Dispersion compensation for an ultrathin metal film using LCD–CCD system*

Dai Yu(代 煜)[a)b)†] and Zhang Jian-Xu(张建勋)[a)]

[a)] *Institute of Robotics and Automatic Information System, Nankai University, Tianjin* 300071, *China*

[b)] *State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin* 150080, *China*

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A dispersion compensation method is introduced to correct the distorted image passing through an ultrathin metal film. An LCD–CCD system is modeled by the back propagation network and used to evaluate the transmittance of the ultrathin metal film. Training samples for the network come from 729 images captured by shooting test patches, in which the RGB values are uniformity distributed between 0 and 255. The RGB value of the original image that will be distorted by the dispersion is first transformed by mapping from the LCD to the CCD, multiplied by the inverse matrix of the transmittance matrix, and finally transformed by mapping from the CCD to the LCD, then the corrected image is obtained. In order to verify the effectiveness of the proposed method, ultrathin aluminum films with different thicknesses are evaporated on glass substrates and laid between the CCD and LCD. Experimental results show that the proposed method compensates for the dispersion successfully.

Keywords: ultrathin metal film, dispersion compensation, back propagation network, LCD–CCD system

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1. Introduction

It is well known that the effective permittivity of an ultrathin metal film (UMF) can be different from that of the corresponding bulk material.[1] The reason for this is that the structure of the material is different. The growth mechanisms for evaporated, sputtered, and laser deposited films can be different, and consequently the film structures can be different. As the film changes from an isolated island of the material to a continuous film with more or less surface roughness, these changes may be presented at different film thicknesses for different growth methods and conditions. Usually the permittivity of the ultrathin film can be modeled using effective medium approximations, such as the Maxwell-Garnet[2] and the Bruggeman[3] models, but these models can only be used on the assumption that the volume fraction of the metal is known. The Maxwell-Garnet model is theoretically proven, while the Bruggeman model has an empirical justification, so the Maxwell-Garnet model should be more accurate. Du *et al.*[4] investigated the direct current conductivity of the ultrathin titanium film and showed that the Maxwell-Garnet model gives a better fit with the experimental data than the other model when the volume fraction of the metal is less than 0.4. Sun *et al.*[5] gave the transmittance and reflectance as a function of wavelength in the visible band for the ultrathin aluminum films with different thicknesses through experiments. The evaluation of optical dispersion and effective permittivity of the UMF are of considerable importance for applications such as microelectronic and optoelectronic materials.

Most of the previous investigations on the optical dispersion of the UMF were focused on the dispersion relationship of the surface plasmon.[6–8] Few reports have been focused on the dispersion compensation, especially the correction of the transmitted image beam through the UMF. The aim of the present work is to introduce a dispersion compensation method to correct the distorted image passing through the UMF.

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†Corresponding author. E-mail: daiyu@nankai.edu.cn

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2. Method

2.1. Model of the LCD–CCD system

Figure 1 shows the transformation process of an image as it passes through a metal film. The liquid crystal display (LCD) screen displays a user-selected image. The resulting appearance is captured by the charge coupled device (CCD). The UMF on the glass substrate is laid between the LCD screen and the CCD camera. The LCD screen is a SamSung 2243BW, and the camera is a Sony progressive scan CCD ICX445 with a resolution of 1280 × 960 pixels.

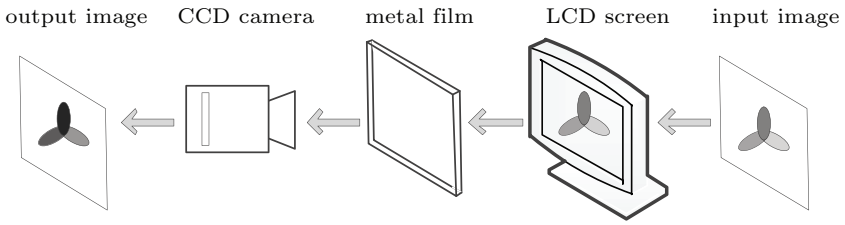


Fig. 1. Transformation process of an image as it passes through a metal film.

Because of the nonlinear relationship between the RGB values of the LCD and the CCD, a radiometric mapping between the LCD and the CCD image planes should be obtained first. As the RGB values that serve as the input to the LCD screen and that of the camera pixels are both discrete, we could refrain from requiring one to one mapping, but it should be monotonic. Bimber *et al.*[9] and Grossberg *et al.*[10] have investigated the radiometric model for the projector-camera system and given the model as

$$\boldsymbol{C} = \boldsymbol{V}\boldsymbol{P} + \boldsymbol{F}, \tag{1}$$

where

$$\boldsymbol{C} = \begin{bmatrix} C_R \\ C_G \\ C_B \end{bmatrix}, \quad \boldsymbol{V} = \begin{bmatrix} V_{RR} & V_{RG} & V_{RB} \\ V_{GR} & V_{GG} & V_{GB} \\ V_{BR} & V_{BG} & V_{BB} \end{bmatrix},$$

$$\boldsymbol{P} = \begin{bmatrix} P_R \\ P_G \\ P_B \end{bmatrix}, \quad \boldsymbol{F} = \begin{bmatrix} F_R \\ F_G \\ F_B \end{bmatrix}.$$

The matrix $\boldsymbol{V}$ is the color mixing matrix. The vector $\boldsymbol{F}$ is the the contribution of the environmental lighting to camera irradiance and camera noise. The matrix $\boldsymbol{C}$ is the three color channels (red, green, and blue) of the camera, and the matrix $\boldsymbol{P}$ is the projection pattern. Because the three color channels typically have broad and overlapping spectral curves in both the camera and the projector, the matrix $\boldsymbol{V}$ is not diagonal. Grossberg *et al.*[10] have calculated the parameters in Eq. (1) through decoupling the three color channels and recovering the projector nonlinearity, but the method is complicated and needs some assumptions. In this paper, we use the artificial neural network to obtain the relationship between the RGB values of the LCD and CCD, as shown in Fig. 2.

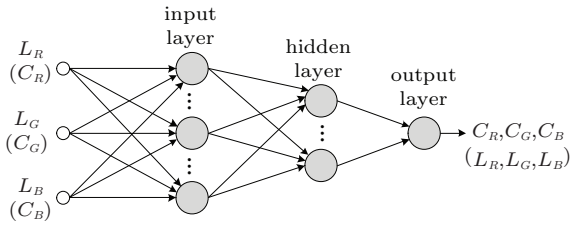


Fig. 2. A back propagation neural network developed for characterizing the mapping from the LCD to the CCD and that from the CCD to the LCD, where L_R, L_G, and L_B are the three color channels of the LCD screen, C_R, C_G, and C_B are the RGB values of the CCD camera.

The neural network has a good ability to learn and describe the highly-nonlinear and strongly-coupled relationships between multi-input and multi-output variables. The use of the back propagation (BP) network presents a new approach to capturing the underlying nonlinear coupling relationship between the RGB values of the LCD and CCD. The most common training algorithms of the BP neural network are the Levenberg–Marquardt optimization (LMO), the resilient BP algorithm (RBA), and the adaptive learning algorithm (ALA). In this study, all of the above mentioned algorithms are investigated and compared. Based on the comparison, the LMO model, which includes an input layer with three neurons, a hidden layer with six neurons, and an output layer with one neuron, is adapted for modeling the LCD–CCD system. Because both the input and the output data are positive integers, a log–sigmoid transfer function is used in the BP network. This transfer function is

commonly employed in the BP network. The BP network is programmed and executed using the neural network toolbox in MATLAB (version 7.13, 2011b). In Table 1, 729 (i.e., 9^3) data sets are employed for model training. The input samples are displayed on a number of test patches, and figure 3 gives an example of several such patches. The output samples of the BP network are given by the mean values of variables C_R, C_G, and C_B, which are averaged over a certain area on the color picture captured by the CCD when establishing the mapping from the LCD to the CCD. If mapping from the CCD to the LCD is needed, mean values of C_R, C_G, and C_B will be collected to form the input data for training the BP network, and L_R, L_G, and L_B will serve as the output samples. All input and output data are normalized by dividing the maximum value of the RGB channels. The technical parameters of the BP network include the initial maximum number of epochs 2000, learning rate 0.01, momentum constant 0.9, and minimum performance gradient 1×10^{-5}. When the LCD–CCD system is modeled by the BP network, the UMF will not be laid in the system.

Table 1. Training samples for the BP network, where p_1, p_2, and p_3 are integers within interval [1, 9].

Number	Input sample			Output sample		
	L_R	L_G	L_B	C_R	C_G	C_B
1	25	25	25			
2	25	25	50			
...		...		captured by CCD		
81(p_1-1)+9(p_2-1)+p_3	25p_1	25p_2	25p_3			
...		...				
729	225	225	225			



Fig. 3. (colour online) One test patch used to generate the color image for training the BP network.

2.2. Transmittance measurement

Since the CCD exhibits a linear response of the raw pixel value with the incident light intensity,[10,11] it can be used to perform optical transmittance measurements. To measure the transmittance of the UMF, we take the ratio of the intensity of the transmitted light through the UMF to that of the light acquired by the CCD directly. Thus, the transmittances (T_R, T_G, and T_B) of red, green, and blue bands are defined as

$$T_R = \frac{C_{Rf} - F_R}{C_{Rd} - F_R},$$

$$T_G = \frac{C_{Gf} - F_G}{C_{Gd} - F_G},$$

$$T_B = \frac{C_{Bf} - F_B}{C_{Bd} - F_B}, \tag{2}$$

where C_{Rf}, C_{Gf}, and C_{Bf} represent the values of red, green, and blue channels when the images are taken by the CCD camera through the UMF, while C_{Rd}, C_{Gd}, and C_{Bd} represent the values of red, green, and blue channels when the images are taken by the CCD camera directly.

2.3. Model of the LCD–UMF–CCD system

Based on Eq. (1), the radiometric model of the LCD–UMF–CCD system is given by

$$\boldsymbol{C} = \boldsymbol{T}(\boldsymbol{V}\boldsymbol{L} + \boldsymbol{F}), \tag{3}$$

where

$$\boldsymbol{T} = \begin{bmatrix} T_R & 0 & 0 \\ 0 & T_G & 0 \\ 0 & 0 & T_B \end{bmatrix}, \quad \boldsymbol{L} = \begin{bmatrix} L_R \\ L_G \\ L_B \end{bmatrix}.$$

If we multiply both sides of Eq. (3) by $\boldsymbol{T}^{-1}$, we have

$$\boldsymbol{T}^{-1}\boldsymbol{C} = \boldsymbol{V}\boldsymbol{L} + \boldsymbol{F}. \tag{4}$$

It can be seen from Eqs. (1) and (4) that if we want to make the output image of the LCD–CCD system similar to that of the LCD–UMF–CCD system, the images displayed on the two LCD screens must be different. The image needs to be processed to avoid the distortion, the RGB value of the compensated image can be calculated using the transmittance matrix and the radiometric model of the LCD–CCD system.

2.4. Process of dispersion compensation

The process of dispersion compensation is shown in Fig. 4. Firstly, the RGB values (L_{R1}, L_{G1}, L_{B1}), which will be displayed on the LCD screen, are treated as the input for the LCD–CCD mapping, and let the output of the mapping be (C_{R1}, C_{G1}, C_{B1}). Secondly, (C_{R1}, C_{G1}, C_{B1}) are compensated as follows:

$$\begin{bmatrix} C_{R2} \\ C_{G2} \\ C_{B2} \end{bmatrix} = \boldsymbol{T}^{-1} \begin{bmatrix} C_{R1} \\ C_{G1} \\ C_{B1} \end{bmatrix} = \begin{bmatrix} 1/T_R & 0 & 0 \\ 0 & 1/T_G & 0 \\ 0 & 0 & 1/T_B \end{bmatrix} \begin{bmatrix} C_{R1} \\ C_{G1} \\ C_{B1} \end{bmatrix}. \quad (5)$$

Finally, (C_{R2}, C_{G2}, C_{B2}) are treated as the input for the CCD–LCD mapping, and the output data (L_{R2}, L_{G2}, L_{B2}) are the RGB values after dispersion compensation.

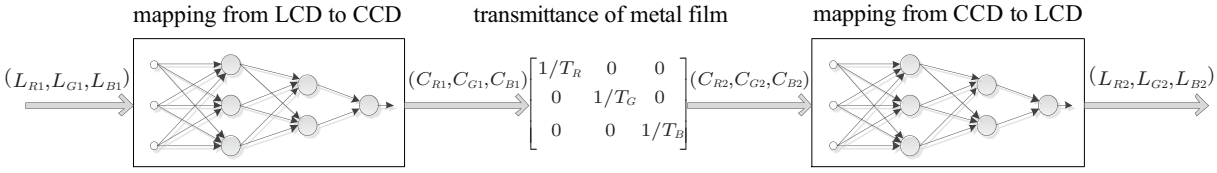


Fig. 4. Process of dispersion compensation.

3. Experimental results

An ultrathin aluminum film on a glass substrate is prepared using a ZZ1400 high vacuum coating machine. The SiO_2 protective layer is evaporated on the aluminum film, and the thickness of the protective layer is about 300 nm. Ultrathin aluminum films with different thicknesses are obtained by varying the deposition time with a stable deposition rate. Figure 5 presents the optical transmittances calculated by Eq. (2) for ultrathin aluminum films with different thicknesses on the glass substrate. For both the films, the transmittances increase with decreasing incident wavelength.

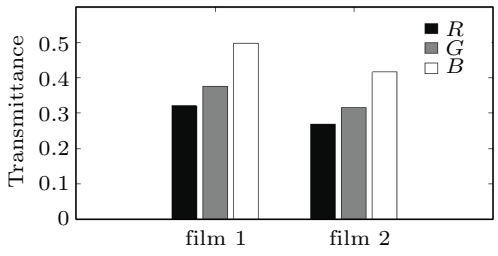


Fig. 5. Transmittances for ultrathin aluminum films with different thicknesses.

To verify the effectiveness of the proposed dispersion compensation method, some experiments are performed. We take 12 arbitrary original images and apply the dispersion compensation process shown in Fig. 4 to generate the corrected images. Figure 6 shows the modeling errors of the BP network. The modeling errors are the differences of the values of the RGB channels between the output of the BP network and the output of the CCD when establishing mapping from the LCD to the CCD. The experimental results show that the BP network has a good modeling ability for the LCD–CCD system. After that, the corrected image is displayed on the LCD screen and captured by the CCD through the film. We compare this with the image obtained by shooting the original image directly. The differences between values of the RGB channels between these two images act as

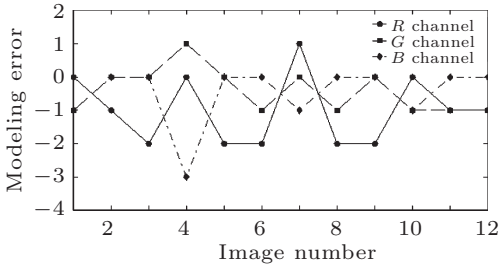


Fig. 6. Modeling errors of the BP network.

the dispersion compensation errors and are shown in Fig. 7. As shown in Fig. 7, the dispersion compensation errors are not larger than 4.

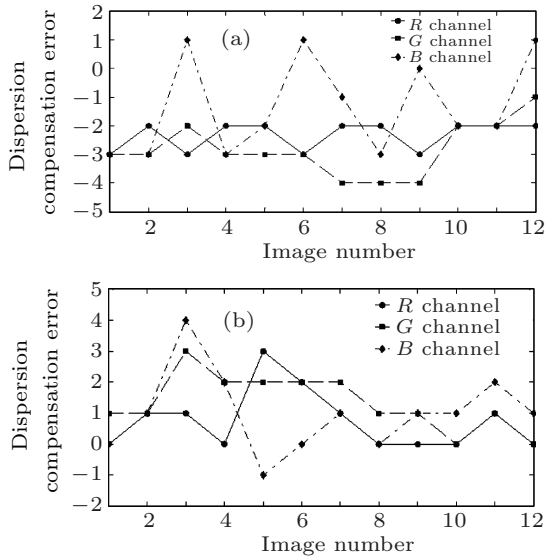


Fig. 7. Dispersion compensation errors of three color channels for (a) film 1 and (b) film 2.

4. Conclusion

In this paper, an effective dispersion compensation method is introduced to correct the distorted image passing through the UMF. This method is based on the radiometric model of the LCD–CCD system. The BP network is used to construct the mapping from the LCD to the CCD and the mapping from the CCD to the LCD. Experiments show that the dispersion compensation method works very well. It is noted that many color images must be collected and used to train the BP network, which is really time-consuming work. But after the network learns to model the LCD–CCD system successfully, the training period of the BP network is ended, and then the computational complexity decreases greatly. The real-time color video correction is feasible, since the efficiency of our method enables the dispersion compensation at frame-rate. In addition, the dispersion compensation method can be used to reduce the visual discomfort of the developed three-dimensional display.[12] This is because the distorted image passing through the UMF can be corrected by our method.

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