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Color-fringe pattern profilometry using an efficient iterative algorithm

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ABSTRACT

Colored fringe pattern approach has been proposed to overcome the limitations of the sequential phase-shifting fringe pattern profilometry for dynamic measurements. However, the use of colored fringe patterns leads to a mayor problem, the color cross-talk, which has been considered to be equivalent to reconstructing the phase map from the fringe patterns with unknown phase shifts. Therefore, phase error is introduced when conventional phase-shifting algorithms with fixed phase shift values are used to retrieve the phase. To overcome the cross-talk issue, we propose the use of a fringe pattern normalization algorithm to achieve the intensity modulation balance among the different color channels and then the use of an advanced iterative algorithm to retrieve the phase. Simulations and experimental results show that the proposed procedure can significantly reduce the influence of the color cross-talk.

1. Introduction

Phase shifting profilometry (PSP) is one of the most popular noncontact approaches for measuring three-dimensional object surfaces. Most of the techniques use phase-shifting interferometry (PSI)-algorithms for profile retrieval, and the experimental setup consists of a commercial video projector, and a digital camera for projecting and acquiring a sequence of phase-shifted sinusoidal fringe patterns [1–4].

The standard approach described above has several drawbacks. First, at least three shifted patterns will be required for retrieving the 3D shape profiling; this makes a slow technique, which limits its applicability considering that more and more applications, such as automatic online inspection, objects moving at high speed and body scanning require dynamic (moving or deforming) 3D and real time measurements capabilities [5–8].

To overcome the dynamic limitations of the sequential PSP, a color-channel based PSP approach has been proposed [9]. Here, the phase-stepped fringes are simultaneously projected as a colored fringe pattern. Thus, the fringe pattern will be formed by three phase-shifted sinusoidal fringe patterns codified in red, green, and blue color channels of a RGB image, so that the three patterns can be projected (acquired) simultaneously. However, the use of colored fringe patterns leads to a mayor problem, the cross-talk, which has been widely discussed in previous papers [9–11].

Recently, Hu et al. [11] proposed an adaptive color demixing scheme that does not require any prior knowledge of the system or any probing signals. However, it has some inherent drawbacks, such as a high computational complexity and an unstable convergence due to the iterative technique used [12]. In order to improve this technique, Ma et al. [12] proposed the blind phase error suppression approach (BPES), a technique based on isotropic n-dimensional fringe pattern normalization [13] and carrier squeezing interferometry [14] to retrieve the phase without artifacts. Also, Ma and coworkers proposed the use of a random phase-shifting algorithm [8], but they did not estimate the phase error introduced by cross-talk problem using these kind of algorithm in comparison with other ones. Both, Ma and Hu considered that the problem of retrieving phase from color fringe pattern is equivalent to reconstructing the phase map from the fringe patterns with unknown phase shifts. Considering this point of view, Flores et al. [15] proposed the use of generalized phase-shifting algorithms (GPSA) with arbitrary phase shift values for phase retrieval [16]. In those algorithms, one presupposes that the phase steps are known. Therefore, they will be determined previously from the experimental fringe patterns by the use of different methods [17–20].

In this work, we propose a color-channel approach to overcome the problem of the cross-talk of the projector/camera system, considering it as a problem of retrieving the phase map from the fringe patterns with unknown phase shifts. For that purpose we will use: Firstly, a fringe pattern normalization algorithm to achieve the intensity modulation balance among the different color channels, in particular the algorithm described in [13] and then an algorithm for phase extraction from randomly phase-shifted patterns, in this work we propose the use

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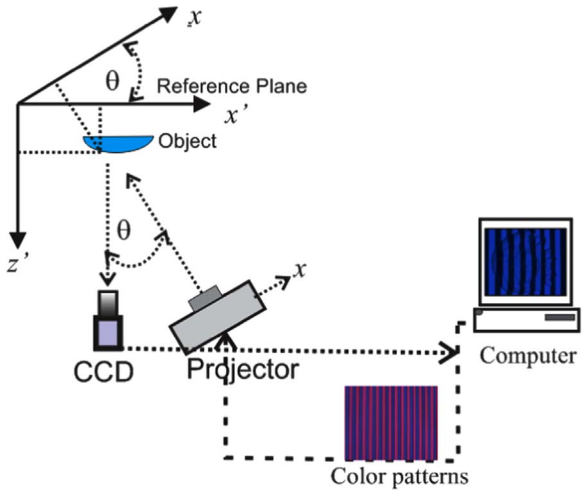

Fig. 1. Experimental setup.

of the advanced iterative algorithm which was introduced by Wang and Han [20].

The rest of this paper is organized as follows. In the next section, we describe in some detail our proposal. In Sections 3 and 4, numerical simulations and experimental results are presented. Finally, the conclusions are presented in Section 5.

2. Description of the method

2.1. Ideal case without color cross-talk

A typical 3D shape measurement system based on projected fringe is shown in Fig. 1. It consists of a DLP video projector for projecting software-generated color patterns, a high-resolution color CCD camera to capture the fringe patterns modulated by the object surface, and a flat plate for calibration. In 3D profile reconstruction using PS algorithms, one considers a sequence of phase-shifted patterns with intensity distributions given by

$$I_k(x, y) = a(x, y) + b(x, y)\cos[\phi(x, y) + \delta_k], \quad \text{for} k = 1, 2, \ldots, M, \tag{1}$$

where (x, y) is the camera coordinate system, δ_k are the phase-steps, and $a(x, y)$ and $b(x, y)$ are functions associated to the average intensity and modulation of the sinusoidal fringe, respectively. In the present work, the three-step algorithm has been chosen because it fits perfectly with a RGB image, i.e., the three phase-shifted sinusoidal patterns can be codified in red, green, and blue color channels, and projected as single pattern [9–12]. In the ideal case, after projecting the patterns and the reflection process, the patterns captured by a camera can be expressed as:

$$I_R(x, y) = a_R(x, y) + b_R(x, y)\cos[\phi(x, y) - 2\pi/3] \tag{2}$$

$$I_G(x, y) = a_G(x, y) + b_G(x, y)\cos[\phi(x, y)] \tag{3}$$

$$I_B(x, y) = a_B(x, y) + b_B(x, y)\cos[\phi(x, y) + 2\pi/3], \tag{4}$$

where $I_R(x, y)$, $I_G(x, y)$, and $I_B(x, y)$ are the intensities of the R, G, and B channels, respectively. In a same way, a_i and b_i(with i= R, G, B) are the average intensity and the intensity modulation for each channel, respectively.

However, the projectors, monitors and cameras are usually designed to present some spectral overlaps between the color channels. Therefore, the color channels cannot be separated perfectly, which will certainly result in measurement errors.

A colored fringe pattern can be represented by a mixed matrix [11]

$$\begin{pmatrix} I_{R'} \\ I_{G'} \\ I_{B'} \end{pmatrix} = \begin{pmatrix} \alpha_{rr} & \alpha_{gr} & \alpha_{br} \\ \alpha_{rg} & \alpha_{gg} & \alpha_{bg} \\ \alpha_{rb} & \alpha_{gb} & \alpha_{bb} \end{pmatrix} \begin{pmatrix} I_R \\ I_G \\ I_B \end{pmatrix} \tag{5}$$

where $I_{R'}$, $I_{G'}$ and $I_{B'}$ are the actually acquired signals in the RGB-channels of the camera, and $\alpha_{m,n}$ (for $m = r,g,b$ and $n = r,g,b$) are positive real quantities that take into account the coupling factor between color channels. For the sake of simplicity we can assume that $\alpha_{rr} = \alpha_{gg} = \alpha_{bb} = 1$ and considering that in single sensor camera with Bayer filter the color interference occurs mainly between adjacent channels: green into red, green into blue, and blue and red into green, therefore we will also assume that $\alpha_{br} = \alpha_{rb} = 0$. Thus, the captured fringe patterns can be expressed as,

$$I_{R'} = \alpha_{gr} a_G + a_R + b_{R'}\cos(\phi + \theta_{R'}), \tag{6}$$

$$I_{G'} = a_G + \alpha_{bg} a_B + \alpha_{rg} a_R + b_{G'}\cos(\phi + \theta_{G'}), \tag{7}$$

and

$$I_{B'} = a_B + \alpha_{gb} a_G + b_{B'}\cos(\phi + \theta_{B'}), \tag{8}$$

for intensities of the R, G, and B channels, respectively. Due to cross-talk, the acquired patterns result unbalanced i.e., intensity modulation of the acquired patterns are not equal ($b_{R'} \neq b_{G'} \neq b_{B'} \neq b$, where b is a constant) and also, the phase-shift steps are not uniformly spaced because of $\theta_{R'} - \theta_{G'} \neq \theta_{B'} - \theta_{G'} \neq 2\pi/3$, i.e., $\delta_k \neq 2\pi k/3 \quad (k = 1, 2, 3)$, see ref. [15]. Following Hu et al. [11], as the DC components do not contain any phase information; they can be easily removed by subtracting the mean value of each pattern. Thus, after removing the DC components, the "zero-mean" $I_{R'}$, $I_{G'}$, and $I_{B'}$ can be expressed as

$$\begin{aligned} I_{R'} &= b_{R'}\cos(\phi + \theta_{R'}) \\ I_{G'} &= b_{G'}\cos(\phi + \theta_{G'}) \\ I_{B'} &= b_{B'}\cos(\phi + \theta_{B'}). \end{aligned} \tag{9}$$

We can notice that although the DC components have been removed, the set of sinusoidal signals remains unbalanced. Therefore, the problem of color cross-talk cannot be simply solved by adding and/or multiplying the intensities of the color channels by a set of coefficients to achieve balance. Under these conditions, the use of traditional 3-step algorithm to retrieve the phase will result in errors. In order to reduce the phase error, one can use: Firstly a normalizing algorithm, e.g. in this work we used the algorithm described in [13], and then the advanced iterative algorithm (AIA) for phase extraction described in [20]. The last algorithm is based on the assumption that the phase-steps are arbitrarily spaced and unknown.

2.2. Description of advanced iterative algorithm

In this section, for completeness, we describe the scheme developed by Wang and Han [20] to estimate phase-steps and phase-wrapped map in an iterative procedure. The intensity of an interferogram can be also expressed as

$$I_i^k = A_i^k + B_i^k\cos(\phi_i + \delta_k) \tag{10}$$

where A_i is the background intensity, B_i is the fringe contrast or fringe amplitude, ϕ_i is the phase unknown function and δ_k is the phase-shifts to be estimated. Furthermore, the pixel index is $1 \le i \le N$ and $3 \le k \le M$ is the fringe-pattern index, i.e. they are spatial and temporal dependences, respectively. The Eq. (10) corresponds to a non-linear problem of size N^2, which is difficult to solve due to its complexity. In this context, the AIA scheme transforms the non-linear problem into a two-step iterative linear least-squares problem. In the first step, we estimate the unknown phase by fixing the phase-shifts parameters which transform the non-linear problem into a linear least-squares problem. Similarly, on the second step we fit the data to obtain phase-shifts by fixing the last phase map. The details of the AIA's iteration are described below.