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# A bioinspired flexible optical sensor for force and orientation sensing

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Flexible optical sensors have been an emerging paradigm for applications in robotics, healthcare, and human-machine interfaces due to their high sensitivity, fast response, and anti-electromagnetic interference. Recently, Marques reports a bioinspired multifunctional flexible optical sensor (BioMFOS), achieving a forces sensitivity of 13.28  $\mu\text{N}$ , and a spatial resolution of 0.02 mm. The BioMFOS has a small dimension (around 2 cm) and a light weight (0.8 g), making it suitable for wearable application and clothing integration. As proof-of-concept demonstrations, monitoring of finger position, trunk movements, and respiration rate are realized, implying their prominent applications in remote healthcare, intelligent robots, assistance devices teleoperation, and human-machine interfaces.

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Over the past decade, we have witnessed the rapid development in the flexible sensor for applications in personal healthcare, smart robots, and human-machine interfaces<sup>1-3</sup>. As an alternative to electronic skin (e-skin) sensors, considerable efforts have been made to develop the flexible optical sensor due to the high sensitivity, fast response, electrical safety, free of electromagnetic interferences, and potential for miniaturization<sup>4,5</sup>. For example, optical micro/nanofiber (MNF) enabled flexible sensors have achieved a pressure sensitivity of 1870  $\text{kPa}^{-1}$ <sup>6</sup>, a fast temporal frequency response up to 30 kHz<sup>7</sup>, and a small footprint suitable for minimally invasive surgery<sup>8</sup>. Based on the MNF tactile sensors, smart textiles for human-machine interaction<sup>9</sup>, and soft robotic skin for multifunctional humanoid tactility<sup>10</sup> have been realized. Usually, the fabrication of these MNF sensors relies on individual micromanipulation of tiny MNFs, posing a challenge to their mass production and applications in daily life.

Recently, flexible optical waveguides made from elast-

ic polymer have been intensively explored owing to their excellent biomechanical properties and sensing performance together with low cost, reliability and potential for large scale fabrication<sup>4,11-14</sup>. Typically, elastic polymer waveguides with a core-cladding structure are fabricated using molding, coextrusion or dip coating methods<sup>15</sup>. By measuring the output intensity of the waveguide, the exerted force or deformation can be obtained. For instance, a soft prosthetic hand equipped with multiple flexible optical sensors can feel the shape and softness of tomatoes<sup>16</sup>. The other prominent example is a stretchable distributed fiber-optic sensor enabled glove, which can reconfigure all types of finger joint movements and external presses simultaneously<sup>17</sup>. It is worth noting that most of the reported flexible optical sensor using a one-dimensional structure, which is difficult to sense the force and orientation simultaneously. To address this issue, one can employ fiber array to construct a diffuse light field, which can be decoupled through machine learning techniques<sup>18</sup>, or use two flexible fibers

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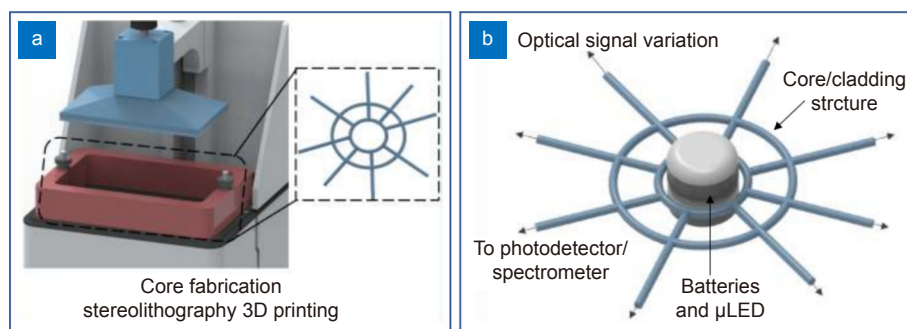
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**Fig. 1 |** (a) Schematic representation of the core/cladding fabrication using stereolithography 3D printing technique. (b) Representation of the batteries and  $\mu$ LED assembly in the structure.

with a crossed-over layout, to form a multiaxis sensor<sup>19</sup>. However, the relatively large size of these sensors may limit their practical applications in wearable sensors or space confined scenarios.

In a recently published paper in *Opto-Electronic Advances*, Carlos Marques and his colleagues at University of Aveiro and Federal University of Espirito Santo report a bioinspired multifunctional flexible optical sensor (BioMFOS) as an ultrasensitive tool for force (intensity and location) and orientation sensing<sup>20</sup>. Inspired by the spider web, the authors design and fabricate a frame structure with radial and frame elements using so-called micro-opto-electro-mechanical systems. In this work, polydimethylsiloxane (PDMS) and photocurable resins that have high refractive index contrast (1.43 vs. 1.50), excellent viscoelasticity and high transparency over a wide spectral range, are used as the cladding and core, respectively. As shown in Fig. 1(a), the photocurable resin core is fabricated using stereolithography 3D printing technique. To form a core/cladding structure, the photocurable resin core was placed inside a container filled with the PDMS resin, and followed by a thermal curing. As shown in Fig. 1(b), the core/cladding structure with eight radial elements is integrated with a PDMS packaged battery-LED assembly, which works as both light source and proof mass. In this case, the force applied at different locations of the BioMFOS can be detected through the optical signal variation on the sensor due to its viscoelastic response. The as-fabricated BioMFOS has a small dimension (around 2 cm) and a light weight (0.8 g), making it suitable for wearable application and clothing integration.

Experimentally, the BioMFOS can detect forces in the  $\mu$ N range, making it promising in a wide range of critical applications. By analyzing four radial element's signals, the spatial resolution is about 0.02 mm. Compared with

inertial measurement unit, the BioMFOS achieved a correlation coefficient higher than 0.9, indicating the capability of the orientation detection in 3D plane, such as movement analysis and classification applications. For example, when a BioMFOS is positioned on the top of the user's hand, the finger positions can be recognized based on the sensors' signal variations. As it does not need additional accessories and is not directly connected to the user's joints, the BioMFOS provides comfort for the user. Moreover, the authors demonstrate an application of cloth integrated BioMFOS for trunk's orientation and respiration rate sensing. This advantageous result indicates that the BioMFOS can be employed on the continuous assessment of elderly with fall risk as well as activity monitoring in different healthy or injured subjects. To mitigate the impact of transverse forces or pressures applied in the top plane of the BioMFOS on the 3D orientation assessment, a protective cover was added to the sensor structure, which makes the BioMFOS robust and reliable for practical applications. Therefore, the BioMFOS opens new avenues for developing novel human-machine interface, high performance robotic tactile units, compact biomechanical analysis devices, and remote healthcare systems.

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