Abstract: Today, three dimensional (3D) reconstruction of human face is gaining more importance, with many applications. Among the various methods, this paper uses shadow moiré method which has superiorities over other methods. In shadow moiré method an iterative three-step phase shifting method is proposed which increases the measurement accuracy by eliminating nonuniform phase shift error. The method is simulated in 3ds-Max environment and through system analysis and experimental results it has been shown that the presented method is a powerful tool for 3D reconstructing of human face with high accuracy.

Keywords: Shadow moiré, phase shifting, 3D face measurement, phase unwrapping

1. Introduction

3D surface measurement constitutes an important topic in computer vision due to its wide field of applications. Some examples of applications are industrial inspection of manufactured parts, reverse engineering, 3D map building, biometrics and social security applications like identification and 3D face recognition systems.[1] The developed solutions are traditionally categorized into contact and noncontact techniques.

Contact measurement techniques have been used for a long time in reverse engineering and industrial inspections. Contact 3D scanners probe the subject through physical touch. A coordinate measuring machine (CMM) is an example of a contact 3D scanner. It is used mostly in manufacturing and can be very precise. The disadvantage of CMMs is that it requires contact with the object being scanned. Thus, the act of scanning the object might modify or damage it. This fact is very significant when scanning delicate or valuable objects such as historical artifacts. The other disadvantage of CMMs is that they are relatively slow compared to the other scanning methods and also they have high cost price.

Noncontact techniques were developed to cope with this problem by extracting the geometry information from the image of the measured object.

Moiré technique is one of the noncontact techniques, which has high precision and high speed. Moiré methods are based on Moiré effect that occurs when two structures (for example two grids) with periodic geometry are superimposed. Moiré techniques can be divided into two groups: Shadow moiré and projection moiré. Shadow moiré uses the reference gratings superimposed on its shadow to form a moiré pattern. In projection moiré a grating is projected onto the object and then viewed through a second grating in front of the viewer. The difference between projection and shadow moiré is that two different gratings are used in projection moiré[2, 3]. Shadow moiré has been chosen as the measuring method because of its simple configuration.

It is organized as follows. In the next section the principle of 3D shape measurement by shadow moiré and phase shifting is reviewed. Then the process of phase unwrapping is discussed. Finally, in order to show the accuracy of measurement, the simulation results are compared with reference model.

2. Principle of Shadow Moiré

Superposing two Ronchi gratings generates moiré patterns. When the two structures have the same or slightly different line spacing and their lines are approximately parallel, a new coarse pattern appears. This pattern is known as a Moiré pattern. The spacing and orientation of the Moiré fringes depend on the spacing and orientation of the structures being overlapped. Fig. 1 shows the moiré pattern produced by two identical Ronchi gratings rotated by a small angle relative to each other.

Shadow moiré technique uses this phenomenon to measure object height. In the shadow moiré setup, as shown in Fig. 2, one of the two periodic images is a grating placed near the object. The other is the shadow of the grating lines on a surface being measured. The light source and the camera are placed at the same distance from the grating plane. The shadow of the grating casts onto the object and interferes with the grating itself when the camera looks through the grating[4].

The recorded image by the camera can be expressed as:

\[ I(x, y) = a(x, y) + b(x, y) \cos(\varphi(x, y)) \]  

(1)

where \(a(x, y)\), \(b(x, y)\), and \(\varphi(x, y)\) are the mean intensity , modulation factor and the angular phase information of the fringe pattern, respectively. With the phase known, the object height can be obtained as[5]:

\[ z(x, y) = \frac{p \varphi(x, y)}{2\pi b - p \varphi(x, y)} \]

(2)

Where, \(p\) is the period of the Ronchi grating, \(b\) is the distance between light source and camera, \(h\) is the distance from grating plane to the light source and camera, and \(z(x, y)\) is the surface height measured from the grating plane.

To obtain object height, firstly phase information should be calculated from Eq. (1). There are three unknowns in Eq. (1), namely \(a, b\) and \(\varphi\). Three equations are needed to calculate these unknowns. Experimentally,
the three equations can be obtained by recording a series of intensity distributions with a known amount of phase change.

Fig. 1. (a) Ronchi grating. (b) Moiré between two Ronchi gratings of the same pitch and different orientation.

According to Eq. (3), \( \delta(x, y) \) is related to object height which is unknown. In experiments that object height is negligible in comparison with distance between object and camera \((h \gg z(x, y))\), a simple estimate of the phase step could be obtained by neglecting the \( z \) in the denominator of Eq. (3):

\[
\delta(x, y) = \frac{2\pi b \Delta l}{ph}
\]

But when the object is face, this estimation produces error, because face height isn’t negligible in comparison with \( h \). This paper proposes a new iterative method based on three-step phase shifting to calculate phase step \( \delta(x, y) \). In proposed method the estimated phase step \( \delta \) in Eq. (5) is used as the start of iterative algorithm. So, the first approximation of the phase can be determined as [6, 7]:

\[
\varphi(x, y) = \tan^{-1}\left(\frac{1 - \sin(\delta(x, y))}{\cos(\delta(x, y))}\left[\frac{I_1(x, y) - I_3(x, y)}{2I_2(x, y) - I_1(x, y) - I_3(x, y)}\right]\right)
\]

Fig. 2. Sahadow moire setup

3. Phase Shifting

As mentioned above, in order to obtain phase from Eq. (1), three equations are needed. These equations are three images with different phases. To produce phase shifts across the field of view, the grating is shifted two steps in equal distances and in the direction perpendicular to the grating plane. Thus generates three positions. In each position, the grating has a \( \Delta l_i = -\Delta l, 0, \Delta l \) \((i = 1, 2, 3)\) difference with respect to the original grating position. Then the generated phase step is [4]:

\[
\delta(x, y) = \frac{2\pi b \Delta l}{p[h + z(x, y)]}
\]

And three recorded images can be expressed as:

\[
\begin{align*}
I_1(x, y) &= a(x, y) + b(x, y)\cos(\varphi(x, y) - \delta(x, y)) \\
I_2(x, y) &= a(x, y) + b(x, y)\cos(\varphi(x, y)) \\
I_3(x, y) &= a(x, y) + b(x, y)\cos(\varphi(x, y) + \delta(x, y))
\end{align*}
\]

This phase is in the range of -\( \pi \) to \( \pi \). The \( 2\pi \) discontinuities are removed by phase unwrapping. Then object height can be obtained from Eq. (2). This estimation of height is substituted in Eq. (3) and then phase step is updated. This new phase step is used to calculate new phase from Eq. (6) and then object height is updated from Eq. (2). By iterating these steps, object height can be obtained accurately. Thus, proposed phase shifting method can be expressed in the following way:

1. Use the Eq. (5) to obtain an initial estimation of phase step.
2. Calculate phase \( \varphi(x, y) \) from Eq. (6) by using estimated phase step.
3. Unwrap the phase \( \varphi(x, y) \) and use it to achieve object height \( z(x, y) \) by Eq. (2).
4. If the difference between two consecutive \( z(x, y) \) is less than required accuracy, terminate the iteration else, go to step 5.
5. Update the estimated phase step by Eq. (3) and go to step 2.

4. Phase unwrapping

Due to the use of arctangent function, the extracted phase \( \varphi(x, y) \) is wrapped into the interval \((-\pi, \pi)\) and discontinuities of values of \( 2\pi \) appear. Therefore it needs to be unwrapped in order to provide the required continuous phase information. Many 2D phase unwrapping algorithms are developed. In this paper 2D unweighted least-squares phase unwrapping with use of fast cosine transform is used. This method, which is well explained in [8], attempts to minimize the difference between the unwrapped phase gradients and the wrapped values of the wrapped phase gradient, with the minimization performed in a least-squares manner. Each pixel's value in the image is uniquely determined by
solving the Discrete Poisson's equation with Newman boundary conditions which makes the least-squares solution of the wrapped and unwrapped phase difference minimum. The advantage of this method is processing the whole image at once and so it is fast and good choice for iterative algorithms.

5. Simulation Experiments

In this section, firstly the face modeling and configuration of shadow moiré setup in 3ds-Max environment is discussed. Then in shadow moiré setup, three frames are captured and proposed phase shifting method is applied to extract height information of the face. The results show that, proposed phase shifting shadow moiré is a powerful technique in 3D reconstructing of human face.

5.1 Face Modeling and configuration of setup in 3ds-Max

To perform shadow moiré on human face and evaluate accuracy of reconstructed model, a detailed 3D human face model is needed. For this purpose “FaceGen Modeller” software is used. By using it, a 3D face model with 7731 vertices is generated. This model is shown in Fig. 3. Moreover, in order to make it more realistic, it is textured with real face image. The generated model is imported in 3ds-Max environment and optical geometry of shadow moiré techniques is arranged there.

Shadow moiré geometry which is shown in Fig. 4, consists of a face model, a light source, a Ronchi grating placed near the face and a camera which sees the face through the grating. In this setup the face height is measured from the grating which is placed in front of the face and near to it. The camera and light source are at the same distance from the grating, and optical axis of camera is perpendicular to the grating plane. The system parameters in simulation are as follows: The period of Ronchi grating (p) is 0.6 mm, distance between camera and grid (h) is 3 meters and distance between camera and light source (b) is 750 mm.

Fig. 4. Shadow moiré setup

5.2 Simulation results of shadow moiré

The proposed phase shifting shadow moiré technique is verified by applying it on simulated face model in 3ds-Max. Fig. 6(a)–(c) shows the phase shifted shadow moiré patterns on face captured in 3ds-Max. They are obtained by translating the grating two times in direction perpendicular to the grating plane with translation step of ±0.6 mm. The proposed iterative phase shifting algorithm is applied on the phase shifted fringe patterns of Fig. 6 by five iterations to reconstruct 3D model of face. Fig. 5(a) shows the wrapped phase map obtained from first iteration, it is unwrapped by unweighted least-squares phase unwrapping and shown in Fig. 5(b). In order to make the reconstructed model look more realistic, a human face texture is mapped on it and displayed in Fig. 8.

In order to show the superiority of iterative three-step phase shifting to the non-iterative one, a comparison is performed. Fig. 7 shows the reconstructed cross section of face without iteration and with five iterations. This comparison is performed numerically and results are shown in Table 1. The numerical analysis is performed in terms of maximum, mean, variance and standard deviation of absolute value of error between extracted model and reference model. This comparison demonstrates that the proposed phase shifting by iteration can extremely increase measurement accuracy and successfully retrieve the 3D shape of the face.

Fig. 5. Extracted phase by shadow moiré (a)wrapped (b)unwrapped
Fig. 6  phase shifted Shadow moiré patterns with grating

Fig. 7  comparison of reconstructed cross section by five iteration and without iteration

Table 1.  reconstructed cross-section error

<table>
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<tr>
<th>method</th>
<th>Max error</th>
<th>Mean error</th>
<th>Variance of error</th>
<th>Standard deviation of error</th>
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<td>shadow moiré with three-step phase shifting and five iterations</td>
<td>0.7017</td>
<td>0.3112</td>
<td>0.0343</td>
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<td>shadow moiré with three-step phase shifting without iteration</td>
<td>1.8293</td>
<td>0.7506</td>
<td>0.3504</td>
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6. Conclusion

To enhance 3D reconstructing of human face by shadow moiré, a modified phase shifting shadow moiré was presented. The proposed method uses iterative three-step phase shifting to increase the measurement accuracy by eliminating nonuniform phase shifting error.

In order to show the validity of proposed method, the reconstructed cross section by proposed method and ordinary phase shifting is compared with the original signal. The results show that iterative phase shifting shadow moiré is a powerful technique for 3D reconstructing of human face and leads to higher accuracy in comparison with ordinary phase shifting method.

References