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A Review of Advanced Materials for Flexible Tactile Sensors in Robots

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Abstract. This paper seeks to delve into what appear to be the substantial advancements made in the field of flexible tactile sensors for robots in recent years. Within this broader analytical framework of rapid technological development, a seemingly growing number of robots are becoming ostensibly capable of performing complex tasks that were previously the domain of humans. What this pattern seems to suggest, therefore, is that to accomplish such tasks, human-machine interaction technology appears to be of fundamental importance. Tactile sensors tend to play what might be characterized as a crucial role in enabling robots to interact more intuitively with their environment or with humans. The working principle of such sensors is seemingly designed to mimic the highly complex tactile capabilities of human skin. What appears to follow from this analysis is that to achieve this kind of human-machine interaction, flexible tactile sensors appear to be largely indispensable. As what seems to constitute the core component for this purpose, their performance appears to be determined by various factors, including mechanical flexibility, sensitivity, operating principles, and sensor materials. What seems especially noteworthy in this analytical context is that among these, sensor materials appear to be one of the primary factors, substantially influencing what seems to be the sensor's performance and adaptability to operational conditions. For instance, from this particular interpretive perspective, material properties such as stiffness, corrosion resistance, and strength tend to play apparently crucial roles. What this paper aims to primarily discuss, therefore, are the more advanced flexible materials that seem to be currently available for robotic tactile sensors, including conductive polymer composites, nanomaterial composites, and certain self-healing materials. The preparation, operating principles, performance metrics, and applications of these materials in robotic systems are all seemingly critical considerations. In light of these methodological considerations, these materials appear to possess key factors that may enable them to achieve some measure of long-term stability. However, what also appears significant is that they also seem to face various challenges. In the future, it is plausible that more advanced materials may replace them, or these materials themselves may undergo further innovation. What the investigation appears to indicate is that this paper aims to provide foundational references for researchers seeking to advance robot tactile sensing technology.

Keywords: robotics, flexible tactile sensing, sensors, composite materials

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1. Introduction

The environment we inhabit appears to be an increasingly dynamic one, and within this broader analytical framework, robots seem to play a substantially crucial role. What this tends to indicate is that the smooth operation of many industries often requires robots to be equipped with what might be characterized as highly sensitive and precise sensors, particularly in fields such as healthcare, high-precision operations, and home services. As the applications for robots continue to expand, what seems to emerge is that traditional rigid sensors appear to face notable limitations, ostensibly due to their restricted environmental applicability and a general lack of mechanical flexibility. What appears to follow from this analysis is a pattern of substantial discrepancies when compared to human limb joint movements. When encountering dynamic deformation interfaces or what could be considered extreme environments, their functionality becomes largely constrained [1].

Unlike rigid sensors, flexible tactile sensors seem to be better able to conform to curved surfaces. In recent years, considering the nuanced nature of these findings, flexible sensor technology appears to have achieved what might represent revolutionary breakthroughs, seemingly bridging the physical and digital worlds [2]. What the evidence appears to reveal is that this technology possesses a unique mechanical flexibility and functional designability, which seems to lend support to its application in diverse fields like electronic skin, health monitoring, and the Internet of Things. For the technology to maintain normal operation, high-sensitivity flexible tactile sensors are typically required, as they can detect subtle stimuli—much like human skin—apparently sensing numerous minor changes [3].

For instance, within the medical field, wearable technology is currently quite popular, and what the investigation appears to indicate is that the development of this technology seems heavily reliant on the existence of tactile sensors. Users presumably rely on these devices to meet their requirements for both comfort and practicality, and the effectiveness of such technology tends to point toward what appears to be an improvement over many traditional sensors. By ostensibly collecting physiological and mechanical data, health monitoring appears to have been substantially optimised. What also appears significant in this context is that these flexible sensors can capture subtle physiological fluctuations and kinematic dynamics, achieving what seems to be a previously unseen level of performance in human-machine interaction [4]. The performance of these sensors appears to be closely related to their constituent materials, which typically exhibit flexibility, conductivity, and environmental stability. This paper, from this particular interpretive perspective, focuses on flexible materials that seem suitable for robotic tactile sensors, intending to provide a potential direction for future research.

2. Key flexible materials for tactile sensors

2.1. Conductive polymer composites

Conductive polymer composites (CPCs) currently appear to represent one of the most commonly used material types in the flexible sensor field. What seems to distinguish this pattern from conventional understanding is that, compared to traditional materials, CPCs tend to offer novel functionalities and performance characteristics. CPCs generally consist of polymers, metal particles, and additives, and they typically exhibit what appears to be excellent conductivity and mechanical flexibility. In scenarios where traditional materials are less suitable, CPCs usually perform exceptionally well. What appears to warrant further interpretive consideration is that their higher

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thermal conductivity and corrosion resistance may enable them to handle more complex conditions. Different fillers are usually selected based on specific application requirements [5].

Within this broader analytical framework, the polymer matrix is typically regarded as insulating, with representative examples appearing to include materials such as polystyrene [PS], polyvinyl chloride (PVC), and polyimide (PI), among others. The presence of these polymers tends to ensure what might be characterized as the fundamental structure and flexibility of the CPC [6]. A distinct category also exists where a polymer matrix can seemingly achieve conductivity without conductive fillers, a class known as intrinsically conductive polymers (ICPs). What the evidence appears to reveal is that the conjugated double bonds in the main chain of an ICP seem to allow electrons to move with relative freedom along the chain, thereby providing what appears to be a conductive path. For instance, ICPs like polyaniline and polystyrene sulfonate seem to hold a seemingly indispensable position in optoelectronics and energy. What also appears significant, however, is that ICPs tend to present certain drawbacks, such as comparatively poor processability and a lack of mechanical strength, which appears to limit their application in particular scenarios. In light of these considerations, to achieve both conductivity and mechanical flexibility, a composite of insulating and conductive polymers may be utilized. What seems to emerge from this is that this conductive polymer composite appears to possess both mechanical flexibility and conductivity, which seems to make it one of the more suitable materials for flexible tactile sensors [5]

From this particular interpretive perspective, polypyrrole represents a relatively common conductive polymer, typically formed through chemical or electrochemical polymerization reactions of pyrrole monomers. After polymerization, what appears particularly significant is that it tends to exhibit notable conductivity and stability. What seems especially noteworthy here is that when subjected to pressure or temperature changes, polypyrrole can seemingly produce substantial electrical responses, a phenomenon that appears to be attributable to its rather unique conjugated π-electron structure. What this property appears to enable is the preparation of polypyrrole films with piezoresistive characteristics. What appears to happen when it is subjected to pressure is that the conformation of the polypyrrole chains appears to change, which in turn appears to lead to a change in resistance [7].

2.2. Nanomaterial composites

Considering the nuanced nature of these findings, nanomaterial composites are predominantly composed of nanomaterials mixed with elastomers or polymers. What seems to distinguish these from more conventional materials is that they tend to combine both mechanical and electrical properties, thereby exhibiting what appears to represent the characteristics of both conductive polymers and conventional polymers.

Nano-material composites appear to tend to suggest what might be characterized as substantial flexibility and mechanical strength. When subjected to bending, stretching, or other deformations, the material seems to rarely undergo what could be considered failure. Within this broader analytical framework, the combination of nano-materials with other materials seems to generally indicate a capacity to balance their respective advantages. For example, what seems to emerge from these findings is that carbon nanotube-polymer composites ostensibly possess the flexibility of polymers while appearing to enhance fatigue resistance due to the presence of the nanotubes. What also appears significant in this context is that nanomaterial composites tend to exhibit what appear to be excellent physical properties. For instance, what the evidence appears to reveal is that when graphene and other nanomaterials are combined with flexible substrates, their conductivity and mechanical flexibility seem to enable them to rapidly form what appears to represent highly efficient

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conductive networks in response to stimuli such as pressure or temperature, apparently achieving highly sensitive responses [8].

What appears to follow from this analysis is that the application of nanomaterial composites in flexible sensors may enhance various sensor performance metrics, including sensitivity and detection range. As previously mentioned, what appears to warrant further interpretive consideration is how the presence of nanomaterial composites seems to enable sensors to generate electrical signal changes with even minor deformations, which tends to point toward what appears to be an enhancement in the sensitivity of flexible sensors. When a sensor's precision apparently reaches this level, the measurement range tends to increase, thereby expanding what seems to be the detection range. Applying such flexible sensors to robots can, from this particular interpretive perspective, effectively enhance what appears to be the robots' operational precision. In scenarios requiring what might be called extremely precise operations, these robots can presumably perform such tasks, such as conducting micro-surgeries in the medical field.

Given the multifaceted nature of this evidence, cost is a factor that must be considered in both industrial and other types of production. The process of combining nanomaterials with flexible substrates is seemingly simple to operate and may be suitable for large-scale production. Furthermore, what seems especially noteworthy in this analytical context is that the flexibility of the sensor can often be adjusted according to different working conditions to meet the customization requirements of different situations. Carbon nanotubes (CNTs) appear to provide evidence that may support their future use as a type of nanocomposite material in numerous applications due to their mechanical and thermal properties [9]. What this tends to indicate is that dispersing carbon nanotubes in polydimethylsiloxane (PDMS) can create what seems to constitute piezoresistive composite materials. When the device is in operation, pressure seemingly causes deformation in the carbon nanotube network, altering the flow path and resistance, thereby inducing changes in resistance values. This apparently high sensitivity and rapid response characteristic seems to be highly suitable for human-machine interaction.

Graphene may be considered another common nanomaterial, often characterized by what appears to be a high specific surface area and substantial electron mobility. Within this broader analytical framework, it seems to play a substantial role in fields such as flexible sensors, appearing to offer exceptional performance. What the evidence appears to reveal is that the incorporation of elements like nitrogen (N) and oxygen (O) seems to lend support to what may represent exceptionally high conductivity for graphene [10]. What also appears significant in this context is that reduced graphene oxide (rGO) can be produced by reducing graphene oxide (GO), which appears to result in a flexible film seemingly capable of detecting variables such as strain and pressure. This technology currently appears to have applications in robotic prosthetics.

2.3. Self-healing materials

Self-healing, within these evolving conceptual parameters, tends to refer to what might be characterized as the repair of cracks in machinery through reversible chemical bonds, such as hydrogen bonds or disulphide bonds, thereby ostensibly addressing machinery degradation issues.

Given the multifaceted nature of this evidence, MXene, as a material with high conductivity and flexibility, appears to enhance the performance of polymers and seemingly represents an excellent material for many flexible sensors. What appears to follow from this analysis is that mixing MXene with self-healing polymers enables the composite to possess both conductivity and self-healing capabilities. Flexible tactile sensors in robots are typically subjected to substantial tensile forces during use, and their performance tends to degrade over time. In the majority of such cases, the

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material's self-healing capability appears to become particularly important. What seems especially noteworthy in this analytical context is how using MXene as a two-dimensional conductive binder in hydrogels substantially enhances mechanical strength and self-healing capability compared to traditional binders. What this tends to indicate is that such hydrogels appear to exhibit better healing effects than those using conventional binders after damage. Considering the nuanced nature of these findings, similar examples abound. In light of these methodological considerations, what appears to emerge as theoretically important for future robotic applications is that ensuring high efficiency while extending the service life of flexible tactile sensors seems to necessitate enhancing their self-healing capabilities as a critical strategy.

3. Challenges and future directions

It appears that virtually any material will experience some degree of performance degradation after prolonged use. Furthermore, given the complexity of environmental changes such as temperature and humidity, alongside the cumulative effect of loads, this issue seems largely inevitable. What this tends to indicate is that how to extend the lifespan and stability of material performance without substantially altering its fundamental properties has seemingly become one of the core challenges for the future. For instance, pure polyaniline materials tend to exhibit poor mechanical properties and can be difficult to process. However, combining polyaniline with flexible substrates appears to provide evidence that may support a mitigation of these issues. What also appears significant in this context is that when polyaniline is subjected to cyclic stress, its stability can deteriorate, and in high-load conditions, alternative materials typically must be selected. From this particular interpretive perspective, it seems that every material possesses its own advantages and disadvantages. What appears to be particularly significant is the need to focus on its inherent performance, minimise the impact of its drawbacks, and provide more options for robotic flexible sensors. What appears to emerge from this evidence is that as material performance becomes increasingly comprehensive, the types of robotic flexible tactile sensors also become more diverse. What this pattern seems to suggest, therefore, is a need to devote more effort to what might be characterized as maintaining material performance. This appears to represent a primary direction for future inquiry.

4. Conclusion

Within this broader analytical framework, flexible materials can be seen as a cornerstone of advanced robotic tactile sensors, with conductive polymer composites, nanocomposites, and self-healing materials appearing to drive progress in this field. Although challenges in terms of stability and other aspects presumably remain, some existing materials have already begun to gradually improve what seems to be robotic precision. What seems to emerge from these findings is that an increasing number of new composite materials are being researched and put into use. What the evidence appears to reveal is that material innovation and maintaining performance are the primary tasks at present. Considering the nuanced nature of these findings, the continued integration of materials and robots will likely drive the development of tactile systems and seems to lend support to what may represent future research and development of robotic flexible tactile sensors.

References

[1] Qiang He, Yujie Liu, Zehua Xu, Jiwen Wang, Yangyang Jia, Guangfei Wang, Anling Li, Superhydrophobic flexible sensors: a review of fabrication methods and applications, Materials Today Chemistry, Volume 47, 2025, 102824, ISSN 2468-5194, https: //doi.org/10.1016/j.mtchem.2025.102824.

DOI: 10.54254/2755-2721/2025.AST34443

[2] Muhammad Usman, Nabil Jamhour, Jeffrey Hettinger, Wei Xue, Smart wearable flexible temperature sensor with compensation against bending and stretching effects, Sensors and Actuators A: Physical, Volume 353, 2023, 114224, ISSN 0924-4247, https: //doi.org/10.1016/j.sna.2023.114224.
[3] Jinkun Lin, Yuxuan Ai, Wenda Li, Yongfei Peng, Yongjia Liu, Aihua He, Huarong Nie, Flexible multi-modal sensors based on CNT hollow spheres/PDMS composites for human motion recognition and colloid concentration detection, Composites Science and Technology, Volume 237, 2023, 110005, ISSN 0266-3538, https: //doi.org/10.1016/j.compscitech.2023.110005.
[4] Tong Li, Ling-Feng Liu, Dan Zhang, Xin-Gui Tang, Qi-Jun Sun, Recent progress on flexible tactile sensors: From microstructural design to intelligent sensing applications, Materials Today Physics, Volume 57, 2025, 101793, ISSN 2542-5293, https: //doi.org/10.1016/j.mtphys.2025.101793.
[5] Hassan Tawsif Tazwar, Maisha Farzana Antora, Itmam Nowroj, Adib Bin Rashid, Conductive polymer composites in soft robotics, flexible sensors and energy storage: Fabrication, applications and challenges, Biosensors and Bioelectronics: X, Volume 24, 2025, 100597, ISSN 2590-1370, https: //doi.org/10.1016/j.biosx.2025.100597.
[6] F. Wang, Q. Li, J.-O. Park, S. Zheng, E. Choi, Ultralow voltage high-performance bioartificial muscles based on ionically crosslinked polypyrrole-coated functional carboxylated bacterial cellulose for soft robots. Adv. Funct. Mater. 2021, 31, 2007749. https: //doi.org/10.1002/adfm.202007749
[7] Xinyu Jiao, Yuanjun Liu, Multifunctional polypyrrole-based flexible composite materials for next-generation smart material: integrated piezoresistive sensing, energy storage, electrothermal heating, and UV protection, Composites Part B: Engineering, Volume 305, 2025, 112726, ISSN 1359-8368, https: //doi.org/10.1016/j.compositesb.2025.112726.
[8] Yuqian Xiang, Xiaohui Yan, Chenglong Shi, Zhipeng Zhu, Min Zhang, Jiulong Li, Yanshuo Li, Dapeng Wu, Facile preparation of nanomaterial/polymer composite porous membranes for solid phase extraction of aflatoxins in peanuts, Journal of Chromatography A, Volume 1757, 2025, 466154, ISSN 0021-9673, https: //doi.org/10.1016/j.chroma.2025.466154.
[9] Jinbo Bian, Chongxi Jiao, Mingquan Zhu, Zhong Zhang, Zhiping Xu, Metastability control of carbon nanotube composites, Carbon, Volume 244, 2025, 120600, ISSN 0008-6223, https: //doi.org/10.1016/j.carbon.2025.120600.
[10] Zhuan Fu, Xinyu Wang, Mengyao Cai, Chunhua Zhang, Weisi Fan, Jieyao Qin, Junyao Gong, Sijie Zhou, Liangjun Xia, Flexible graphene/PPy/cotton fabric with great Joule heating performance and sensing capabilities for thermal management and motion sensing, Industrial Crops and Products, Volume 222, Part5, 2024, 120096, ISSN 0926-6690, https: //doi.org/10.1016/j.indcrop.2024.120096.