Asian Journal of Physics
Vol. 31, Nos 9-10 (2022) 955-960
Available on: www.asianjournalofphysics.com

Investigation of rapid phase unwrapping technique for deformation metrology in digital holographic interferometry

Allaparthhhi Venkata Satya Vithin[1], Jagadesh Ramaiah[1] and Gannavarpu Rajshekhar[1,2]

[1]*Department of Electrical Engineering, Indian Institute of Technology, Kanpur-208 016, India*

[2]*Center for Laser and Photonics, Indian Institute of Technology, Kanpur-208 016, India*

In this paper, we explore the application of a fast phase unwrapping method in digital holographic interferometry for deformation analysis. In the proposed approach, we formulate the phase unwrapping equation using Poisson's equation and solve it using graphics processing unit computing. We demonstrate the method's ability to handle noisy signal data in a computationally efficient manner using numerical simulations. We also present the experimental results to show the method's practical utility in digital holographic interferometry.

Keywords: Digital holographic interferometry, Phase unwrapping, Graphics processing unit.

1 Introduction

Digital holographic interferometry (DHI) [1] is one of the prominent optical techniques for non-destructive testing [2], experimental mechanics [3], biomedical imaging [4] and material inspection [5]. This technique relies on recording of two holograms at the camera plane. After recording operation, we perform numerical reconstruction using digital Fresnel transform [1] to obtain the complex object wavefield signals, and subsequently perform conjugate multiplication to obtain the complex fringe signal. The main quantity of interest in DHI is the interference phase, which is encoded in the complex fringe signal. The reliable recovery of phase measurements enables us to quantify measurements related to refractive index, height profile, deformation and defects.

By computing the argument of the complex fringe signal using the arctangent operator, we obtain the wrapped phase map which contains discontinuities and lies between the interval $[-\pi, \pi]$. But the actual phase is a smooth and continuous distribution without any phase jumps or discontinuities. Therefore, phase unwrapping is an important tool for practical applications. Many techniques have been reported for phase unwrapping. The conventional technique for phase unwrapping involves Itoh's algorithm [6] whose major strength is computational simplicity, but it is error-prone in the presence of noise. To overcome this, many noise robust algorithms have been proposed. These methods are broadly classified into two classes. The first class includes path-dependent methods such as Mask cut [7], quality guided [8] and Flynn's [9] algorithms. In the second class, methods including the least squares method [10] and polynomial fitting [11] are based on path-independent algorithms. In addition to accuracy, speed also plays an important role in phase unwrapping. In the least-squares method, an unwrapping model was developed to arrive at Poisson's equation [12,13]. Further, this derived equation was solved using computationally efficient fast Fourier transforms (FFT) and graphics processing units (GPU) [14,15]. In this paper, we apply GPU based rapid phase unwrapping on the noisy fringes obtained in DHI for studying a deformed test specimen.

Corresponding author
e mail: gshekhar@iitk.ac.in (G Rajshekhar)

2 Theory

Let the object wave-field be considered as a complex signal with amplitude and phase. The wrapped phase is obtained by computing the argument of the wave-field. The unwrapped phase is given by

$$\phi(x, y) = \varphi(x, y) + 2p(x, y)\,\pi \tag{1}$$

Here, $\phi(x, y)$ denotes the unwrapped phase, $\varphi(x, y)$ indicates the wrapped phase and $p(x, y)$ is an integer function. Further, (x, y) are the pixel coordinates. Using the least squares approach, the phase unwrapping problem can be modeled in the form of a Poisson equation [14],

$$\nabla^2\phi(x, y) = L(x, y) \tag{2}$$

where, L is the input to the Poisson solver. We solve the equation using the discrete cosine transform (DCT) and inverse DCT operations as [15],

$$\phi(x, y) = IDCT\{[DCT\rho\ (x, y)]/\left(2\cos(\pi x/M) + 2\cos(\pi x/N) - 4\right)\} \tag{3}$$

The DCT is efficiently implemented using GPU computing [16,17]. The core idea of a GPU is to perform the operations in parallel as opposed to sequential operations. In the GPU, at the beginning of the program, multiple threads are launched. Each thread acts as a single processor. Programs written on a GPU are called device functions, whereas host functions are written on the central processing unit (CPU) of the computer. The GPU computing model has several important and computationally efficient packages to perform operations such as CUFFT and CUBLAS. The computationally intensive operations of the unwrapping procedure can be delegated to execute on the GPU device using the CUDA model which allows for massive parallel computing facilities and can result in high computational efficiency.

The algorithmic flow is shown in Algorithm 1. The noisy wrapped phase is loaded onto GPU memory. Then, it is transferred to the GPU device. Further, to obtain the phase initializer, Laplace's equation is computed on the GPU. Subsequently, the unwrapped phase is updated iteratively using the conjugate gradient algorithm until the convergence is obtained. Then the obtained unwrapped phase is transferred from GPU to CPU.

4 Results

For analysis of proposed method, we performed numerical simulations using noisy data. For the simulation, we modeled a unit amplitude signal with a polynomial phase function. Further, we added white Gaussian noise to the simulated signal. For error analysis, we provide error plots and the root mean square error. The results obtained from the proposed method are presented in Fig 1.

In Figs 1(a,d,g), we portray the simulated wrapped phase with AWGN of signal to noise ratio (SNR) values of 15, 10 and 5 dB, respectively. Figures 1(b,e,h) detail the estimated phases in radians. In Figs 1(c,f,i), we show the errors for phase estimation. The root mean square errors (RMSE) for the phase maps obtained from the proposed method for 15, 10 and 5 dB SNR values were computed as 0.44, 0.47 and 0.48 radians.

We demonstrate the gain in computational efficiency using a graphics processing unit based implementation in Table 1. The first column of the table indicates the image size in pixels. The second column indicates the execution time in seconds (s) required for the phase unwrapping method using a sequential implementation based only on CPU computing. In the table, the third column indicates the execution time in milliseconds (ms) for the parallel GPU based implementation of the unwrapping method. Next, we estimated the speed-up or gain in computational efficiency as the ratio (rounded to nearest integer) of the execution time values in second and third columns. The fourth column of the table indicates the gain in computational efficiency. From the table, we infer that GPU phase unwrapping has enormous speed benefits. For our GPU implementation, we used the NVIDIA Quadro M-2000 as the GPU device. The workstation had an Intel Xeon E3-1240 processor with 65 Gigabyte memory and 3.5 GHz clock speed.

Algorithm1: Implementation of phase unwrapping algorithm in GPU

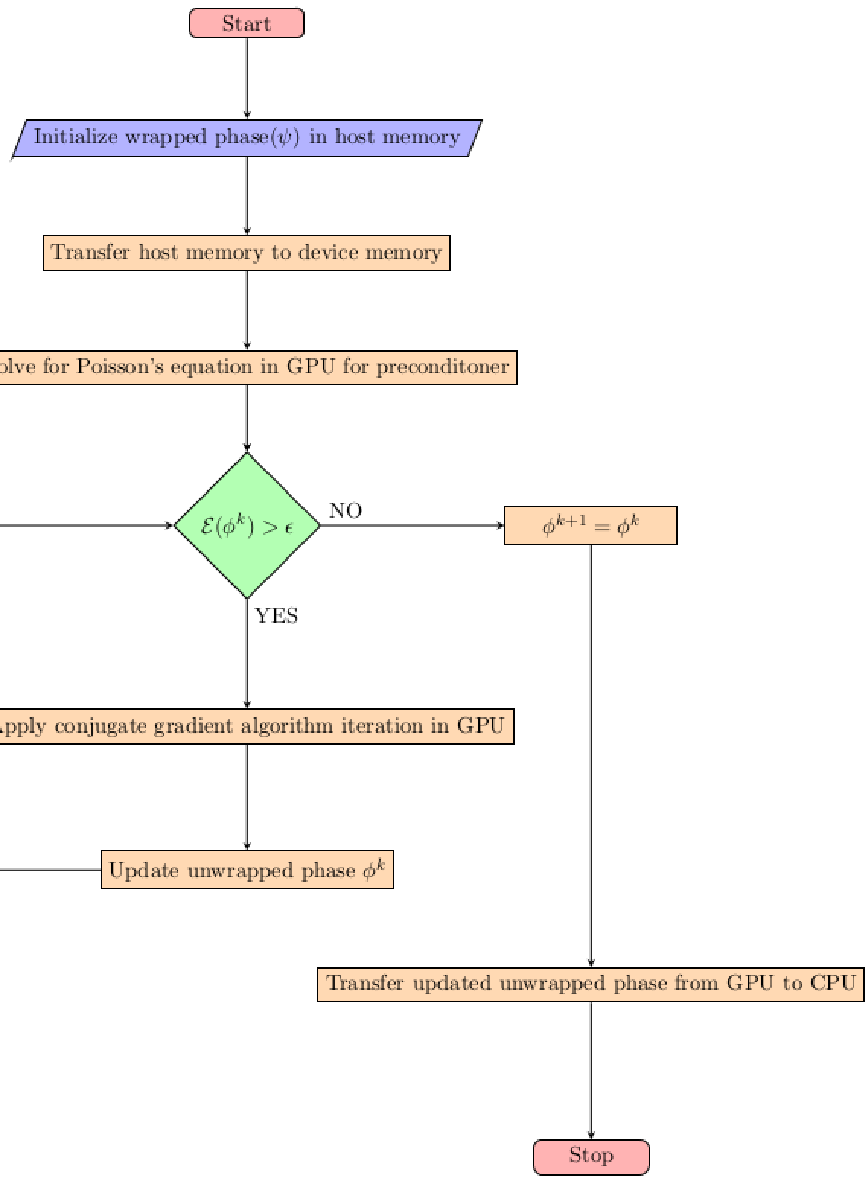

Table 1. Computational performance of GPU implementation

Image Size (pixels)	**Sequential implementation**	**GPU implementation**	**Gain**
250*250	2.34 s	34 ms	69
512*512	11.23 s	125 ms	90
1024*1024	47 s	500 ms	94

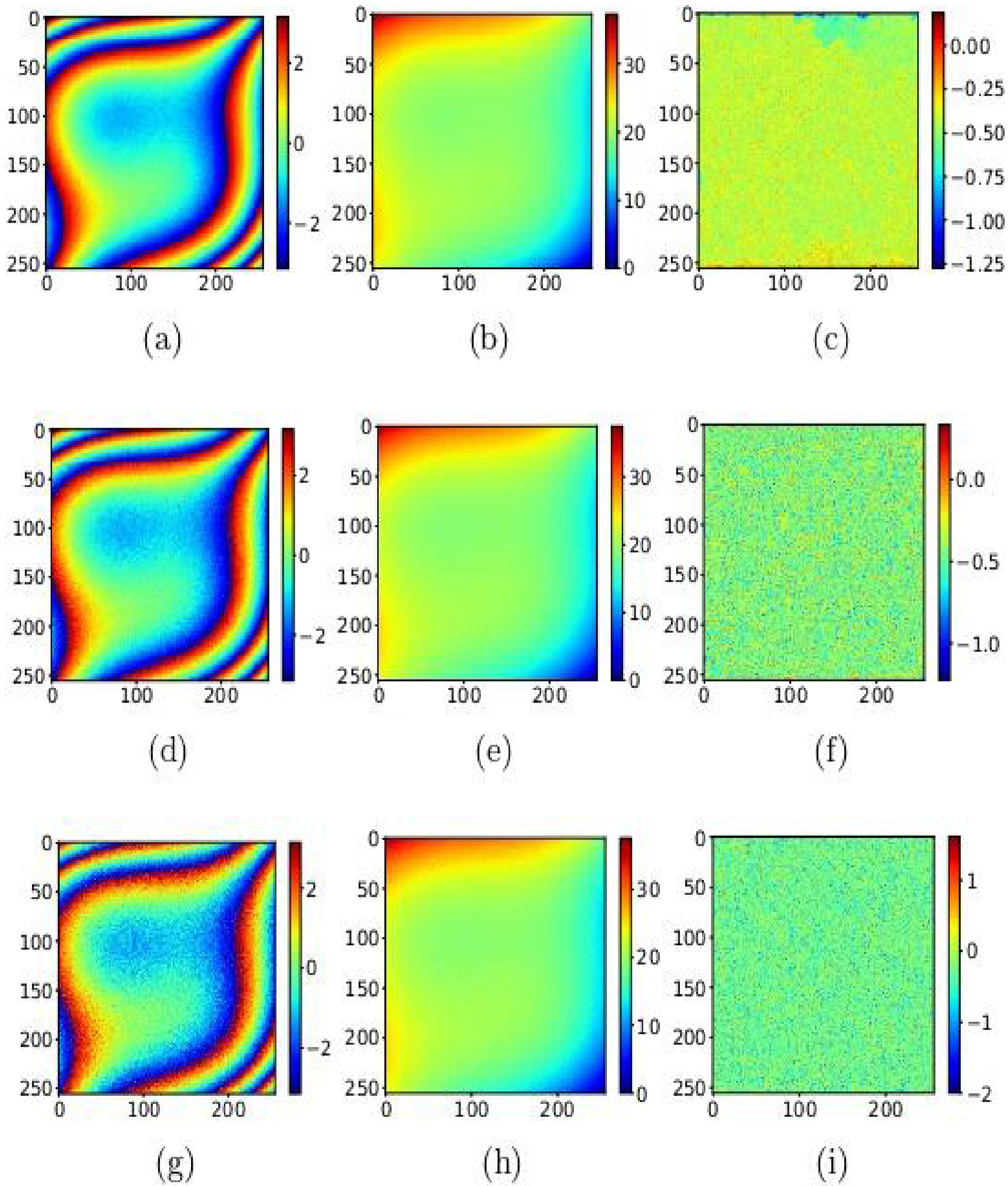

Fig 1. (a,d,g) Noisy simulated wrapped phases. (b,e,h) Estimated unwrapped phase maps in radians. (c,f,i) Phase estimation errors.

Next, we applied our method for deformation metrology using DHI. We used a circularly clamped Aluminum disk as the test specimen and applied deformation to it using a point load mechanism. We recorded the prior and post deformation holograms using a digital camera. The hologram processing was performed using the numerical reconstruction procedure followed by a complex superposition operation to obtain the complex fringe signal. The setup details are given in [18]. We applied the GPU enabled method to extract the unwrapped phase map from the wrapped phase or the argument of the complex fringe signal.

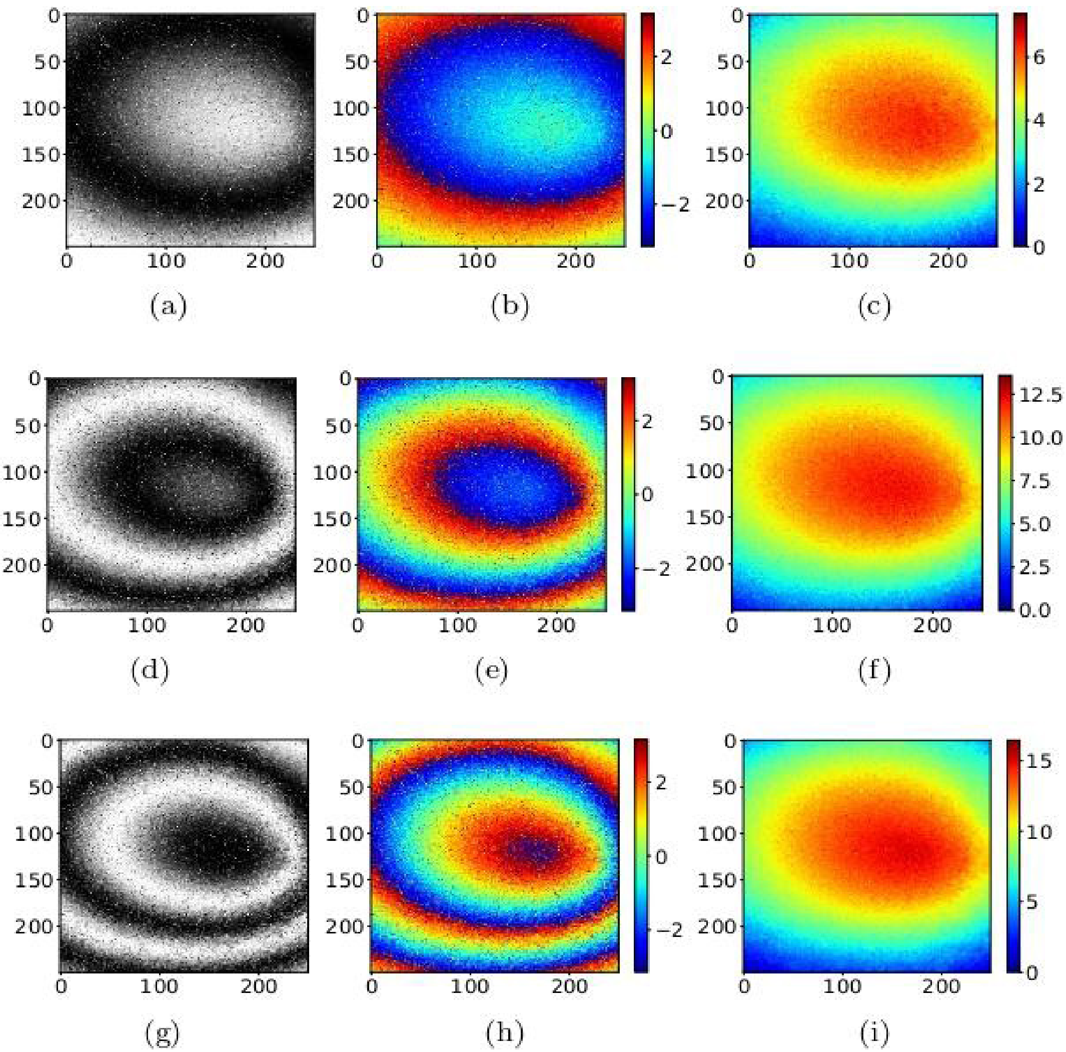

Fig 2. (a,d,g) Noisy experimental fringe patterns. (b,e,h) Wrapped phase maps. (c,f,i) Estimated unwrapped phase maps in radians.

In Figs 2(a,d,g), we show three fringe patterns, experimentally recorded in our DHI setup. We show the wrapped phases in Figs 2 (b,e,h). The unwrapped outputs obtained using our method are given in Figs 2 (c,f,i). From the fringe patterns, we observe an increase in fringe density which indicates the progressive increase in the deformation. This is also evident from the changing phase map range in the three cases. It is important to note that for dynamic studies, where the temporal nature of the deformation needs to be investigated, high computational efficiency is an important requirement. This is mainly because such studies involve the processing of a large stack of images. Hence, for these applications, the high computational performance of the GPU based methods would provide rapid processing capabilities.

5 Conclusion

We proposed the application of a GPU assisted phase unwrapping method in DHI. We observe that the graphics processing unit based phase unwrapping method is noise-resistant and has significant computational efficiency as compared to the sequential implementation. From experiments, we observe the practical applicability of the method in DHI. The main advantage of the GPU computing approach is tremendous reduction in computational complexity which paves the path for dynamic applications [17-19] in digital holographic interferometry.

Acknowledgements

The authors acknowledge the grant received from the Department of Science and Technology, Ministry of Science and Technology (DST/NM/NT/2018/2).

References

1. Schnars U, Jüptner W P O, Digital recording and numerical reconstruction of holograms, *Meas Sci Technol*, 13(2002), R85, doi.org/10.1088/0957-0233/13/9/201.
2. Flores-Moreno J M, la Torre-Ibarra M D, Hernandez-Montes M S, Santoyo F M, DHI contemporary methodologies: a review and frontiers, *Opt Lasers Eng*, 135(2020)106184; doi.org/10.1016/j.optlaseng.2020.106184.
3. Rajshekhar G, Gorthi S S, Rastogi P, Strain, curvature, and twist measurements in digital holographic interferometry using pseudo-Wigner–Ville distribution based method, *Rev Sci Instrum*, 80(2009)093107, doi.org/10.1063/1.3234260.
4. Pantelic D V, Grujic D Z, Vasiljevic D M, Single-beam, dual-view digital holographic interferometry for biomechanical strain measurements of biological objects, *J Biomed Opt*, 19(2014)127005; doi.org/10.1117/1.JBO.19.12.127005.
5. Theodorakeas P, Ibarra-Castanedo C, Sfarra S, N. P. Avdelidis, M. Koui, X. Maldague, D. Paoletti, and D. Ambrosini. NDT inspection of plastered mosaics by means of transient thermography and holographic interferometry, *NDT & E*, 47(2012)150–156.
6. Itoh K, Analysis of the phase unwrapping algorithm, *Appl Opt*, 21(1982)2470–2470.
7. Goldstein R M, Zebker H A and Werner C L, Satellite radar interferometry: two-dimensional phase unwrapping, *Radio Sci,* 23(1988)713–720.
8. Herráez M A, Burton D R, Lalor M J, Gdeisat M A, Fast two-dimensional phase-unwrapping algorithm based on sorting by reliability following a noncontinuous path, *Appl Opt*, 41(2002)7437–7444.
9. Flynn T J, Two-dimensional phase unwrapping with minimum weighted discontinuity, *J Opt Soc Am A*, 14(1997)2692–2701.
10. Ghiglia D C, Romero L A, Robust two-dimensional weighted and unweighted phase unwrapping that uses fast transforms and iterative methods, *J Opt Soc Am A*, 11(1994)107–117.
11. Liang Z-P, A model-based method for phase unwrapping, *IEEE Trans Med Imaging*, 15(1996)893–897.
12. Pritt M D, Shipman J S, Least-squares two-dimensional phase unwrapping using FFT's, *IEEE Trans Geosc Remote Sens*, 32(1984)706–708.
13. Schofield M A, Zhu Y, Fast phase unwrapping algorithm for interferometric applications, *Opt Lett*, 28(2003)1194–1196.
14. Jeught S, Sijbers J, Dirckx J, Fast Fourier-based phase unwrapping on the graphics processing unit in real-time imaging applications, *J Imaging*, 1(2015)31–44.
15. Zhao Z, Zhang H, Ma C, Fan C, Zhao H, Comparative study of phase unwrapping algorithms based on solving the Poisson equation, *Meas Sci Technol*, 31(2020)065004; 10.1088/1361-6501/ab63e8.
16. Sanders J, Kandrot E, CUDA by Example: An Introduction to General-Purpose GPU Programming, Addison-Wesley Professional, 2010.
17. Pandey D, Ramaiah J, Gannavarpu R, Fast measurement of phase and its derivatives in digital holographic interferometry using graphics processing unit assisted state space method, *Optik*, 248(2021)168172; doi.org/10.1016/j.ijleo.2021.168172
18. Ramaiah J, Gannavarpu R, Dynamic displacement measurement in digital holographic interferometry using eigenspace analysis, *Appl Opt*, 60(2021)10468–10476,
19. Vishnoi A, Rajshekhar G, Rapid deformation analysis in digital holographic interferometry using graphics processing unit accelerated Wigner–Ville distribution, *Appl Opt*, 58(2019)4420–4424.

[*Received*: 15.09.2021; *revised recd*: 22.05.2022; *accepted*: 05.10.2022]