
Advanced Sensor Technology and Its Applications: A Survey

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Abstract

This survey paper provides a comprehensive overview of advanced sensor technology, emphasizing its transformative impact across multiple sectors, including healthcare, autonomous vehicles, smart manufacturing, and large-scale IoT networks. The paper highlights the integration of multisensory and multimodal sensors, focusing on innovative design principles, materials, and structural designs that enhance sensor performance and adaptability. Key areas of exploration include the development of embedded machine learning systems and neuromorphic sensing, which are pivotal in advancing intelligent robotics and adaptive systems. The survey underscores the potential of Reconfigurable Intelligent Surfaces (RISs) to enhance localization accuracy and sensing capabilities, addressing existing limitations in wireless systems. In healthcare, the integration of Wearable Internet of Things (WIoT) is anticipated to shift towards personalized and proactive healthcare solutions. The paper also discusses the role of machine learning in addressing security challenges in H-IoT, highlighting the necessity for comprehensive understanding and interdisciplinary collaboration to advance edge AI research. The integration of Time-Sensitive Wireless Interfaces (TWI) in wireless systems is noted for enhancing the reliability of real-time applications. Overall, the survey concludes that ongoing research and development in advanced sensor technology hold immense potential for driving innovation and improving outcomes across diverse domains by addressing current challenges and leveraging emerging technologies.

1 Introduction

1.1 Significance of Advanced Sensor Technology

Advanced sensor technology plays a crucial role in enhancing operational efficiency, precision, and adaptability across various sectors. In healthcare, wearable devices equipped with sensors enable continuous, non-invasive monitoring of vital signs, supporting the independence of aging populations. This integration within the Internet of Things (IoT) framework promotes a proactive healthcare system that addresses rising costs while improving quality of life [1]. Furthermore, advanced sensors are essential in creating interconnected smart systems, particularly in the health and beauty industries [2].

In the manufacturing sector, advanced sensors enhance productivity through real-time defect detection, such as identifying surface porosity in Laser Additive Manufacturing (LAM), which improves structural integrity [3]. The combination of artificial intelligence with advanced sensors leads to innovative solutions, benefiting both manufacturing and healthcare [4]. Additionally, these sensors ensure worker safety in collaborative robot environments through continuous monitoring [5].

In autonomous vehicles, advanced sensors are vital for improving vehicle autonomy and real-time decision-making, effectively addressing the limitations of conventional RGB cameras in adverse conditions [6]. The integration of communications, control, and machine learning in connected and

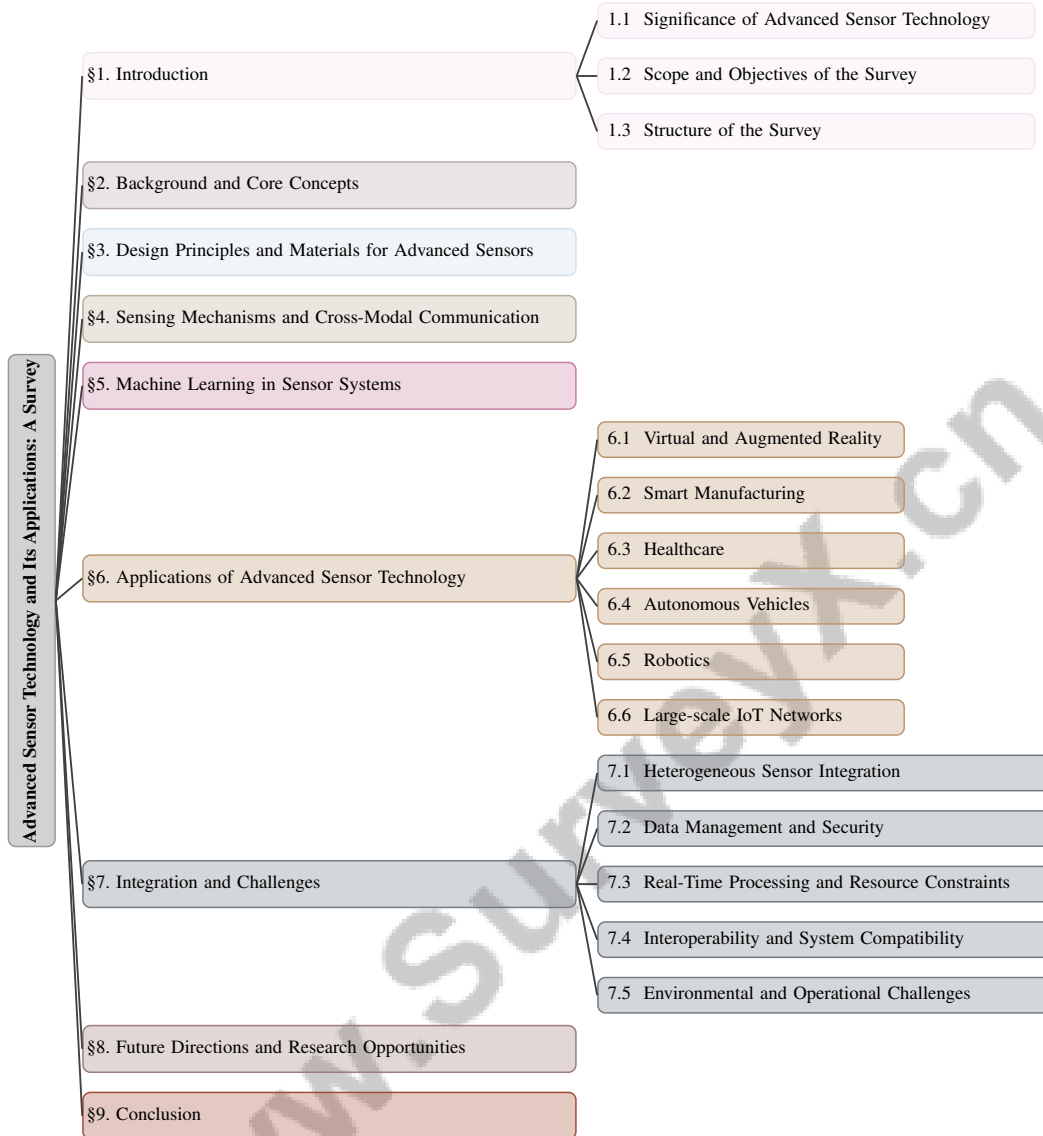


Figure 1: chapter structure

autonomous vehicles (CAVs) enhances road efficiency and reduces human error, supporting various applications, including delivery and smart city surveillance [7].

Advanced sensor technology also significantly contributes to developing intuitive control systems for rehabilitation, illustrated by bio-inspired tendon-routing sensing frameworks [8]. In robotics, these sensors enhance situational awareness and safety, particularly in unstructured environments [9]. The advancement of soft robotics, utilizing composite materials, addresses challenges in actuation speed and environmental adaptability, further enhancing performance [10].

Moreover, advancements in noncontact motion sensing have addressed the limitations of existing methods that require substantial energy and complex hardware [11]. In chemical sensing, calibrating multisensor devices is essential for accurate gas concentration estimation, significantly impacting air quality monitoring [12]. The role of multisensory media (mulsemmedia) in creating immersive experiences that engage all five human senses is increasingly recognized [13].

The potential of advanced sensor technology within the IoT ecosystem is profound, particularly in understanding human wellbeing and controlling physical devices [14]. As autonomous cyber-physical systems (CPS) evolve, sectors such as healthcare, transportation, and energy are set for transformative changes [15]. High-performance piezoelectric devices, developed through advanced

sensor technology, highlight its significance in applications interfacing with the human body and robotics [16]. Furthermore, integrating radar with vision in robotics enhances perception systems, particularly for BEV object detection, illustrating the dynamic landscape of autonomous robotic systems [17]. Advanced sensor technology continues to drive innovation across multiple sectors, addressing critical challenges and unlocking new opportunities for enhanced functionality and integration.

1.2 Scope and Objectives of the Survey

This survey provides a comprehensive analysis of advanced sensor technology, focusing on its integration with machine learning, communication systems, and various advanced technologies, including IoT, cloud computing, fog computing, edge computing, and blockchain. The scope encompasses applications in remote patient monitoring and chronic disease management, where AI significantly enhances healthcare delivery [18]. Additionally, it covers the Internet of Federated Things (IoFT), emphasizing federated learning and its applications in sectors such as manufacturing, healthcare, and energy [19].

The survey also investigates the emerging Internet of Mirrors (IoM) concept, which merges smart mirrors with IoT technologies in health and beauty, identifying challenges and opportunities in this domain [2]. In multimedia systems, the integration of multisensory media is explored, highlighting the creation of immersive experiences through extended reality (XR) and holographic-type communication (HTC) technologies [13]. The effectiveness of multisensory XR applications in exploring volumetric biomedical data is evaluated, providing insights into potential advancements [20].

In the context of IoT systems, the survey emphasizes enhancing decision-making mechanisms to improve efficiency, economics, security, and resilience [15]. It addresses the limitations of existing benchmarks, which often focus on a single sensory modality or prediction task, promoting the development of large-scale models across multiple IoT sensors and tasks [14]. The integration of computation into materials is also examined, showcasing the evolution of material systems with smart functionalities for civilian and military applications [21].

Furthermore, the role of In-Network Computing (INC) and its synergy with communication, computing, and caching (3C) in various applications is analyzed, highlighting its potential impact on sensor technology [22]. The survey investigates task-oriented communication design in industrial IoT, UAV systems, autonomous vehicles, and smart manufacturing, providing theoretical foundations and practical applications [23]. It also addresses the challenges of autonomous navigation for CAVs, focusing on stable path tracking, robust control against cyber-physical attacks, and adaptive navigation controller design [7].

Finally, the survey explores Vision-Radar fusion approaches for BEV object detection systems, covering background information, sensor modalities, and fusion techniques [17]. Through this extensive scope, the survey consolidates current knowledge while identifying gaps and future directions in advanced sensor technology, ultimately contributing to the evolution of intelligent and adaptive systems.

1.3 Structure of the Survey

This survey is structured to provide a thorough exploration of advanced sensor technology and its multifaceted applications. The paper begins with an **Introduction**, establishing the significance, scope, and objectives of the study. It emphasizes the transformative effects of advanced sensors in sectors such as healthcare and smart technology, illustrating innovations like smart footwear that utilize advanced sensors for personalized health monitoring. The introduction also addresses the challenges and opportunities associated with integrating IoT and machine learning into healthcare delivery, setting the stage for a comprehensive exploration of these technologies' implications for data management and analytics in real-world applications [24, 25, 26, 27, 28].

In **Section 2**, the survey delves into the **Background and Core Concepts**, elucidating fundamental ideas related to multisensory and multimodal sensors. This section covers essential design principles, material considerations, and the importance of fabrication and sensing mechanisms, laying the groundwork for understanding advanced sensor development.

Section 3 focuses on **Design Principles and Materials for Advanced Sensors**, discussing innovative design strategies and the utilization of advanced materials. This section emphasizes structural design and fabrication techniques' roles in enhancing sensor performance, providing insights into cutting-edge advancements in sensor technology.

Section 4, titled **Sensing Mechanisms and Cross-Modal Communication**, explores various sensing mechanisms and their roles in cross-modal communication and learning. The mechanisms discussed significantly enhance sensor functionality and integration by enabling effective information transduction through processes such as energy conversion, dispersion, modulation, and the calibration of multisensory devices. These advancements contribute to developing sophisticated sensor systems, including smart footwear for personalized health monitoring and integrating heterogeneous sensor modalities in ambient assisted living environments, ultimately improving data accuracy and operational efficiency in real-world applications [29, 25, 12, 27].

The integration of machine learning into sensor systems is examined in **Section 5, Machine Learning in Sensor Systems**. This section discusses incorporating machine learning algorithms, the development of embedded ML systems, and the impact of neuromorphic sensing and computing, showcasing the evolution of intelligent sensor capabilities.

Section 6 provides an **Applications of Advanced Sensor Technology** overview, illustrating the diverse applications of advanced sensors in fields such as virtual and augmented reality, smart manufacturing, healthcare, autonomous vehicles, large-scale IoT networks, and robotics. This highlights the critical importance of sensor fusion and intelligent robotics in enhancing performance and efficiency within the Internet of Robotic Things (IoRT), particularly in addressing challenges related to data integration from heterogeneous sensor modalities and improving task execution through advanced machine learning techniques [29, 30, 31].

In **Section 7, Integration and Challenges**, the survey addresses the integration of advanced sensors into existing systems and the challenges encountered in this process. It discusses the complexities of integrating diverse sensor technologies, managing extensive data streams, navigating real-time processing limitations, ensuring interoperability among various IoT devices, and overcoming environmental and operational challenges within sectors such as smart manufacturing and healthcare [26, 28].

The survey concludes with **Section 8, Future Directions and Research Opportunities**, identifying potential future directions and research opportunities in advanced sensor technology. This section discusses emerging trends and the need for further exploration in areas such as adaptive systems and intelligent robotics, paving the way for continued innovation and development in the field.

In the **Conclusion**, the key findings are summarized, emphasizing the critical role of advanced sensor technology in diverse applications such as smart footwear and visuotactile sensors. The discussion highlights how innovations in smart shoes enhance personalized health monitoring through features like GPS tracking and obstacle detection, particularly benefiting patients with diabetes. Additionally, the importance of signal processing methods in maximizing the effectiveness of visuotactile sensors in robotics is underscored. The conclusion reflects on the significant potential impact of ongoing research and development in these areas, paving the way for future advancements and applications in healthcare and robotics [27, 32]. The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Fundamental Concepts of Multisensory and Multimodal Sensors

Multisensory and multimodal sensors are pivotal in advancing intelligent systems by integrating diverse sensory inputs such as text, audio, video, and real-world data. This integration enhances perception and interaction in various environments, supporting applications in health monitoring, activity recognition, and virtual reality. Sophisticated multimodal machine learning frameworks address challenges in data representation and interaction, fostering adaptable models that improve real-world outcomes [33, 34, 35, 36]. By amalgamating sensory modalities like visual, auditory, tactile, and inertial inputs, these sensors boost situational awareness, crucial for autonomous vehicles, robotics, and healthcare. For example, the fusion of visual and auditory data enhances manipulation tasks, underscoring the role of multimodal sensors in robotics.

In autonomous driving, traditional RGB cameras' limitations under adverse conditions necessitate multimodal sensor data fusion, such as visual and radar inputs, ensuring reliable object detection [17]. Current multimedia systems primarily engage sight and hearing, highlighting the need for multisensory systems incorporating touch, smell, and taste to create immersive experiences [37].

Flexible hybrid electronics (FHE) exemplify integrating advanced semiconductor devices with 3D printing, producing low-cost, flexible circuits that enhance multimodal sensing capabilities. In manufacturing, multimodal sensors, including acoustic emission, vibration, and thermal sensors, are vital for detecting surface porosity, underscoring their importance in quality control [23].

The transition from centralized to decentralized IoT frameworks, utilizing advanced communication and control processes, improves IoT devices' adaptability and efficiency while preserving data privacy, highlighting multisensory systems' role in advancing IoT technologies [26]. Moreover, task-oriented communication design in cyber-physical systems illustrates multimodal inputs' integration to boost performance [23].

Challenges in multisensory systems include modality heterogeneity and complex interactions, necessitating sophisticated modeling techniques. The dynamic nature of IoT demands innovative multisensory solutions distinct from traditional systems [7].

Multisensory and multimodal sensors are foundational to advanced perception systems, integrating various sensory inputs to enable intelligent functionalities across domains like healthcare, multimedia processing, and autonomous systems. By leveraging modality heterogeneity and interaction principles, these systems enhance performance through effective data fusion, facilitating nuanced understanding and decision-making in complex environments. Recent advancements in multimodal machine learning frameworks, including cross-modal attention and multimodal transformers, support developing adaptable models, driving innovation in affective computing and smart technologies [33, 38, 36]. These systems address challenges such as sensor interference and response times, fostering innovation and enhancing integration capabilities across numerous applications.

2.2 Design Principles and Material Considerations

Advancing sensors relies on strategic design principles and material considerations to optimize performance and adaptability across diverse environments. A primary design principle is integrating multimodal sensory inputs, enhancing the sensor's ability to interpret complex scenarios through diverse data sources, crucial for overcoming traditional systems' limitations [33]. The Unimodal and Multimodal Sensor Fusion (UMSF) method exemplifies this by integrating data from inertial, pressure, and textile capacitive sensors to improve human activity recognition accuracy and robustness [35].

Material considerations are equally essential, particularly through programmable materials that integrate polymer and metal properties, enabling heterogeneous multi-material interfaces for advanced functionalities unattainable with conventional materials. The synthesis of advanced materials and innovative fabrication techniques, such as aerosol jet printing, addresses challenges in creating high-temperature sensors for real-time monitoring. Additionally, programming electrical conductance within sensor arrays enhances computational capabilities, aligning with the trend of integrating computation into materials [39].

Energy efficiency and security are critical in designing advanced sensors, particularly within Healthcare IoT (H-IoT) systems, which face unique challenges across various layers. The integration of energy-efficient sensing techniques and secure communication modalities underscores these considerations' importance in sensor design. Energy harvesting methods are vital for enhancing sensor systems' sustainability, particularly in resource-constrained environments, enabling continuous operation and efficient energy management. These methods are essential for powering bioelectronic sensor nodes in the Internet of Bodies (IoB), where strict limitations on power, area, and computation necessitate innovative energy solutions. By optimizing energy consumption per unit of information and integrating in-sensor analytics, these harvesting techniques support simultaneous sensing and secure communication required for effective monitoring and data collection [40, 25, 41].

Integrating artificial intelligence (AI) into existing systems poses multifaceted challenges, necessitating comprehensive guidelines and policies to navigate issues related to data quality and system integration complexities. This integration is crucial in pervasive AI applications within the IoT, where

real-time data streams from numerous devices require efficient resource scheduling and communication strategies to optimize performance. In sectors like healthcare, substantial data generated by intelligent wearables and IoT devices highlights the need for advanced data analytics and machine learning techniques to enhance decision-making processes and address unique challenges in AI implementation [42, 1, 43, 40, 28]. Additionally, existing tools for prototyping IoT devices, which require predefined mappings between sensors and actuators, underscore the need for more flexible design frameworks.

In advanced sensor development, design principles and material considerations focus on enhancing multimodal integration and programmability while prioritizing energy efficiency and adaptability. This includes employing sophisticated techniques like multimodal sensor fusion to improve real-time defect detection in processes like directed energy deposition, where acoustic and visual data are integrated for precise monitoring. Innovations like programmable image sensors enable in-sensor computing, significantly reducing latency and power consumption, thereby enhancing overall sensor system functionality. Furthermore, integrating intelligent materials in robotics aims to create systems that sense and respond to their environment and actively participate in computational processes, paving the way for robust and versatile applications across various fields [44, 3, 35, 45, 46]. These factors are critical for creating sensors that meet current technological demands and pave the way for future innovations in intelligent and adaptive systems.

In recent years, the development of advanced sensors has been significantly influenced by a variety of design principles and materials. To elucidate this complex relationship, Figure 2 illustrates the hierarchical structure of these design principles and materials. This figure highlights innovative design principles, advanced materials, and structural design techniques, each of which is further divided into key frameworks, methods, applications, and impacts. By showcasing the integration of these elements, the figure effectively demonstrates how they collectively enhance sensor functionality and performance across various applications. Such a comprehensive overview is essential for understanding the multifaceted nature of sensor design and its implications for future technological advancements.

3 Design Principles and Materials for Advanced Sensors

3.1 Innovative Design Principles

Advanced sensor design emphasizes adaptability, efficiency, and scalability, crucial for diverse applications. As illustrated in Figure 3, these key innovative design principles in advanced sensor systems highlight the importance of these attributes alongside multimodal fusion techniques and enhanced material identification methods. The task-oriented communication design (TOCD) framework, which structures research to enhance communication system effectiveness, aligns sensor design with specific application requirements, optimizing performance [23]. Multimodal sensor fusion further enhances robotic and autonomous systems, categorized into early, late, and deep fusion to guide robust system development [17]. The Multi-modal Recursive Material Identification (MMRMI) method exemplifies the integration of vibration and thermal data, improving material identification speed and accuracy through recursive Bayesian estimation [37]. These principles drive intelligent systems' evolution, integrating sophisticated features in smart devices, such as health-monitoring capabilities in smart footwear and personalized healthcare solutions via wearable technology, enhancing wellness tracking and resource management in IoT environments [24, 40, 27].

3.2 Advanced Materials in Sensor Development

Advanced materials significantly enhance sensor functionality, sensitivity, and adaptability. Innovations like piezoelectric polymers and flexible conductive layers transform sensor technology, with electrospun fibers improving piezoelectric properties for high-sensitivity applications [16]. Multi-material 3D printing revolutionizes sensor fabrication, exemplified by the CrystalTac sensors, which showcase the potential of creating sophisticated tactile sensors with enhanced performance [47]. In flexible electronics, 3D-printed mmWave Doppler radars demonstrate the use of conductive layers for performance enhancement [48]. Techniques like FINO-Net's multimodal fusion, combining advanced materials with data processing, enhance anomaly detection and diagnosis [49]. These innovations enable real-time health monitoring, smart footwear interactions, and intelligent robotic systems, transforming industries through AI and edge computing [44, 4, 24, 42, 27]. Table 1 provides

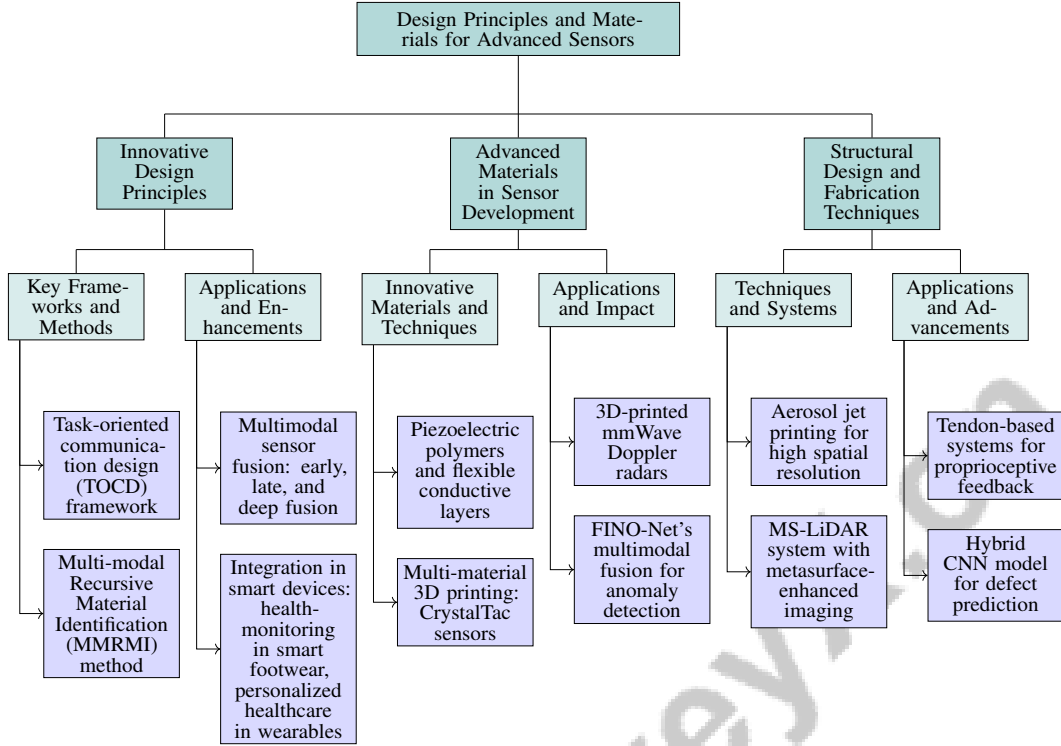


Figure 2: This figure illustrates the hierarchical structure of design principles and materials used in advanced sensors, highlighting innovative design principles, advanced materials, and structural design techniques. Each category is further divided into key frameworks, methods, applications, and impacts, showcasing the integration of these elements in enhancing sensor functionality and performance across various applications.

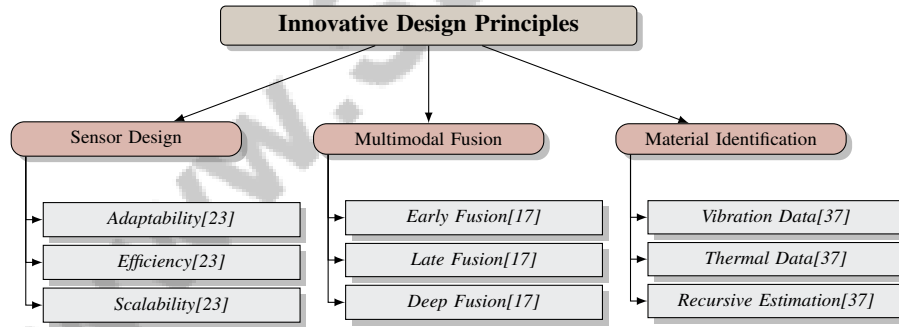


Figure 3: This figure illustrates the key innovative design principles in advanced sensor systems, highlighting adaptability, efficiency, and scalability in sensor design, multimodal fusion techniques, and enhanced material identification methods.

a comprehensive summary of the latest advancements in sensor development, detailing the interplay between material innovations, fabrication techniques, and their respective application domains.

3.3 Structural Design and Fabrication Techniques

Structural design and fabrication techniques are pivotal in enhancing sensor performance. Aerosol jet printing, a direct-write technique, fabricates multimodal sensors with high spatial resolution on complex geometries, facilitating integration into intricate structures [50]. The MS-LiDAR system, with metasurface-enhanced imaging, captures detailed spatial information, illustrating structural design's impact on sensor capabilities [51]. In robotics, tendon-based systems replicating proprioceptive

Method Name	Material Innovation	Fabrication Techniques	Application Domains
EANA[16]	Piezoelectric Polymers	Electrospinning Technique	Health Monitoring
CT[47]	-	Multi-material 3D Printing	Tactile Sensing Tasks
3D-FHE-MMW-Radar[48]	Conductive Layers	3D Printing	Wearable Electronics
FINO[49]	-	-	Intelligent Robotics

Table 1: Overview of advanced material innovations, fabrication techniques, and their application domains in sensor development. The table highlights the integration of cutting-edge materials such as piezoelectric polymers and conductive layers, alongside modern fabrication methods like electrospinning and 3D printing, to enhance functionalities in diverse applications ranging from health monitoring to intelligent robotics.

feedback improve interaction with dynamic environments, showcasing bio-inspired design potential [8]. The hybrid CNN model, integrating acoustic signals and melt pool images, enhances defect prediction, demonstrating structural and computational technique synergy in manufacturing [46]. These advancements enable sophisticated applications in robotics and LiDAR systems, enhancing environmental perception and interaction [52, 51, 32].

4 Sensing Mechanisms and Cross-Modal Communication

4.1 Sensing Mechanisms and Signal Processing

Advancements in sensing mechanisms and signal processing are crucial for enhancing sensor systems' precision and adaptability across diverse applications. Multimodal sensor data integration significantly boosts system performance in complex environments. The Sensor-Agnostic Graph-Aware Kalman Filter (SAGA-KF), for instance, utilizes multi-modal graphs from noisy sensor data to improve state estimation in autonomous driving, demonstrating the efficacy of multimodal fusion [53]. Connected and Autonomous Vehicles (CAVs) benefit from integrated wireless systems, although challenges like delays, packet loss, and cyber-physical threats remain [7].

Piezoelectric materials, known for high sensitivity under varying pressures, are evaluated through voltage output, indicating their potential for precise pressure applications [16]. In extended reality, multisensory systems like haptic gloves enhance user interaction by combining tactile, visual, and auditory stimuli, improving virtual environment realism [20].

Signal processing techniques refine data from these mechanisms. The CARMA method exemplifies dynamic reconfiguration in multi-sensory systems, optimizing energy efficiency and highlighting adaptive signal processing's importance in resource-constrained settings [54]. In mulsemmedia systems, supported by 6G technologies, advanced signal processing plays a crucial role in creating immersive experiences [13].

Innovative techniques like bio-inspired reconfigurable stereo vision enhance depth measurement in non-planar setups [55]. Digital twinning platforms merge real-world data with simulations, improving indoor localization and navigation, showcasing the potential of combining real and virtual data for enhanced spatial awareness [56].

The integration of vibration and thermal sensing data through recursive Bayesian estimation achieves material recognition in under 0.5 seconds, emphasizing sophisticated signal processing techniques' necessity for sensor system efficiency and accuracy [37].

These advancements foster innovation in sensor systems, enhancing integration across domains. Pervasive AI and edge computing significantly boost performance and adaptability, addressing modern applications' demands, such as immersive video conferencing and real-time data analytics. Leveraging IoT-generated real-time data and advanced communication technologies like 5G facilitates efficient distributed computations and resource management, ensuring optimal operation in resource-constrained environments [42, 40].

As shown in Figure 4, the hierarchical structure of advancements in sensing mechanisms and signal processing is categorized into multimodal sensor fusion, advanced materials, and signal processing techniques, each with specific examples. The Robot Vision System and Analog Stochastic Neuron illustrate these categories, with the Robot Vision System integrating sensory and environmental

interaction technologies, enabling robots to perceive and interpret surroundings using light detection. The Analog Stochastic Neuron exemplifies advanced artificial neural networks, emphasizing voltage-controlled components that mimic neural processes. These examples highlight the convergence of mechanical and computational intelligence in modern robotics and neural network design [32, 57].

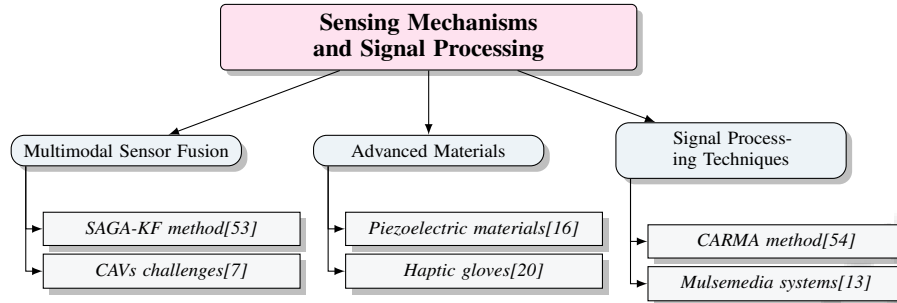


Figure 4: This figure illustrates the hierarchical structure of advancements in sensing mechanisms and signal processing, categorized into multimodal sensor fusion, advanced materials, and signal processing techniques, each with specific examples.

4.2 Cross-Modal Communication and Learning

Cross-modal communication and learning are vital for enhancing sensor capabilities by integrating diverse sensory inputs for comprehensive environmental understanding. Signal processing algorithms and hardware design constraints often limit generalization across sensor designs [32]. Innovations like VibHead, leveraging unique physiological features for user authentication, exemplify cross-modal communication's potential [58].

Robotic middleware integration, facilitated by Wrapyfi, streamlines communication and data exchange, enhancing cross-modal learning efficiency [43]. This integration is crucial for seamless interaction across heterogeneous sensor networks, ensuring effective data combination and analysis from multiple modalities.

Multimodal sensor fusion techniques executed directly in latent representation space accommodate compressed sensing, significantly enhancing data fusion efficiency [31]. Differentiable filters that learn dynamics and measurement models from data further simplify multimodal information fusion, promoting more adaptive sensor systems [59].

Incorporating multimodal data fusion in channel twinning processes enables accurate environmental modeling, enhancing channel information acquisition in communication systems [60]. This approach emphasizes integrating semantic and geometric information from various sensors for comprehensive environmental understanding [53].

Addressing decision-making complexity at the edge, ensuring privacy in data analytics, and adapting AI techniques to dynamic environments are crucial in cross-modal learning [42]. Tackling these challenges is essential for developing robust sensor systems capable of efficient real-time operation in resource-constrained settings.

Cross-modal communication and learning enhance sensor capabilities by integrating diverse sensory inputs, improving data interpretation, and enabling adaptive responses to dynamic environments. This integration facilitates advanced multisensory AI systems that process and analyze information from real-world sensors and wearable devices. Applications in healthcare, autonomous systems, and immersive technologies achieve greater accuracy and efficiency through these capabilities. Recent advancements in multimodal machine learning frameworks enable effective modality combinations, leading to improved understanding and interaction with complex data, fostering more intelligent and responsive systems [33, 36, 34, 35, 38]. These advancements drive intelligent sensor systems' evolution, opening new opportunities for innovation across domains.

4.3 Cross-Modal Fusion Mechanisms

Cross-modal fusion mechanisms are crucial for enhancing sensor integration, enabling seamless data combination from diverse sensory modalities to improve system performance and decision-making. Differentiable filtering architectures enable end-to-end learning of multimodal fusion without predefined models, enhancing interpretability and performance through adaptive fusion strategies [59].

The SAGA-KF exemplifies graph-based representations in cross-modal fusion, integrating data from various sensors to enhance decision-making. By capturing inter-node interactions without explicitly tracking edges, SAGA-KF allows flexible and efficient multimodal data fusion, particularly beneficial in complex environments like autonomous driving [53]. This graph-based approach leverages structural information to improve sensor integration robustness and accuracy.

Cross-modal fusion mechanisms address challenges in heterogeneous sensor networks, harmonizing data from different modalities for coherent environmental understanding. These mechanisms significantly enhance intelligent sensor systems' evolution, enabling effective operation in dynamic, resource-constrained environments. As IoT devices generate vast real-time data, sophisticated models are necessary for accurate decision-making. Advancements in edge computing and communication technologies like 5G optimize AI deployment at the edge, allowing real-time analytics and improved resource management among interconnected devices. These developments enhance sensor system capabilities while addressing communication overhead and computational efficiency challenges in pervasive AI applications [42, 40]. Continuous advancements in fusion strategies underscore cross-modal fusion mechanisms' crucial role in integrating and optimizing sensor technologies across domains.

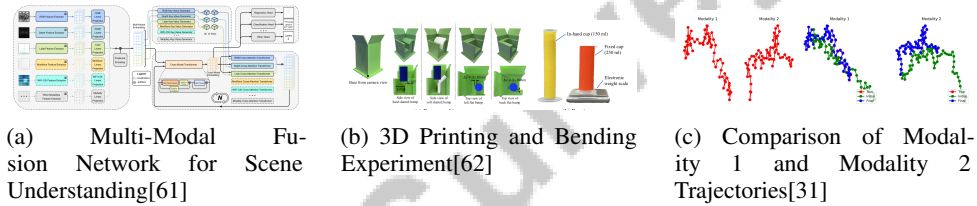


Figure 5: Examples of Cross-Modal Fusion Mechanisms

As shown in Figure 5, integrating diverse sensory inputs is crucial for enhancing system understanding and interaction with complex environments. The "Multi-Modal Fusion Network for Scene Understanding" amalgamates features from multiple sensory modalities, enhancing scene comprehension. The "3D Printing and Bending Experiment" focuses on material flexibility and adaptability. The "Comparison of Modality 1 and Modality 2 Trajectories" provides an analytical perspective by juxtaposing trajectories, visualizing temporal and feature-based variations. These examples underscore cross-modal fusion's potential in creating robust, adaptive systems capable of nuanced understanding and interaction across varied domains [61, 62, 31].

5 Machine Learning in Sensor Systems

5.1 Integration of Machine Learning Algorithms

Integrating machine learning algorithms into sensor systems enhances their capabilities in data processing, feature extraction, and decision-making. As illustrated in Figure 6, machine learning finds applications across various domains, particularly in additive manufacturing for defect detection, human activity recognition (HAR) through multimodal sensor fusion, and improving communication efficiency in multi-user environments. In additive manufacturing, machine learning significantly improves defect detection and in-situ process monitoring by applying explainable AI techniques to multimodal sensor data [3]. HAR systems benefit from machine learning, as demonstrated by the Unimodal and Multimodal Sensor Fusion (UMSF) method, which enhances accuracy and robustness [35]. Deep neural networks (DNNs) enhance multi-user environments by optimizing beam predictions for user equipment, thus improving communication efficiency [63]. The Sensor-Agnostic Graph-

Aware Kalman Filter (SAGA-KF) illustrates machine learning's role in managing multimodal sensor data for state evolution [53].

Future research in extended reality is poised to refine haptic interactions through AI, enhancing real-time data processing and immersive experiences [20]. The demand for real-time resource allocation in mission-critical IoT services underscores machine learning's importance in optimizing dynamic sensor operations [15]. The MULTIIOT benchmark highlights the superiority of multisensory multitask models over unimodal approaches, emphasizing the need for advanced models to handle diverse data [14].

Machine learning integration is crucial for innovation and enhanced sensor functionalities, particularly in healthcare, where intelligent wearables utilize IoT technology for extensive data collection [40, 28, 14]. By enabling sophisticated data processing and adaptive decision-making, machine learning contributes to developing intelligent, responsive systems.

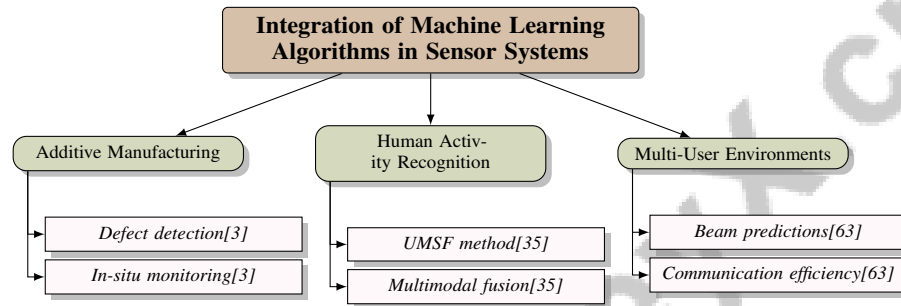


Figure 6: This figure illustrates the integration of machine learning algorithms across various domains, highlighting their application in additive manufacturing for defect detection, human activity recognition through multimodal sensor fusion, and enhancing communication efficiency in multi-user environments.

5.2 Embedded Machine Learning Systems

Embedded machine learning systems revolutionize sensor technology by enabling data processing and decision-making directly at the sensor level. Systems like YOLO Phantom are optimized for real-time applications on resource-constrained devices [64]. Cloud-based architectures, such as the MAISON platform, facilitate enhanced decision-making by analyzing raw multimodal sensor data [65]. Advanced machine learning techniques are pivotal for refining robot hearing systems, with ongoing research aimed at enhancing auditory perception [66].

Exploring neuromorphic computing architectures, such as SpikingJelly, demonstrates the potential for creating efficient sensor systems that balance usability and computational efficiency [67]. Future research will focus on optimizing computational efficiency through hardware solutions and addressing challenges like data deficiency and secure deployment [60]. Embedded systems in healthcare, exemplified by the analysis of physiological signals from wearables, highlight their potential [68].

The integration of embedded machine learning systems transforms intelligent systems, enhancing functionality and adaptability across various applications. These advancements are crucial for developing intelligent wearable devices in healthcare, which must manage vast data efficiently while maintaining low power consumption. Neuromorphic techniques, such as Spiking Neural Networks, enhance adaptability and efficiency, enabling effective operation in dynamic environments [69, 40, 28, 68].

5.3 Neuromorphic Sensing and Computing

Neuromorphic sensing and computing advance sensor systems by emulating biological neural processes, enhancing computational efficiency and adaptability. Organic Electrochemical Neurons (OECNs) exemplify this innovation, utilizing ion modulation for spiking and facilitating integration with biological systems [70]. The Attitude Estimation Spiking Neural Network (Att-SNN) demonstrates significant energy savings and reduced latency, beneficial for autonomous systems

[71]. Neuromorphic technology enhances underwater robotics by reducing power demands while efficiently processing sensory data [72].

Frameworks like SpikingJelly enhance training speed and inference efficiency, suggesting potential for scalable applications [67]. The astrocyte-regulated Spiking Neural Network (SNN)-based Central Pattern Generator (CPG) showcases neuromorphic systems' adaptability in learning locomotion gaits through Reward-Modulated Spike Timing Dependent Plasticity (STDP) [73]. Classical and quantum reservoir computing frameworks reveal the potential for energy-efficient computations in autonomous systems [74]. The Generalized Sensor Fusion (GSF) meta-architecture facilitates modular sensor fusion, enhancing system adaptability [75].

Neuromorphic sensing and computing are crucial for advancing sensor systems, offering enhanced computational efficiency and real-time processing capabilities. Recent advancements catalyze intelligent sensor systems' evolution, unlocking innovative possibilities in fields like robotics and healthcare, exemplified by smart footwear for personalized health monitoring [27, 76].

6 Applications of Advanced Sensor Technology

6.1 Virtual and Augmented Reality

Advanced sensor technology is critical in enhancing virtual and augmented reality (VR and AR) by enabling sophisticated data acquisition and processing for immersive user experiences. Multisensory learning architectures facilitate the integration of visual, auditory, and haptic feedback, enriching user interactions and adapting to inputs in real-time [77]. In VR, precise motion capture systems and inertial measurement units (IMUs) track user movements, creating dynamic environments that reflect real-world actions through multisensory feedback [13, 20, 34, 78, 38].

In AR, sensors collect and analyze data streams to accurately overlay digital information onto the physical world, enhancing interaction and depth perception. This capability is particularly beneficial in fields like healthcare, where multisensory analysis aids in examining complex biomedical data [29, 40, 27, 20]. Cameras and depth sensors capture environmental details, enabling precise digital object placement in applications ranging from education to industrial design.

The benchmark for multisensory learning architectures provides a framework for evaluating these systems' effectiveness in real-world applications [77]. By leveraging advanced sensor technology, VR and AR systems achieve higher immersion and interactivity, paving the way for innovative applications across various sectors. Continuous advancements in sensor capabilities and learning architectures are set to further revolutionize the VR and AR landscape.

6.2 Smart Manufacturing

Advanced sensors are pivotal in smart manufacturing, enhancing operational efficiency and safety. Wearable sensing prototypes recognize worker activities, improving safety protocols and operational efficiency [79]. In cyber-physical systems, sensors integrate physical and digital processes, essential for real-time monitoring and control in manufacturing operations [80].

Cloud-based Industrial Internet of Things (IIoT) systems utilize sensors to analyze large data volumes, driving insights into production efficiency and equipment health. This data-driven approach fosters predictive maintenance, reducing downtime and extending equipment lifespan. Sensors enhance robotic systems' autonomous capabilities, enabling complex tasks and adaptability in dynamic environments. The Internet of Robotic Things (IoRT) allows robots to communicate via IoT platforms, optimizing operations in applications from additive manufacturing to disaster management [44, 81, 82, 30, 83].

Advanced sensors revolutionize traditional manufacturing by enabling smart systems that are efficient, adaptive, and capable of integrating diverse data forms. They enhance operational efficiency, maintain product quality, and support intelligent decision-making. Integrating sensor technology with cybersecurity measures protects smart systems against threats, safeguarding manufacturing operations' integrity [80, 26, 84]. By enabling real-time analysis, sensors optimize operations, improve safety, and enhance productivity, driving the future of smart manufacturing.

6.3 Healthcare

Advanced sensor technology is transforming healthcare by improving diagnostic accuracy, patient monitoring, and therapeutic interventions. Sensors support Human Activity Recognition (HAR) for patient monitoring and rehabilitation, enhancing healthcare outcomes. Wearable sensor-based systems, like those on the MAISON platform, facilitate predictive modeling for health monitoring in older adults, showing potential in healthcare delivery [65]. The Internet of Things (IoT) enhances personalized healthcare by enabling timely interventions and increasing patient engagement.

In clinical settings, advanced sensors improve healthcare delivery through effective defect detection and correction strategies, ensuring high-quality medical device manufacturing [85]. The ID-Sensor approach significantly enhances bed-exit event recognition, exemplifying sensors' potential in clinical applications [86]. Visual and thermal image integration improves thermal super-resolution quality, advancing research [87].

Dynamic calibration of chemical multisensor devices enhances performance under rapid concentration variations, critical for accurate diagnostics [12]. A proposed sensor fusion system improves hand gesture recognition accuracy, indicating potential for mobile health applications [88]. The MC-based ADL system enhances detection and localization capabilities for healthcare applications [89].

Ethical and legal challenges in machine learning for healthcare must be addressed for responsible sensor technology deployment [28]. The ACROSS framework exemplifies utilizing existing datasets from deprecated sensors, enhancing sensor deployment efficiency [90]. The MULTIIOT benchmark supports advancements in healthcare, smart cities, and home automation, emphasizing AI's role in improving healthcare delivery.

Advanced sensor technology is foundational to modern healthcare systems, driving improvements in patient care, operational efficiency, and data security. By harnessing advanced sensor capabilities and IoT integration, healthcare systems enhance patient outcomes and delivery efficiency. Continuous monitoring of vital health data, personalized health management through wearables, and big data analytics facilitate a responsive healthcare experience, addressing individual needs while overcoming traditional system limitations [24, 91, 1, 27, 28].

6.4 Autonomous Vehicles

Advanced sensors are crucial for enhancing safety, efficiency, and adaptability in autonomous vehicles. Multimodal sensor fusion integrates data from various inputs, significantly improving robustness and safety in autonomous driving systems [6]. Bio-inspired reconfigurable stereo vision systems enhance robotic vision adaptability, allowing visual modes tailored to specific tasks [55].

Advanced sensor fusion techniques, like those in FINO-Net, enhance detection and classification capabilities, improving operational safety by accurately identifying potential failures [9]. Integrating radar systems into vehicle body panels facilitates real-time sensing, enhancing situational awareness and decision-making [48]. The convergence of communications, control, and machine learning in Connected and Autonomous Vehicles (CAVs) enhances navigation reliability [7].

Neuromorphic computing offers opportunities for improving computational efficiency and adaptability in autonomous systems, emphasizing classical and quantum approaches for AI systems in drones, robots, and self-driving cars [74]. Experiments with the Unitree A1 quadruped robot demonstrate the effectiveness of neuromorphic approaches compared to reinforcement learning algorithms [73].

The application of advanced sensors in hybrid-directed energy deposition processes for real-time porosity monitoring highlights sensor technology's relevance in additive manufacturing and autonomous systems [3]. Camera-radar fusion enhances 3D object detection reliability, emphasizing affordable sensors' importance for broader adoption in autonomous driving technology [17].

The evolution of autonomous vehicles relies on continuous advancements in sensor technologies and sophisticated computing systems. Recent developments in communication mechanisms support seamless data exchange. Emerging visual sensors like infrared, range-gated, polarization, and event cameras improve perception accuracy in challenging conditions. These advancements are crucial for the safe and effective deployment of autonomous vehicles in complex traffic environments [6, 92, 93].

6.5 Robotics

Advanced sensors significantly enhance robotic systems, enabling complex tasks with greater precision and adaptability. Multisensory self-attention models improve robotic manipulation by leveraging vision, audio, and touch, enhancing robots' interaction with their environment [62]. Visuotactile sensors are valuable in human-robot interaction, industrial automation, and medical robotics, combining visual and tactile information for tasks requiring delicate handling [32].

The development of neuromorphic metamaterials for mechanosensing underscores advanced sensors' potential in robotics, improving sensory feedback and adaptability [94]. Neuromorphic technology enables efficient sensory information processing, mimicking biological systems' neural processes [95]. Advanced sensors detect both straight and curved movements, highlighting their versatility across robotic applications [96].

The integration of advanced sensors into robotic systems transforms the field by enhancing sensory capabilities and enabling complex functionalities. Recent advancements, particularly through cloud computing and soft robotics, drive innovation and create more intelligent robotic systems. These technologies address traditional on-board processing limitations, expanding potential applications across various fields, including healthcare and autonomous systems. The exploration of combining soft and hard robotic capabilities using composite materials promises a new generation of flexible, autonomous robots, transforming both leisure and critical applications [10, 76].

6.6 Large-scale IoT Networks

Advanced sensors are pivotal in developing and managing large-scale Internet of Things (IoT) networks, enhancing data acquisition, processing, and communication capabilities. Integration of Vehicle-to-Everything (V2X) and IoT technologies improves situational awareness for autonomous vehicles (AVs), facilitating real-time data exchange and decision-making [97]. Deploying advanced sensor technologies in IoT networks enhances channel acquisition accuracy and efficiency, as demonstrated by Channel Twinning (CT) techniques in next-generation networks [60]. Sensor-aided beamforming strategies improve spectral efficiency, critical for managing large-scale IoT networks' high data demands [63].

In autonomous vehicles, designing computing systems for low-speed vehicles in the micromobility market highlights the importance of selecting appropriate hardware solutions to address IoT integration challenges [93]. The extensive dataset from real-world driving underscores the need for robust sensor systems capable of effective operation in diverse environments [98].

Advanced sensors are integral to deploying and managing large-scale IoT networks, offering enhanced capabilities for data acquisition, communication, and processing. Recent advancements in artificial intelligence (AI), edge computing, and communication technologies are transforming the IoT landscape, enabling efficient, scalable, and real-time solutions across diverse applications. This includes autonomous vehicles, which require rapid data processing and decision-making, and micromobility markets, where real-time analytics and connectivity are essential. Integrating AI with IoT facilitates distributed computations and improved data management, while innovations in 5G and future 6G networks support low-latency, high-capacity communication, driving smarter, more responsive systems in sectors such as healthcare, transportation, and urban infrastructure [30, 40, 42, 99, 28].

7 Integration and Challenges

7.1 Heterogeneous Sensor Integration

Integrating heterogeneous sensors into cohesive systems presents multifaceted challenges, spanning technical, operational, and environmental aspects. Variability and uncertainty in sensor data, often due to malfunctions, noise, or incomplete data, demand robust probabilistic models and advanced data fusion techniques for reliable integration [53]. The MDF platform exemplifies the complexity of managing data from diverse sensors, posing significant challenges for real-time applications [5].

In sectors like manufacturing and healthcare, multimodal sensor integration is often hindered by the limitations of individual modalities. IMUs, despite their prevalence, frequently struggle with comprehensive human activity tracking, underscoring the need for sophisticated integration strategies

[65]. The high costs and complexities of incorporating new sensors into existing systems, coupled with varying deployment maturity levels, create substantial barriers [6]. The MAISON platform highlights challenges related to limited interoperability among commercial devices, complicating the integration process [65].

Nonetheless, several strategies facilitate heterogeneous sensor integration. Bio-inspired reconfigurable stereo vision systems offer flexibility in camera alignment, enhancing adaptability through improved depth perception and broader fields of view [55]. The Loaded Dice approach fosters innovative integration by encouraging spontaneous exploration of sensor-actuator combinations [100]. Furthermore, FINO-Net's ability to process raw sensory data in real-time and integrate multiple modalities enhances failure detection, showcasing the potential for improved sensor integration [49].

Overcoming the challenges of heterogeneous sensor integration requires innovative strategies, robust security measures, and efficient data processing techniques. Addressing these issues can unlock the full potential of heterogeneous sensor systems, enabling advanced applications such as precise wireless localization and sensing for navigation, healthcare, and smart environments. This progress will enhance system capabilities across various domains, promoting seamless connectivity and improved decision-making through sophisticated data fusion techniques and emerging technologies like reconfigurable intelligent surfaces and wearable IoT devices [24, 101, 29, 40, 27].

7.2 Data Management and Security

Effective data management and security are crucial in deploying advanced sensor technologies, especially within IoT and wearable devices. The integration of diverse technologies necessitates robust data management strategies to handle vast data volumes, ensuring efficiency and reliability [24]. Challenges include limitations in communication bandwidth and battery life of wearable devices, which can hinder data transmission and processing capabilities [24].

Data security and privacy are critical, particularly in healthcare applications involving sensitive personal information. Federated Learning frameworks offer a promising solution by enhancing data privacy through decentralized processing, mitigating data breach risks [102]. However, careful management is essential to integrate these frameworks with existing systems.

Robust security mechanisms against adversarial threats in IoT networks are vital for maintaining sensor data integrity and confidentiality. These mechanisms must counter cyber-attacks that could compromise sensor systems' functionality and reliability [15]. Integrating machine learning in IoT healthcare systems presents unique challenges in data management and security, necessitating real-time data analysis systems that adhere to stringent security protocols for successful deployment [28].

Addressing data management and security challenges in sensor applications requires a multifaceted approach incorporating advanced technologies, robust security measures, and effective data management strategies. Overcoming challenges such as complex construction, poor fit, and high costs can significantly enhance sensor systems' efficiency, reliability, and security, broadening their applicability, particularly in personalized healthcare through innovations like smart footwear that integrates advanced sensors for health monitoring and utilizes IoT for real-time data collection and analysis [24, 27].

7.3 Real-Time Processing and Resource Constraints

Real-time processing in sensor systems is vital for enhancing performance and efficiency across diverse fields, including manufacturing, healthcare, and environmental monitoring. This capability enables the extraction of meaningful events from low-level IoT sensor data, crucial for effective business process management and decision-making. Advancements in calibration algorithms and machine learning approaches improve real-time data interpretation accuracy, facilitating continuous monitoring in uncontrolled environments. As pervasive AI integrates with IoT, efficient resource scheduling among devices becomes increasingly important for optimal operational performance [12, 24, 26, 40, 27]. The primary challenge in achieving real-time processing lies in the inherent resource constraints of sensor systems, including limited computational power, energy efficiency, and communication bandwidth, necessitating innovative strategies to optimize processing capabilities without compromising performance.

Integrating edge and fog computing paradigms offers a promising solution to alleviate resource constraints by enabling data processing closer to the data generation source. This approach reduces latency and enhances real-time processing capabilities by offloading computational tasks from centralized cloud servers to edge devices [15]. Deploying lightweight machine learning models on resource-constrained devices, such as those in wearable and IoT systems, further optimizes real-time processing by enhancing computational efficiency and energy consumption [24].

In autonomous vehicles, real-time processing is critical for ensuring safety and reliability. Multimodal sensor fusion techniques, which combine data from various sensors like cameras, lidar, and radar, enhance situational awareness and decision-making capabilities, improving real-time information processing [6]. Neuromorphic computing architectures, which mimic biological neural processes, hold significant promise for reducing power consumption and enhancing processing speed, making them suitable for real-time applications [71].

Moreover, implementing task-oriented communication design frameworks in cyber-physical systems optimizes resource allocation for real-time processing, ensuring critical tasks receive priority in resource-constrained environments [23]. This is particularly beneficial in smart manufacturing and healthcare applications, where timely data processing is essential for maintaining operational efficiency and ensuring patient safety.

Addressing real-time processing and resource constraints in sensor systems requires a comprehensive strategy integrating advanced computing paradigms, such as pervasive AI, with efficient machine learning models tailored for diverse sensory modalities. This strategy should also incorporate resource allocation frameworks that facilitate cooperation and resource scheduling among IoT devices and infrastructure, minimizing communication and computation overheads while optimizing performance. Insights from recent research, such as the MULTIIOT benchmark, can enhance the scalability of machine learning solutions across heterogeneous data streams in the IoT context [40, 14]. By overcoming these challenges, sensor systems can achieve enhanced performance and adaptability, enabling more efficient and reliable real-time applications across various domains.

7.4 Interoperability and System Compatibility

Interoperability and system compatibility are critical for the successful integration of advanced sensor systems, particularly within heterogeneous sensor networks and IoT ecosystems. The ability of diverse sensor systems to communicate and operate seamlessly with one another and with existing infrastructure is essential for maximizing deployment efficiency and effectiveness. Interoperability ensures that sensors from different manufacturers and specifications can work together, facilitating data exchange and enhancing overall network functionality [15].

Achieving interoperability requires adherence to standardized communication protocols and data formats, enabling sensors to interface with a wide array of devices and platforms. This standardization is crucial for developing scalable and flexible sensor systems that can adapt to evolving technological landscapes and application requirements. In the IoT context, interoperability facilitates the seamless integration of sensors into existing networks, enhancing the collection, processing, and analysis of data from diverse sources [7].

System compatibility focuses on the ability of sensor systems to integrate with existing hardware and software infrastructure, ensuring efficient operation within available resource constraints, such as power, computational capacity, and communication bandwidth. Compatibility is particularly important when sensors must interact with legacy systems, necessitating careful consideration of backward compatibility and potential bridging technologies [97].

The challenges of achieving interoperability and compatibility are compounded by the rapid pace of technological advancement, necessitating continuous adaptation and innovation in sensor design and integration strategies. Developing flexible and adaptive sensor systems that can accommodate new technologies and application domains is essential for maintaining competitiveness and ensuring the long-term viability of sensor networks [6].

Interoperability and system compatibility are foundational elements in integrating advanced sensor systems, enabling cohesive and efficient networks that support a wide range of applications. By emphasizing advanced sensor integration, data connectivity, and personalized health monitoring, sensor systems can enhance their flexibility, scalability, and adaptability. This approach fosters

innovation and improves smart environments' functionality across diverse fields, including healthcare, where technologies like smart footwear utilize features such as GPS tracking and real-time data analysis to support personalized health management and assistive capabilities for individuals with specific needs [24, 1, 27].

7.5 Environmental and Operational Challenges

Deploying advanced sensor systems in diverse environments presents several environmental and operational challenges that must be addressed to ensure optimal performance and reliability. One significant challenge is the increased computational demands associated with multimodal filtering, which can hinder real-time performance in applications requiring rapid data processing [103]. This is particularly pertinent in systems like multisensory anti-collision designs for autonomous vehicles, where limited onboard processing power can restrict system performance and response times [104].

The stochastic nature of Laser Additive Manufacturing (LAM) processes introduces variability that can lead to defects, affecting the overall quality of manufactured parts. This unpredictability poses a challenge for integrating advanced sensors aimed at monitoring and improving these processes [85]. Additionally, the cost and effectiveness of existing methods for detecting porosity in Directed Energy Deposition (DED) processes remain significant hurdles, complicating the widespread adoption of sensor technologies in these applications [3].

In soft robotics, environmental factors such as temperature, humidity, and external mechanical forces can significantly impact functionality, underscoring the vulnerability of these systems to external conditions [10]. The complexity of implementing molecular communication systems further exacerbates operational challenges, requiring advanced technologies and a deep understanding of biological interactions for successful deployment [89].

Wearable sensor systems face challenges related to user acceptance and constraints imposed by device size and design, potentially limiting practicality and widespread adoption [35]. Similarly, specific biological assumptions in neuromorphic systems, such as those involving astrocyte functions, may not be universally applicable across all robotic systems, posing limitations on the generalizability of these technologies [73].

Moreover, the need for improved haptic feedback in multisensory systems, coupled with the lack of explicit tasks during evaluation, presents challenges in achieving desired user interaction and immersion [20]. Addressing these environmental and operational challenges necessitates ongoing innovation and adaptation in sensor system design and deployment to effectively overcome the constraints imposed by diverse application settings.

8 Future Directions and Research Opportunities

8.1 Enhancing Sensor Integration and Multimodality

Advancing sensor integration and multimodal capabilities is essential for the progression of intelligent systems across various applications. Emphasis should be placed on refining data fusion algorithms and exploring additional sensing technologies to improve platforms like the Multisensory Edge-Cloud Platform (MDF). Developing resilient frameworks for sensor fusion alongside adaptable AI algorithms is crucial for performance in complex environments [5, 6]. Future research should enhance sensor fusion techniques and algorithm efficiency for real-time processing, facilitating cost-effective widespread adoption.

In Human Activity Recognition (HAR), it is vital to improve method robustness and expand applications to diverse real-world scenarios, particularly in smart environments [35]. Research should also focus on automating interaction function generation and enhancing framework scalability to accommodate heterogeneous nodes [53]. Additionally, task-oriented communication design frameworks should be explored to address task characteristics impact on communication, develop efficient training methods for distributed systems, and tackle scalability challenges [23].

Future directions in material recognition involve integrating sensory modalities, such as visual data, to enhance capabilities [37]. This can extend to collaborative perception frameworks among multiple autonomous vehicles, advancing transformer-based sensor fusion methods [17]. In robotics,

developing subject-specific prototypes and extending tendon-routing architectures to other joints can further enhance sensor integration and multimodal capabilities [8].

Integrating complex biological mechanisms in Central Pattern Generator (CPG) modeling and investigating additional interneurons can significantly improve locomotion capabilities in neuromorphic systems [73]. These advancements are crucial for developing more adaptive and intelligent robotic systems. Addressing challenges in multimodal research, including representation, alignment, reasoning, generation, transference, and quantification, can lead to significant strides in enhancing multimodal sensor systems across various fields, including wearable activity recognition and multi-sensory artificial intelligence. By employing multidisciplinary approaches that integrate expertise in sensor technologies, data fusion algorithms, and machine learning, researchers can develop robust systems that effectively leverage complementary information for real-world impact [35, 36].

8.2 Advancements in Machine Learning and Neuromorphic Computing

Advancements in machine learning and neuromorphic computing are set to transform sensor systems, enhancing efficiency, adaptability, and functionality across diverse domains. A key focus is developing lightweight, energy-efficient machine learning models for Healthcare IoT (H-IoT) devices, crucial for secure and reliable operations in healthcare environments. Integrating emerging technologies such as 5G with advanced machine learning models is vital for addressing data privacy concerns and improving system reliability [91].

Future research in neuromorphic computing should prioritize online adaptivity to enhance sensor robustness against noise in dynamic environments. Incorporating additional sensors for comprehensive 3D attitude estimation can significantly improve autonomous systems' performance, underscoring the importance of neuromorphic approaches across applications [71]. Optimizing neuron models and developing spiking-based regression frameworks are promising directions for advancing machine learning in underwater robotics, showcasing the versatility of neuromorphic technologies [72].

Hybrid architectures combining Spiking Neural Networks (SNNs) and Artificial Neural Networks (ANNs) offer enhanced processing capabilities and energy efficiency, representing a critical area for future research. These architectures can improve event stream processing in sensor systems, leveraging the strengths of both SNNs and ANNs [105]. Additionally, exploring the scalability of unipolar memristors in complex tasks will balance biological realism with computational efficiency [106].

The development of SpikingJelly, an open-source machine learning framework, aims to enhance compatibility with neuromorphic chips and expand the library of datasets and models. This expansion is crucial for broadening the applicability of neuromorphic computing across various sensor systems [67]. Furthermore, quantum reservoir computing presents a promising avenue for future research, focusing on optimizing performance, exploring new physical phenomena, and developing hybrid systems that integrate classical and quantum approaches [74].

In machine learning, refining decision mechanisms, improving scalability, and integrating emerging technologies are vital research directions. These efforts will enhance sensor systems' functionality and adaptability, enabling more intelligent and responsive applications across diverse fields [15]. Exploring advanced federated learning strategies and adversarial machine learning can further enhance navigation and security in Connected and Autonomous Vehicles (CAVs), ensuring robust performance in complex environments [7].

Enhancing AI interpretability and addressing privacy concerns through federated learning and blockchain are also critical areas for future research, particularly in healthcare applications. The application of reinforcement learning in healthcare offers additional opportunities for innovation, driving improvements in patient monitoring and treatment outcomes [18].

Advancements in machine learning and neuromorphic computing have the potential to transform sensor technology, enhancing capabilities, efficiency, and adaptability. By addressing identified research opportunities, the field can achieve substantial advancements in developing intelligent and responsive sensor systems, leveraging technologies such as the Internet of Things (IoT), artificial intelligence, and reconfigurable intelligent surfaces. These advancements can enhance various applications, including personalized healthcare through smart wearables, efficient data management,

and improved localization and sensing accuracy in diverse environments, ultimately leading to more effective health monitoring solutions and better decision-making in healthcare [24, 101, 40, 27, 28].

8.3 Improving Security and Privacy in Sensor Applications

Enhancing security and privacy in sensor applications is a critical research direction, especially with the increasing integration of Internet of Things (IoT) devices in sensitive domains like healthcare. Current studies often struggle with data integration challenges and inadequately address privacy and security concerns, highlighting the need for comprehensive frameworks to ensure data protection [1]. Future research should prioritize developing models capable of efficiently managing multimodal data complexities while incorporating privacy-preserving techniques to safeguard sensitive information in IoT applications [14].

In the context of Generative AI (GAI) and Human Digital Twins (HDT), enhancing the interpretability of GAI models is crucial for ensuring transparency and trust in applications. Addressing ethical concerns and exploring the integration of GAI-driven HDT into broader healthcare systems are essential for achieving secure and privacy-focused implementations [107]. As these technologies evolve, robust mechanisms must be developed to protect against potential breaches, ensuring that data remains confidential and secure throughout its lifecycle.

Moreover, exploring federated learning and blockchain technologies offers promising avenues for enhancing data privacy and security in sensor networks. These technologies can facilitate decentralized data processing, reducing the risk of data breaches and ensuring compliance with privacy regulations. By concentrating on critical research areas such as integrating artificial intelligence with IoT, developing resource-efficient distributed AI systems, and advancing wearable IoT technologies for personalized healthcare, the field can significantly enhance the security and privacy of sensor applications. This progress is essential for establishing trust and reliability within IoT ecosystems, particularly as these technologies generate vast amounts of data and face challenges related to network attacks, data privacy, and effective data management. Ultimately, these advancements will enable the creation of intelligent and secure healthcare solutions, smart cities, and other applications that prioritize user privacy and data integrity [40, 99, 24, 28].

8.4 Emerging Technologies and Their Impact on Sensor Systems

Emerging technologies are set to revolutionize sensor systems by enhancing their performance, adaptability, and integration across various applications. The adoption of a server+FPGA heterogeneous platform is a notable advancement, allowing for the offloading of specific tasks to optimize performance and reduce latency in autonomous systems [93]. This architectural innovation is particularly beneficial in applications such as autonomous vehicles, where real-time processing and decision-making are critical.

Integrating multiple sensor modalities and mechanical enhancements is crucial for improving the safety and reliability of autonomous vehicles, especially under adverse weather conditions [97]. This underscores the importance of robust sensor integration strategies that can adapt to varying environmental challenges, ensuring consistent and reliable performance.

In eHealth and automated driving, developing advanced multimodal sensor fusion techniques significantly contributes to both academic and industrial applications [31]. These techniques enable seamless integration of diverse sensory inputs, enhancing the accuracy and efficiency of sensor systems in complex environments.

The emergence of 6G wireless systems presents significant opportunities for the evolution of sensor systems, particularly in enhancing immersive experiences through improved communication capabilities [13]. This advancement is expected to drive the development of more sophisticated sensor networks that can support high-bandwidth applications and facilitate seamless connectivity across devices.

Future research directions also include improving the robustness of origami structures and extending these methods to more complex intelligent tasks, indicating the potential impact of emerging technologies on sensor systems [108]. These advancements highlight the ongoing evolution of sensor technology, driven by the integration of innovative materials and design principles.

Emerging technologies are poised to significantly impact sensor systems, offering enhanced capabilities and new opportunities for innovation across various domains. By leveraging recent technological advancements in sensor systems—such as integrating advanced sensors in smart footwear for personalized health monitoring, resource-efficient distributed artificial intelligence in IoT applications, and AI at the edge for real-time processing—these systems can enhance functionality, efficiency, and integration capabilities. This evolution not only facilitates the development of innovative applications, including immersive video conferencing and autonomous vehicles, but also addresses critical societal needs, paving the way for the next generation of intelligent solutions responsive to real-time data and user requirements [42, 40, 27].

8.5 Expanding Applications and Interdisciplinary Collaboration

The expansion of sensor applications across diverse fields underscores the critical role of interdisciplinary collaboration in driving innovation and addressing complex challenges. Integrating advanced sensor technologies into emerging domains such as Connected and Autonomous Vehicles (CAVs) necessitates concerted efforts from machine learning researchers, automotive engineers, and cybersecurity experts. This collaboration is essential to tackle challenges posed by adversarial machine learning, which can compromise the safety and reliability of CAV systems [109].

Interdisciplinary collaboration is vital for leveraging sensor technologies in various fields, particularly in developing advanced solutions for complex challenges such as human activity recognition (HAR) and smart healthcare. By integrating expertise from diverse domains—including sensor technology, signal processing, data fusion algorithms, and healthcare analytics—researchers can create intelligent wearable devices that collect and analyze extensive data on behavioral, psychological, and physical health. This holistic approach enhances solution accuracy and effectiveness while addressing significant challenges in data management and decision-making in modern healthcare systems, especially in light of recent global health crises [28, 35]. In healthcare, converging sensor technology with artificial intelligence and data analytics facilitates creating personalized healthcare solutions, enhancing patient outcomes and operational efficiency. Similarly, in smart manufacturing, integrating sensors with advanced communication and control systems fosters the development of intelligent production processes, improving productivity and reducing waste.

The potential for expanding sensor applications is vast, with opportunities in fields such as environmental monitoring, agriculture, and smart cities. These applications require a collaborative approach, drawing on expertise from various disciplines to design and implement effective sensor systems that can operate efficiently in complex and dynamic environments. By promoting interdisciplinary collaboration among researchers and practitioners, integrating diverse technologies such as IoT, machine learning, and advanced sensor systems can lead to transformative advancements in sensor technology. This synergy enhances the capabilities of intelligent wearable devices and smart footwear for personalized healthcare while addressing critical challenges in data management and analysis, ultimately driving innovations that significantly improve health outcomes and societal well-being [34, 24, 35, 27, 28].

The expansion of sensor applications and the importance of interdisciplinary collaboration are integral to the continued evolution of sensor technology. By integrating advancements from various disciplines, the rapid development and deployment of innovative sensor solutions can effectively tackle existing challenges in healthcare, such as personalized health monitoring and data management in intelligent wearable devices, while simultaneously laying the groundwork for future breakthroughs in smart technologies like footwear sensors and IoT applications [27, 28].

9 Conclusion

Advanced sensor technology has emerged as a pivotal force driving innovation across multiple domains, including healthcare, autonomous vehicles, smart manufacturing, and IoT networks. This survey highlights the integration of cutting-edge materials, sophisticated design strategies, and novel sensing mechanisms that collectively enhance sensor functionality and adaptability. Reconfigurable Intelligent Surfaces (RISs) stand out for their ability to significantly elevate localization precision and sensing capabilities, thereby overcoming inherent limitations in traditional wireless systems. Similarly, the Internet of Robotic Things (IoRT) is poised to transform industrial landscapes by advancing communication and automation, despite the accompanying ethical and regulatory challenges.

In the healthcare sector, the Wearable Internet of Things (WIoT) is expected to catalyze a shift towards more personalized and proactive healthcare models. The synergy of Generative AI (GAI) with Human Digital Twins (HDT) in IoT-healthcare settings offers personalized services that enhance patient outcomes and operational efficiency. Machine learning emerges as a robust tool in addressing security challenges within the Healthcare IoT (H-IoT) framework, emphasizing the importance of a comprehensive understanding of these issues.

The survey underscores the necessity of interdisciplinary collaboration in advancing edge AI research, particularly in managing the trade-offs between safety, privacy, and performance. The integration of Time-Sensitive Wireless Interfaces (TWI) in wireless systems is identified as a critical advancement, enhancing the reliability of timestamping and ensuring precise temporal ordering and causality in real-time applications.

Ongoing research and development in advanced sensor technology are expected to further elevate capabilities and efficiencies across a spectrum of applications. By overcoming current obstacles and harnessing emerging technological advancements, the field is well-positioned for substantial progress, fostering innovation and improving outcomes across diverse sectors.

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