รหัสโครงการ SUT1-107-56-12-38

รายงานการวิจัย

การวิเคราะห์รูปทรงสามมิติแบบดิจิตอลฟูริเยร์ทรานฟอร์ม โดยการลบสัญญาณตรง

(Efficiency enhancement of digital Fourier transform profilometry using DC subtraction)

ได้รับทุนอุดหนุนการวิจัยจาก
มหาวิทยาลัยเทคโนโลยีสุรนารี

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(Efficiency enhancement of digital Fourier transform profilometry using DC subtraction)

คณะผู้วิจัย

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บทคัดย่อภาษาไทย

ฟูเรียร์ทรานสฟอร์มโปรฟิโลเมตทรี (Fourier transform profilometry) หรือ เอฟทีพี (FTP) เป็นเทคนิคหนึ่งของการวัดรูปทรงในสามมิติโดยไม่มีการสัมผัส เทคนิคเอฟทีพีจะฉายภาพเกรตติ้งลงไปบนวัตถุ จากนั้นบันทึกภาพของเกรตติ้ง แล้วนำมาวิเคราะห์เฟสที่เปลี่ยนไปของสัญญาณภาพที่วัดได้ โดยใช้เทคนิคการแปลงฟูเรียร์ ซึ่งจะทำให้ได้ข้อมูลความสูงของวัตถุที่ต้องการทดสอบ อย่างไรก็ตาม ความแม่นยำของความสูงที่ได้จะขึ้นอยู่กับความถูกต้องของเฟสที่วัดได้ ซึ่งมักจะถูกรบกวนโดยสัญญาณพื้นหลังของภาพที่บันทึกโดยระบบ

ในโครงการนี้ ทีมวิจัยได้พัฒนาเทคนิคใหม่ของการกำจัดสัญญาณพื้นหลังของภาพเกรตติ้งโดยลบสัญญาณตรง ซึ่งจะใช้การถ่ายภาพเพียงแค่ครั้งเดียว ระบบการทดลองในระดับห้องปฏิบัติการได้ถูกสร้างขึ้นเพื่อทดสอบประสิทธิภาพและความถูกต้องของเทคนิคที่พัฒนาขึ้น ทั้งนี้ เทคนิคที่นำเสนอมีข้อดีกว่าวิธีการเดิม คือ มีต้นทุนการผลิตที่ถูก มีขั้นตอนการวัด และการสอบเทียบที่ไม่ซับซ้อน และมีความเร็วของการวัดที่สูง จึงสามารถลดสัญญาณรบกวนจากการสั่นของระบบได้ดี เพมาะกับการนำไปประยุกต์ใช้ในระดับภาคสนามต่อไป

บทคัดย่อภาษาอังกฤษ

Fourier transform profilometry (FTP) is one of the useful three-dimensional (3-D) shape measurement methods. When a sinusoidal grating is projected onto an object surface being studied, phase of the projected grating pattern is modulated by spatial profile of the object. This phase modulation is encoded into fundamental frequency spectra of the grating pattern. By recording the deformed grating pattern with an image acquisition sensor, this phase information can be retrieved from the fundamental spectrum by using Fourier transformations. The retrieved phase information is then employed for reconstructing 3-D object surface profile. However besides fundamental components, deformed grating images may also contain lower and higher orders of spectra. When the fundamental component has broad bandwidth, it may be corrupted by the other spectra. This is the inherent drawback of the conventional FTP.

In this project, a new white light non-phase-shifting method for eliminating unwanted background in FTP is proposed by using an object image being measured and a single grating image deformed by this object. The background signal of the deformed grating image can be eliminated by using the object image scaled by a contrast ratio of the two images. The proposed method has advantages over the previous works in that firstly, uses of a white light illumination and a monochrome image sensor results in low-cost system. Moreover, the calibration process of the mean and the contrast values is simpler and independent upon characteristics of the image sensors. In addition, the use of a single grating pattern minimizes simultaneously projection and image acquisition times and phase error caused by abrupt change in amplitude or timing of light projector's synchronization signals known as jitters.

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Chapter 1
Introduction

1.1 Background and Significance

Optical methods for three-dimension (3D) shape measurement and imaging have found growing interest in many industrial applications such as object modeling, medical diagnostics, computer-aided design and computer-aided manufacturing. Non contact and non invasive abilities to make such measurements are the reason for this growing interest. Among those methods, Fourier transform profilometry (FTP) has been widely studied [1-6]. The FTP has found various applications in diverse fields such as biomedical applications [7-11], quality control of printed circuit board manufacturing [12-16], kinematic study of a moving creature [17-19], cultural heritage and preservation [20,21], global measurement of free surface deformations [22,23], and biometric identification [24] etc.

In the FTP, a Ronchi grating or a sinusoidal grating pattern is projected onto the specimen to be profiled. To a CCD sensor camera viewing the specimen, height variations of the surface are encoded as phase modulations of the observed fringe pattern, with a sensitivity that depends on the angle between the illumination and observation directions. Accurate and reliable extraction of the phase information is therefore the key to this shape measurement technique. In order to extract the phase variation, a FFT algorithm is used to digitally compute the 1D signal of the deformed grating captured by the CCD. After selecting only the fundamental spatial-frequency spectrum component and taking its inverse Fourier transform, the height information can be decoded from the extracted phase [1,2].

The FTP has a drawback in that deep phase modulation will cause overlapping between the desired fundamental spatial-frequency spectrum and the zero-order spectrum. As a result, the measurable height is limited by the phase modulation. Several methods for solving this drawback by using π-phase shift [25,26] and orthogonal gratings [27] have been reported. However it is a fact that jitter on a LCD projector may cause phase deviation of the projected grating pattern. This jitter is abrupt variations in amplitude or timing of synchronization signals that cause instability of video or image reproduction [28-31]. It may arise from electromagnetic interference, cross talk with carriers of other signals, intrinsic circuit problems, and cable and/or connection issues. Therefore, the jitter-induced phase error can be obviated by minimizing the number of the projected gratings patterns. Second, time delay for projecting many grating patterns is reduced.

In this project, a new method for eliminating the zero-order spectrum of the FTP by using simple dc or background subtraction is studied. Instead of using the π-phase shifted grating patterns, the proposed method employs images of the object and the reference plane generated by using uniform light to remove the unwanted background. The reasons for this interest are that first, phase deviation from periodicity of the grating pattern caused by jitter may be obviated. Second, time delay for projecting the π-phase shifted grating pattern is solved. However, due to unbalanced illumination caused by the grating pattern and the uniform light, a dc component of each recorded image will be different. Therefore in order to remove effectively the background, the dc bias of each captured image must also be eliminated.

1.2 Objectives

1. To verify feasibility of 3-D height reconstruction by using the dc subtraction method
2. To develop software for extracting phase modulation and reconstructing 3-D height
3. To compare the proposed method and the π–phase shifting technique

1.3 Scope

In this study, a sinusoidal grating digitally generated by using a LCD projector is projected onto a 3-D test object. Firstly, grating patterns deformed by the object and the reference plane are captured by a CCD camera connected to a computer system. Secondly, the images of the object and the reference plane are recorded. After calculating contrast and filtering out first-order spectrum of each image, the background signal is subtracted from the deformed grating. Desired phase modulation is then extracted from the background-eliminated deformed grating. 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

1.4.1 The result of this research project is useful for electronic manufacturers, automation industries, health care and medical diagnostics, cultural heritage and preservation, security etc.

1.4.2 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 Height Reconstruction Using DC Subtraction

Figure 1 shows a schematic diagram of crossed-optical-axes setup for implementing the proposed method. Under uniform light illumination generated from a LCD projector, the images of the object and the reference plane recorded by a CCD camera can be mathematically expressed as $g_1(x,y) = o(x,y)$ and $g_2(x,y) = r(x,y)$, respectively. Here, $o(x,y)$ and $r(x,y)$ correspond to the irradiances caused by non-uniform light reflection of the object and reference plane. In the case of the illumination by using the sinusoidal grating pattern, the grating images deformed by the object and the reference plane are given by

$$g_3(x,y) = o(x,y) + bo(x,y)\cos[2\pi f_0 x + \phi(x,y)] \tag{1}$$

and

$$g_4(x,y) = r(x,y) + br(x,y)\cos[2\pi f_0 x + \phi_0(x,y)], \tag{2}$$

respectively. In the above equations, f_0 stands for the carrier frequency of the observed grating image, while b is the modulation factor. $\phi(x,y)$ and $\phi_0(x,y)$ are the phase modulations arising from the height profile of the object and the reference plane, respectively. Note that the higher the profile, the broader the phase modulation.

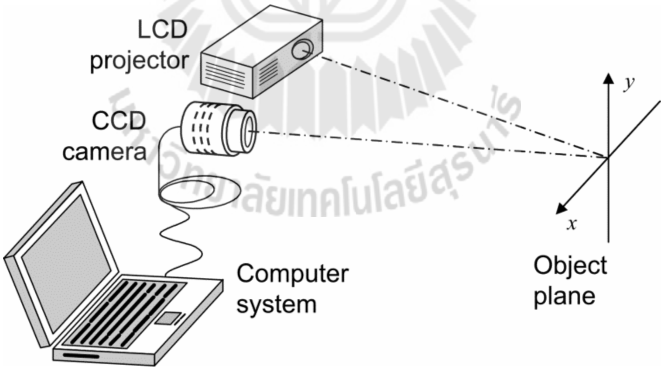


Figure 2.1 A schematic diagram of an optical setup for implementing the proposed FTP by using the dc background subtraction method.

To remove the dc bias from each digital image, its value is determined by

$$g_{dc}(x,y) = \frac{1}{N \times M} \sum_{k=1}^{M} \sum_{l=1}^{N} g(k\Delta x, l\Delta y) \tag{3}$$

with N and M are the number of pixels, while Δx and Δy are their corresponding pixel sizes in the horizontal and the vertical directions, respectively. The unwanted backgrounds are then eliminated by the following subtractions

$$\begin{aligned} g'(x,y) &= g_3(x,y) - g_{3dc}(x,y) - \left[g_1(x,y) - g_{1dc}(x,y)\right]/c_r' \\ &= bo(x,y)\cos[2\pi f_0 x + \phi(x,y)]/c_r' \end{aligned} \tag{4}$$

and

$$\begin{aligned} g''(x,y) &= g_4(x,y) - g_{4dc}(x,y) - \left[g_2(x,y) - g_{2dc}(x,y)\right]/c_r'' \\ &= br(x,y)\cos[2\pi f_0 x + \phi_0(x,y)]/c_r'', \end{aligned} \tag{5}$$

where c_r is the contrast ratio of images obtained with the grating and the uniform light illuminations. The contrast of each image is calculated by using [7]

$$c = \int \left|G(f_x)\right| df_x \Big/ \left|G(0)\right|, \tag{6}$$

where $G(f_x,f_y)$ and $G(0,0)$ correspond to the amplitude spectrum of any image $g(x,y)$ and its zero frequency component. The division of the second terms in Eqs. (4) and (5) by c_r are used to equalize the ac component of the images generated by the grating and the uniform illuminations. This ensures that the unwanted backgrounds are completely eliminated and the desired phase information encoded into the fundamental spectra can be extracted by using the Fourier transformation. By filtering only a single fundamental spectrum and taking its inverse Fourier transform, Eqs. (4) and (5) reduce to

$$g'(x,y) = 0.5bo(x,y)\exp[i\phi(x,y)]/c_r' \tag{7}$$

and

$$g''(x,y) = 0.5br(x,y)\exp[i\phi_0(x,y)]/c_r'', \tag{8}$$

respectively. The phase can be extracted from by taking a complex logarithm of the product of Eq. (7) and the conjugate of Eq. (8)

$$\begin{aligned} \log\left\{g'(x,y)g''^{*}(x,y)\right\} &= \log\left[0.25b^2 o(x,y) r(x,y)/c_r' c_r''\right] \\ &\quad + i[\phi(x,y) - \phi_0(x,y)]. \end{aligned} \tag{9}$$

Finally, the height distribution is calculated according to

$$h(x,y) = \frac{l_0[\phi(x,y) - \phi_0(x,y)]}{[\phi(x,y) - \phi_0(x,y)] - 2\pi f_0 d}, \tag{10}$$

where l_0 and d are the separation distances between the CCD camera and the reference plane and between the camera and the projector.

Chapter 3
Materials and Methods

In order to verify feasibility of our proposed method, an isosceles prism shown in Fig. 3.1 with dimension of 133.12 mm ×70.1 mm × 81.24 mm was employed as the test object. The uniform light and the sinusoidal grating pattern were projected from a LCD projector (Toshiba TLP-X2000) with resolution 1024 × 768 pixels. The four images were recorded by using the CCD camera (Hamamatsu C5948) with resolution 640 × 480 pixels in 8.3 mm × 6.3 mm sensor area and saved into tiff format. The distances l_0 and d were 100 cm and 53 cm, respectively. The grating pitch at the reference plane was 5.35 mm. All computations were done by using Matlab.

Figure 3.1 Isosceles prism object.

Chapter 4

Results and Discussions

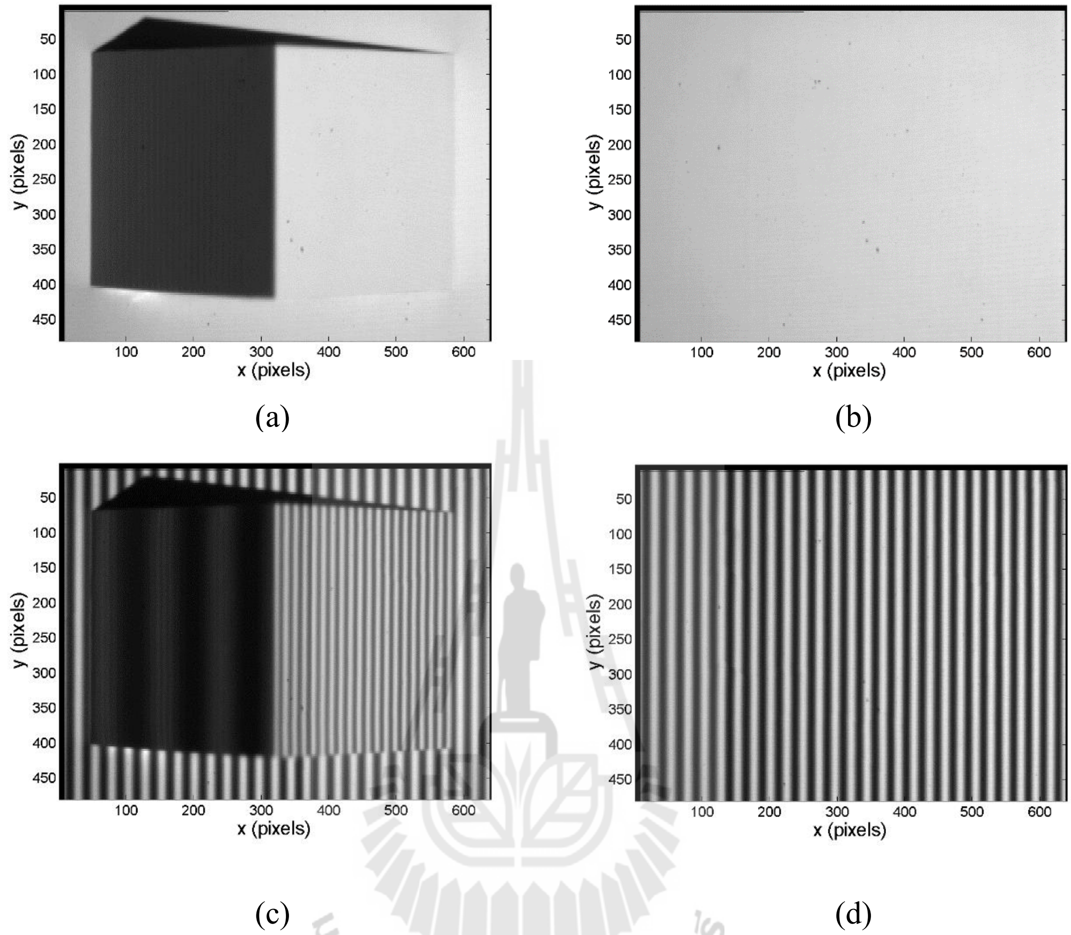


Fig. 4.1 Images of (a) the prism object and (b) the reference plane generated by using uniform light. Grating patterns deformed by (a) the object and (b) the reference plane.

Figures 4.1 (a) and (b) show the images of the object and the reference plane, respectively; their corresponding deformed grating images are shown in Figs. 4.1 (c) and (d). Figures 4.2 (a) and (b) show the image intensities scanned at the row 100^{th} of the grating image deformed by the object and the reference plane, respectively. It is clear that both amplitude and phase of the grating patterns are modulated by the profiles of the object and the reference plane. Due to different reflectivity and height, the two images have different dc bias levels. The resultant background elimination obtained by computing Eqs. (4) and (5) are shown in Figs. 4.2 (c) and (d). They have zero dc biases.

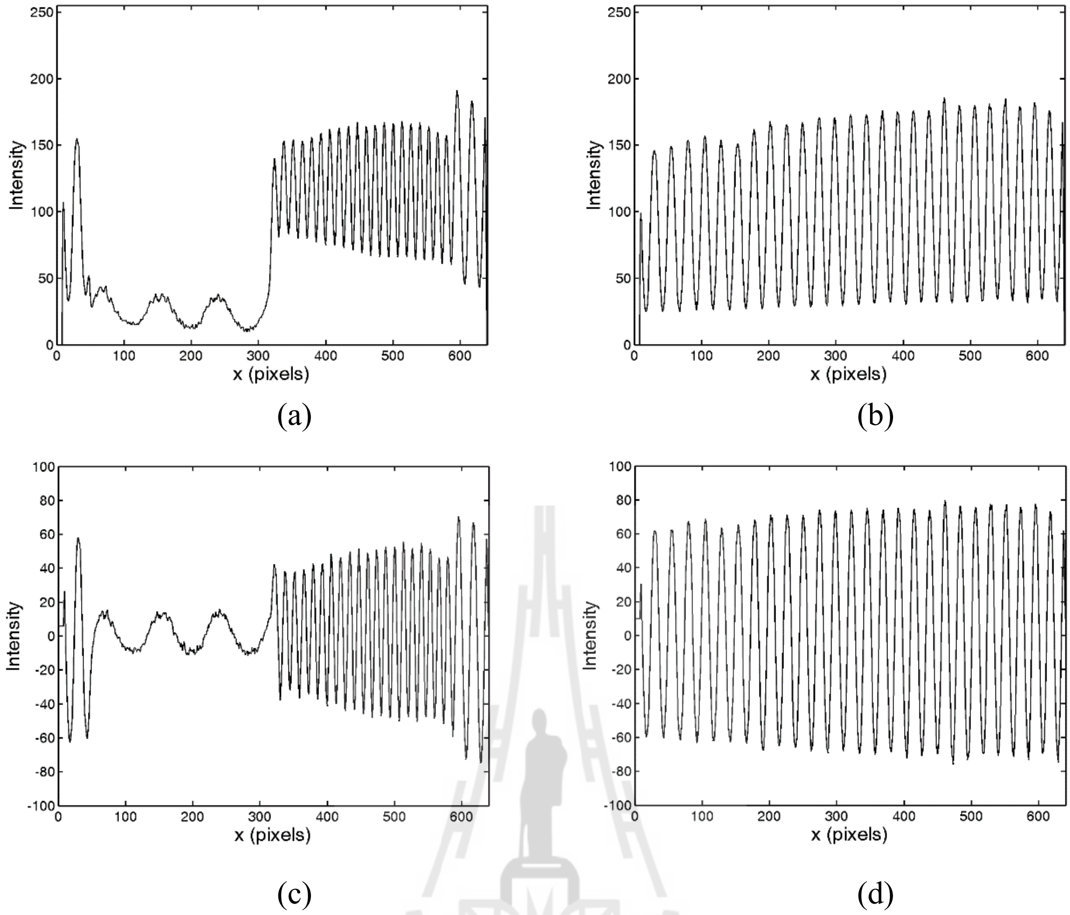
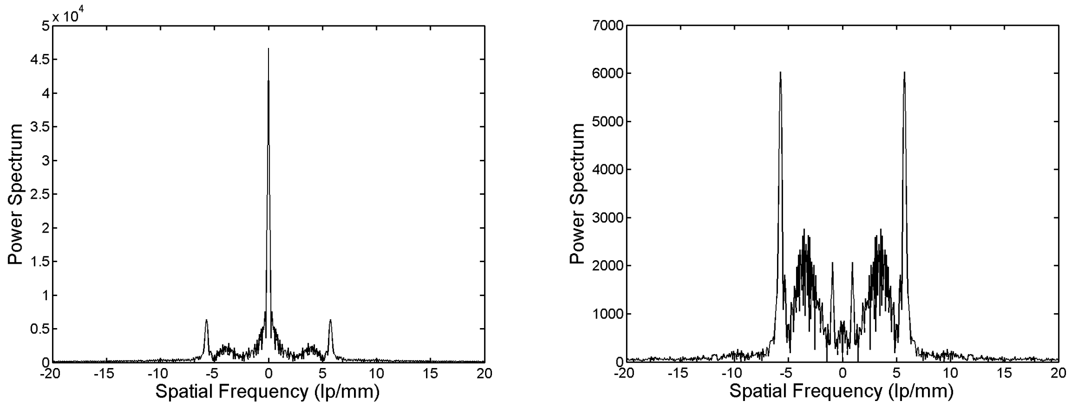


Fig. 4.2 Intensities scanned at the row 100th of the grating images deformed by (a) the object and (b) the reference plane. The resultant signals obtained by eliminating the background from (c) Fig. 4.2 (a) and (d) Fig. 4.2 (b).

Figures 4.3 (a) and (b) correspond to the power spectra of the two signals shown in Figs. 4.2 (a) and (c), respectively. In the conventional FTP, besides its high amplitude and broad spectral width, the presence of the zeroth-order spectrum causes problem in localizing the fundamental spectra. The Frequency spectrum of the same grating image obtained by the proposed background elimination is shown in Fig. 4.3 (b). It is obvious from this figure that the fundamental spectra with broad spectral width can be clearly identified.

Figure 4.4 shows the reconstructed height distribution obtained by using the conventional FTP and the proposed method. The band-pass filter used to select the fundamental spectrum had cutoff frequencies of 0.6016 and 8.1211 lp/mm. It is clear that the conventional FTP fails to reconstruct the surface, because the low cutoff frequency of the filter which is closed to zero overlaps with the zero-order spectrum. In contrast, the proposed method does not have difficulty in selecting the fundamental frequency. 8 cm height of the object and the reference plane which has zero height can be correctly reconstructed.



(a) (b)

Fig. 4.3 Power spectra of the grating pattern deformed by the object obtained by using (a) the conventional FTP and (b) the proposed method.

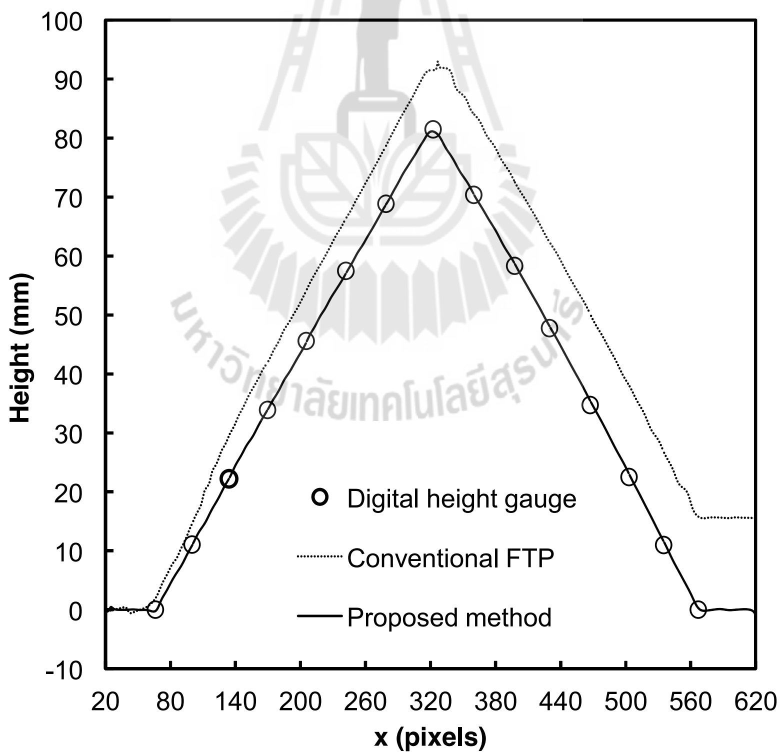


Fig. 4.4 Comparison between the height profiles reconstructed by using the conventional FTP, the direct contact and the proposed method.

Chapter 5
Conclusions

We have proposed and verified experimentally a new method for the 3D height profile reconstruction by using the FTP with the dc background subtraction method. In order to remove the space-varying dc signal, the proposed method employed images of the object and the reference plane. The experimental verifications show that the proposed method can reconstruct the 3-D object height although the original fundamental spectra are corrupted by the zeroth-order spectrum. The proposed method also has an advantage over the π-phase shifting technique in that less projected grating is used.

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Biography

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