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Perspective

Advancing tele-perception: a paradigm shift from traditional non-contact sensing to adaptive embodied artificial intelligence systems

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In today's fast-evolving technological landscape, the growing deployment of smart systems demands more efficient and adaptive information acquisition capabilities. Traditional contact-based sensors [1,2] are proving increasingly inadequate, facing limitations such mechanical abrasion, reduced stability, and constrained adaptability to dynamic environments, particularly evident in applications like smart homes and medical monitoring. The advent of non-contact sensing presents a transformative solution, offering safer, more durable, and versatile alternatives across diverse sectors. Leading this transition, tele-perception emerges as a cutting-edge paradigm, extending beyond conventional non-contact methods through the use of advanced electret materials that enable stable, long-range perception. Tele-perception technologies facilitate stimulus detection without physical contact, establishing a foundational component of adaptive embodied artificial intelligence systems across diverse fields including robotics, autonomous driving, and human–machine interaction (HMI).

Non-contact sensors [3,4] comprise a broad spectrum of types, each presenting unique advantages optimized for specific applications (Fig. 1). Capacitive sensors, which detect electric field variations, offer rapid and high-precision monitoring for liquid levels and proximity sensing. Infrared sensors measure temperature changes through emitted infrared radiation, proving indispensable in security and fire alarm systems. Ultrasonic sensors, utilizing high-frequency sound wave reflections, excel in long-range measurements and are integral to robotic navigation. Laser sensors, emitting and detecting laser reflections, enable precise distance measurements and are valued in industrial automation and 3D modeling for their exceptional resolution and stability. Magnetic sensors, sensitive to magnetic field fluctuations, serve crucial roles in electronic locking systems and intelligent transport, noted for their resilience in varied environmental conditions. Optical sensors, which measure light variations to determine object position, shape, or motion, are widely utilized in precision metrology and medical imaging. Despite these high performances across applications, non-contact sensors face limitations in range, environmental adaptability, and cost-efficiency, especially in dynamic, complex settings. The triboelectric nanogenerator (TENG) [5,6], an innovative sensing technology based on electrical signal generation through contact electrification, has emerged as a promising solution. TENG offers exceptional sensitivity, durability, and adaptability, maintaining stable functionality under diverse conditions while remaining cost-effective. This breakthrough not only extends the operational scope of non-contact sensing but also establishes a high-efficiency framework essential for the development of next-generation Internet of Things (IoT) systems. However, with escalating demand for robust sensing capabilities, particularly in extended-range and complex environments, all these traditional non-contact sensing technologies are increasingly limited by intrinsic challenges: (1) Restricted sensing range: current non-contact methods perform well in close proximity but fall short in long-range applications; (2) Limited data acquisition: conventional sensors capture narrow data sets, inadequate for comprehensive multimodal analysis in complex settings; (3) Signal transmission and processing constraints: non-contact sensors often produce weak, interference-prone signals, compromising performance in demanding environments.

Tele-perception technology emerges as a transformative solution to address the limitations of traditional sensors. Unlike conventional sensors, which are vulnerable to complex environmental factors such as humidity, light, or obstacles, tele-perception enhances the local electric field through charge-trapping strategy and achieves efficient charge capture and retention by creating stable charge traps, even in complex environments. Moreover, tele-perception by integrating intelligent algorithms to enable real-time data fusion, allowing it to simultaneously capture and analyze diverse parameters such as proximity, motion, and environmental fluctuations something traditional sensors, often limited to a single data modality, cannot achieve. The incorporation of adaptive machine learning (ML) algorithms further enhances signal processing by filtering out noise, ensuring high quality signal transmission even in complex and dynamic environments. These advancements make tele-perception a more accurate, resilient,

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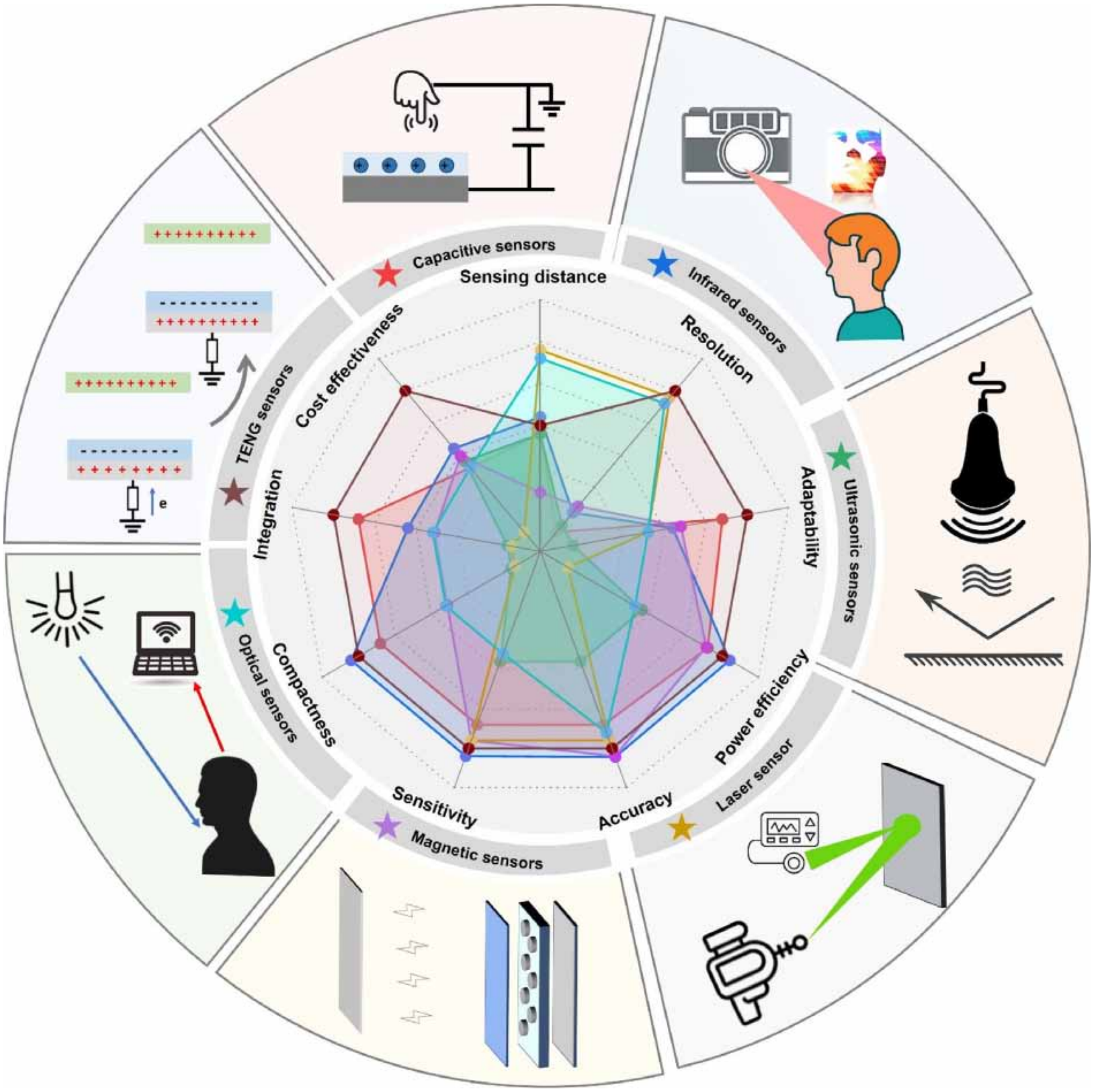

Fig. 1. Various types of non-contact sensors and their characteristics and the comprehensive comparison of non-contact sensors across nine key parameters, including sensing distance, resolution, adaptability, power efficiency, accuracy, sensitivity, compactness, integrability, and cost effectiveness. This comparison highlights the performance differences and advantages of different sensors in their respective application domains, providing a reference for sensor selection in specific use cases.

and versatile solution for sensing applications in challenging conditions. Recently, we introduced the concept of "tele-perception [7]" as a transformative paradigm to expand human sensory and cognitive horizons. Through the integration of inorganic nanoparticles into ordered arrays to establish charge traps, mimicking the bionic structure of the platypus, we achieved substantial enhancement of local electric fields and increased charge retention. This design enables detection of human presence at a distance of 1.55 m, with a sensitivity of $\Delta V/\Delta d$ = 14.2, significantly surpassing current technological standards. This breakthrough underscores the imperative of extending sensing beyond physical contact, forming a solid foundation for tele-perception's continued evolution. Unlike traditional sensing technologies, which often rely on direct physical measurements, tele-perception focuses on detecting subtle variations in electric fields to identify proximity or presence. This approach provides high-resolution sensitivity to the immediate environment, capturing dynamic, temporally dependent changes without requiring direct line-of-sight or extensive illumination. As a result, tele-perception systems offer a unique capability to perceive environmental changes that complement long-range sensing technologies, particularly in environments where electric field variations serve as key indicators of presence or movement. Realizing the full potential of tele-perception requires a paradigm shift from traditional non-contact sensing to adaptive embodied intelligent systems. This shift demands not only optimized charge-capturing mechanisms and greater stability under complex conditions but also the integration of artificial intelligence and ML algorithms at the software level. Such integration is essential for enabling intelligent, real-time decision-making and adaptive responses in dynamic settings. Embodied intelligent systems, augmented by pervasive sensing technologies, are pivotal to this evolution. This holistic approach will catalyze advances across fields like smart cities, healthcare, autonomous systems, and environmental monitoring, where sensing, interpreting, and intelligent adaptation to dynamic conditions are crucial for optimal performance even in complex, unpredictable scenarios.

Charge-trapping strategy. The key strategy for enhancing tele-perception capabilities was achieved primarily through charge-trapping strategies, focusing on the doping of functional materials, material modification, and optimization of the charge-capturing intermediate layer to improve signal capture (Fig. 2a). Doping functional materials [8], such as high-dielectric-constant materials (e.g., calcium titanate ($CaTiO_3$), lithium niobate ($LiNbO_3$)), was employed to enhance the dielectric constant of the electret, thereby improving its charge trapping capacity. The integration of conductive polymers (e.g., polyaniline, polyvinyl alcohol) significantly enhanced charge transport efficiency, thereby achieving enhanced sensor sensitivity and accelerated response times. Furthermore, doping with ferroelectric materials (e.g., barium titanate ($BaTiO_3$), lead zirconate titanate ($Pb(Zr,Ti)O_3$)) enhanced polarization capacity, boosting charge trapping and overall system stability. However, in high-frequency dynamic environments, the dielectric response of these materials became constrained, leading to reduced charge trapping and retention capability. Excessive conductive polymer content could compromise mechanical strength and induce charge leakage, while the polarization strength of ferroelectric materials deteriorated under varying humidity and temperature conditions, negatively impacting charge retention. To address these challenges, nanomaterials (e.g., graphene, carbon nanotubes) were incorporated to improve high-frequency dielectric response, and multilayer structures were engineered to optimize charge trapping and retention capability. Conductive polymer doping levels were precisely adjusted to balance charge transport efficiency with mechanical integrity, while self-healing materials or reinforced composites were introduced to enhance mechanical strength and minimize charge leakage. Surface functionalization or adaptive coatings on ferroelectric materials further mitigated environmental sensitivity, while multilayer structures or sensor arrays provided resilience against temperature and humidity fluctuations.

Material modifications [9], including polymer grafting and functional group incorporation, can significantly enhance charge trapping and transport properties. Grafting high-dielectric-constant polymers (e.g., polyvinyl chloride (PVC), polytetrafluoroethylene (PTFE)) increases the specific surface area and polarizability of the material, thereby boosting charge trapping capacity and improving sensor sensitivity. The introduction of functional groups such as polar groups (–OH, –COOH, $–SO_3H$, –SH) enhances the

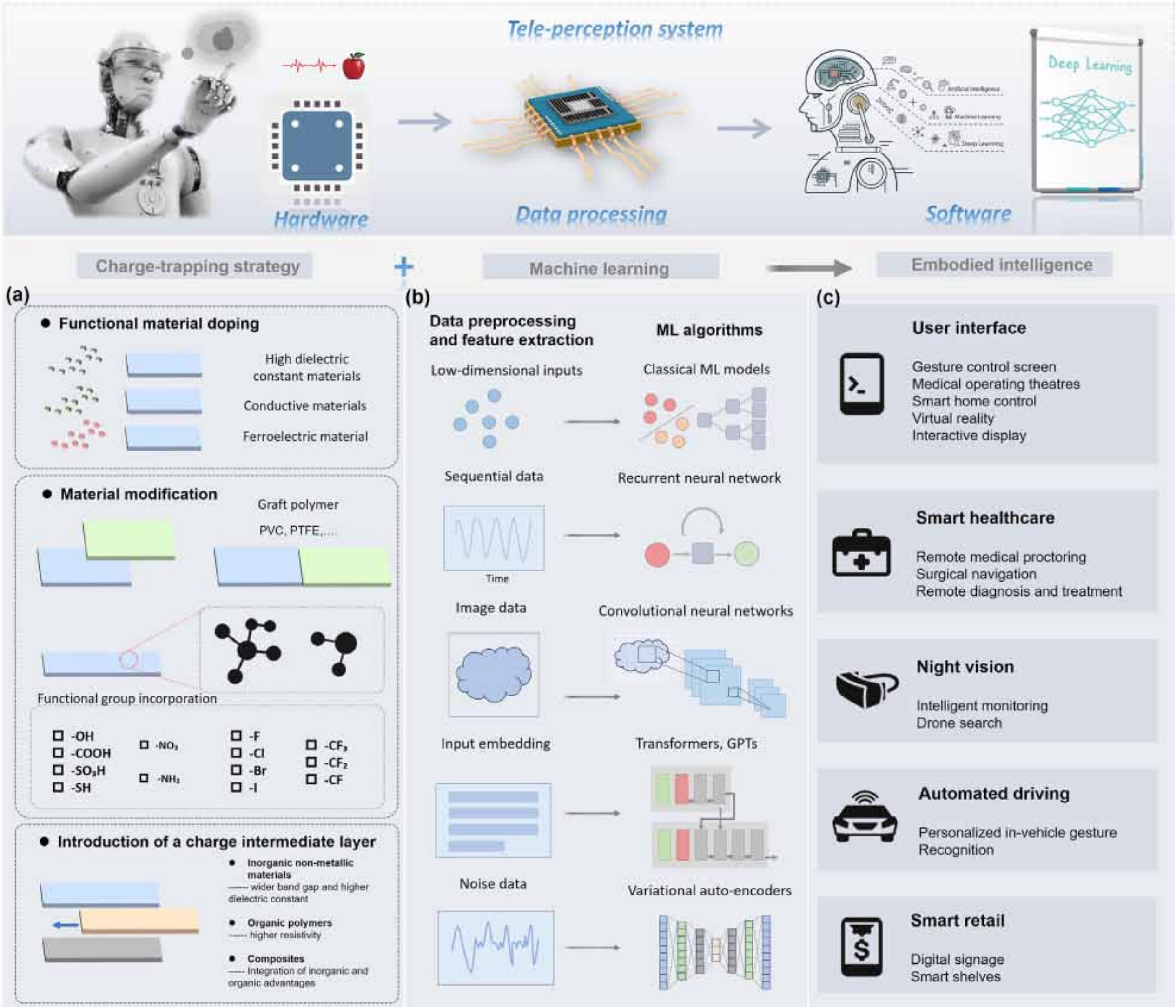

Fig. 2. Future advancements in tele-perception will arise from the integration of hardware and software, enhancing system accuracy, adaptability, and efficiency in complex environments, thus advancing intelligent sensing technologies. (a) The charge-trapping strategy is used to trap the charge. (b) Machine learning-enhanced tele-perception somatosensory. (c) The future applications of tele-perception technology may extend to more complex and multidimensional sensing scenarios.

material's polarization capability, while electron-withdrawing groups (–NO_2) and electron-donating groups (–NH_2) improve charge transfer efficiency by promoting increased polarization and charge transport, respectively. Electronegative groups (–F, –Cl, –Br, –I) and fluorinated groups (–CF_3, –CF_2, –CF) improve environmental stability by enhancing material resilience. However, excessively high polymer grafting densities may compromise mechanical properties, especially in flexible sensor applications. Over-modification of functional groups can lead to a conflict between charge trapping and transport efficiency, thereby reducing overall sensing accuracy. Additionally, strong electron-withdrawing and halogen groups may accelerate material degradation and charge leakage over time due to heightened polarizability. To mitigate these issues, optimizing polymer grafting densities and functional group distribution, employing multilayer structural designs to maintain mechanical integrity, and utilizing surface functionalization or coating techniques can enhance environmental adaptability and ensure long-term stability and charge trapping efficiency under complex conditions.

Optimizing the charge trapping [10] intermediate layer is also essential to improving charge transfer efficiency in tele-perception systems. Inorganic non-metallic materials (e.g., $BaTiO_3$, silicon dioxide (SiO_2), aluminum oxide (Al_2O_3)) are valued for their high dielectric constants and wide bandgaps, providing excellent charge retention and stability. However, their relatively low conductivity limits rapid charge transfer, especially in high-frequency dynamic sensing applications. On the other hand, organic polymers (e.g., polyvinylidene fluoride (PVDF), PTFE) exhibit high resistivity, which effectively prevents charge leakage and ensures long-term charge retention, but their low dielectric constants and weak polarization capabilities reduce charge trapping efficiency, limiting their effectiveness in complex environments. Composite materials (e.g., PVDF/$BaTiO_3$, PTFE/zinc oxide (ZnO)) combine the advantages of both organic and inorganic materials, enhancing charge retention and transfer performance. However, interface compatibility remains a significant challenge, as defects may form at material interfaces, reducing transfer efficiency. To address these challenges, conductive fillers such as carbon nanotubes and graphene can be incorporated into inorganic materials to improve conductivity and facilitate charge transfer. In organic polymers, doping with high-dielectric materials or employing self-assembly techniques to create ordered structures can improve charge transfer pathways and enhance charge flow efficiency. In composite material design, multilayer structures can optimize charge trapping and transfer, as well as regulate electric field distribution to enhance sensing sensitivity. Interface compatibility issues can be minimized through surface functionalization or the incorporation of transition layers to reduce defects at interfaces and further enhance charge trapping and transfer performance.

Machine learning-enhanced tele-perception somatosensory. The performance of tele-perception systems depends not only on the optimization of material charge-trapping strategies but also on the integration of advanced ML algorithms [11] to enhance intelligent perception capabilities (Fig. 2b). ML significantly improves system performance by enabling in-depth analysis of sensor data, enhancing signal recognition, filtering noise, and facilitating multi-dimensional information fusion. For low-dimensional data, models such as Support vector machines (SVM), decision trees, and random forests effectively identify and classify simple features. For sequential data, recurrent neural networks (RNN) and their variants, including long short-term memory (LSTM) networks and gated recurrent units (GRU), capture dynamic temporal patterns, improving system adaptability. Convolutional neural networks (CNN) excel in learning spatial features through convolutional layers, making them ideal for complex image processing tasks. Transformer-based architectures and generative pre-trained models (GPT) handle intricate data representations using self-attention mechanisms. Variational auto-encoders (VAE) address noise and missing data in challenging environments, ensuring system accuracy and reliability. In summary, tele-perception systems comprise a sensor module for detecting electric field and visual signals, a machine learning processing module that integrates multimodal data through algorithms such as classical ML, RNNs, CNNs, Transformers, and VAEs, and a decision module that converts the processed data into actionable insights. This structured framework enhances the precision of environmental sensing, ensures robust data interpretation, and facilitates adaptive decision-making, thereby enabling reliable performance in highly dynamic and complex scenarios.

However, tele-perception systems primarily rely on electrical signals to perceive the environment and extract information through the analysis of electric field variations. In complex and dynamic environments, one of the primary challenges faced by tele-perception systems is the processing of temporally dependent electrical signal data. Due to environmental fluctuations, these signals are typically continuous and sequential, posing challenges to traditional sensor processing, especially under conditions of high noise levels or environmental interference. Among various algorithms, LSTM networks are particularly well-suited for capturing long-term dependencies in time-series data, making them highly applicable to tele-perception systems. LSTM networks can predict future states based on historical electrical signal data and extract meaningful information from fluctuations in time-series data. For example, when sensors detect changes in the electric field, LSTM models not only analyze the current electrical signals but also incorporate historical data to predict future variations in the electric field, thereby improving the accuracy and responsiveness of tele-perception systems. Since tele-perception systems rely on electrical signals, noise interference is a common issue. Leveraging their unique memory mechanisms, LSTM networks can automatically identify and suppress noise, enhancing signal stability and ensuring system reliability. Moreover, tele-perception systems often require the integration of data from multimodal (e.g., object motion, environmental conditions). LSTM networks effectively fuse temporal data and identify correlations between sensor arrays inputs, thereby improving the system's overall perceptual capability. By adopting LSTM models, tele-perception systems are better equipped to handle the challenges of temporal data in dynamic environments, such as signal noise, fluctuations, and multimodal data integration. The incorporation of LSTM networks enhances the adaptability, stability, and accuracy of tele-perception systems, providing a more intelligent and robust solution for advanced perception technologies.

In summary, ML enhances tele-perception systems by addressing challenges unique to their reliance on electric field sensing, such as processing temporally dependent signals, mitigating noise, and integrating multimodal data. LSTM networks excel at capturing temporal dependencies, enabling systems to predict future states and adapt to environmental changes. They also improve signal stability by filtering noise and ensure reliable performance in dynamic, noisy environments. Additionally, ML facilitates the integration of data from sensors array, enhancing the system's overall perceptual capability. These contributions highlight the essential role of ML in advancing tele-perception within adaptive embodied artificial intelligence systems.

Perspective and challenges. Tele-perception technology, distinguished by its high sensitivity in intricate environments, is emerging as a transformative direction in pervasive sensing for the future of intelligent systems and human–machine interfaces (HMIs) [12]. Embodied intelligent systems enhanced by tele-perception and pervasive sensing technologies are set to transform fields like user interface (UI) optimization in next-generation HMIs, intelligent healthcare, autonomous driving, night vision systems, and smart retail. By leveraging real-time data from tele-perception, these systems enable dynamic, adaptive interactions, enhancing decision making, user experience, and operational efficiency in complex environments As tele-perception systems evolve, their potential is further amplified through the integration with vision technologies, which offer high-resolution spatial awareness. While tele-perception excels at detecting subtle electric field variations, vision systems provide detailed, spatially oriented information, creating a more comprehensive environmental understanding. This fusion of vision and tele-perception offers a holistic approach to perception, making adaptive intelligence even more robust. By capturing both visible and invisible elements in dynamic environments, this integration enhances system versatility, especially in contexts where both subtle electric field changes and high-resolution spatial data are critical for decision making. Ultimately, this integration not only extends the perception capabilities of conventional electronics but also significantly enhances adaptability to complex environmental dynamics, unlocking immense potential for diverse applications. Integrating advanced machine learning algorithms, such as Generative Pre-trained Transformer (GPT), Bidirectional Encoder Representations from Transformers (BERT), and Vision Transformers (ViT), further amplifies these capabilities. These large model technologies, capable of processing vast datasets, improve the interpretation of sensory inputs from tele-perception, boosting context awareness and predictive accuracy. This synergy enables systems to make intelligent, real-time decisions in highly adaptive environments, ensuring robust, efficient responses and seamless interaction between humans, their surroundings, and intelligent systems (Fig. 2c). Despite its promising prospects, several challenges must be addressed for its widespread practical applications. (1) Environmental adaptability and stability: The performance of tele-perception technology varies significantly under different environmental conditions. In extreme temperatures, humidity, and varying light conditions, the sensitivity and response of the sensors may degrade. Therefore, developing materials and systems that can withstand complex and dynamic environments while maintaining long-term stability is a critical challenge for the practical deployment of this technology. (2) Balancing sensing range and accuracy: While tele-perception aims to extend the sensing range, the increase in distance often leads to signal attenuation and reduced accuracy. Achieving high detection precision over long distances with minimal error rates requires continuous optimization of materials, structural design, and signal processing. (3) Energy efficiency [13,14] and power management: Tele-perception systems require continuous operation for real-time monitoring, placing significant demands on energy efficiency current sensing systems tend to consume more power as range and accuracy increase, particularly in long-term, multi-source sensing tasks. Future advancements should focus on developing low-power, high-efficiency sensors and optimizing power management to ensure stable operation without compromising performance. (4) Fusion and processing of multi-source sensing information: In complex environments, tele-perception systems often need to integrate data from multiple sensors to provide comprehensive environmental awareness. Efficient, real-time data processing and fusion, with effective noise and error minimization, are key challenges. The speed and accuracy of this process directly affect system safety and reliability, particularly in critical applications such as autonomous driving and intelligent healthcare. (5) Sensor integration and miniaturization: To meet the demands of various application scenarios, tele-perception systems need to be integrated with existing devices while maintaining portability and flexibility. Ensuring high-performance sensing in a compact form presents significant challenges for manufacturing processes and materials, especially for maintaining sensing capabilities in lightweight, miniaturized and integrated devices. (6) Data privacy and security concerns: As tele-perception technology involves monitoring surrounding environments and human activities, data privacy and security are major concerns. With increasing adoption, ensuring robust data protection mechanisms and preventing data misuse or leakage are critical to protecting user privacy.

In conclusion, tele-perception technology holds immense potential for future intelligent applications, significantly enhancing the sensing capabilities of smart devices and driving innovations in areas like HMIs, healthcare, and autonomous vehicles. However, to achieve large-scale implementation, challenges related to environmental adaptability, range-accuracy balance, power management, data processing, and security must be overcome. With continued technological advancements, tele-perception is poised to become a foundational component of embodied artificial intelligence systems, driving the deep integration of technology with human life in the near future.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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