Embedded Phase Shifting: Robust Phase Shifting with Embedded Signals

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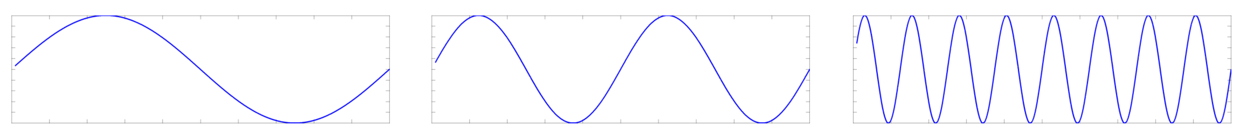
Objective:

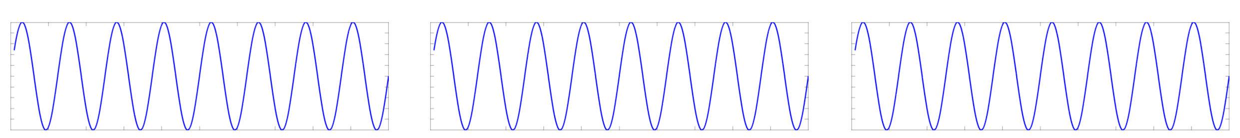
To create a Phase Shifting (PS) method for 3D scanning robust to global illumination effects and with low decoding computational cost.

Related work:

- ❑ Multiple PS [1] projects patterns of multiple frequencies and uses Temporal Phase Unwrapping [2], which is accurate and computationally efficient, but it is not robust to global illumination effects.

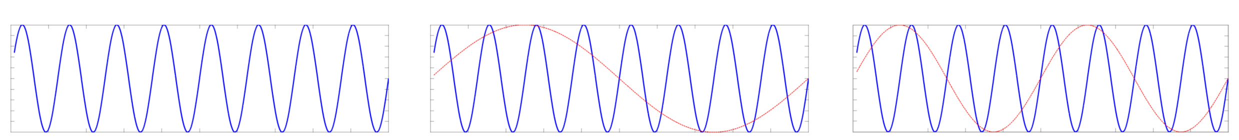


- ❑ Micro PS [3] is robust to global illumination effects, because it uses only high frequency patterns, but decoding requires search in a LUT which is inefficient and produces frequent errors.



Embedded PS:

- ❑ **High frequency patterns robust to global illumination**
- ❑ **Embedded low frequencies permit efficient and accurate phase unwrapping**
- ❑ **Every projected frequency generates a depth measurement, multiple measurements combined produce more accurate results.**



Coding Method:

Let be $\{T_1,\ldots,T_M\}$ real numbers greater than 1. We define M embedded frequencies F_m as:

$$F_m = \frac{1}{T_1}\cdots\frac{1}{T_m}.$$

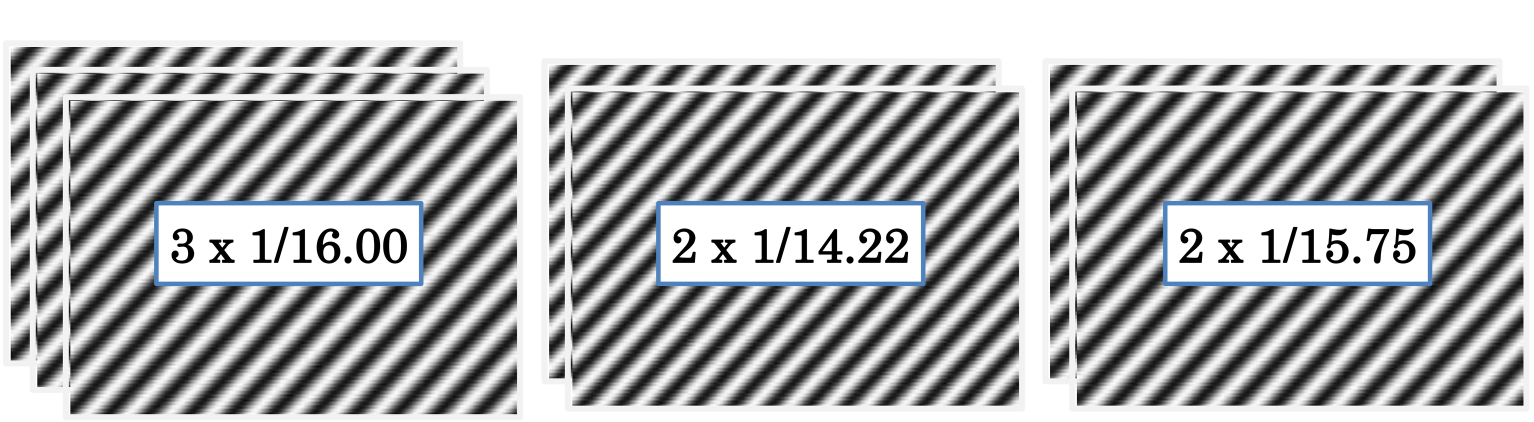
We define M pattern frequencies f_m as:

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_M \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & & 0 \\ 1 & 1 & 0 & \ldots & 0 \\ 1 & 0 & 1 & & 0 \\ & \vdots & & \ddots & 0 \\ 1 & 0 & 0 & \ldots & 1 \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ \vdots \\ F_M \end{bmatrix}.$$

Create a sinusoidal pattern for each of the M pattern frequencies.

Example: if T_1=16, T_2=8, and T_3=8; then

- embedded frequencies are F_1=1/16, F_2=1/128, and F_3=1/1024
- pattern frequencies are f_1=1/16, f_2=1/14.22, and f_3=1/15.75



7 patterns

Decoding Method:

Use image intensities to recover the phase vector:

$$\mathbf{u} = [o, c_1, s_1, \ldots, c_M, s_M]^T, \quad c_m = a_m\cos(\omega_m\phi_m),\; s_m = a_m\sin(\omega_m\phi_m).$$

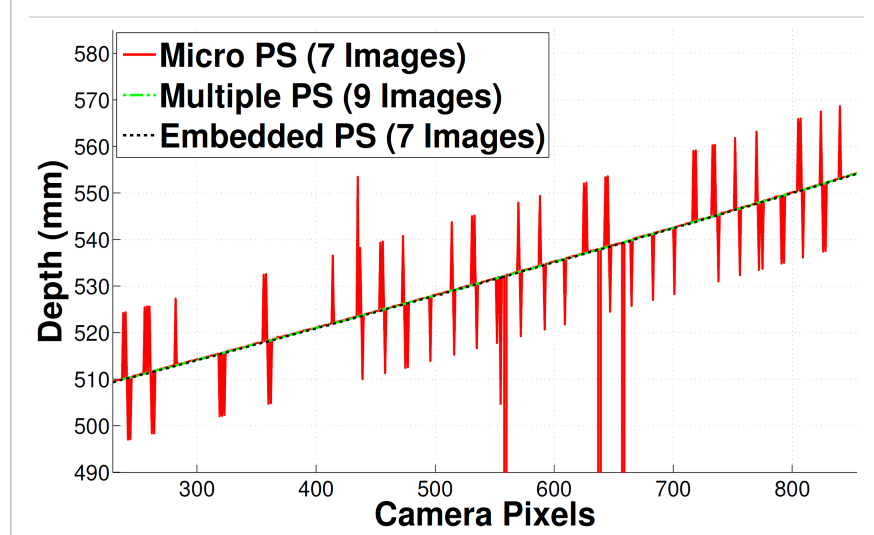
Each relative phase ϕ_m corresponds to a pattern frequency. Extract the embedded frequencies:

$$\begin{cases} \Phi_1 \equiv \phi_1 \\ \Phi_m = \phi_m - \phi_1 \quad \text{for } m > 1. \end{cases}$$

Use Temporal Phase Unwrapping [2] to unwrap the embedded frequency phases Φ_m and pattern frequency phases ϕ_m.

Each pattern frequency phase provides a separate depth measurement.

Comparison of PS unwrapping methods:



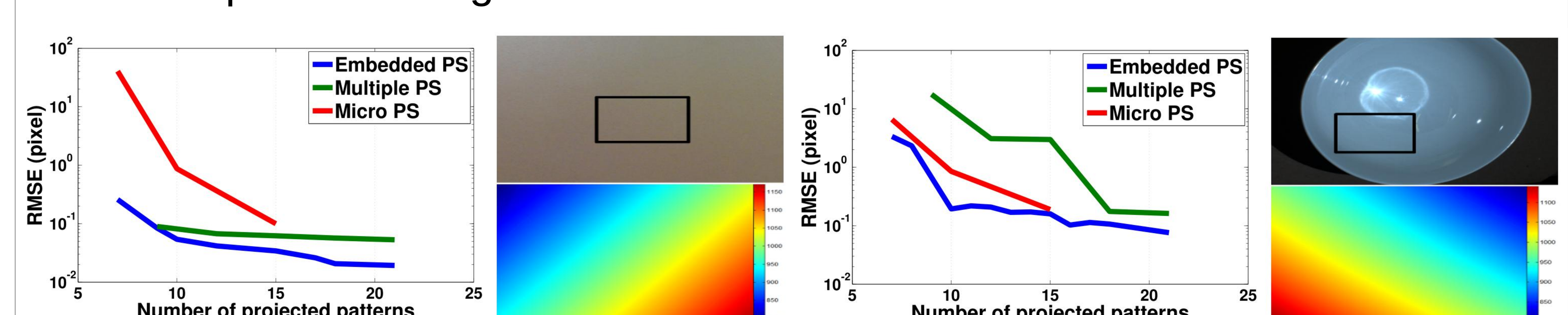
Profile of a metal plane:

- Micro PS produces frequent unwrapping errors, some of them can be corrected with a median filter.
- Multiple PS and Embedded PS show now errors.

Surface Properties:

a) **Lambertian Surface**: in the absence of global illumination effects Embedded PS and Multiple PS performs similarly.

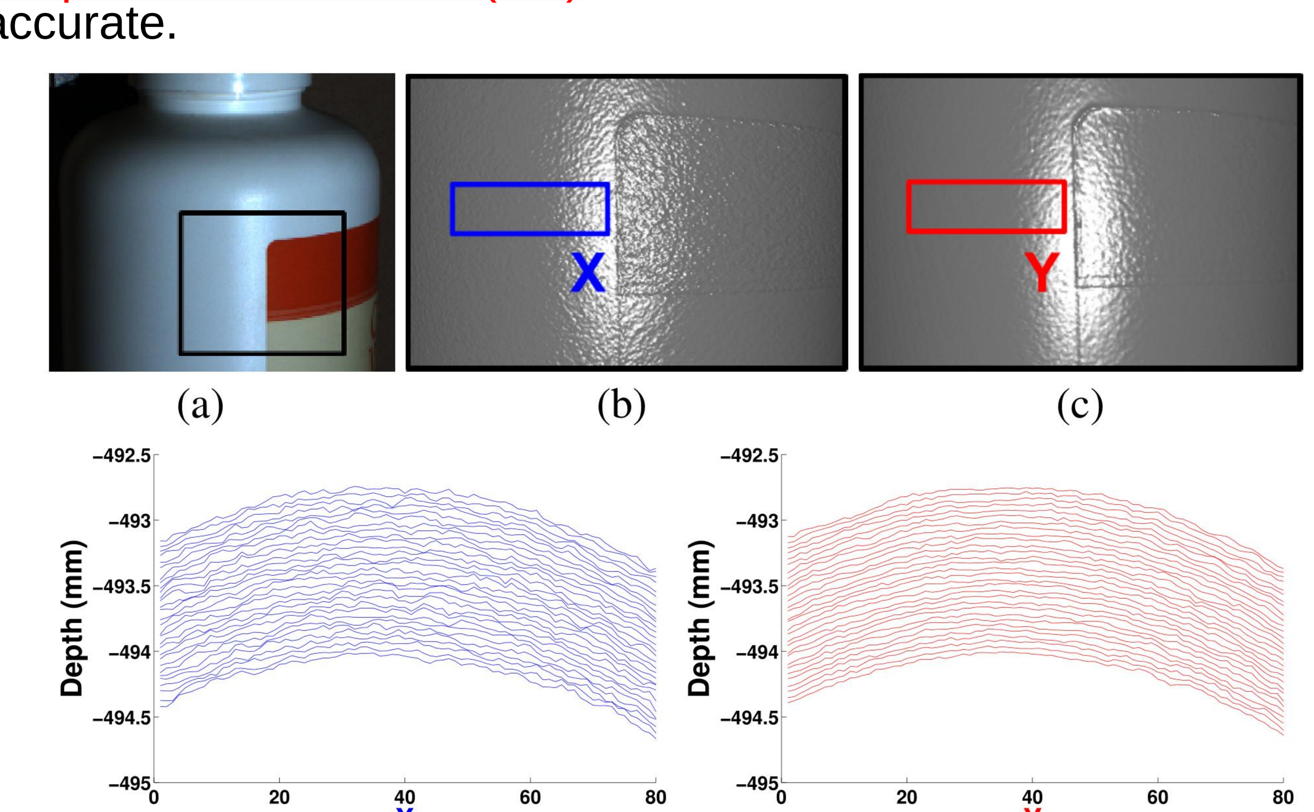
b) **Specular Concave Surface**: Embedded PS and Micro PS performs well in the presence of global illumination effects



(a) (b)

Multiple Measurements:

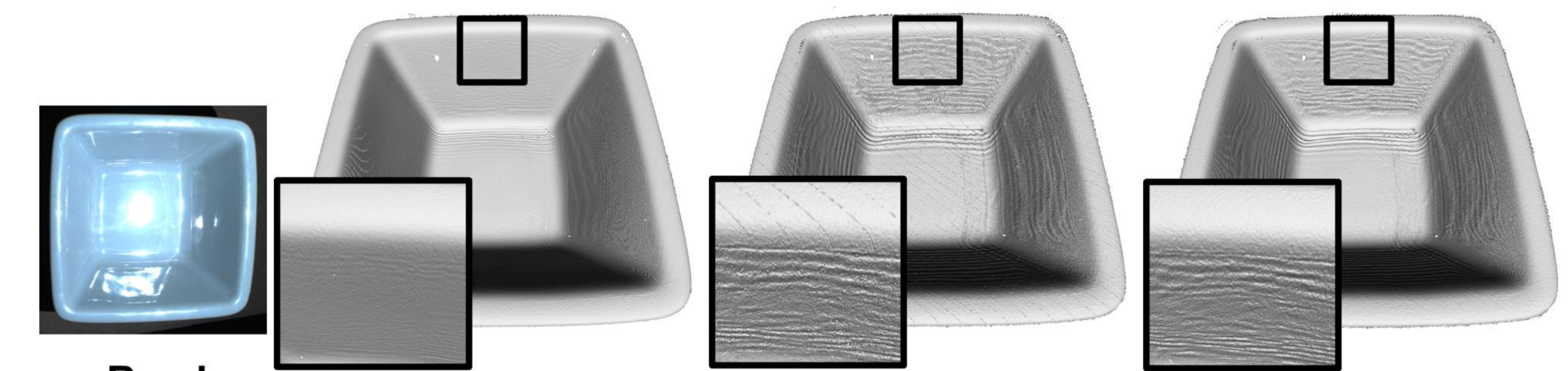
3D models from same image data using only a single measurement (blue) and multiple measurements (red). The latter one has less noise and it is more accurate.



(a) (b) (c) (d) (e)

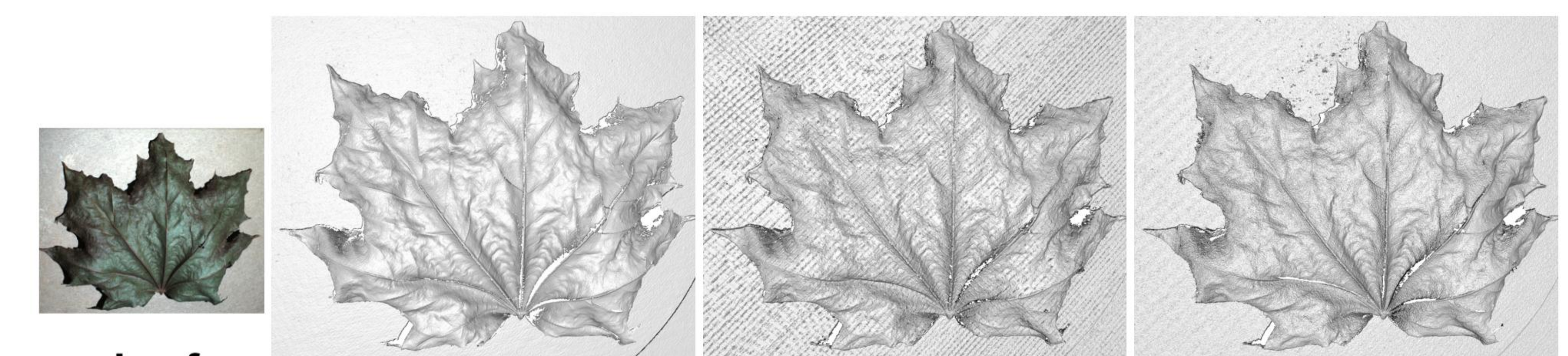
3D Model Comparison:

Embedded PS   Micro PS   Multiple PS



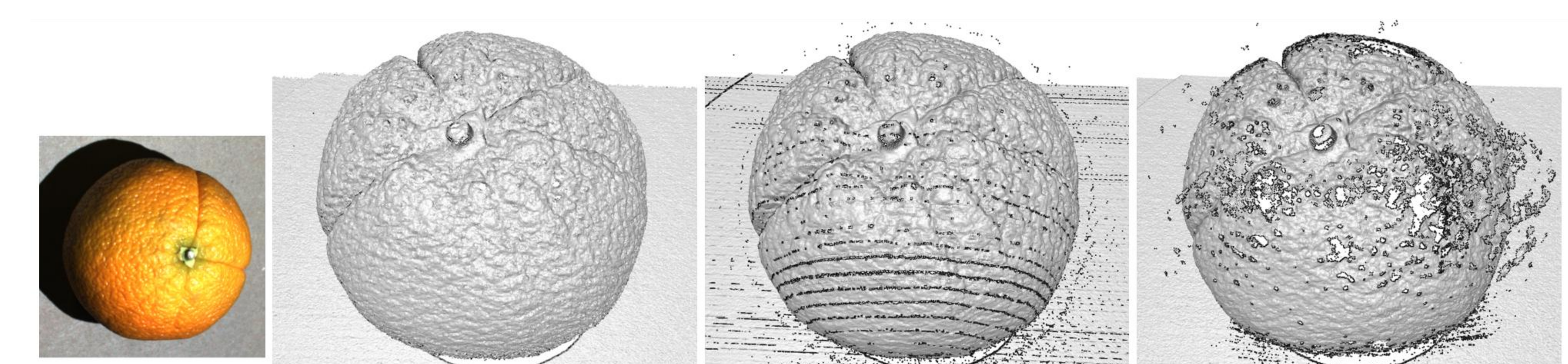
Bowl   15 images   15 images   15 images

Rectangular Bowl: concave object with specular surface, exhibit strong interreflections



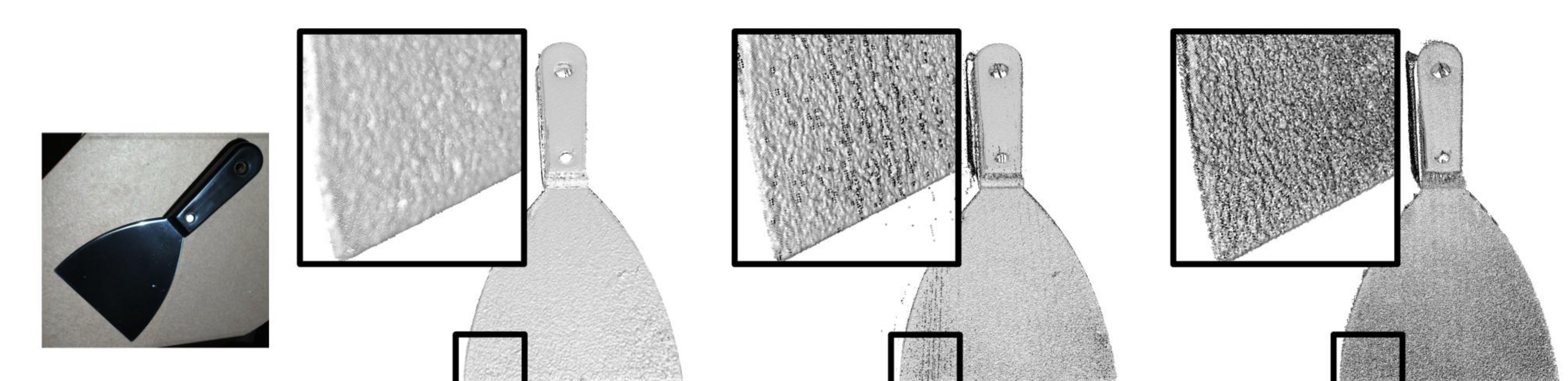
Leaf   7 images   7 images   9 images

Tree Leaf: fine structures with small details



Orange   6 images   7 images   6 images

Orange: semi translucent skin results in subsurface scattering

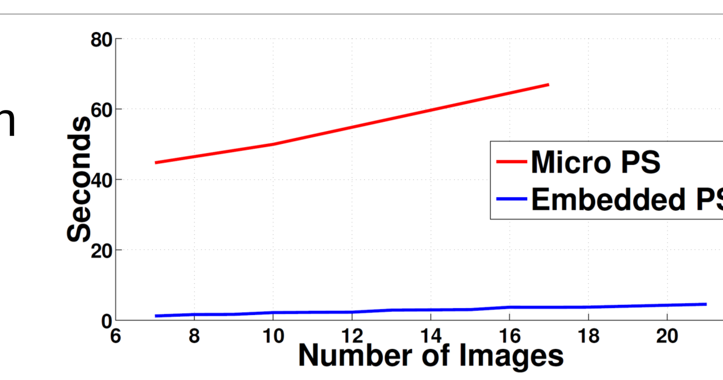


Spatula   9 images   10 images   9 images

Spatula: polished metal anisotropic surface

Computation Complexity:

Plot of the decoding algorithm computation time vs. the number of captured images.



Conclusion:

Embedded PS is robust to global illumination effects, it is fast and accurate, and produces multiple measurements which are used to generate 3D models with very low noise.

References:

[1] T. Pribanić, H. Džapo, and J. Salvi. Efficient and low-cost 3D structured light system based on a modified number-theoretic approach. EURASIP, pages 1–11, 2010

[2] H. O. Saldner and J. M. Huntley. Temporal phase unwrapping: application to surface profiling of discontinuous objects. Applied optics, 36(13):2770–2775, 1997

[3] M. Gupta and S. Nayar. Micro Phase Shifting. In CVPR, pages 1–8, Jun 2012.