Single-Ended Robotic Arm Pose Sensor Based On A Multimode Fiber with Point Reflectors And Deep Learning

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Abstract We propose and demonstrate a single-ended multimode fiber (MMF)-based shape sensor for robotic arm pose estimation. Swept-wavelength interferometry interrogates weak pointer reflectors micro-machined along the MMF and spatially resolves modal dispersion. Deep learning offers 100% accuracy for classifying six different poses. ©2023 The Author(s)

Introduction

Robotic arms composed of segmented joints that allow rotational and linear motion have been widely applied in various applications such as arc welding, painting and assembly. Precise motion control on the arms are essential to perform complex tasks and prevent mechanical failures and accidents. Robotic arm pose estimation is often achieved by processing images taken by a camera. However, target occlusion and depth ambiguities dramatically increase estimation errors[1],[2].

An alternative solution is to integrate fiber optic based shape sensors which reconstruct the shape of a flexible optical fiber into an robotic arm. Distributed fiber bending parameters can be resolved using a multi-core fiber (MCF) with fiber bragg grating at each core[3],[4]. Recently, shape sensors employing modal interference of the spatial modes guided by a multimode fiber (MMF) have been proposed[5]–[9]. Current MMF-based shape sensors require access to both proximal and distal ends of the MMF and use speckle patterns captured by a camera to distinguish different bending situations.

In this paper, we propose and demonstrate an MMF-based shape sensor for robotic arm pose classification without the need to access to distal end. Fig. 1 shows the schematic of the single-ended robotic arm pose sensor using an MMF with point reflectors and the workflow of signal processing. Single-ended MMF monitoring is enabled by using a swept-wavelength interferometry (SWI) to interrogate the modal dispersion of backscattered signal from 12 equally-spaced weak pointer reflectors inscribed along the MMF using a femtosecond laser[10]. Deep learning based on separable convolutions[11] is used to classify robotic arm poses.

Swept-Wavelength Interferometry

Fig. 2(a) shows the setup of a time-multiplexed multiport SWI with an MMF interface. The time multiplexed multiport SWI[12],[13] has been applied to handle spatial modes primarily to measure components used in space-division multiplexed (SDM) communication systems such as mode multiplexers (MMUX), MMF and MCF. SWI uses a frequency swept laser to probe a device under test (DUT) which is an MMF with distributed point reflectors in our case, see Fig. 2(b). The MMF is taped down on a programmable 6 degrees of freedom (6DOF) robotic arm. The SWI measures the output against the swept laser passing through a reference arm in a phase-diversity coherent receiver essentially measuring the DUT’s amplitude and phase transmission directly in the spectral domain[14].

Fourier transform of the spectral domain produces the impulse response of the device and therefore a longer path length difference between the DUT and the reference arm introduces high frequency fringes and map to longer delays.
Fig. 2: (a) Setup of a swept-wavelength interferometry (SWI) with a multimode fiber (MMF) interface, (b) image of a robotic arm whose shape is being sensed through an MMF with point reflectors, (c) reflectometric trace in the time domain of the 12 distributed point reflectors, (d) zoom feature of a single point reflector, (e) spectral responses of all the 12 point reflectors for round-trip (upper) LP$_{01}$, (middle) LP$_{01} + LP_{11}$ and (lower) LP$_{11}$ mode after applying temporal filtering.

A mode-selective photonic-lantern based MMUX supporting LP$_{01}$, LP$_{11a}$ and LP$_{11b}$ modes is applied. The impulse responses of different input and output spatial modes are delayed temporally using different fiber delays ($\tau_1, \tau_2, \tau_3, \tau_4$) into non-overlapped time slots and distributed over the entire measurement range. The delays are longer than the total impulse response of the 12 point reflectors with a 10-mm spacing, whose reflectometric trace in the time domain is given in Fig. 2(c).

Point Reflector
The MMUX is with a graded-index (GI) 3-mode MMF pigtail which is directly spliced to a 2-m step-index (SI) MMF with a weak coupling between mode groups. The differential group delay (DGD) between the LP$_{01}$ and LP$_{11}$ mode is around 4.4 ps/m. The point reflectors were fabricated using a frequency doubled solid state Yb:KGW (ytterbium-doped potassium gadolinium tungstate) laser delivering femtosecond pulses at a central wavelength of 515 nm. The laser operated with a temporal duration of 206±5 fs and a pulse energy of 3±0.2 µJ. The inscription was carried out with a 0.4 NA objective lens and had a depth of 9±1 µm at the focal point. The MMF is translated using a dedicated high precision motorised rewinding system. An automated machine vision system was used for fibre alignment ensuring consistent reflectivity values for the reflectors.

Modal Dispersion
Around -15-dB inter-mode group coupling between the LP$_{01}$ and LP$_{11}$ modes is measured at each point reflector in the backward direction. Round-trip signal under different coupling conditions can be separated temporally in the SWI measurements after dispersion compensation due to the existence of DGD, as indicated by the three peaks in Fig. 2(d). The left and right peaks represent the signal coupled back to its originally launched mode state, either LP$_{01}$ or LP$_{11}$ mode, in backward propagation. The middle one is for the case as signal is carried by different modes in forward and backward propagation, which is labelled as round-trip LP$_{01} + LP_{11}$. Fig. 2(e) gives the spectral responses of all the 12 point reflectors after applying temporal filtering for round-trip (upper) LP$_{01}$, (middle) LP$_{01} + LP_{11}$ and (lower) LP$_{11}$ mode. The spectral responses are calculated by summing up the power of $2 \times 2$ Jones matrix at each frequency bin. Flat curves of the upper plot in Fig. 2(e) indicate a neg-
ligible polarization mode dispersion (PMD) for the $LP_{01}$ mode over the short sensing MMF. Constant spectral ripples with a free space range (FSR) of 200 GHz across all the point reflecting planes can be observed in the middle plot for round-trip $LP_{01} + LP_{11}$ mode. The spectral responses of round-trip $LP_{01} + LP_{11}$ mode are insensitive to external fiber perturbations. It may be attributed to the DGD of the GI 3-mode MMF pigtail of the MMUX, which introduces a spectral phase between the two modes. The lower plot in Fig. 2(e) shows the spectral response affected by modal dispersion within $LP_{11}$ mode group, which is sensitive to fiber bending and twisting. Moreover, modal dispersion within a same mode group is more resilient to temperature variations compared to that between different mode groups due to one order of magnitude smaller differences in propagation constant.

Experiment
In the experiment, the robotic arm is configured at six different poses, see Fig. 3(a). At each pose, we collect 50 measurements. Each measurement contains $6 \times 6$ (3 spatial modes $\times$ 2 polarizations) complex coupling matrices over frequency range from 187.7 to 198.5 THz at twelve different reflection planes. We apply temporal filtering to select round-trip $LP_{11}$ mode and calculate its spectral response, as shown in the lower plot of Fig. 2(e). In total, there are 108 spectral responses (3 input modes $\times$ 3 output modes $\times$ 12 reflection planes). 300 measurements are split into training and testing sets with a split ratio of 80% and 20%.

Fig. 3(b) illustrates the network architecture applied for pose classification. Seven 1D separable convolution layers are used in series to extract features from the input spectral responses, where $k$, $s$ and $p$ stands for kernel size, stride and padding, respectively. A flatten layer is applied sequentially to convert a 2D matrix into a 1D vector, followed by linear and nonlinear (ReLU) layers for pose classification. We use the cross entropy criterion for loss calculation and Adam method with a learning rate of 0.001 for optimization. A batch size of 5 and epoch of 20 are applied in the training.

We investigate the required number of spectral responses as input features for successful pose estimation. Using the 12 spectral responses for any input and output spatial mode, instead of all the 108 responses, can already offer 100% classification accuracy. We expect the system can be applied to sense a large number of different poses by leveraging all the information from all the input and output mode combinations. We placed the point reflectors section with a length of 0.12 at the end of the robotic arm with a total length of 0.45 m to be able to sense the deformation of the whole arm. By more equally distributing the reflectors along the arm, we expect to be able to sense bending/twisting condition for each joint.

Conclusions
We demonstrated a single-ended MMF-based shape sensor for the first time using modal dispersion within a same mode group. A time-multiplexed multiport SWI was applied to interrogate weak pointer reflectors inscribed along the MMF. Six different robotic arm poses were successfully classified using deep learning. The number of spectral features increases quadratically with the mode count. In our future work, we will investigate the shape sensing capability of MMFs supporting more spatial modes.

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References


