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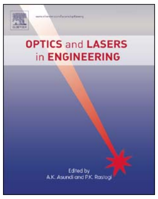

Optimum projection pattern generation for grey-level coded structured light illumination systems

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ABSTRACT

Structured light illumination (SLI) systems are well-established optical inspection techniques for noncontact 3D surface measurements. A common technique is multi-frequency sinusoidal SLI that obtains the phase map at various fringe periods in order to estimate the absolute phase, and hence, the 3D surface information. Nevertheless, multi-frequency SLI systems employ multiple measurement planes (e.g. four phase shifted frames) to obtain the phase at a given fringe period. It is therefore an age old challenge to obtain the absolute surface information using fewer measurement frames. Grey level (GL) coding techniques have been developed as an attempt to reduce the number of planes needed, because a spatio-temporal GL sequence employing p discrete grey-levels and m frames has the potential to unwrap up to p^m fringes. Nevertheless, one major disadvantage of GL based SLI techniques is that there are often errors near the border of each stripe, because an ideal stepwise intensity change cannot be measured. If the step-change in intensity is a single discrete grey-level unit, this problem can usually be overcome by applying an appropriate threshold. However, severe errors occur if the intensity change at the border of the stripe exceeds several discrete grey-level units. In this work, an optimum GL based technique is presented that generates a series of projection patterns with a minimal gradient in the intensity. It is shown that when using this technique, the errors near the border of the stripes can be significantly reduced. This improvement is achieved with the choice generated patterns, and does not involve additional hardware or special post-processing techniques. The performance of that method is validated using both simulations and experiments. The reported technique is generic, works with an arbitrary number of frames, and can employ an arbitrary number of grey-levels.

1. Introduction

Structured Light Illumination (SLI) systems [1–3] are important techniques for 3D surface measurements in various technological and scientific applications. Their success can be traced back to their simplicity: SLI systems project one or more illumination patterns onto an object and a camera captures the distorted patterns. The information in the measurement frames is used to calculate the object shape. Many different projection patterns can be employed for that purpose. Sinusoidal SLI systems [1,2] project a series of phase-shifted sinusoidal patterns, where the measured intensities are processed with a temporal phase shifting algorithm [4] to obtain the phase map, and hence, the surface information. Nevertheless, in contrary to some coherent measurement techniques [5,6], there is an ambiguity in the phase when using sinusoidal SLI. Hence, the obtained phase map needs to be unwrapped in order to achieve absolute shape measurements [7–12]. Numerous techniques have been employed for that purpose. Multi-frequency sinusoidal SLI techniques [2,13–19], combine the phase information obtained at different fringe periods in order to calculate the absolute phase. However, it can be argued [20] that these techniques are inefficient for numerous practical applications, because too many measurement frames are needed. For instance, when assuming one requires four phase shifted sine patterns to estimate the phase map accurately, a three frequency (or period) sinusoidal SLI technique [2,19] needs 12 measurement frames in total. Other techniques however, obtain the unwrapped phase with less images.

Gray Code (GC) techniques [1,3,20–23] project a series of binary stripes so that a given spatial location corresponds to a unique temporal sequence of dark and bright illuminations. In this way 2^m fringes can be unwrapped, where m is the number of frames, provided the width of the stripes equals the period of the sinusoidal patterns. Nevertheless, in practical applications, one seeks to unwrap ~200 fringes, and hence,

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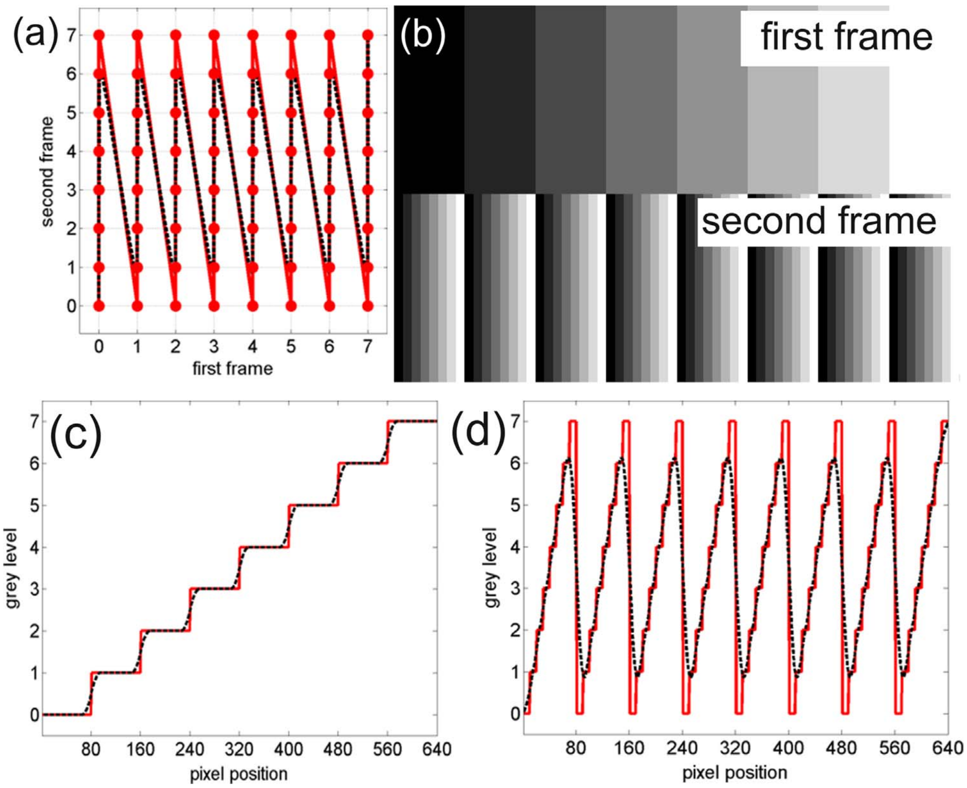

Fig. 1. Code-space diagram for $p = 8$, $m = 2$ (a) of the spatio-temporal sequence (b) that is generated using the CNO. A cut through the centre of the first and second projection frame in (b) is shown in (c) and (d), respectively. The red curves in (a), (c), (d) correspond to the ideal curve, and the dashed black curve in (a), (c), (d) corresponds to the case of defocus errors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

GC based techniques require $m = 8$ additional images. The advantage to a three frequency sinusoidal SLI technique is therefore marginal. More efficient methods [1,3,20,24,25] are so-called grey-level (GL) techniques. GL techniques are similar to GC based techniques, but employ p grey levels. In this way, up to p^m stripes may be coded, i.e. for $p = 8$ and $m = 3$ up to 512 fringes may be unwrapped.

However, one disadvantage of conventional GL techniques are errors that occur near the border of the stripes [20,25]. These errors originate from the loss of high frequencies in the measurement (due to the optical transfer function or defocusing) that creates a loss of sharpness in the image. Hence, an ideally sharp intensity transition cannot be measured.

When applying thresholding it is possible to overcome the loss of sharpness by relating the measured intensity to one of the discrete grey-levels in GL coding. However, this implies that the change in grey-level is sufficiently small, i.e. less than half of the interval between the discrete grey levels in GL coding. This can be ensured by designing projection patterns that have a minimal intensity gradient between neighboring stripes, where ideally the intensity change is only one discrete grey-level unit of the GL coding. Nevertheless, to this day, there are no GL projection patterns available, which work with an arbitrary number of discrete grey-levels and frames and also fulfill this condition: the closed loop space filling curve reported in [20] has a minimal intensity gradient in the projection patterns, but has only been reported for the case of two measurement frames. The space filling Hilbert curves (SFHC) of [24], generate patterns with intensity gradients, where the intensity changes not more than one discrete grey-level unit. However, SFHCs can only be implemented with 2, 4, 8, 16, 32, etc. grey levels and have only been reported for two and three measurement frames.

This work proposes an optimization technique for GL based techniques [3,20,24] that re-arranges the order of spatio-temporal sequences, where the spatio-temporal sequence may employ an arbitrary number of grey-levels and number of measurement frames. The illumination patterns of this work have lower intensity gradients and less spatial frequencies, so there is a higher robustness in case of defocusing. This gives a higher accuracy of the fringe values near the border of a stripe, and thereby, a higher measurement accuracy in case of defocusing. The optimization proposed in this work adopts the concept of code-space diagrams to describe spatio-temporal sequences in a simple way [20,24]. In this representation, a given set of projection patterns used for the measurement are simply described by a single curve in code-space that connect various combinations of grey-levels. The optimization procedure employed here transfers the problem of "minimizing the intensity gradients in the projection patterns" into an equivalent problem of "finding the shortest route for a curve through code-space", which is optimized using a travelling salesman problem (TSP) solver [26].

This paper is organized as follows: Section 2 provides an overview of common GL techniques using the concept of code-space diagrams. Section 3, introduced the TSP technique for the optimization of projection patterns, where various examples for TSP optimized curves are presented. Section 4 discusses possible decoding techniques for GL based SLI systems. Section 5 presents various experimental results when using this technique and compares it to other measurement methods. Finally, the conclusions are presented in Section 6.

2. Theory

Code-space diagrams [20,24] are a neat and easy way to visualize spatio-temporal sequences. An example of a code-space diagram is shown in the red curve of Fig. 1a for the case of $p = 8$ grey levels and $m = 2$ measurement frames. The corresponding projection patterns are shown in Fig. 1b, where a cross-cut through the centre of the first and second frame is shown by a red curve in Fig. 1c and d, respectively. For convenience, all projection patterns of Sections 2 and 3 have a stripe width of 10 pixels. The horizontal and vertical axis of the two dimensional code-space diagram represent the grey-levels of the first (Fig. 1c) and second (Fig. 1d) frame, respectively. In common jargon,