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FAST MEASUREMENTS OF ANATOMICAL STRUCTURES USING STRUCTURED LIGHT ILLUMINATION SYSTEMS WITH INTENSITY DISCRETE ILLUMINATION PATTERNS

Konstantinos Falaggis [a, c], Rosario Porras-Aguilar [a, b],

[a] Departamento de Óptica, Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis Enrique Erro No. 1, Sta. Ma. Tonantzintla Puebla, México CP 72840, Mexico. falaggis@inaoep.mx, rporras@inaoep.mx

[b] Consejo Nacional de Ciencia y Tecnología, Av. Insurgentes Sur 1582, 03940 México, D.F., México.

[c] Instituto de Micromecánica y Fotónica, Universidad Politécnica de Varsovia, 8 Sw A. Boboli Str, 02-525 Varsovia, Polonia.

ABSTRACT
Spinal deformities affect all age groups, leading to the most frequent postural and pain problems in modern societies. Back pain is one of the diseases, which usually lowers the quality of life. Faulty postures and associated disorders should be detected as early as possible to apply preventive measures against major consequences in old age. Back examination is performed by physicians based mainly on the observation of the body, sometimes followed by simple linear or other more precise measurements. Radiography is carried out in the most suspected cases and is the main method for periodical evaluation of deformity changes during treatment. This implies intensified, repeated x-ray exposure, which should be avoided in general, especially in adolescents. A few systems for back shape assessment already exist, allowing the accomplishment of the task of documentation. Alternatives are Optical systems that are mainly based on the moiré technique, laser and structured light illumination (SLI) in order to analyze mutual position of certain anatomical structures, where SLI is a well-established technology for noncontact 3D surface measurements. A common challenge in those SLI systems is to obtain the absolute surface information using few measurement frames. This work proposes a new grey level coding scheme for SLI that uses only few measurement frames, overcomes typical defocus errors, and has an error detecting feature. The latter feature makes the need of separate error detecting algorithms obsolete. This so-called closed-loop space filling curve can be implemented with an arbitrary number of N grey-levels enabling to code up to (2N) code-words. The performance of this so-called closed-loop space filling curve is demonstrated using experimental data.

1. INTRODUCTION
The measurement of anatomical structures can be performed most conveniently using Structured Light Illumination (SLI) systems, which project a series of light patterns onto an object to be measured. Commonly, those types of surface measurements can be performed by projecting a series of sinusoidal illumination patterns or Gray-Coded Sequences. This is done, in order to make absolute surface measurements [1–4]. Notably, This research area is closely related to phase unwrapping methods in optical metrology [5–7], e.g. multi-wavelength interferometry [8–11]. or fringe projection profilometry (FPP) [12–16]. Traditionally, SLI systems used sinusoidal FPP techniques [7,13,17,18], where the reconstructed wrapped phase maps are combined in order to obtain an absolute phase map. The phase can then be converted into a height map, giving the 3D-surface. However, sinusoidal FPP techniques [19] still require a large number of intermediate fringe patterns, and are therefore not suitable for fast applications. An attempt to reduce the number of intermediate fringe patterns were Number theoretical methods [3,13,20,21] and have been proposed by Gushov and Solodkin [20] or Towers [3]. Other techniques, used a so-called look-up table (LUT) technique [22–30] to

improve the noise robustness. Finally, in reference [31] an analytical method for the phase unwrapping problem has been presented, so that a direct result can be obtained with high noise robustness but without the need of using an LUT.

It is interesting to notice, that reference [4] showed that for the case of SLI it is not efficient to measure additional phase maps, because it would require too many measurement frames. Reference [4] proposed the projection of intensity discrete patterns for a high robustness using a small number of frames. Furthermore, the coding scheme in [4] also allows including an error detecting feature, which allows excluding erroneous pixels from the measurement during the decoding procedure, and therefore, making a separate error detecting algorithm obsolete [32].

2. THEORY

Grey-level (GL) based techniques tend to require less measurement frames than sinusoidal FPP techniques. First systematic GL implementations have been reported by Horn [33], who investigated for a given level of noise the smallest number of projection patterns that meet application-specific accuracy requirements. Reference [33] concluded that a family of sub-optimal but for the experimental practice interesting solutions can be derived from space-filling Hilbert curves (SFHCs), which employ a spatio-temporal coding approach similar to the GC technique. There, the projected intensity patterns have only M equidistant grey values within the minimal and maximal value of the projected intensity, i.e. for 8-bit projectors between the grey levels 0 and 255. The number of projected grey levels are determined by the order of the SFHC (denoted as q) as $M = 2^q$, e.g. third order SFHC give M = 8. In SFHC coding two grey-level patterns are sequentially projected onto the object of interest, so that each grey level pair is unique for a given spatial location. The curve that connects the points in code-space define the sequence of the code words, as shown in Fig. 1 for M=8 (q=3).

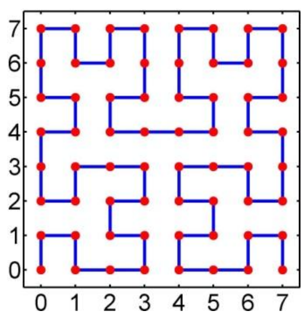

Fig. 1. Example of a two-dimensional SFHC of order 3.

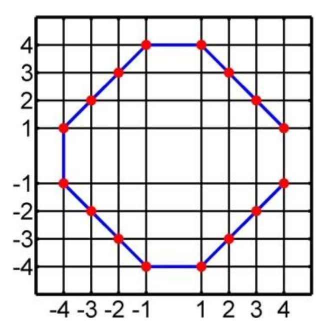

Fig. 2. Example of a two-dimensional closed-loop SFCs employing 8 grey levels (a).

Nevertheless, reference [4] showed that SFHC are subject to defocus errors and that a closed-loop SFC is a better solution, because the first and last element of the code-sequence are neighbors in space. Here we adopt a coding scheme similar to the one shown in Fig. 2 to avoid defocus errors. The two-frame closed loop SFC can decode up to 16 different code words when using 8 grey levels. When combining this technique with a sinusoidal SLI technique, the addition of two frames can unwrap the phase with an ambiguity of 16 fringes.

3. EXPERIMENTS

For the experiments we used an SLI system that adopted the closed-loop SFC of Fig. 2. However, the projected grey-levels have not been aligned on a diamond in order to pre-compensate the gamma non-linearity. In this way, it is ensured that the measured grey-levels lie on a diamond in the code-space. The code-space of the projected and measured code-words used for the experiments are shown in Fig. 3.

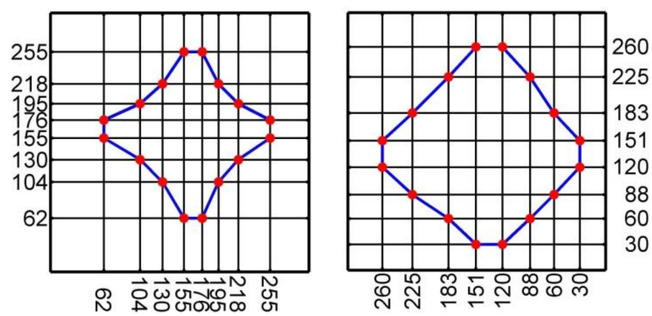

Fig. 3. Code-space used for the projected code words (left) and code-space of the measured code words (right).

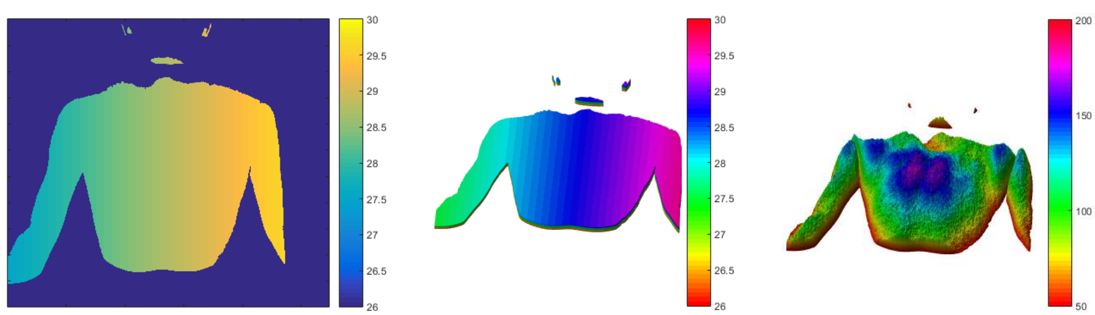

Fig. 4. Measured 3D surface of a patient (left) and 3D view (centre) and 3D view of intensity illuminating the patient (right).

The described SLI system has been used to measure the back of an patient. The project 4 frames in total (2x two code pairs), where the second code pair has a stripe-length equal to the code-length of the first code pair. In this way 16 x 16 = 256 code words can be encoded, when using only 4 measurement frames. The information contained in the four measured frames are then decoded and converted into a depth information used to calculate the 3D-surface. The results for an exemplary measurement with a real patient is shown in Fig. 4.

4. CONCLUSIONS

This work presents an SLI system employing a grey-level coding based on closed loop SFC. The advantage of this approach is that this techniques requires significantly less measurements than alternative approaches. It is shown that using only 4 measurement frames it is possible to measure the 3D-surface (back of a patient). This systems can be used to measure relatively fast the spinal deformities of a patient and thereby avoiding invasive diagnostics based on x-ray exposure.

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