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Fast optical image processing system using photonic reservoir computing

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Abstract– Photonic computing is promising for image processing because it can process information at ultra-high speed and low power consumption. Whereas photonic computing-based image processing have been intensively studied, optical image processing in the GHz band, which far exceeds the frame rate of conventional image sensors, is still challenging. In this study, we propose an image processing system based on photonic reservoir computing and single-channel acquisition technique using fast random pattern projection and demonstrate its capabilities for fast image recognition and image reconstruction.

1. Introduction

Photonic computing technology has recently attracted much attention because of its potential capabilities of ultra-fast operation with low energy consumption [1,2]. However, when photonic processing units are used to process signals acquired by sensing devices, the processing speed of the entire processing system may be essentially limited by data acquisitions in sensing devices and their transfer to the processing units. This gets serious when image sensors with many pixels are used, where spatial information acquired by an image sensor is converted into an electrical domain with a digital format, and huge amounts of memory are required for data storage. The electrical domain conversion and memory access of large amounts of data are significant bottlenecks that hinder the speeding up of image processing.

To address this issue, we proposed an image-sensor free optical image processing approach [3]. This approach is based on a fast random pattern projector [4] for transforming real-world visual information to time-domain information and a photonic reservoir computer used for the image-encoded time-domain signal. In this study, we demonstrate that the proposed image processing approach enables dynamic image recognition and learning-based imaging.

2. Image processing system

The proposed image processing system is composed of a fast random pattern projector and a photonic reservoir chip developed in our previous research (Fig. 1). The laser light is sent to a multimode fiber (MMF) to generate random speckle patterns. The speckle patterns can change with time by the phase modulation at GHz rates. The dynamic speckles are projected onto a physical object to be recognized. The reflected light is collected by a lens and received by the fiber. In this process, the image information of the object can be converted into time-domain information. The image-encoded time-domain signal is directly sent into the photonic reservoir chip. Importantly, the proposed system enables fully photonic information processing from the acquisition of the image information to the reservoir processing. The acquisition time can be controlled by the phase modulation rate. In this experiment, we set the rate as 25 Gigasamples/sec, which corresponds to the switching time interval of 0.04ns. Therefore, it can be applied to fast image recognition and image reconstruction that can reproduce fast phenomena.

In this study, we demonstrate that the image recognition and image reconstruction can be achieved using the reservoir outputs in the proposed image processing system. The image recognition can be done by the logistic regression using the reservoir outputs as the inputs. In the image reconstruction task, the reservoir outputs are sent to the neural network for the reconstruction. See Ref.[3] for the detailed method.

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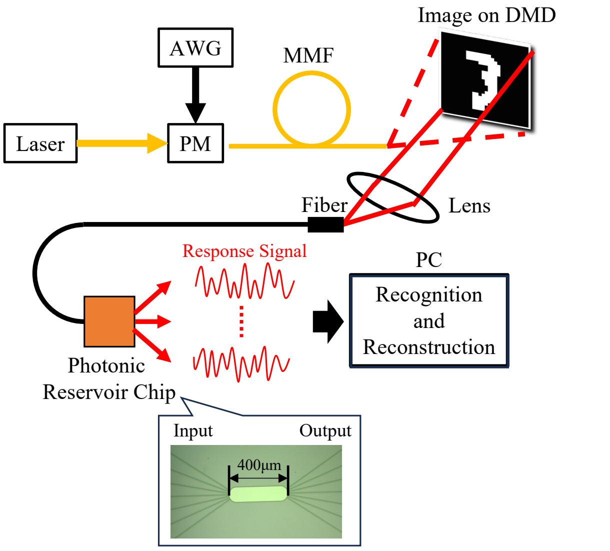

Fig. 1 Schematic of the proposed image processing system AWG: arbitrary waveform generator, PM: phase modulator, MMF: multimode fiber, DMD: digital mirror device

3. Results

We demonstrate the performance of the proposed system by performing image recognition (10-classification) and image reconstruction on two tasks: MNIST handwritten digits and Fashion MNIST. 10,000 images were projected onto the digital micromirror device (DMD) for each task, and the reservoir chip's responses were acquired. The response signal of 9000 images was used as training data and the response signal of 1000 images as validation data. The image recognition results for 10-classification showed that the MNIST handwritten digits had a maximum accuracy rate of 79.8% at the acquisition time of 12 ns per im-age (Fig. 2(a)), and the Fashion MNIST had a maximum accuracy rate of 88.2% at 8 ns per image (Fig. 2(b)).

The image reconstruction results are shown in the Fig. 3. The "Target image" in Fig. 3 represents a binarized image (0 or 1) projected onto the DMD, and the "Reconstructed image" represents the image reconstructed from the image-encoded time-domain signals using a neural network for decoding.

4. Summary

We showed photonic image recognition and reconstruction based on photonic reservoir computing and single-channel acquisition technique using fast random pattern projection. Combining the wavelength-division multiplexing approach with our approach can result in further improvements on the processing rate.

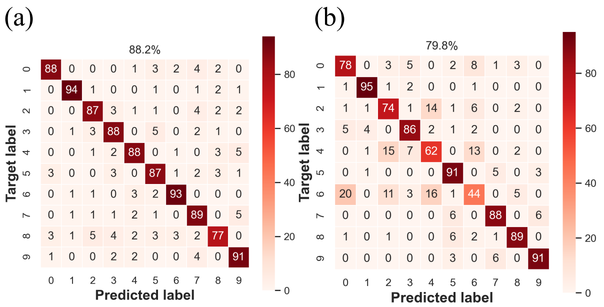

Fig. 2 Confusion matrix of image recognition results (a) MNIST handwritten digits (b) Fashion MNIST

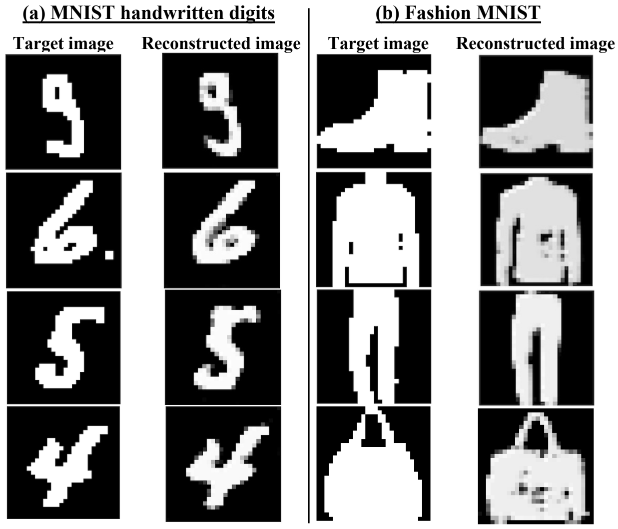

Fig. 3 Image reconstruction results (a) Evaluation of MNIST handwritten digits: MSE = 0.0297, SSIM = 0.822 (b) Evaluation of Fashion MNIST: MSE = 0.0541, SSIM = 0.705 (Average of validation data)

References

[1] B. J. Shastri *et al.*, Photonics for artificial intelligence and neuromorphic computing, Nature Photonics 15, 102 (2021).

[2] J. Feldmann *et al.*, Parallel convolutional processing using an integrated photonic tensor core, Nature 589, 52 (2021).

[3] T. Yamaguchi *et al.*, "Ultrafast single-channel machine vision based on neuro-inspired photonic computing," arXiv. 2302.07875

[4] J. Hanawa *et al.*, Gigahertz-rate random speckle projection for high-speed single-pixel image classification, Opt. Express 30, 22911 (2022).