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Research Article

Smart Home Sensor Systems: Advancements and Applications

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Abstract: A smart home is a technologically equipped residence that proactively observes its residents and offers various services. It has emerged as a potential solution to support independent living for people with disabilities and older adults, while also relieving the burdens on family caregivers and healthcare providers. A fundamental aspect of smart homes is their capability to monitor daily living activities and ensure residents' safety by detecting changes in their routines. With the advancements in technology, modern smart homes are furnished with numerous low-power sensors, radios, and embedded processors that collaboratively process data to assess the home's state and the behaviors of its occupants. This article delves into the sensor technology employed in smart homes, with a particular focus on direct environment sensing and infrastructure-mediated sensing. It explores the strengths and limitations of different sensor technologies and discusses the challenges and opportunities from technical, and ethical perspectives.

Keywords: Sensor Technology; Smart Home; Applications; Challenges.

أنظمة الحساسات الذكية للمنازل: التطورات والتطبيقات

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الملخص: المنزل الذكي هو سكن مجهز تكنولوجياً يراقب سكانه بشكل استباقي ويقدم مجموعة من الخدمات المختلفة. ظهر كحلاً محتملاً لدعم العيش المستقل للأشخاص ذوي الإعاقة وكبار السن، وفي نفس الوقت تخفيف أعباء مقدمي الرعاية العائلية ومقدمي الرعاية الصحية. جانب أساسي للمنازل الذكية هو قدرتها على رصد أنشطة الحياة اليومية وضمان سلامة السكان عن طريق اكتشاف التغييرات في روتينهم. بفضل التقدم التكنولوجي، تتمتع المنازل الذكية الحديثة بالعديد من الأجهزة المنخفضة الطاقة مثل الحساسات والأجهزة اللاسلكية والمعالجات المضمنة التي تقوم بمعالجة البيانات بالتعاون معًا لتقييم حالة المنزل وسلوك سكانه. تتناول

هذه المقالة تكنولوجيا الحساسات المستخدمة في المنازل الذكية مع التركيز بشكل خاص على استشعار البيئة المباشرة والاستشعار المتوسط للبنية التحتية. كما تستكشف مزايا وعيوب مختلف تقنيات الاستشعار وتناقش التحديات والفرص من منظورات فنية وأخلاقية.

الكلمات المفتاحية: تكنولوجيا الاستشعار ؛ المنزل الذكي؛ التطبيقات ؛ التحديات.

1. Introduction

A smart home denotes a technologically augmented dwelling equipped with an array of sensors to meticulously monitor the surrounding environment, complemented by sophisticated devices and actuators, all of which work in concert to offer proactive and contextually tailored services [1,2]. The primary objective of this cutting-edge concept was initially centred on optimizing convenience, fortifying security measures, and curbing energy consumption. However, over the past decade, there has been a noticeable shift in the focus of smart home technology towards accommodating individuals with compromised capabilities due to the effects of ageing or disability. This growing interest can be attributed to the potential of smart homes to empower older adults and individuals with disabilities to retain their independence while residing in the familiar comfort of their own homes, thereby mitigating the often considerable demands placed on familial or professional caregivers [3,4].

In the contemporary landscape, smart homes have proliferated across the globe, encompassing a diverse array of implementations. Notably, a significant proportion of these domiciles primarily serve as corporate exhibition spaces or research laboratories, devoid of regular residents, and function as platforms for demonstrating the cutting-edge capabilities of the technology. Conversely, there exists a smaller subset of smart homes that genuinely serve as residential abodes, including group homes, outfitted with sensors adept at monitoring resident behaviors and promptly detecting anomalies [5].

An integral facet bolstering the functionality of a smart home lies in its adeptness at meticulously monitoring the inhabitants' activities of daily living and ensuring their safety. This capability is made possible by the widespread availability of cost-effective, low-power sensors, radio frequency chips, and embedded processors, which collectively furnish existing smart homes with an extensive array of networked sensors. These sensors collaboratively process and infer insights from the gathered data about both the state of the domicile and the activities and behaviors of its occupants. The present article undertakes a comprehensive examination of sensor technologies utilized within smart homes, meticulously analyzing the respective strengths and limitations inherent to different sensor types. Figure 1. presents the working of the sensor. Furthermore, the discourse expounds upon potential avenues for future advancements in this domain.

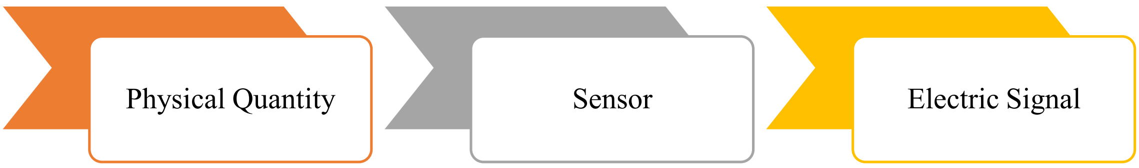

Figure 1. Illustration view on the working of the sensor.

According to [6], the unyielding progression of technological advancements has given rise to captivating prospects for smart home services. However, before smart home technologies and their equivalents attain a level of maturity denoted by a sufficiently high technology readiness level (TRL), there exist substantial hurdles that must be surmounted for these innovations to achieve mainstream integration. The challenges encountered are multifaceted, encompassing the inherent intricacy of smart home systems, despite their constrained operational environments. Numerous technical obstacles, such as the scarcity of robust and scalable technologies, impede the seamless deployment of smart home solutions. Moreover, challenges arising from human factors and sociotechnical considerations further compound the complexities faced in this domain.

In reference [7], the study elucidates the conceptualization and realization of a novel platform founded on the principles of the Internet of Things (IoT) and cloud computing. This platform is specifically engineered to empower users with remote control and monitoring capabilities over a Wi-Fi wireless e-switch installed within their homes through a dedicated mobile application. By its implementation, this platform serves as an initial stride toward transforming a conventional dwelling into an intelligent and interconnected smart home environment. A prominent feature of this system is its adeptness in capturing and storing pertinent information about the e-switch, facilitating its utilization for subsequent processing and comprehensive analysis.

The present study [8] posits a novel smart home environment comprising edge nodes and users, aiming to optimize user utility. By envisioning all users and edge nodes within a market-based framework, we proffer a pricing-oriented resource allocation model specifically designed for utility maximization. This research endeavour holds the potential to usher in a new era of secure, efficient, and interconnected smart home ecosystems, leveraging the transformative capabilities of edge computing. By shedding light on the promise of edge-based solutions, this study contributes to the advancement of the Internet of Things (IoT) for Smart Homes, unravelling novel prospects and avenues for exploration in this dynamic and burgeoning field.

The remaining sections of the paper are organized as follows: In **Section 2**, the paper delves into the core concepts of sensor technology for smart homes. **Section 3** presents a comprehensive overview of the different types of sensors used in smart homes. In this **section 4**, the paper explores the diverse applications of sensor technology in smart homes. **Section 5** addresses the challenges associated with implementing sensor technology in smart homes. The final section, **Section 6**, presents a concise summary of the paper's key findings and discussions.

2. Sensor Technology

Sensor technology plays a pivotal role in the paradigm of smart homes. A prevalent approach adopted by contemporary smart homes involves the implementation of ubiquitous sensing, wherein a network of sensors is intricately integrated with a network of processing devices, yielding a comprehensive and multi-modal data stream [9-13]. This intricate web of sensory data is subject to rigorous analysis aimed at identifying and monitoring both basic and instrumental activities of daily living undertaken by the residents, encompassing tasks such as bathing, dressing, meal preparation, and medication adherence. By employing this approach, smart homes possess the inherent potential to capture and discern patterns that may serve as indicative reflections of the resident's physical and cognitive well-being. Consequently, this analytical prowess facilitates the timely recognition of deviations from individualized norms, and can promptly identify atypical behaviour that might signify underlying issues or necessitate timely intervention [15,16].

2.1 Direct Environmental Sensing

In the realm of smart homes, direct environmental sensing is a prevailing approach that entails the strategic deployment of numerous simple binary sensors positioned throughout the household, in conjunction with the incorporation of video cameras and Radio-Frequency Identification (RFID) technology. Through this arrangement, a wealth of valuable insights can be gleaned, offering a comprehensive understanding of the residents' activities and the contextual nuances of their living environment. However, it is essential to acknowledge that such an approach is not bereft of practical and complex costs, as highlighted in prior research. One prominent challenge pertains to the expenses incurred during the installation and maintenance phases of this sensor infrastructure. These costs can be substantial, particularly when attempting to retrofit existing homes with the requisite sensor networks. The intricacies involved in integrating sensors seamlessly into the pre-existing infrastructure of homes can lead to cost-prohibitive measures. Moreover, the maintenance of this intricate sensor network demands diligent oversight and upkeep, which may contribute to ongoing financial burdens.

Another critical aspect that warrants consideration is the potential intrusion on residents' privacy. The deployment of video cameras for surveillance purposes, while instrumental in capturing detailed visual information, can raise concerns about the infringement of personal space and data security. Addressing these privacy apprehensions is paramount to ensuring the successful adoption and acceptance of smart home technologies within society. Furthermore, it is imperative to recognize the limitations of an instrumented environment when dealing with scenarios involving multiple residents cohabiting within the same living space. The capacity to accurately discern activities and behaviours becomes inherently complex in such instances, as the amalgamation of different individuals' actions can obscure the interpretability of sensor data. This highlights the need for sophisticated algorithms and advanced processing techniques to disentangle and attribute activities to specific individuals in multi-resident environments.

2.2 Infrastructure Mediated Systems

In recent times, infrastructure-mediated systems have garnered significant attention as an unobtrusive, cost-effective, and practical approach to activity classification within the domain of smart homes. In comparison to the conventional installation of simple binary sensors throughout an entire household, infrastructure-mediated systems necessitate the strategic placement of one or a limited number of sensors along the pre-existing infrastructure. This streamlined deployment approach results in a notable reduction in both the financial outlay and the intricacy of setup and maintenance procedures. Nevertheless, it is essential to acknowledge that such systems may not fully encompass the granular details pertaining to activities and their respective contexts. An illustrative example of this infrastructure-mediated approach is the work conducted by Patel et al., wherein the existing ductwork infrastructure of central heating, ventilation, and air conditioning (HVAC) systems was ingeniously utilized for activity detection purposes. The researchers equipped the HVAC's air filter with five pressure sensors, each capable of bidirectional sensing. By analyzing the magnitude of pressure fluctuations across all sensors, they sought to identify distinctive changes in airflow within the physical space, attributable to human inter-room movements. These encompassed activities such as individuals walking through specific doorways or the act of opening and closing particular doors. Initial findings from this endeavor demonstrated the system's competence in accurately classifying unique transition events with a notable accuracy range of 75–80%. This outcome serves as a promising indicator of the potential effectiveness of infrastructure-mediated systems for activity classification in smart homes. While infrastructure-mediated systems offer compelling advantages in terms of cost efficiency and practicality, it is essential to recognize that their efficacy might be constrained concerning capturing intricate activity details. Consequently, further research and refinements are warranted to enhance the resolution and comprehensiveness of these systems for robust and context-rich activity classification within smart home environments.

3. Types of Sensors

The integration of sensor technology into smart homes has revolutionized the way we interact with our living spaces. Sensors are small, sophisticated devices that detect changes in the environment and convert them into electrical signals [17-22]. In smart homes, these sensors play a crucial role in automating various tasks, optimizing energy consumption, ensuring safety, and providing enhanced comfort for the occupants. Here are some of the most common types of sensors used in smart homes:

- Motion Sensors: Motion sensors detect movement within their range and are used for various applications, such as turning on lights when someone enters a room or triggering security alarms.
- Temperature Sensors: These sensors measure the ambient temperature and are essential for controlling heating, ventilation, and air conditioning (HVAC) systems to maintain comfortable indoor temperatures.
- Light Sensors: Light sensors measure the intensity of ambient light and can be used to automate lighting systems, adjusting artificial lighting based on natural light levels.
- Occupancy Sensors: Similar to motion sensors, occupancy sensors are specifically designed to detect the presence of people in a particular area. They help manage lighting, HVAC, and security systems efficiently by determining when rooms are occupied or vacant.
- Humidity Sensors: Humidity sensors monitor the moisture levels in the air and are crucial for maintaining a healthy indoor environment and preventing issues like mold growth.
- Door and Window Sensors: These sensors detect whether doors and windows are open or closed. They play a vital role in smart home security, alerting homeowners to any potential breaches.
- Contact Sensors: Contact sensors can be used on doors, windows, cabinets, or drawers to detect when they are opened or closed, providing additional security and automation options.

- Smoke and Carbon Monoxide Sensors: These sensors are critical for safety. They detect the presence of smoke or dangerous levels of carbon monoxide and trigger alarms to protect the occupants.
- Water Leak Sensors: Water leak sensors are placed in areas prone to water leaks, such as near plumbing fixtures, to detect leaks early and prevent water damage.
- Gas Sensors: Gas sensors detect the presence of various gases, such as natural gas or propane, and can be used for safety or environmental monitoring purposes.
- Motion-Activated Cameras: These devices combine motion sensors with cameras to provide security monitoring and video recording when motion is detected.
- Flood Sensors: Flood sensors are designed to detect rising water levels, helping to prevent flooding and water damage in basements and other vulnerable areas.
- CO2 Sensors: CO2 sensors monitor the carbon dioxide levels in indoor environments, assisting in maintaining good air quality.
- Sound Sensors: Sound sensors can detect certain noises or sound patterns and be used for applications like detecting glass breakage or monitoring a baby's cries.
- Proximity Sensors: Proximity sensors can determine the presence or absence of an object or person close to the sensor, enabling touchless control in some scenarios.

Sensor technology is a cornerstone of smart homes, enabling homeowners to create energy-efficient, secure, and convenient living environments. While there are some challenges to address, continuous advancements in sensor technology and home automation systems steadily overcome these obstacles. As smart homes become more accessible and refined, the benefits they offer in terms of comfort, efficiency, and safety are expected to become increasingly widespread and impactful.

4. Applications

Sensor technology has a wide range of applications in smart homes, enabling automation, enhancing security, improving energy efficiency, and providing personalized comfort. Table 1, presents several applications of sensor technology for smart homes.

Table 1. Several applications of sensor technology for smart homes.

Ref.	Year	Type of Sensor	Aim	Application
[23]	2023	wearable sensors	• This paper aims to make use of low-cost wearable sensing devices from Apache Flink and MbientLab an open-source broadcast engine, a short-term with a long memory network architecture, and categorization of fall. • This paper also examines the ideal Nyquist rate, sensor positioning, and multiple channeling information change using the training set, which was developed using the published dataset "MobiAct." With a 95.87% accuracy rate, our edge computing system can detect falls using real-time data stream analytics.	Smart home-care technology with the Internet of Things (IOT)
[24]	2023	Smart lighting system	• This article aims to design an IoT-based smart lighting system that reduces development costs and saves power consumption. • The system can be controlled using an app to turn on/off and adjust the luminance of lighting devices. Lastly, the lighting devices equipped with sensors collect specific data on cloud servers for analysis.	Lighting
[25]	2023	Remote patient monitoring (RPM)	• This paper aims to discuss the challenges and trends to adopt AI to RPM systems and implementation issues. The future directions of	Healthcare applications

			AI in RPM applications are analyzed based on the challenges and trends.	
[26]	2023	Contactless Sensing	• This paper demonstrates how two basic contactless sensors, such as piezoelectric transducers and strip electrodes (in a longitudinal interdigitated configuration to sense impedance inside and outside of the pipe with potential for impedimetric leak detection). • The paper investigates the measurement of water flow rate (up to 24 m3/s) and temperature with ultrasounds and of the pipe filling fraction (capacitance at 1 MHz with ~cm3 resolution) and ionic conductivity (resistance at 20 MHz from 700 to 1400 µS/cm) by means of impedance.	Smart Monitoring of Pipelines
[27]	2022	a natural wood-based triboelectric self-powered sensor (WTSS)	• This article deals with a WTSS for building the smart home system. Based on an effective and simple treatment strategy for natural wood, the WTSS shows superior sensitivity, flexibility, stability, and thinness. • Owing to the extensive use of wood materials in home construction, the WTSS is integrated with household facilities and applied in three real-time human–machine interfaces, including a smart home control system, a smart password gate control system, and a smart floor monitoring system.	Potential applications in the construction of smart homes and future cities
[28]	2022	Smart Wireless Climate Sensor	• This paper aims to present a smart wireless climate sensor node for indoor temperature and humidity monitoring with a powering strategy and design approach for autonomous operation. • This paper aims to develop a sensor node, which has a small error for temperature, and relative humidity sensed values resulting from calibration. • The experiment aims to show that the indoor temperature and relative humidity were measured and recorded in the range of 25–30 °C and 30–40%, respectively.	Indoor Comfort Quality Monitoring Application

These applications showcase the versatility and transformative power of sensor technology in creating smarter, safer, and more energy-efficient homes. As sensor technology continues to advance, smart homes are poised to become even more integrated, intuitive, and personalized to meet the diverse needs and preferences of their occupants

5. Challenges

While sensor technology for smart homes offers numerous benefits, it also presents certain challenges that need to be addressed for widespread adoption and seamless integration. Several of the key challenges include:

- Privacy and Data Security: With sensors continuously collecting data about occupants' activities and behaviours, there are legitimate concerns about data privacy and security. Unauthorized access to sensitive information could lead to breaches of privacy or even potential risks such as burglaries if data about occupancy patterns fall into the wrong hands.
- Interoperability: Smart homes often use devices from different manufacturers, leading to compatibility issues and difficulties in getting them to work together seamlessly. A lack of

standardized communication protocols can hinder the integration of various sensors and devices into a unified smart home ecosystem.

- Reliability and False Alarms: Sensors are susceptible to false alarms, which can erode trust in the system's effectiveness. Motion sensors, for example, may trigger false alarms due to pets or sudden movements, leading to unnecessary alerts and inconvenience for homeowners.
- Calibration and Maintenance: Sensors require periodic calibration and maintenance to ensure accurate and reliable performance. Dust, environmental factors, or wear and tear can affect sensor accuracy, leading to inaccurate readings or system malfunctions.
- Power Source and Battery Life: Many sensors rely on batteries for power, and frequent replacements or recharging can be inconvenient. Ensuring long battery life for sensors is crucial to minimize maintenance efforts.
- Cost: The initial investment in sensor technology can be significant, especially when retrofitting an existing home with smart capabilities. The cost of high-quality sensors and their installation can deter some homeowners from adopting smart home solutions.
- The complexity of Installation and Setup: Integrating multiple sensors and devices to work cohesively can be technically complex and may require professional installation. This complexity can be intimidating for some users who are not tech-savvy.
- False Sense of Security: While smart home sensors enhance security, over-reliance on technology can lead to complacency. Homeowners might assume that the system is foolproof, neglecting other security measures like physical locks or offline backups.
- Environmental Impact: The manufacturing and disposal of electronic sensors can have environmental consequences. Minimizing waste and using eco-friendly materials in sensor production are vital considerations.
- Connectivity and Network Reliability: For smart home systems to function properly, they depend on a stable and reliable internet connection. Network outages or connectivity issues can disrupt sensor data transmission and control functionalities.

Addressing these challenges requires collaboration among manufacturers, policymakers, and industry stakeholders. Striking a balance between innovation, privacy protection, and user experience is essential to ensure the successful integration of sensor technology for smart homes in a way that benefits consumers while safeguarding their privacy and security.

6. Conclusion

In conclusion, sensor technology has ushered in a new era of convenience, efficiency, and security for smart homes. By harnessing the power of various sensors, homeowners can transform their living spaces into intelligent environments that adapt to their needs and preferences. The applications of sensor technology in smart homes are diverse, ranging from energy optimization and enhanced security to health monitoring and environmental sustainability. However, the widespread adoption of sensor technology for smart homes also brings forth certain challenges that must be addressed. Privacy and data security concerns require robust measures to safeguard sensitive information and protect homeowners from potential risks. Ensuring interoperability among different devices and standardizing communication protocols will facilitate the seamless integration of smart home systems. To foster trust and reliability, efforts should be made to reduce false alarms and improve the calibration and maintenance of sensors. Additionally, cost considerations, installation complexity, and the environmental impact of sensor technology necessitate a mindful approach to balance accessibility, sustainability, and usability. As technology continues to evolve, manufacturers, policymakers, and industry stakeholders must collaborate to overcome these challenges and continue refining sensor technology for smart homes. Striking the right balance between innovation and user-centric design will pave the way for even greater advancements, making smart homes more accessible, secure, and efficient for a broader population. Ultimately, sensor technology for smart homes holds immense potential to revolutionize the way we live, creating spaces that are not only connected and automated but also responsive to the needs and well-being of their occupants. With careful consideration of challenges and a commitment to continuous improvement, the future of sensor technology in smart homes promises to be bright, offering unparalleled comfort, safety, and sustainability for homeowners worldwide.

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