

# IMPROVEMENT OF 3D SHAPE MEASUREMENT OF TRANSLUCENT OBJECTS BY APPLYING DIRECT-GLOBAL LIGHT SEPARATION

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**Abstract** This paper presents a novel approach for high-precision optical 3D shape measurement of translucent objects based on phase-shifting fringe pattern projection. To address the problem of subsurface scattering, the concept of separating direct and global light components is integrated into fringe projection to enable phase value recovery solely from direct light components. In the proposed approach, the fringe patterns are modulated with shifting perpendicular high-frequency stripes, and a sparsification of these fringe-stripe patterns is applied to reduce residual phase crosstalk. Furthermore, a method for the correction of phase jumping due to global illumination in gray code projection was developed. The 3D measurement of a translucent resin plate with aluminium regions validated this proposed approach. Compared to conventional fringe projection, the proposed method reduced the mean and maximal phase error by 62.2 % and 52.5 %, respectively, and the root mean squared error in the plane fitting using reconstructed 3D points of the plane object was reduced from 225.4  $\mu\text{m}$  to 110.1  $\mu\text{m}$ . These results confirm the potential of the developed technique for accurate 3D measurement of plastic materials and biological tissues.

**Keywords:** Optical metrology, 3D measurement, fringe projection, direct-global separation

## 1. INTRODUCTION

Phase-shifting fringe projection [1] is a well-established optical technique for 3D shape measurement. A typical setup for the implementation of this method consists of a digital pattern projector and two cameras in stereo arrangement. The projector projects  $N$  periodic sinusoidal fringe patterns with a constant phase shift. At each object point, the phase value  $\varphi$  can be calculated from the temporal intensity stack  $I_i$  using equation (1) for the stereo matching between the cameras:

$$\varphi = -\arctan\left(\frac{\sum_{i=1}^N I_i \cdot \sin\left(\frac{2\pi}{N} \cdot (i-1)\right)}{\sum_{i=1}^N I_i \cdot \cos\left(\frac{2\pi}{N} \cdot (i-1)\right)}\right) \quad (1)$$

However, applying this method to translucent objects remains a significant challenge. On translucent surfaces, a part of the incident light at a given object point is directly reflected, while another part passes into the subsurface, undergoes scattering, and exits at a different location on the object. The subsurface scattering can lead to substantial phase jumping errors as well as small-scale phase errors, resulting in artifacts in the measured 3D point cloud of object surface.

To mitigate the phase jumping errors, methods such as modulated phase-shifting [2] and micro phase-shifting [3]

have been investigated. However, they do not correct the residual small-scale phase errors. For further enhancement, computational approaches have been proposed by Lutzke et al. [4–6]. While effective in principle, these methods require precise knowledge of material properties and involve high computational effort due to the iterative optimization of the object’s surface geometry via simulation and rendering. Deep learning techniques can be also considered for this problem. However, they require large effort to collect an appropriate dataset and may lack in physical interpretability.

A concept proposed by Nayar et al. [7] based on structured high frequency illumination enables the separation of direct and global light components. Inspired by this idea, a novel technique for 3D shape measurement of translucent objects is proposed by integrating Nayar’s concept into phase-shifting fringe projection. In the proposed approach, phase values can be calculated solely from the separated direct light images, thereby avoiding phase errors due to global illumination.

## 2. METHODS AND PROCEDURES

For the direct-global separation, shifting high-frequency binary stripe patterns can be used. It is observed that residual errors in the separated direct light image are more significant in the direction perpendicular to the orientation of stripes. Since fringe patterns exhibit consistent phase values along the direction of the fringes, each fringe pattern is modulated with six binary stripe patterns oriented perpendicular to the fringe direction, as illustrated in Figure 1.

Furthermore, to suppress remaining phase errors due to residual errors in the direct-global separation, a sparsification strategy is introduced: instead of projecting full fringe-stripe patterns, each modulated fringe pattern is divided into a set of sparse patterns, each of which contains only the fringe pattern parts corresponding to a single phase value, as illustrated in Figure 2. This strategy effectively limits phase crosstalk at each object point to its immediate neighbourhood, further enhancing the accuracy of phase recovery.

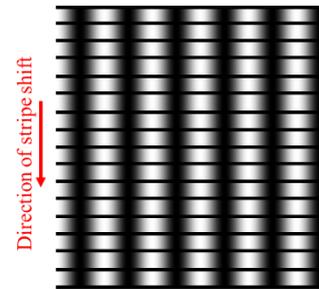


Figure 1. A periodic sinusoidal fringe pattern modulated with high-frequency binary stripes. For the purpose of visualization, the spatial frequency of stripes shown here is much lower than in the actual implementation.

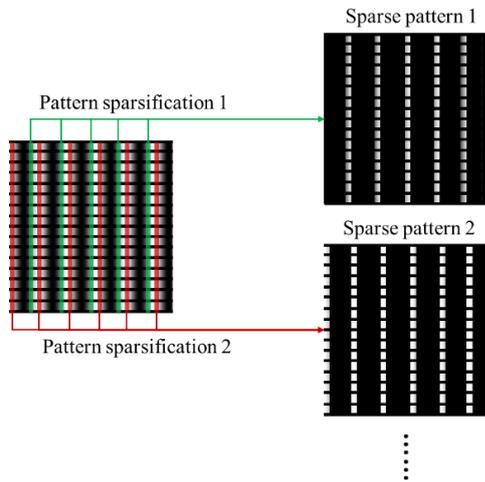


Figure 2. Sparsification of one modulated fringe patterns.

By these, a set of fringe-stripe patterns are generated from each fringe pattern. From this pattern set, sparse direct light fringe patterns are firstly calculated using Nayar’s algorithm. Then, a full direct light fringe pattern can be recovered by accumulating all sparse fringe patterns. Finally, phase values are calculated from the recovered direct light fringe patterns. The phase unwrapping is performed using additional gray code patterns. To correct phase unwrapping errors in the gray code transition regions, a correction method based on the assumption of object surface continuity that generally holds in industrial applications, is applied. Phase values that deviate from their neighbouring values by more than 360 degrees are identified as outliers and corrected to the same phase period of their surrounding values.

### 3. RESULTS AND DISCUSSION

To validate our method, we developed an experimental setup consisting of a high-speed digital projector and two cameras with a triangulation angle of about 20 degree and a measurement volume of 200 mm × 200 mm × 100 mm and conducted 3D measurements at a translucent cast resin plate with very thin opaque aluminium stripes on its surface, see Figure 3.

The phase errors in the resin regions were calculated using both conventional fringe patterns and the proposed sparse fringe-stripe patterns. We assume that the phase values from the aluminium regions are reliable and fitted a 3D plane from them. The phase errors in the resin regions are calculated as deviations from the 3D phase plane. Using conventional fringe projection, the mean absolute phase error was 9.35 degrees, while the maximal error was 18.35 degrees. Using the proposed method, the mean and maximal error were reduced to 3.53 degrees and 8.71 degrees, respectively.

Figure 4 shows the measured 3D profile of the cast resin plate using both methods. In the 3D profile measured using conventional fringe patterns, a remarkable deviation between resin and aluminium regions can be observed, with obvious artefacts in the resin regions. Applying the proposed method, this deviation is significantly suppressed, while the maximal negative and positive deviation were reduced from -465.8 μm to -305.2 μm and from 934.4 μm to 395.9 μm, respectively. In total, the root mean square error of plane fitting using all reconstructed 3D points was reduced from 225.4 μm to 110.1

μm, indicating a significant improvement in 3D measurement accuracy of over 50% by reducing deviations in resin regions.



Figure 3. Experimental setup (left) and test object (right).

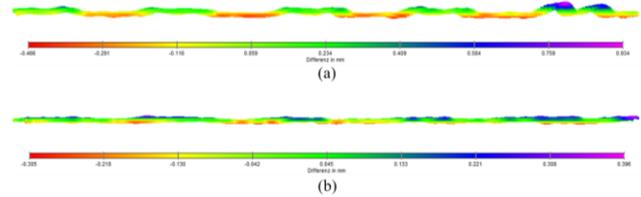


Figure 4. Measured 3D profile of the cast resin plate: using conventional fringe patterns (a), using sparse fringe patterns (b).

### 4. CONCLUSIONS

The proposed method can significantly reduce errors in 3D surface shape measurement of translucent objects and be easily integrated into conventional fringe projection setups to improve the measurement accuracy for objects with moderate translucency, such as 3D printed components and biological tissues.

### ACKNOWLEDGMENTS

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