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A single scan longitudinal calibration technique for fringe projection profilometry

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ABSTRACT

Fringe projection profilometry is an efficient approach for shape reconstruction. An essential step in fringe projection profilometry is the calibration of both the transverse (axial) and longitudinal (depth) directions. In the present work, a longitudinal calibration method for fringe projection profilometry is proposed. In the proposed approach a stepped board is used to calibrate the measurement system in a single scan. Each step of the board represents a different position and therefore only a single scan is required to calibrate the measurement system. The proposed approach neither requires a translating stage nor taking multiple scans of a reference board at various positions, as in traditional techniques. The proposed approach was validated by reconstructing a real object and evaluating its main dimension. Experimental results show the reliability and effectiveness of the proposed method. Measurement errors evaluated for a system calibrated using the proposed approach are relatively smaller than those obtained using a traditional calibration approach. The proposed approach is considerably faster than traditional calibration methods besides being much simpler to implement for onsite measurements.

1. Introduction

Non-contact three-dimensional scanning techniques based on structured light, such as fringe projection profilometry, have the advantage of being faster and more accurate. A well-known method of fringe projection profilometry is phase shifting profilometry. Phase shifting profilometry is an effective reconstruction technique because of its robustness and wide range of applications compared to other reconstruction techniques [1]. Jeught and Dirckx [2] presented a chronological overview of optical profilometry systems. Their operating principles, strengths and weaknesses have been discussed. Zhong et al. [3] discussed the advantages of phase shifting profilometry over laser scanning systems. They emphasized its high spatial resolution, measurement capability, popularity in geometric dimension evaluation and reduced number of required images.

A typical fringe projection system consists of a projector and a CCD camera connected to a computer. The projector illuminates the test object surface with a sinusoidal fringe pattern while the camera captures images of the object with the projected pattern. Variations in the test object height modulate the projected fringe pattern. Images of the modulated fringe patterns are processed to extract the phase difference between the reference wavefront and the object wavefront. The phase difference is directly related to the object surface height variations [4].

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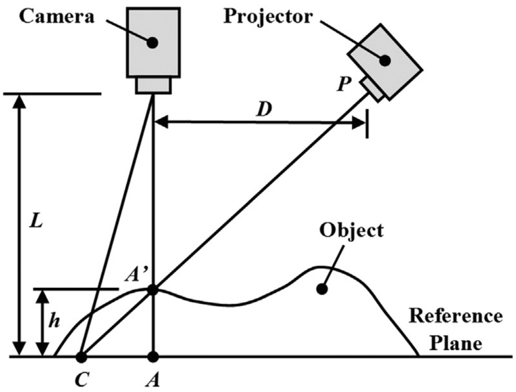

Fig. 1. Structured light shape reconstruction system.

A wide range of techniques are used to evaluate phase shift [5], these techniques may be categorized into spatial and temporal techniques. Zuo et al. [6] compared various temporal techniques by analytical, numerical and experimental methods. The evaluated phase is usually wrapped between $+\pi$ and $-\pi$, due to the use of the arctan function. Thus, the extracted phase shift requires unwrapping [7], which can be done using path dependent or path independent algorithms. The unwrapped phase is proportional to object height, thus three-dimensional profile of test object surface can be recovered by accurately calibrating the measurement system. Gorthi et al. [8] give an extensive review of fringe projection techniques and applications.

A crucial step in shape reconstruction is efficient calibration, not only phase to depth calibration but also transverse calibration. Calibration techniques are usually divided into analytical and empirical techniques. Analytical calibration techniques, as explained by Chen et al. [9], rely on the numerical evaluation of the intrinsic and extrinsic parameters for both the camera and the projector. The relationship between the reconstructed object coordinates and the real-world coordinates can therefore be evaluated. Using empirical techniques, the same relationship can be evaluated using experimental methods.

Empirical calibration is performed for both transverse and longitudinal axes. Calibration of the longitudinal direction is usually performed by translating a flat calibration board along multiple predefined positions and reconstructing the board at each position. The difference in the unwrapped phase values between each reconstructed position and the initial one can be evaluated and correlated to the real-world distance using an empirical function. The empirical function obtained is then used to relate the extracted unwrapped phase to the test object surface heights. Linear [10], nonlinear [11] and polynomial [12] fitting functions have been proposed to relate the unwrapped phase to the test object surface heights. Accuracy of each of these fitting functions depends on the characteristics of system components and the object to be reconstructed.

One major problem with traditional empirical calibration techniques is that they are time consuming and must be repeated whenever the positions of the camera or the projector change. Furthermore, traditional calibration methods may be not practical, complicated or sometimes not accurate enough due to actual industrial environment [3,13,14]. Ke et al. [15] emphasize the need for new calibration techniques due to the difficulty and prolonged time associated with traditional techniques. Another problem is the impracticality of using a translating stage for onsite measurements. Moreover, the accuracy of such calibration techniques is affected by the accuracy of the translation stage [16]. To overcome the need for a translating stage and shorten the time required for calibration, Anchini et al. [17] proposed a longitudinal calibration technique where the phase maps for only three planes placed within the calibration volume are measured. The phase maps for a number of other virtual planes are then estimated. A similar technique was proposed by Tavares and Vaz [18], where only one reference board in an inclined position is used. Although these procedures are faster than traditional calibration techniques, their accuracy compared to analytical calibration techniques is limited.

This paper presents a relatively easier and faster approach with adequate accuracy to calibrate the system in the longitudinal direction. Instead of translating a calibration board into multiple predefined positions, a single stepped calibration board is used. Each step of the board represents a different position and therefore only a single scan is required to calibrate the measurement system. The calibration volume boundaries are determined by the first and the last step of the calibration board. Linear interpolation is then used to relate the unwrapped phase evaluated from each reconstructed step and the real-world distances as with traditional methods.

2. Theoretical approach

2.1. Triangulation in fringe projection system

Fringe projection profilometry depends on the concept of triangulation. Fig. 1 illustrates the relative position of the camera, projector and object for a typical fringe projection system. The normal distance between the camera and a reference plane is *(L)*, *(h)* is the height of the object at point *(A')*, and *(D)* is the distance between camera and projector.