Montecarlo computational proyect: Implementation of DBS algorithm

Juan Andrés González Moncada
Physics Department, XYZ University.
(Dated: March 23, 2024)

In the context of computer generated holography, the generation of binary amplitude holograms is of great interest, as the modulators required to project such holograms have a high refresh rate and are considerable affordable compared to other light modulators. The direct binary search algorithm is an algorithm for generating binary amplitude holograms that is generally considered to produce better results than any similar algorithm, at the cost of being time-consuming. In this work we implement the traditional direct binary search algorithm for amplitude modulation and corroborate that introducing random sampling increases the convergence rate of the algorithm, decreasing its time requirement. We also propose a modification of the algorithm that allows for complex modulation of the reconstructed field and test its results using numerical simulations.

I. INTRODUCTION

Computer generated holography (CGH) is a technique that has been of great interest due to its capability to control optical fields with unmatched precision, allowing the projection of scenes that were not previously recorded [1]. As a result, this technique has become a useful tool in a variety of applications [2–5]. In particular, it has been extensively studied in recent years in hopes of realizing holographic displays that would allow for virtual reality and augmented reality [6].

Despite its potential applications, CGH must overcome its share of challenges. One of these challenges lays in the lack of spatial light modulators (SLM) able to reproduce the holograms generated. There are no SLMs able to achieve full complex modulation without resorting to extremely precise arrangements that make the resulting systems bothersome to work with. As a result, computer generated holograms are mostly limited to amplitude-only holograms and phase-only holograms that can be projected using existing devices [7].

Another challenge that CGH faces is the speckle noise that arises from using coherent light sources [8]. This noise reduces the quality of the reconstructed image and limits its applications in potential holographic displays. Some studies have proposed eliminating speckle noise by using partially coherent or incoherent light sources [9–11], but this approach also reduces the maximum resolution of the resulting image. An alternative proposal is using temporal multiplexing to project multiple holograms with linearly independent speckle noise, so that the overall noise in the registered image is smoothed [12].

The registered speckle noise is reduced as the number of holograms projected through temporal multiplexing increases. However, projecting a high number of holograms in quick succession requires a SLM with a high refresh rate. Among existing devices, binary SLMs offer the highest refresh rates. In particular, binary amplitude SLMs such as digital micro-mirror devices (DMD) exceed the refresh rate of other alternatives by several orders of magnitude [13]. Additionally these devices are considerable cheaper than other SLMs. As a result, the generation of binary amplitude-only holograms is of great interest for achieving affordable holographic displays that could realize real time holographic video projection with high resolution and image quality through temporal multiplexing.

Binary amplitude-only hologram generation has been extensively studied and many algorithms have been proposed [2–5] . In particular, the direct binary search (DBS) algorithm often produces the best results, but it is computationally time consuming [14], defeating the purpose of using it for real-time holographic video projection. Recent studies have proposed modifications to the algorithm that increase its convergence rate and allow for parallel processing, resulting in much lower time requirements [15]. In this study, we implement this modification of the algorithm and analyze its results decreasing the time requirement. Additionally, we proposed a modification that increases the versatility of the algorithm by allowing to control the amplitude and phase of the resulting field, and tested it using numerical simulations.

II. METHODOLOGY

The DBS algorithm is an iterative algorithm for binary amplitude hologram generation, where each iteration is illustrated in 1. This algorithm receives an initially random binary hologram and switches the value of an individual pixel to check whether its reconstruction on the Fourier plane in a region of interest (ROI) better resembles a target image [16]. The quality of the reconstruction is measured using a metric that quantifies the similarity between the intensity of the reconstructed field and the desired image. In this study we used mean squared error (MSE) as a similarity metric. The MSE between two images X and $\hat{X}$ of size $N \times M$ pixels is defined as

$$\mathrm{MSE}(X, \hat{X}) = \sum_{n=1}^{N} \sum_{m=1}^{M} \left(X(n,m) - \hat{X}(n,m)\right)^2., \qquad (1)$$

so that its value decreases as the two images become more similar to each other. The pixel retains its new value if doing so improves the reconstruction; otherwise, the change is undone. Each pixel of the hologram is examined in this manner for each iteration of the algorithm, and the process continues until the metric surpasses a defined threshold.

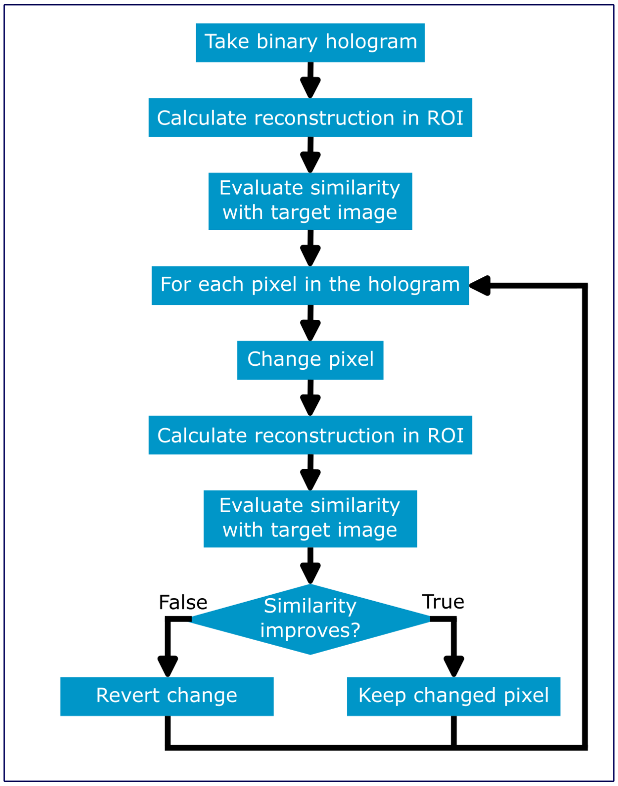

FIG. 1. Flowchart of DBS algorithm. ROI: Region of interest.

Traditionally, the DBS algorithm tests the pixels in the hologram in lexicographic order; that is, starting from the top left and moving forward row by row. Examining each pixel in this order is considered inefficient, as the initial optimizations must usually be reverted in subsequent iterations. Examining each pixel in a random order has been reported to produce better results in a lower number of iterations as it avoids this issue.

Regardless of the examining order, the DBS algorithm ultimately achieves amplitude modulation of the reconstructed field by ensuring that its intensity produces a given image. Nonetheless, the optical field produced by the holograms generated using this algorithm are complex fields, so it would be beneficial to extend the control and versatility of the algorithm by achieving complex modulation of the reconstructed field. To do this, we propose using a new similarity metric that seeks to approximate the produced complex field $C(x, y) = A(x, y) + iB(x, y)$ to a target complex field $\hat{C}$ by analyzing it real and imaginary part. The new metric is defined as

$$\text{Metric}(C, \hat{C}) = \text{MSE}(A, \hat{A}) + \text{MSE}(B, \hat{B}). \qquad (2)$$

where $\hat{A}$ and $\hat{B}$ are the real and imaginary parts of the target complex field. By reconstructing the complex field we expect to achieve independent complex and phase modulation.

III. RESULTS

We analyzed the effect of the testing order on the convergence rate of the DBS algorithm. We did so by implementing the algorithm using both lexicographic and random order to generate a binary 1024×1024 pixels amplitude-only hologram that reconstructed a 256×256 pixel object in a given ROI whose MSE with respect to a target images was less than 0.02. This test was made using an Intel Core i9-13900KF CPU with a RTX 4090 GPU. The results are shown in 2, it includes the final reconstruction, insets of each image for better visualization, and their MSE with respect to the original images.

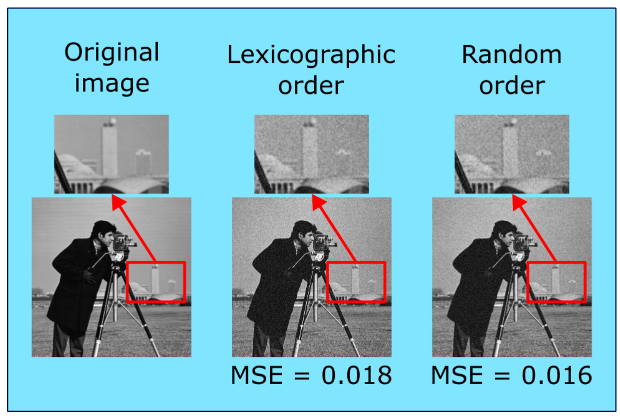

FIG. 2. Results using the DBS algorithm using lexicographic and random order. The result using lexicographic order was obtained using 4 iterations of algorithm while the result using random order was obtained using 2 iterations.

Given that the final result is required to have a MSE less than 0.02, the results using lexicographic and random order are quite similar. However, the algorithm using lexicographic order needed 4 iterations to reach the defined threshold, while the algorithm using random order only needed 2 iterations. This means that testing the pixels random order increased the convergence rate of the algorithm, saving a considerable amount of time by only requiring half as many iterations, where each iteration took in average 307 seconds to complete.

We tested whether the modification proposed to the algorithm using equation 2 enables complex modulation. To do this, we generated a complex field with a size of 128×128 pixels whose magnitude and phase each encoded an individual image. We then used 5 iterations of the modified DBS algorithm using both lexicographic and 5 iterations using random order to generate a 1024 × 1024 binary amplitude hologram whose Fourier transform hopefully reconstructs this complex field. The results of this test are shown in 3.

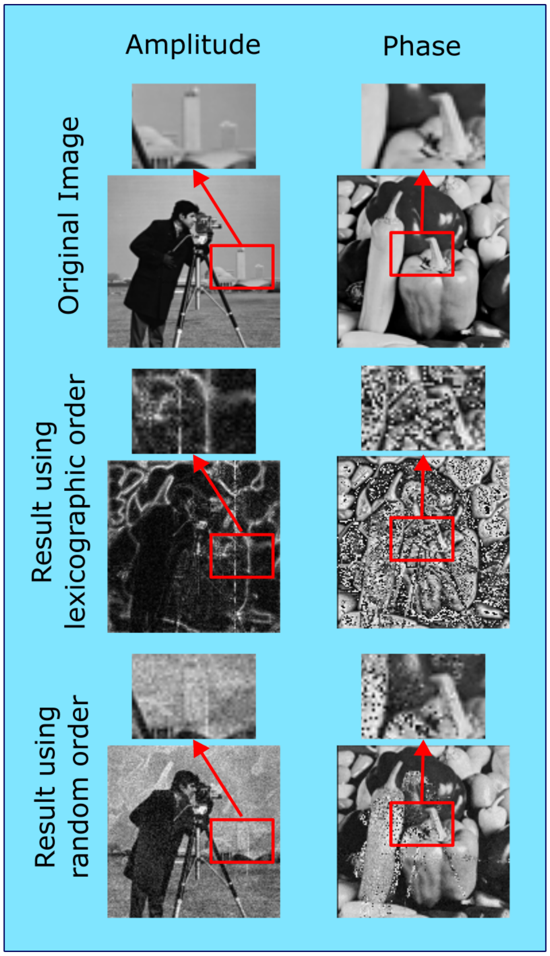

FIG. 3. Results using the DBS algorithm modified for complex modulation using lexicographic and random order.

We see that testing the hologram pixels in lexicographic order produces a final result where both images interact with each other in a manner that makes it impossible to retrieve any of two. Meanwhile, using random order to test the hologram pixels greatly reduces the crosstalk between both images, though the recovered images are still degraded with respect to the original ones. This crosstalk decreases as the number of iterations of the algorithm increases. Overall, the results for complex modulation using the modified DBS algorithm with random testing order are satisfactory.

IV. CONCLUSSIONS

We achieved intensity modulation using the DBS algorithm and corroborated that testing the hologram pixels in a random order increases the convergence rate of the algorithm. We also proposed and successfully implemented a modification of the algorithm for complex modulation. The effect of testing pixels in a random order on the convergence rate was proved once again, as the modification only achieved satisfactory results when doing so. Nonetheless, the time requirements of both algorithms are still excessive, making them unfit for temporal multiplexing. To face this challenge, modifications to the algorithm to allow for parallel processing and the use of machine learning should be explored as alternatives to speed up the binary hologram generation.

V. REFERENCES

[1] C. Slinger, C. Cameron, and M. Stanley, Computer-generated holography as a generic display technology, Computer **38**, 46 (2005).

[2] J. R. Moffitt, Y. R. Chemla, S. B. Smith, and C. Bustamante, Recent advances in optical tweezers, Annu. Rev. Biochem. **77**, 205 (2008).

[3] P.-A. Blanche, Holography, and the future of 3d display, Light: Advanced Manufacturing **2**, 446 (2021).

[4] M. Kumar, O. Matoba, X. Quan, S. K. Rajput, Y. Awatsuji, and Y. Tamada, Single-shot common-path off-axis digital holography: applications inbioimaging and optical metrology, Appl. Opt. **60**, A195 (2021).

[5] Y. Emery, T. Colomb, and E. Cuche, Metrology applications using off-axis digital holography microscopy, Journal of Physics: Photonics **3**, 034016 (2021).

[6] P.-A. Blanche, Holography, and the future of 3d display, Light: Advanced Manufacturing **2**, 446 (2021).

[7] E. Sahin, E. Stoykova, J. Mäkinen, and A. Gotchev, Computer-generated holograms for 3d imaging: a survey, ACM Computing Surveys (CSUR) **53**, 1 (2020).

[8] R. S. Sirohi, *Speckle metrology* (CRC Press, 2020).

[9] T. Tahara, Y. Zhang, J. Rosen, V. Anand, L. Cao, J. Wu, T. Koujin, A. Matsuda, A. Ishii, Y. Kozawa, *et al.*, Roadmap of incoherent digital holography, Applied Physics B **128**, 193 (2022).

[10] T. Kozacki and M. Chlipala, Color holographic display with white light led source and single phase only slm, Opt. Express **24**, 2189 (2016).

[11] S. Lee, D. Kim, S.-W. Nam, B. Lee, J. Cho, and B. Lee, Light source optimization for partially coherent holo-

graphic displays with consideration of speckle contrast, resolution, and depth of field, Scientific reports **10**, 18832 (2020).

[12] B. Lee, D. Kim, S. Lee, C. Chen, and B. Lee, High-contrast, speckle-free, true 3d holography via binary cgh optimization, Scientific reports **12**, 2811 (2022).

[13] S. Turtaev, I. T. Leite, K. J. Mitchell, M. J. Padgett, D. B. Phillips, and T. Čižmár, Comparison of nematic liquid-crystal and dmd based spatial light modulation in complex photonics, Opt. Express **25**, 29874 (2017).

[14] J.-P. Liu, C.-Q. Yu, and P. W. M. Tsang, Enhanced direct binary search algorithm for binary computer-generated fresnel holograms, Appl. Opt. **58**, 3735 (2019).

[15] J.-H. Kang, T. Leportier, M. Kim, and M.-C. Park, Non-iterative direct binary search algorithm for fast generation of binary holograms, Optics and Lasers in Engineering **122**, 312 (2019).

[16] M. A. Seldowitz, J. P. Allebach, and D. W. Sweeney, Synthesis of digital holograms by direct binary search, Applied optics **26**, 2788 (1987).

[17] B. Lee, D. Kim, S. Lee, C. Chen, and B. Lee, High-contrast, speckle-free, true 3d holography via binary cgh optimization, Scientific reports **12**, 2811 (2022).

[18] H. Goi, K. Komuro, and T. Nomura, Deep-learning-based binary hologram, Applied Optics **59**, 7103 (2020).

[19] P. Tsang, A comparison of several methods for generation of binary holograms of three dimensional (3d) scenes, 3D Research **3**, 1 (2012).