A high precision 3D dynamic measurement prototype system based on color-coded fringe and phase shifting

Dahui Qin[1], Jianjun Liu[1,2] , Fuzhen Liu[1] and Xiaojun Dai[1]

[1] School of Civil Engineering and Architecture, Southwest Petroleum University, Chengdu, China;

[2] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (Southwest Petroleum University), Chengdu, China;

Abstract

Accurate dynamic measurement of the 3-D shape of moving objects is a rapidly expanding field, with applications in entertainment, design, and manufacturing. In this work, the two CCD/CMOS cameras are calibrated with a flexible and accurate camera calibration method. Then, a new approach based on color-coded fringe is proposed for high precision 3D dynamic measurement. The method is based on phase shifting and stereo vision. Combination of color coding and phase shifting can make automatic phase unwrapping, stereo vision can accomplish stereo matching and 3D points reconstruction automatically according to phase map after unwrapping. An experimental result is presented to demonstrate the performance of the method.

Keywords: *3D dynamic measurement; color-coded fringe; phase shifting; camera calibration.*

1. Introduction

Accurate dynamic measurement of the 3-D shape of moving objects is a rapidly expanding field, with applications in entertainment, design, and manufacturing. Among the existing 3-D shape measurement techniques, the techniques based on stereo vision using digital projection of structured light and recording by CCD/CMOS cameras are increasingly used due to their fast speed and non-contact nature. In this work, we developed a 3D dynamic measurement system consists of two CCD/CMOS cameras and a DLP projector. There are two key techniques in this system: camera calibration and absolute phase unwrapping using an image

Calibration of camera is a prerequisite for the extraction of precise 3D information from some images. Much work about camera calibration has been done in the photogrammetry community[1] , and also in computer vision[2-4]. In this work, we use the flexible camera calibration method proposed by Zhang[3] . It only requires the camera to shoot a planar pattern shown at a few (at least three) different orientations. Either the camera or the planar pattern can be freely moved. The motion need not be known. Radial and tangential lens distortion is modeled.

After the two cameras are calibrated, our system becomes able to perform a 3D dynamic measurement. In this work, we proposed a new method based on color coding , phase shifting and stereo vision for high precision 3D dynamic measurement. Combination of color coding and phase shifting can make automatic phase unwrapping, stereo vision can accomplish stereo matching and 3D points reconstruction automatically according to absolute phase map after unwrapping.

2. Camera calibration

2.1 Pinhole model

In order to perform 3D measurement with our system, the two cameras must be calibrated. The camera is modeled by the pinhole model. A 3D point $M=[X,Y,Z]^T$ in the world coordinate system and its 2D image projection point $m=[u,v]^T$ in a camera image coordinate system are related by:

$$s\tilde{m} = A[R \quad t]\tilde{M} \qquad (1)$$

Where tilde means homogeneous coordinates, $\tilde{M}=[X,Y,Z,1]^T$ and $\tilde{m}=[u,v,1]^T$, s is an arbitrary scale factor, A is the intrinsic matrix consists of the intrinsic parameters, [R t] is the extrinsic matrix. R and t are the extrinsic parameters, and they are the rotation matrix and the translation vector which relate the world coordinate system to the camera coordinate system. The intrinsic matrix A consists of the intrinsic parameters and is given by:

$$A=\begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

Where α and β are scale factors consist of a focal length of a lens and a size of a cell of the image sensor. γ

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is a parameter which represents the skewness of the two axes in the image coordinate system. (u_0, v_0) is the coordinate of the principal point.

2.2 Radial distortion

The image taken with a camera is distorted by the lens, and that image is different from the image taken with the ideal pinhole camera. Therefore, the lens distortion must be considered to deal with the model of the imaging system which is close to the actual camera[3]. The most commonly used correction is for the radial lens distortion that causes the actual image point to be displaced radially in the image plane. The radial distortion can be approximated using the following expression:

$$\left.\begin{aligned} \delta_{xr} &= x\left(k_1 r^2 + k_2 r^4 + k_3 r^6 + \cdots\right) \\ \delta_{yr} &= y\left(k_1 r^2 + k_2 r^4 + k_3 r^6 + \cdots\right) \end{aligned}\right\} \quad (3)$$

Where δ_{xr} and δ_{yr} are the radial distortion values, (x, y) is the ideal normalized image coordinates, k_1 , k_2 , k_3 , $\cdots$, are the parameters describing the radial distortion, and $r = \sqrt{x^2 + y^2}$.

2.3 Tangential distortion

For Accurate dynamic measurement of the 3-D shape of moving objects, the tangential distortion of the camera lenses must be taken into account. The expression for the tangential distortion is often written in the following form:

$$\begin{aligned} \delta_{xt} &= 2p_1 xy + p_2\left(r^2 + 2x^2\right) \\ \delta_{yt} &= 2p_2 xy + p_1\left(r^2 + 2y^2\right) \end{aligned} \quad (4)$$

Where δ_{xt} and δ_{yt} are the tangential distortion values, (x, y) is the ideal normalized image coordinates, p_1 and p_2 are the parameters describing the tangential distortion, and $r = \sqrt{x^2 + y^2}$.

2.4 Camera calibration

In this work, we use the flexible camera calibration method proposed by Zhang[3] . The method can obtain the intrinsic and extrinsic parameters, and the distortion parameters of the lens according to 3D coordinates on the model plane and their correspondences of image coordinates.

Zhang's calibration procedure is as follows:

1. Shoot a few images of the model plane under different orientations by moving either the plane or the camera.

2. Detect the image feature points.

3. Preliminary estimate the five intrinsic parameters and all the extrinsic parameters using the closed-form solution.

4. Refine all parameters, including lens distortion parameters, by maximum likelihood estimation.

3 3D dynamic measurement

Phase-shifting method has been used extensively in optical metrology to measure 3-D shapes of objects at various scales. In this paper, a phase-shifted sinusoidal fringe patterns are recorded in a color image, from which the phase information at every pixel is obtained. This phase information is then converted to xyz coordinates of the object surface after the system is calibrated. In this work, we use a DLP projector projects a computer generated color-coded image onto the object. The fringe patterns included by a color-coded image, which are deformed by the object surface, are captured by two cameras synchronously. Then a phase-wrapping and phase-unwrapping algorithm and a phase-to-coordinates conversion algorithm are used to reconstruct the 3D geometry. DLP projector can project color image, and at same time eliminate phase shift error.

3.1 color coding method

For 3D dynamic measurement, the key is that 3D reconstruction must be acquired through one image. So three-step phase shifting information must be in a image. Color image include three channels (red, green and blue channels), and a channel include a phase shifting 2/3 π fringe. The cameras of the 3D dynamic capture color-coded fringe which is illustrated in Fig.1.

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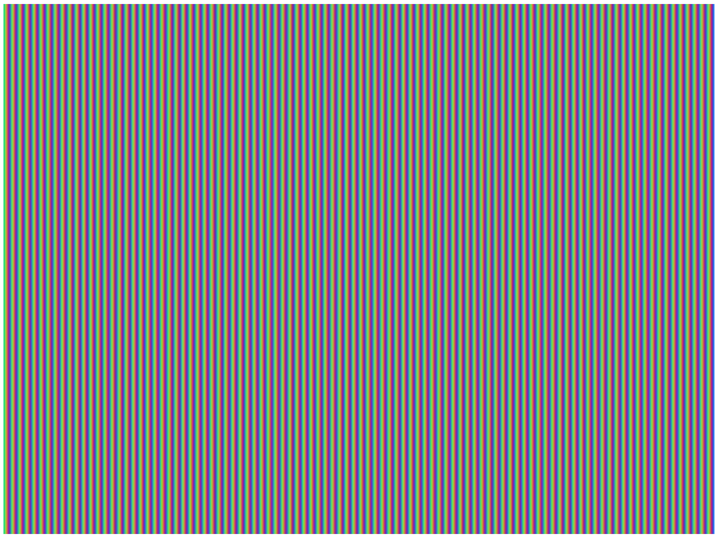

Figure 1. Color-coded fringe image

A color-coded frnge image include three different phase information. The 24 bits true color image is projected by DLP projector, in which each pixel values are divided into R, G, B component of three primary colors. So each channel image is obtained.

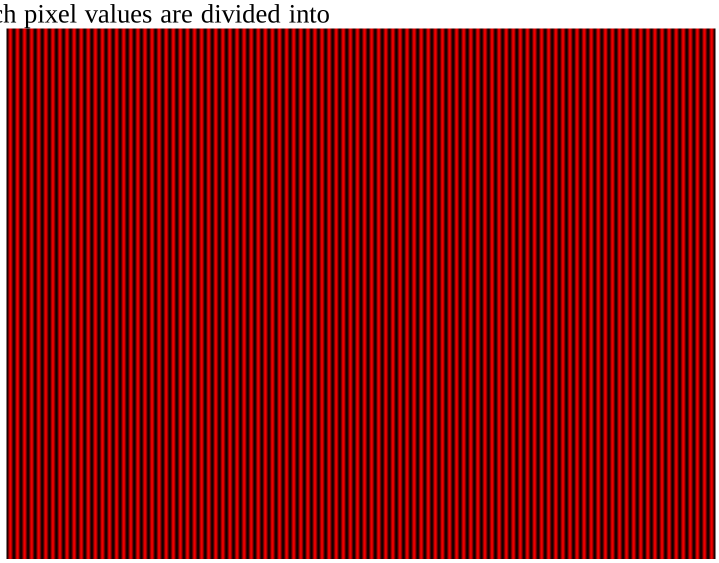

Figure 2. Red channel fringe image

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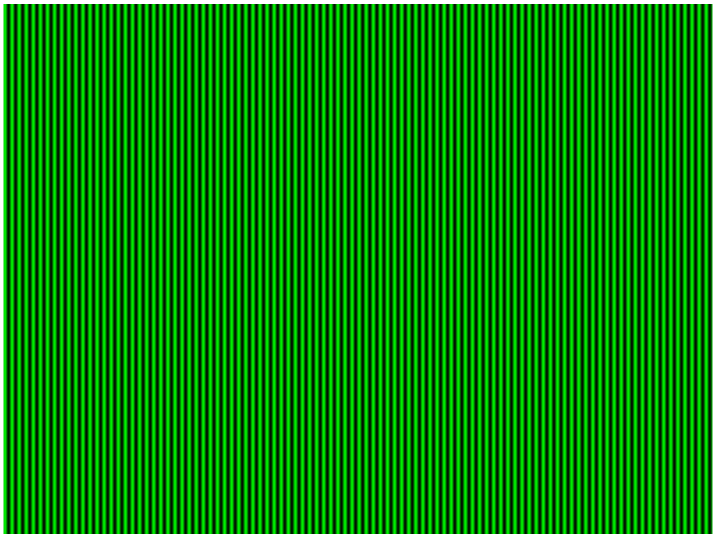

Figure3. Green channel fringe image

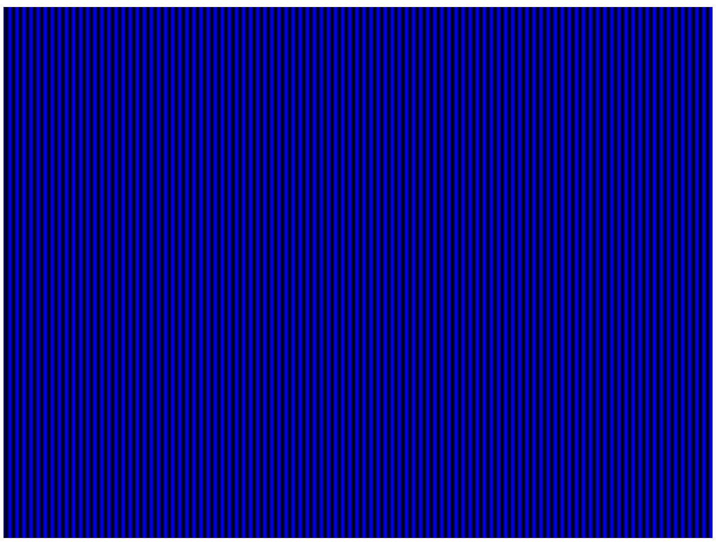

Figure4. Blue channel fringe image

3.2 Phase shifting

Many different phase-shifting algorithms have been developed[5]. A well known method for determining these parameters is the so called three-step phase shifting . Let us assume that a total of three phase-shifted fringe images are captured, each with a phase shift of $\delta_i(i=1,2,3,4)$. Then the intensity of the i-th image can be represented as:

$$I_i(x,y)=I^{'}(x,y)+I^{"}(x,y)\cos[\phi(x,y)+\delta_i] \quad (5)$$

Where $I^{'}(x,y)$ is the average intensity, $I^{"}(x,y)$ is the intensity modulation, and $\phi(x,y)$ is the phase to be determined. By solving equation (5) simultaneously, we can obtain the phase:

$$\varphi(x,y)=tg^{-1}\frac{I_3-I_2}{I_1-I_2} \quad (6)$$

Phase $\phi(x,y)$ in algorithm (6) is the so-called modulo 2π phase at each pixel whose value ranges from 0 to 2π . If the R, G and B fringe patterns are obtained, phase unwrapping is necessary to remove the sawtooth-like discontinuities and obtain a continuous phase map[5].

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3.3 Stereo vision

In order to compute the 3D coordinate, we need to obtain correspondences of the two images. In this work, we divide the color-coded fringe image into three channels fringe images, and then a series of contour lines and obtain pixel point sets in these lines and a series of phase grey curves through three-step phase shifting algorithm described in section 3.1. Then we implement the matching point sets in the left-right images according to the each absolute value of phase grey lines. Finally we get the corresponding points by epipolar constraint within the matching point sets. Assuming the corresponding points to be (u_r, v_r) and (u_l, v_l), the world coordinates of the point to be (x_w, y_w, z_w), we have the following equation that transform the world coordinates to the camera image coordinates:

$$\begin{aligned} s\{u_r, v_r, 1\}^T &= P_r\{x_w, y_w, z_w\}^T \\ s\{u_l, v_l, 1\}^T &= P_l\{x_w, y_w, z_w\}^T \end{aligned} \tag{7}$$

Where P_r and P_l are the calibrated matrix for the two cameras,

$$\begin{aligned} P_r &= A_r[R_r \quad T_r] \\ P_l &= A_l[R_l \quad T_l] \end{aligned} \tag{8}$$

From Equations 7 and 8 we can obtain four linear equations:

$$\begin{aligned} f_1(x_w, y_w, z_w, u_r) &= 0, \\ f_2(x_w, y_w, z_w, v_r) &= 0, \\ f_3(x_w, y_w, z_w, u_l) &= 0, \\ f_4(x_w, y_w, z_w, v_l) &= 0. \end{aligned} \tag{9}$$

Where u_r, v_r and u_l, v_l are known. Therefore the world coordinates (x_w, y_w, z_w) of the point can be solved by least square algorithm.

3.5 3D dynamic measurement system

In this paper, we developed a 3D measurement system consists of two CCD/CMOS cameras and a DLP projector. The system overview is shown in figure 4.The camera image resolution is set 1024×820 and the projector image also is 1280 × 1024. The procedure of 3D dynamic measurement with this system is as follows. Firstly, the two cameras are calibrated with a flexible and accurate camera calibration method. As soon as the cameras calibration is finished 3D dynamic measurement becomes to be able to perform. Secondly, the DLP projector projects a color-coded fringe image which designed in section 3.1 to the object surface and the two CCD/CMOS cameras capture the one modulated image simultaneously respectively. Then, we compute the actual phase of the two cameras using three-step phase shifting and get two phase maps. Finally, we accomplish stereo matching and points reconstruction automatically according to the two phase maps after unwrapping.

Fig.5. 3D measurement system

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4 Experiments

In this work, a 400mm×300mm high precise calibration board with 99 circle marks is used to obtain calibration data sets for the camera calibration. In order to ensure the precision of the camera calibration, twelve groups of calibration images are captured from different orientation, which is shown in Fig.6. Then the coordinates of center of circles were extracted automatically. We calibrate the two cameras using the extracted coordinate of central of the circle. The cameras calibration results are shown in Table 1.

Table 1. Cameras calibration results

		Left camera	Right camera
intrinsic parameters	Focal Length	422.27651861 5421.97530654	3102.24690491 3029.02660688
	Skrew:	0	0
	Principal Point	562.45214993 340.19617783	627.16132910 287.89371002
	p_1	0.00109245	0.01331403
	p_2	0.00219015	-0.00099325
	k_1	0.22341062	-0.04855767
	k_2	6.16265442	0.71134609
extrinsic parameters	R	0.95804156 -0.00892189 0.28649044 0.00091801 -0.99941480 -0.03419366 0.28662786 0.03302195 -0.95747273 0.99086	0.99572594 -0.09228766 -0.00358354 -0.09191234 -0.98637979 -0.13640759 0.00905401 0.13615395 -0.99064632
	T	-100.25315756 101.35010168 1396.12329433	77.63567398 188.32795872 1306.35646977

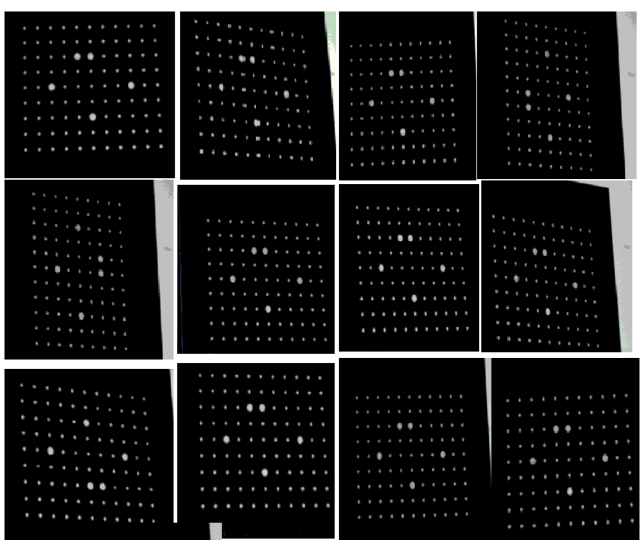

Fig.6 Calibration images

To verify the performance of the method proposed in this work, a face model is measured. Pair of color fringe images is captured during the measurement process. The measurement result is shown in Fig.7 .

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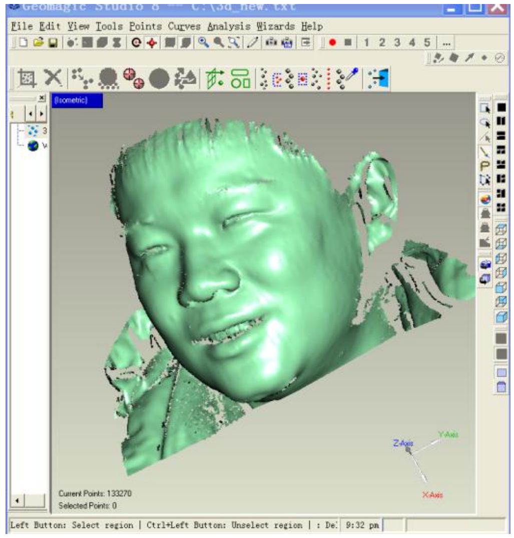

Fig.7 3D measurement result of the face model

5. Conclusion

In this paper, we have developed a 3D dynamic measurement system consists of two CCD/CMOS cameras and a DLP projector. By using a flexible calibration method, the system can be constructed easily. After the cameras calibration, we have proposed a method based on color-coded fringe, phase shifting and stereo vision for high precision 3D dynamic measurement. A face model has been measured and the reconstructed 3D model is very smooth

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