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A Hybrid Algorithm to Reduce the Computation Time of Genetic Algorithm for Designing Binary Phase Holograms

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A new approach to design binary phase holograms, with less computation time and equal efficiency compared with the genetic algorithm method, is proposed. Synthesized holograms having diffraction efficiency of 75.8% and uniformity of 5.8% are tested in computer simulation and experimentally demonstrated.

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I. INTRODUCTION

Recently, computer-generated holograms (CGHs) having high diffraction efficiency and flexibility of design have been widely developed in many applications such as optical information processing, optical computing, optical interconnection, etc. Among the proposed optimization methods [1-3], Genetic Algorithm (GA) has become popular due to its capability of performing a massive parallel search through a huge space of possible solutions to a given problem, allowing nearly global solutions to be achieved. However, there exists a drawback to consider when we use the genetic algorithm. It is the large amount of computation time to construct desired holograms. One of the major reasons that the GA's operation may be time intensive results from the expense of computing the cost function that must Fourier transform the parameters encoded on the hologram into the fitness value [4-6]. For example, a GA with a population of 100 trial holograms, the cost function will be called 100 times per generation corresponding to the calculation of the Fourier transform of 100 holograms. Depending on the speed of computer, this could lead to the GA taking an unacceptable time. In trying to remedy this high computation cost, an artificial neural network (ANN) has been put forward that enable CGHs to be created easily and quickly [7]. Unfortunately, the quality of reconstructed image is not high enough to use in applications of high precision.

In this paper, we describe a hybrid algorithm combining the good properties and performance of both the GA and ANN to synthesize desired holograms in an acceptable time. Analysis of structure, mechanics, and performance of the system is presented with experimental demonstration.

II. DESIGN OF BINARY PHASE HOLOGRAMS

1. Design of binary phase holograms

The process of synthesizing a hologram can be broken into three parts: (1) Computing optimal phase configfurations of the hologram field from which one can reproduce the desired images, (2) Determining the suitable representation of the complex field in the hologram field and (3) transferring the encoded representation of the fields to a transparency.

In this research, we restrict ourselves to the first part for the case of Fourier holograms only. Our holograms are binary, i.e., they consist of an array of $K \times L$ square cells represented as a rectangular function and a phase $\theta_{k,l}$ to be of either 0 or π. Accordingly, the hologram is written as

$$g(x,y) = \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} \exp(i\theta_{k,l}) \mathrm{rect}\left(\frac{x-k/K}{1/K}, \frac{y-l/L}{1/L}\right) \tag{1}$$

where $g(x,y)$ is the phase transmission function of the hologram, K and L are the number of cells in the x and y directions, respectively.

Illuminating the designed hologram by a plane beam, the complex amplitude of diffraction light in the Fourier plane $G(m,n)$ is given by

$$G(m,n) = \frac{1}{KL}\exp\left(i\pi\left[\frac{m}{K}+\frac{n}{L}\right]\right)\mathrm{sinc}\left(\frac{m}{K},\frac{n}{L}\right)\sum_{k=0}^{K-1}\sum_{l=0}^{L-1}\exp(i\theta_{kl})\exp\left(-2\pi i\left[\frac{mk}{K}+\frac{nl}{L}\right]\right) \quad (2)$$

and $\mathrm{sinc}(x,y) = \mathrm{sinc}(x)\mathrm{sinc}(y)$, m and n are the diffraction orders of the reconstructed image.

The design of the hologram renders to the assignment of determining the phase $\theta_{k,l}$ at each cell so that the diffracted intensity $|G(m,n)|^2$ is as close as possible to the desired intensity.

2. Optimization Procedure

The process of optimizing a hologram using the GA is composed of: (1) Randomly creating an initial population of holograms, (2) Determining fitness of each hologram by applying the cost function, (3) Discarding a percentage of population that is the least fit, (4) Randomly crossing over surviving holograms, (5) Randomly mutating values of each hologram within the population, and (6) Repeating Step 2 for a set number of iterations or until the cost is acceptably minimized.

Note that two important quantities as the diffraction efficiency and uniformity of the reconstructed image should be contained in the cost function, which is presented as

$$g(x) = \sum_{m'=1}^{M}\sum_{n'=1}^{N}(T_{m'n'} - I_{m'n'})^2 + W\sum_{m'=1}^{M}\sum_{n'=1}^{N}(\mathit{eff}/\mathit{spots} - I_{m'n'})^2 \quad (3)$$

where m' and n' are cell indexes of the hologram, $T_{m'n'}$ is the target intensity, $I_{m'n'}$ is the intensity of diffraction beams, *spots* is the number of diffraction beams, *eff* is the calculated efficiency, and W is a weight factor that controls the uniformity in regard to the diffraction efficiency. The former part of the equation is the term considering diffraction efficiency and the latter is the term considering uniformity.

One disadvantage of the optimization procedure using the GA is its random initiation. The randomly generated population of trial holograms is equivalent to a large population size required for finding the desired hologram. Accordingly, a large number of times of calculating Fourier transforms, which are time intensive, must be calculated. It will be more effective if one can minimize the GA's population size, yielding to the reduction in the performance time of the Fourier transform and the GA's operation as well. The ideal is that instead of merely generating random holograms in the initial process, a set of approximately desired holograms is employed. The initial population of trial holograms now is composed of both the approximately desired holograms obtained from the well-trained ANN and arbitrarily generated holograms. This way not only does the initial population contain less trial holograms but also the whole solution space is searched. Accordingly, a hybrid algorithm that utilizes an ANN trained with a suitable data set and an effective learning algorithm to initiate the GA's procedure is applied. Fig. 1 is the flowchart of the hybrid algorithm in comparison with the classical GA. In this paper, we used a learning algorithm for training the neural network called back-propagation

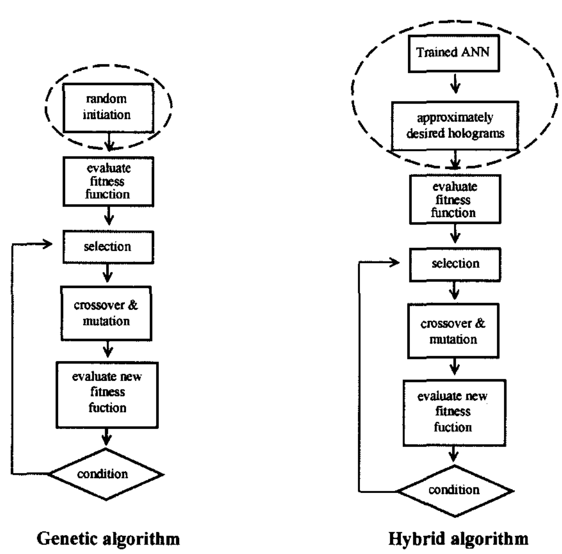

FIG. 1. Comparison between the genetic algorithm and hybrid Algorithm

TABLE 1. Diffraction efficiency vs. population size

Population size	20	30	40	50	60
Computation time [s]	121	198	283	354	426
Uniformity [%]	6.5	5.4	5.9	5.7	5.6
Diffraction efficiency [%]	36.7×2	38.2×2	37.8×2	37.9×2	38.1×2

(BP). The BP algorithm performs a gradient descent technique that involves taking a small step in the opposite direction of the gradient vector, recalculating the gradient vector at this new point and repeating [8]. Since a trained ANN can achieve many different patterns of the approximately desired holograms, the training process of ANN is not included in the synthesis of holograms of the hybrid algorithm. The structure and mechanics of this network system are explained in Ref [7,8].

It is worth noting that there are some other kinds of hybrid schemes applied to improve GA, for example, GA is used to search the initial solution globally and another fast and strongly converging algorithm is adopted for the fine improvement of the comparatively coarse initial solution obtained by GA. However, since randomness plays a large role in GA's, two runs with different random trial holograms will require different generations to reach a global solution; consequently, combining GA and an iterative algorithm faces the challenge of finding out where we should stop running GA and follow by the iterative algorithm. In our hybrid scheme, we select high potential solutions at first and then GA is carried out until the saturation status. It means that the global solution is highly reached.

III. PERFORMANCE

1. Computer Simulations

The procedure of synthesizing a hologram on computer is divided into two steps. First the simulation of holograms based on ANN method [7] to acquire approximately desired holograms is carried. With a teaching data set of 9 characters, including B, C, D, G, K, I, L, M, S, and R, obtained from the classical GA and the listed below parameters resulting from our empirical investigation, the artificial neural network trained enables us to attain the hologram and its reconstructed image as illustrated in Fig. 2 (no specific reason in choosing the letter "O" as the desired image).

Hologram of letter "O" Reconstructed Image

FIG. 2. The binary phase hologram and its reconstructed image obtained using Neural Network

- Number of layers: 3
- Number of hidden nodes: 100
- Learning rate: 0.3
- Momentum: 0.5

The reconstructed image in Fig. 2 is in fairly good agreement with what we suggested in the theory. In other words, approximately desired holograms can be constructed by using the ANN method.

The second step, effect of several parameters on the operation of the hybrid algorithm is investigated. In principle, the operation of the hybrid algorithm and GA are the same except the modification of the initial step. Hence, the verified results in Ref [6] of the parameters such as the probability of crossover and mutation, the tournament size, and the crossover block size remain unchanged, beside of the reduced population size. Table 1 shows the reconstruction efficiency versus the population sizes using the hybrid algorithm as the probability of crossover is 0.75, and probability of mutation is 0.001. The reconstructed image of about 76% diffraction efficiency and 5.4% uniformity is achieved when the population size and iteration number are 30 and 2000, respectively.

In order to demonstrate the efficient performance of the new method, a comparison between it and the GA in term of diffraction efficiency and computation time is also evaluated as shown in Fig. 3. The hybrid algorithm gives a 66.7% reduction in computation time and a 2% increase in diffraction efficiency compared to the GA method. Because of the difference in the initial population of the hybrid algorithm and GA, the diffraction efficiency values at the initial point (time = 1) consequently are different.

In addition, the stable ability of the hybrid algorithm is also verified through results on holograms of

TABLE 2. Comparison in the performance of hybrid algorithm and genetic algorithm

	Hybrid Algorithm			Genetic Algorithm		
	Efficiency (%)	Uniformity (%)	Computation Time (s)	Efficiency (%)	Uniformity (%)	Computation Time(s)
A	37.51×2	6.2	210	37.02×2	5.9	624
F	37.93×2	5.8	189	37.41×2	6.0	587
O	38.23×2	5.4	198	37.10×2	5.6	602
J	37.38×2	5.3	205	36.84×2	5.7	635
P	37.35×2	5.7	197	37.23×2	6.2	590
X	38.11×2	6.1	182	37.69×2	6.4	583

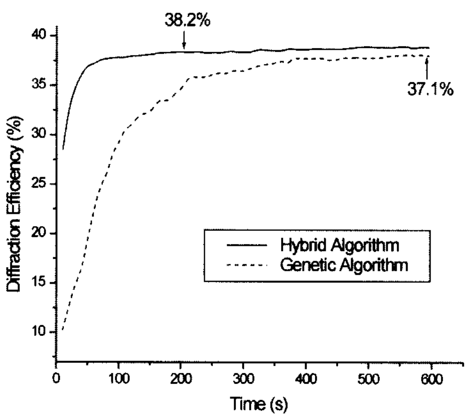

FIG. 3. Comparison in terms of computation time between hybrid algorithm and genetic algorithm

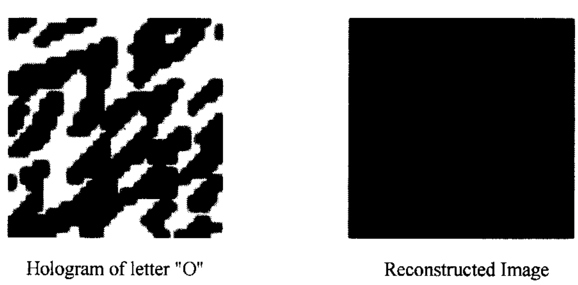

FIG. 4. The binary phase hologram and its reconstructed image obtained using the hybrid algorithm

different patterns as given in Table 2. Even holograms synthesized in short computation time still are ensure to have high diffraction efficiency and uniformity. As a matter of fact, the new technique is superior to the classical genetic algorithm, especially, in the aspect of time.

Fig. 4 is photographs of the hologram transmittance function of 32×32 and corresponding digitally reconstructed image.

2. Optical Experiments

To confirm the simulated results, the efficiency and uniformity of reconstructed images are measured

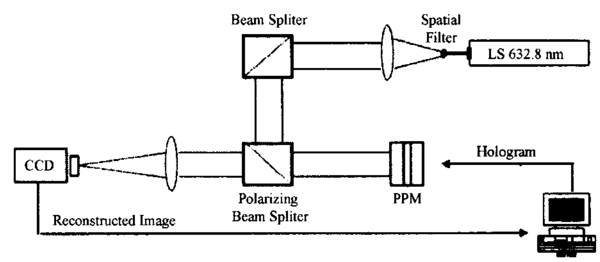

FIG. 5. System architecture for the optical reconstruction using PPM

by using the setup shown in Fig. 5. The programmable phase modulator (PPM) is used to display hologram patterns. After being filtered and collimated by the spatial filter and convex lens, the beam from the 633 nm He-Ne laser source is incident on the polarizing beam splitter (PBS). The light illuminating the PPM is polarized in the direction parallel to the liquid crystal director [9,10]. The diffracted light from the PPM is taken the Fourier transform to the focal plane of the output lens at which it is captured by a CCD camera. Diffraction efficiency is measured with an optical meter and an aperture in front of the detector.

We define the diffraction efficiency of the hologram in the various orders as

$$\eta_i = \frac{I_i}{I_0} \tag{4}$$

where η_i is the diffraction efficiency in to the ith order, I_0 is the *0*th order with zero write-light intensity, and I_i is the intensity of the ith order. In our experiment, the diffraction efficiency of 75.8% that is sufficiently close to the simulation results is obtained.

Besides, the uniformity of diffracted image is also measured by using a geometrical transformation. This process begins by saving data obtained at the CCD camera to a raw file and then transforming it to 0 $\sim$ 255 gray level. Using these transformed values, the uniformity, that is a deviation between the output spots, is calculated as follows $(I_{max} - I_{min})/I_{avg}$.

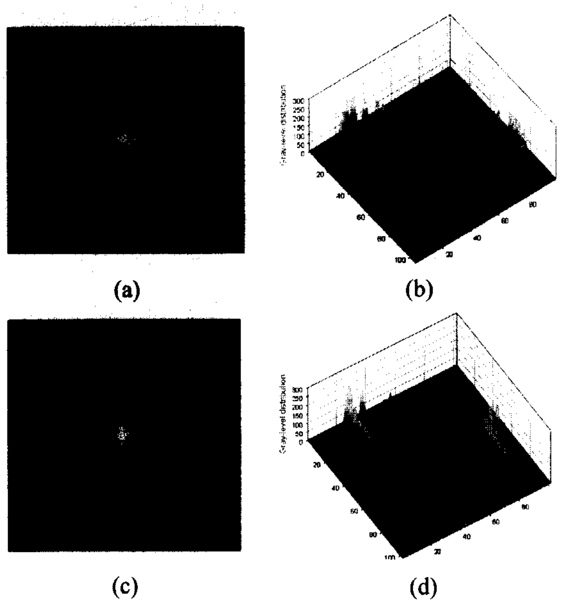

FIG. 6. Diffracted pattern of the designed hologram using the hybrid algorithm (a) Reconstructed image of letter "O" (b) Spatial distribution of the reconstructed image of letter "O" (c) Reconstructed image of letter "J" (d) Spatial distribution of the reconstructed image of letter "J".

For letter "O", the mean of beam intensity as a gray level is 224, the maximum value is 232, the minimum value is 219, and uniformity is quantitatively 5.8%.

Figs. 6(a), (b), (c), and (d) are pictures of diffracted patterns of the letters "O" and "J" from the holograms generated using the hybrid algorithm. The center spot is the zero-order diffraction and is caused by the phase mismatching of PPM, not by the simulation.

IV. CONCLUSION

We present the implementation and testing of the hybrid method that utilizes artificial neural networks to initiate genetic algorithms in designing binary phase holograms. This method gives a significant reduction in computation time compared to the GA method while still allowing holograms of high diffraction efficiency and uniformity to be achieved. In our experiment, diffraction efficiency of 76% and uniformity of 5.8% are obtained within 200 seconds, which is 66.7% less than the GA method. Further research on applications of hybrid algorithm to programmable optical interconnection and image processing in conjunction with SLM is in progress.

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