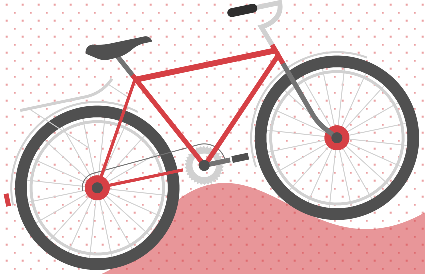
PHYSICS 301
Advanced Signal and Image Processing

ACTIVITY

08 PHASE SHIFT PROFILOMETRY



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objectives

Derive phase from images projected with phase shifted sinusoids.

Unwrap phase image. (Optional: use quality-guided phase unwrapping algorithm.

Reconstruct 3D from phase difference of reference and object image phase.

key take-aways

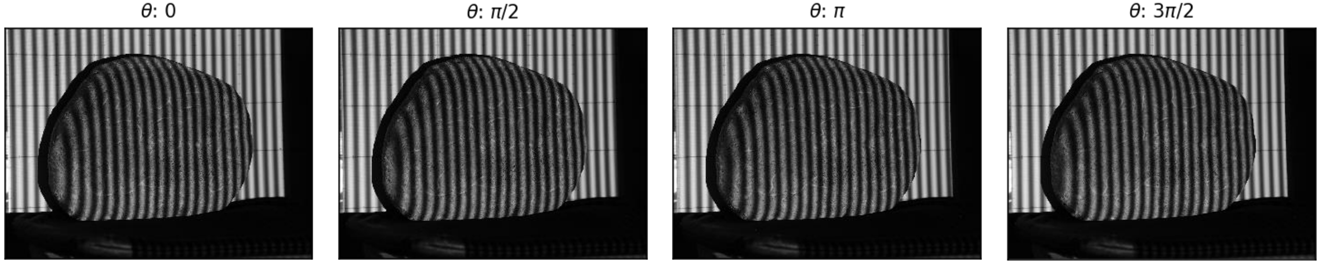
- The quality of 3D reconstruction using Phase-Shift Profilometry was improved by
  - implementing the algorithm in a select ROI at a time,
  - introducing perspective transformation, and
  - applying Fourier transform filtering to remove visible artifacts.

SOURCE CODE

- Physics-301/Activity 08 - Phase Shift Profilometry.ipynb at main · reneprincipejr/Physics-301 (github.com)
- https://drive.google.com/file/d/16xJkmief_X15NMBJYi6X5PeF0PFxxntN/view?usp=sharing

Structured Light

Projecting corrugated roof based on sinusoidal intensities constitute what we call **structured light illumination** [1]. In this activity, we try to **extract height information** by seeing how the object **bends** along the projected alternating patterns. Using four phase-shifted sinusoids, shown below is the object illuminated with structured light.



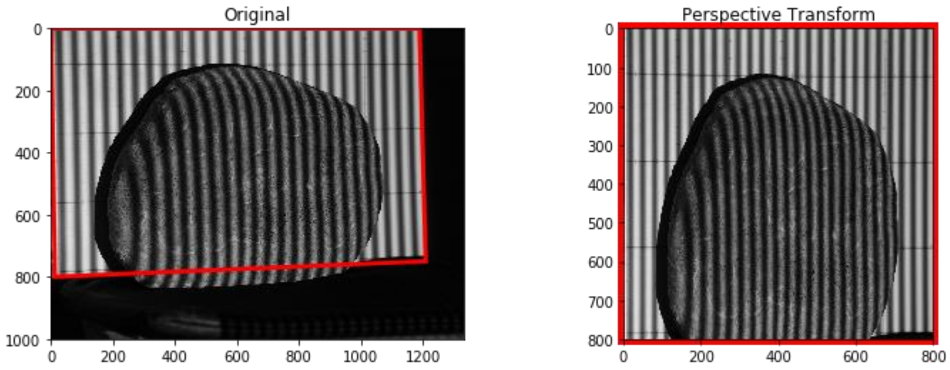
The intensity functions of these four images are given by

$$I_1(x,y) = I_0(x,y) + I_{mod}(x,y)\cos\big(\phi(x,y)\big)$$
$$I_2(x,y) = I_0(x,y) - I_{mod}(x,y)\sin(\phi(x,y))$$
$$I_3(x,y) = I_0(x,y) - I_{mod}(x,y)\cos(\phi(x,y))$$
$$I_4(x,y) = I_0(x,y) + I_{mod}(x,y)\sin(\phi(x,y))$$

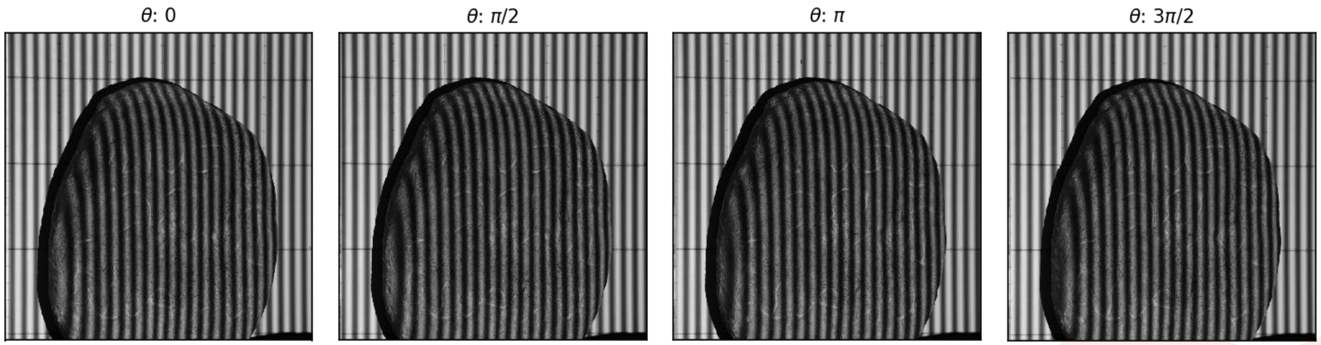
where $I_0(x,y)$ is the mean background intensity and $I_{mod}(x,y)$ is the intensity value of the fringe pattern [1].

Perspective Transform

Before proceeding, it's important to note that (1) the images are skewed in perspective and (2) we don't have the images of flat reference. To address the first problem, **we applied warp perspective functions** from Open-CV [2].

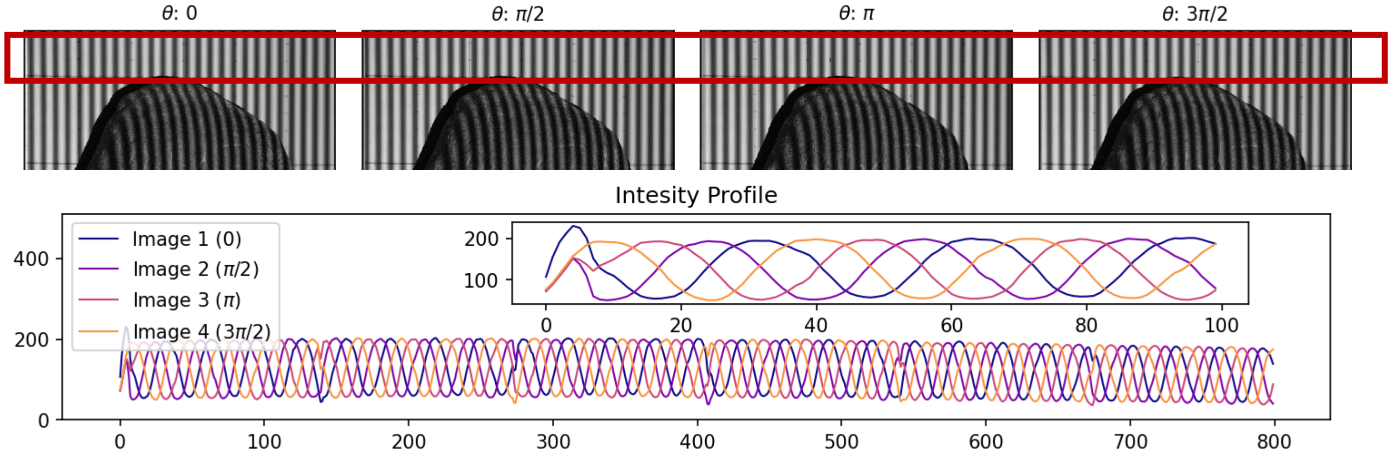


Shown below are the results of the perspective transform. It's much more uniform and the uninterrupted sinusoids are now vertically aligned.

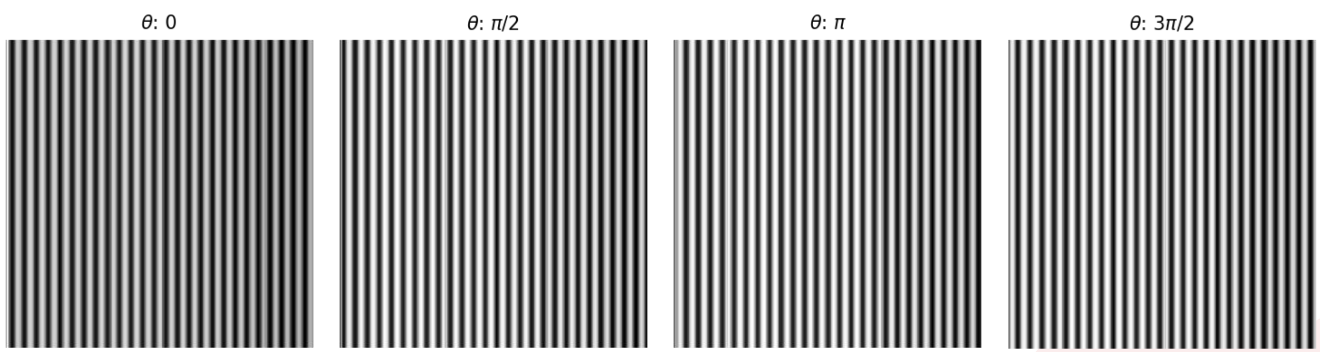


Flat reference

To address (2), we **synthetically reconstruct the sinusoidal structured light** from the regions in the image where the object doesn't obstruct the view.



By interpolating background information, we can **reconstruct the flat reference image** and the results are shown below.

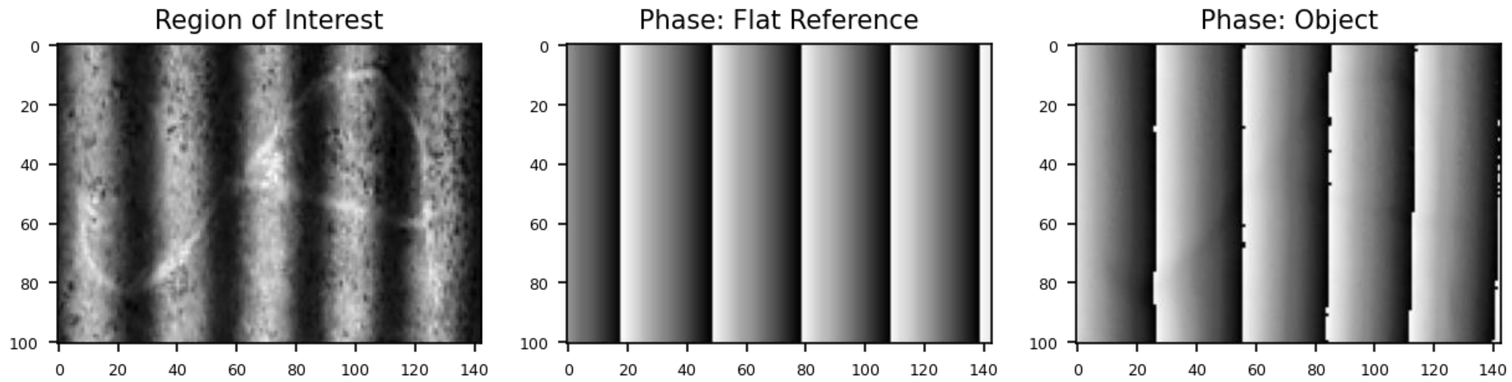


Phase Calculation

Our immediate goal is to obtain the phase $\phi(x, y)$ images for both the object and the flat reference using the intensities we pre-processed:

$$\phi(x,y) = \tan^{-1}\left(\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}\right)$$

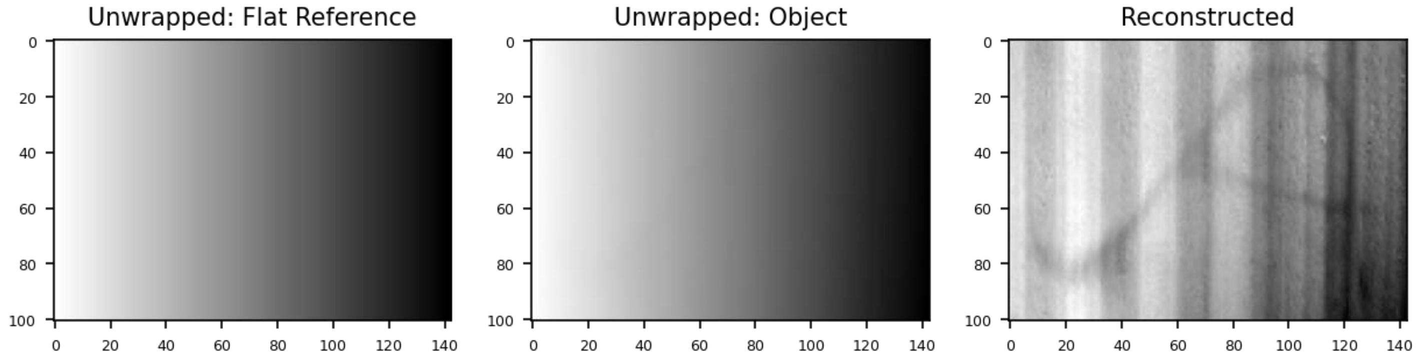
To do away with branch cuts singularities, we performed phase-shift profilometry on select regions of interest at a time, not on the entire image.



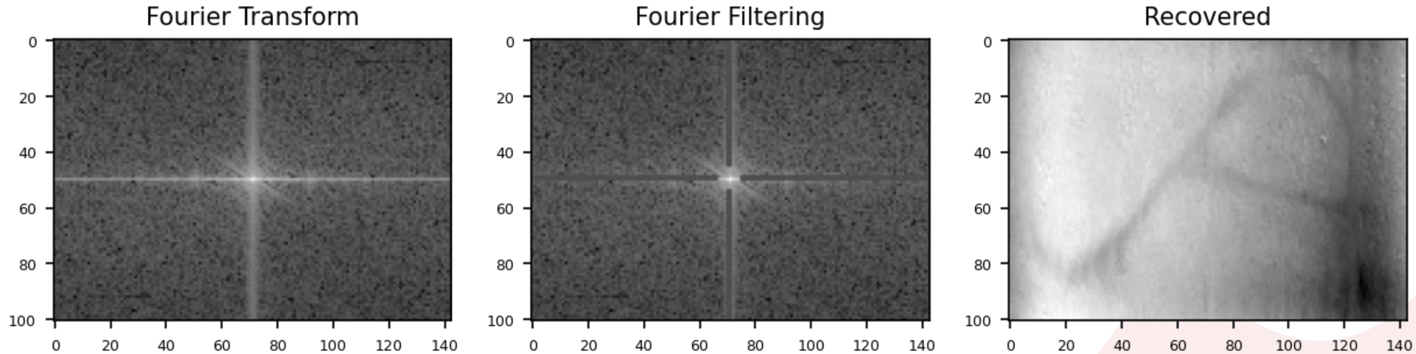
Notice that the phase images obtained were **discontinuous** due to the inverse tangent operation, hence, we must **apply phase unwrapping** which essentially adds 2π to the segments with π to $-\pi$ jumps.

Phase Difference

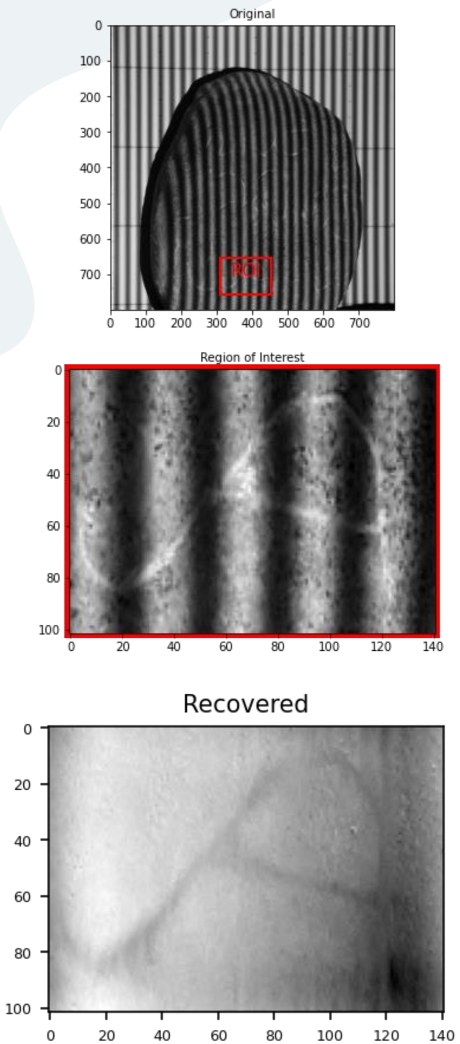
We can get a rough idea of the height information by getting the phase difference on the unwrapped images of the reference and object as shown:

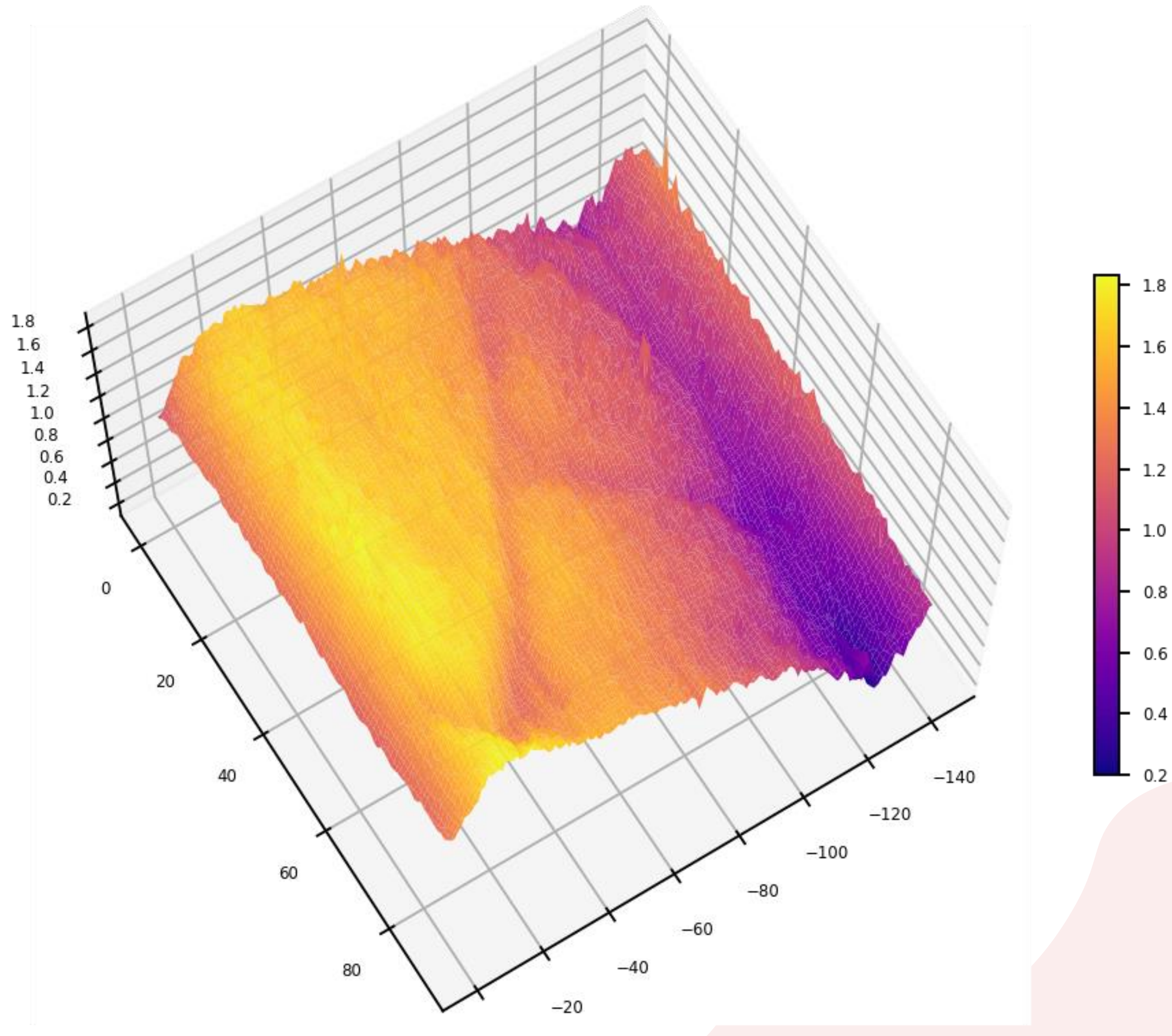


Notice that there are still noticeable reconstruction artifacts and so, we implement **Fourier filtering to remove unwanted frequencies**. Results show better reconstruction of the object of interest.

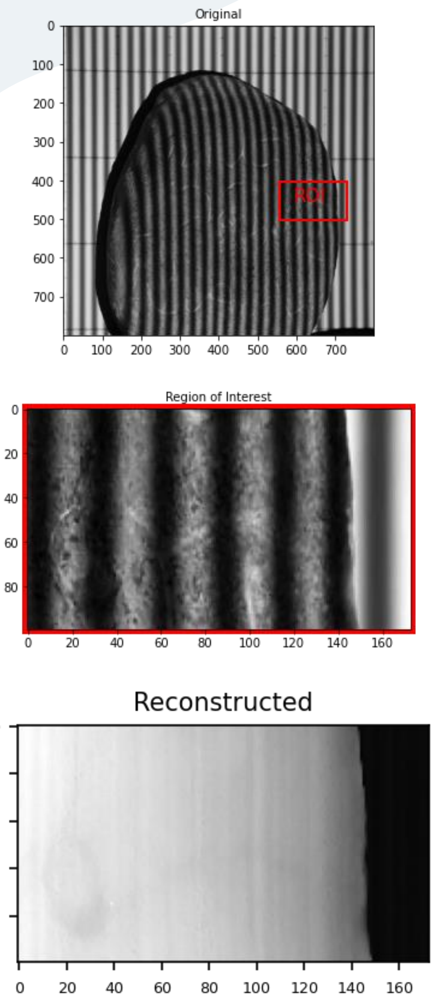


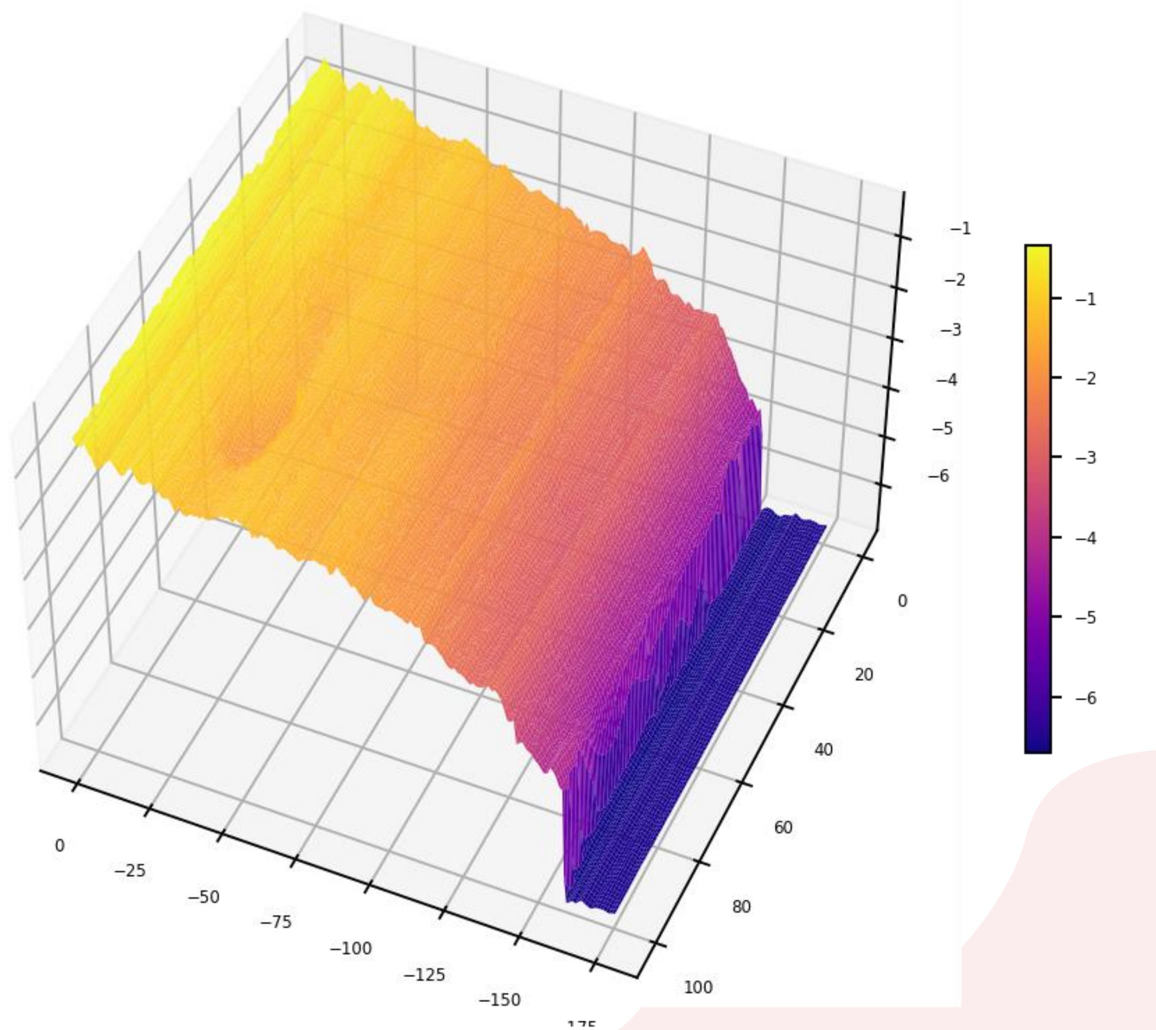
3D Reconstruction



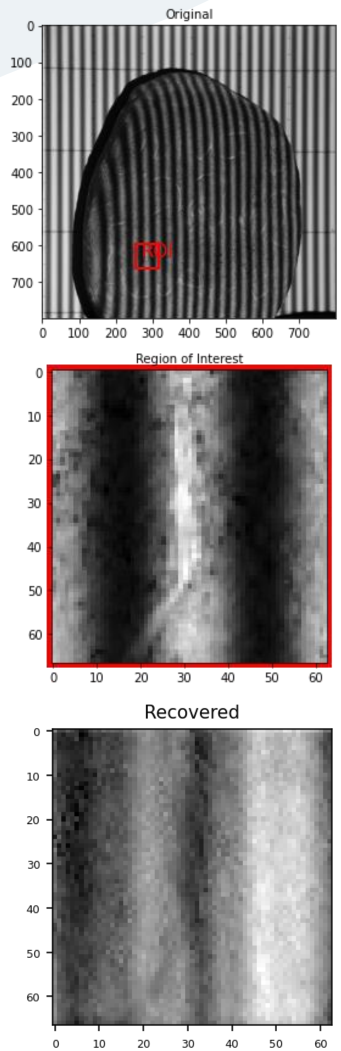


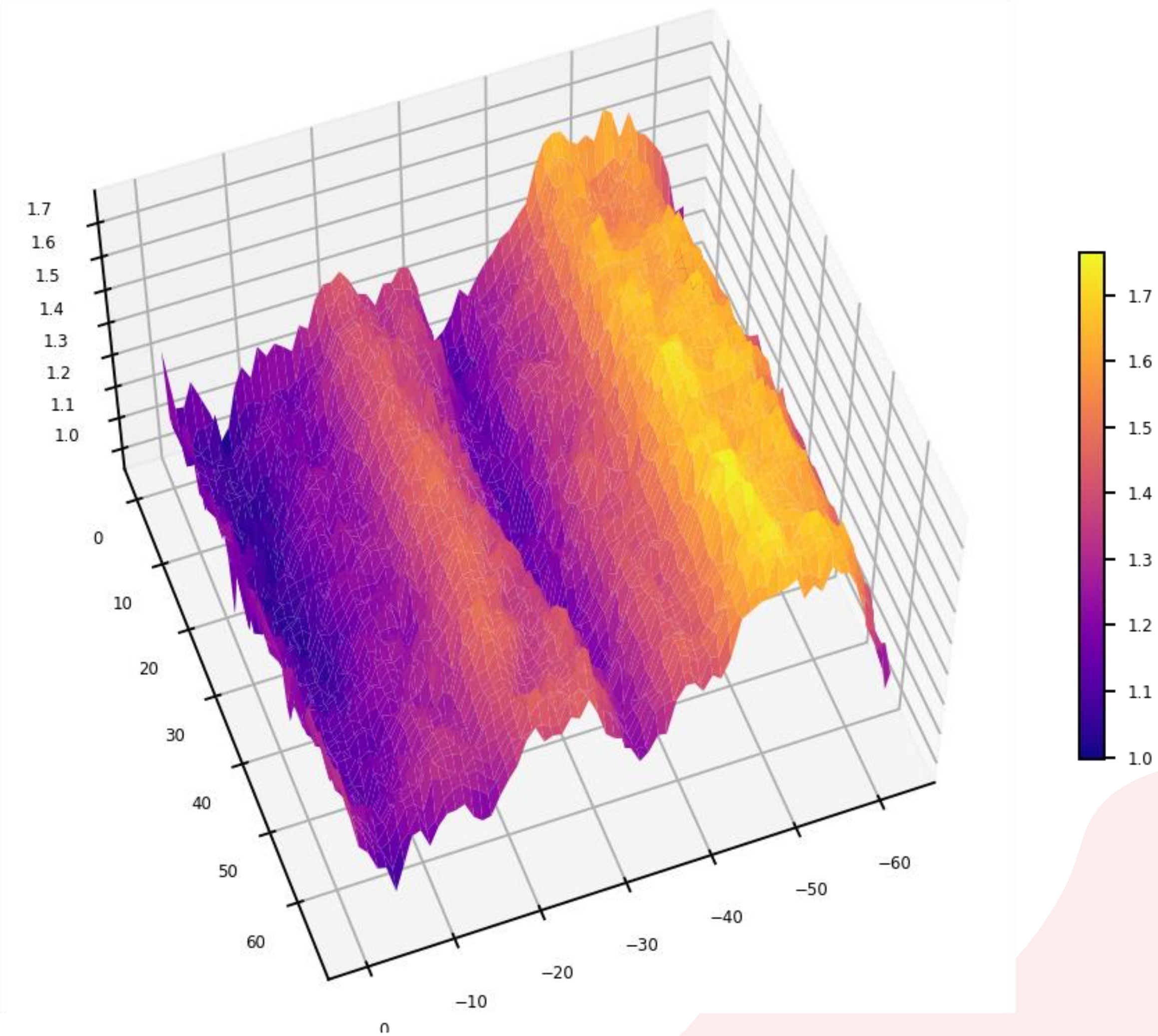
3D Reconstruction



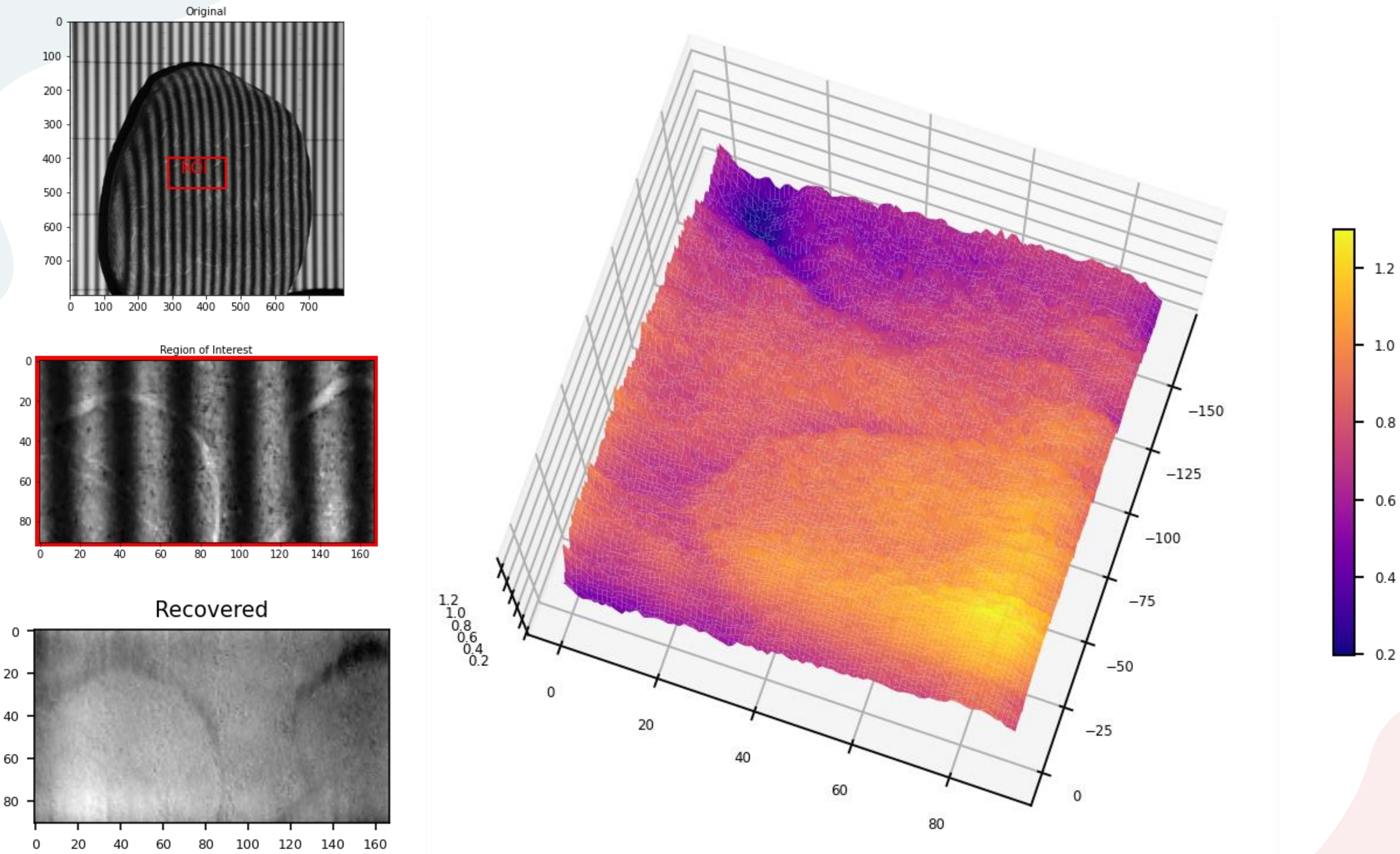


3D Reconstruction

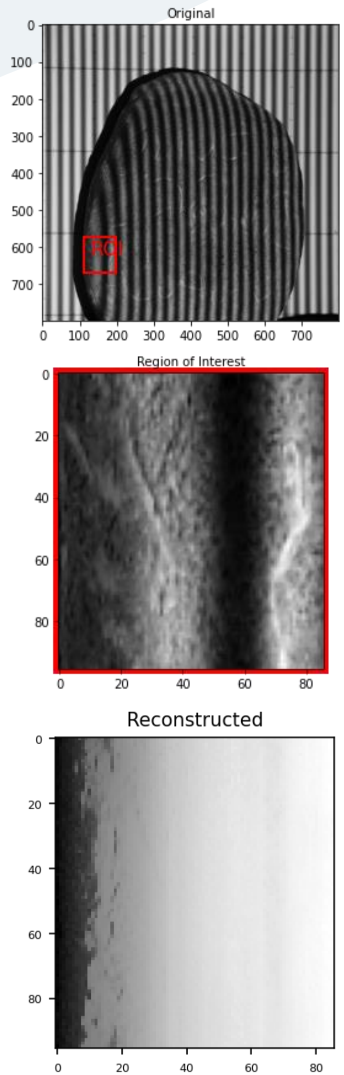


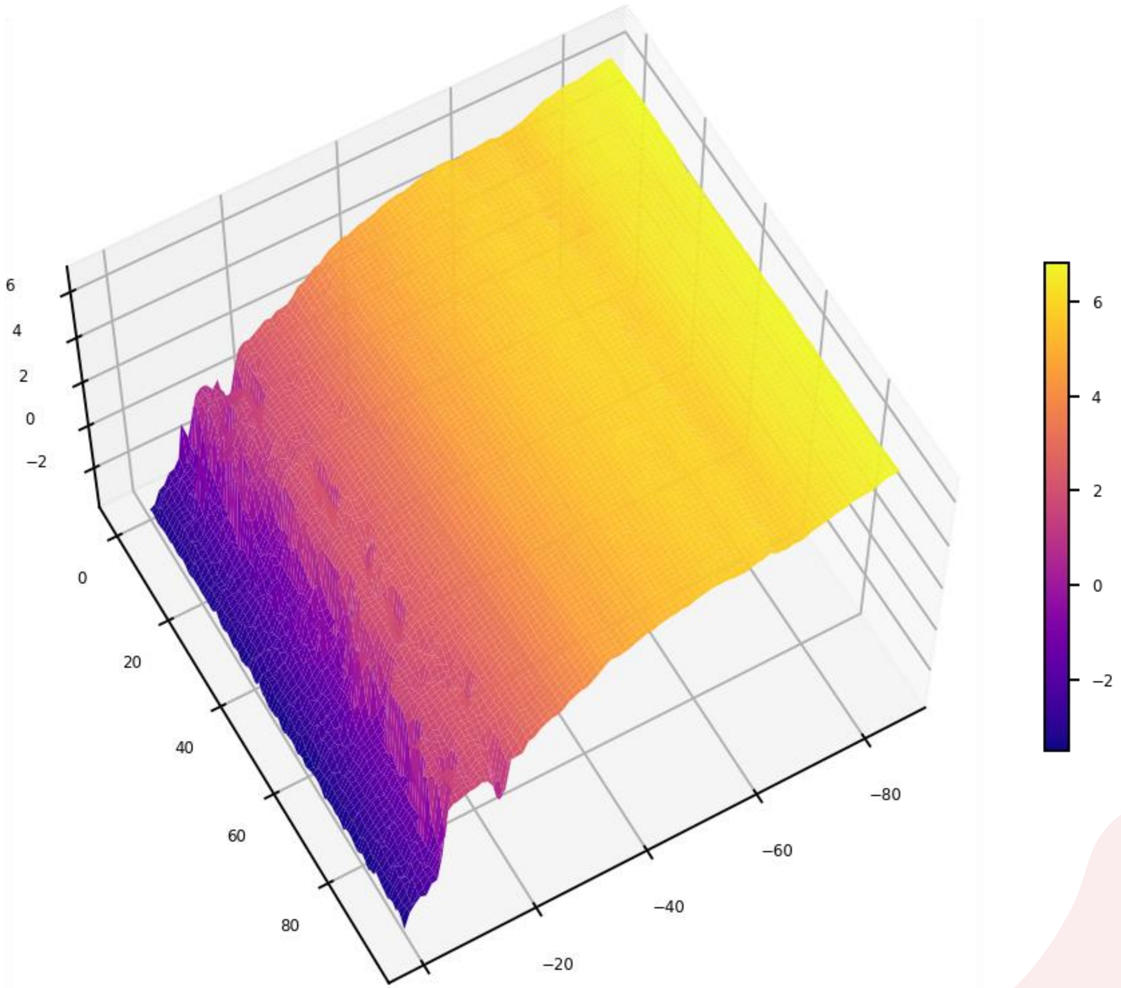


3D Reconstruction



3D Reconstruction





reflection

In conclusion, I was able to implement phase-shift profilometry (PFP) on a challenging object. Additional insights such as synthetically generating the flat reference and performing PFP on select regions of interest were the added-value compared to what we did in App Physics 187. Supplemental steps such as perspective transform and Fourier transform filtering that I implemented in this activity contributed greatly to yielding good qualitative results. 3D mesh maps of the character engravings, the texture, and the shape of the stones were generated accordingly. Unfortunately, I couldn't explore on implementing quality-guided unwrapping as suggested due to time constraints but considering our current results, I think it would be possible to perform full image PFP with better unwrapping algorithms to eliminate singularities and branch cuts. I genuinely had fun doing this activity and will surely explore the full extent of its strengths and limitations in the future.

With that said, I'd give myself a score of **98/100.**

references

- [1] M. Soriano, Physics 301 – Phase Shift Profilometry, (2022).
- [2] cv2.warpPerspective() | TheAILearner