Experimental demonstration of single-pixel imaging using a multi-core fibre

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This letter reports a proof-of-concept experiment conducted on a novel application of the multi-core fibre (MCF), where image reconstruction is based on a single-pixel imaging (SPI) technique and the diffraction pattern emitted from an MCF. The technique is intended to reduce the size of the SPI system, the applications of which can now be extended with the help of this study.

Introduction: Research and development of multi-core fibres (MCFs) is ongoing to realize high-capacity, high-speed data communication in today’s increasingly information-driven society [1–3]. MCFs represent a new type of optical fibres with multiple cores installed in the cladding to expand the data-carrying capacity of optical communications. Recently, MCFs are being applied to applications other than optical communication [4], e.g. temperature sensors [5], directional curvature sensors [6], and shape sensors [7, 8]. Further applications can be expected because of their unique advantages, such as their low weight, compactness, and flexibility.

Among optical fibre-based imaging systems, fibrescopes using image fibres have been practically realized. However, only a few imaging systems using multi-core fibres exist. To reduce the size of the fibrescope system, it is crucial to reduce the diameter of the optical fibre. Moreover, there is a possibility that the fibrescope can be made even thinner using multi-core fibres. We propose a single-pixel imaging (SPI) system using the MCF technology, namely MCF-SPI, which combines MCF technology and an SPI algorithm [9]. The proposed imaging system is thinner than conventional fibrescopes [10]. The SPI systems can be miniaturized by using an MCF to generate the spatial modulation illumination. Furthermore, the system can potentially improve the measurement speed issues of SPI technology using a modulation technique for fibre-optic communication, which is substantially faster than the liquid crystal spatial light modulator.

In this letter, we report on a proof-of-concept experiment conducted on a novel application of the MCF, where image reconstruction is based on the SPI technique and the diffraction pattern emitted from an MCF.

Single-pixel imaging using multi-core fibre: SPI is a technique employed to image an object using a single-pixel point-type photodetector and spatially and temporally modulated pattern illumination. Because it uses a point-type photodetector instead of a 2D array pixel sensor, it has advantages, such as low cost and widely adaptable wavelength range, and is expected to be applied to various applications [11, 12]. In the proposed MCF-SPI system, spatiotemporally modulated pattern illumination is generated using a multi-core fibre. Figure 1 shows the schematic of a multi-core optical fibre single-pixel imaging system. Specifically, the light outputted from the laser is divided into several cores in the multi-core fibre and is then inputted to the MCF and emitted from the end face of the MCF. The spatial pattern is projected onto an object, and the light from the object is received by a point-type photodetector. When the ith pattern \( P_i(x, y) \) generated using the multi-core fibre is projected onto an object \( O(x, y) \), the total intensity of the reflected or transmitted light \( I_i \) can be expressed mathematically as the inner product of \( P_i \) and \( O \):

\[
I_i = P_i(x, y) \cdot O(x, y).
\]

The pattern can be modulated by modulating the parameter of the light in the fibre for a structured illumination in the SPI system. The light in the fibre is modulated, the spatial pattern illumination for projection is changed, and the light intensity is obtained repeatedly. After the system performs measurements \( M \) times, a linear equation set is formed as follows:

\[
I = \begin{bmatrix}
I_1 \\
I_2 \\
\vdots \\
I_M
\end{bmatrix} = \begin{bmatrix}
P_1(1, 1) & P_1(1, 2) & \cdots & P_1(N, N) \\
P_2(1, 1) & P_2(1, 2) & \cdots & P_2(N, N) \\
\vdots & \vdots & \ddots & \vdots \\
P_M(1, 1) & P_M(1, 2) & \cdots & P_M(N, N)
\end{bmatrix} \begin{bmatrix}
O(1, 1) \\
O(1, 2) \\
\vdots \\
O(N, N)
\end{bmatrix}
\]

where \( I \) is a 1D array of \( M \) measurement intensity values, \( N \times N \) is the spatial sampling number of the object, and \( P \) is an \( M \times N^2 \) 2D array, known as the set of illumination patterns. Based on the projected patterns and the obtained light intensities, an object can be reconstructed using the following formula:

\[
O = P^{-1} I.
\]

If \( M < N \), a compressed sensing algorithm, which can solve the \( \ell_1 \) norm optimization problem, can be used to reconstruct the image required to be retrieved [13].

Experiment: Figure 2a shows a schematic of the experimental setup used for the proof-of-concept experiment of the proposed system. A semiconductor laser with a wavelength of 669 nm was used as the light source. The light was directly coupled into a 1 × 2 single-mode fibre optic coupler (TN632R5F1, THORLABS). The 1 × 2 single-mode fibre optic coupler was connected to 1 × 4 single-mode fibre optic couplers (TNQ630HF, THORLABS). The divided lights were connected to each core of an MCF using a fan-in device. The seven-core MCF, shown in Figure 2b, was used in the experiment. The MCF was designed and developed to achieve long-distance transmission [14]. The core pitch and cladding diameter of the MCF were set to 49 and 195 \( \mu \text{m} \), respectively. These cores are designed to set each core’s mode field diameter to 10.6 \( \mu \text{m} \) with a wavelength of 1550 nm.
In this experiment, the spatial patterns, which were generated with polarization and phase fluctuations, were used to reconstruct object images using the SPI algorithm. A camera was set up to monitor the projected pattern. For the wavelength of the laser used in this experiment, the maximum number of spatial modes that could be present in each core was 13, theoretically. Figure 3 shows examples of the spatial illumination patterns obtained in the experiment.

After the pattern passed through the object, the intensity from the object was obtained using a photodetector (PDA100A2, THORLABS). The obtained optical intensity was analogue-to-digital converted, and a computer was used to implement the image reconstruction calculation. Figure 4 shows the SPI results reconstructed in the experiment using the MCF with $N = 64$ and $M = 1024$. We used the line and numbers on the Negative 1951 USAF Target (R3L3S1N, THORLABS) as the object.

Conclusion: This paper reports on the results of proof-of-concept experiments where an image was reconstructed using a single-pixel detector and the diffraction pattern emitted from a multi-core fibre. The experiments demonstrated a very thin imaging system using a multi-core fibre whose cladding diameter is 195 μm. To the best of our knowledge, this is the first report on an experimental demonstration of a system that combines a multi-core fibre and an SPI algorithm for imaging. This system is particularly advantageous when used in narrow places. We believe that this study will help to downsize and expand the applications of SPI systems.