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A review on advances and applications of smart sensors in the internet of things: From industrial systems to smart cities

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Abstract

The integration of smart sensors with the Internet of Things (IoT) has accelerated the development of intelligent systems across various sectors, notably in industrial environments and smart city infrastructures. Smart sensors, equipped with embedded processing and communication capabilities, enable real-time monitoring, data collection, and automated decision-making. This paper presents a comprehensive overview of the latest advancements in smart sensor technologies and their practical applications within industrial systems and urban settings. In industrial domains, smart sensors enhance operational efficiency, support predictive maintenance, and improve safety protocols. Within smart cities, they contribute to intelligent transportation systems, environmental monitoring, energy management, and public safety initiatives. The paper also discusses the technical challenges associated with sensor interoperability, data security, energy efficiency, and scalability in large-scale IoT deployments. By examining both current innovations and emerging research directions, this study emphasizes the transformative role of smart sensors in realizing fully connected, sustainable, and responsive environments.

Keywords: IoT; Smart Sensors; Wireless Sensor Networks (WSNs); Industrial IoT; Smart Cities; Real-Time Monitoring; Predictive Maintenance; Sensor Interoperability; Data Security; Urban Infrastructure

1. Introduction

The Internet of Everything (IoE) is an advanced concept that extends the IoT by going beyond simple machine-to-machine (M2M) communication and including people, processes, data, and things. Initially developed by companies like Cisco and Qualcomm, IoE is now widely used by organizations around the world. It transforms how people and objects interact, how data is collected and used, and how different components work together to deliver smart and efficient services. While IoT began in the late 1990s with the use of open-source microcontrollers like Arduino and Raspberry Pi, which mainly focused on real-world entities such as sensors, IoE has evolved further by integrating micro and nano sensors into various fields, including IoT and the Web of Things (WoT). IoE is considered the business version of IoT, encompassing multiple sub-domains that aim to enhance productivity and connectivity. It is built on four main pillars: people, processes, data, and things, each playing a distinct role. These pillars enable four major types of interactions: people-to-people (P2P), people-to-machine (P2M), M2M, and machine-to-people (M2P). Among these, the most common application of IoE is in scenarios like smartwatches that connect directly to the human body to measure and transmit data via the internet, which is then processed and used to provide meaningful feedback[1].

WSNs are a vital component of IoT and have been widely implemented in various applications such as transportation systems, building automation, agriculture, and health monitoring. Despite their growing use, WSNs face significant limitations in battery capacity, storage, and data transmission rates, which can negatively impact the overall network

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lifetime. To address these challenges, Piyare et al. proposed a flexible and dynamic architecture that integrates WSNs with cloud computing, forming what is known as the Sensor Cloud (SC). This integration enhances not only the network lifespan but also service quality, energy efficiency, and computational performance. The primary purpose of the SC is to enable a single WSN to provide sensing services for multiple applications at the same time. Over the past decade, various studies have explored IoT, WSN, and SC, proposing advanced solutions, evaluation methods, and architectures. However, until now, no research had comprehensively examined the similarities and differences among these three domains. To fill this research gap, a comprehensive survey was conducted covering literature from 2010 to 2020 to analyze the current state, performance metrics, use cases, architectural approaches, and evaluation techniques across IoT, WSN, and SC. The survey was carried out through a thorough search process to ensure that all relevant studies were included. It presents findings based on the characteristics of the selected studies, their proposed contributions, real-world applications, evaluation mechanisms, performance measurements, and architectural designs. The aim is to offer a complete overview of the existing work, identify commonalities and distinctions among the domains, and highlight areas that still require further attention from the research community[2].

Both IoE and WSNs, though conceptually different, share a common objective of enhancing data collection, communication, and intelligent service delivery. They rely on real-world sensing and data sharing, where WSNs provide the fundamental layer for sensing and communication, and IoE expands on this to include broader interactions among people, data, processes, and things[1][2]. The integration of cloud computing into WSNs through SC reflects a shift toward more intelligent and flexible systems, similar to the IoE approach that also emphasizes efficiency, responsiveness, and scalability across domains[1][2]. Both frameworks are being used in fields like healthcare, agriculture, and automation, where accurate sensing, real-time data transmission, and intelligent feedback are critical[1][2].

2. Foundations and Benefits of Sensors in IoE

The IoE is an advanced evolution of the IoT, enabling intelligent connectivity among people, processes, data, and things. At the core of IoE are sensors—particularly micro and nano sensors—that facilitate communication between devices through wired and wireless means. These sensors play a vital role in various applications, including healthcare, smart homes, smart cities, and other emerging domains. IoE, IoT,WSN, and SC technologies all rely heavily on effective data collection mechanisms enabled by such sensors, emphasizing their foundational role in interconnected systems [1][2].

A comprehensive survey of data collection methods across WSN, IoT, and SC highlights that while research in these areas has traditionally been conducted separately, integrating insights from all three domains provides a holistic understanding of their roles within the broader IoE ecosystem. As IoE continues to evolve, it is expected to integrate with Industrial IoT (IIoT), Consumer IoT (CIoT), and the WoT, forming a globally connected environment where data from diverse sensors can be harnessed efficiently through various models, algorithms, and frameworks [1][2].

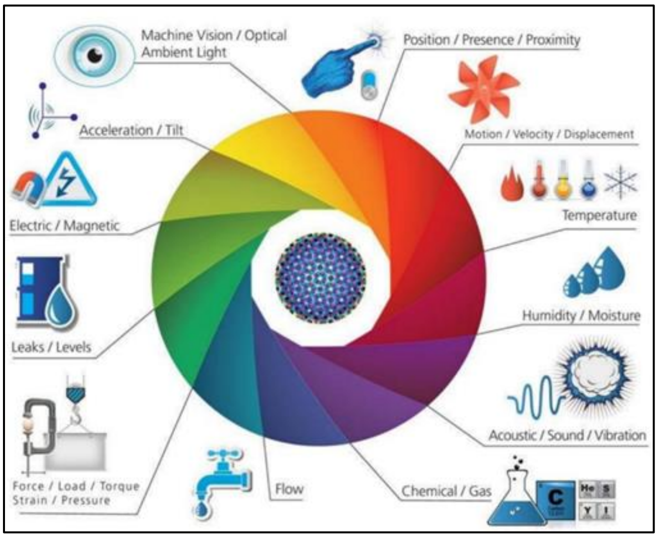

Figure 1 Sensors used in IoE [1]

Stable research output over the past five years reflects consistent interest and advancement in sensor-based technologies and their application in intelligent systems. Across these domains, nine key contributions have been identified—framework, algorithm, model, protocol, approach, method, architecture, system, and topology—with models, algorithms, and frameworks being the most common. Evaluation mechanisms such as simulation, experiment, case study, theoretical analysis, and comparative analysis are frequently used, with simulation being the most prevalent approach [2].

The number and complexity of sensor deployments are anticipated to grow significantly, enhancing the efficiency and intelligence of interconnected systems. These developments are supported by research identifying performance measures, architectures, and use cases across IoE, IoT, WSN, and SC, while also highlighting both their similarities and distinct characteristics [1][2].

2.1. Sensors in the Internet of Everything (IoE):

2.1.1. Temperature Sensors

Temperature sensors detect the heat energy produced by or transferred to an object or environment. They are crucial in smart homes, agriculture, and healthcare monitoring systems. Thermocouples work by converting temperature differences into voltage, which increases proportionally with heat. Resistor Temperature Sensors, such as RTDs or thermistors, change resistance as temperature varies—typically increasing in the positive direction. IC (Semiconductor) Sensors provide digital temperature readings and are best suited for measuring lower temperature ranges. Infrared (IR) Temperature Sensors detect emitted infrared radiation from objects, making them ideal for non-contact temperature measurement of solids and liquids.

2.1.2. Proximity Sensors

Proximity sensors detect the presence or absence of nearby objects without requiring physical contact. These sensors are widely used in automation systems, especially in retail, manufacturing, and smart home environments for tasks like object detection, inventory monitoring, and automated lighting control.

2.1.3. Pressure Sensors

Pressure sensors convert pressure from liquids or gases into electrical signals. They are vital in water supply and heating systems, as well as in industrial manufacturing processes. These sensors help detect fluctuations or drops in pressure, ensuring safe and efficient system operation.

2.1.4. Water Quality Sensors

Used extensively in smart water management systems, water quality sensors monitor various parameters to ensure water safety and cleanliness. The Chlorine Residual Sensor offers a cost-effective way to measure chlorine levels. The Gravity Arduino Turbidity Sensor detects suspended particles in water, commonly used in wastewater treatment. Conductivity Sensors assess ion concentration, while pH Sensors determine acidity or alkalinity on a scale of 0 to 14. Oxidation Reduction Potential (ORP) Sensors measure a solution's capacity to oxidize or reduce contaminants. Other sensor types in this category include chemiresistor, electrochemical gas, fluorescent chloride, hydrogen sulfide, nondispersive infrared, pH glass, potentiometric, and zinc oxide nanorod sensors.

2.1.5. Chemical Sensors

Chemical sensors detect chemical changes in air or liquids. They are extensively used in environmental monitoring, industrial process control, hazardous chemical detection, laboratories, and pharmaceutical applications. These sensors help maintain safety standards and ensure process accuracy.

2.1.6. Gas Sensors

Gas sensors, a subcategory of chemical sensors, focus specifically on air quality monitoring and detecting gas concentrations. Common types include Carbon Dioxide (CO_2) Sensors, Carbon Monoxide (CO) Sensors, Hydrogen Sensors, and Breathalyzer Sensors. The Hygrometer, though slightly different, is often grouped here as it measures humidity levels in the atmosphere.

2.1.7. Smoke Sensors

Smoke sensors are vital for early fire detection in homes, offices, and industrial buildings. Optical Smoke Sensors detect smoke particles using light scattering, while Ionization Smoke Sensors detect changes in ionized air caused by smoke. Both are critical for maintaining safety in various environments.

2.1.8. Infrared (IR) Sensors

Infrared sensors detect infrared radiation in the surrounding environment. These are widely applied in health monitoring (e.g., measuring blood flow and blood pressure), smartphones, smartwatches, remote controls, and smart appliances. IR sensors are also used in home security systems for motion detection and intruder alerts.

2.1.9. Level Sensors

Level sensors are used to determine the level or flow of fluids and other substances. They are crucial in industrial automation, IT infrastructure (e.g., cooling systems), and process control. There are two main types: Point Level Sensors, which detect whether a substance has reached a certain level, and Continuous Level Sensors, which provide real-time level measurements across a range.

2.1.10. Image Sensors

Image sensors convert optical images into electronic signals for storage or processing. They are central to devices like digital cameras, night vision equipment, medical imaging tools, radar, sonar, thermal imaging devices, and biometric systems such as facial or fingerprint recognition.

2.1.11. Motion Detection Sensors

Motion detection sensors identify and respond to physical movement. These are commonly used in security systems, lighting automation, smart devices, and activity tracking in fitness and healthcare applications. They convert motion into electrical signals that trigger predefined system responses such as alarms or lighting.Lastly, ongoing research continues to address challenges and outline future directions to improve data collection, system integration, and intelligent decision-making across these sensor-driven technologies [1][2].

3. Wearable and Health Monitoring Sensor Systems

Outdoor industrial workplaces can be tough environments, so keeping workers safe and healthy is a top priority. This smart wearable system helps by using small, comfortable sensors that workers can wear throughout the day. These sensors keep an eye on both the surrounding environment and the worker's health, checking things like air quality, temperature, heart rate, and more. The information is shared instantly using Bluetooth for nearby devices and a Long-range (LoRa) wireless connection to reach systems that are farther away. It's a practical and reliable way to stay connected and make sure workers are safe no matter where they are on the job site. Data is transmitted to a smart IoT gateway, which processes and forwards it to the cloud for storage, visualization, and analysis. When hazardous conditions are detected, the system provides immediate alerts to workers. The system architecture includes both hardware and software components, with detailed design of sensor nodes, gateway implementation, and cloud integration. Future work aims to incorporate additional sensor types for varied environments and to develop a mobile-based gateway to enhance system flexibility [3].

Cyber-Physical Systems (CPS) and Body Area Sensor Networks (BASNs) play a pivotal role within the evolving landscape of IoT and smart cities. CPS are complex, highly distributed, and autonomous systems that operate under critical constraints such as cost, security, safety, power efficiency, performance, and size, often exhibiting emergent and unpredictable behaviors. Enabled by high-speed broadband, the convergence of the physical and cyber worlds through IoT allows numerous devices to exchange data, access web services, and interact with people, forming the backbone of smart city infrastructure [4].

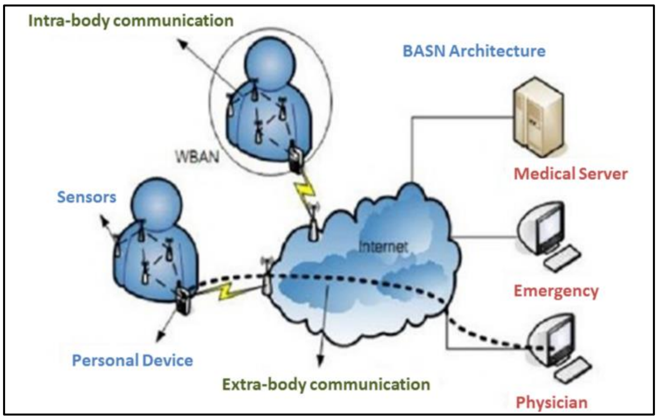

Figure 2 Architecture of BASN [4]

The integration of wearable sensor networks with CPS and BASNs enhances the development of intelligent environments, particularly in smart cities and industrial workplaces, by enabling real-time health and safety monitoring and efficient data-driven decision-making [3][4]. These systems benefit significantly from cloud-based IoT frameworks that support storage, analysis, and visualization of sensor data, contributing to more responsive and adaptable urban services [3][4]. Active citizen involvement and community collaboration are essential to maximize the benefits of these technologies for urban services and quality of life [4].

Despite significant progress, many technical challenges remain before CPS and BASNs can be efficiently and industrially deployed As a practical demonstration of their potential, a funded research project (2016–2017) was undertaken to develop a Smart and Safe Wearable System for Hand Pattern Recognition integrated with a cloud-based IoT framework. Initial results will be reported in future work, further illustrating the capability of CPS and BASNs to enhance smart city technologies [3][4].

4. Industrial IoT and Smart Factory Applications

A next-generation blockchain-integrated WSN has been developed for secure data transmission in IIoT settings. By combining a hierarchical routing protocol (EDNCP) with blockchain features like smart contracts, consensus validation, and decentralized storage, this architecture ensures strong protection against spoofing, data tampering, and unauthorized access. Digital signatures and public key encryption further enhance the model's data integrity, although the system cannot support firmware updates due to strict hash verification mechanisms [5].

To complement such secure architectures, a reconfigurable smart sensor interface designed for industrial WSNs uses a Complex Programmable Logic Device (CPLD) and the IEEE 1451.2 smart sensor standard. This setup allows for high-speed, parallel, and real-time data acquisition while simplifying programming complexity and enhancing flexibility [6]. Both the blockchain model and the CPLD-based interface prioritize secure, reliable, and modular IIoT sensor deployments, making them suitable for dynamic and safety-critical environments [5][6].

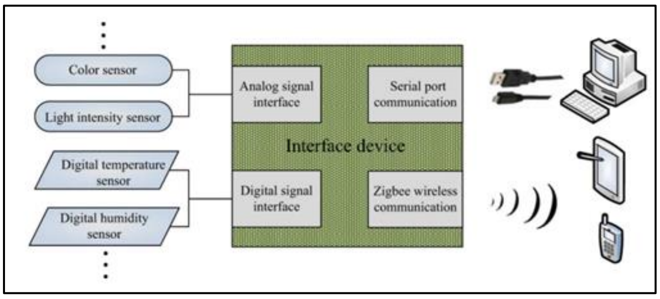

Figure 3 Application and working diagram of the reconfigurable smart sensor interface device[6]

Further enhancing industrial reliability, a smart sensor architecture built on Field Programmable Gate Arrays (FPGAs) and System-on-Chip (SoC) platforms supports real-time data processing, reconfigurability, and secure communication via protocols like IEEE 1588, HSR, and PRP. It achieves low latency and encryption at Layer 2, offering a scalable and robust solution for time-sensitive IIoT applications [8]. The flexibility and real-time performance of both CPLD- and FPGA-based systems show a clear focus on adapting sensor hardware to evolving industrial demands [6][8].

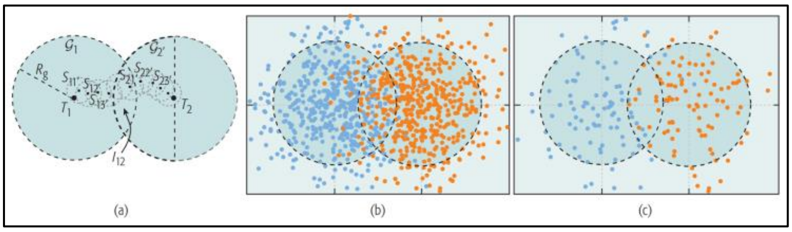

Figure 4 Illustration of a communication path between deployment points T1 and T2 via multihop wireless sensors between groups G1 and G2; b) 500 sensors; c) 100 sensors are deployed in each group according to a normal distribution[7]

Similarly, low-power sensor node designs for IIoT, built around a three-tier data center network, emphasize energy harvesting and performance optimization under varying signal-to-noise ratios and server loads. These systems demonstrate strong throughput, long-term reliability, and suitability for cost-effective industrial use [10]. Both solutions focus on enhancing sustainability, energy management, and operational lifetime of IIoT systems through strategic deployment and hardware-level efficiency [7]-[10].

From a device management and integration perspective, a lightweight, cloud-based RESTful service using a cross-layer design enables scalable and efficient control of WSNs. Designed for battery-powered, resource-constrained nodes, the architecture simplifies industrial IoT device integration while maintaining performance and reducing network complexity [9]. This complements hardware-focused solutions by ensuring that efficient management protocols support the growing complexity of IIoT infrastructures [9][10].

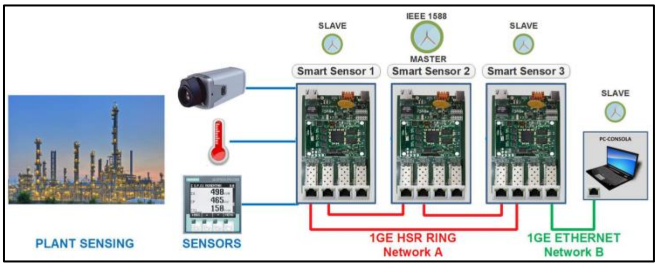

Figure 5 Concept-proof setup for Smart Sensor. Case 1, Smart Sensor 1collects sensor data through the digital, analog, Ethernet (video) and serial interfaces (MODBUS). Smart Sensor 2: It works as HSR node (DANH) and master IEEE 1588. Smart Sensor 3: It works as a Redundancy Box (RedBox)to connect the HSR ring with the regular Ethernet network. The PC is used to access the data stored in the Smart Sensor 1 through a web server[8]

5. Smart Cities and Urban Infrastructure

Wireless passive Surface Acoustic Wave (SAW) sensors have been investigated for monitoring temperature and pressure in water pipeline systems within IoT applications. Unlike traditional sensors, SAW sensors eliminate the need for a direct power supply by harvesting energy from Radio Frequency (RF) pulses. Signal comparison in wired and wireless modes revealed that wireless interrogation results in a signal attenuation of about one-fifth. Moreover, deployment in a simulated water pipeline environment showed only slight signal loss compared to air, confirming the effectiveness of SAW sensors for pipeline monitoring in embedded, energy-autonomous scenarios [11].

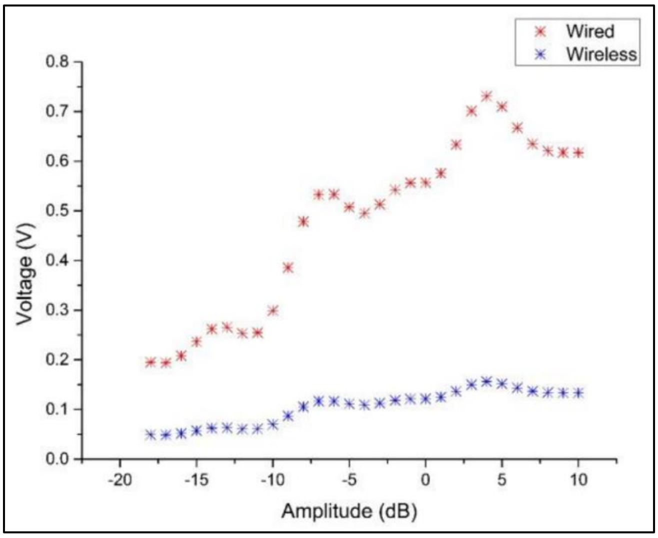

Figure 6 The attenuation of the received wireless signal against the wired signal[11]

In line with the focus on IoT-enabled environmental monitoring, a smart drainage system was developed for Hong Kong to tackle urban flooding caused by heavy rainfall. This system integrates water flow and water level sensors with Raspberry Pi hardware and software tools like Python and R to collect real-time data. An Artificial Neural Network (ANN) is trained on this data to predict drainage conditions with up to 99% accuracy, enabling predictive maintenance and rapid flood response. The integration of IoT and Artificial Intelligence (AI) offers tangible benefits for urban infrastructure planning and flood prevention [12].

Similarly, an air pollution monitoring system designed under the Thailand 4.0 initiative utilizes environmental sensors—CO, O_3, PM10, NO_2, and SO_2—alongside Arduino MEGA 2560 and Raspberry Pi 3 to measure and transmit air quality data over a Narrowband IoT (NB-IoT) network. A web interface visualizes the Air Quality Index (AQI) in real time, providing timely environmental insights. Tested in the Sai Mai District of Bangkok, the system showed good air quality and demonstrated its potential to improve public health through real-time pollution monitoring [13].

All three systems highlight the importance of IoT-based sensing for real-time monitoring in smart city contexts—whether for water pipelines, drainage infrastructure, or air quality—while utilizing low-power, compact hardware platforms and scalable communication frameworks for effective environmental data acquisition [11]-[13].

Focusing on energy efficiency and long-term reliability, a LoRa-based wireless sensor node called Water Grid-Sense was developed for harsh industrial environments such as smart water management systems. Built using a SoC design, the node integrates all essential components on a single board. It also includes a solar panel for energy harvesting, allowing battery recharging and reduced maintenance. Experiments showed that it can operate for over two months on battery alone, down to a cut-off voltage of 3.2V, and ensures high signal reliability even in challenging conditions [14].

Both the SAW-based sensor for pipelines and the Water Grid-Sense node demonstrate self-sustaining energy models that eliminate or minimize the need for manual intervention, emphasizing the value of energy harvesting and autonomous sensing solutions for remote or industrial applications [11]-[14].

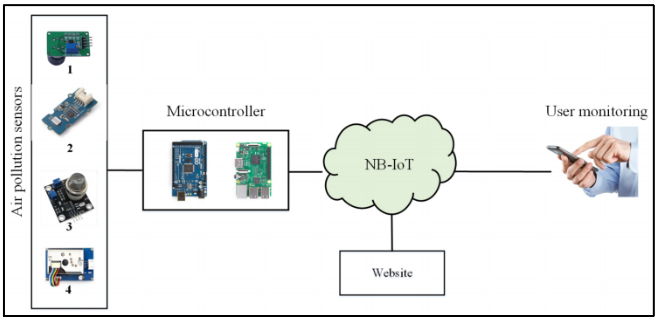

Figure 7 Block diagram of design and implementation of air pollution detection sensors[13]

Moreover, the smart drainage system and WaterGrid-Sense both aim for long-term deployment in water-related infrastructure, combining robust environmental sensing with reliable communication and energy-efficient operation, making them suitable for critical infrastructure management in smart cities [12][14].

6. Machine Learning, AI, and Big Data with Sensors

Sensors play a critical role in modern systems by measuring physical stimuli such as heat, light, sound, and motion, serving as foundational components of the IoT and IIOT ecosystems. These sensors are embedded in various environments ranging from homes and hospitals to industrial settings, generating massive volumes of real-time data that require complex management and analysis [16][17].

To address challenges in sensor reliability and data accuracy within these environments, machine learning techniques like Bayesian modeling and Bayesian Principal Component Analysis (PCA) are employed for real-time sensor abnormality detection. This approach detects anomalies caused by calibration errors, low battery, or hardware faults, classifies the type of error, and recovers faulty readings, thereby improving the overall reliability of IoT sensing systems [15].The integration of AI with IoT, known as Artificial Intelligence of Things (AIoT), enhances these sensing systems by enabling devices to learn from data, make intelligent decisions, and perform smart actions. This convergence empowers smart sensing systems that provide context-aware insights, improving efficiency across individuals, businesses, and economies [16][17].

In industries, AI works together with Big Data and Edge Computing to keep a close eye on machines and the factory environment in real time. Sensors track things like vibration, temperature, humidity, and air pressure, and this data helps detect problems early and keep operations running smoothly. Deep learning models running at the edge analyze this data to detect and predict potential faults, enhancing operational efficiency and reducing downtime in Industry 4.0 applications [17].

Despite these advancements, security concerns remain a limitation for IIoT systems that leverage AI and edge computing, highlighting the need for future improvements in secure system frameworks [17].Together, these studies highlight the evolution toward intelligent, autonomous IoT and IIoT ecosystems where sensor data is not only collected but also intelligently analyzed in real time to ensure system reliability, operational efficiency, and predictive maintenance [15]-[17].

7. Wireless Sensor Communication and Integration

WiFi-based WSN offer significant advantages over traditional Zig Bee-based WSNs by providing higher bandwidth, faster transmission rates, longer range, and non-line-of-sight (NLOS) communication capabilities. These features make WiFi-based networks especially suitable for real-time data transmission and video monitoring in various Internet of Things (IoT) applications, including smart agriculture, intelligent environmental protection, and smart grids. The ongoing research aims to adapt WiFi-based solutions to meet diverse IoT demands effectively [18].

To make sensors more accurate and energy-efficient in IoT setups, researchers have come up with a battery-free external sensor card that works using Near Field Communication (NFC). This card can measure things like temperature, humidity, UV, and light levels in the environment. Compared to the sensors built into smartphones or Bluetooth-based systems, the NFC sensor card is three times faster and uses ten times less energy.

By offloading sensing tasks to an external NFC card, this approach avoids accuracy issues caused by internal heat sources like the CPU, GPU, and battery, making it particularly practical for applications such as personal health monitoring [19].

Both technologies emphasize improving data transmission and sensing accuracy while addressing energy consumption challenges in IoT systems. WiFi-based WSNs enhance communication capabilities for large-scale and real-time applications, whereas NFC-based external sensors offer precise, low-energy environmental monitoring, especially suitable for mobile platforms [18][19].

8. Smart Homes and Building Automation

The role of IoT sensors in smart homes is crucial for enhancing energy efficiency, environmental monitoring, and residents' social well-being, with ongoing research focused on improving sensor functionality and addressing both technical and economic parameters. Next-generation IoT sensors are particularly emphasized for smart home energy management, reflecting the growing momentum in this field [20].

Similarly, different levels of building automation—scheduling-based, sensor-based, and IoT-enabled control—have been investigated for optimizing energy consumption and occupant comfort in residential buildings, especially for Heating, Ventilation, and Air Conditioning (HVAC) systems. The findings show that sensor-based control significantly reduces energy use and improves comfort over basic scheduling, while IoT-enabled control slightly increases energy usage by 0.4% but improves occupant comfort by 2%, demonstrating a favorable trade-off. This highlights the importance of IoT integration in enhancing efficiency, comfort, resource allocation, and service capabilities in smart homes [21].

Both studies underscore the pivotal role of IoT technologies in smart home environments to meet global energy and sustainability challenges and improve quality of life, while also calling for further research to expand IoT applications beyond HVAC systems to include lighting, appliances, and more complex comfort models [20][21].

9. Agriculture and Environmental Monitoring

The integration of the IoT and WSNs has significantly transformed traditional farming into smart agriculture by enabling real-time, cost-effective, and efficient management of agricultural resources. In modern farming environments, various IoT-based sensors—such as soil moisture sensors, temperature sensors, and water volume sensors—are strategically deployed throughout the field to continuously monitor environmental conditions. These sensors collect valuable data, which is then transmitted via a wireless sensor network to a central server. The WSN facilitates seamless long-distance communication among all sensor nodes without the need for complex wired connections. Once the data reaches the central server, it is analyzed against predefined parameters, and based on the results, automated decisions are made—such as adjusting irrigation levels, activating environmental controls, or notifying farmers of specific actions needed. This system not only reduces the manual labor and time required to monitor and manage farm activities but also ensures optimal use of resources such as water, energy, and fertilizers. Its flexible and scalable architecture allows it to adapt to different farm sizes and types, from small plots to large-scale agricultural operations. Moreover, the ability to continuously monitor environmental conditions contributes to improved crop yields, better resource conservation, and overall increased productivity. As a result, smart farming powered by IoT and WSN technologies offers a forward-looking solution that empowers farmers with actionable insights and precise control over their farming operations[22].

10. Sensor Security and Trust

Fully decentralized IoT architecture based on Distributed Ledger Technology (DLT) and smart contracts ensures secure and traceable sensor data exchange without relying on third-party trust, custom tokens, or centralized databases, with adaptable smart contracts controlling access by verifying authorized wallets and enabling secure interactions among users, software services, and IoT devices like smart sensors [23]. However, as IoT devices become increasingly integrated into homes, offices, cities, and industrial settings, they face growing security challenges, including sensor-based attacks due to a lack of proper security controls over sensors such as accelerometers, gyroscopes, and microphones [24][25].

This convergence of IoT with industrial environments introduces new attack surfaces, especially in mixed environments where IoT devices coexist with classical operational technology (OT) systems, often bypassing traditional security architectures like the defense-in-depth model outlined in standards such as IEC 62443 [25]. Sensor-based threats include data theft, malware delivery, and triggering harmful actions, necessitating robust protection strategies and comprehensive countermeasures, as detailed in surveys analyzing sensor types, known threats, and mitigation approaches [24].

Network segmentation emerges as an immediate security strategy when IoT devices lack built-in protections, while hybrid security approaches combining traditional industrial layers with dedicated IoT measures such as device authentication, access control, secure software deployment, and automated security management are recommended for future research [23]-[25]. Transparency and scalability are maintained through decentralized blockchain computations, public source code access, and smart contract execution records, demonstrated in industrial smart temperature sensor applications, offering a flexible solution while emphasizing ongoing security challenges in IoT sensor ecosystems [23]-[25].

11. Conclusion

The convergence of sensor technologies with the IoT, IoE, AI, and WSN has revolutionized modern infrastructures across multiple domains including industrial automation, smart cities, healthcare, and agriculture. Sensors serve as foundational elements enabling real-time data acquisition, intelligent decision-making, and autonomous system operations.

A comprehensive overview was presented, covering sensor classifications, architectures, and their integration across diverse applications—ranging from wearable health monitoring systems and industrial IIoT frameworks to environmental monitoring and smart home automation. Emphasis was placed on the role of machine learning, AI, and blockchain technologies in enhancing the reliability, intelligence, and security of sensor-based systems. Innovations in energy harvesting, wireless communication protocols, and cloud-edge integration have further driven sensor networks toward greater efficiency and scalability.

Despite these advancements, challenges remain in areas such as security, trust, and interoperability across heterogeneous systems. Addressing these limitations requires the development of robust, secure, and scalable sensor infrastructures capable of adapting to dynamic environments while ensuring data integrity and system resilience.

In summary, sensors are not merely data-gathering components but critical enablers of smart, connected ecosystems. Their ongoing evolution will continue to influence the trajectory of digital transformation in smart cities, industrial systems, and beyond—reinforcing their indispensable role in automation, intelligence, and sustainability.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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