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A unified-calibration method in FTP-based 3D data acquisition for reverse engineering

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Abstract

Reverse engineering plays an important role in product design and manufacturing due to the need for the improvement of existing products. Acquisition of 3D data of existing products is one of the most fundamental processes in reverse engineering. This paper proposes a unified-calibration method for Fourier Transform Profilometry (FTP)-based 3D data acquisition. In current FTP methods, the system parameters, such as positions and orientations of the camera and projector and the reference plane location, are needed to convert the phase map into 3D coordinates of the object. Generally, it is difficult to measure these parameters directly. Therefore, a calibration procedure is required in current FTP methods. In this research, a novel method is proposed for the calibration. Only one image is used to calculate all system parameters in the proposed method. The experiments show the method is simple and feasible for FTP-based 3D data acquisition.

Keywords: Reverse engineering; 3D modeling; Image processing; Fourier transform profilometry

1. Introduction

Product development includes the improvement of existing products. Some existing parts of the product may not have digital models to identify their design parameters in the modification and remanufacturing. Reverse engineering provides a useful tool for the need of the design modification of existing products.

The acquisition of 3D data of existing products is a key element for reverse engineering. One of the 3D data acquisition methods is the use of tracking systems. The tracking systems can acquire 3D data by positioning a probe on the object and triggering the computer to record 3D coordinate positions of the probe. Coordinate measuring machines (CMMs) are robust 3D mechanical trackers. Electromagnetic and ultrasonic trackers are also used in some tracking systems. These tracking systems are limited by mechanical or electromagnetic problems in the object size, measurement volume and materials used [1]. Industrial X-ray computed tomography (CT) is also an approach to capture 3D data [2]. It scans an object using X-ray and gets a series of slices of the object. The slices can then be used to acquire 3D data of the object. But the system is generally expensive and needs a big space for installation. The laser has been used as an accurate tool for acquiring 3D data of existing objects. There are four methods that use laser to acquire 3D coordinates [3]. They are time/light in flight, point laser triangulation [4], laser speckle pattern sectioning and the laser tracking system. The processing is slow using a laser beam to capture 3D data because the surface has to be scanned line-by-line. The system is expensive. The high-energy laser beam needs to be treated with care [1].

Comparing with the tracking systems, industrial CT or laser scanners, the image-based 3D data acquisition methods provide effective and low-cost tools to acquire 3D data of objects. Shape-from-shading (SFS) is a method that can reconstruct the 3D shape of an object by the mapping between the shading and surface shape in terms of

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the reflectance function [5]. In SFS method, the reflection model of an object's surface has to be assumed. Real images of the object's surface do not always follow the assumed model. Therefore SFS method is somewhat inaccurate and is sensitive to noise. Moiré method needs two gratings, one is a master grating and the other is a reference grating, from which contour fringes can be generated and resolved by a charged couple device (CCD) camera. Using the contour fringes the 3D shape of an object can be obtained [3]. Moiré methods have phase discrimination problems when the surface is not smooth. This problem makes that Moiré methods cannot avoid errors when the slope of the surface is greater than a certain value. The system structure and algorithm of Moiré methods is complex. Photogrammetry method uses two or more images acquired by either several cameras at the same time or by one camera at different times to calculate 3D coordinates of the objects [6,7]. The key to the method is the correspondence problem that is to determine the point in one image that corresponds to a given point in another image. Generally, it is hard to solve the correspondence problem on a smooth surface. In phase-measuring profilometry (PMP) method, a fringe pattern is projected onto the object by varying the phase of the pattern [8,9]. Three or more deformed fringe pattern images are captured by a camera and the phase distribution of the object can be calculated by these images. The 3D data of the object can be recovered by mapping the phase distribution to the height. In the fourier transform profilometry (FTP) [10] method, a Ronchi grating or a sinusoidal grating is projected onto the object surface (Fig. 1). The deformed grating image is captured by a camera. The 3D shape of the object can be obtained by calculating Fourier transform of the image, filtering in spatial frequency domain and calculating inverse Fourier transform.

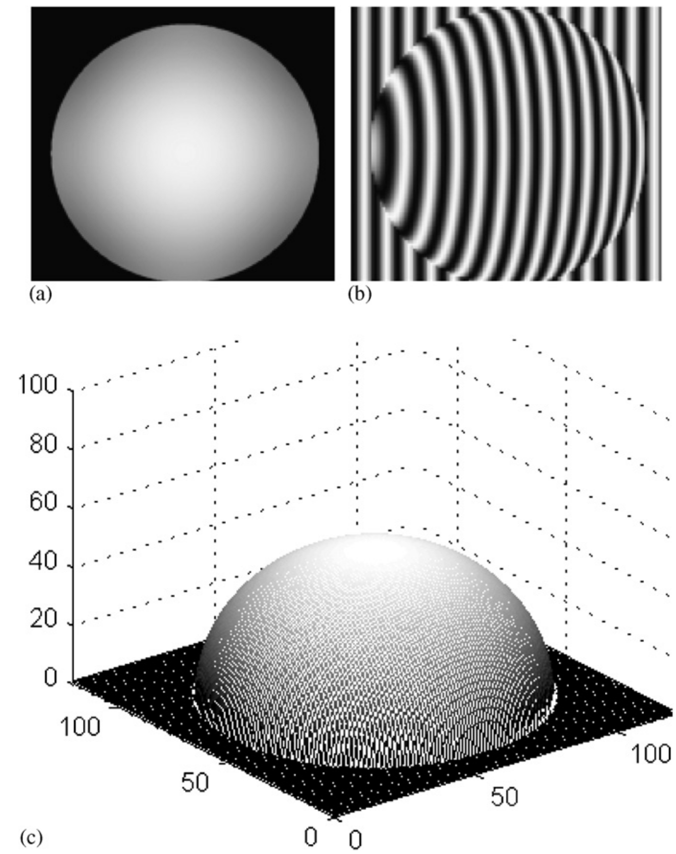

Fig. 1. (a) An image without grating; (b) An image with deformed grating; (c) 3D plot of the reconstructed object.

These image-based methods vary in their accuracy and calculation speed, each being suitable for certain types of applications. This research searches for a novel solution for the 3D data acquisition for reverse engineering. The simple, fast and cost-effective technique is the objective of the research. The FTP method has the advantages of requiring only one (or two) image(s) to do full field analysis, and effective removal of noise and background power fluctuations by a band-limited filter in the frequency plane. Therefore the FTP method is selected in this research for 3D data acquisition.

The use of FTP method results in a phase map that is not scaled to provide 3D data of the objects. Therefore, it is necessary to convert the phase map into 3D coordinates of the object surface. The conversion is dependent on the system parameters including positions and orientations of the camera and projector, and the reference plane location. In most cases, these parameters are difficult to measure directly. Therefore, a calibration procedure is needed in FTP method to determine the parameters [11–14]. The calibration procedure includes a height calibration (Z-axis) and a plane calibration (X-axis and Y-axis). A series of images are taken in different locations of the calibration pattern. The mass data of the images have to be processed. The calibration procedure is time-consuming. In this paper, a unified calibration method for the FTP-based 3D data acquisition is proposed. There is only one image of a special designed pattern required to calibrate the system. The height calibration and the plane calibration are unified in one step. Experimental results show that this method is a simple and fast way to calibrate the FTP-based 3D data acquisition system.

This paper is organized as follows: Section 2 introduces the FTP method and the system parameters obtained from the calibration using the FTP method. In Section 3, the image-based parameters measurement method is discussed. The principle of the method is described. The hardware of the system is described and the process of the FTP-based 3D data acquisition method is discussed in Section 4. Finally, Section 5 gives the experimental result and discussion of the proposed method.

2. The FTP method and 3D coordinates calculation

2.1. The object's 3D shape and phase

Fig. 2 shows the geometry of the projection and imaging system. Point P and E are the optical centers for projector