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Advances in Chemical Functionalization and Engineering of Optical Fiber Composites and Multifunctional Sensor Complexes in Robotics

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Abstract Optical fibers have emerged as critical enablers in modern robotics. In particular, their integration into composite structures and functionalized sensor complexes supports real-time sensing, proprioception, and environmental interaction. This review comprehensively examines the chemical components (core and cladding materials such as silica glass and polymethyl methacrylate (PMMA)), composite materials (fiber-reinforced elastomers and carbon-fiber reinforced polymers (CFRP) with embedded optical fibers), and sensor complexes (indicator-doped coatings, sol-gel matrices, and biorecognition elements) that underpin fiber-optic technologies in robotic systems. Key applications span soft robotics (shape sensing via fiber optic shape sensors (FOSS) and polymer optical fibers (POF)), continuum manipulators, exoskeletons, and structural health monitoring (SHM) in rigid robotic platforms. Moreover, advances in stretchable waveguides, multicore fibers, and hybrid composites enable submillimeter resolution in curvature, strain, twist, collision detection, and stiffness perception. However, challenges including cross-sensitivity (strain-temperature), mechanical delamination, integration complexity, cost, and data processing overhead limit widespread adoption. Therefore, future directions emphasize AI-enhanced signal decoupling, scalable 3D-printed multifunctional fibers, and bioresorbable complexes for biomedical robotics.

Keywords: Optical fiber sensors, polymer optical fibers (POF), fiber-reinforced composites, soft robotics, shape sensing, fiber Bragg gratings (FBG), challenges in robotics.

I. INTRODUCTION

Robotics increasingly demands lightweight, flexible, and multifunctional materials capable of simultaneous actuation, sensing, and structural integrity. Consequently, optical fibers, traditionally used for data transmission, have been repurposed as embedded sensors in robotic systems. This shift occurs due to their electromagnetic interference (EMI) immunity, high sensitivity, and compatibility with harsh environments. Furthermore, when composited with polymers, elastomers, or carbon fibers and functionalized with chemical complexes, they enable distributed sensing over extended lengths without line-of-sight requirements [1,2,3].

This review focuses on three interconnected aspects: (i) chemical components of optical fibers tailored for robotics, (ii) composite materials and fabrication techniques for seamless integration, and (iii) sensor complexes (e.g., indicator-doped claddings or biorecognition layers) that extend functionality to chemical and biological detection. In addition, applications in soft, continuum, and rigid robotics are detailed, followed by technical challenges and future perspectives. Overall, the analysis draws on recent literature to highlight the transformative potential of optical fiber sensors while addressing barriers to commercialization [4].

II. CHEMICAL COMPONENTS OF OPTICAL FIBERS FOR ROBOTICS

Optical fibers in robotics primarily utilize silica-based (glass) or polymer-based cores and claddings. Silica fibers (core refractive index ~1.46, cladding ~1.44) dominate high-precision applications. This dominance stems from their low attenuation (<0.2 dB/km) and thermal stability up to 900°C in specialized coatings. Standard diameters range from 80–230 µm, with draw-tower gratings (DTG) at 80 µm minimizing invasiveness in composites [5].

On the other hand, polymer optical fibers (POF), such as PMMA (core index ~1.49) or polydimethylsiloxane (PDMS)-based variants, offer superior flexibility (Young’s modulus 0.2–3.0 MPa), high strain tolerance (>300% in hydrogels), and biocompatibility for soft robotics. Moreover, PDMS POFs exhibit attenuations as low as 0.11 dB/cm in the near-infrared and tunable mechanical properties via molding. Stretchable optical waveguides, fabricated from elastomers like Dragon Skin 20 or Ecoflex, further enable co-molding into actuators without compromising deformation [6, 7].

Chemical modifications include buffer coatings (acrylate or polyimide) for protection during embedding, or their removal for direct strain transfer. For chemical sensing extensions, claddings are replaced with organophilic or hydrophobic layers that selectively adsorb analytes (e.g., volatile organic compounds (VOCs) or pH indicators). Therefore, these components ensure EMI immunity and galvanic isolation, which are critical for noisy robotic environments [8].

III. COMPOSITE MATERIALS AND FABRICATION IN ROBOTIC SYSTEMS

Composite integration significantly enhances mechanical robustness while embedding sensing capability. For instance, fiber-reinforced soft actuators combine silicone elastomers (e.g., Dragon Skin 20 matrix) with woven fiberglass strain-limiting layers and Kevlar windings. This creates anisotropic composites that direct bending while housing fiber optic shape sensors (FOSS) in Teflon-lined lumens. Fabrication involves multistep molding: 3D-printed molds define geometry, reinforcements are applied, and silicone is vacuum-cured under pressure (70 psi) to encapsulate sensors along neutral axes [9,10].

In rigid robotics, optical fibers are embedded in carbon fiber reinforced polymer (CFRP) laminates via hand lay-up, resin transfer molding (RTM), or automated fiber placement (AFP). Longitudinal alignment minimizes delamination ("eye" defects), thereby preserving more than 95% of baseline tensile strength. Hybrid composites integrate multicore glass fibers (~200 µm diameter, 66 turns/m helix) with carbon reinforcements for structural health monitoring (SHM) in robotic arms or aerospace manipulators [11].

Advanced techniques, such as 3D printing of continuous fiber composites and thermally drawn multimaterial fibers, enable scalable production of instrumented tendons or exoskeleton shanks. Consequently, these materials achieve specific stiffness comparable to metals at a fraction of the weight, which is ideal for mobile robots [12].

IV. SENSOR COMPLEXES AND FUNCTIONALIZATION

Sensor "complexes" refer to functionalized coatings or biorecognition elements that transduce external stimuli into optical signals. For mechanical sensing, fiber Bragg gratings (FBG) rely on periodic refractive index variations (sensitivity ~1.2 pm/με strain, ~11.6 pm/°C temperature). Polymer FBGs exhibit negative thermo-optic coefficients for enhanced temperature response [13, 14].

In addition, chemical and bio-complexes utilize sol-gel or xerogel matrices doped with ruthenium complexes (for O_2), HPTS dyes (pH), or enzymes/antibodies for analyte-specific fluorescence quenching or absorbance changes. Intrinsic fiber optic chemical sensors (FOCS) replace cladding sections with indicator-doped permeable layers, enabling distributed chemical mapping in hazardous robotic environments (e.g., VOC detection in industrial manipulators). Extrinsic configurations, on the other hand, transport light to remote probes for Raman or laser-induced fluorescence spectroscopy [15, 16].

Hybrid complexes combine FBG with long-period gratings or Fabry-Perot interferometers for multi-parameter discrimination. Biorecognition elements (whole cells, nucleic acids) entrapped in alginate/silica matrices support biosensing in biomedical robotics. Thus, these complexes maintain reversibility and selectivity while integrating seamlessly into composites [17].

V. APPLICATIONS IN ROBOTICS

Soft and Continuum Robotics

FOSS (multicore glass fibers with OFDR interrogation) integrated into fiber-reinforced actuators enable submillimeter 3D shape reconstruction, twist detection (±90°), and collision localization (errors 1.3–2.7 mm). For example, demonstrations include environmental mapping (sawtooth/sinusoidal surfaces), stiffness perception (distinguishing durometers ≤50A), and proprioception for closed-loop control [1,20]. In addition, POF-based tactile sensors in coiled or twisted configurations detect strain, bending, pressing, and twisting for intelligent grasping in soft grippers [17].

Exoskeletons and Wearable Robotics

POF sensors embedded in 3D-printed exoskeleton shanks provide simultaneous strain/angle measurement for gait assistance. Stretchable waveguides in prosthetic hands detect surface shape and roughness. Therefore, these systems significantly enhance human-robot interaction in rehabilitation [18].

Rigid and Industrial Robotics

Embedded fiber optic sensors in CFRP robotic arms monitor fatigue, vibration, and delamination under dynamic loads. Moreover, optical sensors in continuum robots support medical interventions (e.g., needle tracking) and hyperspectral imaging for chemical composition detection in unstructured environments [19].

Chemical and Hybrid Sensing

FOCS complexes enable real-time analyte monitoring (pH, O_2, toxins) during robotic exploration or manipulation in contaminated zones, thereby extending functionality well beyond mechanical sensing.

VI. CHALLENGES

Despite their numerous advantages, several hurdles persist. Integration and mechanical issues arise because non-stretchable FOSS require precise neutral-axis placement; larger diameters (10–15× reinforcement fibers) can induce delamination or strength loss in composites. Additionally, minimum bend radii (10 mm) limit further miniaturization [20].

Cross-sensitivity and data processing challenges also remain significant. Strain-temperature interference demands hybrid designs or reference gratings, while high data volumes (1700 points/packet) necessitate downsampling for real-time control. As a result, error accumulation increases with sensor length [21].

Fabrication and cost issues further hinder widespread adoption. Labor-intensive embedding, fragile ingress/egress connectors, and expensive interrogators reduce scalability. Drift in stretchable matrices and biofouling in chemical complexes also reduce long-term reliability [22, 23].

Finally, environmental and safety concerns must be addressed. Harsh robotic conditions (torsional flex >25 million cycles) severely test durability, while biocompatibility remains critical for medical applications [24, 25].

VII. FUTURE PERSPECTIVES

Advances in AI/ML for signal decoupling, miniaturized photonic integrated circuits (PIC), and fully stretchable multimaterial fibers (via thermal drawing or direct ink writing) will effectively address current limitations. Bioresorbable POF complexes and self-healing composites promise fully implantable or disposable robotic systems. Furthermore, hybrid optical-electrical or spectroscopic enhancements will enable multimodal perception. Scalable robotic manufacturing of composites (AFP, 3D printing) is expected to drive commercialization in aerospace, healthcare, and industry.

VIII. CONCLUSION

Optical fiber composites and functionalized sensor complexes represent a paradigm shift in robotics. By systematically addressing chemical components, fabrication techniques, and existing challenges, researchers can realize adaptive, intelligent systems capable of sophisticated interaction with dynamic environments. In conclusion, continued interdisciplinary efforts will unlock their full potential for next-generation robotics.

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