



24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-5720

STEREOSCOPIC FRINGE PROJECTION SYSTEM FOR HUMAN TOOTH ARCADE MEASUREMENT

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Abstract. *Three-dimensional (3D) measurement of human body has different application in bioengineering and health areas. 3D models can be important to analyse hand function and behaviour and quantify pathology parameter, for example. The base of human measurement analysis is the use of a fast, minimally invasive and non-contact system. This work aims to develop a stereoscopic measurement system by fringe projection making use of two digital cameras to acquire the images of a series of phase shifted fringes projected into the measurement surface by a DLP projector. A software was developed in order to process the images and using the concepts of phase unwrapping and epipolar geometry and then retrieve the 3D measurement of the surface under test. A plaster model of tooth arcade was used to test the measurement performance.*

Keywords: *3D measurement, phase unwrapping, human body.*

1. INTRODUCTION

An optical measurement system of phase shifting fringe projection and stereoscopy is proposed to evaluate three-dimensionally (3D) a plaster model of tooth arcade based on photogrammetry (Reich *et al.*, 2000 and Zhang, 2010).

In the last years, the use of phase-shifting fringe projection as a way to retrieve 3D measurement has shown promising results (Albertazzi Jr. *et al.* 2008, Tian *et al.* 2008, Zhang, 2012, Bian *et al.* 2013, Cabral, *et al.* 2016, Dai *et al.* 2017). The combination of stereoscopic view and phase shifting reduce the measurement uncertainties and scanning speed (Song *et al.* 2016). Indeed, different measurement environments have benefited of structured light projection. Bräuer-Burchardt *et al.* (2015) show the principle of optical 3D surface measurements based on the fringe projection technique for underwater applications.

Also, when the measurement time needs to be reduced different techniques can be incorporated. Chen *et al.* (2015) proposed a snapshot phase shift fringe projection 3D surface measurement method using polarization-coded light illumination and polarization camera, which was insensitive to motion and has the potential for ultrafast 3D surface imaging. Gai *et al.* (2016) proposed a 3D shape measurement system based on the combining projection of single digital speckle pattern and phase-shifting fringe patterns. At the beginning, the initial corresponding point for each pixel is obtained by a novel speckle-phase combination method. Unlike the conventional methods, it is not necessary to obtain the unwrapped phase, therefore the number of projected patterns is reduced greatly. Then accurate corresponding coordinates are obtained according to the wrapped phase.

When using a system with one or more cameras it was necessary to calibrate them in order to get information about camera's position and optical parameters. Generally, this is a previous process to the 3D measurement. Zhong *et al.* (2016) presented a pre-calibration-free 3D shape measurement method based on fringe projection, which performed calibration and 3D shape measurement concurrently. The captured phase-coded fringe images were utilized to obtain homogenous control points from two camera viewpoints, and the rough 3D structure of these points can be retrieved.

In this paper, four digital sinusoidal phase shifted fringe patterns are projected by a DLP projector and recorded synchronously by two GigaEthernet video cameras. In order to solve the problem of phase unwrapping, Gray-Code sequences (Sansoni *et al.*, 1999 and Proll, 2004) are also projected and acquired by the system sequentially to the sinusoidal patterns retrieval. A total of 11 images were necessary to measure the arcade model.

2. METHODOLOGY

Two GigaEthernet CCD cameras of 1034x779 pixels resolution with lens of fixed focal length of 25mm connected to an N-band router and a DLP projector of 1024x768 pixels resolution were used in the measurement set up. Also a microcomputer to establish the communication with the devices and to process the images was employed. The cameras were displaced on the right and on the left of the projector that was normal to the measurement object, Fig.1.



Fig. 1. Measurement set up.

A dedicated software controls the DLP and cameras interface, generating the patterns to be projected and respective image acquisition, storage and processing. Calibration of each camera was performed according to Zhang, 2000. Their projection matrix, composed of intrinsic and extrinsic parameters, are used to feed the software. A triangulation method is used to retrieve the point of clouds of the measured plaster model, based on the comparison of unwrapped phase maps calculated for each camera.

In this way, four digital sinusoidal phase shifted fringe patterns were projected by a DLP projector and recorded synchronously by two GigaEthernet video cameras. Figure 2 (a and b) shows an example of zero degree phase shifted vertical fringe projected on a reference plane. Making use of the images of the arcade with the 4 phase-sifted projected on it, the relative phase map was calculated according to Eq. 1.

$$\phi(x, y) = \tan^{-1} \left(\frac{\sum_{i=0}^{k-1} I_{i \frac{360}{k}}(x, y) \sin(i \frac{360}{k})}{\sum_{i=0}^{k-1} I_{i \frac{360}{k}}(x, y) \cos(i \frac{360}{k})} \right) \quad (1)$$

Where I_i represents the modulated intensity captured by the image sensor for each phase sift introduced to the fringe pattern. So, in this paper, I_i varied from I_1 to I_4 , showing the intensity matrices from the first to the fourth image of measurement object with projected fringes. Figure 2c shows the relative phase map of a reference plane and Fig. 2d a line profile of the relative phase at line 380, where it can be seen the phase jumps of 2π characteristics of phase maps.

In order to solve the problem of phase unwrapping, Gray-Code sequences are also projected and acquired by the system sequentially to the sinusoidal patterns retrieval. A total of 11 images are necessary to measure the arcade model: 4 with phase-shifted projected fringes, 1 totally white, 1 totally black and 5 with projected gray-code, Fig. 3. Making use of the gray code maps according to Proll (2004) it was possible to perform the phase unwrapping, Fig. 4.

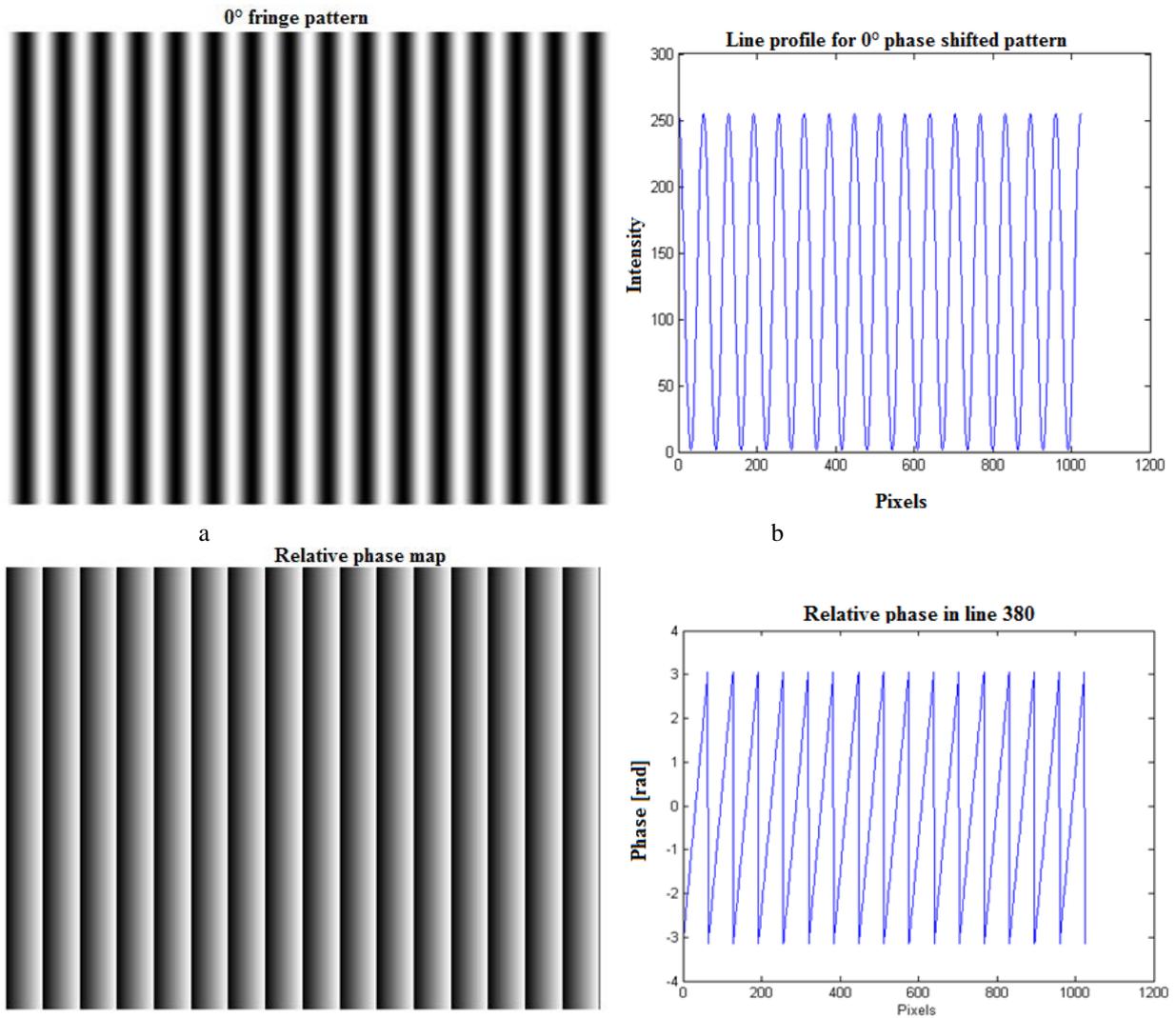


Fig. 2. a) Phase shifted fringe pattern at 0°; b) its sinusoidal line profile; c) relative phase map and d) line profile of relative phase at line 380.

The software was developed in a way to minimize the human intervention in the processing steps. The basic steps were: camera parameters adjustment (image size, exposure time and gain), projector parameters adjust (size and projection image position); acquisition of images of a pattern plane (like a chessboard) for camera calibration and identification of the intrinsic and extrinsic parameters; projection of phase shifting pattern under the measurement object. In this step, it was possible to choice the fringe orientation (vertical or horizontal), number of fringes and number of steps for phase shifting. Finally, the relative phase map and absolute phase map calculation were performed. Here, the aim was to remove the phase jumps of the measurement signal. Using the absolute phase maps, according to Hofmann (2006), Lee *et al.* (2006) and Hong *et al.* (2009), it was possible to identify the homologous points of the images of the two cameras and finally retrieve the 3D model of the arcade, according to an algorithm called Zscan developed by Fantin *et al.* (2007). All steps can be seen in Fig. 5 in sequence.

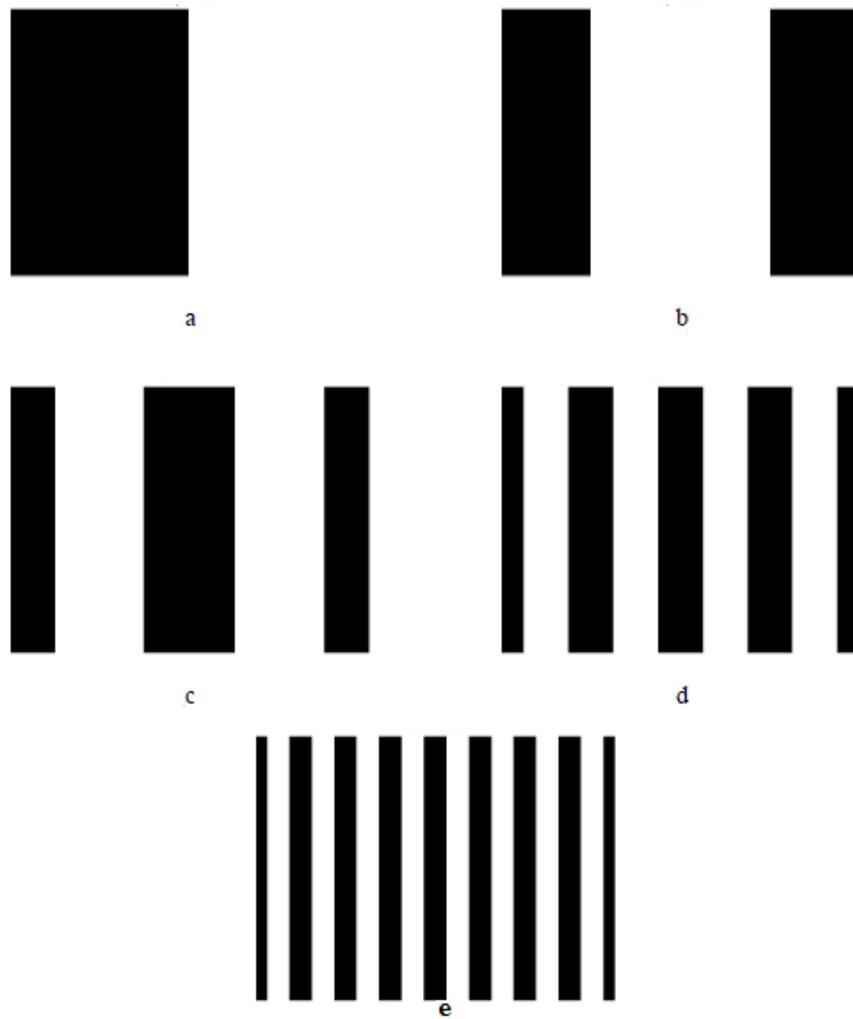


Fig. 3. a) Gray code pattern of 1 bit; b) Gray code pattern of 2 bit; c) Gray code pattern of 3 bit; d) Gray code pattern of 4 bit and e) Gray code pattern of 5 bit.

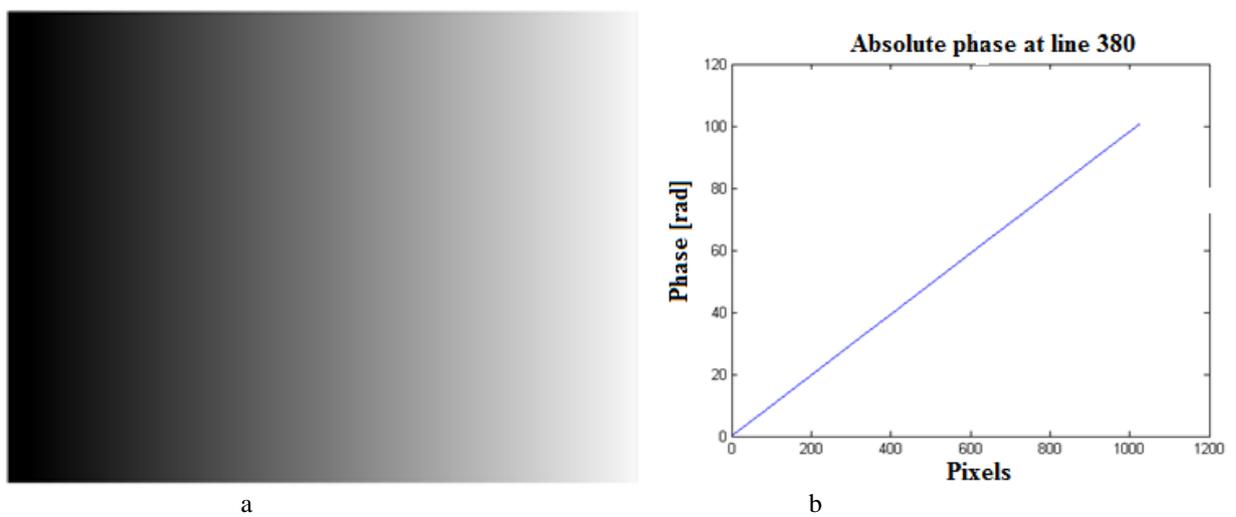


Fig. 4. a) Absolute phase map and b) line profile of absolute phase at line 380.

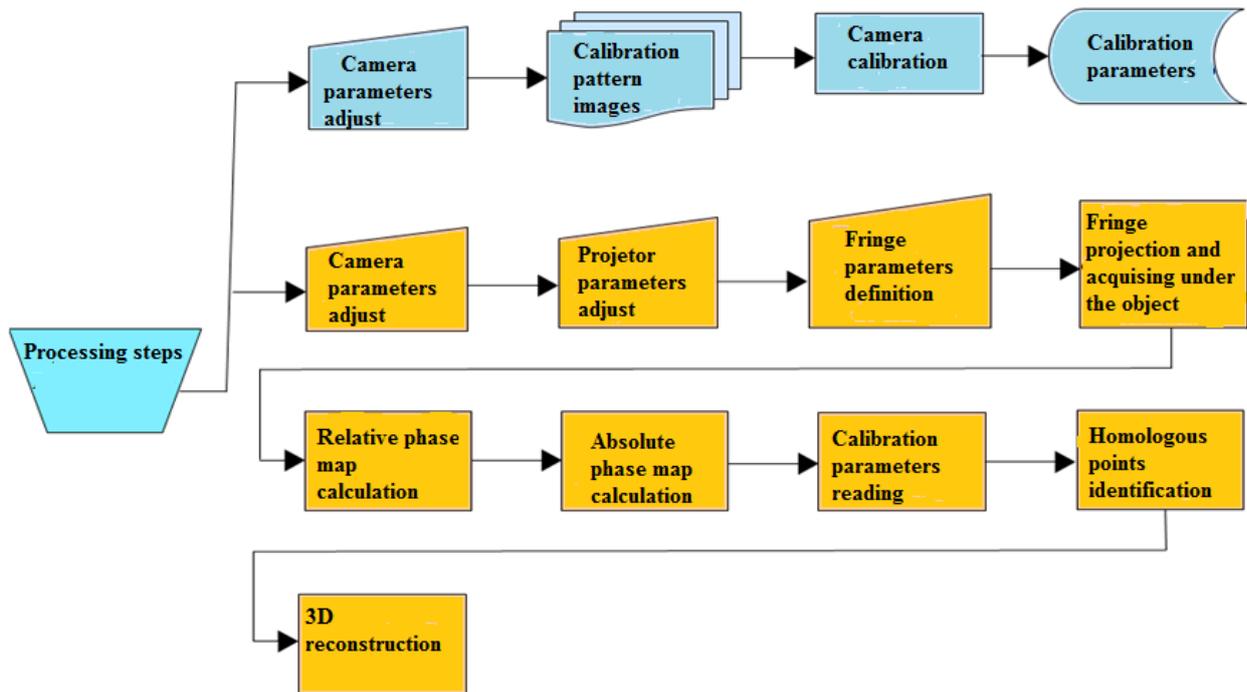


Fig. 5 – Main steps for 3D reconstruction

3. RESULTS

The results show that the system is able not only to measure geometries with hollowed areas, such as the palate, but also the teeth profiles. The measurement results are shown in Figure 6. All results are in millimeters.

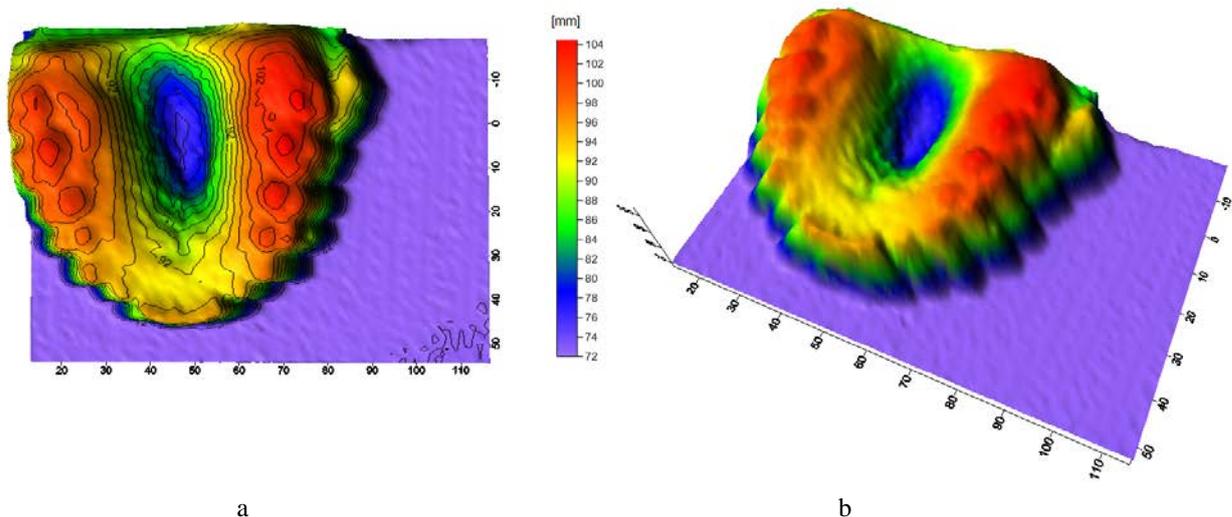


Figure 6. Arcade measurement results: a) contour lines and b) perspective model.

This was the first try to see if the proposed measurement system was capable of retrieve 3D information of a geometry like the arcade, including the palate region. In future works, the idea is to miniaturize the system and apply it inside the mouth in order to help professionals of the odontological area to identify different pathologies related to abnormal development of the teeth and palate.

Cui *et al.* (2013) presented a miniaturized 3D optical measurement system for tooth restoration. The measuring process is based on the structured light measurement principle and phase-shifting method. So, it is important to go on the

improvement of the measurement system, mainly because it takes 10s to acquire the images, which can be an acceptable time to keep the mouth opened, however it takes 10 minutes to process the images and display the 3D results.

4. CONCLUSION

The measurement system showed itself very robust even at positions with abrupt change of depth. In this paper, no comparison of different methods will be performed but merely a suggestion for phase unwrapping with the use of Gray-Code sequences is given. Although a short recording time of the image sequences is necessary, approximately 10 s, improvements must be done in order to perform the reconstruction of living objects which can be without motion only for a little short time and other measurement tasks which require real-time processing. Another challenge is to miniaturize the measurement system in order to make it useful for dentistry applications.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of FAPEMIG (Foundation for Research Support of Minas Gerais), through the provision of financial support to project.

The first author would also like to acknowledge CAPES (Coordination for the Improvement of Higher Education Personnel), for the scholarship and all support given during the Sandwich doctorate program. In addition, the Professor Pinotti, for being always an example person and motivator.

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