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A calibration approach for decoupling colour cross-talk using nonlinear blind signal separation network

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A Calibration Approach for Decoupling Colour Cross-talk using Nonlinear Blind Signal Separation Network

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***Abstract*— We present a calibration approach to invert the nonlinear mixing process of colour cross-talk in multi-channel profilometry systems. Parameters of the inverse network are determined by a nonlinear blind signal separation algorithm. Experimental and simulation results demonstrate that proposed approach can effectively reduce colour leakages and improve the measurement accuracy.**

I. Introduction

Fringe pattern profilometry (FPP) is one of the most popular non-contact methods for measuring the three-dimensional surface of an object in recent years. With FPP, a Ronchi grating or sinusoidal grating is used to project fringe patterns onto a three-dimensional diffuse surface which results in deformed grating images. The deformed grating images are captured by a CCD camera and are processed to yield the shape of the object. In order to reconstruct the 3-D surface information from the pattern images, a number of fringe analysis methods have been developed, including Fourier Transform Profilometry(FTP) [1], Phase Shifting Profilometry (PSP) [2], Special Phase Detection (SPD) [3], Phase Locked Loop (PLL) [4] and other analysis methods [5, 6].

Phase shifting profilometry is based on the triangle function relationships among a sequence of phase-stepped pattern images. With PSP, phase-stepped fringes are projected onto the object and acquired by CCD camera. However, PSP method is not very suitable for real-time and dynamic data processing because sequential projection of phase-stepped fringe patterns requires time.

In order to overcome the shortcomings of the PSP method, multichannel approach [7] was presented, in which the phase-stepped fringes are implemented using different colours and the fringe patterns are projected onto the object simultaneously. A straightforward way is to generate three phase shifted fringe patterns by three fundamental colours (Red, Green and Blue) respectively: each of which carries a phase-shifted fringe, so that three images with different phase steps can be projected and detected at one time. To achieve comparable performance as the original PSP approach, it is important to have perfect isolation among different colour channels. However, there is always colour leakage in one channel to others, referred to as cross-talk between the channels, which will degrade the performance of 3-D surface shape measurement. Hence the undesired cross-talk should be eliminated as the measurement accuracy will degrade otherwise. In [8] an approach was proposed, which uses optical lenses to reduce the leakage. However, this approach requires physically switch of the lenses, which then makes the dynamic or real-time measurement impossible.

The purpose of this paper is to build an decoupling network to invert the colour leaking process and reduce the colour cross-talks between each channel. In additional, we will present a calibration approach to determine the parameters of the decoupling network.

This paper is organized as follows. In section II, we briefly introduce the principle of multichannel PSP and basic formulas. In section III, we present a mathematical model to describe the colour leaking process and propose a inverse network to decouple the leaked colour signals. In section IV, a calibration method based on a nonlinear blind signal separation algorithm is presented. In section V, the improvement of measurement accuracy is shown by experimental and simulation results. Section VI concludes this paper.

II. Principle of Multichannel PSP

A typical arrangement of fringe pattern profilometry system is shown in Fig.1 In PSP system, N $(N = 3, 4, 5, \ldots)$ grating patterns with $2\pi/N$ phase difference between adjacent frames are projected onto the reference plane and the object surface. The intensities of the fringe pattern captured in the nth step on the reference plane and on the surface of objects at point x can be respectively expressed as: (Note: when we are considering the sections of object surface for each given y, we can simply use single variable functions to denote the intensity of fringe pattern)

$$p_n(x) = a + b\cos(2\pi f_0 x + 2\pi n/N) \tag{1}$$

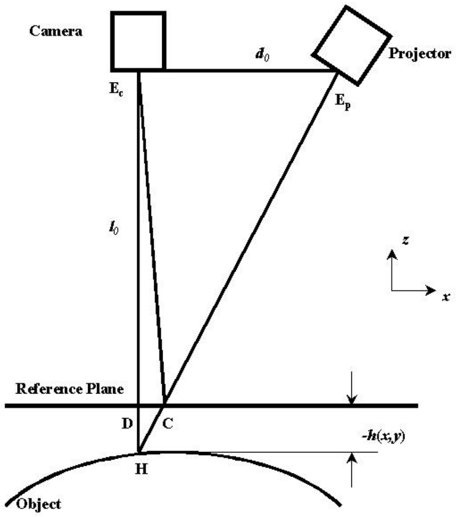

Fig. 1. Optical arrangement of fringe pattern profilometry system

and

$$q_n(x) = a + b\cos(2\pi f_0 x + \phi(x) + 2\pi n/N) \quad \text{for n=0,1,2,...,N-1} \tag{2}$$

where a represents the background illumination and b is the contrast between light and dark fringes captured by CCD.

With PSP method, the phase map $\phi(x)$ can be obtained by following formula:

$$D = \tan(2\pi f_0 x + \phi(x)) = -\frac{\sum_{n=0}^{N-1} q_n(x)\sin(2\pi n/N)}{\sum_{n=0}^{N-1} q_n(x)\cos(2\pi n/N)} \tag{3}$$

Similarly, for original fringe patterns, we have:

$$R = \tan(2\pi f_0 x) = -\frac{\sum_{n=0}^{N-1} p_n(x)\sin(2\pi n/N)}{\sum_{n=0}^{N-1} p_n(x)\cos(2\pi n/N)} \tag{4}$$

Therefore, the phase map can be retrieved by:

$$\phi(x) = unwrap(\arctan(D)) - unwrap(\arctan(R)) \tag{5}$$

where $unwrap$ is so-called phase unwrapping operation. And by the recovered absolute value of phase $\phi(x)$, height distribution can be calculated by: [1]

$$h(x) = \frac{l_0\phi(x)}{\phi(x) - 2\pi f_0 d_0} \tag{6}$$

For multichannel PSP, three colour channels, Red, Green and Blue are used for carrying three different phase shifted fringe patterns. That means we use the Eq.(3), (4) and (5) on the condition of $N = 3$ and q_0, q_1, q_2 are the deformed fringe patterns in Red, Green, Blue channel respectively, p_0, p_1, p_2 are the original fringe patterns in R, G, B channel respectively.

However, because of the existence of colour cross-talk, measurement errors will be introduced. In next section, in order to reduce the colour distortion caused by colour leakage, we will present a decoupling network to invert the mixing process and recover the original signals in each colour channel.

III. Colour Mixing Model

The colour leakage is caused by the unideal characteristics of both digital projector and CCD camera. Actually, The signal captured in one colour channel is a mixed signal composed of the distorted original signal in this channel and the other signals leaked from the other channels. If the intensity of distorted signal in one channel and the intensity of the leaked signal between channels are proportional to the intensities in their original channels respectively, we say the mixture is linear and can be modeled by following equation:

$$d(x) = As(x) \tag{7}$$

where A is an unknown mixing matrix, $s(x) = [s_1(x), s_2(x), s_3(x)]^T$, $s_n(x)$,$n = 1, 2, 3$, represent the original signals in R,G,B channel respectively. Similarly, $d(x) = [d_1(x), d_2(x), d_3(x)]^T$ is the captured signal in R,G,B channel. In this paper, the transpose operation is denoted by $(\cdot)^T$. However, because the mixing process is not always linear, nonlinear mixture is more realistic in practice. Considering the nonlinearity generally exists in both own channels and cross channels, a general mixture model can be expressed as: [9]

$$d(x) = f(s(x)) \tag{8}$$

where $f(\cdot)$ is an unknown nonlinear function. Assuming the function $f(\cdot)$ is invertible, we can approximate the inverse mixing process $f^{-1}(x)$ by a two-layer perceptron with n hidden neurons:

$$s(x) = f^{-1}(f(s(x))) = f^{-1}(d(x)) \approx Cg(Bd(x) + \theta_0) \tag{9}$$

where B and C are square matrices and $g(\cdot)$ is a sigmoid function. A similar nonlinear mixing model can be found in [10]. By this model, the decoupling network can be designed as Fig.2. In Fig.2, $W_2 = B$, $\theta = \theta_0$ and $W_1 = \Lambda PC$, where Λ

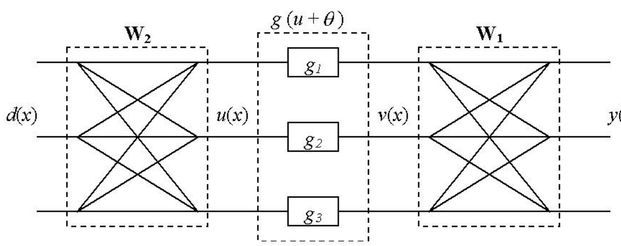

Fig. 2. colour decoupling network

is a diagonal matrix and P is a permutation matrix. Therefore, the output of this network $y(x)$ is:

$$y(x) = W_1 g(W_2 d(x) + \theta) = \Lambda Ps \tag{10}$$

Because Λ is a diagonal matrix, it results in the output signals with different amplitude. Meanwhile, as Eq.(3) and (4) only require the signal amplitude in each channel are equal, we can simply normalize the amplitude of output signal to be the same value. On the other hand, as the original signal $s(x)$ in each channel are phase-shifted sinusoidal signals, the permutation of original signals will still obtain the same absolute value with

the true value of height distribution, but might get different symbols. However, It is not the problem because the symbol of reconstructed height distribution can be determined by the prior knowledge of the relative location of the object and the refernece plane. Thus, as long as we get the decoupled signal y, the 3-D reconstruction can be achieved. Therefore, our purpose of calibration is to determine the parameters of W_1, W_2 and θ.

IV. Calibration Approach

For calibration, we have to utilize a kind of well-designed signal to simplify the determination for the decoupling network parameters. In fact, the calibration process is to approximate a nonlinear mixture system. A natural and simple idea is to determine the network by training and making the output to be a expected signal. However, for multichannel method, supervised training methods are not very suitable, because it is difficult to obtain an exact supervisor signal. Although we can generate a supervisor signal by computer, it will be a fairly complicated work to match the resolution of generated supervisor signal and captured signals by CCD camera. It needs a very accurate measurement for visual field and the number of pixels, i.e. we have to have all the prior knowledge about the exact intensity for all the pixels in given locations, which is difficult to be implemented. Therefore, we should use a unsupervised approach to determine the network parameters. In this paper, we present a calibration approach based on information BP (IBP) algorithm proposed in [9]. The calibration procedure is as follow:

Step 1: Projecting a colour fringe pattern on reference plane as a calibrating fringe pattern with three independent signals in R, G, B channel respectively.

Step 2: Capture the projected calibrating fringe pattern.

Step 3: Using IBP algorithm to determine the parameters of decoupling network for every row of captured image.

For IBP algorithm, the leaning rule of the parameters is expressed by following equations:

$$\frac{\mathrm{d}W_1}{\mathrm{d}x} = \eta[I - \tilde{y}y^T]W_1 \quad (11)$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}x} = -\eta[\Phi_2(u) + D(u)W_1^T\tilde{y}] \quad (12)$$

$$\frac{\mathrm{d}W_2}{\mathrm{d}x} = \eta[I - \Phi_2(u)u^T - D(u)W_1^T\tilde{y}u^T]W_2 \quad (13)$$

where

$$\tilde{y} = j_1(k_3, k_4)\cdot y^2 + j_2(k_3, k_4)\cdot y^3, \quad (14)$$

$$j_1(r,t) = -\frac{1}{2}r + \frac{9}{4}rt, \quad (15)$$

$$j_2(r,t) = -\frac{1}{6}t + \frac{3}{2}r^2 + \frac{3}{4}t^2 \quad (16)$$

$$\Phi_2(u) = -[\frac{g_1''(u_1+\theta_1)}{g_1'(u_1+\theta_1)}, \dots, \frac{g_n''(u_n+\theta_n)}{g_n'(u_n+\theta_n)}]^T \quad (17)$$

$$D(u) = diag(g_1'(u_1+\theta_1), \dots, g_n'(u_n+\theta_n)) \quad (18)$$

η is a learning rate and k_n is the n order cumulant of signal y, which can be calculated by its definition, or use following tracing equations to reduce the computation:

$$\frac{\mathrm{d}k_3}{\mathrm{d}x} = -\mu(k_3 - y^3), \quad (19)$$

$$\frac{\mathrm{d}k_4}{\mathrm{d}x} = -\mu(k_4 - y^4 + 3) \quad (20)$$

where μ is another learning rate. More detailed derivations for IBP algorithm are given by [9].

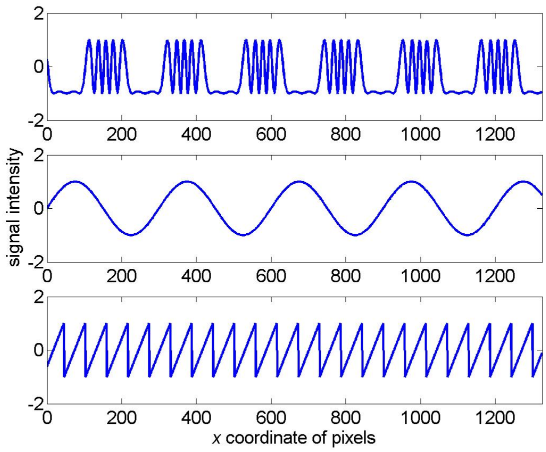

Fig. 3. Independent signals used for nonlinear blind signal separation calibration

V. Simulation and Experiment

Theoretically, any mutually independent signals with at most one Gaussian signal can be used for blind signal separation. In our experiment, we designed three independent signals to be projected via R,G,B channel as a calibrating fringe patterns, which is expressed by Eq.(21) and shown in Fig.3:(Note: the intensities of the three signals are normalized from -1 to 1)

$$s(x) = \begin{pmatrix} -\sin(2\pi 0.05x) - 6\cos(2\pi 0.01x) \\ \sin(2\pi 0.007x) \\ \dfrac{\mathrm{mod}((x+1), 27) - 13}{13} \end{pmatrix} \quad (21)$$

In our experiment, the captured calibrating fringe pattern on the reference plane in R,G,B channel are shown in Fig.4. we can see that due to the colour cross-talk, the signals in each colour channel are distorted. By utilizing IBP algorithm, the distorted signals can be separated and at the same time, parameters of the decoupling network can be determined. The separation result is shown in Fig.5. It can be seen the original signals are demixed and clearly recovered by IBP algorithm. Similarly, the original sinusoidal signals also can be recovered by inputting the captured sinusoidal fringe patterns into this determined decoupling network.

In our simulation, we assume the object surface is a given paraboloid with known height distribution. Based on the experimentally captured sinusoidal fringe pattern, the fringe

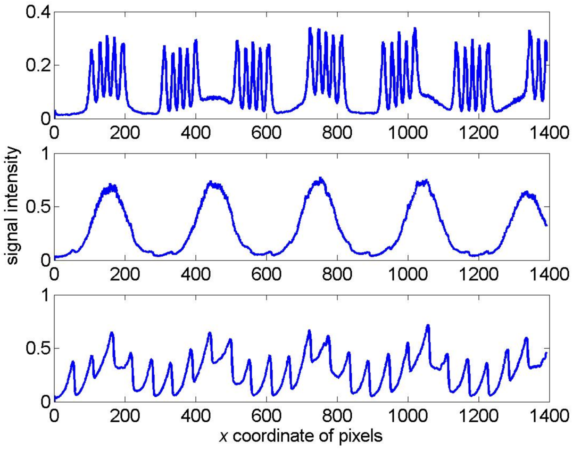

Fig. 4. Nonlinearly mixed independent signals

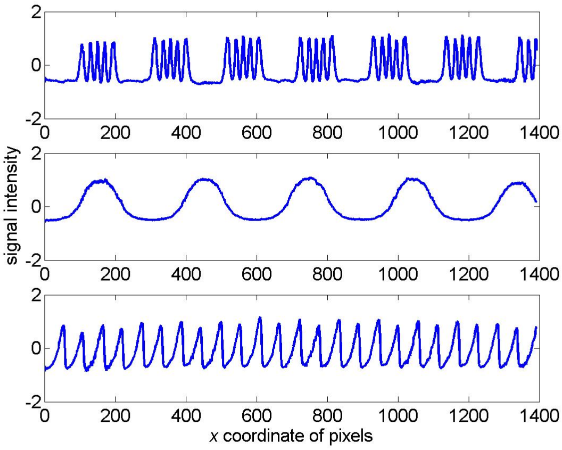

Fig. 5. Separation result of independent signals

pattern deformed by the object surface can be mathematically calculated and generated for the simulation. Utilizing the decoupling network, both the original sinusoidal fringe pattern on the reference plane and the original pattern deformed by the object surface can be retrieved. Hence having eliminated colour cross-talks, the measurement accuracy can be improved. The surface reconstruction results of using IBP calibration and without using calibration are shown in Fig.6. The dash-dot line is the reconstruction result without colour calibration, solid line refers to the reconstruction result after using our proposed calibration method, and dashed line is the true value of the height distribution. It can be seen that by our proposed calibration method, the measurement accuracy has been significantly improved, and the reconstruction result becomes very close to the true values.

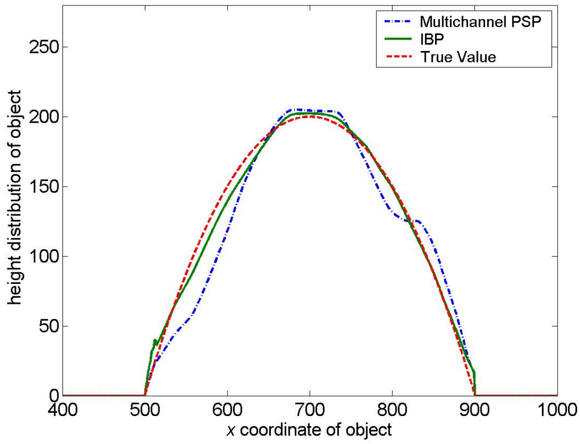

Fig. 6. Comparison of reconstruction results

VI. Conclusion and Discussion

In this paper, we have presented a colour calibration approach based on IBP algorithm to determine the parameters of the colour decoupling network. By experimental and simulation results, it is demonstrated that measurement accuracy is much improved by our calibration approach. Additionally, although without loss of generality, nonlinear blind separation algorithm are used in this paper, according to the most of our experimental results, using linear blind separation algorithms also can obtain similar results to nonlinear algorithms, which implies in most cases, colour cross-talk can be approximated by a linear instantaneous mixing process.

References

[1] X. Su and W. Chen, "Fourier transform profilometry: a review," *Optics and Lasers in Engineering*, vol. 35, pp. 263–284, 2001.

[2] H. Su, J. Li, and X. Su, "Phase algorithm without the influence of carrier frequency," *Optics Engineering*, vol. 36, pp. 1799–1805, 1997.

[3] S. Toyooka and Y. Iwaasa, "Automatic profilometry of 3-d diffuse objects by spatial phase detection," *Applied Optics*, vol. 25, pp. 1630–1633, 1986.

[4] R. Rodriguez-Vera and M. Servin, "Phase locked loop profilometry," *Optics and Lasers Technology*, vol. 26, pp. 393–398, 1994.

[5] A. Moore and F. Mendoza-Santoyo, "Phase demodulation in the space domain without a fringe carrier," *Optics and Lasers in Engineering*, vol. 23, pp. 319–330, 1995.

[6] J. Villa, M. Servin, and L. Castillo, "Profilometry for the measurement of 3-d object shapes based on regularized filters," *Optics Communication*, vol. 161, pp. 13–18, 1999.

[7] P. Huang, Q. Ho, F. Jin, and F. Chiang, "Colour-enhanced digitial fringe projection technique for high-speed 3d surface contouring," *Opt Eng*, vol. 38, pp. 1065–1071, 1999.

[8] L. Kinell, "Multichannel method for absolute shape measurement using projected fringes," *Optics and Lasers in Engineering*, vol. 41, pp. 57–71, 2004.

[9] H. H. Yang, S. ichi Amari, and A. Cichocki, "Information-theoretic approach to blind separation of sources in nonlinear mixture," *Signal Processing*, vol. 64, no. 3, pp. 291–300, Feb. 1998.

[10] Y. Tan and J. Wang, "Nonlinear blind source separation using higher order statistics and a genetic algorithm," *IEEE Transactions on Evolutionary Computation*, vol. 5, no. 6, pp. 600–612, Dec. 2001.