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Evaluation of the optimal steepest ascent algorithm for focusing light through turbid media

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ABSTRACT

We experimentally compare the optimal steepest ascent algorithm and the sequential method for feedback based iterative wavefront shaping. The former converges significantly faster and leads to a sharp focus behind a turbid medium.

Keywords: Imaging through turbid media; Medical and biological imaging; Non-invasive medical diagnostics

1. INTRODUCTION

Scattering of light is a fundamental physical phenomenon that scrambles light paths and limits the optical imaging resolution considerably. Apart from absorption and reflection, light scattering in biological tissues is originated from microscopic refractive index inhomogeneities due to which the light transmission decreases exponentially with thickness. It has been shown that there exist a number of eigen-wavefronts with transmission coefficients close to one in a highly scattering and non-absorbing random medium¹. Vellekoop and Mosk conducted breakthrough experiments showing multi-fold intensity enhancement behind scattering media using feedback based iterative wavefront optimization algorithms²⁻⁴. The time taken by these algorithms was limited by the low refreshing rate of spatial light modulators (SLMs). There have been multiple attempts to develop faster algorithms which require fewer iterative updates through the SLM⁵. Recently, several numerical approaches based on backscattered intensity analysis using the steepest ascent algorithm was developed for increasing the transmission when focusing through highly scattering random media^{6,7}. It was numerically shown that their algorithms converge very quickly to reach the optimum wavefront in just a few iterations.

We used the optimal steepest ascent algorithm combined with iterative feedback from forward scattered light behind the scattering media to get the optimum eigen-wavefront. Our preliminary experimental results showed that the optimal steepest ascent algorithm can achieve an enhancement factor of around 20 in contrast with respect to the background when the number of independently controlled input channels in the SLM was 100, which is comparable to the traditional sequential method. More importantly, the former algorithm was about 3 times faster. The speed improvement can be more significant when the number of independently controlled input channels in the SLM was faster.

2. EXPERIMENT

We spatially filtered and expanded a 532nm vertically polarized laser (Spectra Physics Millennia eV 5s) and divided it into two parts using a non-polarizing 50-50 plate beam splitter BS₁ as shown in figure 1. The transmitted beam is incident on a phase only LCoS SLM (Holoeye Pluto-Vis) giving a maximum phase shift of nearly 2π while the other part of the beam is dumped. The beam from the SLM display is then reflected back onto BS₁, deflected and then spatially filtered using two lenses L₂ (f=150mm) and L₃ (f=60mm) and a pinhole P₂ (500 μ m), to remove high frequency components arising from the pixelated structure of the SLM display chip. The SLM display plane is imaged on to the back of a 50x microscopic objective MO₂ which focuses the beam on to the diffusive portion of a frosted glass slide G. A portion of the forward scattered light is collected through another microscopic objective lens MO₃ (40x) and recorded by a CMOS camera (Hamamatsu ORCA-flash 4.0 v3). The intensity then is analysed by the OSA algorithm through MATLAB from which a feedback signal is generated and given to the SLM.

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Assuming that the whole wavefront of the initial beam is divided into several smaller segments (say M), the surface of the SLM display is also divided into the same number of superpixels M ($M=100$ in our case) so that each of those superpixels have a one to one correspondence with each of those wavefront segments respectively. We update the phase at each of those segments according to the feedback signal. Initially a random phase is applied all over the SLM display. The OSA algorithm then uses the gradient approach^{6,7} along with a golden section search algorithm to find the best magnitude of the M -dimensional phase vector, i.e. $\vec{S}$, in which each element is the phase of one superpixel, for maximizing the contrast at the focus behind the frosted glass slide G . This iterative process can be expressed by the following equation,

$$\vec{S}_{i+1} = \vec{S}_i + \mu \times \vec{\nabla} C \quad (1)$$

in which $\vec{S}$, μ and $\vec{\nabla} C$ denotes the M -Dimensional phase vector, step size and the M -dimensional gradient of the normalized contrast C at the targeted focus respectively. Once the gradient of the contrast is determined, we use the golden section search algorithm to find the best magnitude of the step size μ corresponding to the maximum contrast of the focus behind the frosted glass slide G . The whole process is continued till the OSA algorithm converges and a stable focus is obtained behind the scattering medium G .

Figure 1. Setup for the experiment. MO, L, P, BS₁, D and G stand for the microscopic objective, converging lens, pinhole, 50-50 non-polarizing plate beam splitter, SLM LCOS display and frosted glass slide, respectively.

3. RESULTS AND CONCLUSION

The experimental results are compiled in figure 2. Figure 2(a) shows the performance of the optimal steepest ascent algorithm over the sequential algorithm with respect to time. It shows the intensity at the focus behind the frosted glass slide G with respect to time. It can be seen that with the OSA algorithm the intensity at the focus rapidly increases and converges in only a few iterations, which is much faster than the sequential scanning algorithm. Moreover, if any perturbation is imposed on the light distribution inside the scattering medium, the OSA algorithm can restore the focus faster than the conventional sequential algorithm. This is because the OSA algorithm recalculates the optimum phase vector $\vec{S}$ in each iteration whereas in the sequential method each SLM channel is scanned only once for the optimum phase. This is particularly important in dealing with dynamic media, e.g. biological tissues. The speed of the current system is limited by the refreshing rate of SLM (currently operating at 5Hz). Figure 2(b) shows the optimized wavefront in grayscale (0 to 2π). Figure 2(c) show the initial distribution of intensity in the form of speckles behind the frosted glass slide and figure 2(d) shows the bright focal spot formed behind the frosted glass slide after completion of the OSA algorithm.

Figure 2. (a) Light intensity at the focus behind the frosted glass slide G with respect to time for both the optimal steepest ascent (black circles) and sequential algorithm (red circles); (b) the optimized wavefront; (c) and (d) show the intensity distribution before and after running the OSA algorithm, respectively.

In conclusion, we experimentally compared the performance of the optimal steepest ascent algorithm OSA and the conventional stepwise sequential algorithm for feedback based wavefront shaping. Both algorithms enable us to focus light behind the scattering medium (a frosted glass slide in our case). As it is evident from the experimental results, the OSA algorithm converge faster than the sequential algorithm. The amount of time required to reach 90% of the maximum enhancement is about three times in the OSA algorithm. Apart from being faster, another advantage of the OSA algorithm is that it is more appropriate for dynamic media than the conventional sequential algorithm as it can recover the focusing behind a scattering medium faster in just a few iterations.

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