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CNN-based multiplexed optical fiber sensors for multi-load mapping on 2D structures ☆

Vinicius de Carvalho, Victor Hugo Martins, Walter Oswaldo C. Flores, Marcia Muller, José Luís Fabris, André Eugenio Lazzaretti

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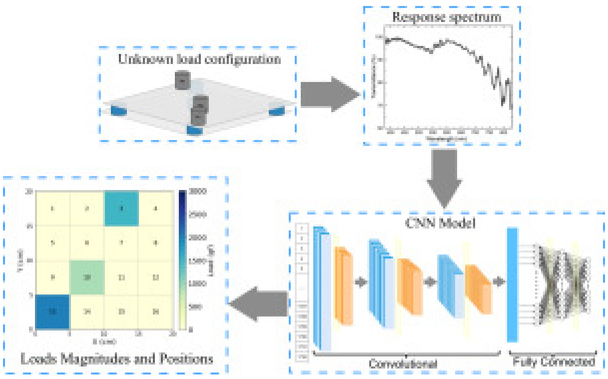
Highlights

- Convolutional Neural Network for load mapping using optical fiber sensors.
- Load magnitude and location estimated on 3 of 16 zones via 5 macrobend sensors.
- Mean absolute error in load magnitude detection was 11% of max evaluated load.
- F1 scores of 0.84–0.93 and Hamming 0.93 in load presence detection task.
- Spectral data processed using convolutional neural networks is demonstrated.

Abstract

This paper reports the application of a Convolutional Neural Network specifically designed for one-dimensional optical signal processing to determine the magnitude and position of loads acting on a structure instrumented with multiplexed macrobend optical fiber sensors, offering a cost-effective and low complexity alternative for force monitoring solutions. The system effectively localized and quantified one, two, or three simultaneous loads within 16 distinct sensing areas, utilizing only five in-series optical fiber sensors, which were spectrally interrogated in transmission mode. The monitored loads ranged from 1000 to 2000 gf. The use of the Huber loss function allows the model to adaptively predict values associated with regions with or without loads. Experimental results showed an average mean absolute error of 224±65 gf during testing. By applying a straightforward post-processing method for load presence detection in each region, the system achieved average F1 scores ranging from 0.84 to 0.93 across the monitored regions, and an average Hamming score of 0.93. These findings demonstrate the system's effectiveness in monitoring multiple loads, underscoring the potential of optical fiber sensors and CNNs in sensing applications.

Graphical abstract



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Introduction

Artificial intelligence (AI) methods have been widely used in various applications due to their ability to process large volumes of data and recognize complex patterns. Traditional techniques, such as algorithms based on Support Vectors, Random Forest, and k-Nearest Neighbors, have been extensively utilized for these purposes. However, Neural Networks and, particularly, Convolutional Neural Networks (CNNs) have demonstrated significant advantages in discovering hierarchical patterns in data. CNNs offer generalization capabilities and robustness that make these networks an attractive and effective choice for a variety of sensor data processing tasks. Moreover, the computational efficiency of CNNs is particularly beneficial for managing large datasets, which are common in optical sensor applications [1], [2].

In the field of sensing, there is a growing need to simultaneously monitor multiple parameters in complex environments. This requires the implementation of advanced sensing technologies that can operate in demanding conditions and provide high performance with the collected data. In this context, optical fiber sensors (OFS) offer significant advantages compared to systems based on electrical signals. They exhibit immunity to electromagnetic interference and possess features related to the physical structure of the fiber, such as high resistance to corrosion, relatively low maintenance costs, great flexibility, and small size [3], [4]. These characteristics allow the development of sensing systems capable of operating in environments unsuitable for electrical systems [5].

Spectral optical sensors usually generate complex datasets, which can be challenging to interpret. Conventional methods rely on manual techniques and mathematical modeling, while modern AI techniques, such as CNNs, can learn and extract complex features in data patterns [6]. These networks are effective in handling the complexity of datasets generated by optical sensors, making them a powerful tool for sensing applications. Li et al. (2022) developed an optical fiber curvature sensor using a machine learning model to process specklegram data from the facet of a multimode fiber (MMF). In that work, the curvature sensing was treated as a regression problem [7]. Specklegrams, resulting from mode interference in a 10-cm-long, step-index MMF, were collected under various curvatures and used as input data into a CNN for training, validation, and testing of the predictive model. The authors successfully predicted curvatures from 57 different specklegrams, demonstrating the effectiveness of CNNs in curvature sensing of optical fibers. The CNN implemented in that work was a vision model developed in 2014 by the Visual Geometry Group Network. Also based on specklegrams of MMFs processed by CNN, Lu et al. in 2023 detected the magnitude and position of a force applied to the MMF [8]. Both of these studies employed MMFs and image processing methods. In 2023, Lin et al. demonstrated a method for temperature detection using a one-dimensional CNN. This approach utilized a peanut-shaped structured Mach–Zehnder interferometer as the sensor, which is highly responsive, and cost-effective. The method improved detection speed and reduced system costs by mapping demodulation from the spectral domain to the temporal domain through dispersion optical fiber [9]. Also utilizing a Mach–Zehnder-based OFS, Tan et al. (2024) achieved wide-range curvature sensing. The introduction of CNNs fully utilized the information contained in the transmission spectrum, significantly improving the performance of the OFSs. The proposed method enabled the sensor to perform curvature sensing in four directions as well as over a relatively large curvature range [10].

When focusing on force monitoring, force mapping systems have applications across various fields. In diagnostic medicine, force sensors monitor pressures during physical exams, aiding in identifying anomalies and health parameters [11], [12]. In robotics, force mapping allows robots to perceive and respond to their environment accurately, facilitating delicate manipulations and safe human interactions [13], [14], [15]. In Structural Health Monitoring (SHM), these systems monitor changes in engineering structures to detect and prevent damage [16], [17].

Among optical sensing technologies, macrobend sensors have been widely used due to their ability to detect changes in the transmission properties of light induced by fiber bending. These sensors have been applied to monitor a variety of physical parameters. For instance, in humidity and temperature sensing, the integration of mid-infrared super-continuum sources and macrobend structures has enabled the development of sensors with nearly linear responses and sensitivities of 314 pm/%RH and 5.37 nm/°C, respectively [18]. In liquid level monitoring, macrobend polymer optical fibers with coupling structures have achieved superior signal-to-noise ratios, allowing dynamic measurements with resolutions below 0.3 mm and a range up to 350 mm [19]. Similarly, temperature sensing using plastic optical fibers has demonstrated linear responses with sensitivities of $8.95 \cdot 10^{-4}$ °C^{-1}, leveraging a self-referencing transmittance ratio to minimize power fluctuation errors [20]. Furthermore, refractive index sensors have combined macrobend structures with surface plasmon resonance mechanisms, achieving sensitivities of 1570 nm/RIU and 43 dB/RIU for a refractive index range of 1.33 to 1.40 [21]. Macrobend-based displacement sensors have been proposed with the objective of providing a simple and effective solution for displacement monitoring [22]. The system utilizes a concentric gear shaft to bend the optical fiber with a constant radius, converting displacement into measurable macro-bending loss. Calibration experiments demonstrated linearity, with a measurement range of 200 mm, a sensitivity of 0.1668 dB/mm, and a minimum displacement resolution of 0.06 mm.

Macrobend-based sensing platforms have shown significant potential for force monitoring applications. As an example, [23] reported a 20 × 20 cm pressure-sensitive platform divided into sixteen 5 × 5 cm regions, instrumented with five in-series macro-bend sensors. In that work, principal component analysis was employed to reduce dimensionality, and k-nearest neighbors classification and support vector regression were used to interpret the spectral data. The system achieved 94% accuracy for pressure location within the range of 3.74–9.98 kPa, with a mean absolute error of 0.31 kPa (less than 5% of the maximum applied pressure).

The present work undertakes the more challenging objective of monitoring multiple simultaneous loads. Innovative aspects of this study include using a quasi-distributed sensor system, which enables the detection of loads and provides information on both the magnitude and position of each detected load, with the capability to identify one to three simultaneous loads applied to the structure, while employing fewer macrobend sensors than monitored regions. This study employs a 1-D CNN specifically designed for processing spectral data from the macrobend sensor system, representing a state-of-the-art application of artificial intelligence methods. The CNN model's architecture captures basic and complex patterns from optical spectra, utilizes Huber loss for robust performance in highly imbalanced datasets, and interprets load magnitudes in the monitored structure. An important feature of our approach is the use of multiplexed sensors within a standard single-mode optical fiber link, significantly reducing the cost and complexity of the system and making it an attractive option for monitoring applications.

Section snippets

Materials and methods

In this section, the materials and methods enabling the operation of the proposed sensing system will be detailed. Fig. 1 presents a schematic of the load mapping system operation, highlighting the experimental setup of the optical system and computational modeling that resulted in the mapping of forces associated with applied loads. The tactile system, comprising a macrobend-based optical fiber sensor array, is connected to a UV–Vis spectrometer and an optical source. The transmitted spectral …

Analysis of the transmission spectra

Table 4 lists the load configurations associated with five randomly selected samples from the test dataset. Fig. 2 presents the transmission spectra for these samples.

It is evident that each load configuration on the structure generates a unique transmission spectrum, which, as demonstrated in [23], is reproducible under repeatability conditions of measurement. This indicates the feasibility of sensing multiple loads based on the data. Regardless of the degree of similarity among spectra …

Conclusions

The specially developed 1D-CNN allowed the expansion of the sensing capabilities of the sensor to map multiple loads, demonstrating effectiveness in detecting and quantifying forces in multiple regions of a structure. This model was particularly suitable for processing the optical transmittance data, especially with adjustments to the architecture and loss function. Macrobend OFS exhibit low production complexity and have demonstrated multiplexing capabilities by enabling the monitoring of …

CRediT authorship contribution statement

Vinicius de Carvalho: Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Victor Hugo Martins:** Writing – review & editing, Investigation, Conceptualization. **Walter Oswaldo C. Flores:** Writing – review & editing, Investigation, Conceptualization. **Marcia Muller:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition. **José Luís Fabris:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition. **André Eugenio** …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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