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Fourier-transform profilometry calibration based on an exhaustive geometric model of the system

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ABSTRACT

In Fourier-transform profilometry (FTP), the height information is extracted from the phase distribution through triangulation; the relationship between the phase and height distribution depends on the system parameters such as the relative position of the projector and the camera, the fringe frequency and the reference plane position. In this paper, we propose a novel calibration approach for FTP that uses calibration planes to calculate the system parameters. The main innovation of this method is the application of an exhaustive geometric model of the FTP that expresses the phase-to-height relationship in the most general way with a camera and a projector not aligned; the aberration due to optics is also considered and compensated for. The obtained calibration data have a precise physic meaning and can be easily compared with the real system. Tests on both simulated and real data showed that the proposed method is robust, even in the case on non-negligible noise level.

1. Introduction

Fringe projection profilometry has been intensively studied in the last few years due to its several applications in many fields such as industrial inspection, computer and robot vision, manufacturing, reverse engineering and medical diagnostics. The advantages of these techniques are the non-contact and full-field measurement, the low cost and the speed in obtaining the three-dimensional (3D) information. The interest in fringe projection technique is increased by the recent improvements in image projection speed and image acquisition technology [1–4]. All the available fringe techniques are based on the same physical principle. A fringe pattern is generally projected onto an object surface and then viewed from another direction by a camera that acquires the image. The object topography deforms the fringe pattern, the corresponding image is acquired on the sensor plane of the camera and then processed to obtain the height information. The height information is usually extracted from the phase distribution of the acquired image and then converted in spatial coordinates by triangulation. The phase distribution is expressed as phase difference between the Fourier transform of a fringe pattern projected onto a reference plane and one (or more) fringe patterns projected onto the object. The procedure used to determinate the phase distribution is the main difference among the several fringe projection methods proposed in literature [5,6]. The two main fringe projection methods are the phase shifting and the Fourier-transform profilometry (FTP). Phase-shifting methods are implemented because of their high resolution of the measurement [7–11], whereas Fourier-transform profilometry is popular because only one deformed fringe pattern image is needed [12–26]. In this work we will focus on the Fourier-transform profilometry. It should be noted that the FTP technique is based on digital images acquisition and process; the information about the 3D shape of the object to be measured is then available in a regularly spaced grid, according to the discretisation due to pixels of the camera. As a consequence of this, the maximum derivative of the object surface and the maximum spatial frequency that can be measured depends on the characteristics of both the projection device (mainly the fringe pattern wavelength) and of the camera (above all the sensor resolution and the lens zoom), as described in detail in [19].

The calibration methods proposed in literature till now can be distinguished in three categories: model-based, polynomial and neural networks [27–38]. As explained before, the height information is extracted from the phase distribution through triangulation. This means that the relationship between the phase and height distribution depends on the system parameters such as the relative position of the projector and the camera, the fringe frequency and the reference plane position. It is possible to define the phase-to-height conversion with the determination of the system parameters, performing a calibration procedure called *model-based*. As a matter of fact, the direct determination of these parameters is difficult to achieve, as well as the geometric conditions under which the phase-to-height relationship is valid, i.e., the perfect alignment between the camera and projector pupils. Moreover, this calibration method needs to calculate the internal parameters of the camera and the projector, to define their models and to elaborate the roto-translation matrix between

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the camera and the projector retinal planes. The main drawbacks of the so called model-based calibration are the assumptions introduced about the camera and the projector model that must be compensated with a nonlinear data fitting [27–31]. A way to avoid all these problematic steps is a *polynomial* method. A target object, usually a plane, is placed at known positions with respect to the camera and measured to get the phase distribution. Then the polynomial coefficients of the function that best fit the phase-height data are determined by least-squares algorithm to produce a calibration map. The main limits of these methods are the restricted measurement volume, the errors introduced by the wrong placement of the planes and the noise that affects the acquired images used in the calibration steps [32–37].

In this paper, we propose a novel calibration approach that uses calibration planes to calculate the system parameters. The main innovation of this method is the application of an exhaustive geometric model of the Fourier-transform profilometry that expresses the phase-to-height relationship in the most general way with a camera and a projector not aligned. The geometric parameters will be estimated with a least-square fitting between the phase-height data using the model equation. The goal reached with this method is a calibration based on a complete geometric measurement model that is not restricted to a limited volume, has a physic meaning easily comparable with the real system setup, and moreover allows for a simpler estimation process compared to a model-based one.

In Section 2, the geometric measurement model will be presented as it was proposed by Mao [39,40]. Section 3 describes the calibration method implemented, which is the innovation presented by this paper. Section 4 shows the results obtained by the method in many simulated conditions, whereas Section 5 reports the experiments results.

2. Improved Fourier-transform profilometry

Mao has recently proposed a new phase mapping formula based on a complete geometric model of the projection profilometer, where the projector and the camera can be set freely as long as the full-field fringe pattern can be obtained [39]. As will be clarified further, the traditional FTP formula, which converts phase-to-height, is just a special case of this general formula and is suitable only when pupils of the camera and the projector are aligned [12]. This is the main difference between our calibration method and the others proposed till now, based on a simplified geometric model.

The widest formulation of the problem concerns a projector and a camera not aligned, as shown in Fig. 1(a). The camera is

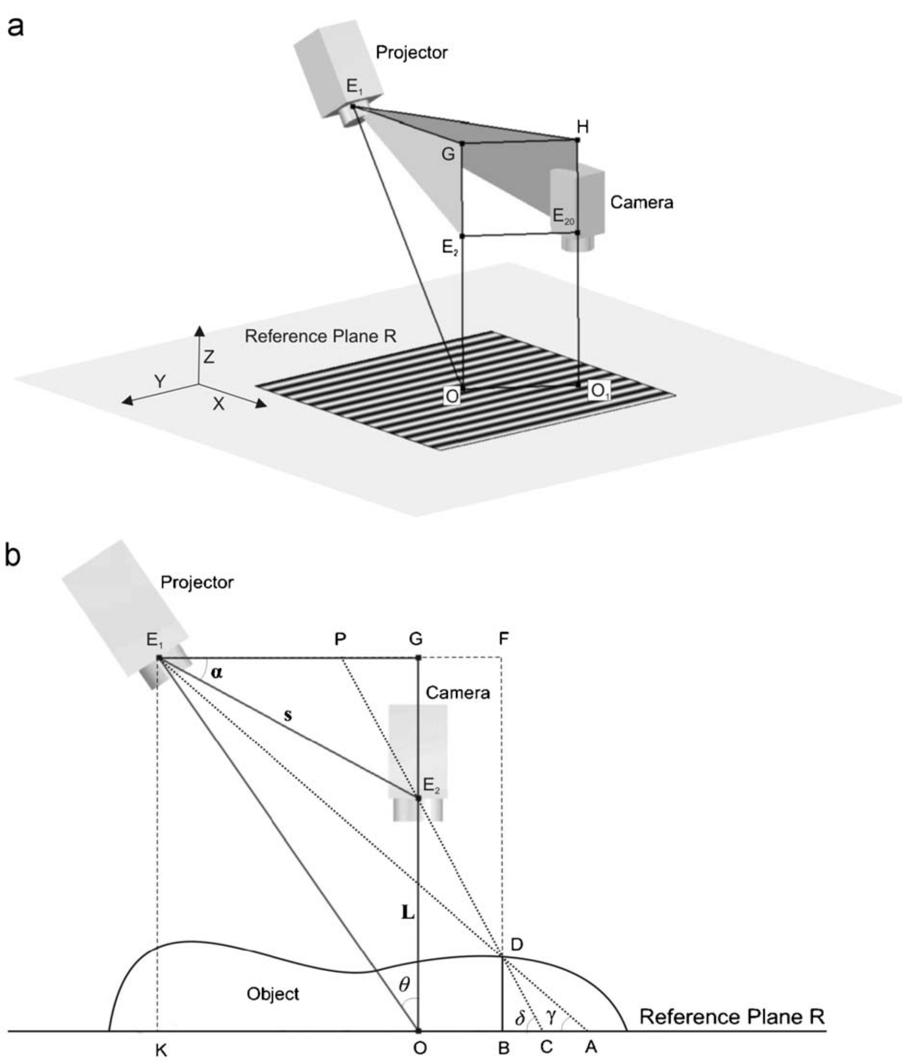

Fig. 1. *Geometry setup*: (a) the camera and the projector are not in the same figure plane; (b) the camera and the projector are both in the figure plane and their optical axis cross the reference plane at the same point.