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Spatial encoding brings high-density 3D shape sensing to a single-mode fibre

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Abstract

Existing three-dimensional fibre shape-sensing systems involve trade-offs among compactness, spatial sampling density, and interrogation complexity. Luo et al. addressed these challenges by spatially encoding orthogonal curvature components using axially misplaced eccentric scatterers in a standard single-mode fibre, enabling millimetre-scale, single-channel reconstruction and scalable integration into robotic and minimally invasive devices.

Keywords: Three-dimensional shape reconstruction, Spatial encoding, Femtosecond laser inscription, Misplaced orthogonal eccentric scatterers, Optical fibre shape sensing

Shape sensing is increasingly important for soft robots, steerable endoscopes, and minimally invasive instruments, where real-time knowledge of three-dimensional deformation is required for navigation, manipulation, and closed-loop control in confined or delicate environments[1–3]. Optical fibre shape sensors are particularly well suited for this task because they are thin, flexible, lightweight, and immune to electromagnetic interference. In addition, they can be embedded in narrow instruments without substantially increasing the probe size[4–7].

Accurate three-dimensional shape reconstruction requires continuous or densely sampled measurements of both the local curvature and the bending direction along the sensing fibre[8]. Point bending sensors, such as those employing Mach–Zehnder interferometers[9,10] and Fabry–Pérot interferometers[11], can provide high sensitivity; however, their sparse sensing locations limit the reconstruction of complex, continuous shapes. Quasi-distributed sensing based on fibre Bragg gratings (FBGs)[12,13] and distributed sensing based on optical frequency domain reflectometry (OFDR)[14-16] have emerged as the two principal approaches for three-dimensional fibre shape sensing. However, recovering both the magnitude and direction of the local curvature generally requires axial-strain measurements at multiple spatially separated positions across the fibre cross section. Therefore, conventional systems rely on multiple fibres or multicore fibres, requiring each sensing channel to be interrogated separately. This increases the sensor size, interconnection and packaging complexity, and overall system cost.

Femtosecond-laser inscription of multiple off-axis or cladding FBGs in a standard single-mode fibre provides a compact single-fibre solution, in which the relative intensities of spectrally distinguishable gratings are used to determine the bending direction[17,18]. However, the finite interrogation bandwidth limits the number of gratings that can be resolved in a single channel, restricting the system's

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capacity to simultaneously achieve a high sensing-point count and fine spatial resolution. While OFDR, provides densely distributed strain sampling, a conventional single-core fibre core does not provide sufficient independent transverse information to recover both the bending magnitude the and direction[15,16]. Achieving direction-resolved, densely sampled three-dimensional shape sensing in a standard single-core fibre using only one interrogation channel thus remains a central challenge.

Against this backdrop, Luo et al. developed a three-dimensional deformation-encoding and shape-sensing approach based on misplaced orthogonal eccentric scatterers (MOESs) inscribed in a standard single-mode fibre[19]. The MOESs consist of femtosecond-laser-written, micrometre-scale Rayleigh scattering-enhancement structures positioned in the fibre cladding along alternating orthogonal azimuthal directions. Fibre bending changes the overlap between the guided mode and each eccentric scatterer, modulating its backscattered intensity according to the local curvature component along the corresponding direction. Unlike orthogonal FBGs, which are distinguished by their wavelengths, these scatterers have no intrinsic spectral labels. Therefore, they are axially staggered such that each generates a distinct peak in the spatial OFDR trace. The orthogonal eccentric positions encode the two transverse curvature components, whereas the axial displacement assigns each response a distinct spatial address within a single OFDR channel. Therefore, each adjacent orthogonal pair forms an effective sensing point that encodes the local directional-curvature information required for three-dimensional reconstruction into a one-dimensional sequence of scattering-peak intensities.

Using a reel-to-reel femtosecond-laser writing system, the authors inscribed 450 scatterers along a 1.13-m fibre, corresponding to 449 sensing locations at 2.5-mm spacing, with a total added loss of only about 0.38 dB. Three-dimensional reconstruction was demonstrated over an approximately 9-cm section containing 36 scatterers and 35 sensing points. The two orthogonal scatterer sets showed approximately sinusoidal responses with bending direction, a phase offset of about 90°, and an average maximum sensitivity of approximately 0.05 dB·m. The three-dimensional trajectory was then reconstructed using the

Table 1 Representative comparison of optical-fibre-based bending and three-dimensional shape-sensing approaches[9,11,13,15,17,19-23]. Note: SMF, single-mode fibre.

Work	Sensing fibre / element	Sampling / sensing length	Capability / range	Accuracy	Readout	Channel(s)	Main comment
Tan et al., 2024[9]	Mach–Zehnder interferometer	1 local point	0–10.42 m^{-1};4 directions	–	Transmission spectra + CNN	1	Directional local sensing only
Oliveira et al., 2022[11]	FP cavities in a seven-core fibre	1 local plane	2D vector bend; 0–6.4 m^{-1}	<4%	Reflection spectra	Multicore	Directional local sensing only
Hadad et al., 2023[20]	Step-index multimode fibre	3 points over 2 m	1D position tracking	≈97% step accuracy	Proximal reflected speckle + CNN	1	Sparse point tracking
Roodsari et al., 2024[21]	Five eccentric-FBG triplets in SMF	5 planes; 5-cm spacing; 30 cm	3D shape; 0.58–33.5 m^{-1}	2.1-mm median tip error	Reflection spectra + CNN	1	DL-enhanced but data-dependent
Meng et al., 2023[13]	FBG arrays in anti-twist seven-core fibre	6 planes; 3-cm spacing; 15 cm	Real-time 3D shape	3.33% max median tip error	FBG reflection spectra	Multicore	Accurate but multichannel
Fu et al., 2024[15]	Weak-FBG arrays in seven-core fibre	60 points; 1-cm spacing; 60 cm	2D/3D shape	1.08%/1.07%	OFDR + cross-correlation	Multicore, switched	Dense but multichannel
Meng et al., 2025[22]	WDM/IW-FBG arrays in seven-core fibre	20 planes; 2-cm spacing; 40 cm	2D/3D shape	2.61%/2.75%	OFDR	1, seven-core synchronous	Single-channel but wavelength-coded
Qiu et al., 2026[23]	Helically wrapped SMF	2.6-mm strain sampling; 1.45 m	2D/3D shape + twist	2.15%/5.32%; twist 7.90%	OFDR + SSTFT	1	Twist-aware but geometry-dependent
Luo et al., 2025[17]	Cascaded orthogonal cl-FBGs in SMF	26 points; 1-cm spacing; 25 cm	2D/3D shape	<8%/≈3%	OFDR intensity	1	Four wavelength labels; twist-sensitive
Luo et al., 2026[19]	MOESs in SMF	449 points; 2.5-mm spacing; 1.13 m	2D/3D shape	3D End/relative errors <8%/<6%	OFDR intensity	1	Dense single-core sensing; noise/twist limits

Frenet–Serret equations. For circular arcs with radii of 6–12 cm, the relative error remained below approximately 6% and the endpoint error was below 8%. The crossed, S-shaped, and spiral configurations were qualitatively reproduced. Temperature and axial-strain tests further indicated robustness to uniform environmental perturbations. Although weak-signal fluctuations and cumulative reconstruction errors remain important limitations, this study establishes a distinct spatial-encoding strategy for dense, direction-resolved three-dimensional shape sensing in a standard single-core fibre using only one interrogation channel.

Table 1 compares the present results with those reported in a representative, though non-exhaustive, selection of prior studies in the field[9,11,13,15,17,19-23]. Existing approaches generally involve trade-offs among the sensor size, number of interrogation channels, spatial sampling density, and three-dimensional reconstruction capability. Local interferometric sensors cannot readily support axial shape reconstruction[9,11], whereas multicore or multi-fibre schemes increase the system integration and demodulation complexity[13,15,22]. Existing single-fibre approaches are often constrained by the wavelength-multiplexing capacity[17,21] or by application-specific sensing geometries with limited effective spatial sampling[20,23]. By introducing MOESs into a standard single-mode fibre, Luo et al. unified directional-information encoding and axial signal addressing in the spatial domain, thereby enabling high-density three-dimensional shape sensing with a single fibre and interrogation channel. The significance of this work lies not only in improving an individual sensing metric but also in establishing a deformation-encoding paradigm that avoids reliance on multicore structures and wavelength labels. Combined with reel-to-reel femtosecond-laser writing, this approach also provides a potential route toward long-length, high-density, and scalable manufacturing of shape-sensing systems.

Possible extensions may include improving robustness against signal fluctuations, fibre twisting, and sharp-bend loss, as well as validating the approach under dynamic deformation. Its compact architecture may also facilitate the integration of force sensing, intraoperative imaging, or closed-loop control in continuum robots and minimally invasive instruments[24,25].

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Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The authors declare no competing interests.

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