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3-D shape measurement of rail achieved by a novel phase measurement profilometry based on virtual reference fringe generated by image interpolation

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ABSTRACT

The 3-D measurement of rail shape is important for the safety of railway transportation. Phase Measurement Profilometry (PMP) is chosen to measure rail shape in this paper for its advantages of non-contact, high accuracy and fast speed. In traditional Phase Measurement Profilometry (T-PMP), the setting of the reference plane plate plays an important role, and it is a critical step to capture the reference fringe pattern projected onto the reference plane plate. However, it is sometimes difficult to choose or place the physical reference plane plate in practical applications with complex environments, such as in rail shape measurement. In this paper, a novel PMP based on virtual reference fringe (VRF-PMP) is proposed to deal with the problem. The virtual reference fringe is obtained through extending a partial undeformed fringe pattern intercepted from the whole fringe pattern using image interpolation methods, including Nearest Interpolation, Bilinear Interpolation, Bicubic Interpolation and a proposed One-dimensional New Edge-directed Interpolation (ONEDI). Simulation and experimental results show that VRF-PMP can reconstruct the 3-D shape of rail effectively without a physical reference plane plate. This paper provides a new suggestion for actual detection by PMP.

1. Introduction

Optical three-dimensional (3-D) shape measurement plays an increasingly important role in enormous fields including automated manufacturing, quality control, 3-D sensing, and so on [1–3]. Fringe Projection Profilometry (FPP) has attracted much attention over the past few decades for its low cost, high reliability, high accuracy, and fast speed [4–7]. With FPP, periodic fringe patterns are projected onto the object surface, and the deformed fringe patterns caused by the depth variations of the surface are recorded by cameras. By analyzing the deformed fringe patterns, the depth map of the object could be reconstructed [8]. FPP consists of many techniques, like Fourier Transform Profilometry (FTP) and Phase Measurement Profilometry (PMP), etc. [9–11]. Each of the specific techniques has its unique features and could be well used in certain applications. For example, FTP is suitable for real-time 3-D measurement because only one deformed fringe pattern is required for the algorithm, while PMP is mostly applied to static measurements for its high accuracy and good robustness.

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In PMP, a sequence of fringe patterns with spatially varying intensity profiles and relative phase shifts between them are projected onto the object. PMP is generally well-suited to measure objects with poor overall or local reflective properties. However, many practical problems need to be faced in different applications. The periodic nature of the technique introduces the problem of ambiguous phase extraction and requires additional phase unwrapping calculations to retrieve the continuous phase map, which is deeply studied and well settled with different methods [12]. For dynamic 3-D measurements, different motion artifacts are analyzed and compensated using the statistical nature of the fringes [13]. To tackle the problem of background and shadow in PMP, modulation-level histogram of fringe patterns and a new weighting factor are applied, which lead to a better measurement performance [14]. A pre-coding gamma correction method is proposed to attenuate the gamma distortion effect [15]. To deal with the problem of specular reflection of the measured objects, different methods are proposed and discussed [16,17]. And a homography fringe generation method of fringe projection profilometry technology is proposed to settle the problem of fringe correction [18].

Image interpolation is one of the key techniques in image processing, which can be categorized into non-edge-directed and edge-directed methods in general [19,20]. Non-edge-directed methods, whose main advantage is computational simplicity, include Nearest Interpolation (NI), Bilinear Interpolation (BLI), Bicubic Interpolation (BCI) and so on [21–23]. Characterized by high computational complexity and better performance, edge-directed methods also consist of various algorithms [24–26], with New Edge-Directed Interpolation (NEDI) [27] as representative.

The 3-D shape measurement of rail is important to ensure the safety of railway transportation. With the increase of usage time, rail shape will change constantly because of overload and abrasion, which is dangerous for the moving trains with high speed. The change of rail shape needs to be measured and monitored regularly. The traditional manual measurement method is inaccurate and inefficient for rail shape measurement. And optical 3-D measurement including PMP is a main developing direction for its high accuracy and fast speed in the field of rail shape measurement. It is important to point out that the rail is quite long in reality. The selection and placement of the reference plane plate is much difficult in practical measurement process using PMP.

For traditional PMP (T-PMP), the selection and placement of the reference plane plate is a key step [28,29]. The needed reference fringe pattern originates from the projected periodic fringe pattern on the reference plane. Much work about reference plane for 3D measurement has been done in recent years [30,31]. However, it is difficult to choose or place the reference plane plate in the application of rail shape measurement.

To deal with the problem, a novel Phase Measurement Profilometry based on virtual reference fringe (VRF-PMP) is proposed in this paper. The virtual reference fringe (VRF) is generated based on image interpolation. By intercepting a small undeformed part from the whole deformed fringe pattern and extending it to a large undeformed fringe pattern by interpolation method, the proposed VRF is obtained. Different interpolation methods are used and analyzed in the paper. At the same time, it needs to be emphasized that a One-dimensional New Edge-directed Interpolation (ONEDI) method is novelly proposed to generate VRF pattern in this paper. VRF-PMP is simulated and subsequently used for recovering rail shape by replacing the actual reference fringe pattern with the VRF pattern. Experimental results show that 3D shape reconstruction of rail can be achieved successfully using VRF-PMP.

2. Principle

2.1. Traditional phase measurement profilometry (T-PMP)

The measurement of object shapes by T-PMP involves these steps: (1) projecting sinusoidal fringe patterns onto an physical reference plane plate; (2) recording the undeformed reference fringe patterns; (3) projecting sinusoidal fringe patterns onto the object to be measured, which is placed on the physical reference plane; (4) recording the deformed fringe patterns which is phase modulated by the object height distribution; (5) calculating the phase modulation by analyzing the images; (6) using a suitable phase unwrapping algorithm to get continuous phase distribution which is proportional to the object height variations; (7) calibrating the system for mapping the unwrapped phase distribution to real world 3D coordinates.

The basic process of 3-D measurement using T-PMP is shown in Fig. 1. As can be seen, a physical reference plane plate is necessary for T-PMP to complete 3-D measurement, which means the setting and placing of the plate is an indispensable work for T-PMP.

The schematic diagram for T-PMP is shown in Fig. 2. Sinusoidal fringes are projected onto the object by a projector, and the deformed sinusoidal fringe patterns captured by CCD camera can be expressed as:

$$I(x, y) = R(x, y)\{A(x, y) + B(x, y)cos[\varphi_0(x, y) + \varphi(x, y)]\} \tag{1}$$

where, $R(x, y)$ is the surface reflectance of the object, $A(x, y)$ and $B(x, y)$ are the background intensity and the intensity modulation, $\varphi_0(x, y) = 2\pi f_0 x$ is the initial phase of the fringe pattern, and $\varphi(x, y)$ is the phase distribution modulated by the height of the measured object. Typically, N frames of sinusoidal fringe image with constant phase-shifting amount are used for calculating$\varphi_0(x, y) + \varphi(x, y)$. When the phase of sinusoidal fringe shifts N times and phase shifting each time is $1/N$ times of the period, the corresponding deformed fringe patterns can be presented as:

$$I_n(x, y) = R(x, y)\{A(x, y) + B(x, y)\cos[\varphi_0(x, y) + \varphi(x, y) + 2n\pi/N]\} \tag{2}$$