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Grayscale imbalance correction in real-time phase measuring profilometry

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A R T I C L E I N F O

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A B S T R A C T

Grayscale imbalance correction in real-time phase measuring profilometry (RPMP) is proposed. In the RPMP, the sufficient information is obtained to reconstruct the 3D shape of the measured object in one over twenty-four of a second. Only one color fringe pattern whose R, G and B channels are coded as three sinusoidal phase-shifting gratings with an equivalent shifting phase of $2\pi/3$ is sent to a flash memory on a specialized digital light projector (SDLP). And then the SDLP projects the fringe patterns in R, G and B channels sequentially onto the measured object in one over seventy-two of a second and meanwhile a monochrome CCD camera captures the corresponding deformed patterns synchronously with the SDLP. Because the deformed patterns from three color channels are captured at different time, the color crosstalk is avoided completely. But due to the monochrome CCD camera's different spectral sensitivity to R, G and B tricolor, there will be grayscale imbalance among these deformed patterns captured at R, G and B channels respectively which may result in increasing measuring errors or even failing to reconstruct the 3D shape. So a new grayscale imbalance correction method based on least square method is developed. The experimental results verify the feasibility of the proposed method.

1. Introduction

Optical 3D measurement which specially features non-contacting, high precision, high speed and high resolution is widely used in plastic surgery [1,2], industry inspection [3,4], reverse engineering [5,6] and so on. With the requirement of high accuracy and real time in 3D measurement to ensure the production quality, real-time 3D measurement [7,8] is needed urgently to obtain the sufficient information for 3D shape reconstruction at the frame rate of 72 fps or more.

Among the optical 3D measurement methods [9–11], both FTP and PMP based on color structural light have a huge potential for real-time 3D measurement. Due to the filtering procedure in FTP, the accuracy of FTP is somehow limited. PMP has higher accuracy than FTP [12,13] but it needs three or more phase-shifting deformed patterns, which may spend more time. In 1999, a color-encoded digital fringe projection technique for high-speed three-dimensional surface contouring in which only one color fringe pattern whose R, G and B channels were coded by three phase-shifting sinusoidal gratings with an equivalent shifting phase of $2\pi/3$ was projected and only one color deformed pattern was needed to be captured by a color CCD camera was proposed by Huang et al. [14]. But due to the wider spectral bandwidth of the color CCD camera, there are obvious color crosstalk and grayscale imbalance problems among the R, G and B channels which may lead to decreasing the 3D reconstructing accuracy. In 2002, an improved RGB tricolor based fast phase measuring profilometry [15] in which the chroma transfer function (CTF) was introduced to calibrate the color crosstalk and imbalance among the R, G and B channels as far as possible was proposed by Cao et al. Other methods for addressing the color crosstalk and grayscale imbalance have been further studied. Crosstalk matrix and coupling matrix [16] work well for addressing these problems, but they are obtained in a tedious procedure. The influence of the color crosstalk is well reduced by Huang et al. [17] and Flores et al. [18], but the color crosstalk can not be addressed completely. In addition, because Flores et al. ignore the color imbalance, the color imbalance is not addressed. Algorithms for calibrating the grayscale imbalance have been creatively proposed by Quiroga et al. [19] and Ma et al. [20], but the filtering procedures in their algorithms may impair the measurement accuracy and make the obtained 3D shape distort. Although the above methods can obtain the 3D shape to some extent, it is hard to solve the color crosstalk and grayscale imbalance caused by the color CCD camera completely, which results in increasing measuring errors or failing to reconstruct the 3D shape. Pan et al. have addressed the color crosstalk problem completely by designing a three-CCD camera and three color filters detect system. Though an algorithm was

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proposed to compensate for the color imbalance as far as possible [21], the nonlinear color filtering operation may make the color imbalance compensation complicated and somehow reduce the measuring accuracy. And the additional multiple CCD cameras and color filters may make the measuring system more complicated. Zhang et al. have skillfully addressed the color crosstalk and grayscale imbalance problems completely [22,23] by unloading the color wheel of the ordinary digital light projector (DLP) based on metal halide lamp (white light) and color wheel RGB separation and just passively utilizing the color wheel's control signal to trigger CCD camera capturing images synchronously. But the used DLP needs to be dismantled and reinstalled, it may bring some inconvenience. Furthermore, the used DLP's size is big enough for heat dissipation. With the development of the DLP technique, the RGB LEDs based DLP with features of miniaturization, low power and portability becomes very popular. We have just utilized this kind of DLP in the proposed method. In order to address color crosstalk and grayscale imbalance problems in a simple and accurate way, a monochrome CCD camera is substituted for the color CCD camera and an actively designed specialized time division multiplexing (TDM) timing sequence is used to control the CCD camera and the specialized DLP (SDLP) synchronously in the proposed real-time phase measuring profilometry (RPMP).

In this RPMP, only one color fringe pattern whose R, G and B channels are coded with three sinusoidal gratings is designed and sent to a flash memory on the SDLP. Then the fringes in the R, G and B channels of the color fringe pattern are projected rapidly and sequentially by the SDLP and the corresponding deformed patterns are captured by a monochrome CCD camera synchronized with the SDLP. With a timing sequence and the monochrome CCD camera, the color crosstalk can be perfectly avoided, but the grayscale imbalance among the captured deformed patterns from the R, G and B channels caused by the different spectral sensitivity of the monochrome CCD camera exists still. In this paper grayscale imbalance correction method based on least square method is developed for addressing the grayscale imbalance problem.

2. The principle of the RPMP

Fig. 1 shows the layout of our RPMP system which consists of a personal computer (PC), a SDLP, a CCD camera and a reference plane fixed on a step motor. The moving direction is along the x axis. Only one color fringe pattern whose R, G and B channels are coded by three phase-shifting sinusoidal gratings (I_r, I_g, I_b) with an equivalent shifting phase of $2\pi/3$ is designed and saved as a 24-bit

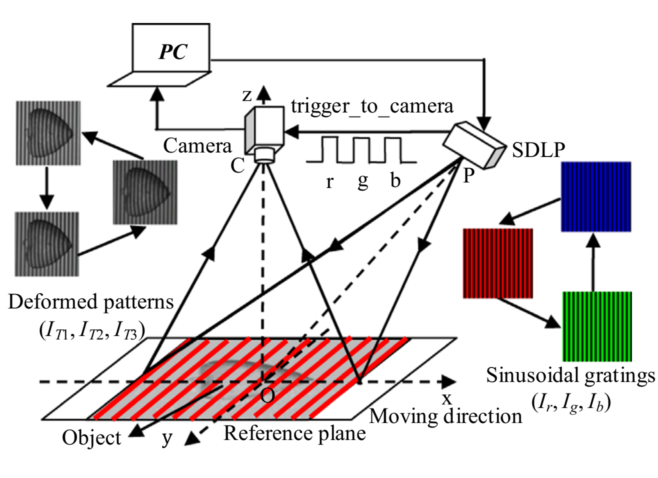

Fig. 1. The layout of the proposed RPMP.

color bitmap image by the PC. Then we send this color fringe pattern to the flash memory on the SDLP. As long as we can obtain the sufficient information for reconstructing the 3D shape of the measured object in the time period of less than 1/24 s, the real-time 3D measurement can be realized at more than 24 fps. Because the color fringe pattern is compound of three phase-shifting sinusoidal gratings, we actively design a TDM time sequence by subdividing the real-time period into three parts and each subdivided time period is less than 1/72 s, actually, 1/75 s is actively set in our method to guarantee the real-time 3D measurement at 25 fps. Under the active control of the specialized TDM timing sequence, sinusoidal gratings (I_r, I_g, I_b) are projected and the corresponding deformed patterns (I_{T1}, I_{T2}, I_{T3}) are captured synchronously at the frame rate of 75 fps. It means the 3D shape reconstruction information of the measured object can be obtained in real time.

Due to the color crosstalk problem in R, G, B channel of the color CCD camera [19], it may result in increasing measuring errors or even failing to reconstruct the 3D shape. In order to address this problem, a monochrome CCD camera is substituted for the color CCD camera. With the specialized TDM timing sequence, the SDLP projects three color channels at different time exclusively and the monochrome CCD camera captures the deform patterns (I_{T1}, I_{T2}, I_{T3}) synchronously with the SDLP. As the RGB tricolor is time divided, the color crosstalk problem is addressed perfectly.

The deformed patterns (I_{T1}, I_{T2}, I_{T3}) can be described as:

$$\begin{cases} I_{T1}(x,y) = S_r(x,y)R(x,y)[A(x,y) + B(x,y)\cos(2\pi f_0 x + \varphi(x,y))] \\ I_{T2}(x,y) = S_g(x,y)R(x,y)\left[A(x,y) + B(x,y)\cos\left(2\pi f_0 x + \varphi(x,y) + \dfrac{2\pi}{3}\right)\right] \\ I_{T3}(x,y) = S_b(x,y)R(x,y)\left[A(x,y) + B(x,y)\cos\left(2\pi f_0 x + \varphi(x,y) + \dfrac{4\pi}{3}\right)\right] \end{cases} \quad (1)$$

where $R(x, y)$ denotes reflectance or spectral reflectance coefficient of the object's surface, $A(x, y)$ denotes the background intensity, $B(x, y)$ denotes the fringe contrast, f_0 denotes the eigenvalue frequency of the deformed patterns. (x, y) denotes the pixel coordinate in which $x\in[1, M]$, $y\in[1, N]$, M is the number of pixels per row and N is the total rows, the $S_r(x, y)$, $S_g(x, y)$ and $S_b(x, y)$ denote the spectral sensitivity of the monochrome CCD camera to R, G and B lights. Due to the monochrome CCD camera's different spectral sensitivity to R, G and B lights, $S_r(x, y)$, $S_g(x, y)$ and $S_b(x, y)$ will be different, which means that there will be grayscale imbalance among these deformed patterns which may result in increasing measuring errors or failing to reconstruct the 3D shape. In order to address this problem, grayscale imbalance correction method based on least square method on a row-by-row basis is developed in the next section. While the grayscale imbalanced deformed patterns (I_{T1}, I_{T2}, I_{T3}) are corrected to be the balanced deformed patterns (I_{c1}, I_{c2}, I_{c3}) by the developed correction method, the wrapped phase $\phi(x, y)$ modulated by the height $h(x, y)$ of the measured object can be retrieved as:

$$\phi(x,y) = \arctan\left[\frac{\sqrt{3}\,(I_{c1}(x,y) - I_{c3}(x,y))}{2I_{c2}(x,y) - I_{c1}(x,y) - I_{c3}(x,y)}\right] \quad (2)$$

Because of the arctan function in Eq. (2), $\Phi(x, y)$ is wrapped in $[-\pi, \pi]$. Then an unwrapping algorithm [24] is used for retrieving the unwrapped phase $\Psi(x, y)$. Finally the 3D shape of the measured object can be reconstructed by phase-to-height mapping [25]:

$$\frac{1}{h(x,y)} = a(x,y) + b(x,y)\frac{1}{\psi(x,y)} + c(x,y)\frac{1}{\psi^2(x,y)} \quad (3)$$

where $h(x, y)$ represents the relative height from the reference plane, the system constants $a(x, y)$, $b(x, y)$ and $c(x, y)$ are