

# Applications of Intelligent Sensors in Smart Homes: A Review

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**Abstract-** Smart homes are swiftly evolving into intelligent, autonomous ecosystems that improve home comfort, security, and energy efficiency. The integration of intelligent sensors, aided by the Internet of Things (IoT), artificial intelligence (AI), and sophisticated wireless communication protocols, is key to this change. This paper provides a comprehensive overview of the types, functions, and applications of intelligent sensors in smart homes, including motion detection, energy management, indoor air quality monitoring, moisture and leak detection, and flame and dangerous gas detection. Edge/fog computing, cloud platforms, and federated learning technologies that enable intelligent sensing are rigorously studied, along with system-level architectures that support seamless automation. Despite the potential, issues such as data privacy, interoperability, system stability, and the limitations of low-cost sensors remain. This study emphasizes on future research approaches focused on robust security frameworks, decentralized intelligence via federated learning, and improved sensor accuracy, all of which aim to achieve scalable, resilient, and truly intelligent smart homes.

**Keywords –** Intelligent Sensors, Smart Homes, Internet of Things (IoT), Wireless Communication Protocols, Artificial Intelligence and Machine Learning.

## I. INTRODUCTION

Smart homes are dwelling environments with all appliances linked together forming a centralized, but controlled and monitored system using Internet of Things (IoT) sensors combined with information and communication technology, providing convenience, strengthening security measures, reducing energy consumption, and promoting smart living [1-5]. Smart homes, also referred as intelligent homes can be monitored, managed and controlled remotely with smartphones, laptops or tablets [6]. The Internet of Things (IoT), a vast interconnected network of computer devices (e.g., intelligent sensors), swiftly exchange enormous amounts of information and stands out as a potential technology for smart home applications (intelligent living) [7, 8].

Traditional home management systems relied mainly on physical interventions and little data analysis. Advances in artificial intelligence (AI) and machine learning (ML) provide increasingly sophisticated methods for analyzing large datasets, predicting future energy trends, and optimizing energy/power using techniques such as Support Vector Machines (SVMs), Random Forests, and Neural Networks [9, 10].

Intelligent sensors collect information about the environment as they detect changes in temperature, light, humidity, motion and energy consumption [9]. Smart houses collect data using sensors, IoT protocols connectivity, and actuators to execute

orders, establishing a digital ecosystem that takes only a few seconds to update the data system [1, 11]. The rapid growth of the Internet of Things, big data technology, artificial intelligence, 5G and virtual technologies, such as augmented reality (AR), virtual reality, and other technologies, has facilitated the continuous innovation of smart products and services, which can better meet the diverse needs of people [12, 13].



Fig. 1. Schematic example of a smart home.

Smart homes equipped with assisted living sensors and intelligent products can offer smart care services to residents by monitoring and observing their environmental conditions, physical signs, voice, and facial expression data, and even contacting designated carers in the event of unusual activity,

thus ensuring the safety and self-reliance of residents' lives, and by monitoring the cognitive status and physical condition of the elderly through intelligent devices, it is feasible to recognize their health problems in advance, which can dramatically extend life expectancy [12, 13]. A schematic example of a smart home equipped with assisted living sensors and smart products is depicted in Fig 1.

## II. OVERVIEW OF SMART SENSORS

A smart home must understand and identify the activities of residents in order to provide smart services [14]. Sensor technology plays a crucial role in the paradigm of smart homes in direct environmental sensing, where binary sensors in conjunction with video cameras and Radio-Frequency Identification (RFID) technology provide a comprehensive understanding of the residents' activities and the contextual nuances of their home's surroundings [5]. Actuators and sensors, which replace traditional light switches, acquire data from the surrounding environment and execute commands. Controllers interpret sensor data manage inter-device communication and user interfaces, serve homeowners in smart home automation [15]. Adhikary et al. [16] said that Field Programmable Gate Array (FPGA) was connected with Global System for Mobile Communication (GSM) handset to overcome issues in continual communication such as poor mobility, limited updating capabilities, and reliance on personal computers. A wireless sensor network (WSN) was built by integrating IoT and ZIGBEE technologies via 3G connection, producing Zi SAS or ZigBee sensors that give smartphone users access and control of their smart homes [1]. The primary categorizations of sensors for detecting human activity in smart homes are illustrated in Fig. 2.

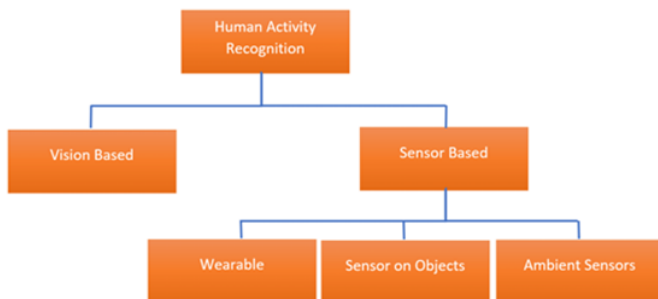


Fig. 2. Human activity recognition approaches[14].

### A. Types of Sensors in Smart Homes

Sensors are small, complex devices that detect changes in the environment and convert them into electrical signals and are employed in smart homes in optimizing energy consumption, ensuring safety, and providing enhanced services and comfort for the occupants[5].

**Motion Sensors:** Motion sensors, electronic devices that detect the motion or changes in position of nearby people or objects

within their range. Motion sensors are grouped into Passive Infrared (PIR), Microwave, Active Ultrasonic, and Dual Tech/Hybrid sensors and work by detecting changes in infrared radiation, heat, or sound patterns, triggered when an object, person, or animal enters its coverage area [17].

**Occupancy Sensors:** Occupancy sensors are indoor devices used to detect the presence of people in a specified space or area. They provide basic data on whether or not an area is vacant or occupied and help manage lighting, HVAC, and security systems efficiently [18].

**Temperature and Pressure Sensors:** Temperature sensors detect and measure temperature changes (heat and cold) and are vital for monitoring and controlling heating, ventilation, and air conditioning (HVAC) systems to maintain comfortable indoor temperatures. Pressure sensors detect and measure the force exerted by a fluid (liquid or gas) on a surface or in the atmosphere and are used for monitoring or detecting the presence of certain indoor gases levels, assisting in maintaining good air quality [19, 20].

**Contact and Proximity Sensors:** One of the ways to enhance security and automation at home is by placing contact sensors on doors, windows, cabinets, or drawers. These sensors will alert you if they are opened or closed. On the other hand, proximity sensors can help determine whether an object or person is near the sensor or not. This feature of the sensor comes handy and allows for touchless control in certain situations [21].

**Chemical Sensors:** Chemical sensors are able to identify different harmful chemicals or pollutants including carbon monoxide, volatile organic compounds, smoke, and gas leakages as well as measure their levels in smart homes for environmental monitoring [22].

**Light Sensors:** Light sensors find the amount of light that is around and how strong it is. They help the applications automatically in controlling the lights, security systems and also in optimizing solar power [23].

**Sound and Acoustic Sensors:** Sound and acoustic sensors are devices that detect and measure the presence and characteristics of sound, such as the level, frequency, or direction [24]. In a smart home setting, these audio sensors are mainly intended to serve as security features or safety devices. For example, they can help detect breaking glass, monitor a baby, and recognize the sound of a smoke or carbon monoxide alarm. Microphone arrays paired with signal processing algorithms can distinguish habitual sounds from unusual incidents, such as a window breaking or a person falling, triggering alarms and activating other security measures. At the same time, voice assistants rely heavily on acoustic sensors and nowadays, they are the main means by which users interact with automated home systems [25].

**Image and Depth Sensors:** Image and depth sensors such as RGB cameras, infrared cameras, and time-of-flight (ToF) sensors provide a spatial and visual context that other sensor

types lack [26]. In smart home scenarios, they assist with gesture-based controls, fall detection for elderly residents, facial recognition for access, and monitoring occupants' posture and activities [27]. Depth sensors offer an extra advantage by capturing three-dimensional spatial data without storing identifiable photographs, which helps mitigate privacy concerns associated with regular cameras [28, 29].

**Vibration and Biometric Sensors:** With vibration sensors, it is possible to detect mechanical vibrations that travel through surfaces [30]. In smart homes, they are used to identify break-in attempts, appliance failures, or structural changes. The most common vibration sensors in smart homes are piezoelectric and MEMS accelerometers. They are installed on doors, windows, and walls and become active when impacted or when unusual vibration patterns occur [31]. Biometric sensors such as fingerprint readers, iris recognition modules, and facial recognition systems offer more security for access control than traditional keypad and RFID card systems. Access is based on the individual's unique physiological characteristics [32].

### III. APPLICATION OF INTELLIGENT SENSORS IN SMART HOMES

With the key developments of 5G communication and Internet of Things (IoT) technologies, varied IoT devices and wearable electronics have been developed in the past few years, aimed for a wide range of applications in environmental monitoring, motion tracking, human-machine interaction, health care, big data, intelligent sport, smart home, smart traffic, smart farming, and smart industry[33, 34].

#### A. Home Automation System Based on Speech Recognition and IoT

Smart home automation systems have utilized innovative methods to improve domestic environments' connectivity, efficiency, and adaptability[35]. Speech recognition has been utilized in smart home automations for organized remote control, demonstrating the potential of voice control to supplement home security, particularly in terms of user experience and accessibility. A Kinect v2 sensor uses voice commands or communications with enhanced audio clarity to send commands to a central controller, which is then processed, as shown in Fig. 3 [1, 35].

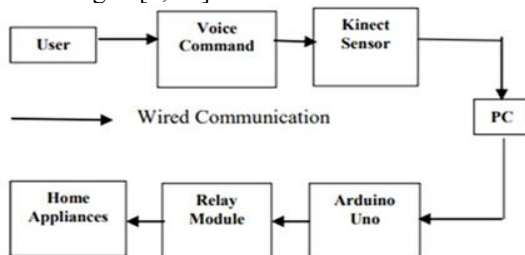


Fig. 3. Schematic representation of home automation system based on speech recognition[1].

Actuators and sensors collect data from the surrounding environment to provide input to home appliances. Microprocessors supply input to the relay board, and the hardware interface module connects the home automation system's sensors and actuators, allowing the end user to access the server with the same technology[1]. IoT-enabled door sensors, motion sensors, and safety cameras detect illegal entries, enhance home safety, and provide cloud-based storage and remote access, as illustrated in Fig. 4 [15]. Raspberry Pi combines cameras and motion sensors into a web application to control household appliances linked to an internet-based monitor. Blynk uses a 4-channel relay module and a NodeMCU ESP8266 to remotely manage and control various equipment in smart homes where the Blynk transmits commands and the 4-channel relay controls appliances [1].

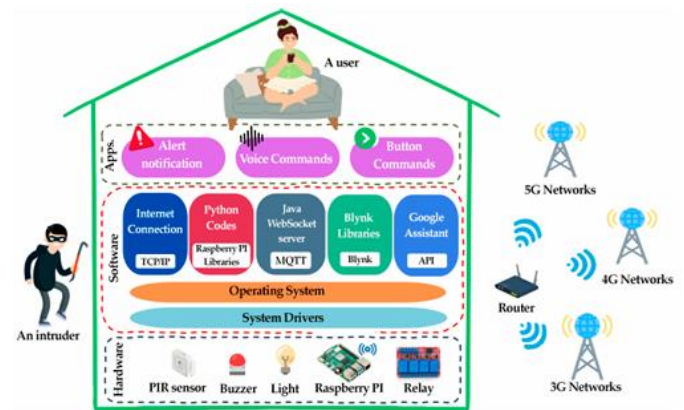


Fig. 4. IoT-based smart home framework using the PIR intruder detection system[35].

#### B. Intelligent Energy Management and Storage

Smart homes incorporate IoT as a means of reducing pollution impacting the environment, enhancing grid stability, user contentment, optimizing energy usage and efficient utilization of renewable energy sources (RESS) [9, 10]. Machine learning algorithms can predict energy consumption using techniques like Support Vector Machines (SVM), Random Forests, and Neural Networks by providing insights into making informed decisions either on when to minimize usage or turn off the appliance. Home Energy Management System (HEMS) as proposed by Carli et al. combines IoT devices for forecasting power demand and optimizing the performance of appliances [6, 10]. Artificial Neural Networks (ANNs) teach machine to interpret data like a human brain in order to predict and solve complex issues with high accuracy without requiring human interference [2]. A simple ANN architecture is shown in Fig. 5a, whereas Fig. 5b illustrates the input-output structure of neurons in an ANN system. The use of low-power devices Wi-Fi when combined with TBSA in wireless sensor networks reduces energy consumption, allowing for additional sensors, a wider coverage range, and efficient encryption of information, hence enhancing overall system efficiency and flexibility [4].

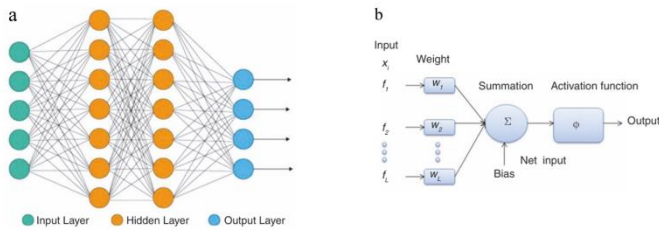


Fig. 5 (a) A simple ANN architecture, and (b) Input-output structure of neuron in ANN system.

IoT-based home energy management system (HEMS) may utilize derivation of comfort temperature, device-free sleep prediction, and occupancy probability-based outing prediction for heating control strategies such as outing, occupancy, comfort, and sleep-based control which tend to reduce energy consumption via real-time control of home appliances [2]. IoT sensors and thermostats can control HVAC systems to enhance comfort and energy efficiency, where smart thermostats recognize user behavior and integrate with occupancy sensors and weather forecasts [15].

Abnormal power usage that may reveal defects, inefficiencies, or unusual activity by users based on anomaly detection. Clustering, autoencoders, and one-class SVM are examples of machine learning-based systems for identifying irregularities in smart homes. These methods use previous data to predict routine power use and raise alerts in unusual situations [10]. Lithium-ion batteries, flow batteries, supercapacitors and emerging technologies such as hydrogen fuel cells, present high energy density, compact size, and cost-effectiveness, making them an ideal fit for residential applications because they enable the storage of excess energy generated by solar photovoltaic (PV) panels or other renewable sources, manage energy demand fluctuations in smart homes [9]. Fig. 6 shows the primary components of a typical smart home system with integrated energy storage.

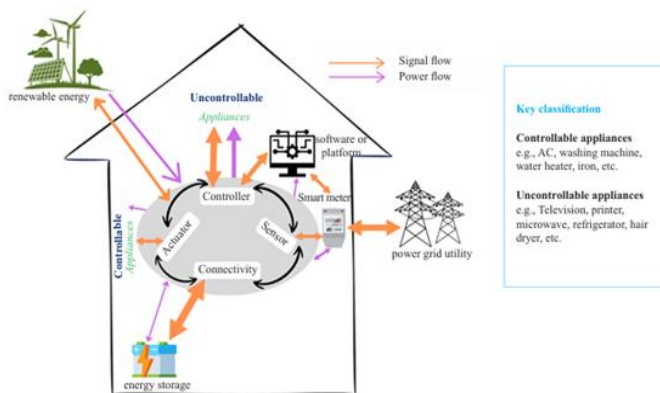


Fig. 6. Components of a smart home system with integrated energy storage [9].

### C. Indoor Air Quality Monitoring

Intelligent sensors in smart homes can monitor harmful pollutants inside buildings, such as carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), volatile organic compounds (VOC), particle matter (PM), aerosols, and biological pollutants. Deploying an air pollution LCS network with advanced communication technologies is sufficient to offer reliable information for analyzing the spatiotemporal distribution of indoor air pollutants and assessing personal exposures in smart homes. The primary steps involved in the successful implementation of smart indoor sensor networks in achieving appreciable indoor air quality (IAQ) is presented in Fig. 7. Indoor air quality (IAQ) is influenced by a variety of thermal comfort characteristics, most notably temperature and humidity. MQ135 is emphasized as a multi-gas sensor for IAQ measurements, as it can measure many various parameters such as CO<sub>2</sub>, benzene (C<sub>6</sub>H<sub>6</sub>), ethanol (C<sub>2</sub>H<sub>5</sub>OH), NO<sub>x</sub>, ammonia (NH<sub>3</sub>), and smoke [36, 37].

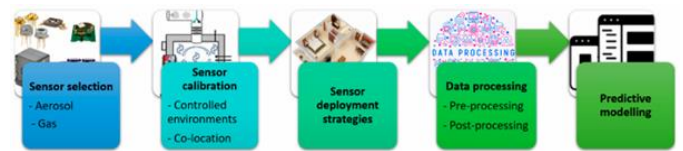


Fig. 7. Essential steps toward a successful implementation of smart indoor sensor network in achieving appreciable indoor air quality (IAQ) and health benefits to home occupants [37].

### D. Intelligent Controlled Moisture-Leak Detection and Home Irrigation/Farming

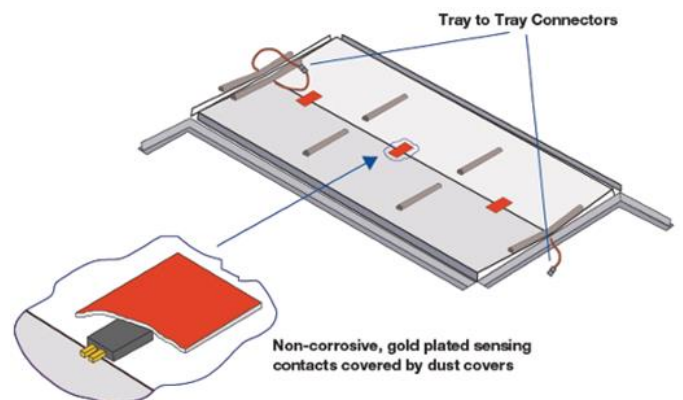


Fig. 8. Ceiling tile water detector [7].

The development of intelligent sensing technologies has enabled the detection of human behaviors by distinguishing both physical and physiological information. High sensitivity and rapid reaction are important for humidity sensors applied in this setting [38]. Moisture sensors can be employed in homes to detect potential leaks and moisture levels. A ceiling tile water detector is illustrated in Fig. 8. Resistive, capacitive, and

thermal conductivity sensors possess electrodes, and when they come into touch with moisture, they change in their resistance/electric flow, charging-discharging, and humidity [7]. IoT sensors can gather data on soil, water, light, humidity, and temperature, among other things. Automation of smart home irrigation or farming management enhances the sanitation and tranquility of the living environment and prevents the infection of hazards posed by epidemic viruses[3].

### E. Flame and Toxic Gas Detection

Gas sensors have posed an important contribution to mankind in the detection of various gases and pollutants and made life comfortable[39]. A flame detector is a sensor developed to detect and respond to the presence of a flame or fire. These sensors work by identifying the radiation (UV, IR, Visible and combinations) emitted at the point of ignition. Photoelectric and ionization sensors detect slow and high burning flames as they are highly sensitive and triggered by stem. Thermocouples have been utilized in heating systems and gas ovens to detect the presence of flames [7]. Toxic gas sensors may detect a variety of gases, including petroleum gas, smoke, alcohol, propane, hydrogen, methane and carbon monoxide (CO). These sensors can distinguish the type of gas based on oxygen density while also measuring current flow [40].

### F. Healthcare and Elderly Care Monitoring

One of the most significant uses of smart home intelligent sensors is in the constant monitoring of health and well-being, especially for elderly or physically challenged residents[41]. Wireless and surrounding sensors can measure vital body signs like heart rate, blood oxygen saturation, respiratory rate, and temperature, warning caregivers and doctors if the readings are abnormal [42, 43]. The use of PIR sensors, accelerometers, or depth cameras in fall detection systems can not only recognize a fall but also send emergency alerts immediately so that help can be dispatched quickly even if the resident is incapacitated. Smart mattresses and floor pressure sensors can measure sleep quality, changes in posture, or detect if a person has been staying inactive for too long. These systems that monitor both mental and physical symptoms over time can not only help in the early recognition of the worsening of a disease but also give support to those who wish to maintain their independence and lead a more fulfilling life especially the elderly who are living alone [43, 44].

### G. Security and Access Control

Smart home security systems combine different types of sensors to create multi-level defense against intrusion, theft, and unauthorized access. A door and window contact sensor, a PIR motion detector, a glass break sensor, and an outdoor camera are the together elements of a solution to monitor the entire perimeter [18, 45]. Video doorbells equipped with motion detection and facial recognition allow homeowners to screen visitors remotely, while smart locks controlled via biometric authentication or mobile credentials eliminate the

vulnerability of traditional physical keys [46-48]. Machine learning algorithms trained on historical activity data can distinguish between normal household patterns and suspicious behavior, reducing false alarm rates and improving response accuracy [49, 50]. Cloud-connected platforms enable real-time notifications and remote arming or disarming of security systems from any location.

## IV. TECHNOLOGIES ENABLING INTELLIGENT SENSING

### A. Internet of Things (IoT)

Intelligent or smart home ecosystems are built on the IoT paradigm, which is defined by a physical device's internet connectivity. IoT-enabled devices with sensors and actuators may communicate with centralized control systems and each other in order to automate, monitor, and remotely manage home environments [51]. The Internet of Things (IoT) provides the framework for connecting sensors to actuators, data hubs, and cloud platforms, as shown in Fig. 9. Devices interact using protocols such as MQTT, CoAP, and HTTP REST APIs, enabling interoperability across different brands and systems [52, 53].

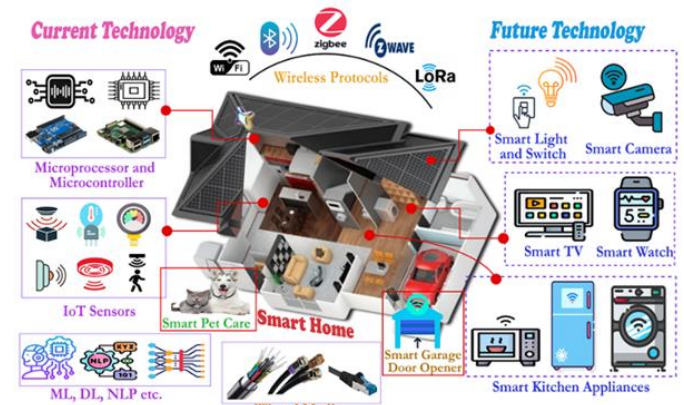


Fig. 9. Intelligent sensing technological evolution in smart home automation[6].

### B. Wireless Communication Protocols

The rapid development of wireless communication technologies has made it possible to connect numerous edge devices to the Internet of Things (IoT) through their intelligent wireless sensing modules, thus bringing about the Artificial Intelligence of Things (AIoT) era [54]. This approach does not require complex wiring and provides a wide range of deployment options[51]. Sensor connection protocols are Zigbee, Z-Wave, Wi-Fi, Bluetooth Low Energy (BLE), and Thread. They differ in range, bandwidth, energy consumption, and device density. Detection of an object's presence and motion can lead to changes in the wireless signal's reflection, which manifest as variations in amplitude, phase, angle of arrival (AoA), and time-of-flight parameters [55-57].

A major step forward for smart home wireless standardization is the Matter protocol, which has major industry players such as Apple, Google, Amazon, and Samsung supporting it. Matter uses Thread for low-power mesh networking and IP-based communication, and it offers a single application layer that enables interoperability across devices and ecosystems, regardless of maker. Its implementation solves the long-standing fragmentation issue in smart home connectivity and will likely speed up device integration and make consumer deployments easier [58].

### C. Artificial Intelligence (AI) and Machine learning (ML)

Intelligent algorithms installed at the edge or in the cloud improve sensor performance via predictive modelling, anomaly detection, and user behavior learning. The integration of ML and IoT can provide intelligent security solutions for smart homes [51]. For instance, sensors trained to recognize breathing patterns can detect sleep apnea.

### D. Edge and Fog Computing

The combination of quantum computing and artificial intelligence, referred to as quantum machine learning, uses established artificial intelligence technology to address quantum computing's problems [54]. Edge computing, rather than transferring all data to a cloud server, enables real-time decision-making on-site. This lowers latency, saves bandwidth, and improves privacy [59].

### E. Cloud Platforms and APIs

Cloud computing platforms provide versatile storage and processing capability to handle and analyse huge amounts of data generated by smart home equipment [51]. Cloud platforms such as AWS IoT, Google Cloud IoT Core, and Azure IoT Hub use APIs to provide remote access, data storage, analytics, and automation logic.

## V. CHALLENGES AND LIMITATIONS

Though Smart Home Energy Management Systems (SHEMS) have progressed quite a bit, figuring out how to ensure users' privacy, having an accurate way to know who's home, and offering ways for homeowners to have res integration with renewable energy sources for management systems are still the challenges that are preventing new developments in this area [10]. Effective connection and interaction are typically hampered by interoperability issues among smart devices from different manufacturers. System malfunctions during network outages or cyberattacks arise, while relying on stable internet access and widespread adoption may be hampered by user adoption difficulties, such as complicated installations and high charges [4].

While smart home sensors strengthen security, excessive dependence on technology can lead to carelessness. Homeowners may believe that the system is foolproof, ignoring

additional security measures like as physical locks or offline backups. Sensors are prone to erroneous notifications, which can undermine trust in the system's performance. Motion sensors, for example, may cause false alarms because of dogs or abrupt movements, resulting in unwanted alerts and inconvenience for homeowners [5].

A great number of low-cost, dangerous gas sensors deployed in smart homes are unreliable because they cannot discriminate between distinct chemicals and instead produce a general estimate, based on a reference gas [7].

## VI. FUTURE PROSPECTS AND RESEARCH DIRECTIONS

Encrypted communication protocols, frequent software updates to patch flaws, and reliable verification techniques such as multiple-factor authentication and biometrics to prevent unauthorised access to devices and data are all ways to ensure privacy and security in smart homes. Empirical risk assessment techniques are vital because they recognise the importance and accessibility to private information, resolving security and privacy issues that result from[4].

Machine learning technologies, which are subsets of AI, power many aspects of modern civilisation and are rapidly being integrated into consumer devices such as cameras and phones. Combining relevant learning algorithms with specific sensing systems can obtain more complete information to effectively regulate the sensor systems [8].

Federated learning and edge computing could be a solution to address the latency and privacy issues in smart home energy management. Federated learning develops ML models directly on the devices instead of sending private data to a central server, thus privacy of the user is ensured. There is a need for future studies to enhance the security, scalability, and efficiency aspects of edge computing and federated learning so that their mass deployment in smart homes is both feasible and performance as well as privacy is maintained [9, 60].

## VII. CONCLUSION

The use of smart sensors in smart homes is not only a matter of having the latest gadgets but it has become an indispensable part of residential infrastructure today. These sensors, which run on the Internet of Things (IoT), Artificial Intelligence (AI), and communication protocols of the modern era, have resulted in precise environmental monitoring, energy optimization, enhanced security, better indoor air quality, and all these combined results in safer, healthier, and more efficient lifestyle spaces. Intelligent sensing has provided such a huge potential to revolutionize home living, that from voice-controlled automation to energy projections based on anomalies to smart

leak detection are just some glimpses of the wide array of possibilities that the smart sensing can offer.

Nonetheless, there are still many challenges that stand in the way of the wide acceptance and use of these systems. The major issues that must be tackled to make the trust and functionality of these systems last in the long run are privacy, system compatibility, sensor false positives, and the limited precision of low-cost detection systems. Besides, due to the reliance on cloud systems, the problems of latency and security risks creep in and these can be handled by edge computing and federated learning.

The big thing for smart homes in the future is decentralization of their intelligence level, enabling them to make even faster and more precise decisions and safeguarding the users' data through secure, adaptive, and context-aware sensing systems. The advancement of AI, particularly in privacy-preserving technologies and hardware-efficient algorithms, will be key components of this evolution. The homes of the future that are equipped with smart technologies will not just react to the users but will also forecast their needs and accordingly change themselves, learn and become fully intelligent environments.

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