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Optimization of focusing through scattering media using the continuous sequential algorithm

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Abstract

The ability to control the propagation of light through scattering media is essential for atmospheric optics, astronomy, biomedical imaging and remote sensing. The optimization of focusing light through a scattering medium is of particular interest for the case of highly scattering materials. Optical wavefront beam-shaping plays a critical role in optimizing such a propagation; however, an enormous field of adjustable parameters makes the overall task complicated. Here, we propose and experimentally evaluate several variations on the standard continuous sequential algorithm that hold a promise of revealing new, faster and more efficient optimization algorithms for selecting an optical wavefront to focus light through a scattering medium. We demonstrate that the order in which pixels are chosen in the continuous sequential algorithm can lead to a 2-fold decrease in the number of iterations required to reach a given enhancement.

Keywords

beam phase shaping; wavefront shaping; optimization algorithm; scattering; continuous sequential algorithm

1. Introduction

As light propagates through a scattering material, interference and scattering effects cause the beam to be scattered in all directions. This reduces the amount of light directly transmitted through the material. This is illustrated in Fig. 1, where a laser focus without a scattering material in the beam is compared to the same laser beam with a scattering material in the beam. This scattering of light appears to cause the information of the laser beam to be lost. However, research has discovered that through the use of adaptive optics and wavefront shaping, the scattering effects caused by a material may be suppressed, and the information recovered. This is demonstrated in Fig. 1(c).

These techniques that utilize wavefront shaping to control the way that light scatters in a scattering medium have been the subject of much research recently. Many possible applications for these techniques have been demonstrated. One of the more interesting applications is the use of wavefront correction to image through[1–5] or around[2, 6] scattering material. Other applications include sub-diffraction and subwavelength

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focusing[7, 8], Compression of ultrashort pulses[9], creating a dynamic waveplate[10], spectral filtering[11], deep tissue chemical imaging[12, 13], and random Raman lasing[14, 15]. It has also been shown that wavefront correction can substantially enhance the total transmission of light through a scattering media[16]. In this case of the enhancement of total transmission, the optimization is not local. On the other hand, the optimization of focusing through scattering media is local and linear, thus larger enhancements are realized more easily.

By modulating the phase of spatial components of a beam of laser light, the amount of light transmitted by a scattering medium can be enhanced[8, 17]. The modulation of the phase of the beam is typically done by a two dimensional liquid crystal spatial light modulator. A pattern is displayed on the spatial light modulator determined by an optimization algorithm that requires feedback from some sort of detector. Different algorithms have been developed in order to find an algorithm that both converges well and fast. The stepwise sequential and continuous sequential algorithms[18] converge well, but the convergence begins slowly. Another method is to directly measure the transmission matrix of the scattering material and then correct for it with phase modulation[19–22]. Other algorithms, such as the partitioning algorithm[18] and genetic algorithms[23] converge more quickly, but may or may not converge as well as the sequential algorithms, depending on the sample used.

One major obstacle to realizing the goal of real time imaging in tissue is the large number of iterations that each of the above algorithms requires. A typical spatial light modulator has on the order of 4×10^5 8-bit pixels. This means there are 10^8 total independent phase masks possible. At a refresh rate of 10 Hz, it is not possible for a typical spatial light modulator to search every possible phase mask in a reasonable amount of time. A decent algorithm can reduce the number of phase masks required to search down to 10^3 or 10^4 . This means a full optimization may still take anywhere from hundreds of seconds to hours. In order to optimize for scattering in living tissue, this time needs to be less than the decorrelation time of the sample which is on the order of one millisecond[24–26] to seconds[27]. Thus, the need for an algorithm that can reach a high level of optimization with a very low number of iterations is vital to the realization of the previously mentioned applications.

In this paper we investigate three geometrical variations of the standard continuous sequential algorithm[18]. This analysis provides some insights into new possible enhancement algorithms. Additionally, by selecting a different geometry of regions of the beam to modulate, the more sensitive regions may be modulated sooner, resulting in a faster optimization.

2. Experimental Setup

Our experimental setup is shown in Fig. 2. The power and polarization of a 532 nm diode pumped solid state laser are selected by a half-wave plate and polarizing beam cube. The polarization is set to match the phase only modulation orientation of a two dimensional liquid crystal spatial light modulator (Hamamatsu X10468-07). This spatial light modulator has an array of 600×792 8-bit pixels, and refreshes at a frequency of 10 Hz. The transverse mode of the laser is also spatially filtered and the beam expanded before the spatial light

modulator to fill more of the 2-D pixel array. After modulation, the light is passed through a telescope with an iris at the focus to remove higher order diffraction modes caused by the spatial light modulator.

After the telescope, the modulated light is directed with a mirror and focused into a ~ 100 μm thick sample of Teflon. Teflon is chosen as a sample because it has a high scattering cross section and a long persistence time. The power of the laser light focused onto the sample is 0.8 mW. On the other side of the sample, a $20\times$ objective with 0.40 numerical aperture is used to collect the transmitted light and image it onto a CCD detector (Mightex CGE-B013-U). A square region of 100 pixels near the center of the CCD is selected, and the individual intensity counts are summed to provide a single value to use as feedback for the optimization algorithm.

3. CSA Algorithm variations

The standard continuous sequential algorithm (CSA) [18] works by selecting a square block of pixels on the spatial light modulator. A series of phase shifts are applied to the selected region of pixels, and measurements made for each phase shift. The optimum phase shift is then applied to the spatial light modulator, and a new block of pixels are selected. This process iterates in a linear fashion rastering over the 2 dimensional pixel array as shown in Fig. 3(a), and can be repeated for additional enhancement.

We investigate the effect of three variations in the pixel selection method on the standard continuous sequential algorithm. These variations are depicted in Fig. 3(b-d). The first two are very similar to the original CSA, however instead of raster scanning through the 2d pixel array, the modulated pixel groups are selected in a spiral pattern starting at the edges (b) or at the middle (c) of the array.

The last geometry (d) selects pixel groups to modulate in a ring geometry. The algorithm cycles through nine rings with different origins, then the radius of the ring is decreased, and the cycle repeats until the ring becomes a spot at each origin. When the rings are large enough to overlap, the phase shift of the new ring is added to the phase shift of the old ring rather than replacing it. The phase shift is wrapped back to zero when the new value exceeds 4π radians. Thus, the structure of the phase mask is not overwritten by new iterations. Additionally, before selecting the rings, the pixel array is grouped into “macropixels” of 36 pixels (6×6) to avoid large power loss due to diffraction.

For the measurements presented here, 12 sizes of rings (or 108 iterations total) are used. For the raster and spiral geometries, 110 pixel blocks are used. Thus, the four algorithms have a comparable number of iterations. For all geometries, eight measurements spanning 2π radians phase shift are made for each iteration.

4. Results

The enhancement as a function of iteration number for the four pixel selection geometries are shown in Fig. 4. The enhancement is calculated as the intensity of light in the region of interest on the CCD divided by the initial intensity of light in the same region. As can be

seen in the figure, the enhancements at the end of the algorithm cycle are comparable. However, the speed at which they reach that level depends on how quickly the algorithm optimizes the center pixels in the 2d pixel array. This is intuitive because the laser beam contains more power in that region.

A simple simulation was done to verify the results of the spiral pixel selection geometries. The intensity of the light detected by the CCD is simulated via the equation[18]

$$|E_m|^2 = \frac{1}{N} \left| \sum_n^N t_{mn} A_n e^{i\phi_n} \right|^2$$

where only one output channel ($m = 1$) is measured, t_{mn} is the transmission matrix of the scattering material, A_n is the 2 dimensional amplitude distribution of the laser (Gaussian), ϕ_n is the phase shift applied by the spatial light modulator, and N is the number of pixel groups (110). t_{mn} is approximated using a complex random Gaussian distribution[18]. While in reality the elements of t_{mn} are correlated[16], this approximation of uncorrelated elements still provides insight into the improvement of optimization algorithms for the case of focusing.

The simulation results are shown in Fig. 5 for zero measurement noise (a) and for noise on the order of $0.1I_0$ (b). In both cases, the spiral out geometry enhances the focus more quickly than the other geometries. This effect comes from the A_n coefficients, which are chosen to mimic the Gaussian profile of the laser beam. Since the center of the beam contains more laser power, modulation of those pixels first returns larger enhancement earlier on in the optimization process. For the zero noise case, the algorithms converge to the same enhancement after a full cycle. However, when noise is introduced, the spiral out geometry does slightly better. This demonstrates the benefit of enhancing the system above the noise earlier on rather than later in the algorithm cycle.

5. Conclusion

In conclusion, we have proposed and experimentally evaluated three variations of the continuous sequential algorithm for wavefront optimization. These variations provide insight into possible ways to improve the optimization algorithms of wavefront shaping. Mainly, by first selecting the region where laser light is brightest on the spatial light modulator, the algorithm will have a greater enhancement early on in the optimization process. Additionally, this can be even more beneficial if there is noise in the system since enhancing the signal above the noise early on will improve the sensitivity of the later, less sensitive modulations.

Furthermore, we have presented a pixel selection geometry that takes into consideration the cylindrical nature of the laser beam, but still provides for a symmetry breaking to relate to the random nature of the scattering material. This new geometry performs similar to the standard continuous sequential algorithm, but future modifications to the technique may

prove fruitful. In the very least, it gives new ideas of how faster optimization may be achieved.

The technique of wavefront shaping to control scattered light is a very powerful tool with many diverse applications. More applications will continue to become readily available as further investigation of optimization algorithms improve the speed of enhancement.

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Figure 1.

Laser spot with (b) and without (a) scatterer in the beam. This illustrates what happens when light propagates through a scattering material. However, wavefront shaping offers a method to counter these effects (c). (a) was attenuated with 4.4 OD and (b) and (c) were attenuated with 1 OD neutral density filters.

Figure 2.

Experimental Setup. Laser power and polarization from a 532 nm laser are selected by a half-wave plate (WP) and polarizing beam splitter (PBS). The laser light is then spatially filtered and expanded. Then the light is modulated by a spatial light modulator (SLM). Higher order diffraction modes from the SLM are removed by an iris inside another telescope. The modulated light is focused onto a sample (S) of Teflon. Feedback to the optimization algorithm is supplied by a CCD camera on the backside of the sample. BS, beam splitter; M, mirror; L, lens; Obj, objective.

Figure 3.

Geometry variations of the pixel selection order of the continuous sequential algorithm. The grayscale illustrates the amount of phase shift applied to the spatial light modulator (SLM), and the arrows show in which direction the pixel selection proceeds. The typical geometry is to raster scan (a) through the pixel groups on the SLM. Other methods examined are to start on the edge and spiral inwards (b), or start in the center and spiral outwards (c). Another pixel selection geometry is constructed of rings of decreasing radius centered at nine different origins (d). When the rings overlap, the phase shifts applied by each ring are added.

Figure 4. Optimization results for four different pixel selection geometries for one complete loop of the continuous sequential algorithm.

Figure 5.

Simulation results for the raster and spiral pixel selection geometries for one complete loop of the continuous sequential algorithm. Results for zero noise (a) and noise of 10% of the initial intensity (b) are shown. Note that for the zero noise scenario, the three geometries result in an identical enhancement.