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Abstract

© 2019 SPIE. In this work, we consider the problem of 3D shape reconstruction with a system with two cameras and one projector, which can be regarded as a composite system with two fringe projection profilometry (FPP) systems and one stereo vision (SV) system. Different from the active SV systems in the literature where FPP is used to assist SV to address the issue of corresponding matching, a new system is proposed in this paper by constructing a fusion cost function with the consideration of both FPP and SV triangulations, so that the measurements of the two cameras can be fused to achieve better measurement performance than that of the active SV and FPP. In addition, a message passing algorithm for 3D shape reconstruction with the system is developed by using the new cost function and exploiting the unknown correlation of object surfaces. Simulation results demonstrate that the proposed system can achieve considerable performance gain.

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Improve 3D shape reconstruction with dual-camera measurement fusion

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ABSTRACT

In this work, we consider the problem of 3D shape reconstruction with a system with two cameras and one projector, which can be regarded as a composite system with two fringe projection profilometry (FPP) systems and one stereo vision (SV) system. Different from the active SV systems in the literature where FPP is used to assist SV to address the issue of corresponding matching, a new system is proposed in this paper by constructing a fusion cost function with the consideration of both FPP and SV triangulations, so that the measurements of the two cameras can be fused to achieve better measurement performance than that of the active SV and FPP. In addition, a message passing algorithm for 3D shape reconstruction with the system is developed by using the new cost function and exploiting the unknown correlation of object surfaces. Simulation results demonstrate that the proposed system can achieve considerable performance gain.

Keywords: 3D shape measurement, active stereo vision, message passing, fringe projection profilometry

1. INTRODUCTION

High accurate and fast 3-D shape reconstruction techniques are increasingly demanded in a variety of fields, such as manufacturing, civil engineering, medical sciences, public security, entertainment, etc [1]. Among those technologies, stereo vision (SV) [2] and fringe projection profilometry (FPP) [3] are two popular non-contact methods, which are extensively researched.

A typical FPP system often consists of one projector which projects one or several fringe patterns on a reference plane, and one camera which captures non-distorted and distorted patterns. By analysing the distorted fringe patterns, the 3D shape of object can be extracted based on the triangulation with various algorithms such as Fourier transform profilometry (FTP) [4] and phase shifting profilometry (PSP) [5], which use one or more sinusoidal fringe patterns. SV uses two or more cameras to take images of the scene from different viewpoints and obtain the 3D information of the scene with those images by triangulation among two cameras and scene points. The conventional passive SV has the correspondence problem arising from ambiguous matches due to e.g., textureless regions, depth discontinuities, etc [6]. To overcome the problem, active SV [7] has been investigated in the literature, where a projector is introduced to the SV system to project structured light such as random dots, striped or sinusoidal patterns. The active SV system with two cameras and one projector can be regarded as the combination of two FPP systems and one passive SV system, where the two FPP systems are employed to retrieve the phase maps for the measured object, and correspondence matching is carried out based on the two phase maps such as in [6], [8]. Another line of the work with the same system configuration was conducted in [9], [10] and [11], where the epipolar geometry is used to unwrap the phase map of one camera and then FPP geometry is used to reconstruct the shape of the object from the unwrapped phase.

In the above systems with two cameras and one projector, either FPP is used to assist SV to address the correspondence matching issue, or SV is used to assist FPP to address with the phase unwrapping issue. Therefore the measurement precision is either limited to the performance of phase map based SV or the conventional FPP with correct fringe orders. In other words, the full potential of combining the FPP systems and SV system has not been explored. In this work, we aim to fuse the two types of systems, thereby achieving performance better than

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Figure 1: Illustration of FPP and SV systems

that of phase map based SV and conventional FPP. In the proposed method, two phase maps are first obtained by the two cameras using an FPP algorithm, and then the measured phase maps are fused by constructing a fusion cost function with the consideration of both FPP and SV triangulations, which leads to better measurement performance. In addition, building upon the new cost function, we design a system to exploit the correlation of object surfaces, achieving higher measurement precision. A message passing algorithm is also developed for implementation.

2. SYSTEM MODEL AND FUSION COST FUNCTION

2.1 FPP and SV

A conventional FPP system is illustrated in Fig.1(a), where E_c and E_p are the optical centres of camera and projector respectively and t is the distance between those two points. The distance between the camera and the reference plane is denoted by L . Based on the triangulation of the system, the height of the point Q on the object can be calculated by [5]

$$h_{fpp} = \frac{AC \times L}{t + AC} \quad (1)$$

where AC is the distance of two points A and C on the reference plane and it can be obtained by phase difference as [12]

$$\Delta\phi_{AC} = \phi_A - \phi_C = -2\pi f_0 AC \quad (2)$$

where f_0 is the spatial frequency of the projected fringe pattern. A typical passive SV system is shown in Fig.1(b), which consists of two cameras C_R and C_T with O_R and O_T being their optical centres respectively. P is a point on the scene, and p and p' are the captured points on the CCD planes of the two cameras, respectively. The focal length of both cameras is f . Based on the triangulation of two cameras and the point, the depth d_{sv} can be calculated as [13]

$$d_{sv} = \frac{Bf}{x_r - x_t} = \frac{Bf}{d} \quad (3)$$

where B is the distance between the optical centres of the two cameras, x_r and x_t are the horizontal coordinates of points p and p' in each image's coordinate system, and $d = x_r - x_t$ is called the disparity of that point P . Hence the height of point P is given by

$$h_{fpp} = L - d_{sv}. \quad (4)$$

2.2 Dual-Camera System

We consider a system with two cameras and one projector, which is shown in Fig.2, which was used in [9] and [6]. We use C_r , C_t and P to denote the optical centres of two cameras and the projector, respectively. The focal length of the two cameras is f and L is the distance from their optical centres to the reference plane. The distances between the cameras and the projector are t_r and t_t , respectively.

Figure 2: Illustration of the dual-camera system.

The system can be regarded as a composite system, which consists of two FTP systems and one SV system, i.e., each of the cameras and the project form a FTP system and the two cameras forms a SV system. In the active SV system in [6], two phase maps are obtained by using the two FPP systems with PSP or FTP algorithms. Then correspondence matching is performed based on the two phase maps, so that the shape of the object can be reconstructed using the SV system. Hence the full potential of the composite system has not been exploited. This work investigates better ways to explore the full potential of the composite system by constructing a cost function with the consideration of both FPP and SV triangulations, which is detailed in the next section.

2.3 FUSION COST FUNCTION

To fully take advantage of the geometry constraints of both FPP and SV in our system, a cost function on the height of one site $s(x, y)$ on the image plane of camera C_t is constructed as

$$F(h_{x,y}) = w_t f_t(h_{x,y}) + w_r f_r(h_{x,y}), \quad (5)$$

where

$$f_t(h_{x,y}) = [\Delta\phi_t(h_{x,y}) - \Delta\phi_t]^2 \quad (6)$$

$$f_r(h_{x,y}) = [\Phi_r^{obj}(x_r(h_{x,y})) - \Phi_r^{ref}(x_r(h_{x,y})) - \Delta\phi_r(h_{x,y})]^2. \quad (7)$$

and w_t and w_r are the weights for $f_t(h_{x,y})$ and $f_r(h_{x,y})$ respectively. The estimate of the height $h_{x,y}$ can be obtained by minimizing the cost function (5). The first term $f_t(h_{x,y})$ in the cost function corresponds to camera C_t . In (6), $\Delta\Phi_t$ is the phase difference on site s , which is obtained based on the phase maps of camera C_t with and without objects, and $\Delta\Phi_t(h_{x,y})$ can be expressed based on the FTP triangulation of camera C_t , i.e.,

$$\Delta\phi_t(h_{x,y}) = 2\pi f_0 t_t \frac{h_{x,y}}{L - h_{x,y}} \quad (8)$$

The second term $f_r(h_{x,y})$ in the cost function corresponds to camera C_r . In (7), $\Delta\Phi_r(h_{x,y})$ can be expressed based on the FPP triangulation of camera C_r , which is similar to $\Delta\Phi_t(h_{x,y})$. $x_r(h_{x,y})$ is the x-coordinate of the point on the CCD of camera C_r , which corresponds to the site $s(x,y)$. $x_r(h_{x,y})$ can be calculated based on the epipolar geometry of the SV system. i.e.,

$$x_r(h_{x,y}) = \frac{Bf}{L - h_{xy}} + x. \quad (9)$$

$\Phi_r^{obj}(x_r(h_{x,y}))$ and $\Phi_r^{ref}(x_r(h_{x,y}))$ can be obtained through interpolation based on the phase maps of camera C_r with or without object.

It can be seen from above that the cost function (5) uses the geometry constraints of both FPP and SV, and the phase maps of the two cameras are fused through the cost function. The weights w_r and w_t weight the contributions of Camera C_r and C_t , and they can be determined based on the MSE performance of with the costs $f_r(h_{x,y})$ and $f_t(h_{x,y})$, respectively. It is found that the weights are not sensitive to SNR.

3. INTEGRATION WITH OBJECT SURFACE CORRELATION AND MESSAGE PASSING ALGORITHM

It has been shown in [14] that, by exploiting the unknown object surface correlation, the measurement performance can be improved significantly. The unknown surface correlation can be modelled with certain models, e.g., AR, with unknown parameters, and the model parameters can be learned from data. In [14], a message passing algorithm is developed to infer the object shape and learn the model parameter at the same time.

The fusion cost function constructed in the previous section can be integrated with object surface correlation to further improve the measurement performance. To achieve this, a likelihood function can be formulated based the cost function, i.e.,

$$P(\Phi|H) \propto \prod_{x,y} \exp(-F(h_{x,y})), \quad (10)$$

where Φ denotes the phase maps obtained by the two FPP systems and $H = \{h_{x,y}, \forall(x,y)\}$. This likelihood function can be used to replace that given by equation (19) in [14]. Then the message passing algorithm can be developed similarly. The details will be provided in our full paper.

4. SIMULATION RESULTS

In this section, simulation results are provided to demonstrate the performance of our system. In the simulation, the cameras are positioned at two sides of the projector and the distance between cameras and projector are both 2cm. The focal length is 5cm and the distance between reference plane to optical center is 100cm. In addition, the image size of two cameras and the projector is 500×400 pixels. Besides, the radius of the generated hemisphere is 36cm. To avoid the occlusion, we use the top part of it, and the maximum height of the surface is 5cm. In addition, we use conventional 3-step PSP as our method to gain phase maps. We examine the system performance at SNR = 10dB and SNR = 20dB.

The performance of different systems in terms of reconstruction errors is shown in Figs. 3-5, where Figs. 3 and 4 are the error plane at SNR=10dB and SNR=20 dB respectively, and Fig. 5 compares the error performance at a cross section. It can be seen that PSP performs worst, and the system with fusion cost function performs better than the phase map based active SV. We can also observe a significant performance gain can be achieved by integrate the fuse function with object surface correlation.

To analyse the performance quantitatively, we define the mean squared error (MSE) as

$$MSE = \frac{1}{MN} \sum_{x=1}^M \sum_{y=1}^N \left| \hat{h}_{x,y} - h_{x,y} \right|^2. \quad (11)$$

The MSE of four methods are shown in table 1. From this table, we can also see that the performance of integration with correlation method outperforms the 3-step PSP in both 10dB and 20dB. Besides, the fusion cost function method performs better than 3-step PSP and phase map based SV.

Figure 5: Reconstruction error comparison at cross-section

5. CONCLUSION

In this paper, we have investigated the issue of 3D reconstruction with a system with two cameras and one projector. A fusion cost function has been constructed by taking the geometry constraints of both FPP and SV into account, so that the measurement of the two cameras can be fused more effectively. It is different from the active SV systems where FPP is used to assist SV in addressing the correspondence matching problem. It has been shown that the proposed method is superior to the active SV and FPP. In addition, the integration of the

Table 1: MSE of four methods at 10dB and 20dB

Method Names	MSE at 10dB	MSE at 20dB
3-step PSP	0.3221	3.2×10^{-2}
SV based on unwrapped phase maps	0.0621	5.9×10^{-3}
System with fusion function	0.0546	4.9×10^{-3}
Integrated with surface correlation	0.0022	9.5×10^{-4}

cost function with object surface correlation has been explored and the corresponding message passing algorithm has been developed to further improve the measurement performance.

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