Embedded Phase Shifting: Robust Phase Shifting with Embedded Signals

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Structured-light (SL) 3D scanning has been traditionally limited to near Lambertian scenes where global illumination effects, such as interreflections and subsurface scattering, are minimum or non-existent. In this paper, we present a phase shifting algorithm, named Embedded PS, which is robust to global illumination effects, it has low computational complexity, and produces better 3D models than the state-of-the-art.

An SL scanner comprises a data projector and at least one camera. The projector illuminates the scene with a sequence of specially designed patterns while cameras capture images of the illuminated scene. Knowledge about the projected patterns is exploited to find correspondences from projector to camera pixels, or between cameras in case of a multi-camera setup, and the principle of optical triangulation is applied to find the 3D location of scene points. Global illumination effects change the light intensity as measured by cameras, producing errors in the final result.

Recent advances on SL 3D scanning have shown that if the spatial frequency on the projected patterns belongs to a narrow range, then global illumination effects are minimized [3]. On the contrary, commonly used SL patterns [6], such as Gray code and Multiple PS, have a very wide frequency range, thus, they are not robust to global illumination. It has also been shown that when the projected patterns have only high frequency content, captured images can be separated in global and direct illumination components [4]. These two observations have led to the development of robust SL methods, first by separating the illumination and "discarding" the global component [1], and later robust methods that require no separation such as Micro PS [2]. Embedded PS belongs to this last group.

Phase shifting (PS) methods project a sinusoidal signal or other periodic signal, where the phase of the signal is related to the data projector column (or row). In this way, each phase value identifies a plane defined by the corresponding column (or row) and its intersection with a ray through a camera pixel gives the scene depth. Therefore, the goal for PS algorithms is to find the phase of the projected signal for each camera pixel. The period of the signal determines the spatial frequency range on the projected patterns. If the frequency is high, many signal periods occur within a single pattern and it becomes necessary to decide to which of all projected periods belongs each recovered "relative" phase value (phase within a single period), a process known as "unwrapping". A simple and effective solution to the unwrapping problem, called Temporal Phase Unwrapping [5], is to project a sequence of patterns from high to the unit frequency and unwrap phases in sequence from the lowest to the highest one. Multiple PS uses this idea but it is not robust to global illumination effects. Micro PS uses only high frequencies, it cannot do temporal unwrapping, and solves unwrapping with a search on a LUT which requires phase quantization and is less efficient and slow compared to temporal unwrapping. Embedded PS is designed to be robust to global illumination errors, by projecting only high frequencies, and to permit fast and accurate unwrapping as Multiple PS. The key idea is to embed low frequencies in the phase of the high frequency patterns, the phase of the embedded frequencies is recovered by the algorithm using simple math and they are used with temporal phase unwrapping to recover the exact phase of the high frequency signals.

Embedded PS unwraps each of the projected high frequency signals providing multiple depth estimates for each camera pixel. Whereas, Multiple PS and Micro PS provide a single depth estimate per pixel since Multiple PS has only one high frequency and Micro PS unwraps only the phase of the first frequency. The extra information generated by Embedded PS can be used to improve the final 3D model. For instance, we show that the average of the phases produces less noisy models and preserves fine details, which would be lost by common smoothing denoising filters.

We have evaluated Embedded PS with multiple experiments. Figure 1 shows how very fine details are correctly measured. Figure 2 compares the three PS methods qualitatively by scanning an orange which presents significant subsurface scattering.

The full paper contains a detailed description of the proposed method and extra results.

This is an extended abstract. The full paper is available at the Computer Vision Foundation webpage.

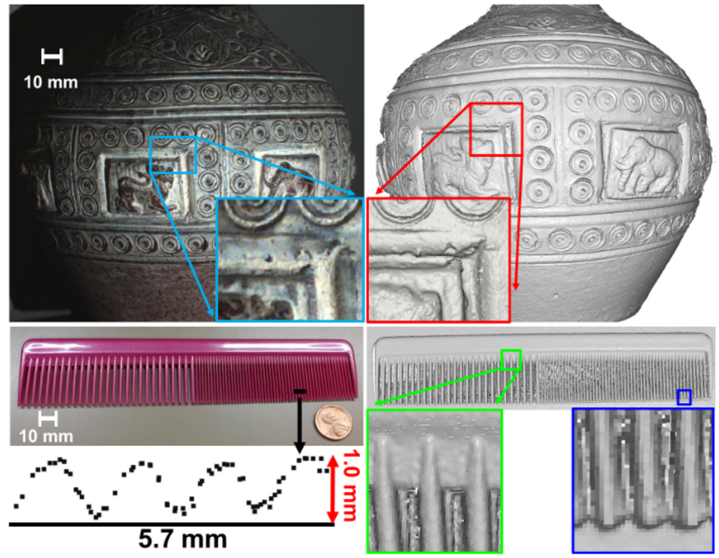

Figure 1: Embedded PS. Models generated from 9 images with no post processing such as filtering or mesh reconstruction. Fine structures below 1mm depth in a 180mm object are accurately measured. Total decoding time with a single thread Matlab implementation takes about 1.2s, image resolution is 1600x1200.

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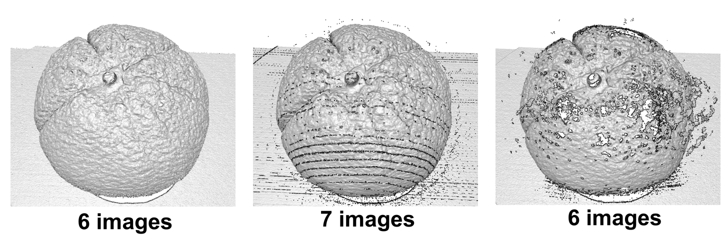
[6] Joaquim Salvi, Sergio Fernandez, Tomislav Pribanic, and Xavier Llado. A state of the art in structured light patterns for surface profilometry. *Pattern Recognition*, 43(8):2666 – 2680, 2010.



(a) Embedded PS (b) Micro PS (c) Multiple PS

Figure 2: Orange skin produces significant subsurface scattering. Embedded PS and Micro PS are robust to it but Micro PS has unwrapping errors.