รหัสโครงการ SUT1-107-52-36-04

รายงานการวิจัย

การพัฒนาระบบสร้างคืนลายเท้าสามมิติโดยใช้การฉายเกรทติ้ง

Development of 3-D Footprint Reconstruction System by Using Grating Illumination

ได้รับทุนอุดหนุนการวิจัยจาก

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ผลงานวิจัยเป็นความรับผิดชอบของหัวหน้าโครงการวิจัยแต่เพียงผู้เดียว

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มิถุนายน 2556

Acknowledgement

The principal investigator acknowledges the research grant supported by the Suranaree University of Technology.

บทคัดย่อ

งานวิจัยนี้นำเสนอการบูรณะภาพสามมิติของฝ่าเท้าด้วยวิธีฉายแสงเกรตติง ข้อได้เปรียบของวิธีการนี้เมื่อเปรียบเทียบกับระบบที่ใช้แสงเลเซอร์คือไม่มีการผิดเพี้ยนของภาพจากรูปแบบการแทรกสอดที่เกิดขึ้น การบูรณะสามมิติของปริซึมสามเหลี่ยมด้วยวิธีการนี้ให้ผลสอดคล้องกับวิธีที่ใช้การสัมผัสโดยตรง ผลการทดลองเบื้องต้นแสดงให้เห็นว่า การเว้าขึ้นและนูนออกของปลายเท้า ส่วนโค้งกลางเท้า และส้นเท้าสามารถบูรณะได้โดยง่ายจากแบบจำลองฝ่าเท้า

Abstract

Three-dimensional (3-D) plantar surface reconstruction by using grating illumination is proposed. The advantage of the proposed method over laser-based systems is that it is free from image distortions caused by interference fringe patterns. 3-D profile of a triangular prism reconstructed by using the proposed method is in agreement with that by using the direct contact method. Preliminary experimental results show that the elevations and depression of toes, arches and heel can be easily reconstructed from a plantar phantom.

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Chapter 1
Introduction

1.1 Background and Significance

In humans, foot is a part of body which plays an important role in biomechanical contribution to postural control. Besides being easily exposed to a variety of potential infections and injuries, there are several genetic conditions that can affect the shape and function of feet, including a metatarsus adductovarus, club foot, flat foot, and congenital vertical talus [1]. In clinical studies, medial longitudinal arch (MLA) height has been widely used for detecting wide variation foot morphology [2-5]. There are two methods for assessing the MLA: the direct method employs either clinical assessment [6] or radiographic and ultrasonographic evaluations [7,8], while the indirect method involves ink or electronic footprint to provide information about abnormalities [9,10]. The clinical assessment is a subjective method. Careful assessments are difficult and lengthy, and the results may vary depending on test conditions. Besides being costly and need of special facilities and qualified personnel, radiographic and ultrasonographic approaches bring potential health risks, particularly for pediatric population. On the other hand, the indirect method offers the safest method. However, it still suffers from some limitations. The drawback of a conventional ink approach is that the footprint is easily contaminated or poorly reproduced. In the case of the electronic approach, its resolution is lower than the ink footprint, because finite size of the capacitance sensors. Further study of comparison between the two approaches by Urry and Wearing shows that the ink approach is superior to the electronic system, because the later cannot detect accurately midfoot area where the foot arch exists [11]. For these reasons, the footprint-based parameters such as footprint angle, contact and non-contact areas, are systematically used to extract the foot arch configuration [12,13].

Although human foot constitutes of three-dimensional (3-D) structures, it is a fact that the footprint method provides only 2-D information of the plantar surface of the foot from which the foot arch must be derived. It is believed that 3-D information of the arch height provides the most precise information of the pathology. Recently, an image processing system for 3-D reconstruction of the foot arch was reported by Lin et al. [14]. In this system, a footprint image is captured from statically standing subject whose feet is immersed into a transparent box filled with blue gel. Besides enhancing contrast of the sole’s image, this gel is used to attenuate intensity of the illuminating light. In order to calibrate depth information, a 3-D miniature white stair with a step height of 2 mm is fixed in the blue gel box and is simultaneously photographed with the foot. After obtaining an average brightness of each step, a cubic spline interpolation is employed to determine the height of the foot arch and then reconstruct the 3-D plantar surface of the foot. However, this method has several drawbacks such that firstly, the accuracy of the reconstruction is determined by the step height of the stair. The finer the step, the higher the accuracy is. Secondly, immersing feet into the blue gel may cause uncomfortable feeling to pediatric subjects.

In order to overcome these problems, a new non-contact method for reconstructing 3-D plantar surface of feet by using grating illumination is proposed. In the proposed method, a 2-D periodic grating pattern is projected onto the subject's feet of during balanced standing and is observed from another direction [15]. The observed image consists of the deformed grating that is the original pattern which is phase modulated by the 3-D plantar surface. Therefore, the phase modulation is associated with the foot arch height. By determining numerically a localized phase value from the deformed grating, the 3-D plantar surface can be reconstructed

1.2 Objectives

1. To develop a non-contact method for reconstructing 3-D plantar surface of foot during balanced standing.
2. To develop an optical system for projecting a grating pattern and recording deformed pattern.
3. To develop software for extracting phase modulation and the 3-D foot arch height.

1.3 Scope

In this study, a sinusoidal grating digitally generated by using a LCD projector is projected onto a plantar surface in order to reconstruct the 3-D foot arch height. Its deformed grating is captured by a CCD camera connected to a computer system. Desired phase modulation is extracted from the deformed grating by using Fourier transform method. After unwrapping the phase, the height distribution is reconstructed. The determination of the phase modulation and the 3-D reconstruction is done by using Matlab 6.0. Calibration of the system will be done by utilizing a 3-D triangular prism with known dimension.

1.4 Expected Benefit

The method proposed in this project can be developed into non-contact and non-invasive instruments which have high accuracy in measurement of the foot arch height and in reconstruction of 3-D plantar surface of foot. It is useful for the fields of biomechanics, orthopedics, and sports medicine and sports science. For examples, the proposed method can be applied to monitoring and assessment of foot abnormalities in athletes, ballerinas and dancers. By having better method for monitoring foot abnormalities, quality of human life can be improved. Participation of graduate students as research assistant provides an opportunity for developing manpower with capability to conduct research in the area of science, medicine and engineering.

Chapter 2

3D Reconstruction Using Grating Illumination

Figure 1 shows a schematic diagram of an optical setup for implementing the proposed method in which the LCD projector displays the sinusoidal grating pattern with the carrier spatial-frequency f_0 onto the plantar surface. The deformed grating pattern captured by the CCD camera can be mathematically expressed as [24]

$$g_1(x,y) = a(x,y) + b(x,y)\cos[2\pi f_0 x + \phi(x,y)]$$

$$= a(x,y) + c_1(x,y)\exp(j2\pi f_0 x) + +c_1^*(x,y)\exp(-j2\pi f_0 x)\,, \qquad (2.1)$$

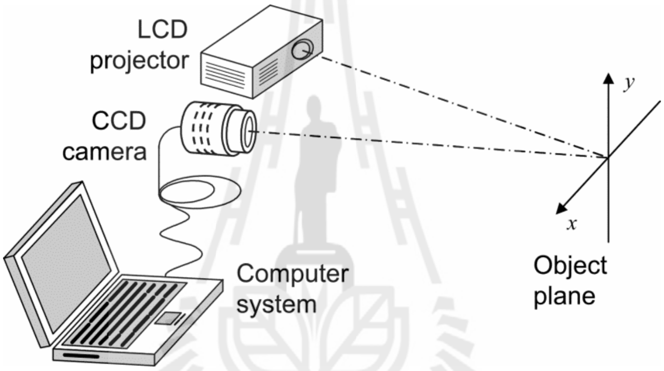

Figure 2.1 A schematic diagram of an optical setup for implementing the proposed 3-D plantar surface reconstruction.

where $a(x,y)$ and $b(x,y)$ correspond to the irradiance caused by non-uniform light reflection of the plantar surface and the grating contrast function, respectively. $c_1(x,y)$ is mathematically equivalent to $0.5b(x,y)\exp[j\phi(x,y)]$ and the phase $\phi(x,y)$ corresponds to the phase distribution of the arch height. To retrieve the phase $\phi(x,y)$ from the captured grating, a 1-D Fourier transform of $g_1(x,y)$ is computed with respect to the x direction

$$G_1(f_x, y) = A(f_x, y) + C(f_x - f_0, y) + C^*(f_x + f_0, y)\,, \qquad (2.2)$$

where $A(f_x,y)$ is the 0th order spectrum, while $C_1(f_x,y)$ and $C_1^*(f_x,y)$ represent the +1st and the -1st order spectra which encode the desired phase information. Note that the width of these spectra is determined by the object profile such that the more abrupt the change of the object height, the broader the spectral width. After selecting the +1st order spectra and taking its Fourier transformation, a complex signal

$$c_1'(x,y) = 0.5b(x,y)\exp\{j[2\pi f_0 x + \phi(x,y)]\} \tag{2.3}$$

is obtained.

In order to remove aberration effects of the optical systems, the same grating pattern is projected onto a flat and uniform reference plane. The second grating image captured by the camera is mathematically given by

$$\begin{aligned} g_2(x,y) &= d(x,y) + e(x,y)\cos[2\pi f_0 x + \phi_0(x,y)] \\ &= d(x,y) + c_2(x,y)\exp(j2\pi f_0 x) + +c_2^*(x,y)\exp(-j2\pi f_0 x) \end{aligned} \tag{2.4}$$

with $c_2(x,y) = 0.5e(x,y)\exp[j\phi_0(x,y)]$ and $\phi_0(x,y)$ is the phase distribution corresponding to the zero height. By performing the same filtering operation, a second complex signal

$$c_2'(x,y) = 0.5e(x,y)\exp\{j[2\pi f_0 x + \phi_0(x,y)]\} \tag{2.5}$$

is generated. By taking a complex logarithm of the product of Eq. (2.3) and the complex conjugate of Eq. (2.5)

$$\log[c_1'(x,y)c_2'^*(x,y)] = \log[0.25b(x,y)e(x,y)] + j[\phi(x,y) - \phi_0(x,y)], \tag{2.6}$$

the phase modulation, $\phi(x,y) - \phi_0(x,y)$, due to the arch height relative to the zero reference is retrieved. The arch height can then be reconstructed by computing [25]

$$h(x,y) = \frac{l_0[\phi(x,y) - \phi_0(x,y)]}{[\phi(x,y) - \phi_0(x,y)] - 2\pi f_0 d}, \tag{2.7}$$

where l_0 and d are the distances between the projector and the object plane and the projector and the camera, respectively.

Chapter 3

Materials and Methods

In this study, the LCD projector (Toshiba TLP-X2000) was used to project the sinusoidal grating pattern with the carrier frequency f_0 = 3 lp/cm onto the object specimen. The CCD camera (Hamamatsu C5948) with resolution 640 × 480 pixels in 8.3 mm × 6.3 mm sensor area was used to capture the deformed grating. The captured images were saved into tiff format. The separation distances l_0 and d were 100 cm and 17.6 cm, respectively. The 3-D shape reconstructions were numerically done by using Matlab 6.0. A triangular prism and a plantar phantom shown in Figs. 3.1(a) and (b) were used as the test objects to verify validity of the proposed method. The prism dimension was 8 cm × 5 cm × 8 cm. The feet phantom had a length of 23.5 cm, while its width was 10.5 cm.

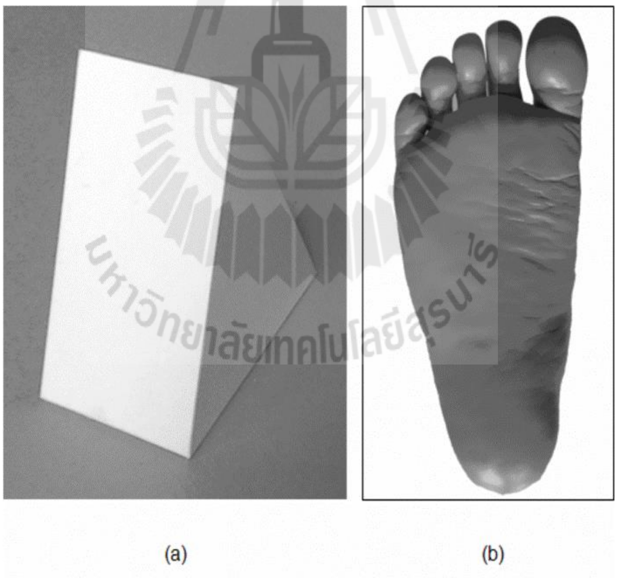

Figure 3.1 (a) The triangular prism and (b) the plantar phantom employed as test objects.

Chapter 4
Results and Discussions

4.1 Reconstruction of the Triangular Prism

Figure 4.1(a) shows the resultant grating image deformed by the triangular prism. It is clear that the triangle profile modulates the projected grating pattern such that its spacing becomes higher or lower than that of the grating pattern appeared outside the object. By applying the Fourier transform method described above, the phase distribution calculated from the imaginary term of Eq. (2.6) was unwrapped in order to get the desired phase $\Delta\phi(x,y)$ shown in Fig. 4.1(b). It is clear that the unwrapped phase distribution has the 3-D profile of the triangle prism. This phase distribution was then used to reconstruct the height distribution according to Eq. (2.7).

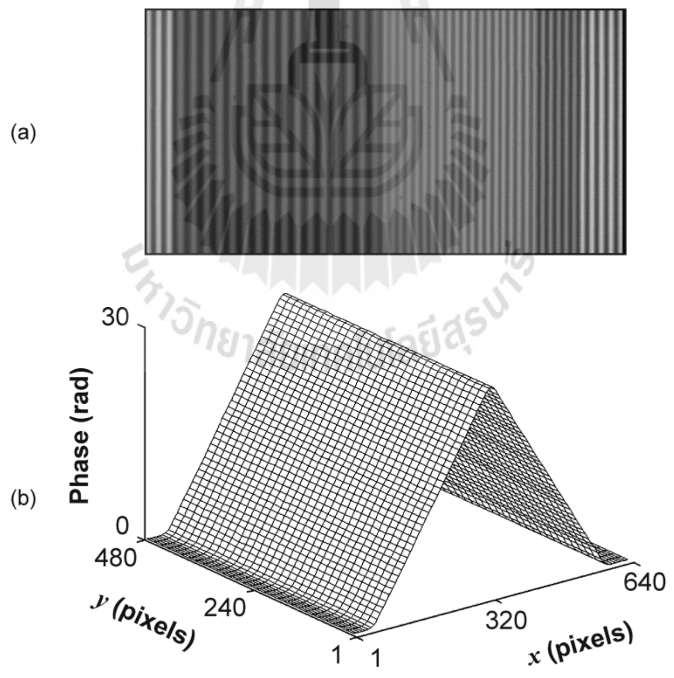

Figure 4.1 (a) The grating pattern deformed by the triangular prism and (b) its unwrapped phase.

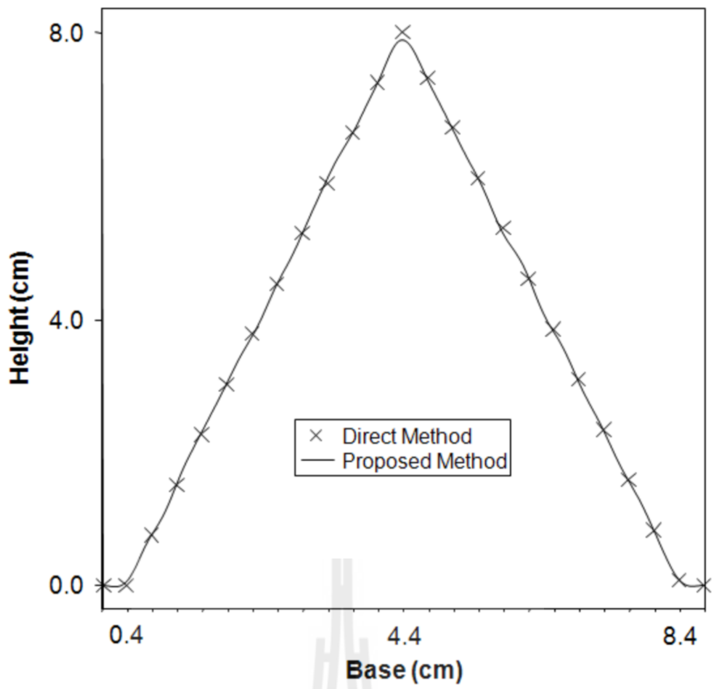

Figure 4.2 1-D height profiles of the triangular prism measured by using the proposed and the direct contact methods.

Figure 4.2 shows 1-D height profiles of the object along the *x* direction measured by using the proposed and the direct contact methods. The solid line corresponds to the reconstruction by using the proposed method, while the cross signs are the data measured by using a digital height gauge (Moore and Wright MW190-30DBL) with resolution of 0.01 mm. It is obvious that the heights along the two sides of the prism obtained by using the proposed measurement match the results of the direct method. However, the results around the three vertices obtained by the proposed method are different than those by the direct method. This is because the grating light illumination is inherently limited by the fact that the zero-order spectrum has a broad width which smears easily the desired first-order spectra. As high spectral components corresponding to the three vertices in the first-order spectra are corrupted, the reconstructed heights deviate from those of the contact method. Note that several methods for solving this problem by using π-phase shift [26,27], orthogonal gratings [28], and windowed Fourier transform [29] have been reported.

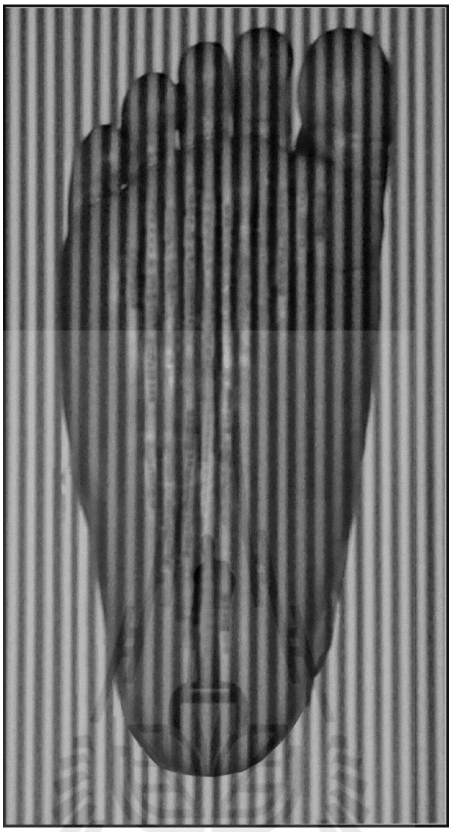

Figure 4.3 The grating pattern deformed by the plantar phantom.

4.2 Reconstruction of the Plantar Phantom

The grating image deformed by the plantar phantom is shown in Fig. 4.3. Since the surface of the plantar phantom has more details than that of the triangle object, the irradiance of the light reflected by the plantar surface is not uniform. However, this does not affect the reconstruction ability of the proposed method. The reconstructed plantar surface shown in Figure 4.4 has similar 3-D profile as the plantar phantom has. Elevations and depression of its toes, arches and heel can be clearly identified from this figure. However, it is hard to observe creases which appear on an anterior sole at the ball of the feet and the inner MLA. This is because their profiles are finer than the grating pitch. In summary, this result verifies the feasibility of the proposed method to reconstruct 3-D plantar surface.

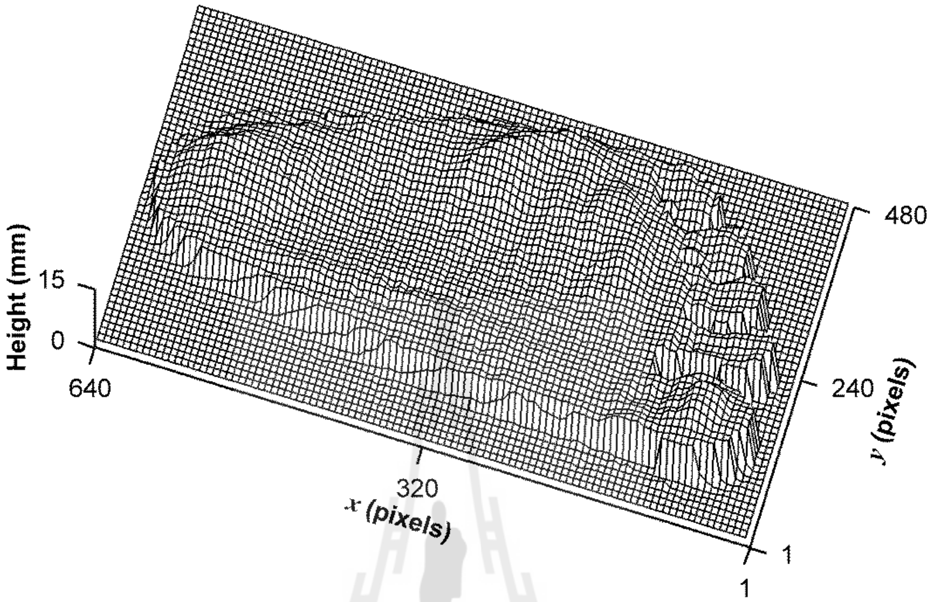

Figure 4.4 The 3-D plantar phantom reconstructed by using the proposed method.

Chapter 5
Conclusions

We have proposed and verified experimentally the 3-D plantar surface reconstruction by using grating illumination. The advantage of the proposed method over the laser-based system is that it is free from image distortions caused by the interference patterns. The triangular measurement by using the proposed method is in agreement with that by using the direct contact method, except its three vertices. The preliminary experimental results show that the elevations and depression of toes, arches and heel can be easily reconstructed from the plantar phantom. Therefore, the proposed method can be used for assessing the MLA and facilitating the fabrication of foot orthotics.

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