Accuracy enhancement of 3D Face Reconstruction Using Undecimated Wavelet Transform

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Abstract: This paper proposes a denoising method for accuracy enhancement of 3D (three dimensional) reconstruction process by shadow moiré. The proposed denoising method based on undecimated wavelet transform (UWT) effectively eliminates noise and grating pattern while retaining useful information. The proposed shadow moiré method is compared with structured lighting method which is a common method for 3D reconstruction, and also it is compared with traditional shadow moiré. Experimental results show that the proposed shadow moiré technique achieves more accuracy in comparison with the traditional shadow moiré and structured lighting techniques.

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1. Introduction

Three-dimensional surface measurement constitutes an important topic in computer vision due to its wide field of applications. Some examples of applications are industrial inspection, reverse engineering, medical and social security applications like identification and 3D face recognition systems [1]. The developed techniques which extract the height information from the image of the object can be categorized into active and passive techniques.

In passive approaches such as stereo vision, the scene is first imaged from two points of view and correspondences between the images are found. The main problem experimented when using this approach is the difficulty to find the corresponding pairs from two camera images. In addition, because of its complicated computations to find corresponding pixels, it is usually time-consuming [2].

Thus, active methods came to cope with this problem. These methods can be divided into structured lighting and shadow moiré techniques. In structured lighting, a Ronchi grating or sinusoidal grating is projected onto the object surface to modulate its height distribution, and then the deformed fringe pattern is imaged from the other view by a camera and processed by a fringe analysis technique to demodulate the 3D shape information [3]. Among the studied fringe analyses, FTP (Fourier Transform Profilometry), introduced first by Takeda [4], is more commonly used, because of its merits of needing only one frame, full-field analysis, high precision and high-speed measurement.

Moiré methods are based on the Moiré effect that occurs when two structures with periodic geometry are superimposed. Shadow moiré uses the reference grating superimposed on its shadow to form a moiré pattern [5, 6]. In order to extract height information from shadow moiré fringes, at least three phase shifted images are needed [7, 8]. In this method, three images are obtained by translating the grid in equal steps and then phase information is calculated from these images. Although phase shifting is a popular fringe analysis technique for shadow moiré, its accuracy is limited because of the grating patterns in phase shifted images. There are some averaging methods to remove these patterns which need more images [9, 10]. This paper proposes an efficient noise removing technique based on UWT, which eliminates grating patterns effectively without need to more images.

In addition, the proposed method is applied to a human face as a complex object, with the results demonstrating its validity.

This paper is organized as follows. In the next section the principle of structured lighting and FTP is reviewed. Then the process of 3D shape measurement by shadow moiré is discussed, followed by the discussion of removing the unwanted grating pattern by UWT. Finally, in order to show the accuracy of measurement, the simulation results are compared with the reference model.

2. Structured lighting technique

The structured lighting technique is a method to measure the depth information of a surface by measuring the deformation in the projected light pattern. In this method as shown in Figure 1, a Ronchi grating is projected onto the object surface and due to the height variation of the object, the projected lines pattern is deformed on the object. The deformed pattern is captured by a camera from a point of view different from the projection axis [3].

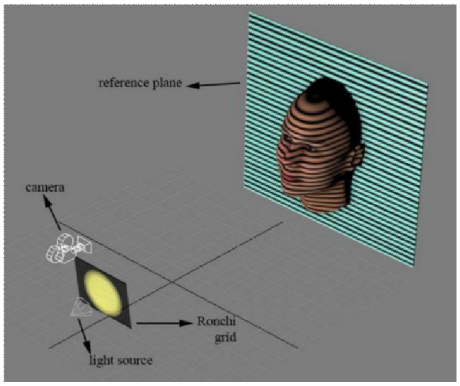


Figure 1. Structured lighting setup

Different analysis methods are developed to extract the phase map of the captured image which contains height information. These methods are Fourier transform profilometry (FTP), Phase Shift Profilometry (PSP) [11], Windowed Fourier Profilometry (WFP) [12] and Continuous Wavelet Transform (CWT) [13]. Each technique has its own advantages and disadvantages. For example PSP needs at least three frames while FTP needs only one frame, but the accuracy of PSP is better than FTP.

In this paper FTP analysis is used to extract phase information due to its simplicity, high speed and capability to analyze dynamic objects. The extracted phase which is wrapped between (-π, π), needs a 2D unwrapping algorithm to achieve a smooth and continuous phase map. Finally, the height information of the object can be recovered by the triangulation technique as [14]:

$$z(x,y) = \frac{ph\Phi(x,y)}{2\pi b - \mathrm{p}\Phi(x,y)} \qquad (1)$$

Where $\Phi(x, y)$ is the unwrapped phase value obtained by FTP, h is the distance between camera and reference plane, b is the distance between camera and light source and p is the pitch of Ronchi grating on the reference plane.

3. Shadow moiré technique

A. Principle of Shadow moiré

Superposing two periodic structures generates moiré patterns. The shadow moiré technique uses this phenomenon to measure the object height. In shadow moiré setup, as shown in Figure 2, one of the two periodic images is a Ronchi grating placed near the object. The other is the shadow of the grating lines on the surface being measured. The shadow of the grating is casted onto the object and interferes with the grating itself when the camera looks though the grating. The light source and camera are placed at the same distance from the grating plane [15].

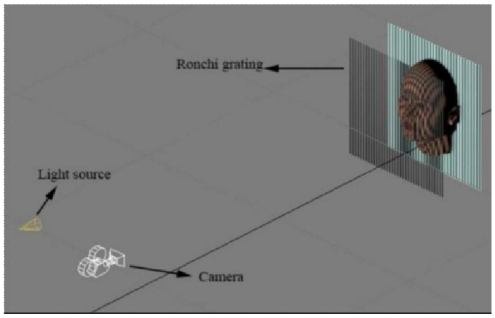


Figure 2. Shadow moiré setup

The recorded image by camera can be expressed as:

$$I(x,y) = a(x,y) + b(x,y)\cos\big(\varphi(x,y)\big) \qquad (2)$$

Where (x, y), $b(x, y)$, and $\varphi(x, y)$ are the mean intensity , modulation factor and the phase information of the fringe pattern, respectively. With the phase known, the object height can be obtained as [9]:

$$z(x,y) = \frac{ph\varphi(x,y)}{2\pi b - p\varphi(x,y)} \qquad (3)$$

Where, p is the pitch of Ronchi grating, b is the distance between light source and camera, h is the distance from the 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, phase information should initially be extracted from Eq. (2). There are three unknowns in Eq. (2), namely a, b and φ. 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 that will be discussed in the phase shifting section.

B. Removing unwanted grating patterns

In the captured image, the fringe patterns contain useful information about object height, while the high frequency grating patterns are useless and are considered as noise. Furthermore, other noises could be added from the camera, defects in optics and imperfect grating replication. These noises extremely corrupt phase unwrapping results and reconstructed height.

To remove grating patterns, Allen et al. [10] translated the grating in its own plane three times and captured four images. They showed that by averaging these four images the grating pattern will be removed. Huang and Guo [9] improved this method by reducing the translation number of the grating to two times. This paper proposes a new method which not only removes the unwanted grating pattern effectively with no need to grating translation, but also efficiently removes other noises resulting from optical setup. This method is based on UWT.

In noise removing, a tradeoff between the removed noise and the blurring in the image always exists. The wavelet's capability to discriminate noise and real data reduces the blurring effect and makes it a powerful tool for noise removing. Based on the concept of wavelet based image denoising by thresholding of wavelet coefficients, a number of techniques have been developed. Among them, undecimated wavelet transform has the best performance in denoising while offering useful properties such as shift invariance which is important in image denoising. Starcket et al. [16] showed that thresholding using an undecimated wavelet transform rather than a decimated one can improve the result by more than 2.5 dB in denoising applications.

To remove noise by UWT, forward UWT is performed to obtain wavelet coefficients. Since the noise in signals usually corresponds to the coefficients with small values, an appropriate threshold is computed to threshold UWT coefficients and then the inverse transform using the thresholded coefficients is performed.

To compute the threshold there are different methods such as: Universal [17], SURE and Hybrid [18]. The *Universal* threshold for an image of N pixels is $=\sqrt{2logN}$. The *SURE* threshold is derived by minimizing Stein's Unbiased Risk Estimate (SURE) [19]. The *Hybrid* threshold is a compromise between the SURE method and the Universal method. When the signal-to-noise ratio of the noisy signal is very low, this threshold is equal to Universal threshold.

The threshold can be applied in two ways: soft thresholding and hard thresholding [20]. Hard thresholding consists of setting to 0 all wavelet coefficients smaller than the threshold and keeping the others, while soft thresholding sets the coefficients smaller than the threshold to 0 and shrinks the others toward 0.

This paper uses the universal threshold by soft thresholding scheme.

C. Phase Shifting Method

As mentioned in section 3.A, in order to obtain phase from Eq. (2), three equations are needed. These equations are three images with different phases which are captured by the camera. 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. This generates three positions. In each position, the grating has a Δli = −Δl, 0, Δl (i =1,2,3) difference with respect to the original grating position. Then the generated phase step is [15]:

$$\delta(x,y)=\frac{2\pi b\Delta l}{p[h+z(x,y)]} \qquad (4)$$

And three recorded images can be expressed as:

$$I_1(x,y)=a(x,y)+b(x,y)\cos\big(\varphi(x,y)-\delta(x,y)\big)$$

$$I_2(x,y)=a(x,y)+b(x,y)\cos\big(\varphi(x,y)\big) \qquad (5)$$

$$I_3(x,y)=a(x,y)+b(x,y)\cos\big(\varphi(x,y)+\delta(x,y)\big)$$

Thus, the phase of image can be determined as [21, 22]:

$$\varphi(x,y)=\tan^{-1}\Big[\frac{1-\sin(\delta(x,y))}{\cos\,(\delta(x,y))}\,\frac{I_1(x,y)-I_3(x,y)}{2I_2(x,y)-I_1(x,y)-I_3(x,y)}\Big] \qquad (6)$$

This phase is in the range of -π to π. The 2π discontinuities are removed by phase unwrapping.
Then object height can be obtained from Eq. (3).

3. Phase Unwrapping

Due to the use of arctangent function, the extracted phase (x, y) is wrapped into the interval $(-\pi,\ \pi)$ and discontinuities of values of 2π 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 the use of fast cosine transform is used. This method, which is well explained in [23], 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 with fewer computations, and so it is a fast algorithm.

4. Simulation experiments

In this section, the face modeling and configuration of the structured lighting and shadow moiré setups in 3ds-Max environment is discussed. Then the height information of the face is reconstructed by applying these methods on the face model.

A. Face Modeling and configuration of setups in 3ds-Max

To perform structured lighting and shadow moiré on the human face and evaluate accuracy of the reconstructed model, a detailed 3D human face model is needed. For this purpose the "FaceGen Modeller" software is used. By using it, a 3D face model with 7731 vertices is generated in which the high number of vertices can detail the head model with lots of polygons. Moreover, in order to make it realistic, it is textured with the human face image.

The generated model is imported in 3dsMax environment and optical geometry of structured lighting and shadow moiré techniques are arranged there.

The structured lighting setup that is displayed in Figure 1 consists of a face model, a reference plane from which the face height is measured, a camera, a light source and a Ronchi grid placed in front of the light source to cast line patterns on the face. The system parameters in the simulation are: p=1 mm, h=3 meters and d= 334 mm. It is worthy to note that the optical axis of the camera is normal to the reference plane.

On the other hand, shadow moiré geometry which is shown in Figure 2, is similar to the structured lighting but the Ronchi grating is near the face, and the camera sees the face through the grating. In this setup the face height is measured from 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 the optical axis of the camera is perpendicular to the grating plane. The system parameters in simulation are: p=1 mm, h=3 meters and b=750 mm.

B. simulation results of structured lighting

In order to extract the height information in structured lighting, Fourier transform technique is applied on capture image shown in Figure 3. Its 2D Fourier transform is shown in Figure 4, which consists of 3 distinctive peaks. By using a 2D band pass filter and shifting the desired spectra to the origin, the wrapped phase is extracted and displayed in Figure 5(a).This wrapped phase is unwrapped by unweighted least-squares phase unwrapping algorithm and exhibited in Figure 5(b). Finally, the height information of the face is computed using Eq.
(1).

Figure 3. Deformed lines pattern on face

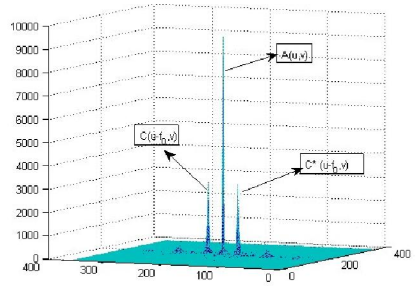
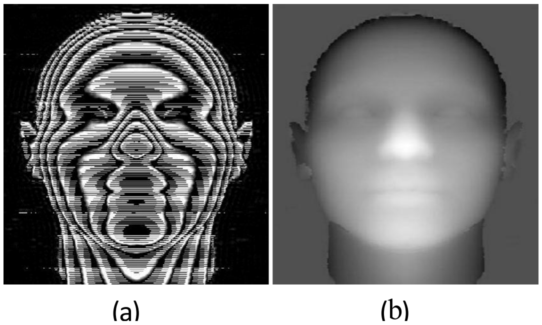


Figure4.Frequency spectrum of deformed lines pattern shown in Figure 3

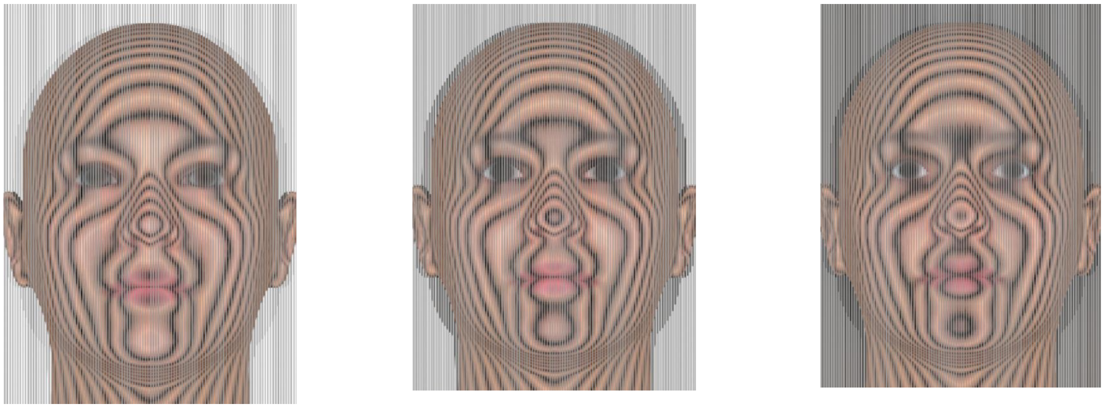


(a) (b)

Figure 5. Extracted phase by structured lighting (a)wrapped (b)unwrapped

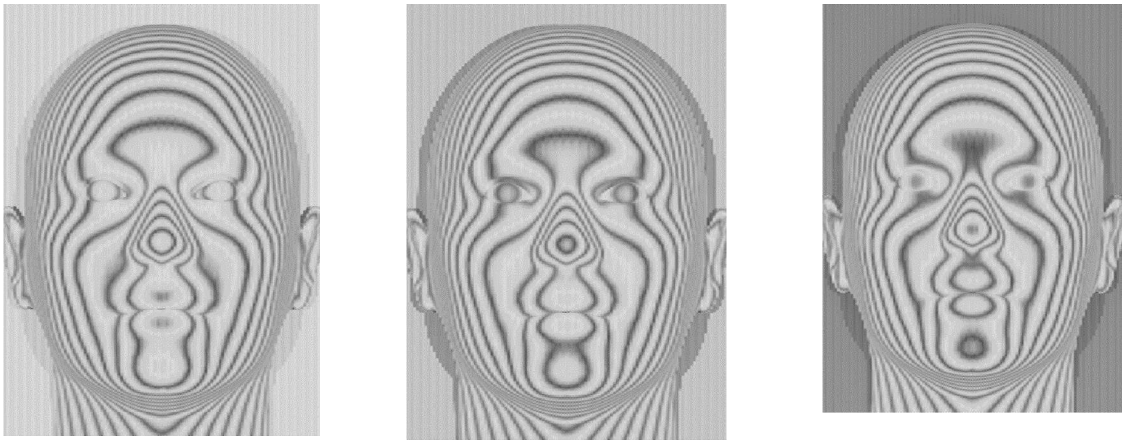
C. Simulation results of shadow moiré

The proposed shadow moiré technique is verified by applying it on simulated face model in 3ds-Max. Figure 6(a)~(c) shows the phase shifted shadow moiré patterns on face. They are obtained by translating the grating two times in the direction perpendicular to the grating plane with translation step of ±0.6 mm. By using UWT, the unwanted grating patterns and noise on these three images are removed and moiré fringe patterns are obtained and shown in Figure 7. Then phase shifting algorithm is applied on the phase shifted fringe patterns of Figure 7. In order to make the reconstructed model look more realistic, a human face texture is mapped on it and displayed in Figure 8.



(a) (b) (c)

Fig. 1 phase shifted shadow moiré patterns with grating



(a) (b) (c)

Fig. 2 Denoised phase shifted shadow moiré patterns

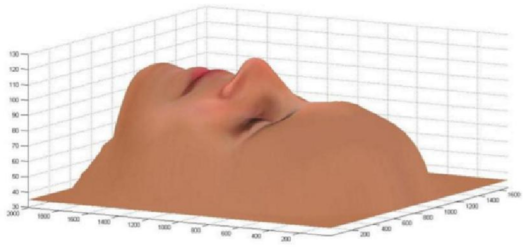


Figure 8 Reconstructed 3D face by structured lighting

To demonstrate the effectiveness of the proposed noise removing technique, two numerical comparisons have been carried out. The noise in three phase shifted images is removed in two ways: by using UWT and by using averaging of three images captured by translating the grating in its own plane two times [9], and the error of reconstructed cross-sections is shown in Table 2. 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. The lower error for UWT reveals that it has better performance in noise removing.

Since the Gaussian noise is a major part of images captured by digital camera, three phase shifted images are contaminated with additive zero mean and 0.01 variance Gaussian white noise. These images are denoised by UWT and the error of reconstructed cross-section is reported in Table 2. These results show that the proposed method of denoising can eliminate noise while retaining the useful information.

D. *Shadow moiré and structured lighting comparison*

To evaluate the performance and accuracy of structured lighting and shadow moiré techniques the extracted height by these methods is compared with real height information of face model obtained from 3ds-Max. The numerical analysis on reconstructed cross-section by these methods is reported in Table 1. As it is obvious from table, proposed shadow moiré method has higher accuracy than structured lighting. Moreover, in structured lighting, calculating grating pitch on reference plane (p) and selecting the optimum filter size in FTP are difficult tasks. But implementing the structure lighting setup is easier, because it does not need to place a grid near the object. And also structured lighting can be analyzed by FTP which is fast and needs only one frame which makes it capable of dealing with dynamic objects. But FTP cannot be used in shadow moiré because of changes in fringe gradient sign [21].

Table 1. reconstructed cross-section error

method	Max error	Mean error	Variance of error	Standard deviation of error
shadow moiré	1.8293	0.7506	0.3504	0.5919
Structured lighting	2.6387	0.4134	0.1843	0.4293

Table 2. reconstructed cross-section error by two denoising methods

method	Max error	Mean error	Variance of error	Standard deviation of error
denoised by UWT	0.7017	0.3112	0.0343	0.1852
Denoised by averaging of three images	0.7745	0.3406	0.0498	0.2231
Noisy images denoised by UWT	1.2157	0.4420	0.0777	0.2787

5. **Conclusion**

To enhance 3D reconstruction by shadow moiré, a modified phase shifting shadow moiré was presented. The proposed method uses UWT for denoising in preprocessing stage which eliminates the need for translation of the grid.

In order to show the validity of the proposed method, we compared the reconstructed cross section of the proposed technique, traditional shadow moiré, with original signal. The results show that using UWT could increase the accuracy of measurement especially in noisy patterns. Moreover, to show the accuracy of measurement, the reconstructed cross section by proposed shadow moiré and structured lighting was compared with original signal. The results show the superiority of shadow moiré to structured lighting in terms of accuracy. All numerical experiments indicate that shadow moiré and structured lighting are powerful techniques for 3D reconstruction, and the proposed shadow moiré leads to high accuracy.

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