle, the F# of the microlens needs to be as small as possible. However, the depth of focus (DOF) of the microlens is proportional to $F\#^2$. So the image depth of the conventional InIm system is always limited.

To reduce the discrepancy between accommodation and disparity, a larger image depth is required for InIm system, and several approaches have been proposed [7]–[9]. However, the most straightforward method is to adjust the focal length of the microlens, so that the image location of each pixel is adapted correspondingly. Ideally, the image location of each subpixel should match the correct image distance given by disparity. However, this requirement is quite challenging, as there are several subpixels under one microlens, and they may require different image distances at the same time.

In our adaptive focus InIm system proposal, each microlens focal length is adaptive, and the image distance of the entire

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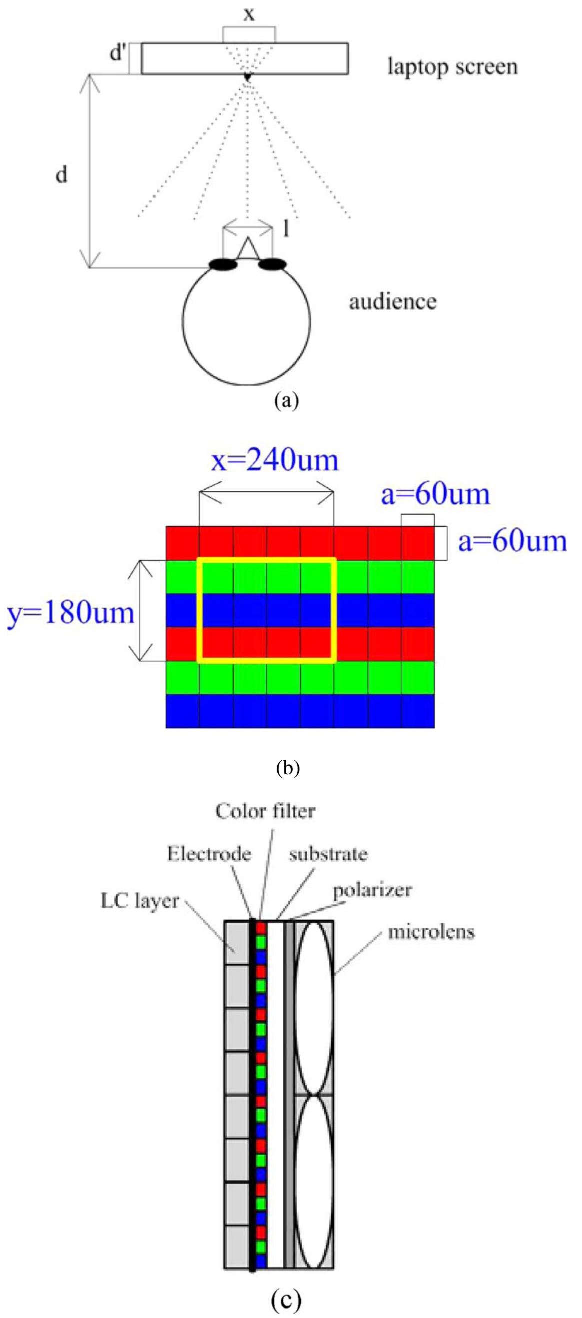


Fig. 2. Adaptive focus InIm system.

pixel below the lens is adjusted as a whole. Although there is still discrepancy for the subpixels inside one pixel, it is greatly reduced. The audience will be more difficult to notice it, and feels more comfortable.

The parameters of our adaptive integral image system are determined by laptop computer display requirement. The system design is shown in Fig. 2. As shown in Fig. 2(a), the viewing distance $d = 0.6$ m for laptop user. The separation of two eyes is $l = 65$ mm for adults. The minimum width of each full- color subpixel is assumed to be $a = 60$ μm, as Fig. 2(b) shows. As a result, the separation between the microlens array and LCD panel is $d' = 0.554$ mm. Assuming that four image signal channels are provided, the image pixel design is shown in Fig. 2(b). An InIm pixel with four full-color subpixels is 240 μm$*$180 μm in size (as marked by the bright rectangular frame). Fig. 2(c) shows the cross-section view of the display system. The microlens is mounted on top of the traditional 2D LCD display panel. The 0.554-mm separation between color pixels and microlens is occupied by the substrate and polarizer.

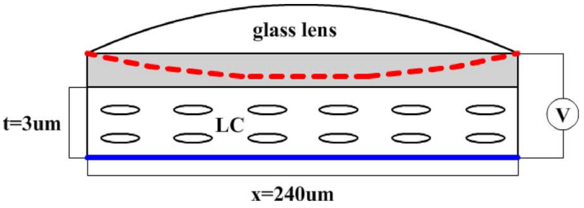


Fig. 3. Proposed LC microlens structure.

TABLE I
PROPERTIES OF UCF-6 LC MIXTURE

Name	UCF-6
n_o	1.517
n_e	1.741
$\varepsilon_{//}$	10.05
$\varepsilon_{\perp}$	3.43
K_{11}(pN)	9.99
γ_1 (mPas)	76.6

III. LC MICROLENS

A. Lens Structure

Various kinds of adaptive lens design could satisfy the focal length adjusting requirement of the adaptive focus InIm system, including liquid lens and liquid crystal (LC) lens [10]–[17]. Nevertheless, according to the system design principle, the microlens needs to adjust its focus length in video speed, which is challenging for all current adaptive lens designs. So we propose a new LC microlens design, which could meet our requirement for fast switching speed. Fig. 3 depicts the LC microlens structure. The LC layer thickness is 3 μm to ensure a fast response time. The top electrode (red dashed curve) is buried inside the grey dielectric layer and provides the gradient electric field for the LC lens. The homogenously aligned LC material is UCF-6 with its parameters listed in Table I.

The theoretical minimum focal length of this LC microlens can be calculated from following equation:

$$f_{\min} = \frac{r^2}{2t \cdot \Delta n} \tag{1}$$

where r is the lens radius, t the LC layer thickness, and Δn the refractive difference between the lens center and the edge. However, according to the calculation, we find that the minimum focal length of this LC microlens is $f_{\min} = 10.7$ mm, which still too large for the InIm system design. So an extra glass lens is added in front of the LC lens. The total optical power of the lens pair is calculated using (2):

$$\frac{1}{f_{\text{total}}} = \frac{1}{f_{\text{glass}}} + \frac{1}{f_{\text{LC}}}. \tag{2}$$

And the image location is determined by the following lens equation:

$$\frac{1}{f_{\text{total}}} = \frac{1}{l_{\text{image}}} + \frac{1}{0.554\ \text{mm}}. \tag{3}$$

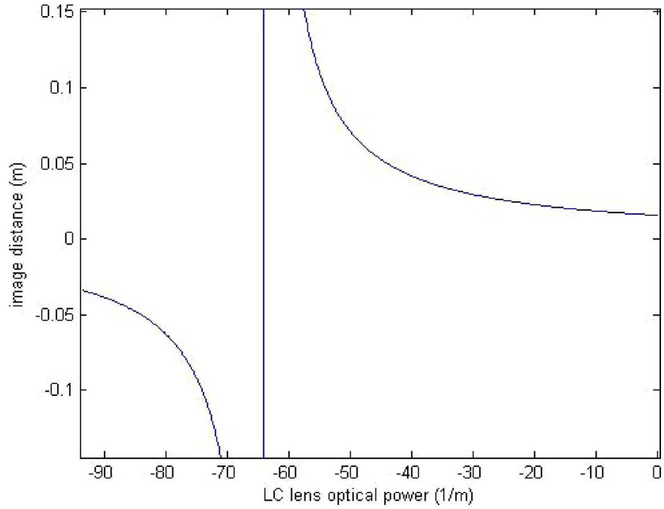


Fig. 4. Relation between LC lens power and image distance.

TABLE II
VIEWING DISTANCE AND FOCAL LENGTH

Image distance (m)	0.3	0.1	-0.1	-0.5
Viewing distance (m)	0.3	0.5	0.7	1.1
LC lens focal length (mm)	-16.5	-18.5	-13.5	-15.1

From (3), we know that in order to achieve the largest dynamic range of image distance, the total focal length of the lens pair should be close to the objective distance (0.554 mm). So we choose $f_{\mathrm{glass}} = 0.535$ mm. When the LC lens' optical power is driven from $-93.5/\mathrm{m}$ to 0 (negative lens) as shown on the x-axis of Fig. 4, the achievable image distance (distance between pixel image and microlens array) is $-\infty \sim -3$ cm and 2 cm $\sim \infty$.

According to Fig. 4, there is a 5 cm "dead zone" in the image distance, which means it is not possible to project the pixel image to this 5-cm range around the microlens array. This defect, however, does not affect the performance of the InIm system seriously, because the accommodation effect of human eye is not quite sensitive, and the 5-cm discrepancy between accommodation and disparity at 60 cm viewing distance will not cause discomfort [4].

B. Driving Scheme

As mentioned above, the accommodation mechanism of human eye is not quite sensitive, so it is not necessary to provide the precise image distance to feed the viewer's accommodation. Instead, we select four discrete image distances [4]. According to [4], these four different image distances should be enough to make the discrepancy of accommodation and disparity irresolvable, and make the viewer feel comfortable. The image distance, image viewing distance and corresponding focal length of the LC microlens are listed in Table II.

The decay time of this LC microlens is calculated from following equation:

$$\tau_0 = \frac{\gamma_1 t^2}{K_{11}\pi^2} \tag{4}$$

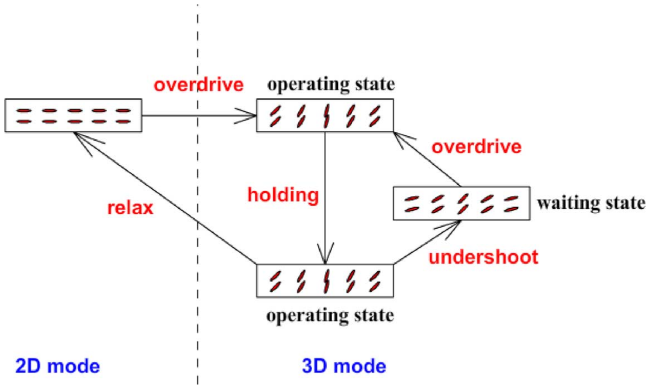


Fig. 5. LC lens driving scheme design.

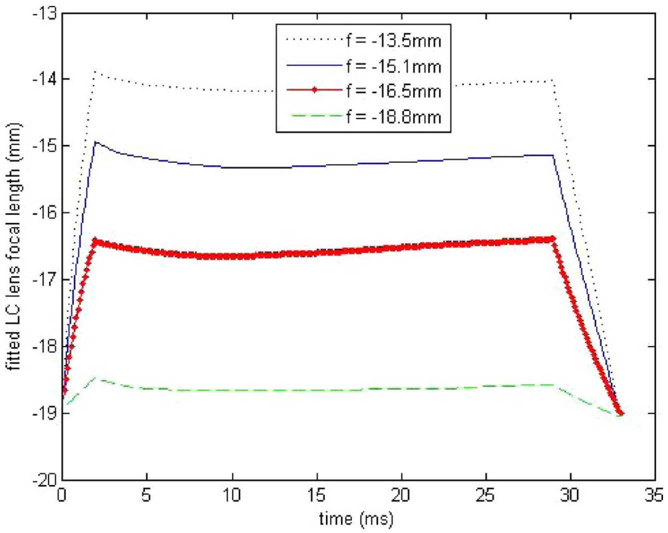


Fig. 6. Actual focal length of the LC lens.

where γ_1 is the rotational viscosity, K_{11} the splay elastic constant and $t = 3$ μm is the LC layer thickness. From (4) we find $\tau_0 = 6.99$ ms. This response time is still too long for the video-rate display requirement. So the overdrive and undershoot driving methods are used [18]–[20]. Besides, the LC director has a long oscillating time after the overdrive voltage pulse, which causes the "drift" of the LC lens focal length during the holding period. To minimize this effect on the precise control of image viewing distance, we introduce a waiting state at which $f_{\mathrm{LC}} = -19$ mm. At the end of each video frame, the LC lens is driven by undershoot voltage back to the same waiting state, and at the beginning of the next frame, the LC lens is overdriven to the required focal length. The driving scheme is shown in Fig. 5.

The dynamic response of LC director orientation is simulated by commercial software DIMOS, and the optical path length (OPL) profile of the LC lens by MatLAB. Using parabolic curve fitting, the effective focal length of the LC lens is derived by MatLAB, too. Table III lists the voltages and overdrive/ holding/ undershoot time. The dynamic response of the LC lens is shown in Fig. 6.

Two points should be noted about Table III and Fig. 6. First is that we use 30 frame/s frame rate. So each frame time is 33 ms. The overdrive and undershoot in each frame takes 6 ms, so in

TABLE III
DRIVING VOLTAGE DESIGN

Expected focal length (mm)	2ms High Voltage Overdrive (V)	27ms Holding voltage (V)	4ms Low Voltage Undershoot (V)
-16.5	2.04	1.72	1.26
-18.5	1.70	1.63	1.58
-13.5	2.90	1.83	0
-15.1	2.50	1.78	0.39

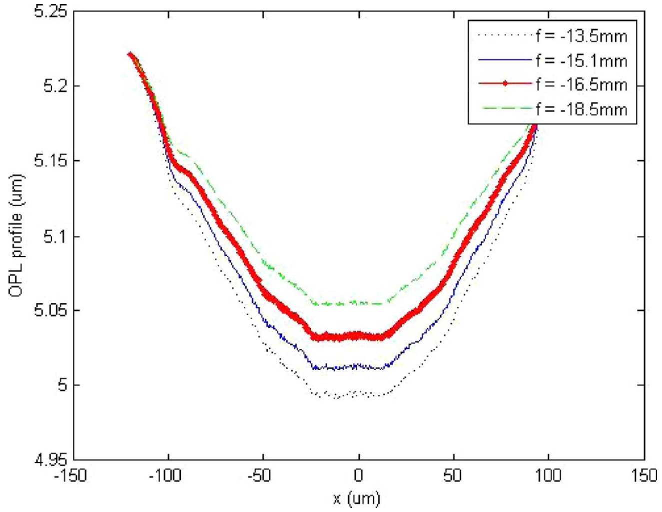


Fig. 7. Optical path length profile of the LC lens.

81.8% time length, the LC lens provides the correct image distance. However, during the remaining 18.2% time, a black frame needs to be inserted between two video frames to prevent incorrect accommodation effect, and 18.2% of illuminance will be sacrificed.

The second point is that the "drift" of focal length still exists in the 27 ms of holding period, although it has been greatly reduced by the introduction of waiting state. The effect of focal length drift upon the image viewing distance has been calculated, showing that the corresponding image distance drift is no more than 9 cm, and in most cases less than 3 cm. Based on our viewing distance selection and human eye's sensitivity, such image distance drift is not resolvable, and would not cause discomfort. If the frame rate is increased to 60 frame/s, the focal length drift can be reduced, but the black frame would occupy 36% of each frame, and 36% of illuminance will be sacrificed.

The OPL profile at 2 ms (the end of the overdrive period) under different overdrive voltages are plot in Fig. 7. From this figure we notice that the OPL is not a perfect parabolic profile, and there are some small blurs in the phase profile. This problem comes due to the optimization requirement of the top electrode. Due to the viscosity of the LC molecules, they have a slow oscillating process during the holding period of each frame, which causes the OPL, the lens focal length, and also the aberration to vary slowly (as shown in Fig. 6). The top electrode shape has to be optimized so as to lower the aberration during the entire frame, which means the aberration cannot be completely removed at each time point.

According to the simulation result, some challenges in the fabrication process of this LC lens could also be noticed. We find that the shape of the top electrode affects the lens' OPL profoundly, which means the manufacturing process of this electrode requires high precision quality control. Besides, the LC layer thickness also affects the OPL, so the cell gap control is also critical to the manufacturing of this LC lens.

IV. CONCLUSION

We propose an adaptive focus integral image system to solve the discrepancy of accommodation and disparity in current 3D display technologies. To realize this system design, a video-rate LC microlens is proposed. Low viscosity of the LC material UCF-6, small LC layer thickness, introduction of a waiting state and overdrive voltage are combined together to achieve this fast response LC lens design.

There are still some problems with our LC lens design, such as the existence of focal length drift, the aberration of the OPL profile after the lens, and the LC microlens structure manufacturing is still challenging. Thus, more work still needs to be done to simplify the LC lens structure, and to improve its performance.

REFERENCES

[1] S. Pastoor and M. Wopking, "3-D displays: A review of current technologies," *Display*, vol. 17, pp. 100–110, 1997.

[2] A. Stern and B. Javidi, "Three-dimensional image sensing, visualization, and processing using integral imaging," *Proc. IEEE*, vol. 94, no. 3, pp. 591–607, Mar. 2006.

[3] M. G. H. Hiddink, S. T. de Zwart, O. H. Willemsen, and T. Dekker, "Locally switchable 3D displays," in *SID Symp. Dig.*, 2006, pp. 1142–1145.

[4] G. Love, D. Hoffman, P. Hands, J. Gao, A. Kirby, and M. Banks, "High-speed switchable lens enables the development of a volumetric stereoscopic display," *Opt. Express*, vol. 17, pp. 15716–15725, Aug. 2009.

[5] S. C. McQuaide, "Three-dimensional virtual retinal display using a deformable membrane mirror," M. S., Dep. Mech. Eng., Univ. of Washington, Seattle, 2002.

[6] J. Arai, M. Okui, T. Yamashita, and F. Okano, "Integral three-dimensional television using a 2000-scanning-line video system," *Appl. Opt.*, vol. 45, pp. 1704–1712, 2006.

[7] D.-Q. Pham, N. Kim, K.-C. Kwon, J.-H. Jung, K. Hong, B. Lee, and J. Park, "Depth enhancement of integral imaging by using polymer-dispersed liquid-crystal films and a dual-depth configuration," *Opt. Lett.*, vol. 35, pp. 3135–3137, 2010.

[8] J.-H. Park, H.-R. Kim, Y. Kim, J. Kim, J. Hong, S.-D. Lee, and B. Lee, "Depth-enhanced three-dimensional-two-dimensional convertible display based on modified integral imaging," *Opt. Lett.*, vol. 29, pp. 2734–2736, Dec. 2004.

[9] Y. Kim, H. Choi, J. Kim, S. -W. Cho, Y. Kim, G. Park, and B. Lee, "Depth-enhanced integral imaging display system with electrically variable image planes using polymer-dispersed liquid-crystal layers," *Appl. Opt.*, vol. 46, pp. 3766–3773, 2007.

[10] S. Xu, Y. J. Lin, and S. T. Wu, "Dielectric liquid microlens with well-shaped electrode," *Opt. Express*, vol. 17, pp. 10499–10505, Jun. 2009.

[11] S. Xu, Y. Liu, H. Ren, and S. T. Wu, "A novel adaptive mechanical-wetting lens for visible and near infrared imaging," *Opt. Express*, vol. 18, pp. 12430–12435, Jun. 2010.

[12] S. Xu, H. Ren, Y. Liu, and S. T. Wu, "Dielectric liquid microlens with switchable negative and positive optical power," *J. Microelectromech. Eng.*, vol. 20, pp. 297–301, Feb. 2011.

[13] H. Ren, D. W. Fox, B. Wu, and S. T. Wu, "Liquid crystal lens with large focal length tunability and low operating voltage," *Opt. Express*, vol. 15, pp. 11328–11335, Sep. 2007.

[14] Y. H. Lin, H. W. Ren, K. H. Fan-Chiang, W. K. Choi, S. Gauza, X. Y. Zhu, and S. T. Wu, "Tunable-focus cylindrical liquid crystal lens," *Jpn. J. Appl. Phys.*, vol. 44, pp. 243–244, Jan. 2005.

[15] Y. P. Huang, L. Y. Liao, and C. W. Chen, "2-D/3-D switchable autostereoscopic display with multi-electrically driven liquid-crystal (MeD-LC) lenses," *J. Soc. Inf. Display*, vol. 18, pp. 642–646, 2010.

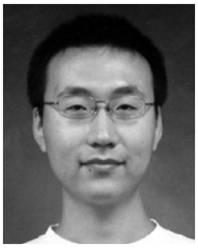
[16] J. G. Lu, X. F. Sun, Y. Song, and H. P. D. Shieh, "2-D/3-D switchable display by Fresnel –type LC lens," *J. Display Technol.*, vol. 7, no. 4, pp. 215–219, Apr. 2011.

[17] H. Ren, Y. H. Fan, S. Gauza, and S. T. Wu, "Tunable-focus flat liquid crystal spherical lens," *Appl. Phys. Lett.*, vol. 84, pp. 4789–4791, Jun. 2004.

[18] S. T. Wu and C. S. Wu, "High-speed liquid-crystal modulators using transient nematic effect," *J. Appl. Phys.*, vol. 65, pp. 527–532, Jan. 1989.

[19] S. T. Wu and C. S. Wu, "Small angle relaxation of highly deformed nematic liquid crystals," *Appl. Phys. Lett.*, vol. 53, pp. 1794–1796, 1988.

[20] Y. Li, Z. Ge, R. Lu, M. Jiao, and S. T. Wu, "Fast-response liquid-crystal displays using crossed fringe fields," *J. Soc. Inf. Display*, vol. 16, pp. 1069–1074, Oct. 2008.



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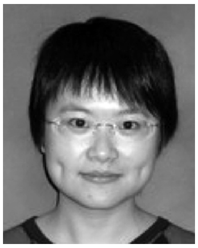

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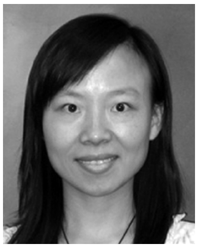

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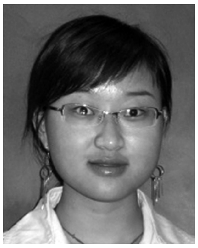

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