Focusing light through Scattering Medium

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1 Introduction

Light focusing and imaging through disordered media are of great significance for biomedical imaging, but they have been considered challenging for decades due to the inevitable multiple scattering of light in biological tissues. The traditional wisdom in this field has assumed that the image formation takes place only by the unscattered light, whose intensity decays exponentially in heterogeneous medium. After propagating more than one transport mean free path, light will be totally scrambled and as a result, the image information will be lost. On the other hand, if the light is coherent, the scattered light will have different optical path lengths and interfere randomly, forming speckles. Recently, researchers successfully overcame the effect of multiple scattering and realized light focusing inside or through disordered media using various techniques one of them being *iterative wavefront shaping.* In this report we demonstrate various iterative wavefront shaping algorithms both through simulation and experiment using a binary Spatial Light Modulator (SLM). All the python codes of the algorithms along with this report are available on Iterative Wavefront Shaping Algorithms.

2 Theory

The forward multiple scattering process is described by the following linear model:

$$E_m = \sum_{n=1}^{N} t_{mn} E_n = \sum_{n=1}^{N} |t_{mn}| exp(i\phi_{mn}) |E_n| exp(i\phi_n)$$

where E_n is the nth complex incident mode with amplitude $|E_n|$ and phase ϕ_n, while E_m is the mth complex optical mode transmitted from the scattering media. t_{mn} is one element in the complex transmission matrix which represents light scattering paths. Phase values in the globally optimal phase pattern satisfy ϕ_n = - ϕ_{mn}. Hence, when the phase is configured to this condition, light will be perfectly focused on the chosen point.

2.1 Step-wise Sequential Algorithm

This is the most basic of all the iterative wavefront shaping algorithms. Here, we use the fact tat the field at the detector is a linear superposition of the contributions from all segments. Hence, we can construct the optimal wavefront by optimizing each of the segments individually. In the case of binary SLM, we flip the value of phase at each of the N segments and monitor if the intensity at the target has increased. If it does, we store that phase as the optimal phase for that segment, otherwise we do the same for the original phase. The phase retardation of the segment is reset to the original phase, in this case 0, before continuing with the next segment. This way the background field (the mean contribution coming from all other segments) remains unchanged. Only after all the iterations are performed, the phase of each segment is set to this optimal value.

We define the persistence time T_p as the decay time of the field autocorrelate of the transmitted speckle, which is a measure of the temporal stability of the sample. Hence, the enhancement for a particular algorithm is limited by the number of iterations that can be performed before the sample changes too much which can be measured by the persistence time. T_p depends on the type of the sample and the environmental conditions.

In the absence of measurement noise or temporal instability, this algorithm is guaranteed to find the global maximum (in case of binary SLM it will be a local maximum) in the least number of iterations possible. However, when $NT_i \gg T_p$, the speckle pattern decorrelates before all measurements are performed and the algorithm will not work. (Here T_i is the time taken for 1 measurement)

2.2 Continuous Sequential Algorithm

The continuous sequential algorithm is very similar to the step-wise sequential algorithm except for the fact that the phase of each segment is set to its maximum value directly after each measurement. This approach has two advantages. First of all, the algorithm runs continuously and dynamically follows changes in the sample's scattering behavior. Furthermore, the target signal starts to increase directly, which increases the signal to noise ratio of successive measurements.

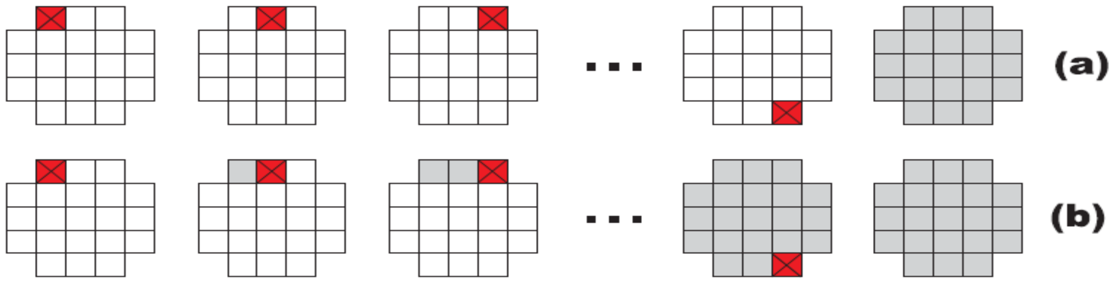

Figure 1: Principle used in the two different optimization algorithms. a) For the step-wise sequential algorithm, all segments are addressed sequentially (marked squares). After the optimal phase is measured for all segments, the modulator is updated to construct the optimal wavefront (light gray squares). b) The continuous sequential algorithm is equal to the first algorithm, except that the modulator is updated after each iteration

2.3 Genetic Algorithm (GA)

The GA technique increases the focal spot intensity faster than than both step-wise and continuous sequential algorithms. It is an optimization algorithm which uses principles inspired in nature to "evolve" toward a best solution. GAs are well-suited for large-scale optimization problems and thus attractive to optimize the phase of the N input modes in the focusing task.

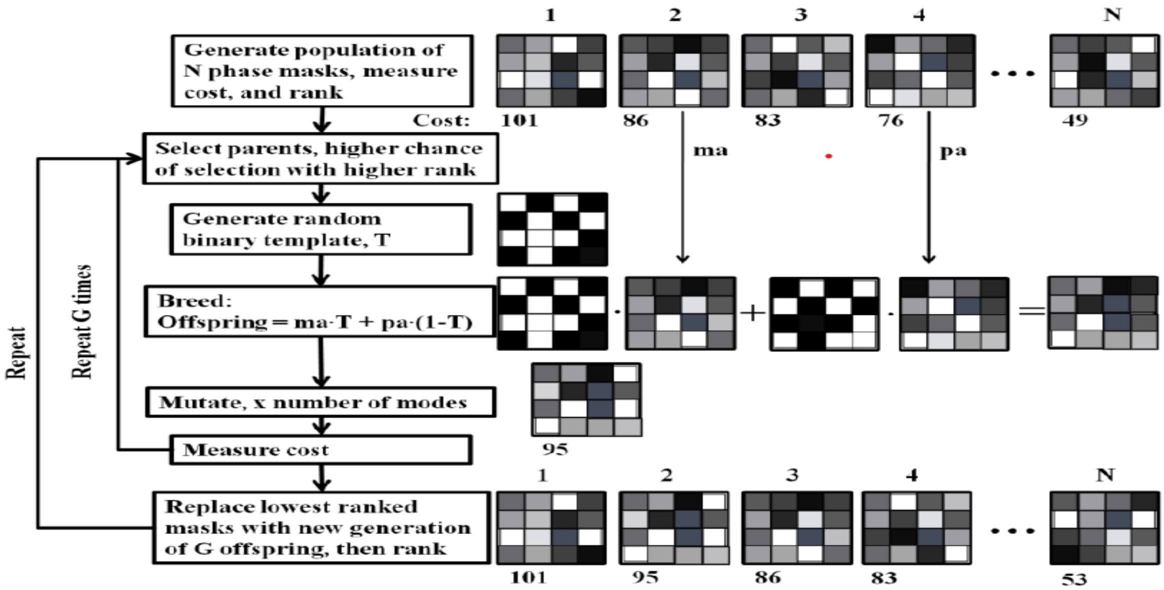

Figure 2: A block diagram showing the steps of genetic algorithm

The technique goes as follows:

- An initial population of random phase masks is generated wherein each phase mask is created by selecting each input mode value from a uniform pseudo-random distribution of phase values, in this case 0, π.
- Once the population is generated, we measure the intensity at the target spot corresponding to each phase mask.
- The population is ranked according to the intensity at target, the phase mask corresponding to higher intensity receiving higher rank.
- The algorithm then iteratively optimizes the phase masks through breeding and mutation operations.
- A random breeding template array, T, is created before breeding and the two parent masks (ma and pa) are selected based on their ranks .

- The input modes of the two parent masks are combined using T to create a new offspring as: Offspring = ma*T + pa*(1-T).
- The new phase masks are mutated by flipping the phase of a set number of input modes which is calculated by the mutation rate R that can be either set as a fixed value or change according to the algorithm performance.
- We generate 2 offsprings of same pair of ma and pa. The offsprings then replace the phase masks belonging to the lower half of the population. In our case, we modify this a bit and increase the population size of second generation by half the original population size. For subsequent generations, the population size then remains the same. The extra offsprings here are the ones which are generated using the offsprings of the phase masks belonging to the original population. **It was seen that this variant of GA converged faster than the basic GA.**
- This whole process repeats for a certain number of iterations or until a satisfactory solution is achieved.

3 Simulations

3.1 Step-wise Sequential Algorithm

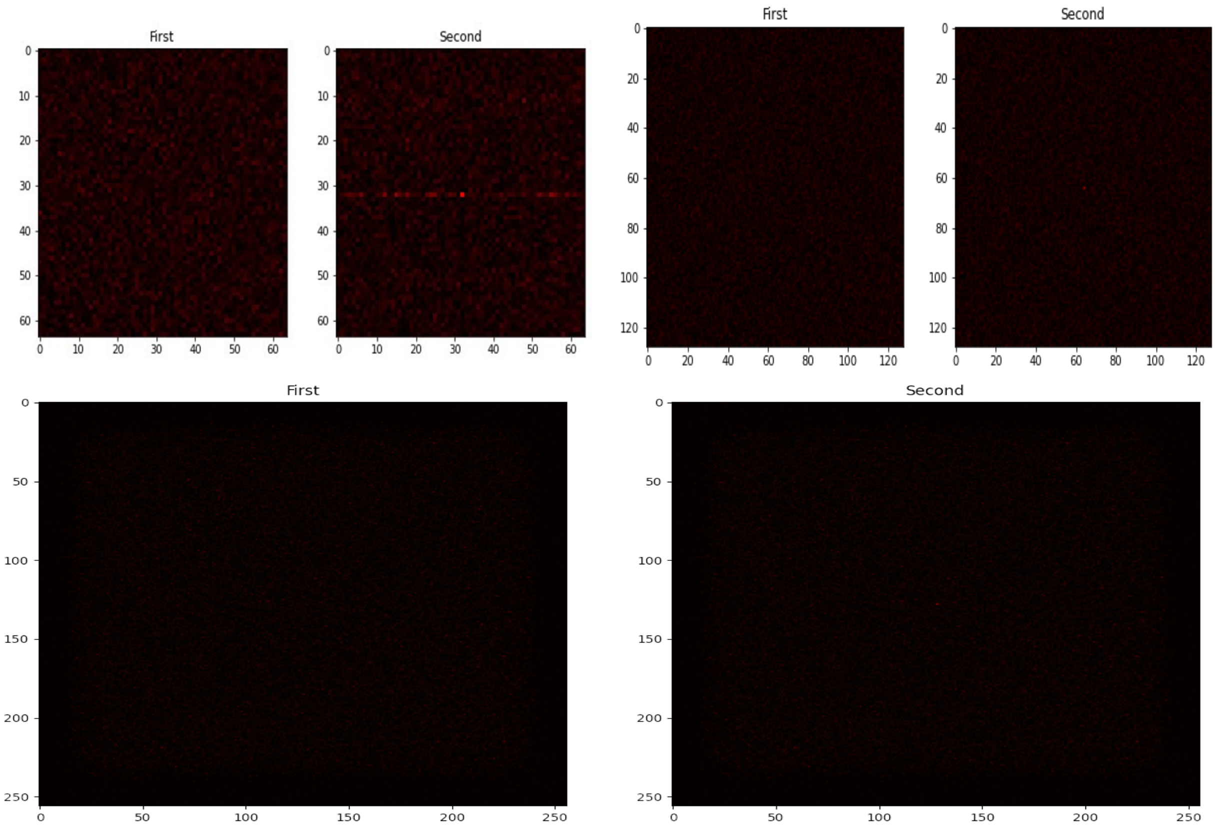

Figure 3: Simulations for 64x64, 128x128 and 256x256 resolution detector. A focal spot can be seen at centre of all three images

Though step sequential algorithm is quite robust, it is very slow and susceptible to dynamic changes in the scattering medium. Also, if the medium has low persistence time, the algorithm is not efficient for large number of input modes. After verifying the results of this algorithm, we proceed to the Genetic Algorithm which offers higher enhancement and works even for low persistence times.

3.2 Genetic Algorithm

3.2.1 Results for Basic GA

The intensity at the target spot increased from 6 to 64 which converged in 182 iterations.

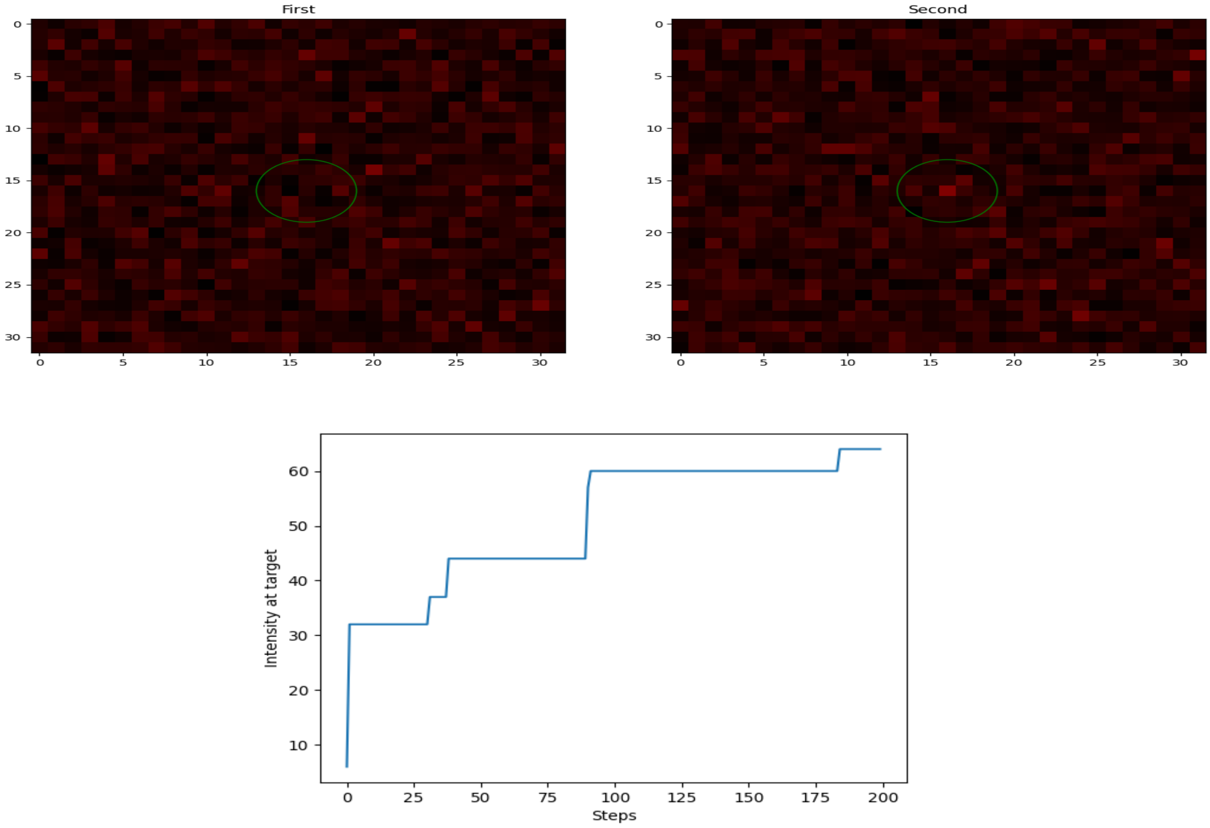

Figure 4: Results for the basic GA a) Images captured by the detector before and after the implementation of algorithm. A clear increase in the intensity can be seen at the centre in the second image. b) Graph of intensity profile at the target spot vs number of iterations

3.2.2 Results for Modified GA

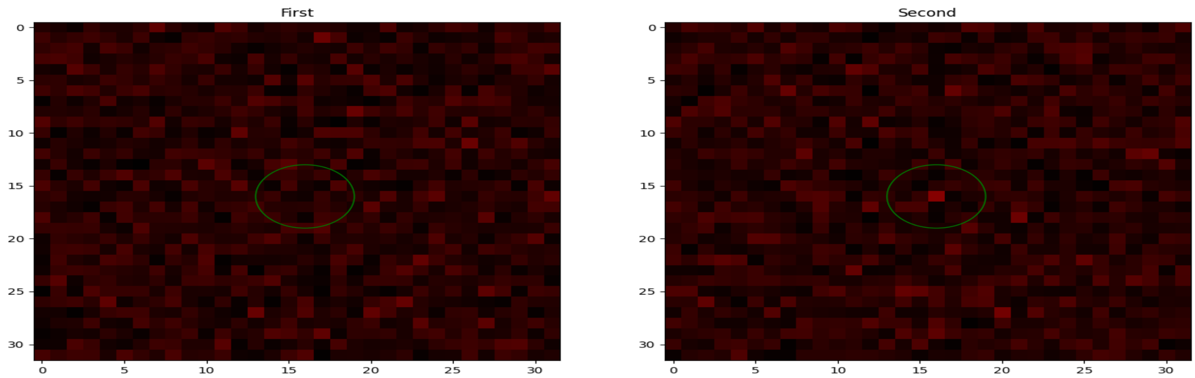

Figure 5: Images captured by the detector before and after the implementation of algorithm. A clear increase in the intensity can be seen at the centre in the second image.

The intensity at the target spot increased from 1 to 71 which took only 38 iterations to converge which is less than the previous case by about 5 times. Both the simulations took the same time of about 13.5 seconds.

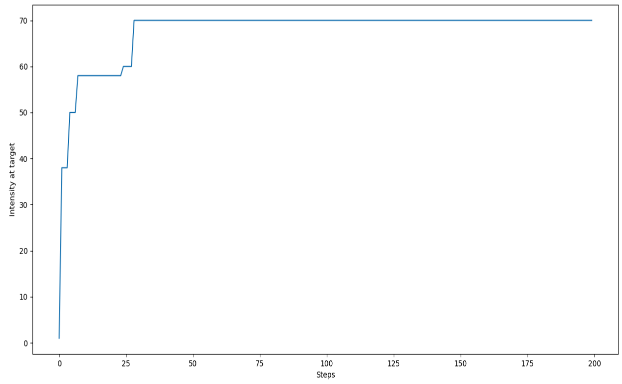

Figure 6: Graph of intensity profile at the target spot vs number of iterations

4 Experiment

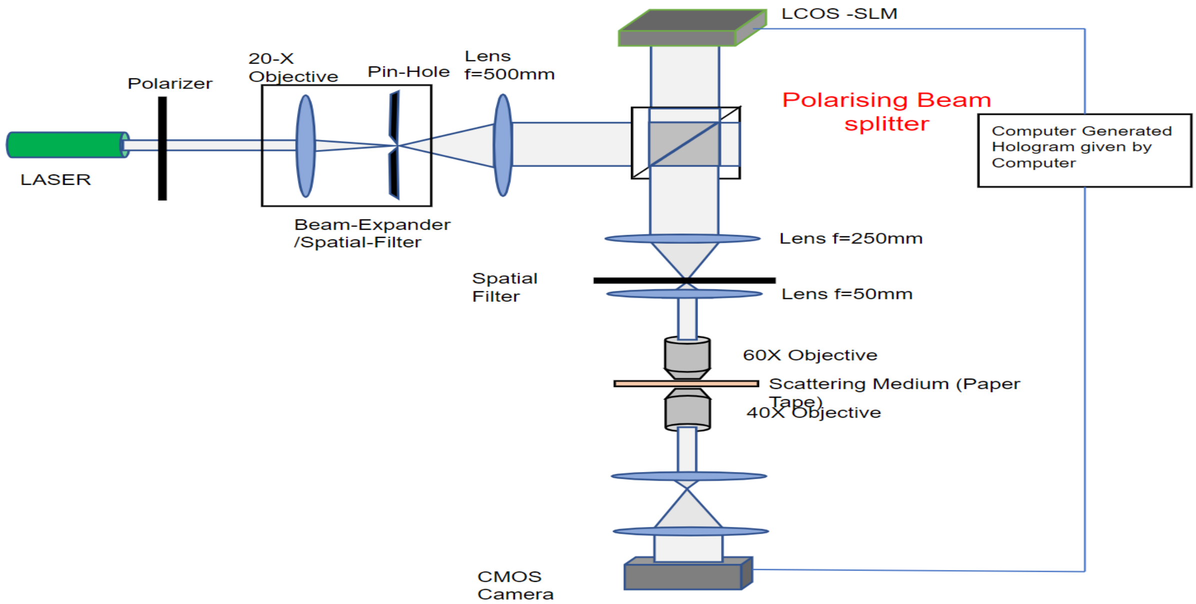

Figure 7: Schematic setup for the experiments

A spatial filter is used to block the unmodulated beam.

4.1 Continuous sequential algorithm

The experiment was performed for phase masks of resolution 20x16. The blue line depicts the maximum intensity reached until that point while running the algorithm. The orange line depicts the intensity at the target at each iteration. The graph indicates that even though a larger value of intensity has been reached, it fails to do so in subsequent iterations for some intervals before increasing again to a greater value. This behaviour is caused due to noise/poor SLM calibration as discussed later. Though the algorithm works, the enhancement is not great due to large amount of noise.

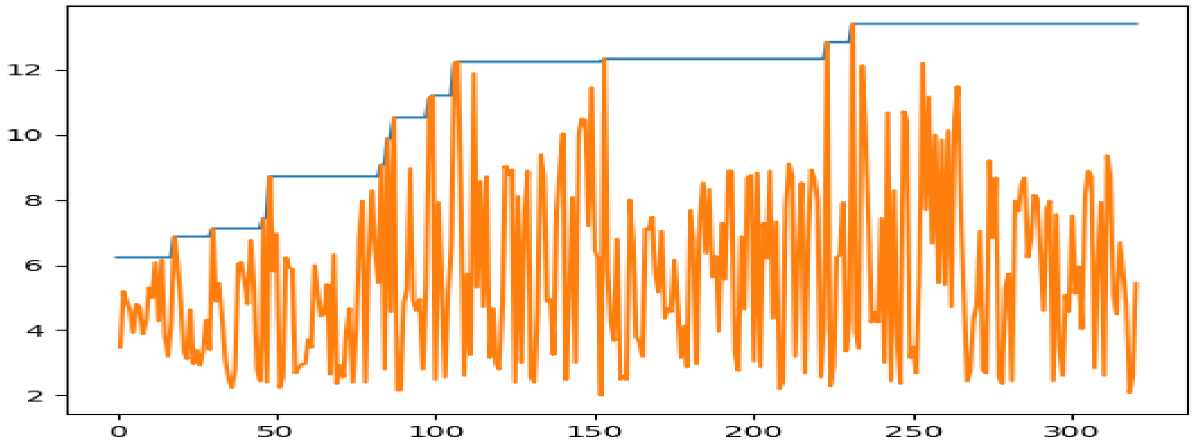

Figure 8: Intensity at the target spot vs No. of Iterations

4.2 Genetic Algorithm

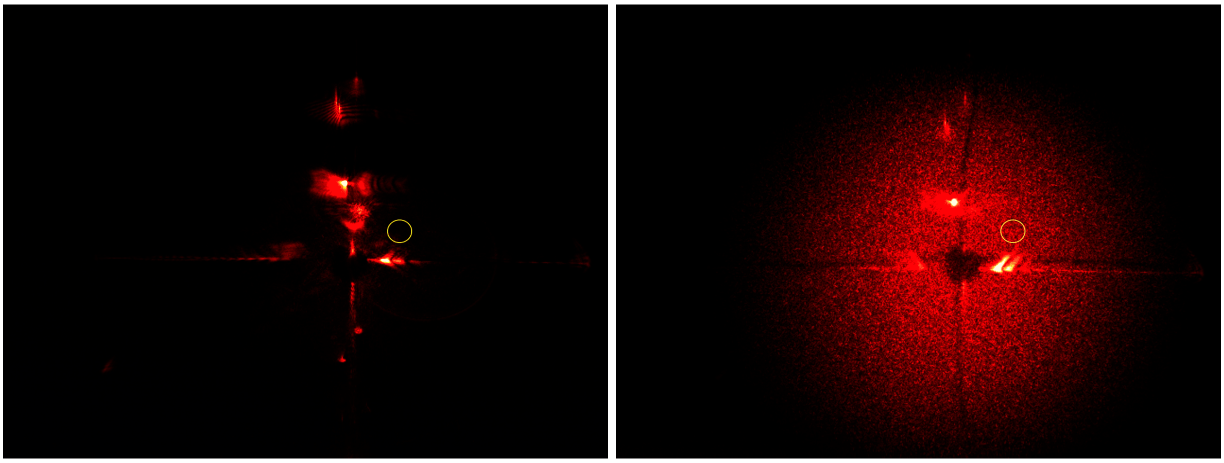

Figure 9: Images captured by the detector before and after the implementation of algorithm.

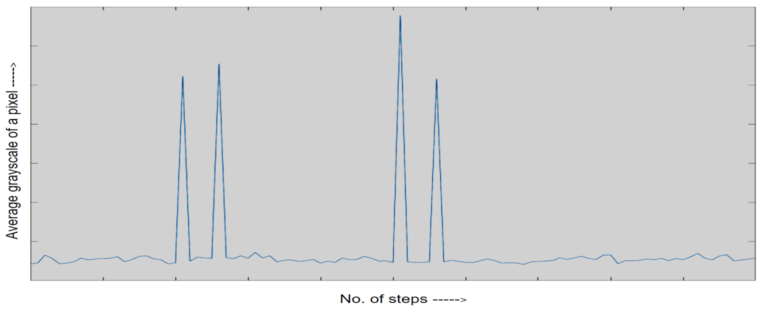

Figure 10: Intensity at target vs no. of iterations

The sudden changes in the intensity vs iterations graph were unexpected and the underlying cause is unknown. This experiment was performed using the resolution of phase mask same as the resolution of the SLM i.e. 1280x1024. The shadow due to zero order block is visible in the centre of both the images.

5 Noise/Poor SLM calibration

Due to unsatisfactory results and huge amount of noise, we decided to check the stability of the setup. To do this, we used a single phase mask and displayed it on SLM each time before capturing the speckle pattern using the camera. The following plots have been generated while using the Basler camera. We also did the same while using ThorLabs camera but the results were almost the same. The following plot shows the average grayscale value at the target at each iteration and it is evident that there is huge amount of noise and some huge dips which make the algorithms quite prone to erroneous results. There are a few outliers in the intensity distribution and also the spread of the

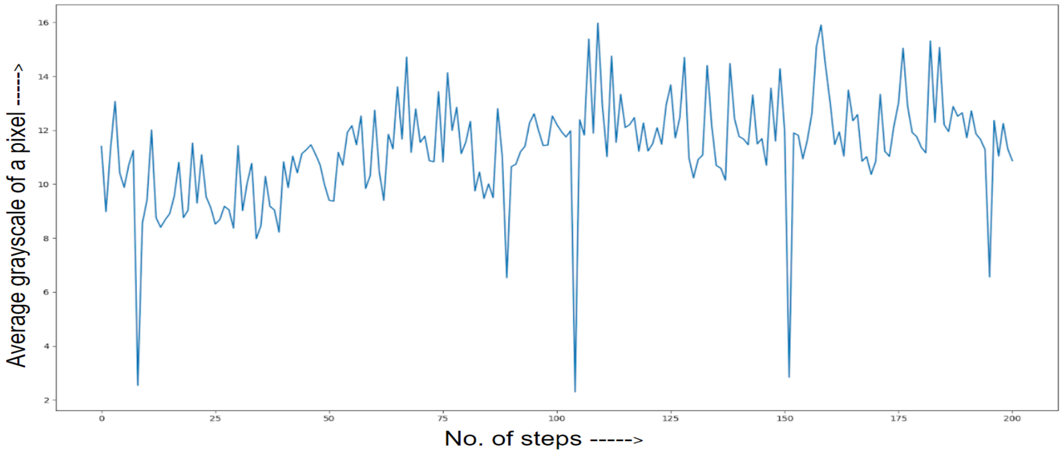

Figure 11: Intensity at target vs no. of iterations

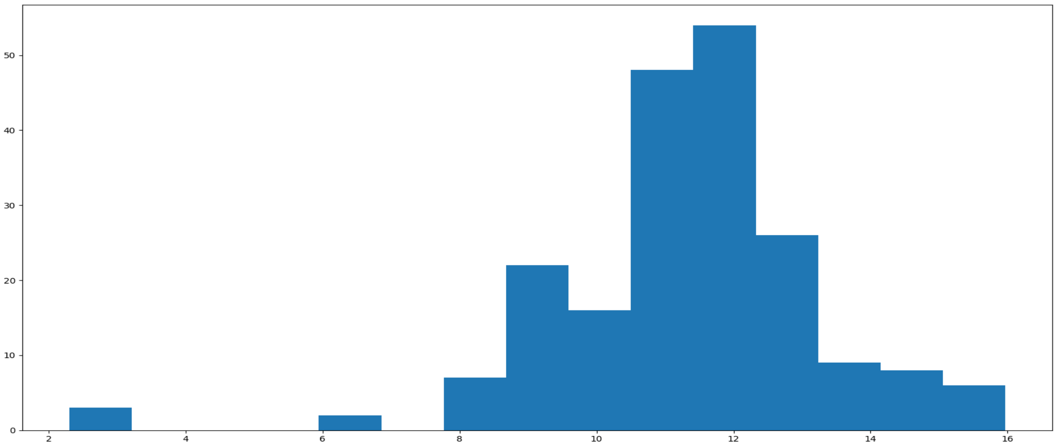

Figure 12: A histogram of the intensity at the target spot

distribution is quite large.

We then captured a series of images while keeping the phase mask constant. After having a look at the images, we realized that the whole image keeps shifting with time and is not stable within a particular region. Hence, the SLM was not able to maintain the position of the intensity pattern even when the scattering medium was a solid and the persistence time was quite large.

6 Conclusion

- We were able to demonstrate the working of the iterative wavefront shaping algorithms using simulations wherein the transmission matrix and the initial electric field were generated using 2D random normal distribution. All algorithms worked well in the simulations with decent enough speed.
- We depicted that the modified version of GA which we used was better than the traditional GA and converged a lot faster, at least in simulations.

- While performing experiments, CSA worked upto some extent but was limited by the noise and slow convergence of algorithm.
- GA was not able to show expected results and didn't work due to continuous movement and instability of the speckle pattern.
- We faced this issue for both Basler and ThorLabs cameras, which shows that the noise is not due to improper functioning of camera but due to poor stability of speckle pattern produced due to phase modulation by the SLM.

7 Acknowledgements

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