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Original research article

Focusing light through scattering media using the harmony search algorithm for phase optimization of wavefront shaping

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ABSTRACT

Utilizing the wavefront shaping technique to focus light through a scattering medium is a newly emerging field and has shown great potential for various applications. A critical task in this field is identifying a fast, robust algorithm for wavefront shaping. In this work, we introduce a simple-structure algorithm, the harmony search (HS) algorithm, for use in the phase optimization of wavefront shaping. We experimentally demonstrate that HS converges faster than the continuous sequential algorithm (CSA) and reaches a higher overall enhancement. In addition, we establish a simulation model based on random matrix theory. The numerical simulation results agree well with the experimental results and show that the HS algorithm is more resistant than the CSA to noise and sample decoherence.

1. Introduction

When light propagates through scattering materials, such as paper and biological tissue, it is scattered by sub-wavelength particles in all directions and forms a random speckle pattern. Multiple scattering events make these materials opaque; as a result, focusing or imaging through a scattering medium was once thought to be impossible. However, in 2007, Vellekoop and Mosk [1] experimentally demonstrated that instead of scattering into a random speckle pattern, coherent light can be focused into a sharp, intense point through scattering materials by using a spatial light modulator (SLM) to compensate the phase distortion of the incident wavefront. Since then, this method, which is called the wavefront shaping technique, has drawn a tremendous amount of interest, and numerous potential applications have been demonstrated in various areas, including light polarization control [2,3], optical trapping [4], super-resolution imaging [5,6], fluorescence imaging [7], and deep tissue microscopy [8,9].

For the wavefront shaping technique, finding a fast, robust optimization algorithm that can compensate for the phase distortion of the incident wavefront is critical. Two basic approaches are currently being adopted in the research of optimizing the phase of the incident wavefront: the transmission matrix (TM) approach and the iterative optimization (IA) approach. The TM approach directly measures the transmission matrix of the scattering medium through an interference method and calculates the phase pattern applied to the modulator using the obtained TM [10]. The IA approach achieves focusing by adjusting the input wavefront according to the feedback signal from the intended point in the output plane [11,12]. The TM approach updates the phase pattern only when all measurements are completed, while the IA approach adjusts the phase pattern during each measurement. Therefore, one of the greatest strengths of IA is its good performance under noisy and decoherence environments, which is important to realizing real-time dynamic focusing and imaging. Thus, several reports

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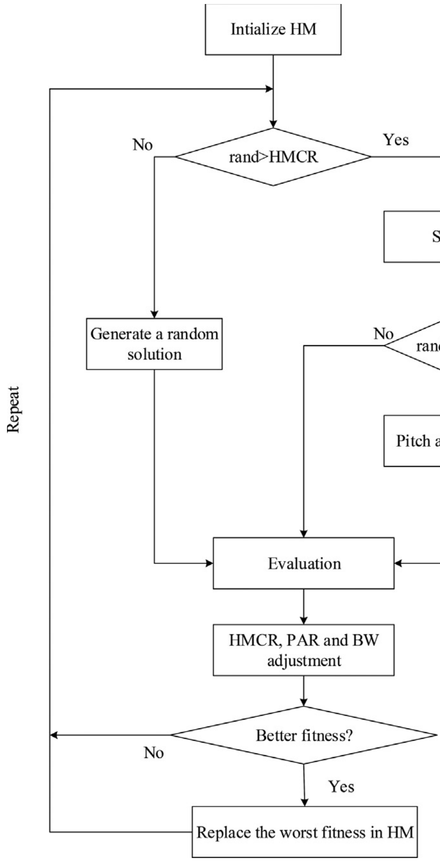

Fig. 1. The flow chart of the HS algorithm.

have been published that identify a fast, robust phase optimization algorithm for IA, including the continuous sequential algorithm (CSA) [11], the stepwise sequential algorithm [11], the partitioning algorithm [11], and the genetic algorithm (GA) [12]. Among these algorithms, CSA and GA are two best-performing and widely used algorithms. As the CSA independently optimizes each input mode, it has a simple structure; however, the enhancement approaches the theoretical maximum more slowly than that of GA and is more sensitive to environmental noise and sample vibrations. In contrast, GA converges faster and performs better, especially in noisy and vibrating environments; however, it suffers from a complex structure. To obtain a faster, more robust algorithm with a simple computation and structure, we propose a harmony search (HS) algorithm to optimize the phase of the wavefront because HS is easy to implement and has been demonstrated to handle optimization problems with a small number of candidates [13].

In this paper, we first describe the operation of the HS algorithm for phase optimization in detail. Then, phase optimization experiments are employed to compare the overall enhancement and convergence speed of HS and CSA. Finally, we build a simulation model to quantitatively study the resistance of the two algorithms to noise and decoherence.

2. Harmony search algorithms applied to phase mask optimization

Inspired by harmony improvisation, the HS algorithm was first proposed by Geem [14,15] to solve the optimization problem of water distribution networks. Since then, HS has been widely applied to various optimization problems, including transportation, manufacturing, robotics, and medical science.

Fig. 1 depicts the flow chart of the HS algorithm for phase optimization of wavefront shaping. First, we generate an n-dimensional HS memory (HM), which is represented as follows:

$$HM = \begin{bmatrix} \varphi_1^1, \varphi_2^1, \ldots, \varphi_n^1 \\ \varphi_1^2, \varphi_2^2, \ldots, \varphi_n^2 \\ \ldots \\ \varphi_1^{HMS}, \varphi_2^{HMS}, \ldots, \varphi_n^{HMS} \end{bmatrix} \tag{1}$$