A Scattering Media-Based Diffractive Neural Network

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Abstract *- Optical neural networks (ONNs), implementing artificial neural network models through optical computing hardware, have demonstrated significant advancements in both computing speed and energy efficiency. Among various ONNs architectures, diffractive neural networks (DNNs) have garnered considerable attention due to their ability to perform large-scale information processing. However, the interconnectivity of neurons within DNNs has been one of the bottlenecks limiting the widespread implementation of DNNs. In fact, while neurons in different layers of DNNs can fully connect through diffraction, the presence of additional layers introduce non-negligible alignment errors, counteracting the DNN scalability. In this work, we propose a more compact optical computing system featuring programmable diffractive optical elements and a scattering media capable of enabling fully interconnectivity of neurons. Instead of relying on multiple layers as in DNNs, the system consists of only one reprogrammable diffractive layer (that shapes the wavefront of the input field) and one scattering medium (that enhances the interconnectivity of optical neurons compared to traditional DNNs), resulting into a more compact computing system and being able to be reconfigured for different machine learning tasks. In simulation, the scattering-media-based DNNs (SM-DNNs) system increases the classification accuracy of the KMNIST dataset by up to 15% compared to an existing single-layer DNNs.*

Introduction

Since its inception in 1956, artificial intelligence (AI) has developed rapidly, with artificial neural networks (ANN) finding applications across a wide range of domains. Traditional computers, operate on a centralized processing architecture, which is inefficient for computational models like ANNs that require distributed, massively parallel, and adaptive processing. Neuromorphic engineering seeks to bridge this gap by developing hardware that mirrors the distributed nature of machine learning algorithms, potentially enabling faster and more energy-efficient information processing.

Photonic computing, which utilizes photons instead of electrons, can offer numerous advantages, including light-speed processing, low power consumption, and high throughput, consequently holding great promise as AI computing solutions, as Moore's law faces limitations [1].

Among various photonic neural networks (PNN) architectures, diffractive neural networks (DNNs) have received significant attention for their ability to facilitate large-scale neural information processing [2]. These networks are composed of layers of diffractive elements (neurons) that are interconnected optically via light diffraction. By employing deep learning techniques, diffractive neural networks are trainable to achieve specific mapping functions between input optical fields and output detection signals via amplitude and phase modulations. DNNs have been successfully deployed in numerous optical information processing tasks, such as object classification, image reconstruction, and logical operations. Recently, wavelength-multiplexed diffractive neural networks and reconfigurable diffractive processing units [3] have demonstrated the potential of these architectures.

Despite these advances, a fundamental challenge remains: in most implementations, multiple diffractive layers are required in experiments. Although all amplitude or phase modulations from different layers could theoretically be represented by a single layer through linear combination, multiple physical layers are still needed to provide sufficient interconnections. However, additional layers introduce alignment and fabrication errors, reducing training efficiency and computation accuracy.

Scattering media have also been explored for optical computing, particularly in reservoir computing [4]. These media provide numerous random coupling weights, and with wavefront shaping techniques, their linear and deterministic scattering properties can be harnessed to perform specific optical computing operations [5]. However, the broader application of scattering media in optical computing is still to be fully explored.

In this work, we propose a novel optical free-space computing system combining a programmable diffractive optical layer with a scattering medium. Utilizing wavefront shaping, our approach aims to mitigate issues of misalignment and enhance performance by replacing multiple diffractive layers with a single programmable diffractive layer and a scattering medium. This architecture significantly reduces system complexity while maintaining or enhancing performance, as validated via image classification simulations.

Methods

As shown in Fig. 1, the proposed optical computing system consists of four main components: 2D input image, a phase-only programmable diffractive layer, a scattering media, and a camera. The system was trained to classify handwritten characters by focusing light on a specific part of the camera, similar to conventional DNNs but using only one trainable layer. First,input images are encoded into intensity-modulated incident

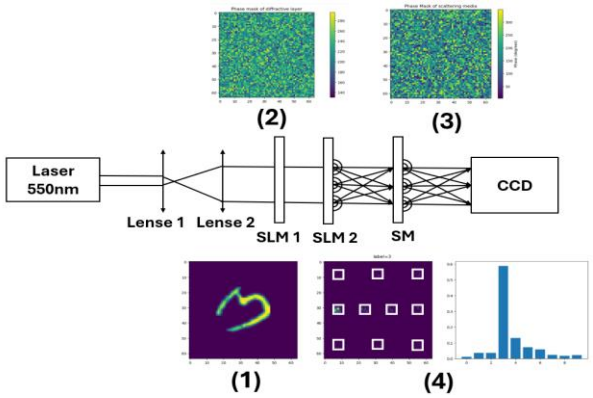


Fig. 1 Schematic for the simulation setup of SM-DNNs, with one spatial light modulator(SLM1) as input data loader, one SLM as reprogrammable diffractive layer(SLM2), one scattering media(SM) represented by random Gaussian phase mask, and one CCD camera with 10 detection regions representing 10 labels in KMNIST dataset. Inset (1) intensity pattern of input image; (2) phase mask of diffractive layer after 10 epochs training; (3) random Gaussian distribution phase mask for scattering media; (4) pattern and histogram of intensity distribution on camera

light fields on SLM1 in Fig. 1, which are then directed to the programmable diffractive layer on SLM2.

Upon interacting with the scattering medium, the encoded light fields formed a random speckle pattern due to refractive index inhomogeneities. In the past, these speckle patterns

were seen as limitations; however, with wavefront shaping, scattering media become powerful platforms for complex interference, enhancing the interconnectivity of optical neurons compared to traditional DNNs.

Wavefront shaping works by constructing the wavefront of incident field, generating a desired transmitted field after scattering media [5]. The transmitted field at *m* segment on the detection plane, E_m, which is represented by *m* segment on CCD camera in Fig. 1, can be expressed as a linear combination of the fields originating from different segments of the wavefront modulator:

$$E_m = \sum_{n=1}^{N} t_{mn} A_n e^{i\phi_n} \qquad (1)$$

where A_n and ϕ_n represent the amplitude and phase of light transmitted from segment *n* on SLM2. One segment could be a single pixel or a group of pixels on CCD an SLM. Here *N* represents total number of segments on SLM2. The propagation of light through the scattering media is described by the transmission matrix T, where each element of the matrix, t_{mn}, describes the field contribution from segment *n* on SLM2 to segment *m* on camera. For focusing through scattering media, enhancement was defined as the ratio between focusing spot intensity and average intensity without training. For phase-only modulation, theoretical expected enhancement η_p [5]:

$$\eta_p = \frac{\pi}{4}(N-1) + 1 \approx 0.79N \qquad (2)$$

Which is significantly surpassing the enhancement η_a of amplitude-only modulation[6],

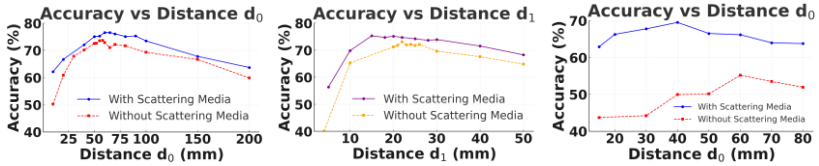
$$\eta_a = 1 + \frac{1}{\pi}\left(\frac{N}{2} - 1\right) \approx 0.16N \qquad (3)$$

In this case we decided to train phase ϕ_n instead of amplitude A_n on SLM2. The scattering media in our system was defined as a random circular Gaussian-distributed phase mask for strongly scattering samples [5]. Ten labeled detectors were placed at the output plane, each corresponding to an input image label (0-9). The classification criterion is to determine which detector received the maximum optical intensity and record the label for that detector as output. If the output matches with the label of input image, both accurate classification number and total classification number would increase by one; otherwise, only total classification number would increase. The accuracy is calculated as the percentage of accurate classification number in total classification number after the entire testing dataset is loaded to the system.

Results

The simulation was designed to demonstrate the classification of the Kuzushiji-MNIST (KMNIST) dataset, which consists of ten classes of Hiragana characters. We encoded the KMNIST dataset on the input field as 32×32 resolution images using a wavelength of 550 nm. The pixel sizes for the input image, the tunable diffractive layer, and the camera were all set to 11 μm^2, reflecting the specifications of commercially available spatial light modulators (SLMs) and digital micromirror devices (DMDs). The Adaptive Moment Estimation (Adam) optimizer and Mean Squared Error (MSE) loss function were used for optimization. The distance between system components is an important variable. Here we evaluate different distances between the diffractive layer and the scattering medium, as well as the detectors, to determine the optimal configuration. Each distance has an

optimal point for maximum accuracy. When the distance is too short, the diffracted images could not fully diverge, and input signals could not adequately interfere, reducing the interconnectivity of the neural network and therefore the accuracy. Conversely, larger distances result in excessive divergence, causing information loss. Across all distances, our proposed scattering-media-based DNNs (SM-DNNs) consistently outperforms the conventional one layer DNNs, demonstrating the advantages of scattering media for enhancing neural network interconnectivity. In Fig. 2(a) I swept d_0, the distance between SLM1 and SLM2 from 10 mm to 200 mm, while keeping d_1, the distance between SLM2 and camera fixed as 24mm. The best accuracy for SM-DNNs is 76.56% when $d_0 = 65\ mm$. The best accuracy for conventional one layer DNNs is 73.68% when $d_0 = 58\ mm$. In Fig. 2(b) I checked the influence of d_1 and kept $d_0 = 80\ mm$. The best accuarcy for SM-DNNs is 75.27% when $d_1 = 15\ mm$, while the best accuarcy for one layer DNNs is 72.11% when $d_1 = 24\ mm$.



(a) (b) (c)

Fig. 2 Accuracy with the change of distance, here (a) d_0 is the distance between SLM1 and SLM2, (b) d_1 is distance between SLM2 and camera, and (c) is the accuracy for d_0 with compact setup.

We further evaluated system robustness in compact setups with spacing between the diffractive layer, scattering media, and detectors were 5 mm. In such setups, the SM-DNNs achieved 69.52% classification accuracy, around 15% higher compared to the conventional DNNs 55.19%, effectively compensating for reduced interconnectivity due to shorter distances.

Conclusions

In summary, we introduce a novel optical computing system that combines programmable diffractive optical elements with scattering media. By leveraging the numerous interconnections provided by scattering media, the system improves classification accuracy by over 15% on the compact architecture for optical computing.

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