1. **Fringe projection**

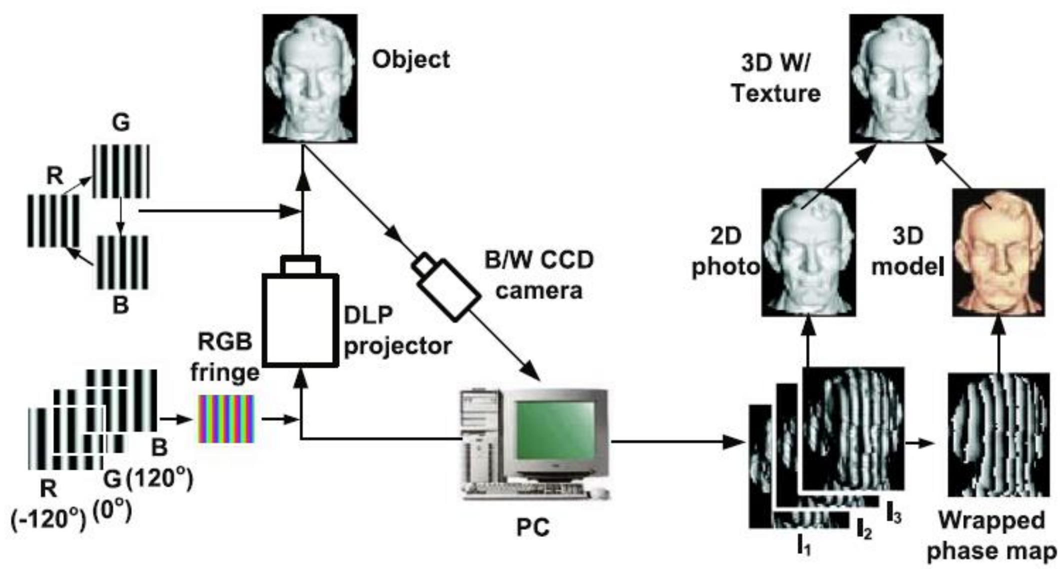
Fringe projection is another sequential projection technique where a set of phase-shifted sinusoids are projected on the target object. The sinusoids are modulated by the geometry of the target object and captured by the camera. The modulated phase is extracted from the captured sinusoid images.

$$I_1(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) - 2\pi/3], \quad (1)$$
$$I_2(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y)], \quad (2)$$
$$I_3(x,y) = I'(x,y) + I''(x,y)\cos[\phi(x,y) + 2\pi/3], \quad (3)$$

where $I'(x,y)$ is the average intensity, $I''(x,y)$ the intensity modulation, $\phi(x,y)$ the phase to be solved for. Solving Eqs. (1)–(3), we can obtain the phase

$$\phi(x,y) = \tan^{-1}\left[\frac{\sqrt{3}(I_1 - I_3)}{2I_2 - I_1 - I_3}\right], \quad (4)$$

Source: Recent progresses on real-time 3D shape measurement using digital fringe projection techniques by Song Zhang



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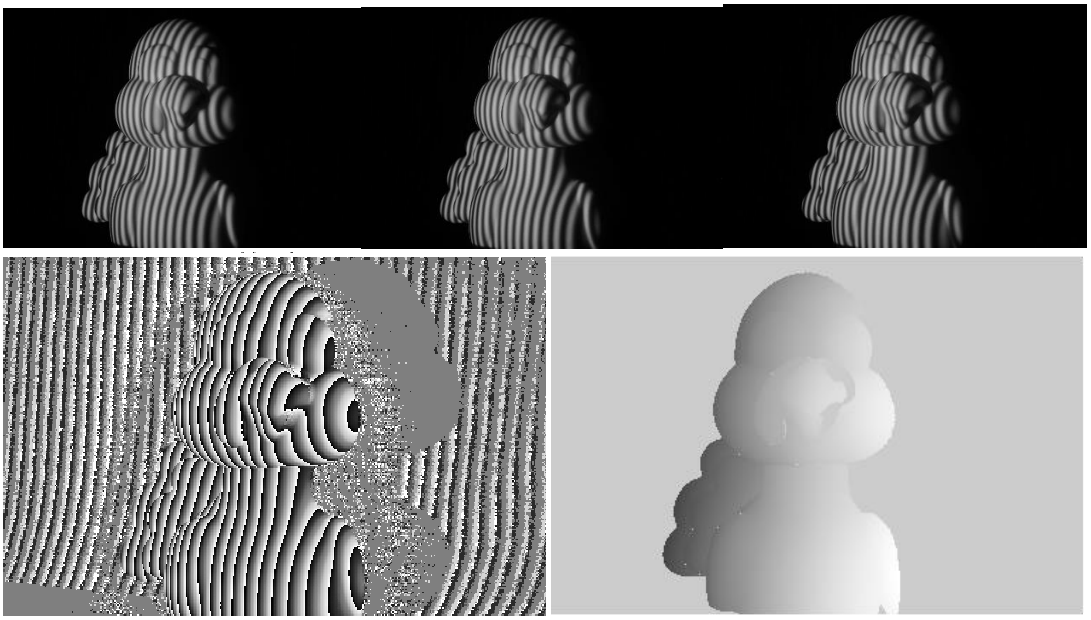
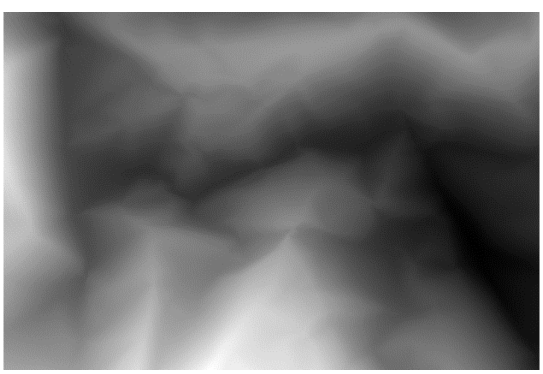
The calculated phase is a relative phase and has discontinuities (due to arc tan). In order to find a continuous phase, we need to apply a phase unwrapping algorithm. We wrote our custom algorithm for phase unwrapping and tried standard python

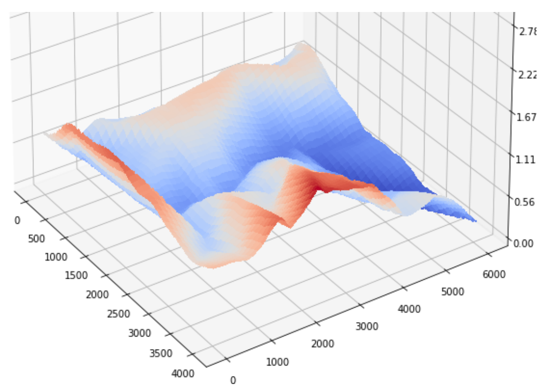
APIs provided by numpy, OpenCV and scikit. We found the scikit API works best in different conditions and have used it everywhere for phase unwrapping.

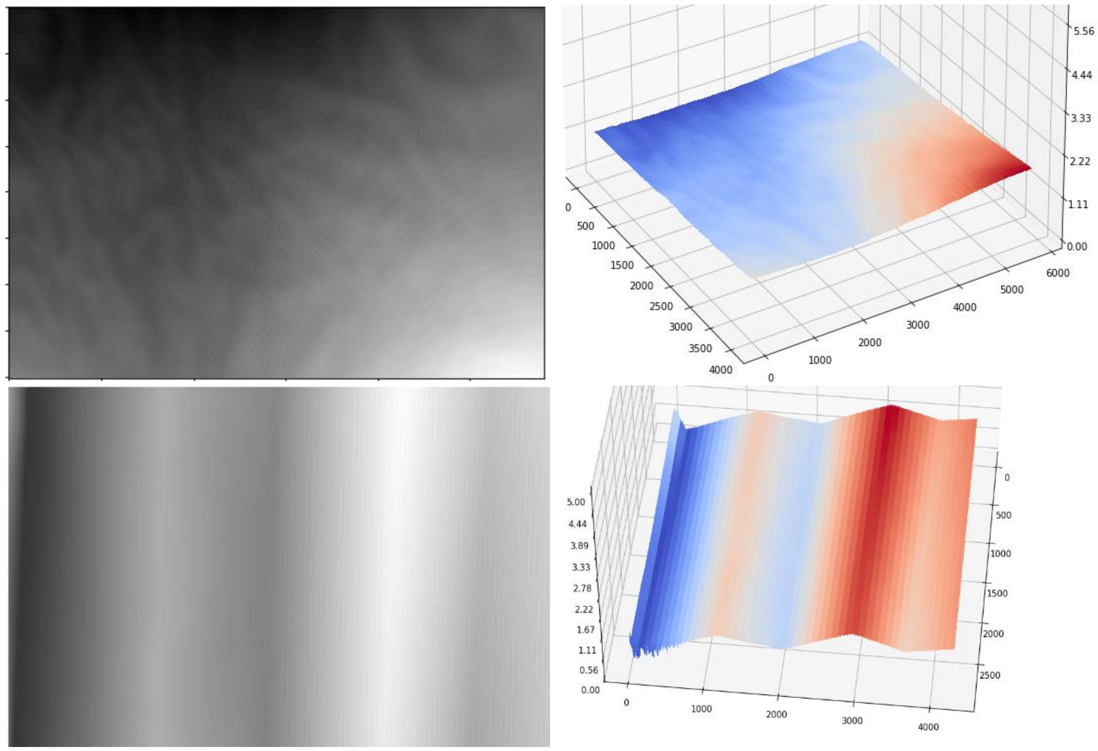


Top: Fringe captured images, Bottom-left: wrapped phase, Bottom-right: Unwrapped phase

The object unwrapped phase is then subtracted from a reference plane unwrapped phase to estimate the depth. The steps are performed on a known calibration object and the ratio of its actual depth and the estimated depth is used a scale to correct depth estimation of target objects. Since our main goal is to model near-planar objects, here are few more examples of depth estimation of some near-planar objects.







Top: Paper, Middle: Manuscript, Bottom: Triangular-wave shaped paper

We also tried other algorithms to extract the modulated phase. One of them was Fourier Transform Profilometry (FTP). We project the fringes on a reference white plane and the target object and captured these projected images. Then we performed Fourier transform for both the images and subtracted frequency components of the reference plane from the object plane. While, theoretically it should have given just the new induced frequencies or the phase modulated by the object, our results did not turn out to be that good. It turns out in real world set up, there are many sources of errors that does not help filtering out the exact frequencies from the target image. The frequency of the fringes projected by the projector may not appear the same in the camera captured images. The possible reasons are:

1. There is a difference in intensity in camera output to projected intensities that may not map the exact smooth intensity value of a sinusoid. Hence a source of different frequencies than the one intended.
2. The perspective distortion may make the sinusoid appear a bit different to the camera.
3. Capturing illumination conditions may affect the captured intensities again messing with the intensities.
4. Other sources of noise.

Another algorithm we tried was multispectral fringe projection. The algorithm is like fringe projection but instead of applying an unwrapping algorithm, it is calculated from wrapped phases by projecting sinusoids with increasing frequencies. This method also did not work at par with our original fringe projection approach.

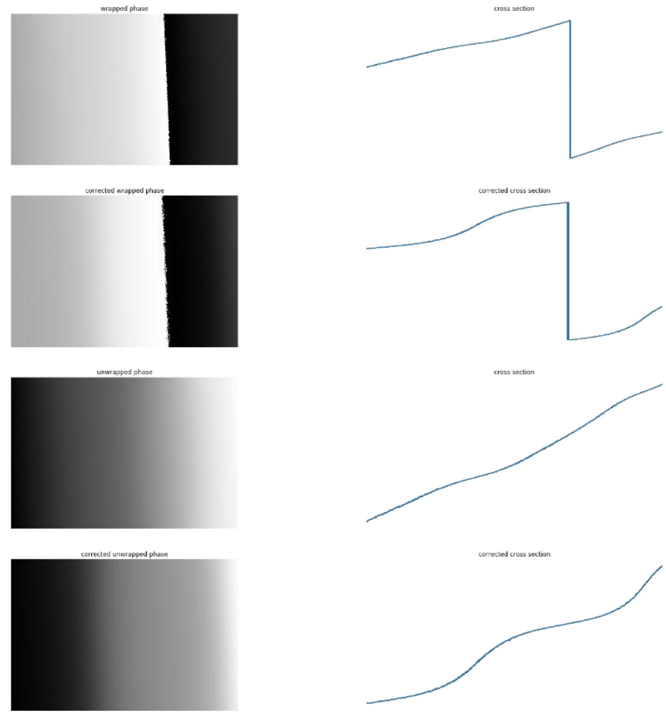
We also used a variant of fringe projection called double step. In this algorithm we project two sets of fringes shifted by a different amount. Overall algorithm is pretty much the same and we could get similar results as our original approach.

Background- Black vs White

Since we had observed from FTP that the captured signals are noisy, we changed background of our objects from a white plane to a black non reflective cloth to minimize the noise in the calculations.

Calibration

Due to inherent non-linearities of camera and projector, the captured and projected values are not the same. We give some intensities to the projector to project sinusoids, but the actual values projected are a result of non-linear projector response. Similarly, captured image also undergo a nonlinear transformation (gamma of the device) to produce final pixel intensities of the image. We need to correct these non-linearities in order to project and capture an accurate sinusoid. We do the camera/projector calibration by standard color checker chart method. Interestingly, we observed that non-linear response of camera and projector tend to cancel each other to produce a linear system response. We tried to confirm this by only calibrating projector and capturing the projected images so that the projector output is linear but that of camera is non-linear. We could find more non-linear variations in the captured image than the original non-linear versions. Hence, we kept the original system without explicitly color calibrating them. However, we have made it a note to correct for small variations in linearity by constructing a look up table with variations at each phase value and apply this correction at respective phase values.



From top: 1. Wrapped phase for uncalibrated setup,2. Wrapped phase for projector-calibrated setup, 3. Unwrapped phase for uncalibrated setup, 4. Unwrapped phase for projector-calibrated setup.