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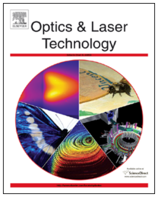

Neural network based color decoupling technique for color fringe profilometry

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ABSTRACT

A color decoupling algorithm based on neural network is proposed to improve the performance of color fringe projection system which suffers from the complicated color coupling effect. We exploit the generalization and interpolation capabilities of a feed-forward backpropagation neural network to map from coupled color data to decoupled color data. The advantage of this algorithm is that the coupling effect is regarded as a nonlinear function which is a rational description of the color CCD camera's imaging principle. Theoretical analysis and the neural network training process are introduced comprehensively. Sufficient experiments are carried out to prove that the proposed method can effectively compensate for both the stripe sinusoidal property and the phase quality.

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1. Introduction

Fringe projection profilometry (FPP) is one of the most widely used techniques in three-dimensional shape measurement because of its insensitivity to the changes of background, contrast and noise. A typical measuring system projects a series of sinusoidal fringes onto the tested object and acquires images of the distorted fringes, then the 3D coordinates of the object can be obtained from such images. Phase shift profilometry (PSP) or Fourier transformation profilometry is used to calculate the phase of the captured sinusoidal fringe patterns [1,2].

Traditionally, at least three gray images need to be projected and taken to calculate the phase using phase shift technique, limiting the technique to the measurement of static objects. Inspired by the fact that RGB components of a color image equal three gray images, the idea to replace gray patterns with color-coded patterns to complete the measurement has been proposed which makes real time measurement possible [3–6]. But color fringe patterns are more sensitive to the changes of the ambient light and the texture of measured object than gray patterns. Besides, one or more color CCD cameras are needed in PSP based on color fringes projection. As is common to all color CCD cameras, the spectra of red, green and blue channels are made to have some overlaps so that there would be no color-blind areas on the spectrum. Unfortunately these overlapping spectra of three channels results in color coupling which is also called cross talk among three channels. Such coupling effect leads to the fact that the three primary color components cannot be split correctly from a color fringe pattern, and the measurement results will be influenced significantly.

To eliminate the color cross talk, many researchers have come up with some solutions [2,7–14]. Huang et al. [2] tried to quantify the coupling effect by calculating the intensity modulation $I^{''}$, the accuracy of this method is not so high because $I^{''}$ is not a constant for the whole pattern; Zhang et al. [7] made further study in Huang's method, he added a light filter in front of the lens to improve the performance efficiently; Pan et al. [9] put a filter in front of the lens to filter the overlaps in the spectrum as well, but this kind of filter works well only on a 3-CCD camera and is invalid for single CCD cameras. She also proposed a calibration method to construct a look-up table (LUT) which built a relationship between the source color and the measured color. The main drawback of this method is that the table should be enormous ($255*255*255$) to achieve the expected accuracy and both the building, thus the searching process is very time-consuming; Caspi et al. [10] built a mathematical model of the color coupling effect. She proposed the concept of coupling matrix to deal with the cross talk and used a light splitter to calculate the matrix; Lar Kinell et al. [11] calculated the coupling matrix by obtaining the intensity modulation $I^{''}$ and decoupled the cross talk using the reverse coupling matrix. Besides, he put an extra filter in front of the camera to achieve a better accuracy; both Zou [12] and Hu [13] proposed mathematical methods to eliminate cross talk: Zou addressed the problem based on bidimensional empirical mode decomposition and Hu introduced a new way to calculate the coupling matrix, both these methods work well but needed complicated computation which took large amount of time.

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In this paper, we propose a color decoupling method by using neural network. The system model and the mathematical model of PSP technique based on color fringes projection are introduced. For the fringe patterns entering into the color CCD cameras, the transfer function is so complicated that it is difficult to find the best coupling model for the CCD camera. Therefore we describe the color coupling effect as a nonlinear function. In order to achieve a high accuracy, a trained three-layer BP (backpropagation) neural network is employed to obtain the complicated transformation. This decoupling algorithm is easy to carry out: once the BP neural network is trained before measurement, the network can be used to weaken the color coupling effect greatly as long as the measuring environment and the fringe patterns used for contouring maintain the same.

The remainder of this work is structured as follows: In Section 2, the system model, neural network topology diagram and the training method are provided. Simulation results are shown in Section 3. The system setup and the experiments are described in Section 4. Section 5 discusses the advantages and shortcomings of the proposed method, and Section 6 concludes this work.

2. Principle

2.1. System model

A typical measuring system based on fringe projection is shown in Fig. 1. A computer is connected to a DLP projector. The computer generates fringe pattern I^s by software and outputs I^s to the projector, and then the projector projects fringe pattern I^p to the tested object. The deformed images are snapped by the CCD camera and sent to computer through an image board. Then the 3D coordinates of the object can be obtained from the phase map of the captured fringe image I^c through a calibration process.

According to Gai and Da [15], the relationship between I^s and I^o is shown as

$$\begin{bmatrix} I_r^o(x,y) \\ I_g^o(x,y) \\ I_b^o(x,y) \end{bmatrix} = \begin{bmatrix} r_r(x,y) \\ r_g(x,y) \\ r_b(x,y) \end{bmatrix} \left\{ P \left\{ \begin{matrix} I_r^s \\ I_g^s \\ I_b^s \end{matrix} \right\} + M_0 \right\}, \tag{1}$$

where $\{I_i^o(x,y), i=r,g,b\}$ means the intensity of the fringe pattern reflected by the object. $\{r_i(x,y), i=r,g,b\}$ represents the reflectance of the object surface, operator P is the transformation from the projection instruction to actual illumination, and $\{I_i^s = a_i + b_i \cos(2\pi f_i u), i=r,g,b\}$ is the fringe pattern generated by the computer; a_i represents the bias range of the fringe images and b_i represents the modulation, f_i is the frequency of I_i^s, and M_0 denotes the illumination intensity.

The reflected pattern $I_i^o(x,y)$ is snapped by the color CCD camera. According to Caspi [10], since there are overlaps in the spectrum of a 3-CCD camera, the transformation from $I_i^o(x,y)$ to the captured images $I_i^c(x,y)$ is a matrix form shown in the following equation:

$$\begin{bmatrix} I_r^c(x,y) \\ I_g^c(x,y) \\ I_b^c(x,y) \end{bmatrix} = \begin{bmatrix} a_{rr} & a_{rg} & a_{rb} \\ a_{gr} & a_{gg} & a_{gb} \\ a_{br} & a_{bg} & a_{bb} \end{bmatrix} \begin{bmatrix} I_r^o(x,y) \\ I_g^o(x,y) \\ I_b^o(x,y) \end{bmatrix} = A \begin{bmatrix} I_r^o(x,y) \\ I_g^o(x,y) \\ I_b^o(x,y) \end{bmatrix}, \tag{2}$$

where

$$a_{ij} = \int_0^\infty f_i(\lambda) I_j^t(\lambda)\, d\lambda, \quad i,j = r,g,b, \tag{3}$$

with a_{ij} being the coupling degree among color channels and $a_{ij} = 1$ if $i = j$, $f_i(\lambda)$ is the spectral response of the camera filter in the i channel, $I_j^t(\lambda)$ represents the spectrum of the output of the projector, A denotes the coupling matrix, I_i^c is the pattern captured by the camera, and λ is the wavelength of the light.

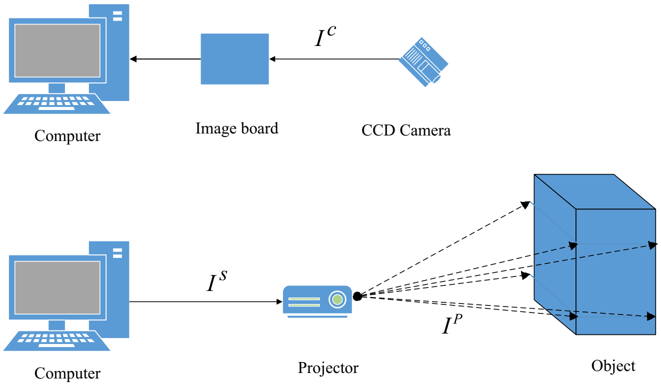

Fig. 1. Model of fringe projection profilometry system.

This mathematical model reveals the transformation of a color fringe pattern from being projected to being captured. It should be noted that this model is established based on the imaging principle of 3-CCD cameras: the intensities of three channels of a color image captured by a 3-CCD camera are

$$R = \int_0^\infty f_R(\lambda) I^r(\lambda)\, d\lambda \tag{4}$$

$$G = \int_0^\infty f_G(\lambda) I^g(\lambda)\, d\lambda \tag{5}$$

$$B = \int_0^\infty f_B(\lambda) I^b(\lambda)\, d\lambda \tag{6}$$

where R, G, B are the intensity of the red, green, and blue channels, respectively, and $\{I^i(\lambda), i=r,g,b\}$ is the spectrum of the light arriving at the camera.

As to single CCD cameras which are also widely used because of their low cost compared to 3-CCD cameras, to quantify coupling effect by using a matrix form is not rigorous. For 3-CCD cameras, there are three charge-coupled devices which can be used to carry the pixel values of three channels of a color image. But for single CCD cameras, only one image sensor with a Bayer mosaic filter can be used to generate color images [16]. To get a color image by only one sensor, the captured raw mosaic image should be converted to color by employing an interpolation algorithm, which means for each pixel in the captured color image, one channel is affected by not only another two channels of this pixel but also the RGB components of its neighboring pixels. This fact makes the coupling effect of a single CCD camera more complicated than that of a 3-CCD camera. Based on this consideration, we propose a more general model which is shown in Eq. (7) to describe the coupling effect for both 3-CCD cameras and single CCD cameras:

$$\begin{bmatrix} I_r^c(x,y) \\ I_g^c(x,y) \\ I_b^c(x,y) \end{bmatrix} = f_{couple} \begin{bmatrix} a_r I_r^o(x,y) \\ a_g I_g^o(x,y) \\ a_b I_b^o(x,y) \end{bmatrix} = f_{couple} \begin{bmatrix} I_r^{nc}(x,y) \\ I_g^{nc}(x,y) \\ I_b^{nc}(x,y) \end{bmatrix}, \tag{7}$$

where the function f_{couple} represents the coupling effect among the three channels, $\{a_i, i=r,g,b\}$ denotes the sensitivity of the camera, and $\{I_i^{nc}, i=r,g,b\}$ represents the captured patterns when the camera is assumed to have no coupling effect (i.e., there are no overlaps in the spectrum response curve). It should be noted that I_i^c and I_i^{nc} denote the captured patterns with and without coupling effect, respectively. They are precisely aligned point-by-point and have the same resolution. How to get the patterns without coupling effect will be further discussed in Section 2.2.

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